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Soil Water Measurement and Thermal Indices for Center Pivot Irrigation Scheduling

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Abstract. *In this two-year study, the relationship between irrigation scheduling using soil water measurements, and two thermal indices was investigated. One-half of a three-span center pivot irrigated field was planted to cotton in circular rows and irrigated with LEPA (low energy, precision application) drag socks in furrow dikes. Infrared thermometers (IRTs), used to measure crop canopy temperature, were mounted on the center pivot spans. Replicated treatments established radially from the pivot point, received four amounts of water, 100%, 67%, 33% and 0%, where 0% was dryland (Dry) and the 100% amount was based on either soil water replenishment to field capacity (manually initiated) or on the automatic irrigation protocol called the Time Temperature Threshold (TTT) method. Three sectors (blocks) of radial plots were irrigated on odd-numbered days of year (DOY) based on neutron moisture meter (NMM) soil water measurements in a 1.5-m profile, while three sectors were irrigated automatically on even-numbered days based on the TTT method. Average cotton lint-yields, dryland, and water use efficiencies for 2007 were not significantly different between the automatic and manual blocks. Averaged paired yields for each irrigation level were only significantly different between manual and automatic blocks in the 67% treatment. A post analysis of the daily theoretical CWSI was performed and compared to a predetermined TTT index for each day during the period of automatic irrigation scheduling, showing that 92% of the automatic irrigation triggers occurred when the TTT index > 450 minutes and the theoretical CWSI was > = 0.5 for the two growing seasons. Combining the theoretical CWSI with a TTT index may improve automatic irrigation scheduling. Yield data for 2008 were not yet available.*

Keywords. center pivot, crop water stress index, irrigation scheduling, time temperature threshold index

Introduction

In the semi-arid Texas High Plains, approximately 75% of crop irrigation is accomplished by center pivots drawing groundwater from the Ogallala Aquifer. Average groundwater levels from the aquifer have declined by more than 50% (McGuire, 2003). From 1950 to 2005, the number of farms in the state of Texas declined by 33%, while land in farms decreased by only 15% (NASS, 2008). This typifies a national trend; the number of farms is decreasing, while farm size is increasing. For production to be profitable on larger farms, farmers must effectively operate their numerous irrigation systems with low management cost. Automated irrigation scheduling and control to meet crop water needs has the potential to improve water-use efficiency, assist in strategies to produce optimal yields, and decrease management time (Evett et al., 1996; 2006).

Irrigation scheduling can broadly be categorized into three paradigms based on measurements of: (1) weather, (2) soil water, and (3) plant condition (Jones, 2004). One method based on plant condition is the Time Temperature Threshold (TTT) method based on a canopy temperature threshold and a time threshold (Peters and Evett, 2007; Evett et al., 2006). Because it is a feedback method of automatic control, the TTT method does not require extensive supplementary inputs for triggering an irrigation; and it has been shown to allow control of water-use efficiency. Yields and water use efficiencies for drip irrigated soybean and corn were not significantly different using TTT than were those of manually irrigated plots (Evett et al., 2006). In work with center-pivot irrigated cotton, automatic irrigation scheduling was limited to even-numbered days of year (DOY) to allow for control sections to be manually irrigated on odd-numbered DOY (Peters and Evett, 2007).

In preparation for commercial application of the TTT method, it is desirable to make the method robust in the face of challenges such as plant disease and uneven plant stand with resulting uncovered soil. Testing of the TTT method in combination with a second irrigation trigger on a field of a larger-scale may help provide adjustments to this irrigation scheduling and control algorithm for successful commercial application.
A second irrigation trigger to consider for irrigation scheduling is the CWSI, developed in the early 1980s by Idso et al. (1981) who originated an empirical approach, requiring measurement of crop canopy temperature, air temperature and relative humidity. Jackson et al. (1981) developed a theoretical approach that required the additional measured inputs of solar radiation and wind speed, and the calculation of aerodynamic resistance (r_a). Researched extensively, the CWSI has been labeled a sensitive means to monitor and quantify plant stress for a variety of crops. Pinter et al. (1983) determined the CWSI to be inversely correlated to cotton yields. Howell et al. (1984) concluded that the CWSI was responsive to both matric potential stress and soil osmotic potential stress for cotton. Colaizzi et al. (2003a) showed that the Crop Water Stress Index was correlated with soil water depletion for a fully developed canopy when no soil reflectance was present. It was also determined that the Water Deficit Index (WDI), which is a two-dimensional CWSI (Moran et al., 1994) normalized for vegetation cover, was correlated with crop water stress (Colaizzi et al., 2003b). The CWSI has also been used to predict yield response of different crops to water stress and to develop strategies for irrigation management decisions (Erdem et al., 2006; Yuan, et al., 2003).

Most temperature-based indices were developed around the assumption that the infrared radiometer (infrared thermometer) views only vegetation. However, soil background is usually present to some extent throughout the season, especially for cotton even when the canopy completely covers the inter-rows. Some indices such as the Water Deficit Index have attempted to account for soil background, but these require soil-specific parameterizations that are not routinely available, and could potentially confound errors associated with interpreting the ensemble (i.e., vegetation and soil) radiometric temperature. Therefore, IRT measurement protocols typically call for viewing the canopy across rows and at oblique angles to minimize soil background. The objectives of this study were (1) to compare the TTT method of automatic irrigation scheduling to manual scheduling using neutron scattering for soil water measurements; and (2) using a post analysis review, to investigate if the CWSI would be a useful addition to the TTT algorithm for automatic irrigation scheduling and control.

MATERIALS AND METHODS

Cotton [*Gossypium hirsutum* L.] was planted on DOY 149, 2007 (cv PayMaster[1] 2280 BG/RR); and on DOY 141, 2008 (cv Delta Pine 117 B2RF). Both cultivars were from Delta Pine Land Co., Scott, MS, and were Bollgard II® Roundup Ready®. The crop was grown in eighteen-row plots on beds spaced 0.76-m apart and formed in circles under a three span center pivot at the USDA-ARS Conservation and Production Research Laboratory, Bushland, Texas (35˚ 11' N, 102˚ 06' W, 1174 m above mean sea level). Irrigations were applied either manually (Manual) or automatically (Auto) by the TTT method. In order to avoid conflicts between manual and automatic irrigations, manual irrigations were applied only on even-numbered days of the year (DOY) and automatic irrigations were applied only on odd-numbered DOY. One half of the center pivot circle was used for the experiment; and it was divided into six sectors, each of which was a block of treatments (Fig. 1). Treatments were assigned randomly in the radial direction within each block and were doubly replicated within blocks. There were four treatments for each method, Manual or Auto, and they were designated 100%, 67%, 33% and Dry. For the Manual method, irrigations were applied weekly fully replenish soil water to field capacity in the 100% Manual treatment. Automatic irrigations were triggered only for TTTI > 452 min where TTTI is the TTT Index, which is the time in min that the canopy temperature exceeds the temperature threshold of 28ºC for cotton each day. For the Auto method, irrigations of 20 mm were applied in the 100% Auto treatment (20 mm is twice the average weekly peak daily consumption of 10 mm). For both methods, irrigation depths in the 67% and 33% treatments were 67% and 33%, respectively, of the 100% treatment depth for the respective scheduling method; and these amounts were achieved by reducing nozzle sizes. The Dry treatment received no irrigation. Low energy precision application (LEPA) drag socks were used in every other furrow with furrow dikes to inhibit runoff and surface redistribution of water. Manual irrigations were based on soil water contents in the top 1.5 m of soil as determined weekly by neutron

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[1] 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.

moisture meter (NMM) readings to 2.4-m depth in 0.20-m increments beginning at 10-cm depth using methods described by Evett (2008).

Canopy temperature was sensed using infrared thermometers (model IRT/c 5:1, Exergen, Inc., Watertown, MA) mounted on the pivot with an oblique viewing angle. Date were continuously recorded and provided canopy temperatures of the entire cropping field when the pivot was moved around the semi-circle area. Pivot mounted infrared thermometers (IRTs) were wired to a datalogger (Model 21X, Campbell Scientific, Logan, UT). When the irrigation system was moving, the mean temperature of each plot, for the center of the time period during which the plot was sensed by the IRTS, was scaled to a stationary reference temperature using the algorithm of Peters and Evett (2004) to produce an estimated daytime temperature curve for that plot. Stationary (reference) IRTs, wired in 2007 and wireless (O'Shaughnessy and Evett, 2008) in 2008, were located in the field within automatically irrigated treatment plots and provided reference crop canopy temperatures.

The soil was Pullman clay loam, a fine, mixed, superactive, thermic, Torrertic Paleustoll (Soil Survey Staff, 2004). Air temperature, relative humidity, solar radiation, and wind speed were measured at 6-s intervals and reported as 15-min mean values at the adjacent Soil and Water Management Research Unit weather station, Bushland, TX (see Evett, 2002 for methods). Average plant height and width measurements were taken every two weeks.

Crop water stress index

The theoretical CWSI was used to calculate a stress index for each day during the irrigation scheduling seasons as:

$$\mathrm{CWSI} = \frac{(T_\mathrm{c} - T_\mathrm{a}) - (T_\mathrm{c} - T_\mathrm{a})_\mathrm{ll}}{(T_\mathrm{c} - T_\mathrm{a})_\mathrm{ul} - (T_\mathrm{c} - T_\mathrm{a})_\mathrm{ll}} \quad [1]$$

where (T_c - T_a) is the measured difference between crop canopy temperature, T_c, and air temperature, T_a, $(T_c - T_a)_{ll}$ is the lower limit representing the temperature difference for a well watered crop and $(T_c - T_a)_{ul}$ is the upper limit representing the temperature difference between the crop canopy and ambient air when the plants are severely stressed (Jackson et al., 1988). The upper limit was calculated using the equation:

$$(T_\mathrm{c} - T_\mathrm{a})_\mathrm{ul} = r_\mathrm{a}(R_\mathrm{n} - G)/\rho C_\mathrm{p} \quad [2]$$

where r_a is aerodynamic resistance, R_n is net radiation (W m^{-2}), G is soil heat flux (W m^{-2}), ρ is the density of air (kg m^{-3}) approximated as a function of elevation, and C_p is heat capacity of air (J kg^{-1} $ºC^{-1}$). Soil heat flux was estimated as

$$\mathrm{G} = 0.1\mathrm{R}_\mathrm{n} \quad [3]$$

Net radiation was calculated as

$$\mathrm{R}_\mathrm{n} = (1 - \alpha)\mathrm{R}_\mathrm{s} + \mathrm{R}_\mathrm{lw\_in} - \mathrm{R}_\mathrm{lw\_out} \quad [4]$$

where α is albedo (estimated to be 0.23), R_s is short wave irradiance (measured at the weather station), R_{lw_in} is incoming long wave radiation and R_{lw_out} is outgoing long wave radiation. The values R_{lw_in} and R_{ls_out} were evaluated according to Jensen et al. (1990). Aerodynamic resistance, r_a (s m^{-1}), was calculated using

$$r_a = \frac{\ln\left(\frac{z-0.63h}{0.13h}\right)}{k^2 u} \quad [5]$$

where z is the reference anemometer height (m), k is the von Karman constant (0.41), u is the wind speed (m s^{-1}) at height z, and h is the vegetation height (m).

The lower limit, $(T_c - T_a)_{ll}$ was calculated using:

$$(T_c - T_a)_{ll} = \frac{r_a R_n}{\rho C_p}\frac{\gamma}{(\Delta+\gamma)} - \frac{e_s - e_a}{(\Delta+\gamma)} \quad [6]$$

where γ is the psychometric constant (Pa ºC^{-1}), e_s is saturated vapor pressure, e_a is actual vapor pressure, and Δ is the slope of the saturated vapor pressure – temperature relationship, which can be estimated using the equation (Jackson et al., 1988):

$$\Delta = 45.03 + 3.014T + 0.05345T^2 + 0.00224T^3 \quad [7]$$

where T is the average of the canopy and air temperature $(T_c+T_a)/2$, expressed in (ºC). The saturated vapor pressure was evaluated using

$$e_s = 0.6108 * \exp\left[\frac{17.27T_a}{T_a + 237.7}\right] \quad [8]$$

where T_a is air temperature (ºC). The actual vapor pressure was taken as e_s (RH/100) where RH is the relative humidity.

Mean values, between 1100 hrs and 1530 hrs, of air temperature (T_a), crop canopy temperature (T_c) from 100% treatment plots in the automatic blocks, RH, incoming short wave radiation (R_s), and wind speed were used to calculate the CWSI. Using mean, rather than point values, is a method similar to Erdem (et al., 2006), and Alderfasi and Nielsen (2001), who used data measurements over time to calculate CWSI.

Time Temperature Threshold Index

The TTTI was calculated as time in minutes for which the crop canopy temperature was above 28ºC. When the pivot was moving, TTTI values were calculated using scaled temperatures per Peters and Evett (2004).

Water use efficiency and yields

Water use (ET, m) was calculated using the soil water balance equation (Evett, 2002):

$$\text{ET} = -\Delta S - R + P + I - D \qquad [9]$$

where ET is evapotranspiration, ΔS is the change in soil water stored in the profile (determined by NMM in the 2.4-m profile, negative when ET is positive), R is total runoff (m), P is the amount of precipitation (m), I is the irrigation water applied (m), and D is the drainage (m). Because the amount of irrigation water was only sufficient to bring the water deficit to field capacity and because furrow dikes prevented most runon and runoff. Drainage and runoff were neglected in our calculations, similar to methods by Schneider and Howell (2000). Water use efficiency (WUE, kg m^{-3}) was calculated as Y_g/ET_i, where Y_g was economic yield (kg m^{-2}) divided by seasonal ET_i (m) for each irrigation level. Irrigation water use efficiency (IWUE, kg m^{-3}) was determined by the equation:

$$\text{IWUE} = \frac{\left(Y_{gi} - Y_{gd}\right)}{\text{IRR}_i} \qquad [10]$$

where Y_{gi} is the economic yield (kg m^{-2}) for irrigation level i, Y_{gd} is the dryland yield (kg m^{-2}), and IRR_i is the applied irrigation water (m) (Bos, 1985; Howell, 2002).

Data analysis

Results were analyzed using Proc Mixed Analysis, Analysis of Variance (ANOVA), linear regression, and the Fisher Least Significant Difference (LSD) test using SAS software (SAS 9.1, SAS Institute Inc., and Cary, NC).

RESULTS AND DISCUSSION

Climatic conditions and irrigation summary

The effective experimental irrigation seasons for 2007 and 2008 lasted for a period of 44 and 25 days, respectively. The planting date for both years was in mid May. Harsh climatic conditions for the 2008 growing season, a combination of high temperatures and wind with low RH, slowed early vegetative growth and made it difficult to wet the soil profile to field capacity. Average temperatures and wind speeds in May and June were higher in 2008 than in 2007, while RH was lower (Table 1). In August 2008, temperatures were cooler, RH was higher and wind speeds were less than in August

2007. Heavy rainfall received in August 2008 (DOY 226 to DOY 229), shortened the irrigation season. A plant regulator (Stance™, Bayer CropScience, Research Triangle Park, NC) was applied on DOY 235, 2008 to induce reproductive development and prevent rank vegetative growth.

A greater volume of water was applied to the manually irrigated plots, i.e. 42.9 and 37.1 mm (at the 100% irrigation level) in the 2007 and 2008 growing seasons, respectively (Table 2). The frequency of automatically scheduled irrigations increased from 1 in 7 days to 1 in 4 days in the late flowering and early boll formation period in 2007. Irrigation scheduling began late in 2008, and automatic scheduling occurred roughly every 4 days in the early vegetative stage.

Yield and water use efficiency

In 2007, yields from Automatic and Manual treatment methods were not significantly different (P =0.83) (Table 3). Irrigation levels significantly affected the dry lint yields (α = 0.05), but there was no significant interaction between the methods and levels of treatment (P = 0.18). The WUE and IWUE values were not significantly different between the manual and automatic irrigated plots in 2007. Overall, the WUE for the dryland plots was not significantly different from any of the irrigated treatment plots due to the mild summer temperatures and above average rainfall. Linear regression demonstrated that cotton lint yields were positively correlated to water use for irrigations < 450 mm (Fig. 2). Yield data for 2008 are not yet available.

Thermal indices

For 2007, there was a weak relationship between the two the CWSI and TTTI thermal indices (ANOVA r^2 = 0.19, F= 12.1, and P <0.001). The TTTI was not significantly related to the CWSI in 2008; this may be related to the limited number of data points collected in 2008 due to the shortened irrigation season.

Most TTTI triggers occurred when the CWSI > 0.5 (Fig. 3a, b, quadrant I). Less than 5% and 10% of TTTI values > 452 min occurred when CWSI was < 0.5 for both the 2007 and 2008 seasons, respectively (Fig. 3a, b, quadrant II). Data points representing TTTI <452 min and corresponding CWSI < 0.5 can potentially be classified as “non-triggers” (Fig. 3a, b, quadrant III). Data points for which CWSI > 0.5 when TTTI < 452 min represented 32% of the measured data in 2007, occurring generally during the early vegetative stage (Fig. 3a, quadrant IV). This could possibly mean that the TTTI is more robust than the CWSI when soil background is present. In 2008, most of the data points falling into this category did so from DOY 210-216, during cloudy days.

If the calculated theoretical CWSI > 0.5 was used to trigger automatic irrigations (calculations made on odd numbered DOY only), then the number of automatically scheduled irrigations would increase by ten and two for 2007 and 2008, respectively.

Figures 4a and 4b provide a time series depiction of the calculated theoretical CWSI and the TTTI during the automatic scheduling periods for 2007 and 2008.

A disadvantage to considering the use of both of these indices is that under partial canopy, soil temperatures will invariably influence the composite temperature measured by the IRTs. Additional sensors and modeling approaches can help reduce these inherent problems.

CONCLUSIONS

Yield results showed that the TTT algorithm for automatic irrigation scheduling of a center pivot for LEPA irrigated cotton successfully controlled the amount of irrigation water applied without significantly affecting cotton yield as compared with water balance irrigation scheduling done using NMM data. For full irrigation, the TTT method produced significantly greater overall WUE than did water balance irrigation scheduling; but differences were not significant for irrigation at reduced rates of 33 and 67% of full. There was a strong positive correlation between lint yield and water use < 450 mm.

Post analysis comparison of the two thermal indices indicated that they have similar trends, but the daily theoretical CWSI > 0.5 would result in additional irrigations. However, future work investigating the CWSI over a daily time step may prove to be a worthwhile index capable of indicating crop water status. Further research is needed to test new algorithms and compare crop yields and WUE.

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Table 1. Climatic data (monthly averages) for 2007 and 2008 growing seasons.

	Rainfall (mm)		T_a (ºC)		RH (%)		u ($m\ s^{-1}$)		R_s ($MJ\ m^{-2}\ d^{-1}$)	
Month\Seasons	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
May	17.8	4.6	17.27	18.4	70.11	47.32	4.26	5.29	24.44	26.52
June	56.4	57.3	21.6	24.29	64.63	47.14	3.81	5.43	25.94	28.89
July	36.60	49.3	23.98	23.83	62.79	60.77	3.23	4.08	23.26	24.61
August	63.70	73.1	24.54	22.58	64.18	66.06	3.70	3.37	23.26	22.34

T_a is air temperature, RH is relative humidity, u is wind speed, and R_s is solar irradiance.

Table 2. Irrigation summary for the 2007 and 2008 growing seasons.

Growing Season	2007	2008
Planting Day (DOY)	149	141
Start of automatic scheduling (DOY)	197	202
End of automatic scheduling (DOY)	241	227
Irrigation water applied to Manual 100% treatment plots[a] (mm)	182	133
Irrigation water applied to Automatic 100% treatment plots[a] (mm)	139	92

[a] Refers to application depth during the irrigation scheduling

Table 3. Cotton Yields 2007: three-span center pivot, Bushland, TX.

Category	Treatment	Average Dry Lint Yield (g m^{-2})	Total Water Use (mm)	WUE (kg m^{-3})	IWUE (kg m^{-3})
Methods	Manual	82a	390a	0.22a	0.20a
	Automatic	82a	370b	0.22a	0.22a
Irrigation Levels	100%	105a	519a	0.20a	0.19a
	67%	96b	425b	0.23b	0.23b
	33%	73c	333c	0.22ab	0.20c
	0%	55d	243d	0.23ab	
Treatment by Irrigation Level	100%-Manual	102a	543a	0.19a	0.16a
	100%-Auto	108a	494b	0.22b	0.21a
	67%-Manual	102a	436c	0.23b	0.24a
	67%-Auto	90c	414d	0.22b	0.21a
	33%- Manual	72d	338e	0.22ab	0.18a
	33%-Auto	74d	328e	0.23b	0.23a
	0%-Manual	54e	242f	0.23ab	
	0%-Auto	55e	245f	0.23ab	

WUE = water use efficiency

IWUE = irrigated water use efficiency

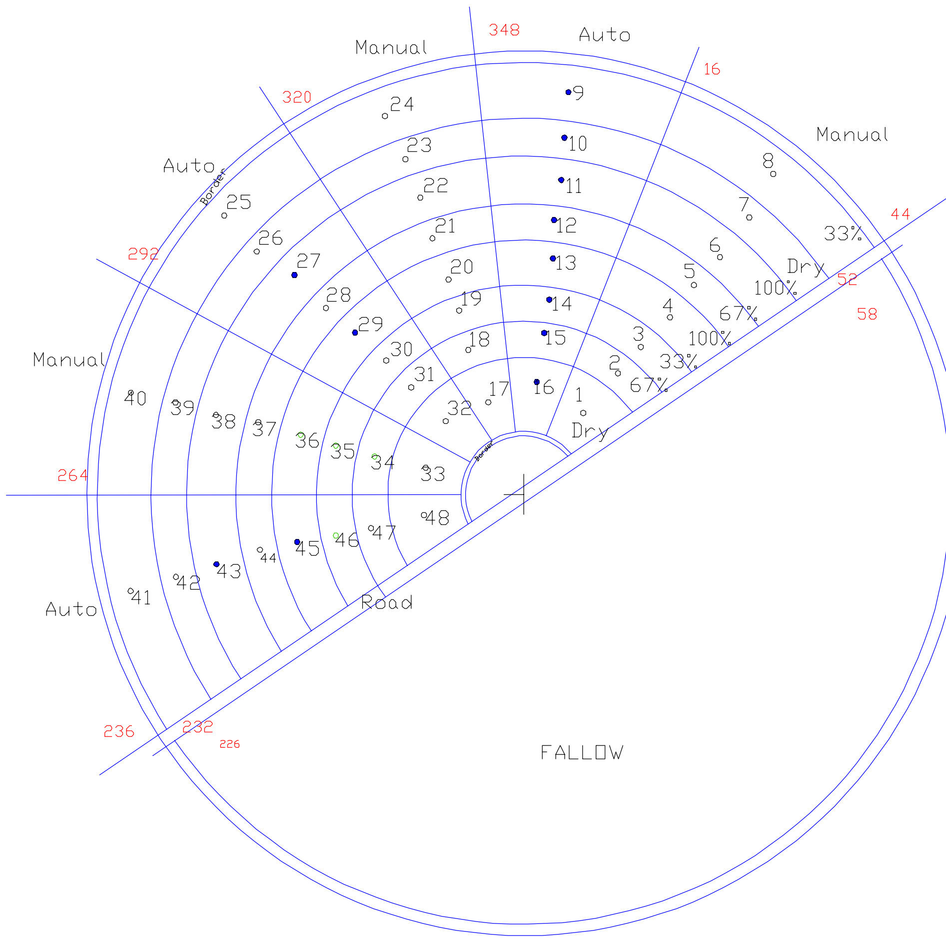


Figure 1. Fully randomized block design for manually (Manual) and automatically (Auto) irrigated treatments, 100%, 67%, 33% and dryland cotton (Dry) under a three-span center pivot system at Bushland, TX, 2007.

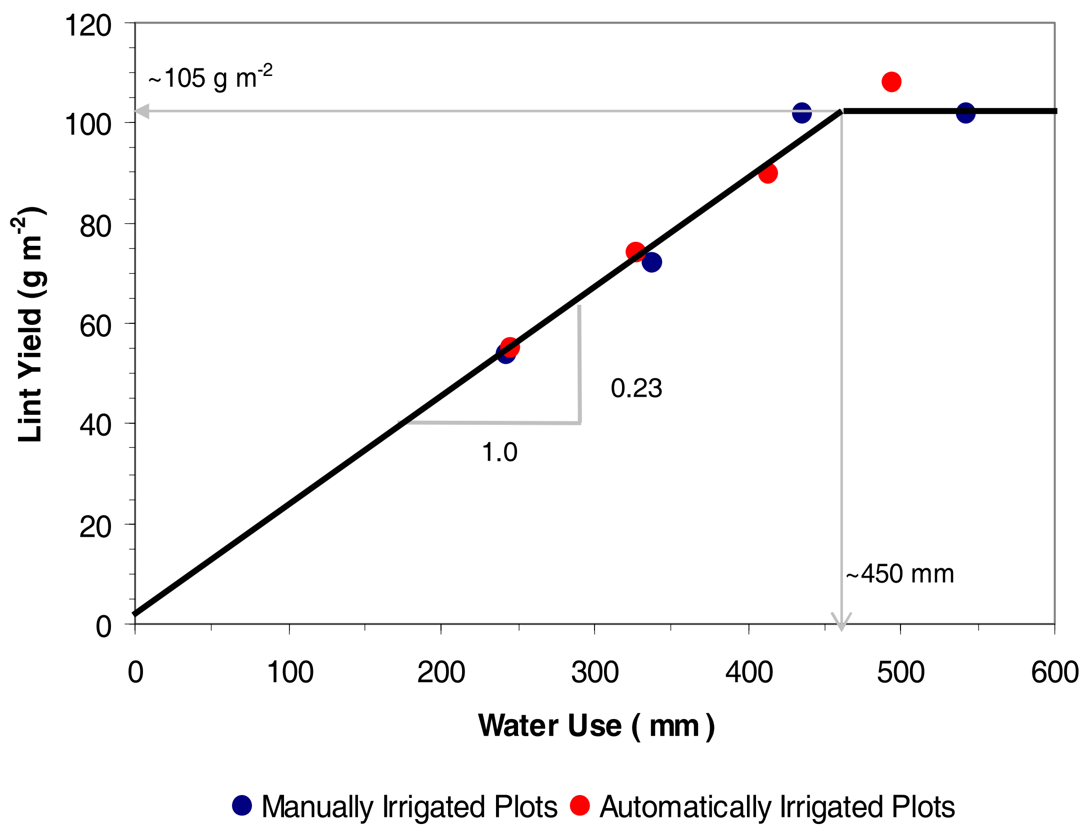
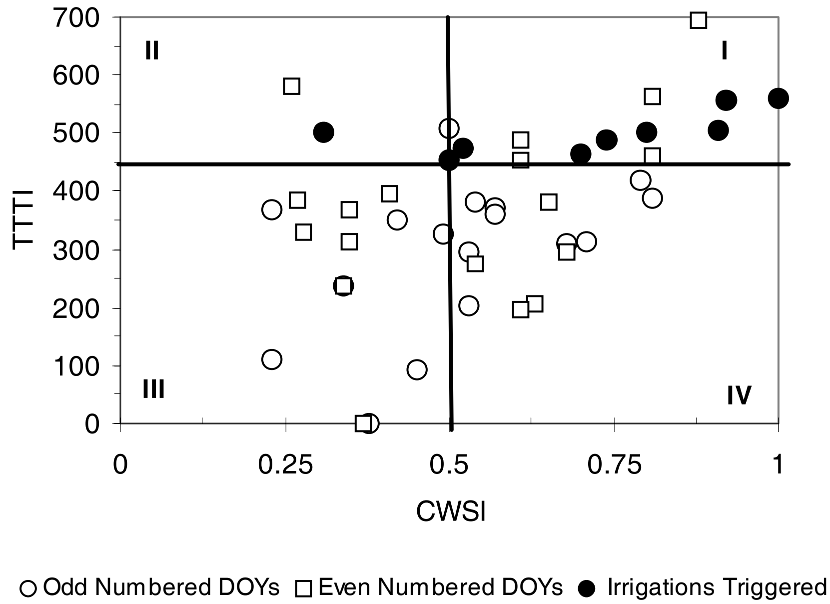
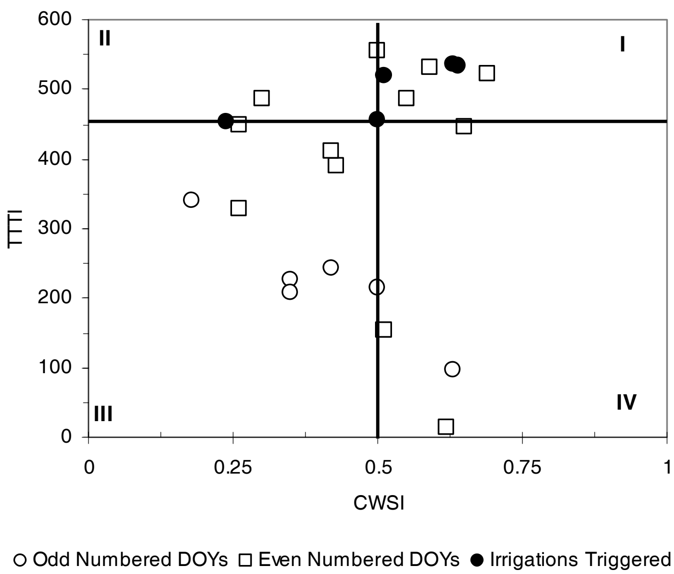


Figure 2. Lint yields versus water use efficiency (WUE) for cotton crop under a three-span center pivot, Bushland, TX, 2007.

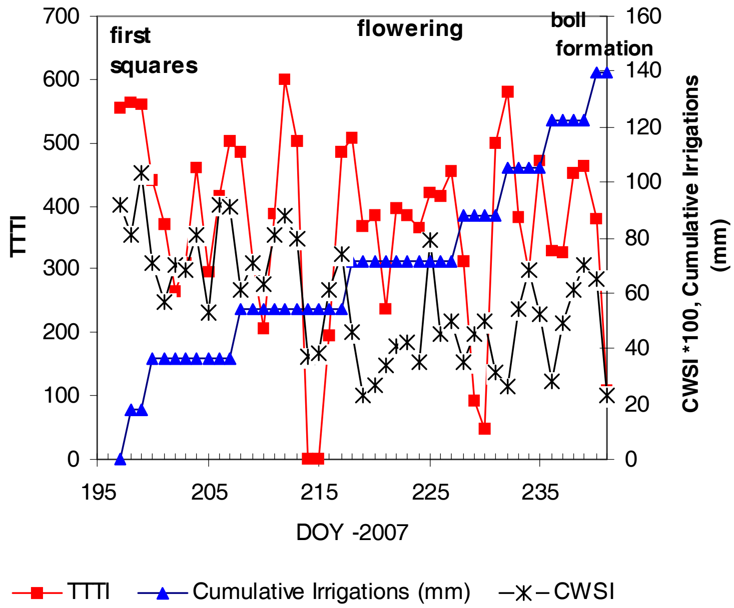


(a)

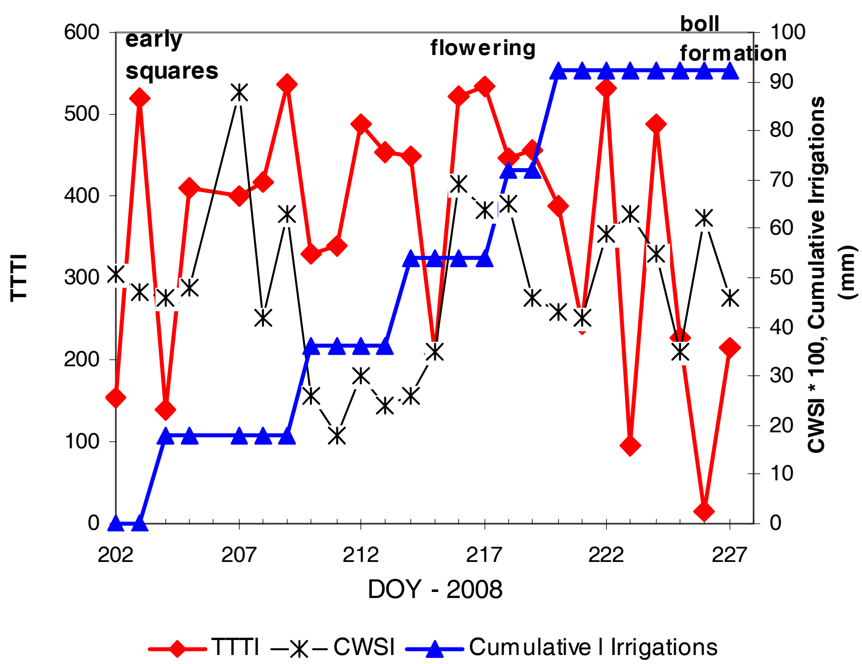


(b)

Figure 3. Relationship between the TTTI and the theoretically calculated CWSI for the (a) 2007 and (b) 2008 growing seasons. Horizontal and vertical lines divide the graphs into four quadrants labeled I, II, III and IV. The horizontal line is drawn at the TTT index threshold of 452 min; and the vertical bar is drawn at a CWSI value of 0.5. Solid squares represent data points that automatically triggered irrigations in the 2007 and 2008 growing seasons. Data points shown as hollow circles in quadrant I are canopy temperature measurements that would have triggered an automatic irrigation; however because their TTT minutes were accumulated on even-numbered DOY, no automatic irrigation was scheduled.



(a)



(b)

Figure 4. Time series plot of TTTI and the theoretical CWSI for the (a) 2007 and the (b) 2008 season.

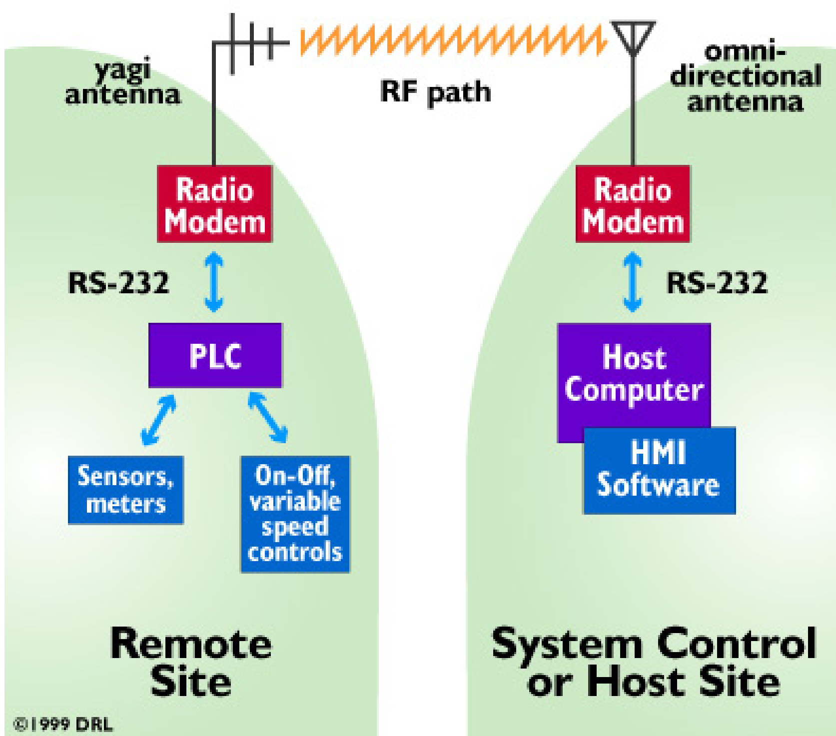
Design and Troubleshooting Wireless Ethernet/Serial Irrigation Systems

By Kim Heiner
Western Regional Sales Manager
CalAmp

SCADA: Supervisory Control and Data Acquisition

The purpose of this article is to provide some insight into design considerations for wireless communication networks as used in modern SCADA systems. With some basic knowledge of design considerations, it is easier to take the right automation approach and choose the right equipment for the task at hand.

Wide area SCADA systems provide a means of remotely monitoring events and controlling machinery at unattended locations. To accomplish this task, as in any system design, various disparate components must be integrated. In this case they include: sensors and metering devices, motor controls, programmable logic controllers, a communications network to link it all together, a host computer and HMI software. Sometimes, remote site hardware and wireless communications gear is packaged together in a NEMA outdoor rated equipment enclosure. In this instance, the equipment may be referred to as an RTU or a Remote Terminal Unit.



Making all these items work together harmoniously to achieve your objectives is the responsibility of the system designer and the system integrator, and this is where they prove their value.

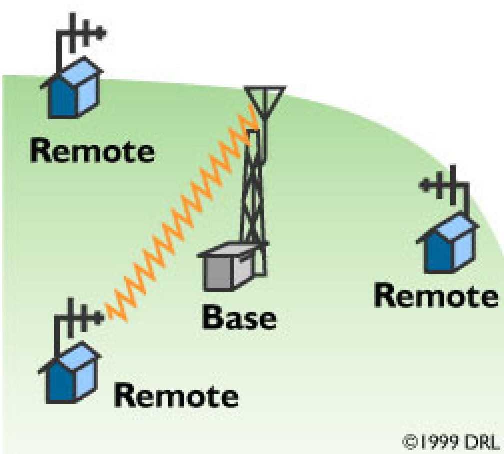
Where did it all start?

In any SCADA system, the remote site's PLC communications to the control point pass through an RS-232 serial port. In older designs, a modem converts the serial digital data into analog 'mark' and 'space' audio tones that are sent long distances over leased or dial-up communications lines. By this means, connectivity is provided for wide area SCADA applications.

Over time, licensed two-way radio displaced the phone line as the most popular communications medium. This has happened for two main reasons. First, though the reliability of the US telephone infrastructure is second to none, mission critical communications are best trusted to a network under one's own direct control. Second, and equally as important, is the high recurring cost of leased telephone lines. SCADA users have historically found that their wireless data network pays for itself in a relatively short period of time.

Architecture

In the SCADA world today, the vast majority of systems are set up in a 'polled' architecture, as opposed to a 'report by exception' architecture. In a polled architecture, the system control point, or host, initiates all data transmission sequences. No remote site reports its status until the host asks for it. Polled systems are designed to poll every few seconds or minutes or hours, depending on how often information updates are required. If pressed, the capabilities of modern high-speed radio modem hardware make it unlikely that any retrieved data will be 'stale.'



'Report by exception' may be utilized when constant operational updates from remote sites are not required and traffic volume is light. In 'report by exception' architecture, remote sites send updates only when a 'change of state' occurs. As remote sites are often out of radio range of each other, some provision must be made for avoidance, and recovery from, 'on the air' collisions as would happen during simultaneous data transmission attempts. This can increase system complexity and cost, and may not offer ideal performance, particularly if later system expansion is anticipated.

Unlicensed vs. Licensed Radio

Today, the savvy wireless data customer is presented with a wide variety of communications options. In addition to licensed radio, there is now unlicensed radio. Unlicensed radio has the obvious appeal of being license free. The downside is that since it is uncoordinated spectrum, unlicensed radio has become somewhat unreliable as it has become more crowded.

Unlicensed wireless SCADA networks find themselves sharing spectrum with an increasing number of industrial and consumer devices such as: cordless telephones, baby monitors, wireless LAN devices, and amateur radio operators. Also, if used legally, the output power of the unlicensed radio must be reduced when very high gain antennas are used. Additionally, radio propagation at higher unlicensed frequencies is relatively unfavorable as compared to the lower frequency licensed bands.

In the past, licensed frequencies were crowded and difficult to obtain. Sometimes it could take many months to obtain operational authority from the FCC. However, since 1997, FCC 'refarming' has made it possible to obtain new communications channels and has greatly relieved communications congestion for wireless data users. Additionally, wireless data users have discovered that by utilizing professional licensing services, they can receive operational authority in a month or less. Be mindful, however, that not all FCC licensing services are experienced, nor up to date, with wireless data applications and the pertinent spectrum rules.

FCC Refarming

Overall, refarming is a decade long multi-step process. It is affecting both radio manufacturers and radio users. Existing users of two-way wireless devices will find the necessity, sooner or later, to upgrade their equipment to modern ‘refarmed’ equipment. They are, or will make, the transition for one of two reasons: 1) Future FCC regulation of some form will make it unattractive to continue holding a ‘full channel’ of spectrum. 2) The other more immediate and compelling reason is that the full channel user may receive harmful adjacent communication channel interference from newly established half channel users. Conversely, the new half channel user is less likely to receive interference from the incumbent full channel user. This is by virtue of the difference of bandwidth in the new and old design transceivers and the relative spectral position of the two signals. There are other more stringent requirements beyond channel bandwidth that refarming has brought to radio manufacturers, but that is beyond the scope of this article. Suffice it to say that today’s radios are designed and perform with a great deal more precision than in the past.

Radio Propagation Studies

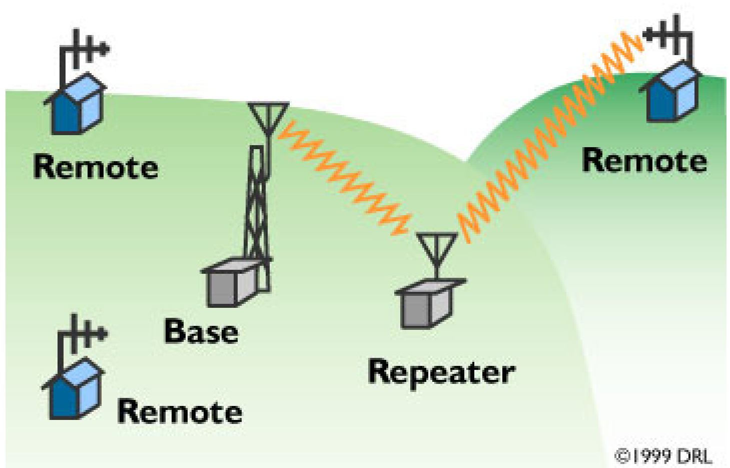
Radio propagation is the study of the behavior of radio waves at particular frequencies over terrain. Regardless of whether you choose licensed or unlicensed radio, it is absolutely essential that you have a propagation study conducted. A radio propagation or path study will determine with a fair degree of certainty whether your radio signal can get there from here. It may demonstrate the need to relocate certain sites or the need to utilize a radio repeater, or use an existing or proposed remote site as a relay station. Additionally, a thorough path study will take into account the need for a 20 to 30 dB fade margin. This allows for uninterrupted communications when the path undergoes temporary and periodic degradation due to atmospheric and/or seasonal changes.

For a small system path study, you may find you can verify radio line of site with portable radios. In doing this, it is essential to eliminate as many variables as possible. Try to simulate the same antenna height and performance and use the same RF output power as will be used in the built-out system. It is also necessary to realize that reliable data communications will require stronger signal strength than for voice communications.

For large systems, it is prudent to perform a computerized path study, preferably before placing a SCADA system job up for bid. Computerized path studies take into account terrain, ground clutter and vegetation profiles, and generally are a good value as they save you and your integrator time and money. If you put your system design out for public bid, you will find that having a previously conducted path study will facilitate the bidding and bid evaluation process for you, and your successful bidder to be.

Repeaters

In some instances, you may discover that your proposed communications to certain remote sites are marginal. Repeaters may be used to extend the communications reach of your control point. Most commonly, an advantageously located remote is utilized as a sub-master which forwards polling requests from the control point to other remote stations.



This type of repeating is called 'store and forward.' It is differentiated from full duplex repeating that performs simultaneous reception and transmission, and requires two radio channels. 'Store and forward' repeating is very common in SCADA system design and it is often chosen for its simplicity and relatively low cost. It takes advantage of features that may already be built into the remote site PLC hardware. Another alternative is to remotely locate your control point radio hardware if your control point does not provide radio coverage to your remote sites.

It may be difficult to justify the added expense of extending your wireless range, but realize that marginal communications will never provide you reliable SCADA system performance, and will cause you aggravation and untimely down time.

Antennas, Feedlines and Lightning Protection

Generally, in a polled system, an omni-directional antenna is employed at the system control point. Omni-directional antennas radiate equally well in all compass headings. The yagi antenna on the other hand is directional and must be pointed in the direction of intended communication. Often, remote sites that communicate only with the control point are equipped with yagi antennas.

Low loss antenna feedline and connectors are required when UHF (commonly 450-470 MHz) or higher frequencies are employed. This is because feedline and connectors exhibit greater losses at higher frequencies, on both transmit and receive. For this reason, UHF frequencies require hardline or rigid wall coax for all runs, whereas low loss RG-8 type coaxial cable can be used for VHF runs of less than 25 feet. Popular UHF (PL-259) feedline connectors can be used at VHF frequencies, but generally the lower loss 'Type N' connector should be utilized for VHF and UHF frequencies.

Lightning is more common in some geographic areas that others. Wherever it happens, catastrophic damage to communications and control system hardware can result. Using a bulkhead mounted lightning surge suppression device with single point earth grounding is a good investment. Many choose to cut corners here, but it is ill advised. Plan to spend money on this part of your system. If you choose to play the odds, you will at some point lose and suffer downtime and loss of system control.

Radio Modem Hardware and PLC Protocols

Customers are also faced with a wide range of radio modem products today. In the past, it was customary to use outboard Bell 202 type 1200 bps modems and interface them to two-way voice type radios. This requires the tedious adjustment, and periodic readjustment, of audio levels between the separate modem and radio.

The Bell 202 solution ignores technology advances that have been made in the last 5 years. Today it is less expensive, over the life of your system, to invest in high speed integrated radio modem products which offer the advantage of easier interfacing and swapping out, higher data and polling rates, more sensitive modem and radio technology, and features like wireless network diagnostics.

Additionally, many users today have a choice between ‘packetized’ and ‘transparent’ radio modem hardware. Before comparing these two alternatives, it is useful to note that PLC devices utilize communication protocols or languages that encapsulate the data stream in an envelope called a ‘packet.’ This envelope surrounds the data with a message start and end marker, an origination and destination address, and a CRC or checksum. These protocols were born in the hardwired world and have transitioned very well into the wireless data world.

As the PLC is already ‘packetizing’ your data, it is more efficient to employ ‘transparent’ communications hardware that does not add an additional second layer of error checking and addressing. There may be situations where this additional overhead buys you something, but in most cases, there is no added value.

MODBUS™ is a popular protocol for wireless communications. Numerous PLC manufacturers have their unique implementation of this protocol. There are other protocols that operate similarly; some are proprietary. Generally, master slave protocols that are framed, employ message addressing, error checking and that are designed for Master-Slave polling, work well in the wireless environment. Truly transparent radio modem hardware requires RTS/CTS hardware handshaking for data flow control. Make sure that your PLC hardware supports this communications requirement if you elect to utilize transparent radio modem hardware.

Wireless Network Diagnostics

Investing your hardware dollars in integrated radio modem devices also provides new features that are becoming indispensable. Wireless network diagnostics is one such feature, which can reduce communication failures, minimize the potential risk of downtime due to equipment or system malfunction, and facilitate a speedy recovery from outages. This results both in a more favorable risk management scenario and a high return on investment for your automation dollars.

In practice, diagnostics at the wireless communication level makes it possible to verify connectivity to a remote site even if your PLC or instrumentation has failed. Some diagnostic methods can even be utilized concurrently with your regular polling cycle to warn of impending communication failures. Your ability to maintain or quickly return your system to service is enhanced by the performance statistics that you can remotely obtain. Diagnostic tools can also be utilized during system deployment, and can speed along the installation process.

Redundancy and Point of Failure

SCADA system designers strive in their work to eliminate as many single points of failure as possible. Redundancy is utilized to minimize the impact of system component failure, often at the system control point. Redundancy increases the system design and deployment cost. If carried to the extreme, it can make operation of the system more complicated and laborious.

In a recent study of automated SCADA systems[1], it was found that 50% of automated systems are run on manual mode. Among the reasons given in this study is "low user confidence in the technology." If system complexity and operator workload is a concern for you, having spare components can be considered a simple and valid safeguard.

In conclusion, it is wise to note that all system design involves 'trade-offs'. It is essential to know and understand the benefits and drawbacks of the individual elements of your system design. Only then will you be able to make the right choice for your application and needs!

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[1] Manning, Alan W. 1999. “Status of Automation in the Wastewater Industry” (information presented at Automatic Monitoring Seminar. Water Environment Federation 72nd Annual Exhibition & Technical Conference).

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Potential Runoff and Erosion Comparison of Center Pivot Sprinklers on Three Idaho Soils

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Abstract. *The operational characteristics of center pivot sprinklers are well documented but few studies have been conducted to evaluate the effects that operating characteristics of a particular sprinkler have on infiltration, runoff, and erosion of specific soil types. The objective of this study was to evaluate potential runoff and erosion from common commercial center pivot sprinklers on three widely distributed, south central Idaho soils. A modified commercial irrigation boom system was used to emulate center pivot irrigation on experimental runoff plots. Sprinklers used in the study were: 1) Nelson R3000 with brown plate, 2) Nelson R3000 with red plate, 3) Nelson S3000 with purple plate, and 4) Senninger I-Wob with standard 9-groove plate. There were significant differences in runoff and erosion rates between sprinkler types for the soils tested and experimental conditions. The I-Wob exhibited the highest overall runoff and erosion rates and the R3000 sprinklers exhibited the lowest rates for the three soils tested. In general, sprinkler types that visually appear to more uniformly distribute sprinkler droplets over the wetted area with respect to time exhibited the highest runoff and erosion rates. The relative differences in runoff between the sprinklers tested for the three soils were not directly proportional to droplet kinetic energy. This outcome is in conflict with conventional theory on soil surface sealing from droplet impact.*

Keywords. Center Pivot, Runoff, Erosion

Introduction

Center pivot irrigation is popular with producers but is not necessarily the best irrigation system choice for all site conditions. Water application rates along the outer portion of the system, which influences the most acres, often exceed soil infiltration rates for medium- and fine-textured soils may result in substantial runoff, erosion and spatial non-uniformity in water application depth on rolling topography. The primary emphasis for many center pivot sprinkler product developments and application studies has been high uniformity which really is not the main challenge for good water application at the outer end of the pivot system. Over the past two decades center pivot sprinkler manufacturers have developed sprinklers that minimize peak water application rates while sustaining high application uniformity. As a result there are numerous center pivot sprinkler choices available for the producer but little quantitative information that relates these choices to infiltration, runoff, and erosion on a particular soil.

The operational characteristics of center pivot sprinklers such as wetted diameter, application rate pattern shape and drop size distribution have been reported in the scientific literature (e.g. Kincaid et al., 1996; Faci et al., 2001; DeBoer, 2001; Sourell et al., 2003; Playan et al., 2004; Kincaid, 2005;). However, studies evaluating the effect operating characteristics of a particular sprinkler have on infiltration, runoff, and erosion of specific soil types are limited. This is especially true for low organic matter calcareous soils in the arid western U.S whose aggregate structure readily breaks down under sprinkler droplet impact to form surface seals that reduce water infiltration rates.

The objective of this study was to evaluate potential runoff and erosion from common commercial center pivot sprinklers on three widely distributed, south central Idaho soils under center pivot irrigation.

Methods and Materials

A 4-wheel commercial irrigation boom 154 ft in length (Briggs Irrigation, Northhamptonshire, UK) was used to emulate center pivot water application on replicated soil plots. The irrigation boom was modified by increasing the boom height 18 inches and adding additional sprinkler outlets along the boom length. Two additional sprinkler outlets were added between each existing outlet to provide 48 to 51 inch spacing between adjacent outlets. A hydraulic cable winch system mounted on the front of a John Deere 1020 tractor was used to mobilize the irrigation boom. Water is supplied to the irrigation boom by a 3 inch, 300 ft drag hose. Travel speed of the boom is computer controlled at a specified constant rate. Specific details on the irrigation system used to emulate center pivot irrigation are provided by King and Bjorneberg (2007).

The effect center pivot sprinkler type has on runoff and erosion for a specific soil was evaluated using raised runoff plot boxes, figure 1. The elevated plot boxes were 4 feet wide by 8 feet long with different end heights to provide a nominal slope of 5%. The bottom of each runoff box was filled with Porteneuf silt loam to a depth six inches below the top. The soil to be evaluated (Table 1) for runoff and erosion was then used to fill the remaining volume in the plot box. This provided a soil depth of 6 inches for runoff and erosion evaluation. A metal frame border measuring 3.3 feet (1 m) wide by 6.6 feet (2 m) long was installed on the box soil surface to collect runoff and prevent plot runon from the surrounding area and eliminate edge effects. The metal frame was made of 3/16-inch thick steel 3-inches in width orientated vertically on three sides. The bottom edge of the metal frame was driven into the soil to a depth of about 1.5 inches to channel the runoff and prevent runon. The down slope outlet end of the frame had a horizontal metal lip along its length about 2.5 inches in width for runoff to leave the frame without excessive erosion due to head cutting. Along the down slope length of the metal lip was a metal trough sloped to one edge of the metal frame to collect runoff and channel it to a collection bucket in a hole dug near the corner of the runoff plot box. The depth of water in the bucket was measured with a ruler to determine runoff volume. The bucket was covered to prevent water from sprinklers contributing to runoff water volume. The combined horizontal width of the lip and trough was about 3.25 inches. Water application to the lip and trough adds to the total runoff volume and was accounted for when calculating plot runoff volume.

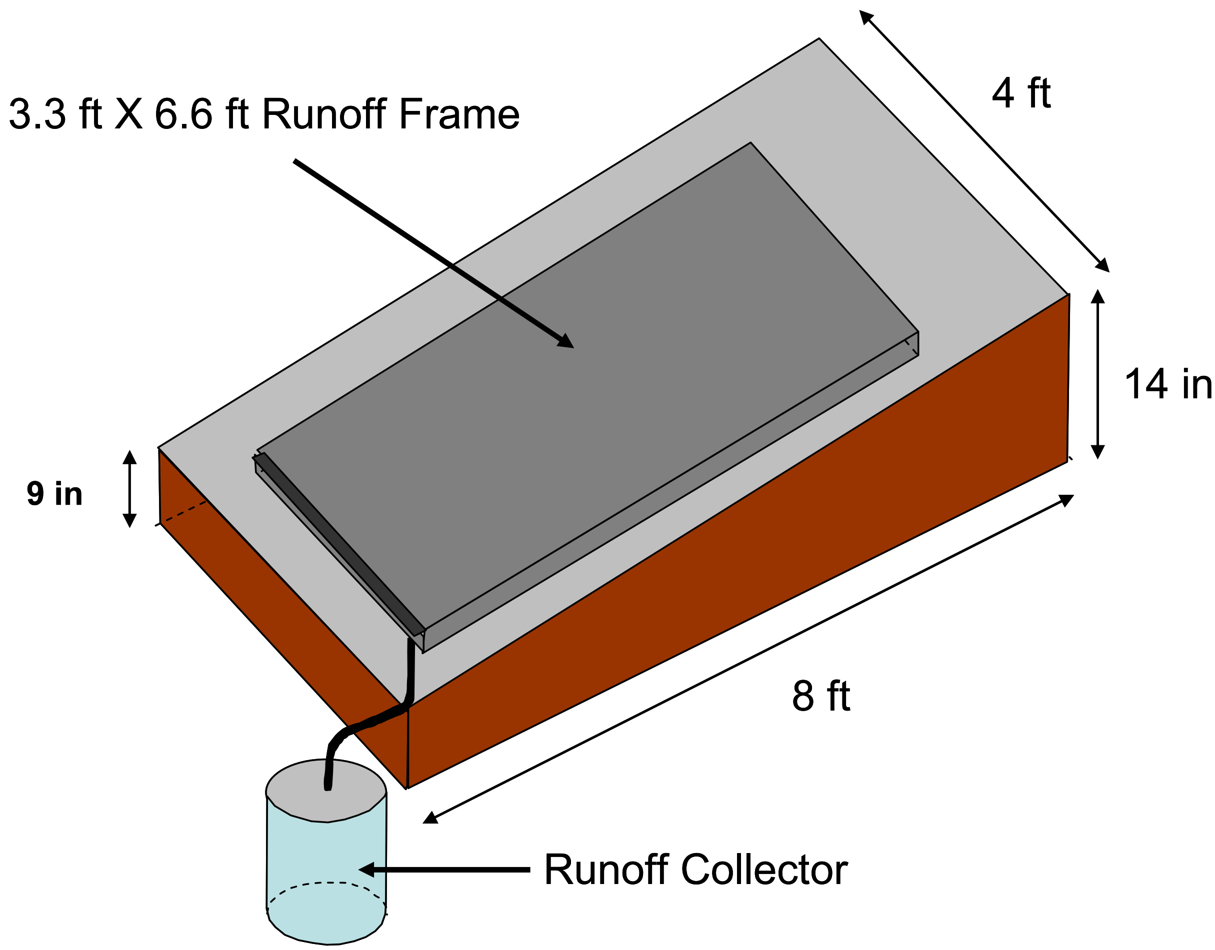

Figure 1. Diagram showing layout, dimensions and features of runoff plot box with metal frame.

Sixteen runoff plots boxes were installed in a four row by four column arrangement as shown in figure 2. The metal frames were installed at a constant slope of 5% on the surface of each runoff plot box and the soil within the metal frames graded smooth. The rather steep slope and smoothed soil surface of the plots was selected to minimize the unknown and variable surface storage component of the infiltration-runoff-erosion process. Consequently, the runoff and erosion rates measured in this study represent maximum rates for worse case conditions. Actual field runoff and erosion rates would be substantially less due to soil surface micro topography storage, sustained higher infiltration rates due to residue management and less slope. The runoff and erosion rates obtained in this study represent potential runoff and erosion for sloping conditions rather than actual field rates. Four common commercial sprinklers were used to evaluate infiltration, runoff and erosion differences. They were: 1) Nelson R3000 with brown plate (Nelson Irrigation Corp., Walla Walla, WA) with a Nelson 20 psi regulator, 2) Nelson R3000 with red plate with a Nelson 20 psi regulator, 3) Nelson S3000 with

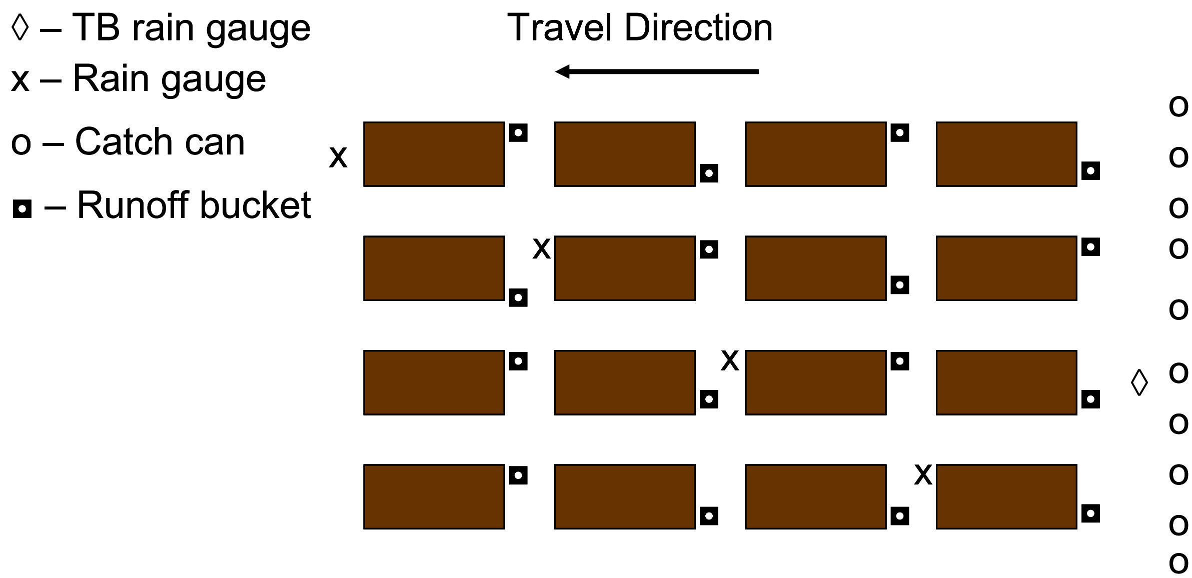

Figure 2. Diagram showing experimental plot layout used to evaluate center pivot sprinkler runoff and erosion potential.

purple plate with a Nelson 15 psi regulator, and 4) Senninger I-Wob with standard 9-groove plate (Senninger Irrigation Inc., Clermont, FL) with Senniger 15 psi regulator. Using manufacturer's data, sprinkler nozzle sizes were selected to be representative of those used on the outer end of ¼-mile center pivot systems in Idaho. The sprinkler nozzle sizes were also selected to provide approximately the same flow rate per sprinkler regardless of operating pressure or manufacturer. The selected sprinkler nozzle sizes and corresponding flow rates were; 1) 0.297 inch (#38) rated at 11.28 gpm, 2) 0.297 inch (#38) rated at 11.28 gpm 3) 0.320 inch (#41) rated at 11.48 gpm, and 4) 0.328 inches (#21) rated at 11.36 gpm, respectively. Sprinkler height was approximately 3 feet above the surface of the runoff plot boxes. Sprinkler spacing along the boom was 96 to 102 inches. Four consecutive irrigations were applied to the runoff plots with an irrigation interval of 5 to 10 days to allow the soil surface to dry and soil profile to drain between irrigations. All irrigation applications were to bare soil conditions. Only half the length of the irrigation boom was used to apply water to the runoff plots.

The four sprinkler configurations (treatments) were randomly assigned to the sixteen plots with one treatment per row and column in order to obtain a Latin Square statistical design. Twelve of the sixteen plots were covered with waterproof polyethylene tarps to protect the soil surface and prevent water application when the irrigation boom passed over the plot area with a particular sprinkler treatment. Then the irrigation boom sprinklers were changed, the tarps repositioned and the irrigation boom repositioned and towed upslope over the plot area again to apply a different sprinkler treatment. Irrigation treatments were completed over a one or two day period. All the tarps were installed and removed at the same time to minimize differences in soil drying between irrigation events. Sediment mass in runoff was measured using vacuum filtration and

Table 1. Soil particle size fractions for the three soils used in the study.

Soil Name	Particle Size Fraction (%)		
	Sand	Silt	Clay
Chijer Fine Sandy Loam	39	45	16
Portneuf Silt Loam	14	65	21
Sluka Silt Loam	27	63	10

filter paper. Statistical analysis of the measurements was conducted using SAS GLM procedure and Duncan's multiple range tests for means comparison (SAS, 2007).

The runoff tests were repeated for each soil type (Table 1). Soil was removed from each runoff plot box by hand and filled with the new soil. The soils used in the test were obtained from commercial farm fields. A large articulated hydraulic loader was used to collect soil from the top six inches of the field and load it on a dump truck. The soil was stock piled on site until used. Soil texture analysis was conduced on each soil using the hydrometer method.

Results

Texture analysis results for the three soils used in the study are listed in Table 1. The soils were selected to cover the range in sand and clay fraction available locally. A 25 percent range in sand fraction was fairly evenly split between the three soils. The range in clay fraction is limited due to the existence of predominately loam and silt loam textured soils in the local area.

Percent runoff (runoff volume / application volume x 100) for each sprinkler type, irrigation event and soil type are shown in figures 3 through 5. Target application depths for the four irrigation events in each series of tests for a specific soil were 0.96, 0.8, 0.6, and 0.6 inches, respectively. In general, the percent runoff for each soil increased with the number of irrigations. This result is attributed to reduced infiltration rates caused by soil surface sealing due to sprinkler droplet impact on the bare soil surface and is consistent with the findings of Thompson and James (1985), DeBoer et al., (1988), Agassi et al., (1994) and Lersch and Kincaid (2000). The development of a soil surface seal after the first irrigation was readily apparent for all the soils. Runoff measurements for a single irrigation event were highly variable despite the controlled experimental conditions and small distances between plots, limiting detection of significant differences in runoff among sprinkler types. Sources of random variability include soil placement and compaction in the runoff plot boxes, soil surface smoothness and structure, location of box within sprinkler overlap pattern and wind speed and direction. To minimize the effect these random factors have on detection of significant differences between sprinkler types, cumulative percent runoff for each sprinkler type was calculated as the sum of measured runoff divided by the sum of measured water application for the four irrigation events and statistically compared. Cumulative percent runoff for each soil type is shown in figure 6. There were significant differences in cumulative percent runoff between sprinkler types. Overall, the I-Wob sprinkler

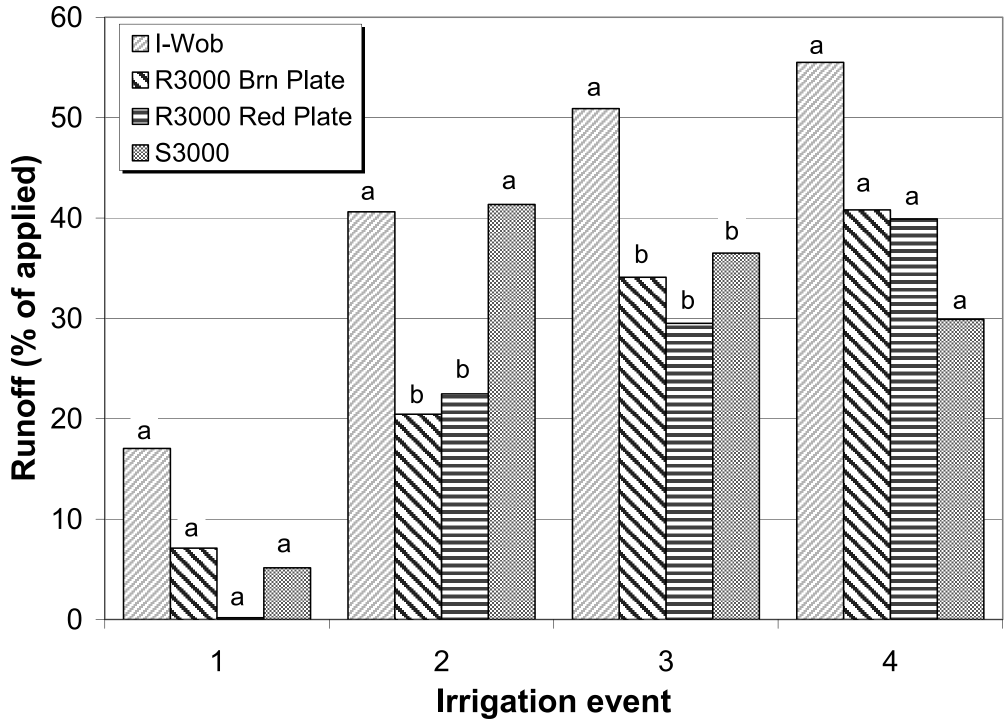

Figure 3. Runoff percentage measured for each of the four irrigation events on the Chijer fine sandy loam. Columns with the same letter for an irrigation event are not significantly different at the 0.05 level.

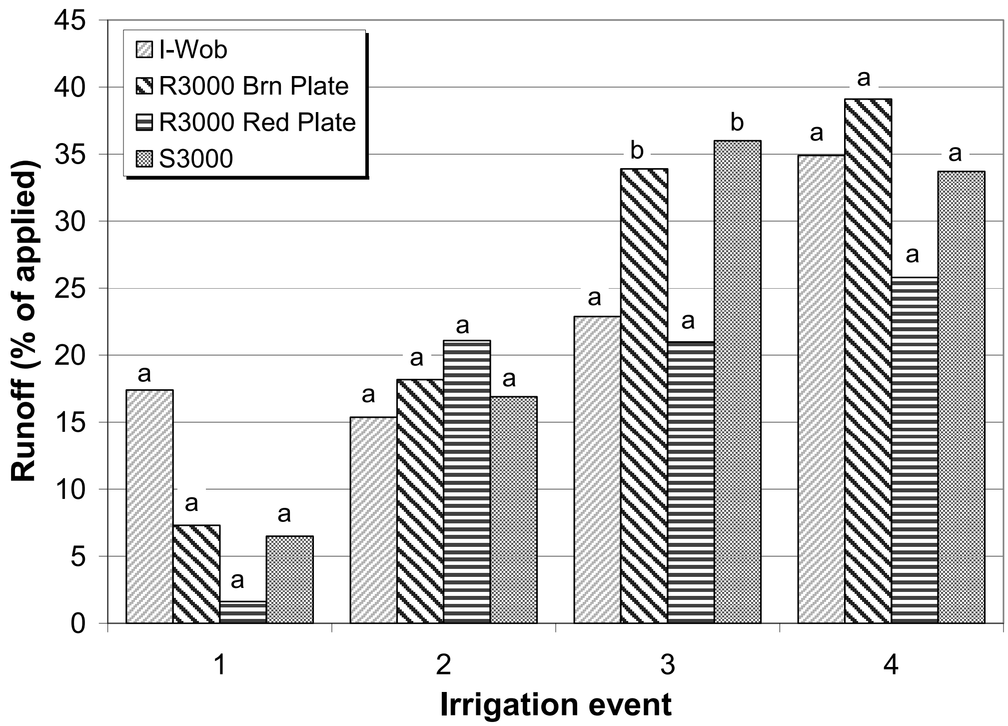

Figure 4. Runoff percentage measured for each of the four irrigation events on the Portneuf silt loam. Columns with the same letter for an irrigation event are not significantly different at the 0.05 level.

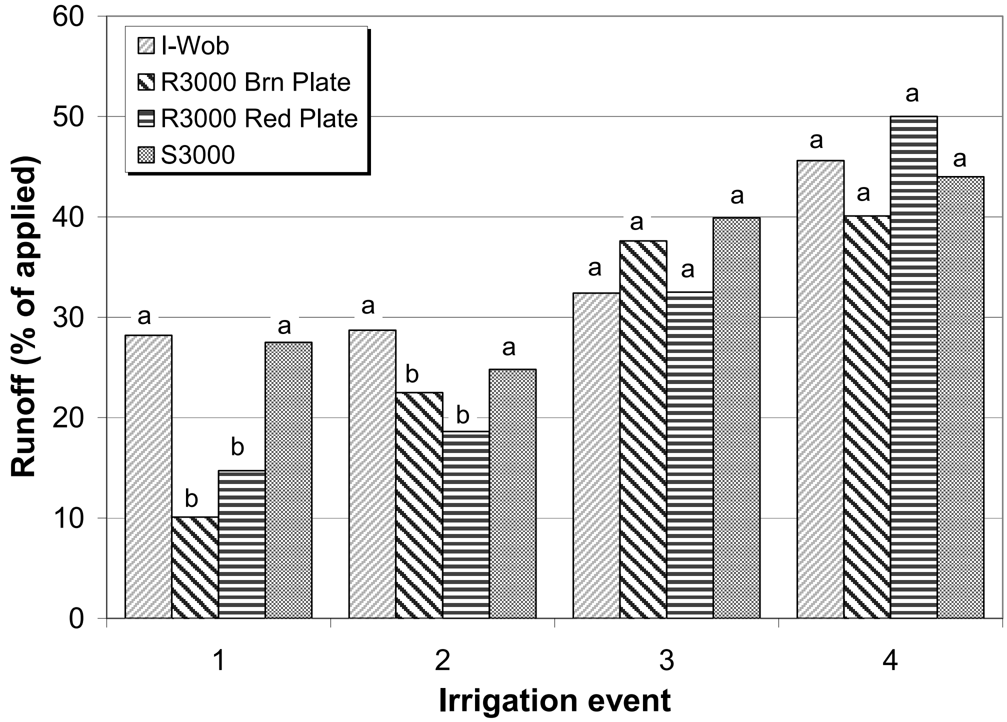

Figure 5. Runoff percentage measured for each of the four irrigation events on the Sluka silt loam. Columns with the same letter for an irrigation event are not significantly different at the 0.05 level.

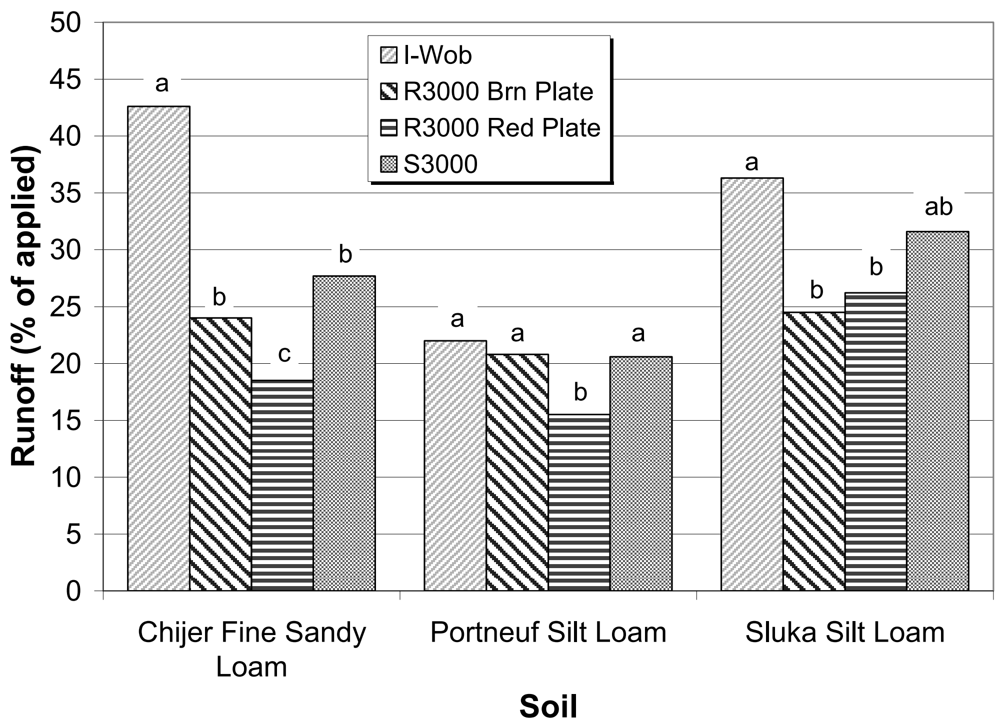

Figure 6. Runoff percentage summed over the four irrigation events for each soil tested. Columns with the same letter for each soil are not significantly different at the 0.05 level.

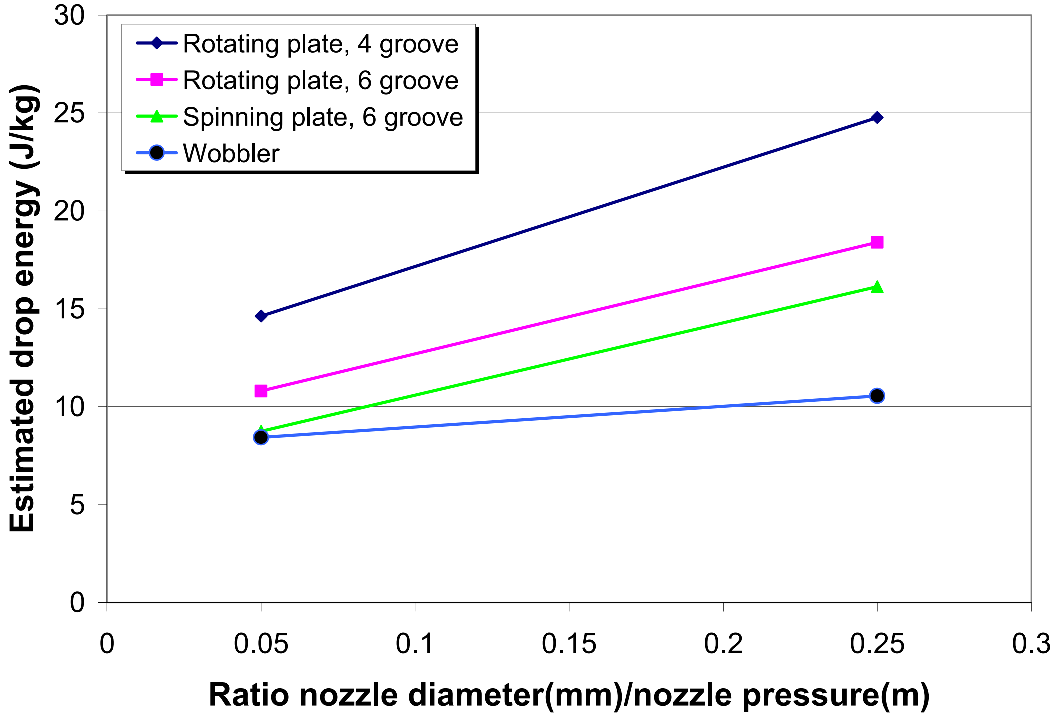

Figure 7. Approximate relative magnitude of droplet kinetic energy for sprinklers similar to those used in this study. Adapted from Kincaid (1996).

produced the highest runoff percentage and the R3000 with red plate sprinkler produced the lowest runoff percentage, for the soils tested. The magnitude of the differences in runoff percentage between sprinkler types is as great as or greater than the differences between the soils tested. In general, sprinkler types that visually appear to more uniformly distribute sprinkler droplets over the wetted area with respect to time produce the highest runoff percentage. Conventional theory on sprinkler droplet induced soil surface sealing and infiltration reduction is based on droplet kinetic energy as the driving factor. Estimated droplet kinetic energy for the sprinkler types used in this study is shown in figure 7 (Kincaid, 1996). Based on measured droplets sizes and modeled droplet velocity, the relative ranking of the sprinkler types in order of increasing kinetic energy is: 1) I-Wob, 2) S3000 spinner, and 3) R3000 red rotator. The results of this study, figure 5, are not directly related to droplet kinetic energy as determined by Kincaid (1996). Sprinkler types with the highest droplet kinetic energy have the lowest runoff (highest infiltration) and vise versa. Possible explanations for this outcome include incorrect representation of droplet kinetic energy, conventional soil surface sealing theory does not apply to the soils used in this study, or some unknown factor is dominating the infiltration and runoff process for the study conditions. Additional research is needed to examine the infiltration and runoff processes under the study conditions in more detail in order to explain the results.

Sediment loss per unit of applied water for each sprinkler type, irrigation event and soil type are shown in figures 8 through 10. Sediment loss is highly correlated with runoff volume because greater runoff provides a greater opportunity for sediment transport. In

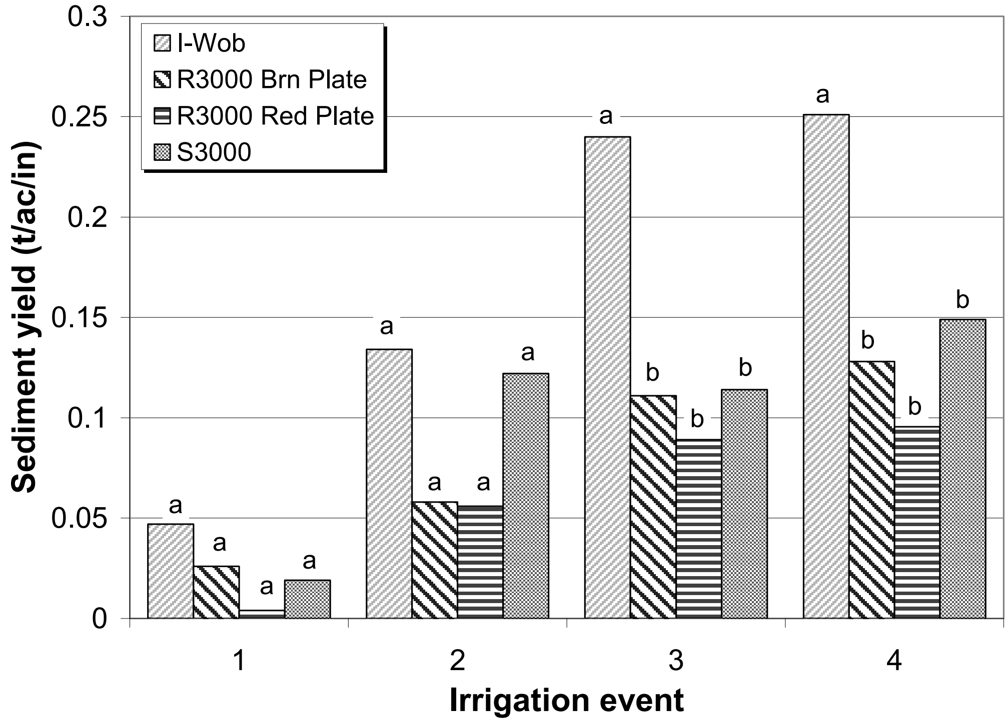

Figure 8. Sediment loss measured for each of the four irrigation events on the Chijer fine sandy loam. Columns with the same letter for an irrigation event are not significantly different at the 0.05 level.

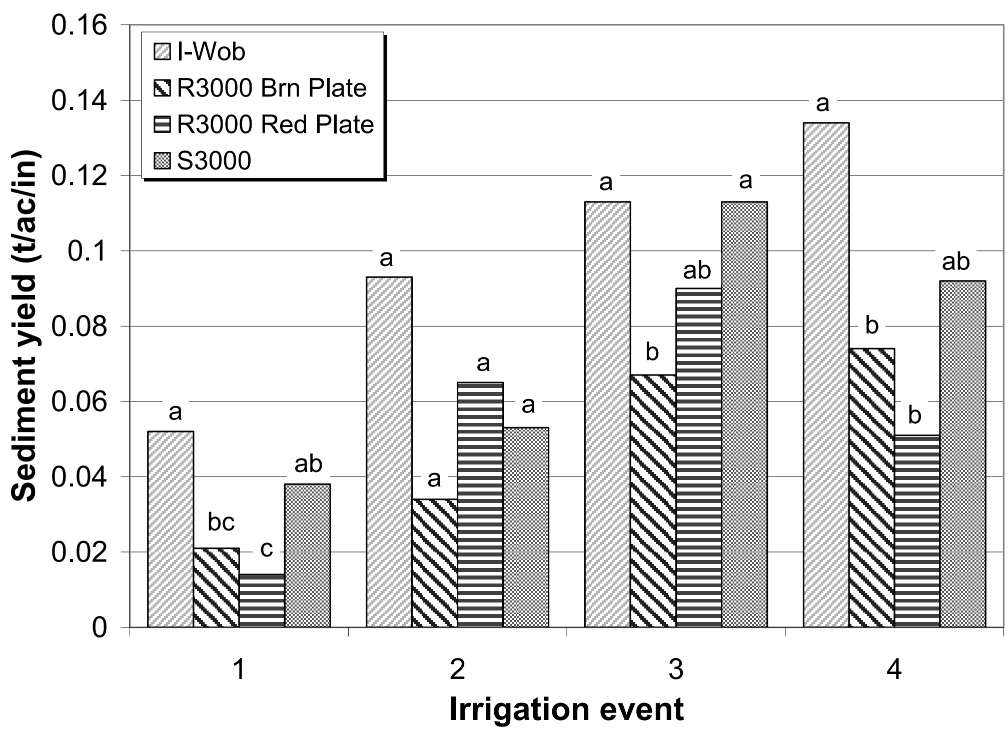

Figure 9. Sediment loss measured for each of the four irrigation events on the Portneuf silt loam. Columns with the same letter for an irrigation event are not significantly different at the 0.05 level.

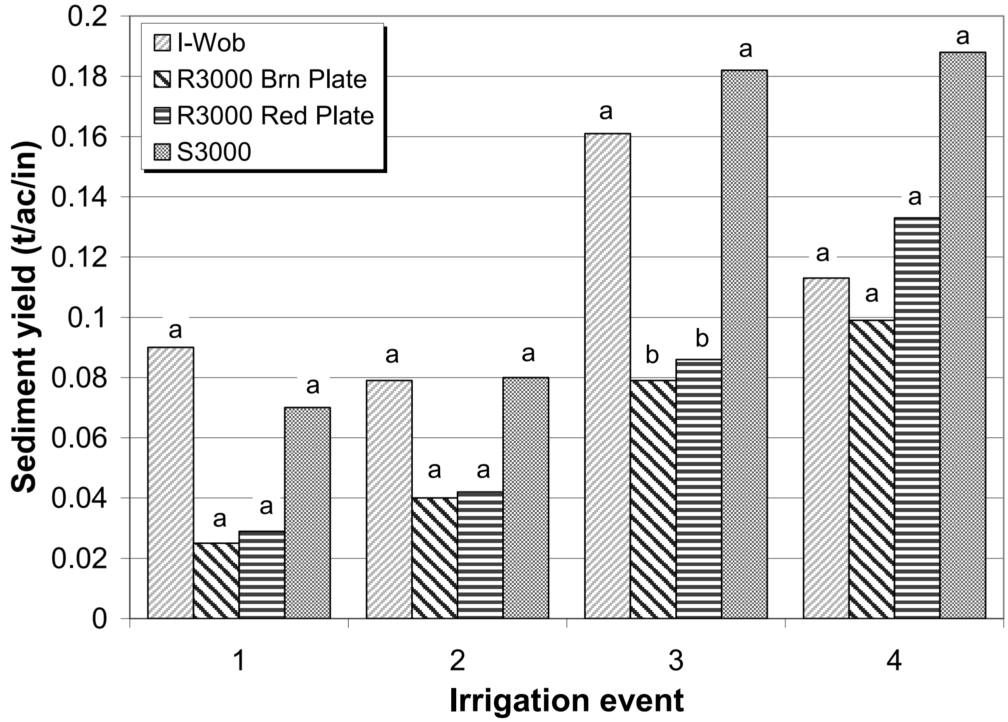

Figure 10. Sediment loss measured for each of the four irrigation events on the Sluka silt loam. Columns with the same letter for an irrigation event are not significantly different at the 0.05 level.

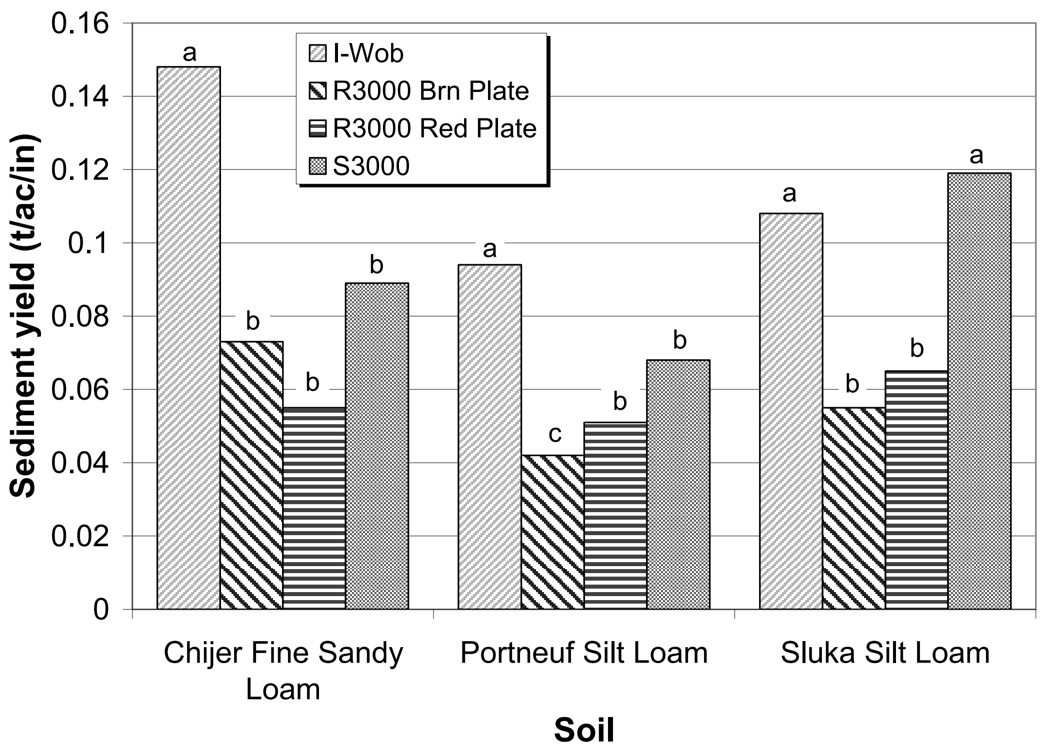

Figure 11. Sediment loss summed over the four irrigation events for each tested soil. Columns with the same letter for each soil are not significantly different at the 0.05 level.

general, sediment loss for individual irrigation events closely follows runoff. Cumulative sediment loss divided by cumulative water application for each soil type was calculated and statistically compared to reduce the effect of random variability. Cumulative sediment loss per unit of applied water is shown in figure 11. Significant differences in sediment loss between sprinkler types exist for each of the three soils tested. The relative ranking of sediment loss for each soil type closely follow the relative ranking for runoff. Overall, the I-Wob sprinkler produced the highest sediment loss and the R3000 with red plate sprinkler produced the lowest sediment loss. Sprinkler types that visually appear to more uniformly distribute sprinkler droplets over the wetted area with respect to time produce the highest sediment loss. This functional difference may cause sediment to remain in suspension in overland flow for a longer duration allowing it to be more readily transported down slope.

Conclusions

Potential runoff and erosion from three Idaho soils were evaluated under emulated center pivot irrigation using four common commercial center pivot sprinkler types. There were significant differences in runoff and erosion rates between center pivot sprinkler types for the soils tested and experimental conditions. The magnitude of the differences is equal to or greater than the differences soils tested. Overall, the I-Wob exhibited the highest runoff and erosion rates and the R3000 sprinklers exhibited the lowest rates for the three soils tested. In general, sprinkler types that visually appear to more uniformly distribute sprinkler droplets over the wetted area with respect to time exhibited the highest runoff and erosion rates. The relative differences in runoff between the sprinklers tested were not directly proportional to droplet kinetic energy. This outcome is in conflict with conventional theory on soil surface sealing from droplet impact. Possible explanations include incorrect representation of droplet kinetic energy, conventional soil surface sealing theory does not apply to the soils used in this study, or some unknown factor is dominating the infiltration and runoff process for the study conditions. Additional research is needed to examine the infiltration and runoff processes under the study conditions in more detail in order to explain the results.

Acknowledgments

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Irrigating Cotton in a Thermally-limited Area

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Abstract: *Southwest Kansas is north of the traditional Cotton Belt and considered a thermally limited area for cotton; however cotton is being grown as an alternative to corn to stretch declining water resources. Producers in this region have adopted both sprinkler and subsurface drip irrigation (SDI), but SDI may result in greater soil temperatures due to less evaporative cooling compared with sprinkler. This is an important consideration for cotton production in a thermally-limited climate. A field demonstration was conducted in 2007 to compare soil temperatures for sprinkler and SDI planted in cotton. The season started with relatively low temperatures but rapidly increased. First bloom occurred on July 24 (63 days since emergence) when cumulative growing degree days (GDD; 60 °F base temperature) reached 847 °F, which was about 100 °F lower from areas in the traditional Cotton Belt. Total GDD from planting date of May 10 to September 30 was 1907 °F, which was about 250 °F less than that expected in the Cotton Belt. The daily average soil temperature was about 6 °F greater for SDI compared with sprinkler. However, lint yield was 1,164 lb ac^{-1} for the sprinkler irrigated field, slightly higher compared to 1,005 lb ac^{-1} for the SDI field. This differential in yield was contributed by timely and higher amount of soil water availability. The sprinkler irrigated field received about 5.7 inches of water input from rain and irrigation, whereas the SDI field received only 3.9 inches combined from irrigation and rain. The SDI field did not receive irrigation after mid-July, but the sprinkler field received irrigation in both late July and mid-August. Irrigation timing and amount applied had effect on yield. Amount of residue cover in no-till effected plant population, but plant population had no effect on yield.*

Keywords: Ogallala aquifer, thermally limited area, cotton, SDI, irrigation

Introduction: In Southwest Kansas, the capacities of irrigation wells are declining with the decline of the Ogallala Aquifer groundwater level. Producers are looking for alternative crops to conserve water and at the same time maintain economic sustainability. Farmers in Southwest Kansas and North Plains of Texas are considering cotton as an alternative crop, which has respectable revenue potential as corn but about half the irrigation requirement (Howell et al., 2004). Acreages were increasing, but in 2004 the heat units were low for cotton. This adversely impacted yield and quality, and as a result the acreage declined. It is also possible that cooling due to surface wetting of canopy and or soil surface from sprinkler or surface irrigation may lower the perceptible heat units for the cotton plant, especially in thermally limited areas. Subsurface drip irrigation (SDI) may result in less evaporative cooling from the soil surface and crop canopy compared with sprinkler irrigation, which could potentially result in earlier establishment and maturity of the crop. The objective of the study was to compare soil temperatures, plant development, and yield for cotton irrigated with sprinkler and SDI.

Procedures

Two fields within a one-mile radius operated by the same producer were selected for the field study and demonstration. One of the fields was irrigated by SDI and the other was irrigated by center pivot sprinkler system. The sprinkler-irrigated field was previously planted in corn and had good residual soil water when the cotton crop was planted. The SDI field was previously planted in grain sorghum for half the length and soybean in the remaining half of the field. Both fields were cultivated in a no-till method. At the time of cotton planting on May 10, 2007, the fields had different amounts of residue cover. The USDA-NRCS Line Transact method was used to determine the residue cover. The sprinkler irrigated cotton was planted with a 45% corn residue cover on the field. The SDI field had only 24% residue cover for the portion that grew grain sorghum. The other half that had soybeans had very little residue.

The residue cover had a big impact on plant stand. Plant population counted initially at emergence for the sprinkler irrigated field with no-till corn residue (45%) was about 20,000 plants ac^{-1}, whereas in the SDI field with Milo residue (24%) the population was more than 25,000 plants ac^{-1}. Plant population in the clean field area was 62,378 plants ac^{-1}, exceeding target plant population of 50,000 plants ac^{-1} (with a seeding rate of 55,000 plants ac^{-1} indicating that the planter dropped more seed then the calibrated rate).

Irrigation was done by the producer as and when available. For the first year no control was imposed. The sprinkler field received 2.5 inches of irrigation and was applied at the critical stages. Rainfall in this site was recorded as 6 inches. The SDI field received 1.7 inches of irrigation at the rate 0.08 inches per day, which was far below the ET rate. Irrigation was not available after July 15 for the SDI irrigated field, a very critical period when the field was in bloom. Rainfall amount at this site was about 4 inches. There was also severe damage from 2-4-D herbicide drift in the SDI field. The sprinkler field experienced no damage from herbicide drift and was irrigated until mid-August which helped the crop at critical bloom stage. A summary of the field conditions are shown in table 1.

Thermocouples were laid in three rows in each site at 4 different depths- at 0, 2, 4, and 6 inches below surface. Temperature was averaged for each field from 24 hours data collected at 15 minutes interval. A solar panel installed at each site provided power to recharge batteries that powered the data logger. Plant growth data were recorded. Yield reported was based on lint weight from total field production. Hand harvested yield is also shown in table 1.

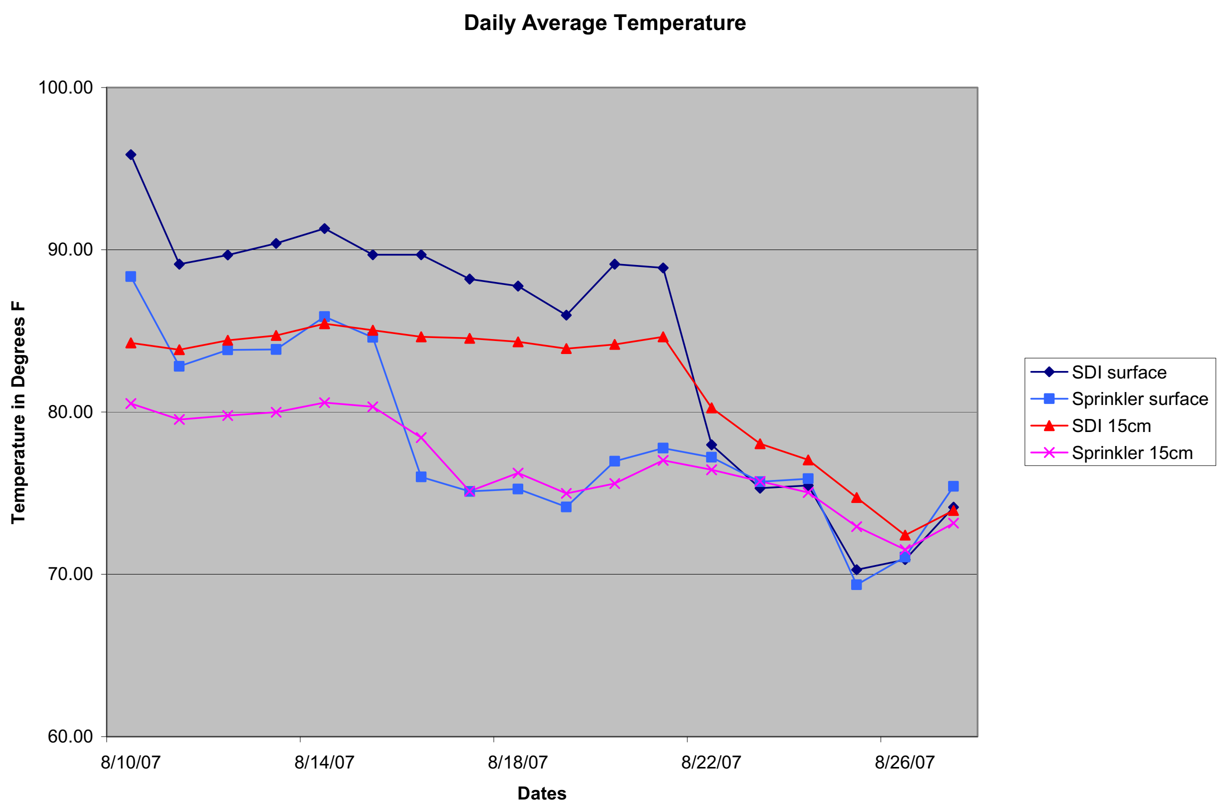
Table 1: Summary of field conditions for the study sites

Sprinkler	Subsurface drip
Hybrid: Paymaster 2145-PGR 4 Cruiser	Hybrid: Paymaster 2145-PGR 4 Cruiser
Seed rate: 55,000 per acre	Seed rate: 55,000 per acre
Target plant population: 50,000	Target plant population: 50,000
Planted in no-till corn residue	Planted in no-till grain sorghum and soybean residue
Residue cover measured using NRCS line transact method was about 45%	Residue cover in grain sorghum was 24% and minimal in soybean residue area
Planting Date: 5/10/2007	Planting Date: 5/10/2007
Start of Emergence: 5/23/07	Start of Emergence: 5/18/07
Plant population per acre at emergence in the count row - 19,863; in harvest row -22,900	Plant population at emergence in count row in grain sorghum – 25,090 and in harvest row 24,891; soybean area at emergence in count row – 62,378 and in harvest row – 51,276
Herbicide: Prowl H2O – 5/12/07 Acephate – 6/2/07, Dual magnum & Omex 22 – 6/19/07, Acephate – 7/5/07,	Prowl – 5/12/07, Omex – 6/2/07, Dual magnum and Omex – 6/19/07, Acephate – 7/3/07
Growth control: Pix (10 oz) – 7/10/07	Growth control: Pix (12 oz) – 7/18/07
Water use: Crop ET – 14.3” (5-23 to 9-30) Reference ET – 33.24” Irrigation: 2.25”, Rain: 3.46” (effective) out of 6.53” (Total water input: 5.71”)	Crop ET – 12.95” (5-23 to 9-30), Reference ET – 33.24” Irrigation: 1.76”, Rain: 2.19” (effective) out of 4.6” (Total water input: 3.95”)
The daily average of 6 degrees lower	The daily average of 6 degrees higher
Av. Bolls/plant as of 9/12/07 is 14.5	Average number 14
Plant height – 30.25”	Plant height 33.7”
2-4-D damage: None	Extensive 2-4-D damage
Cotton GDD = 1907 by Sept. 30	Cotton GDD - 1907
Yield 2.2 bales (average harvest value per acre for the total field). Hand harvest value about 2.6 bales lint.	Yield 1.93 bales (average harvest value per acre for the total field). Hand harvest yield for grain sorghum area 1.3 and soybean area 2.2 bales.

The field trial failed in 2008 due to the lack of initial soil water for planting in the SDI field. The producer delayed planting as the moisture in the planting depth was insufficient. Later, the soil surface was scraped aside and seed planted in the favorable moist zone, but a heavy rainfall event caused soil crusting, which prevented emergence, and the crop was abandoned.

Results and Discussion:

The cotton crop began to emerge 5 days earlier for the SDI field (May 18) compared with the sprinkler field (May 23). This may have been more related to fewer residues in the SDI field resulting in greater daytime soil heating early in the season. Temperatures recorded for August 10-27, 2007 are presented in Figure 1. Soil temperatures were about 5-6 °F greater for SDI compared with sprinkler until August 21. Greater soil temperatures in SDI irrigated fields in the Texas High Plains were also reported by Colaizzi et al. (2006). In this study it was observed that with the cooling of the season the soil temperatures came closer and the difference between surface and 15 cm depth also shrank.



The yield in the sprinkler field was a little better indicating that irrigation at full bloom is more critical for yield. The sprinkler irrigated field received irrigation in late July and early to mid-August, which were critical periods. There was no water available for SDI field after mid-July, and the total water input was less for SDI field. Although soil temperatures were greater for the SDI field, final lint yield was probably limited by water stress during full bloom. It has been reported that use of SDI has resulted in greater crop yields, greater water use efficiency, better cotton fiber quality, and enhanced crop maturity compared with typical sprinkler packages (Bordovsky and Porter (2003), and Colaizzi et al. (2005)

Conclusion

One year field study indicates that a higher soil temperature is maintained in fields irrigated by SDI. This has potential in contributing to yield and quality of cotton, especially in a thermally limited area.

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Revisiting farm ponds for irrigation water supply in the Southeast US

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Abstract. *In humid regions, agricultural irrigation developed using stream and farm pond water sources. The same droughts that pushed farmers to irrigate often made these sources unreliable. Where deep groundwater aquifers existed, wells became the water supply of choice. In the SE Coastal Plain aquifers are showing signs of over-pumping, and high energy costs are causing a fresh look at farm ponds. We cataloged and characterized many of the 60,000 water bodies in the Coastal Plain of Georgia that could be used for irrigation. Proximity to cultivated fields, catchment area, potential pond storage, and proximity to other users were considered. Average pond sizes could not supply full-season irrigation for average pivot fields, although they could for small pivots and other systems. Many pond and catchment sites remain near irrigatable fields. With proper incentives, the irrigators could increase the capacity of surface water supplies for irrigation and decrease pressure on groundwater* aquifers.

Keywords. Southeast U.S., humid region, farm ponds, man-made, reservoirs, impoundments, sprinkler irrigation, surface water supply.

Introduction

As with most regions of the country, the Southeast U.S. has experienced the pinch between water supplies and water demands. Irrigation, mostly by overhead sprinkler systems, has relied upon self-supplied water sources, especially in the Coastal Plain where most row crop and vegetable production occurs. No federal or state programs have developed regional reservoirs or water distribution systems to support production agriculture, and none of the large federal reservoirs have been purposed for agricultural irrigation.

Initially farmers used surface water sources – streams and ponds - but as they became more dependent upon irrigated crop production, they came to rely upon groundwater supplies. While the major aquifers of the region, particularly the Floridan system, are extensive, there are areas with growing evidence that withdrawals may be exceeding long-term recharge. In the Coastal Plain, homeowners, municipalities, and most industries are completely dependent upon these same aquifers. Many are in close proximity to irrigated agriculture. Long term declines in water tables, or hydraulic heads in confined portions of the aquifers, threaten not only agriculture but also industries and other commercial and household uses.

Rainfall in this humid region can supply a portion of the water needed for irrigation, just as it supplies about half of the crops needs directly during the growing season. However, the water for that irrigation must to be captured and stored until irrigation is needed. Farmers have long recognized this. Many built or expanded impoundments on their properties to provide at least a portion of their irrigation water supply.

As the region comes to grips with growing populations, greater competition for existing water supplies, and more frequent shortages during drought, it has looked at all water supplies and demands more critically. As with other regions where agriculture faces competition for water, its water use is being questioned. To the extent that agriculture can secure water that is not in direct competition with that most other users and does not threaten environmental problems, it can secure its survival. With abundant rainfall, even in drought years, the Southeast farmers can probably accomplish this.

Our objective in this study was to determine to what extent could on-farm surface water storage meets irrigation needs in Georgia. Since all planning is local, we also sought to understand where current reliance on farm impoundments was greatest.

Background

Irrigated agriculture is a relatively new phenomena in the Southeast. A humid, temperate to subtropical region, it receives a plentiful supply of rainfall in most years. The rainfall, while never evenly distributed, occurs year-round. In most years, however, evapotranspiration from native vegetation and crops will exceed rainfall from May through October. Most of the river systems are short, extending from the Appalachian Mountains to the sea or Gulf just a few hundred miles away. This combination places a premium on stored water to see users through the summer months. In the past farmers accepted the summer shortfall and just lowered their production expectations. However, in the 1970's farmers began installing irrigation as new pivots and other sprinkler equipment became practical for irregular shaped fields and rolling topography. Within a few years, higher production levels provided a competitive edge, and neither farmers nor their financial backers were willing to accept risk of drought induced crop failures any longer.

Water supplies for these sprinkler systems, which now cover almost 1.5 million acres in Georgia alone, include streams, farm ponds, and groundwater, all located on the irrigator's property. The dense, dendritic network of streams in Piedmont and Coastal Plain landscapes gave most farmers direct access to some flowing water, and withdrawals were secured by their riparian rights. Rights or not, streams of the region generally proved unreliable because of the summer rainfall-ET deficit. Much of the summer rainfall is intercepted by plants and dry soils before it can reach the streams, and many smaller streams go dry or have reduced flow when needs for irrigation are greatest. Farmers turned to their ponds that stored rainfall from the winter excess and from periodic summer runoff events. Many that were originally built for maintaining livestock became irrigation water supplies. As farmers turned to irrigation to maximize their production efficiency, even these ponds were seen as too risky and unreliable. If groundwater was an option, as it was throughout much of the Coastal Plain, it became the preferred water source. Not only was the source less dependent upon in-season rainfall, but also wells could be placed conveniently at the pivot point or other location that minimized pipe and pumping losses. Harrison documented the transition in water supplies in the triennial Georgia Irrigation Surveys (Harrison, $2005_{a,b}$). While the number of irrigation systems supplied from ponds and streams has remained constant at about 6,000 since the early 1970's, systems supplied from wells have increased from fewer than 1,000 in 1972, to 6,000 by 1986, and to more than 10,000 by 2000.

Georgia and US Geologic Survey (USGS) monitor depth of water table or hydraulic head in wells in the primary aquifers in Georgia. While these records show no long-term water table declines in the recharge areas of the principal – Floridan – aquifer, declines of up to 1 to 1.5 ft/y have been observed in confined areas of the Floridan aquifer. These declines are particularly steep in the central Coastal Plain area, and they have persisted for almost 25 years in some wells. During droughts of 1999 to 2002 and more recently 2007 to 2008, well failures have affected many who tapped this aquifer shallowly or who relied upon the shallower Miocene aquifer above it. These are areas with extensive agricultural irrigation. Declines are commonly seen during the pumping season. These partially rebound during Fall and Winter by hydraulic heads are not returning to previous Spring levels.

In the Suwannee and Ochlocknee Basins in the Central Coastal Plain and in selected watersheds within other river basins, withdrawals permitted by the Georgia's Environmental Protection Division (EPD) exceed normal summer and fall flows of their streams. Agricultural withdrawals in Georgia are permitted by pump capacity in gallons per minute with no limits on the daily or monthly pumping. For direct withdrawals from streams that have a 7Q10 value greater than 1 cfs, there are low stream flow levels that are supposed to protect stream base flow, but no surveillance is used to assure that pumps are turned off when these levels are reached. Normally, farmers stop pumping when flow is too low to keep their pumps primed. This occurs regularly, especially during the recent drought.

Because stream flow is unreliable, and because many withdrawals are made from the same stream by neighboring farmers, most have turned to on farm impoundments to catch and retain water. These farm ponds do provide water storage, but farmers do not always have impoundments with enough capacity to last through low rainfall periods between runoff-generating events. Thus many refill their ponds with wells.

As with other areas where agricultural irrigation is practiced, conflicts arise with others who depend upon the same shared sources of surface and groundwater, and ecosystems are challenged when natural flows and discharges from groundwater are altered. In the Georgia portion of the Coastal Plain, agriculture has fewer competitors than found in most irrigated areas. Most of the surface water withdrawn for irrigation is from stream and river systems that have few urban centers downstream. Those that are there rely upon groundwater. However, the regions abundant flora and fauna, well known for its bio-diversity, can be affected when streams dry earlier, reach lower summer levels, or remain low for extended periods because of withdrawals. Interstate challenges to surface water withdrawals are based in part upon impacts on threatened and endangered species. Groundwater withdrawals for irrigation can also compete directly with other users. Rural and urban homes, municipal suppliers of most community water systems, and commercial and industrial users are often close enough to be impacted by farm withdrawals.

Recognizing the value of rainfall and runoff as a source of water in the area, Georgia soil and water conservationists have identified farm ponds as a viable water storage method for agricultural irrigation. Using Farm Bill support, they have cost shared on new or enlarged pond construction when that pond will be used for existing irrigation. This includes systems irrigated by groundwater. With a view towards understanding the overall potential of farm ponds for irrigation supply and particularly identifying areas where ponds could be used more extensively in irrigation, we set out to inventory the existing impoundments and irrigation in the Georgia Coastal Plain

Approach

Most irrigation in Georgia and other Southeastern States occurs in Coastal Plain regions. We used US Geologic Survey maps of sub-basins (HUC8) that covered the Coastal Plain region of Georgia as study areas (USGS, 2005). In Georgia there are 32 sub-basins in the Coastal Plain. Ten of these receive part of the main stem flow from upstream areas that lie in the Piedmont areas of Georgia. These Piedmont streams – Savannah, Oconee, Okmulgee, Altamaha, Flint, and Chattahoochee – pass through the Coastal Plain relatively untapped by agriculture. Together, they account for fewer than 0.1% of all permitted surface water withdrawals in the Coastal Plain. Almost all of the surface water withdrawals for irrigation are from collected runoff and streams from rainfall that originates on the 32 Coastal Plain sub-basins themselves. We sought to identify water stored in impoundments in these areas.

No single comprehensive listing or map of all man-made impoundments exists for Georgia, but several efforts have identified the vast majority of water bodies including impoundments. Water bodies connected with flowing streams have been mapped with the Southeast NHD+ GIS data layer (USGS, 2006). The layer did not provide extensive enough mapping of ponds, but it did provide the most comprehensive mapping of streams in the region, allowing us to understand the extent to which these streams are impounded. The Georgia Department of Transportation undertook the mapping of the water bodies following passage of the Safe Dams Act in 1978. Highway structures including culverts, bridges, and paving are impacted by dam failures, and during storms impoundments may back up water onto rights-of-way. The DOT mapped water bodies of all types and sizes for each of the state’s 159 counties (Georgia DOT, 1999).

Overlay of the NHD and DOT data sets showed that most impoundments of NHD were also mapped by DOT, but their area and shape often differed. In addition 2007 aerial imagery showed additional water bodies that were missed by both efforts. To get a better idea of the relationship of these data sets to visible imagery, and to understand where impoundments were in relation to streams and to each other, we created random transects. Each line was 10 to 25 miles in length with random orientation and starting point in the landscape. All water bodies that were visible on aerial imagery touched by or intersected by the lines were noted and visible boundaries for each drawn. Catchment areas were measured using topographic maps. Distance to nearby upstream and downstream impoundments and stream order and stream number (expressing the position of the impoundment relative to size of the stream) were noted. Sizes of remapped ponds were compared with DOT and NHD. Finally distance to nearby irrigated fields or potentially irrigated fields was measured.

Proximity of impoundments to irrigated fields required map coverage of known irrigation. During 2006-2008, the Georgia Soil and Water Conservation Commission (SWCC) mapped irrigated field areas as they installed flow meters as per 2003 legislation requiring that all permitted water withdrawals be metered. Field technicians used GPS to locate existing withdrawal points, pivot pads, and extent of irrigation hardware, as well as boundaries of irrigated areas for other fields. These were then mapped in GIS, although for pivots, irrigated area was only shown to the end tower for pivots and not the additional area reached by the end gun. We increased wetted areas by 5% to estimate this additional area in computing total irrigation areas from this data source. Georgia's Environmental Protection Division (EPD) also maintains a mapping of irrigation in the State. These were prepared in cooperation with farmers during the permit application and evaluation process or during county based permit days that attempted to bring early permit records up to date. Where subsequent field mapping of irrigated area by the SWCC confirmed these locations, their area values were substituted for EPD's. Finally, center pivots that were not mapped in either record set but were visible in 2007 aerial imagery were mapped by systematic scan of each county's image. Area and location of each field was accomplished in GIS.

Armed with the extensive mapping of ponds and irrigated fields we began a systematic analysis to estimate those ponds which could be used in irrigation and conservatively estimating storage capacities. All ponds of 30 acres or greater were individually inspected and ruled as available or not available for irrigation. Most were ponds owned or operated by electricity generators, municipalities, parks and recreation. Others were built as features in housing developments. Unless they had permitted withdrawals for irrigation (EPD permit records) or were located in areas adjacent to cropland, these were considered unavailable for irrigation. On the other end of the scale there were numerous impoundments created as landscape features, fire protection and livestock watering on individual rural properties. Although small ponds may be drained for irrigation in drought years, ponds under two acres do not provide enough storage for more than a single irrigation on an average irrigated field or perhaps two on a small fields. More commonly when these are used in irrigation, a well is used to refill the pond and hold water that will be pumped out at a rate greater than wells in the area could supply directly for irrigation. Ponds one acre or larger that were not otherwise designated for non-agricultural uses formed the base area for potential surface water storage in the Coastal Plain sub-basins.

Storage capacity was not recorded in either USGS or DOT records of water bodies. Topographic maps can provide estimates of depth of water at the impoundment dam. However, with 10 ft contours in many areas these would be very rough. Instead we used estimates of depth to area as provided by NRCS employees who design these ponds. From their estimates, we used a conservative storage of five feet as an average over all surface area of the pond. This may be too high for older ponds partially silted in from uphill and upstream soil erosion. It is too low for new ponds, especially those over 5 acres in area.

Results

Impoundments in Coastal Plain

Transects intersected 161 pond areas. Almost 65% of these had not been mapped by USGS in its National Hydrologic Data set; however almost all of them were included in Georgia DOT maps. Sizes of these impoundments varied from one to 220 ac, with an average of 11.7 ac. The distribution of pond sizes (Fig. 1) though shows that 75% have less than 9 ac surface area.

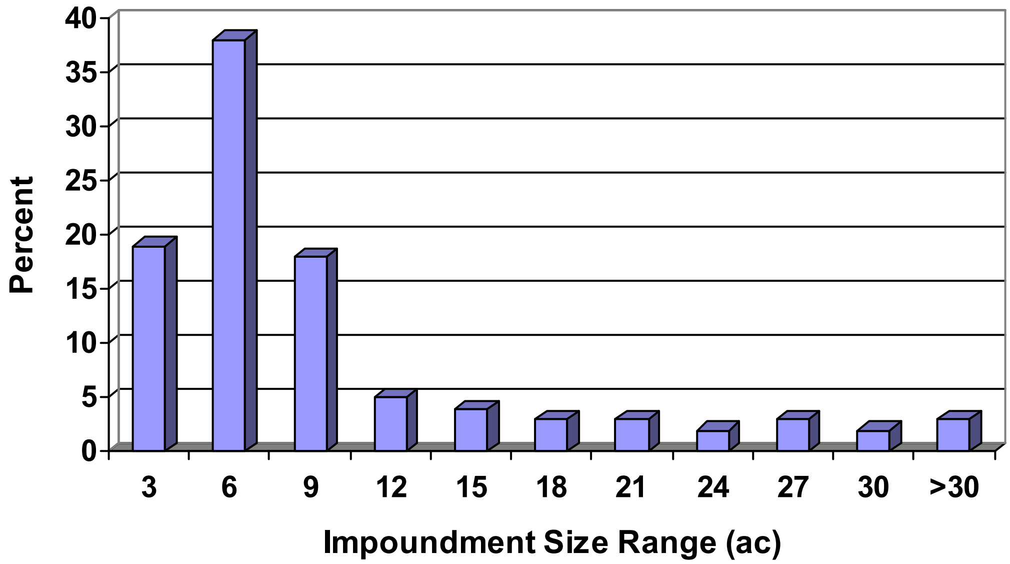

Figure 1. Distribution of pond sizes in the random sample of 161 impoundments intersected by random transects in the Georgia Coastal Plain.

We traced the source of water feeding the ponds. Catchment areas varied from 17 to more than 10,000 ac with average catchment of 900 ac. With less than 5% runoff from a catchment area following a 1 inch storm, the average catchment could provide 45 ac-ft, easily filling most small impoundments that have less than 9 ac surface area.

In the Coastal Plain, most impoundments are formed as a dam is placed across a water course. Of the 160 random ponds studied in detail, 84 or 52% were built across drainage ways that normally have no flow (off-stream). These ponds catch runoff during and immediately after a rainfall event, In a few cases interflow and even seepage from permanent water tables may support the pond. Ponds in these off-stream positions do not interfere with migration of fish or other stream life. These ponds in the Coastal Plain do typically include wetlands soil areas. New ponds require wetland mitigation if they are large, but the US Army Corps of Engineers has given blanket permission to NRCS to exempt small farm ponds for irrigation from wetland rules. While covering wetland areas near drainage ways is common, other parts of the impoundment lie outside of the wetland. This is because broad wetland areas are generally not suitably shaped for pond construction.

In addition to the 52% of ponds that were off-stream, another 36% were on first order streams. This section of the stream is the most upstream segment of flowing water in a stream system. In addition to runoff, first order streams typically are sustained by interflow and seepage from surrounding shallow water tables. They tend to dry up in drought years, but they can refill or maintain pond storage capacity between rainfall in other years. Generally speaking first order streams would have 7Q10 flows of less than 1 cfs, and EPD would not require low-flow shutoff for permitted withdrawals from these streams or ponds on them. Just 10% of ponds were on second order streams – below junction of first order streams – and only 2% of the ponds were on third order streams.

The topography of the area makes construction of large ponds impractical, however, many land-owners build one pond below another in a ‘string-of-pearls’ fashion. Of the transected ponds 46 or 28% of the ponds had at least one pond upstream. On average these were 0.59 mi upstream. There were 71 ponds, 44%, with a downstream pond located an average of 0.55 mi downstream. The close proximity provides options for management including draining an upstream pond to refill a downstream pond if pumping empties it during long rainless periods.

Analysis of ponds mapped by DOT in Georgia is startling. By their classification 81,000 water bodies have been built in the Coastal Plain. These include everything from the largest reservoirs to small dugout ponds located on individual properties. Some canals and industrial lagoons and waste storage ponds were also identified. We examined the classification of all industrial sites where they showed one or more ‘reservoirs” by their terminology using 2006 and 2007 aerial imagery. Often nearby “lake/ponds” had to be added to these sites as industrial . All lakes and ponds greater than 30 acres were also examined. Many of these are operated by others, and they often prohibit agricultural withdrawals. We classified these as power dams or regional reservoirs. A few were also mislabeled natural lakes or lagoons.

Of those impoundments remaining there were 80,000 classified as man-made structures. The distribution of sizes for these are shown in Fig. 2. We removed 35,234 ponds that were drawn with less than 1.0 ac surface area. Most of these would be considered landscape and livestock

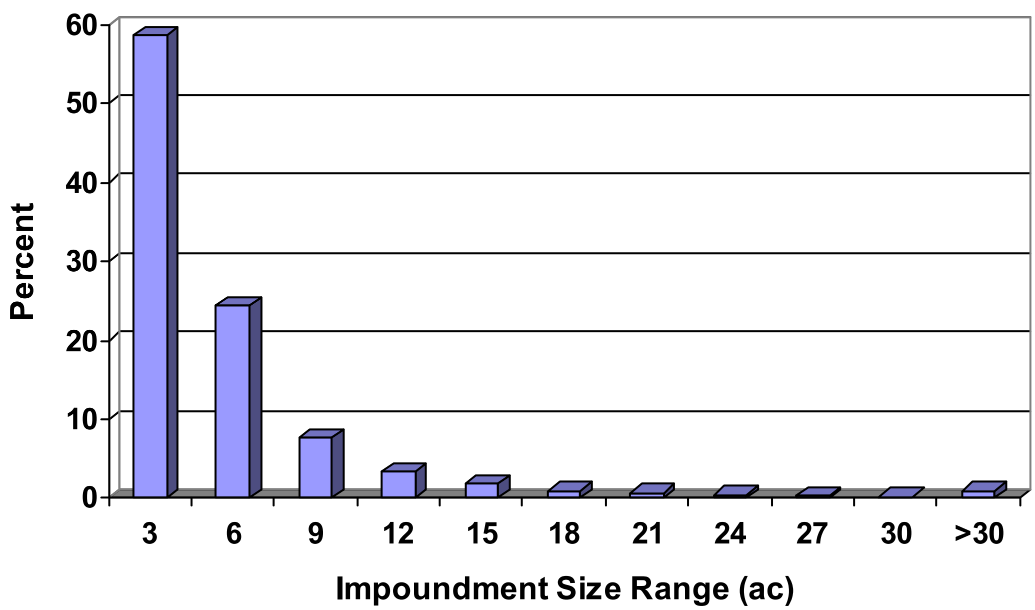

Figure 2. Distribution of pond sizes among the 44,700 ponds mapped by DOT that were greater than 1.0 acre in surface area.

ponds, although some much bigger than 1.0 ac could fit this category as well. The remaining 44,760 ponds included almost 58% that were less than 3 ac in size. Together ponds greater than 10 ac made up less than 10% of all the ponds in the Coastal Plain. Without reconstruction or enlargement, impoundments for irrigation are made up primarily from small ponds. However, the number and distribution of these ponds makes many accessible for irrigation.

Irrigation Proximity to Ponds

Irrigated areas mapped in Georgia show that there are 26,900 irrigated fields covering 1.344 million irrigated acres (Table 1). In the Georgia Department of Natural Resources designated Flint River Basin there are three sub-basins that have irrigated fields covering more than 20% of the basin's area. in the

Table 1. Irrigated field number and area by sub-basins (HUC8) in the Georgia Coastal Plain, computed ratios of irrigated area to sub-basin area, and number of potential farm ponds in the subbasin.

DNR River Basins	Sub-basin	Irrigated fields	Irrigated fields	Irrigated area/basin	Ponds
		no.	ac	%	no.
Altamaha	Altamha	515	16,850	1.88	1,657
Altamaha	Ohoopee	504	18,248	2.12	2,655
Chattahoochee	Middle Chattahoochee	178	5,851	0.32	812
Chattahoochee	Lower Chattahoochee	716	36,998	4.63	399
Flint	Middle Flint	2,226	132,449	13.27	1,534
Flint	Kinchafoonee-Muckalee	1,605	84,572	11.98	808
Flint	Lower Flint	2,231	174,472	21.35	1,284
Flint	Ichawaynochaway	2,187	118,569	16.75	979
Flint	Spring	2,388	146,944	29.06	739
Flint	Apalachicola	44	2,183	3.57	49
Ochlockonee	Apalachee Bay-St. Marks	8	230	0.15	100
Ochlockonee	Upper Ochlockonee	1,278	51,484	8.65	2,623
Ochlockonee	Lower Ochlockonee	264	13,094	5.11	398
Ocmulgee	Lower Ocmulgee	1,867	96,145	6.46	2,930
Ocmulgee	Little Ocmulgee	390	15,699	3.05	1,309
Oconee	Lower Oconee	376	14,027	0.91	2,997
Ogeechee	Upper Ogeechee	457	30,494	2.60	1,785
Ogeechee	Lower Ogeechee	448	25,521	3.18	1,695
Ogeechee	Canoochee	805	27,054	3.05	2,960
Ogeechee	Ogeechee Coastal	26	561	0.06	532
Satilla	Satilla	1,751	61,797	3.61	3,717
Satilla	Little Satilla	360	16,239	3.19	597
Satilla	Cumberland-St. Simons	15	367	0.07	316
Savannah	Middle Savannah	93	7,936	0.68	1,055
Savannah	Brier	192	14,667	2.70	948
Savannah	Lower Savannah	105	5,844	0.98	483
St. Mary	St. Marys	21	573	0.08	200
Suwannee	Aucilla	89	5,357	2.77	258
Suwannee	Upper Suwannee	44	1,012	0.08	308
Suwannee	Alapaha	2,356	89,669	8.14	3,352
Suwannee	Withlacoochee	1,121	51,916	6.26	2,560
Suwannee	Little	2,276	77,520	13.57	2,971

The comparison of pond numbers versus irrigated field numbers gives some impression of disparities that exist in some of the heavily irrigated sub-basins (Table 1). For example in the five sub-basins of the Flint basin that have large numbers of irrigated fields, each has fewer ponds than irrigation systems, often by half. In most of the other basins, ponds outnumber irrigated fields by more than 2:1. The Lower Flint River Basin which includes all or most of the sub-basins shown, is known as the Dougherty Plain. The region is unsuited to pond development. The terrain is nearly flat, and it has few streams. It has karst topographic features from the underlying thinly covered formations that make up the Floridan aquifer. In addition to unsuitable pond sites, shallow and productive wells can provide as much water as irrigators need.

In the Suwannee's Alapaha, Little, and Withlacoochee sub-basins, irrigation systems are also numerous. Here however, the Floridan is overlain by a thick clay and sand layer that serves as an aquiclude preventing recharge to the Floridan. The area can be tapped by wells in most areas, but bore holes are deeper and pumping rates lower than in the Dougherty Plain. The rolling topography known as Tifton uplands and underlying clay created a well-developed network of streams, and ideal pond sites are numerous. Farmers in this area build and depend upon surface water impoundments for part of their water supply. This is also the area where the greatest declines in groundwater head have been observed. Increasing dependence upon surface water here may help stabilize groundwater levels.

While sub-basin examination gives some idea of areas where both ponds and irrigated fields are numerous, it does not show whether they are close enough to irrigated fields to be put to that use. We looked at transect data to help clarify that. Ponds with pumps permitted or metered for irrigation withdrawals were obvious indicators of proximity. Approximately 25% of random ponds in our Coastal Plain transect survey had permitted or metered pumps in place. Additionally, aerial imagery showed that 66% of the random ponds had a farm field within 1300 feet of the edge of the pond. The quarter mile pumping distance is approximately the point at which pipe and installation begin to approach the cost of a well in the region. However, given low yield of some wells, farmers may chose to pump further from a reliable surface water source.

Irrigation Demands versus Supply in Impoundments

Irrigation amounts in the Georgia Coastal Plain were observed between 1999 and 2004 through the Ag Water Pumping study (Hook et al. 2005). For five years, almost 800 farms fields from randomly selected permitted withdrawals were metered. Monthly observations of crop type and irrigation were recorded by a team who drove throughout the region. Data was summarized by water source, sub-region, basin, county and irrigation type. Farmers who irrigated directly from wells applied more water than farmers who used surface water sources. Three of the observation years were during the prolonged 1998- to 2002 drought in the Southeast. Farmers had difficulties obtaining surface water from streams, and ponds did not refill before later season irrigations were needed. Most who used wells, including those who used wells to refill their ponds met reasonable needs for irrigation, as they judged adequate. Because we see these groundwater source irrigation as a truer measure of farmers intention to irrigate, we used the average application depths for them to estimate the irrigation water supply that would be needed if farmers relied upon water stored in the regions ponds. Those irrigation application depths are shown (Table 2) under each basin as a range. The lower number was application depths observed in the basin for 2004, an average year, while the higher value was average application depth for 2000, 2001and 2002, all drought years. The application depths vary by watershed in part because of differences in predominant crops, irrigation systems, soils, and production levels. For the comparison with pond capacity the upper or drought year value was used to compute irrigation amount in ac-ft/year (Table 2) from irrigated acres (Table 1).

Table 2. Irrigation requirements (demand) by sub-basin in drought years, total of pond surface area, estimated pond capacity as computed as 50 % of ponds available for irrigation and all ponds have 5 ft of water over their surface area. Percent of annual irrigation requirement that could be met by that estimated pond capacity for each sub-basin.

DNR Watershed	Sub-basin	Irrigation requirements	Pond area	Pond capacity	Annual Supply
		ac-ft	ac	ac-ft	%
Altamaha	Altamha	8,140	6,163	15400	100
5.2-5.8 in/yr	Ohoopee	8,820	10,031	25100	100
Chattahoochee	Middle Chattahoochee	4,920	4,099	10200	100
7.9-10.1 in/yr	Lower Chattahoochee	31,100	1,634	4090	45
Flint	Middle Flint	111,500	6,954	17400	16
7.9-10.1 in/yr	Kinchafoonee-Muckalee	71,200	4,726	11800	16
	Lower Flint	146,800	6,706	16800	17
	Ichawaynochaway	99,800	6,834	17100	17
	Spring	125,400	2,936	9840	8
	Apalachicola	1,840	144	360	20
Ochlockonee	Apalachee Bay-St. Marks	335	709	1770	100
7.8-17.5 in/yr	Upper Ochlockonee	75,100	10,687	26700	36
	Lower Ochlockonee	19,100	1,701	4250	22
Ocmulgee	Lower Ocmulgee	140,200	13,022	32600	23
7.3-10.9 in/yr	Little Ocmulgee	22,900	5,268	13200	58
Oconee 8.0-11.8 in/yr	Lower Oconee	13,790	14,567	36400	100
Ogeechee	Upper Ogeechee	31,000	8,914	22300	72
9.3-12.2 in/yr	Lower Ogeechee	25,900	7,698	19250	74
	Canoochee	27,500	12,794	32000	100
	Ogeechee Coastal	570	2,493	6230	100
Satilla	Satilla	36,600	13,181	33000	91
5.1-7.1 in/yr	Little Satilla	9,600	2,391	5980	62
	Cumberland-St. Simons	217	1,368	3420	100
Savannah	Middle Savannah	8,070	4,854	12140	100
9.3-12.2 in/yr	Brier	14,900	4,327	10820	73
	Lower Savannah	5,941	2,022	5060	85
St. Mary	St. Marys		837	2092	
Suwannee	Aucilla	3,040	1,348	3370	100
5.2-6.8 in/yr	Upper Suwannee	573	860	2150	100
	Alapaha	50,800	15,982	40000	78
	Withlacoochee	29,400	12,597	31500	100
	Little	43,900	11,867	29700	68

Pond area, the sum of all potential agricultural ponds within a basin was shown in Table 2. Since the transect study showed that already 25% of ponds are involved in irrigation and that 66% were close enough to fields to be used in irrigation, we examined the impact of doubling active irrigation from 25% to 50% of the farm ponds in each basin. Further we assumed that the average pond could yield 5 ft of water over the entire surface area of the ponds. While this could readily be obtained from larger and deeper ponds, some of the smaller ponds may require one refilling to provide that much water, a likely occurrence in most years including drought years in the Coastal Plain. Pond capacity thus was computed as surface area X 0.5 X 5 ft for each sub-basin.

In two thirds of the sub-basins, all of the regions irrigation could be supplied from ponds if 50% of them were used in irrigation as described. The greatest disparity between irrigation demand and pond capacity occurred in the Flint and Ochlockonee Basins. As mentioned earlier the Flint has a plentiful supply of groundwater and little opportunity for increased ponds, particularly in the Dougherty Plain area of the Flint. One fifth to one third of the demand could be met in the Lower and Upper Ochlockonee sub-basins. This is an area where pecan groves, sod farms, and ornamentals are produced and demand is higher her than in most basins. In most of the remaining sub-basins 50% or more of the annual demand could be met if pond withdrawals were increased. In many cases a single filling at the start of the growing season would suffice if seepage and evaporation did not reduce available water in storage.

With an average area for DOT-mapped ponds only 4.5 acres, average pond sizes could not supply full-season irrigation for average pivot fields of 100 acres as indicated in Georgia Irrigation Surveys (Harrison 2005a,b). However, with ponds doubled up and for smaller pivots and other fields, average and larger ponds could serve needs of most farmers of Georgia.

Conclusion

Ponds have been built in Georgia Coastal Plain for many reasons. The relationship of ponds to irrigated field numbers suggests that many were built in part to support irrigation. However, ready access to the Floridan aquifer in most areas of the Georgia Coastal Plain has led many to depend more heavily upon groundwater for irrigation supplies. Analysis of pond numbers, current use for irrigation, and proximity to irrigated fields suggests that in areas where groundwater supplies are overtaxed, farmers could turn to surface water as a reasonable alternative for areas outside of the Flint River basin. With proper incentives, the irrigators could increase the capacity of surface water supplies for irrigation and decrease pressure on groundwater aquifers.

Acknowledgements

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Procedure to easily Fine-Tune Crop Coefficients for Irrigation Scheduling

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Abstract. *A procedure is presented that allows crop coefficient values, as described in FAO-56, to be easily adjusted to meet local conditions. Values are adjusted vertically based on FAO-56 procedures and internal weather databases.*

The paper calculates the season length of corn and soybeans based on Relative Maturity and Maturity Group, respectively. Within the determined growing season, the period of time for the four growth periods was determined by empirical equations relating length in days to air temperature. This is a logical procedure, as common sense dictates that the ***initial period*** *would be longer when planting is done when the weather was cool, as opposed to when it was warm.*

The paper shows how available national weather databases can be used to calculate ***K-c _ini****, which can be difficult to calculate due to the background information required.*

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

Introduction

This paper is based primarily on procedures to adjust crop coefficient (K_c) values as described in *FAO-56, Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56* (Allen et al., 1998). Adjustment procedures of K_c values allow one to take default K_c values as suggested in FAO-56 and make them more accurate for local conditions. Crop coefficient values are used in the following way to predict water use:

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

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

ET_o is reference evapotranspiration (mm or inches)

FAO-56 is actually very Spartan in concept, only dealing with three K_c values to describe conditions of the entire growing season; these points are: Kc_ini, Kc-mid, and Kc-end. Based on local climate conditions, these values can be increased or decreased, and is referred to as *vertical adjustment*.

The horizontal location of these three cardinal values is based on the number of days in each of the four crop stages (initial, development, mid-season, and end) for the crop in question. For each of the many crops discussed in FAO-56, there are generally four or five examples provided from around the world showing the length of time (i.e., the number of days) in each period. Adjusting the length of any of the periods, initiates *horizontal adjustment*. Through the three points which lay out horizontally based on values for the growing periods, a curve is constructed encompassing the whole growing season and is known as the *crop coefficient curve* (figure 1).

In the authors' opinions, FAO-56's weakest component regarding crop coefficients has been the lack of procedures to better determine Growth Period lengths. This paper attempts to provide a methodology to better determine growth period lengths using local weather information and other factors.

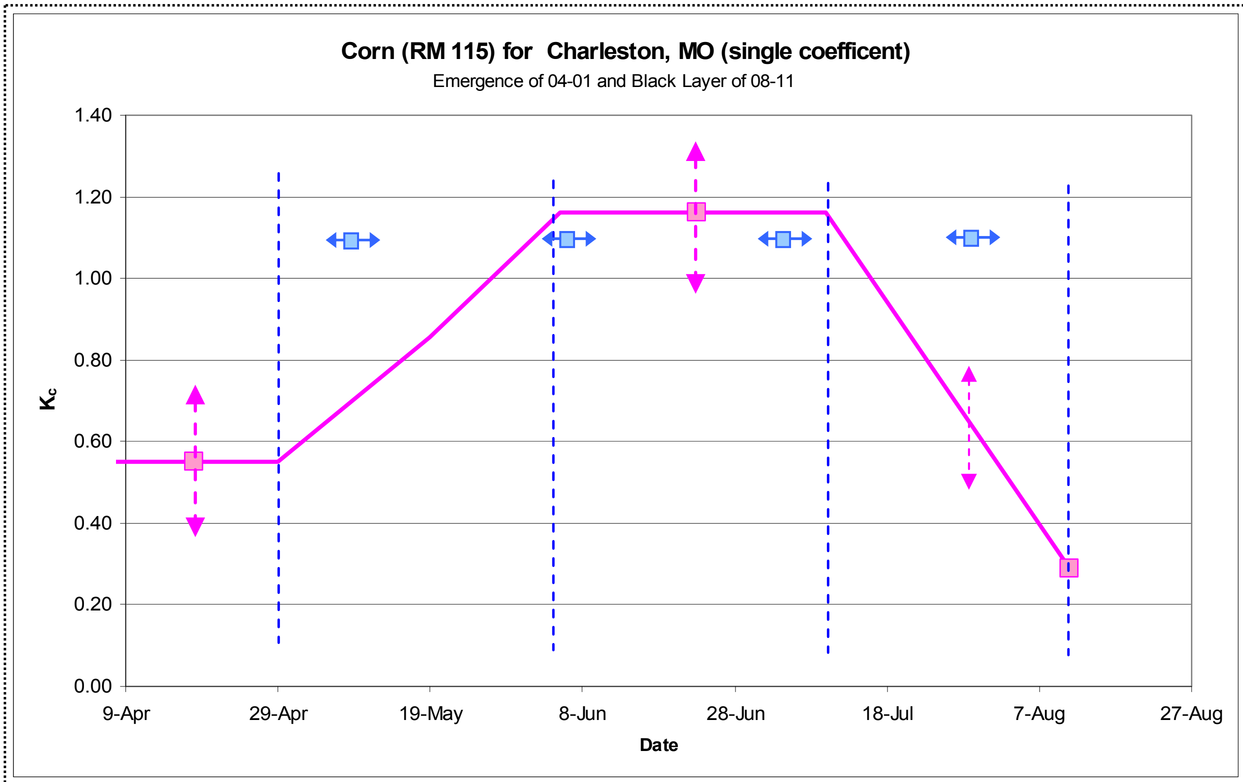

Fig. 1. A seasonal crop coefficient curve developed for corn in SE Missouri, showing the three cardinal K_c values in pink which can be vertically adjusted. Adjusting the lengths of time for each of the four periods (separated by the blue dashed lines) provides horizontal adjustment.

VERTICAL ADJUSTMENT – Coefficient Values

Crop coefficients are of two types. The most commonly used are the *single crop coefficient* (K_c). This one is used when crop transpiration (T) and soil evaporation (E) are combined jointly. The *dual crop coefficient* (K_{cb} +K_e) is used when T and E are calculated separately. The single crop coefficient value will be higher since it has to account for water loss through both T and E. Also, the amount of rainfall events is significant early in the season before canopies close.

Suggested values for both types of coefficients are provided in FAO-56. These values were derived from locations having an average daily minimum Relative Humidity value of 45% and an average daily wind speed of 2 m/s. Locales with different weather parameters can have their coefficient values adjusted using a simple equation (Allen, et al., 1998). Table 1 shows the factors used for adjustment for the three cardinal coefficient values of both types of coefficients.

Table 1. Factors used in adjusting crop coefficient values.

Type of coefficient	Period Coefficient		
	Kc_–ini	Kc_mid	Kc-end
Single crop coefficient (K_c)	~ ETo ~ frequency of wetting ~ wetting depth ~ soil type	~ crop height ~ min. RH ~ wind	~ crop height ~ min. RH ~ wind ~ desired harvest conditions
Dual crop coefficient (K_{cb})	No adjustment	~ crop height ~ min. RH ~ wind	~ crop height ~ min. RH ~ wind ~ desired harvest conditions

The most difficult data to collect needed to modifying crop coefficient values are those data needed for the Kc_ini value of the Single crop coefficient. However, the U.S. Department of Commerce has on line a database of about 300 cities in the US and its possessions that shows the data required to calculate the adjustment (U.S. Department of Commerce, 2008). Data on the number of rainfall events > 0.01 inch per month is used in the equation. Since rainfall on adjacent days is only counted as a single event, it is important to reduce the number or the Kc_ini value will be too high. A factor of 0.5 works well in Missouri. Figure 2 shows a print out of Kc values.

	Kc values from literature	Kc values Modified by local weather	Kc values being Used
Kc-ini [beg]	0.30	see Table 1 below	0.73
Kc-ini [end]			0.84
Kc-mid	1.20	1.15	1.17
Kc-end	0.35	0.35	0.50

Table 1. Kcini values	
Sand	0.58
Loamy sand	0.59
Sandy loam	0.64
Loam	0.66
Silt loam	0.67
Silt	0.68
Silt clay loam	0.66
Silty clay	0.67
Clay	0.67

Fig. 2. Crop coefficient values modified with data in NOAA databases.

HORIZONTAL ADJUSTMENT – Lengths of the Growing Periods

FAO-56 provides helpful information on growth period length. An example, compiled from FAO-56 data on soybeans is shown in Figure 3. It has four locations and the differences in season length vary from 85 days to 135 days. This could be problematic for someone trying to construct a Kc curve for his own locale. One benefit of the data, however, is that the length of the Growth Periods can be seen as a percentage of the whole season. Once the expected season length is determined, for your locale then these percentages – converted to number of days- will be a good starting point.

Background on: Determining the length for the 4 growth periods							
Literature Review (from FAO-56) on Length for Various Periods							
	Initial	Development	Mid-Season	Late-Season	Total	Plant Date	Region
Lit Result 1	15	15	40	15	85	Dec	Tropics
Lit Result 2	20	35	60	25	140	May	Cent USA 1
Lit Result 3	20	30	60	25	135	May	Cent USA 2
Lit Result 4	20	25	75	30	150	June	Japan
Lit Result 5							
Lit Result 6							
Lit Average (days):	**19**	**26**	**59**	**24**	**128**		
Lit Average (% of days):	**15%**	**21%**	**46%**	**19%**			

Fig. 3. Typical growth period length data as reported in FAO-56.

Calculating Season Length

CORN. The termination date of corn can readily be predicted. The corn HU growth model (86◦F / 50◦F) that is universally used was developed at Texas A&M University in the 1950s (Gilmore and Rogers, 1958). Seed companies have made use of it for many years to predict both silking (very important for breeders) and black layer (important in quantifying the growing period required) in their hybrids, so its accuracy has been well established. However, seed companies use another scale to actually categorize hybrid season length, Relative Maturity (RM). RM is the estimated length in days of a hybrid's season. Farmers in a location may commonly have a 10-day span in the hybrids they are using. For example, in southeast Missouri (SEMO) the normal range in hybrids is RM 109 to RM 119. This in itself represents about a 10% error for irrigation programs that deal with corn generically. On top of this, RM values are only approximations based on "average" planting dates for that region, outside of this planting window and local weather patterns, the RM values loose accuracy. For example, in SEMO a hybrid with a RM value of 113 could have a season length ranging from 76 to 124 days depending if it emerged 1 Apr or 1 Jun.

Seed companies normally provide data on HUs to black layer (HU_{bl}). In cases where it is not known, the RM value can be used to predict HU_{bl} as seen in Equation 3.

$$HU_{bl} = -(0.0063 \times RM^3) + (2.20742 \times RM^2) - (204.17 \times RM) + 8407.5 \qquad \text{(Eq. 3)}$$

If where

HU_{bl} = ∑ HUs (86ºF limit on max. temperature and 50ºF-base) to black layer [ºF]

RM = seed company rating system for hybrid season length [days]

Figure 4 shows the relationship of RM to Heat Units.

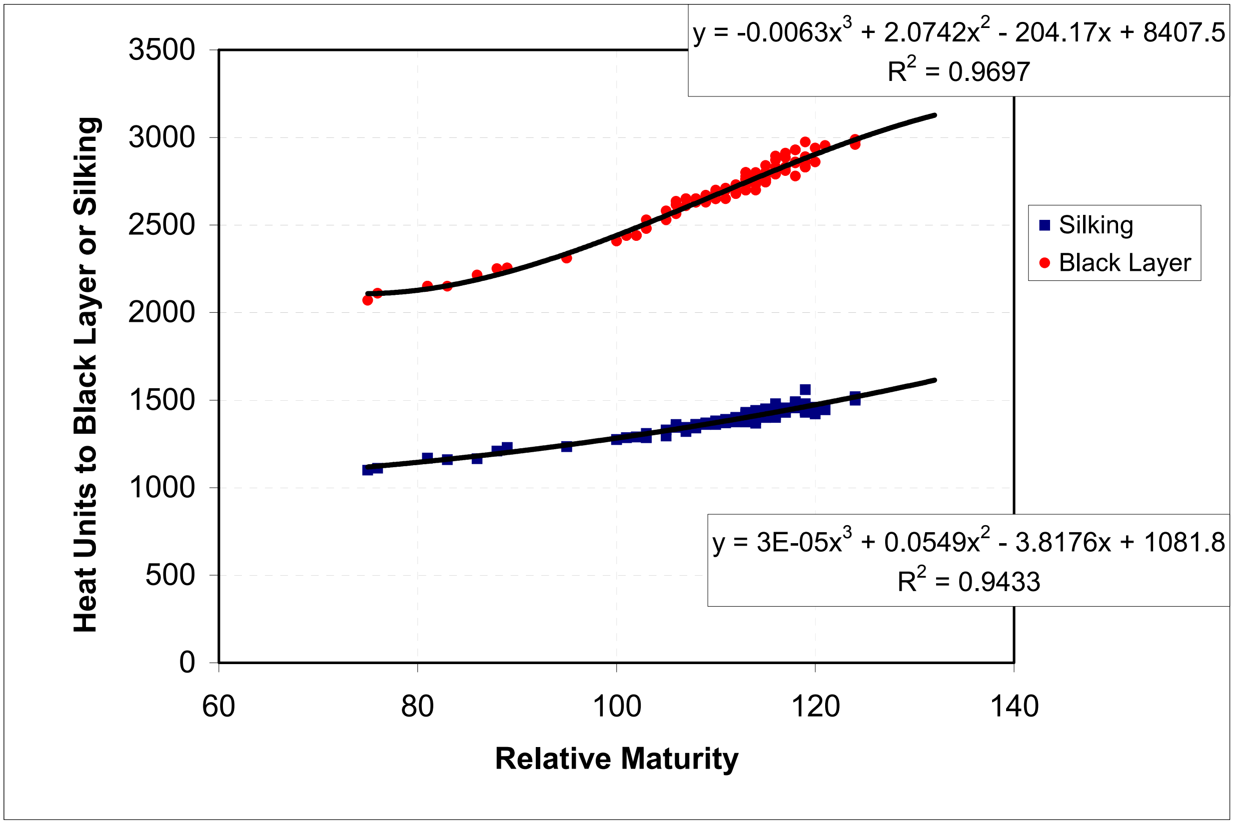

Fig. 4. Heat Units to black layer and silking based on RM of corn.

SOYBEAN. The termination date of soybean is more difficult to determine since most soybeans are day-length sensitive. Based on their normal growing period soybean varieties are categorized by Maturity Groups (MG). The smaller the MG value, the shorter the season. Farmers in Missouri plant varieties with MG values ranging from III to VII. An equation was developed to predict the expected season length of a soybean variety based on its MG, date of planting, and latitude. Data for this model (Eq. 4) was gathered from reported variety tests conducted throughout the Midwest and mid-South that utilized varieties with varying MG values and which reported soybean termination dates for the varieties in the trial.

$$L = -(0.71 \times DOY) + (0.0015 \times DOY^2) + (0.92 \times Lat) + (9.1 \times MG) + 127.6 \qquad \text{(Eq. 4)}$$

where

- L = the season length [days]
- DOY = numerical day of year of planting
- Lat = latitude of location [ºF]
- MG = Maturity Group of soybean variety

Calculating Lengths for Each Growth Period

Since the farmer knows the planting date and Eqs. 3 and 4 will be used to determine crop termination, the season length is now known, thus a reasonable time framework is laid out on which to building the crop coefficient curve. Empirical studies were used to determine the number of days from planting until end of the *initial period* and from planting unit the end of the *development period* based on air temperature. This is a common sense approach and it will lengthen those periods when planting occurs early and it is still cool. Figure 5 shows the results.

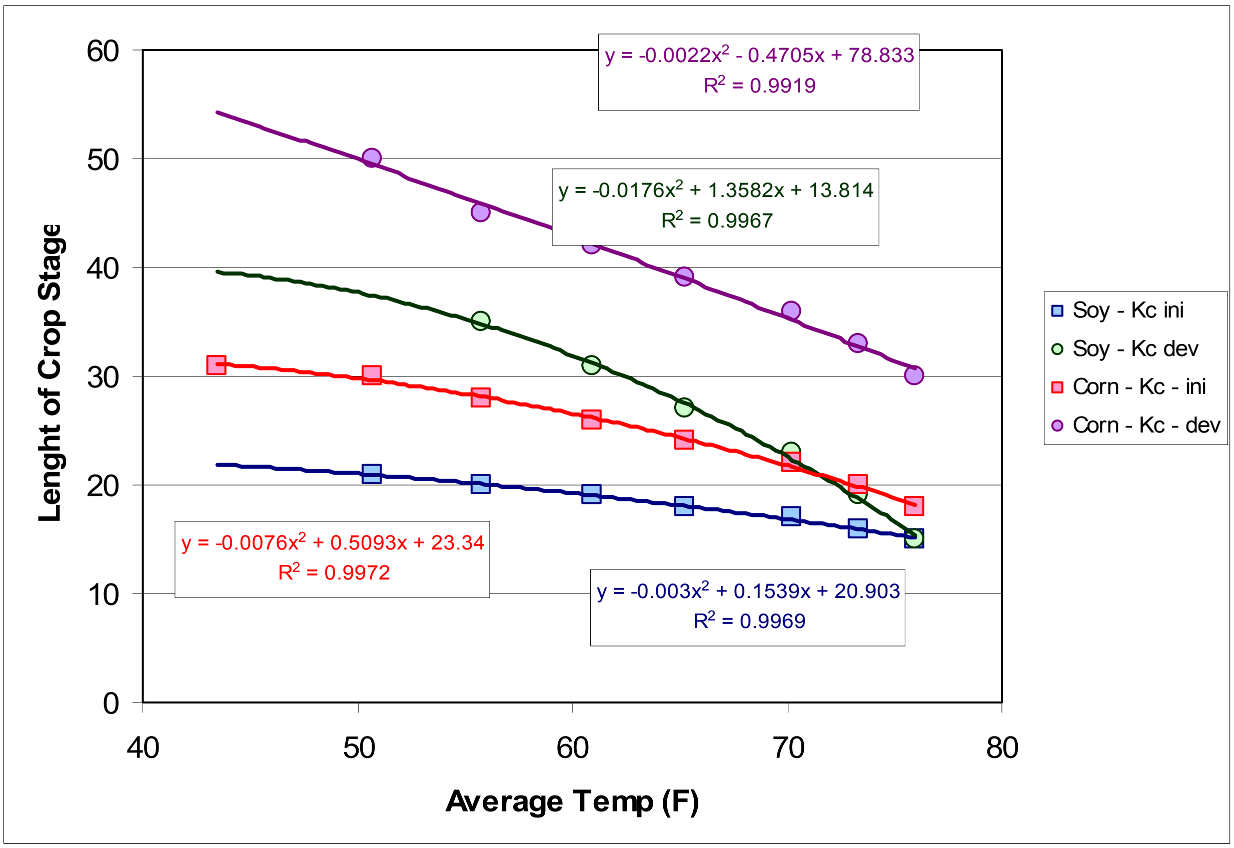

Fig. 5. The amount of time for the initial and development periods for corn and soybean based on temperature.

A period of 24 days was defaulted as the length of the *late period*. This value plus the values from Fig. 5 are used to determine the length of the mid period, which is the residual of season length minus the values for the other periods.

Conclusion

Most irrigators and irrigation programs probably use off-the-shelf crop coefficient values taken from FAO-56. This procedure allows the values to be easily modified to local conditions based on that locale's weather. An on-line Kc value generator will be added to the Missouri Irrigation website in the future (http://agebb.missouri.edu/irrigate/index.htm).

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Evaluating Airborne Remote Sensing ET estimates using Eddy Covariance Systems and a Heat Flux Source Area Function

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Abstract

Growth of population, agriculture, and industry are increasing the demand for water. As competition for water increases, use of water for production of crops must become more efficient. Thus, saving water by managing irrigation systems better may be possible if irrigation scheduling is improved by accurately estimating spatially distributed actual evapotranspiration (ET). ET can be estimated using energy balance algorithms that use agrometeorological and remote sensed surface reflectance/temperature data. In this study, the objective was to evaluate spatial ET estimates obtained with a modified energy balance-based Two Source Model (TSM). For this purpose, two high-resolution aircraft images acquired during the 2008 Bushland Evapotranspiration and Agricultural Remote Sensing Experiment (BEAREX08) at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX, were used. Predicted ET values for cotton fields were compared with measured ET from eddy covariance systems using a heat flux source area function. Results showed that the TSM slightly under estimated ET by 0.5 mm d^{-1}, (or -5.1%) with a standard deviation of 0.6 mm d^{-1}. Overall, the modified TSM performed well for LAI values less than 1.5 $m^2\ m^{-2}$. Further research will test the modified TSM for cotton LAI values larger than 3 $m^2\ m^{-2}$.

Keywords: Southern High Plains, semi-arid environment, remote sensing, two source energy balance model, water management.

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Introduction

Remote sensing (RS) derived evapotranspiration (ET) values can potentially be used as in input in irrigation scheduling and in hydrologic simulations In addition, seasonal ET may be used to assess the overall irrigation project efficiency, provided volumes of water pumped (or diversions) had been measured, i.e. in groundwater management in arid and semiarid regions like the Southern High Plains.

Most of the RS algorithms used to estimate crop ET are based on the land surface energy balance (EB) model. These algorithms are based on the fact that ET is a change of the water state, from liquid to vapor, depending on available energy (net radiation at the surface less the energy into the ground), Su et al. (2005).

Remote sensing (RS) based surface energy balance for land provides instantaneous estimates of latent heat flux (LE) or evapotranspiration (ET); and has been recognized as a feasible method to mapping spatially distributed crop water use (Jackson, 1984).

In terms of remote sensing based EB models, there are several algorithms available in the literature. Gowda et al. (2008) present a description and discussion on most of the EB models that use remote sensing inputs for agricultural water management. Most of the EB models are single source models, e.g. SEBI (Menenti and Choudhury, 1993), SEBAL (Bastiaanssen et al., 1998), SEBS (Su, 2002), METRIC (Allen et al., 2007), etc. These models estimate different components of the EB assuming that the surface heat fluxes originate from a source that is the composite of vegetation and background soil (substrate).

However, there is a fundamental problem in representing a heterogeneous (sparse, non-uniform) surface as a single layer or source because of the significant influence of the soil/substrate on the total surface EB. Thus, the surface resistance to evaporation has lost physical meaning because it represents an unknown combination of stomatal resistance of the vegetation and resistance to soil evaporation (Blyth and Harding, 1995). This resulted in the development of two-source approaches or models (TSM), where the energy exchanges of the soil/substrate and vegetation are evaluated separately (Shuttleworth and Wallace, 1985); i.e. more physically based models that differentiate or partition the EB terms, R_n, H, and LE between the soil and the vegetation canopy, Norman et al. (1995).

Norman et al. (1995) and Kustas and Norman (1999, 2000) developed operational methodology to the two-source approach proposed by Shuttleworth and Wallace (1985) and Shuttleworth and Guerney (1990). Their model showed good agreement with observations (made with meteorological flux stations, eddy covariance/Bowen ration EB systems) over sub-humid prairie, semi-arid shrub, and fully irrigated crops. The TSM methodology generally does not require additional meteorological or information over single-source models; however, it requires some assumptions such as the partitioning of composite radiometric surface temperature into soil and vegetation components, turbulent exchange of mass and energy at the soil level, and coupling/decoupling of energy exchange between vegetation and substrate (i.e., parallel or series resistance networks). The energy exchange in the soil-plant-atmosphere continuum is based on resistances to heat and momentum transport, and sensible heat fluxes are estimated by the temperature gradient-resistance system. Radiometric temperatures, resistances, sensible heat fluxes, and latent heat fluxes of the canopy and soil components are derived by iterative procedures constrained by composite, directional radiometric surface temperature, vegetation cover fraction, and maximum potential latent heat flux.

In an evaluation study, Chávez et al. (2008) found out that the Norman et al. (1995) and Kustas and Norman (1999) TSM algorithm for low biomass (Leaf area index, LAI, less than 3 m^2 m^{-2}) resulted in large under predictions of ET. They added that the ensemble sensible heat flux was better estimated when the surface aerodynamic resistance term was eliminated from the sensible heat flux originating from the ground, in the parallel resistance network model.

Regarding the evaluation of ET estimated using remote sensing imagery, as input in EB models, using measured ET by eddy covariance systems, Chávez et al. (2005) demonstrated that using heat flux source area functions (footprint models) was more appropriate than employing simple AOI (area of interest) polygons that average ET pixels upwind of the eddy covariance tower location.

In this study, a modified TSM, Chávez et al. (2008), was applied to very high spatial resolution airborne remote sensing imagery acquired over cotton fields in the Southern High Plains (SHP) to derive ET. Furthermore, spatially distributed ET pixels were weighted and integrated using a heat source area function (footprint) for comparison to ET measured with eddy covariance systems in order to assess the performance of the modified TSM.

Materials and Methods

Study area

Field data collection and coinciding acquisition of high resolution remote sensing data was made during the 2008 cotton cropping season at the USDA-ARS Conservation and Production Research Laboratory (CPRL), located in Bushland, Texas. The geographic coordinates of the CPRL are [35º 11’ N, 102º 06’ W], and its elevation is 1,170 m above mean sea level. Soils in and around Bushland are classified as slowly permeable Pullman clay loam. The major crops in the region are corn, sorghum, winter wheat, and cotton. Wind direction is predominantly from the south/southwest direction. Annual average precipitation is about 562 mm while about 670 mm of water are needed to grow cotton. Although, only 280 mm of water (depth) fall as precipitation during the cotton growing season, New (2005).

Eddy covariance

Eddy covariance is based on the direct turbulent measurements of the product of vertical velocity fluctuations (w’) and a scalar (e.g. air temperature, water vapor, carbon dioxide, horizontal wind speed, etc.) concentration fluctuation (c’) producing a direct measurement of H, LE, CO_2, and momemtum (shear forces) fluxes respectively; under the assumption that the mean vertical velocity is zero, i.e. if turbulence is treated as a set of flucturations about a mean value, which is called Reynolds averaging, then the value of any variable at a given time is the sum of a temporal mean (over some time period) plus an instantaneous deviation. EC principles and history can be found in Hipps and Kustas (2001), and Shuttleworth (2007) respectively. Burba and Anderson (2007) provide an on-line guidelines for EC method installation, use, maintenance, data post-processing, etc.

Two identical eddy covariance (EC) systems were installed on the East weighing lysimeter experimental fields managed under irrigation (a NE field and a SE field; Fig. 1), [4.7 ha each, i.e. 210 m wide (East-West) × 225 m long (North-South)], close to the center of the field and downwind of the predominant wind direction. Cotton was planted on May 21, 2008, on these East fields; and these fields started being irrigated (Lateral Move) on May 23. The NE field had N-S row orientation while the SE field had E-W row orientation like all prior Bushland ET research. Each EC system consisted of a fast response 3D sonic anemometer (model CSAT3, Campbell Scientific Inc., Logan, UT), a fast response open path infrared gas (H_2O and CO_2) analyzer (model LI-7500, LI-COR Inc., Lincoln, NE), a fine wire thermocouple (model FW05, Campbell Scientific Inc., Logan, UT), an air temperature/humidity sensor (model HMP45C, Vaisala Inc., Woburn, MA), and a micrologger (model CR3000, Campbell Scientific Inc., Logan, UT). A constant air density measured as the mean for each 15-min period was used (model CS106, Vaisala PTB110 barometer, Campbell Scientific, Logan, UT) to compute the flux terms.

The EC system measured turbulent fluxes at a 20-Hz frequency (20 measurements per second) and 15-min average LE and H fluxes were computed. Both EC systems were installed at a 2.5 m height above ground level. The CSAT3 sensor was oriented towards the predominant wind direction, with an azimuth angle of 225 degree from true North. The magnetic declination angle was taken into account in the EC program.

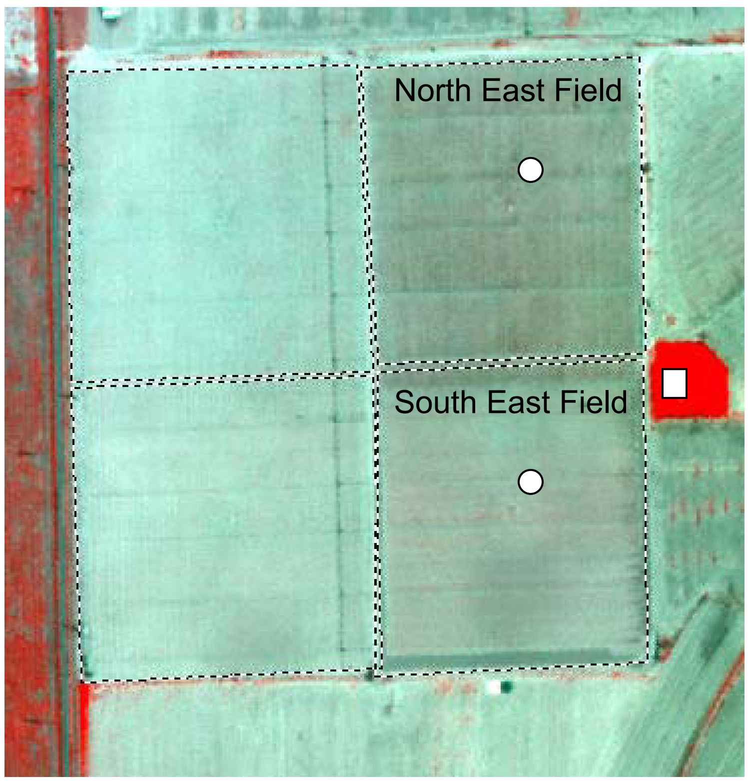

Figure 1. Three-band false color composite reflectance image, DOY 178, showing location of eddy covariance towers (circles) and grass reference weather station (square).

Airborne Remote Sensing Data

The Utah State University (USU) airborne digital multispectral system was used to acquire multispectral remote sensing data at 1-m spatial resolution for visible and near-infrared, and 4-m for thermal-infrared portions of the electromagnetic spectrum. This is a third generation of the system originally described by Neale and Crowther (1994), based on digital frame cameras but following similar image calibration procedures. The USU multispectral system comprises of three Kodak[3] Megaplus digital frame cameras with interference filters centered in the green (Gn) (0.545-0.560 μm), red (R) (0.665-0.680 μm), and near-infrared (NIR) (0.795-0.809 μm) portions of the electromagnetic spectrum. The fourth camera is an Inframetrics 760 thermal-infrared (TIR) scanner (8-12 μm) that provides imagery to obtain surface radiometric temperature images.

Two airborne remote sensing images/scenes were used; each acquired over the CPRL on June 26 (DOY 178), and July 28 (DOY 210), respectively. All images were acquired close to 11:30 a.m. CST to coincide with Landsat 5 TM or ASTER satellite overpasses. These images were calibrated and transformed into surface reflectance and temperature images to be used for the estimation of reflected outgoing short wave and long wave radiation, respectively, with both components required in the estimation of spatially distributed net radiation.

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[3] 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.

Two source energy balance model

To derive LE (or ET_i) Eq. 1 is solved for LE, i.e., as a residual of the surface EB equation (Brown and Rosenberg, 1973; and Stone and Horton, 1974):

$$R_n = G + H + LE \tag{1}$$

where, R_n is net radiation, G is the soil heat flux, and H is sensible heat flux. Units in Eq. 1 are all in W m^{-2}; with R_n positive toward the crop surface and other terms positive away from the crop surface. The conversion of LE to ET as an hourly and daily rate is detailed in the appendix.

This EB model mainly needs, remotely sensed radiometric surface temperature (T_{sfc}, K), air temperature (T_a, K), horizontal wind speed (U, m s^{-1}), leaf area index (LAI, m^2 m^{-2}), vegetation fraction cover (f_c), fraction of LAI that is green (f_g), crop height (h_c, m), average leaf width (w, m), and net radiation (R_n) as input. The remote sensing input dependent variables, among others, are T_{sfc}, LAI, h_c, f_c, surface albedo, etc. In addition, the model needs weather data such as air temperature, horizontal wind speed, incoming short wave solar radiation, and relative humidity values; which were taken from the ARS weather station (ARS-Bushland, square symbol in Fig. 1) at Bushland, TX.

The TSM algorithm solves Eq. 1 for LE after finding separately the canopy R_n and H and the soil R_n, G and H components, i.e. the TSM partitions each of the surface energy balance components into fluxes generated from the vegetation canopy (first source) and the bare soil/background soil (second source) as depicted in Fig. 2. For instance, the ensemble H was estimated by summing sensible heat fluxes from both soil (H_s) and canopy (H_c). H_s occurs between the soil surface and a point above the canopy (Z_h) where air temperature (T_a) is measured; while H_c is generated between the vegetation canopy and a parcel of air at Z_h, assuming a parallel resistance network (Fig. 2).

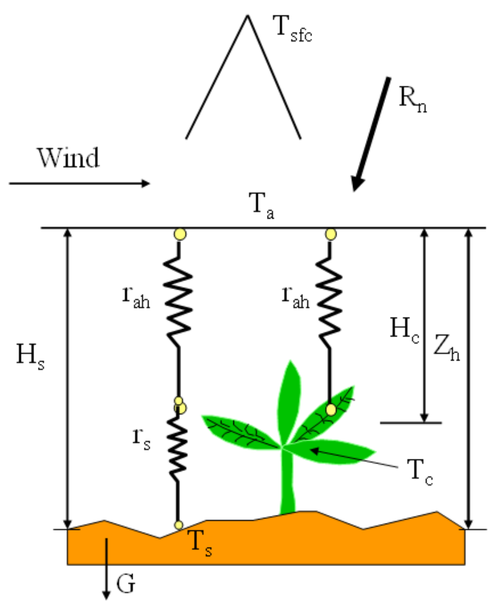


Figure 2. TSM parallel resistance network scheme.

Mathematically H is expressed as:

$$H = H_c + H_s \tag{2}$$

$$H_c = \frac{\rho_a \; Cp_a \left(T_c - T_a\right)}{r_{ah}} \tag{3}$$

$$H_s = \frac{\rho_a \; \mathrm{Cp_a} \left(T_s - T_a\right)}{\left(r_{ah} \;\; r_s\right)} \tag{4}$$

$$r_s = \frac{1}{\left[0.004 + \left(0.012\ U_s\right)\right]} \tag{5}$$

where, T_c is canopy temperature (K), T_s is soil temperature (K), r_s is the resistance to heat flow above the soil (s m^{-1}), r_{ah} is the surface aerodynamic resistance (s m^{-1}) to heat transfer, U_s is horizontal wind speed (m s^{-1}) just above the soil surface, ρ_a is air density (kg m^{-3}), and Cp_a is specific heat of dry air (1,004 J kg^{-1} K^{-1}). T_c and T_s were estimated using Eq. 6 for a Nadir looking thermal infrared remote sensor as:

$$T_{sfc} = \left[\left(f_c \times T_c^4\right) + \left(\left(1 - f_c\right) \times T_c^4\right)\right]^{\frac{1}{4}} \tag{6}$$

where, T_{sfc} is the so-called "ensemble (or composite) radiometric surface temperature," and f_c is the fractional vegetation cover (function of LAI). First, to obtain H, an initial estimation of H_c, applying the Priestley and Taylor (1972) ET model, is performed. Subsequently, the H_c value is used to derive an initial T_c value by inverting Eq. 3 assuming a neutral atmospheric stability condition. Next, Eq. 6 is solved for T_s and updated values of H_c and H_s are computed correcting r_{ah} for atmospheric stability using the Monin-Obukhov (MO) atmospheric stability length scale (similarity theory, Foken, 2006). The MO mechanism is explained in detail in Chávez et al. (2005). T_c and T_s were verified by testing the estimated LE for a negative value, in which case temperatures are not correct, and then the soil is assumed to have a dry surface. A new iteration cycle is needed, in which LE is set to zero for the soil component and H_s is re-calculated. A new T_s and T_c

values are found and sensible heat flux components are again estimated, and canopy LE computed. In this parallel resistances network, r_{ah} was eliminated from the computation of H_s considering it may yield better H_s (H) estimates for sparser vegetation according to Chávez et al. (2008).

Soil heat flux (G, in W m^{-2}) was estimated using three different methods because different remote sensing based G models are developed under different conditions, i.e. crop type, soil background, soil/vegetation moisture levels, etc; thus there was the need to find a suitable G model that would yield accurate values for the cotton fields under the conditions encountered in the CPRL. The first model used was that (Eq. 7) developed by Chávez et al. (2005). A second model was from Norman et al. (1995), who estimated G as a function of the net radiation at the soil surface only (Eq. 8).

$$G = \{(0.3324 - 0.024\,LAI) \times (0.8155 - (0.3032\,\ln[LAI]))\} \times R_n \quad (7)$$

where LAI is leaf area index (m^2 m^{-2}). The G model is valid for the range of LAI values between 0.3 and 5.0 m^2 m^{-2}. This G model is a combination of linear-logarithmic functions and was developed using measured data on corn and soybean fields near Ames, Iowa, and airborne remote sensing based LAI and R_n estimates.

$$G = 0.35 \times R_{n\_soil} \quad (8)$$

where R_{n_soil} (W m^{-2}) is the net radiation at the soil surface (soil only) in W m^{-2}.

Also, the G model developed by Bastiaanssen (2000) was applied (Eq. 9). This model was developed using a wide variety of soil vegetation cover types.

$$G = \{T_B(0.0038 + 0.0074\,\alpha) \times (1 - 0.98\,NDVI^4)\} \times R_n \qquad (9)$$

where T_B (ºC) is remotely sensed brightness (at sensor) surface temperature, i.e. the resulting temperature from converting the remote sensing thermal band digital numbers to radiance (system calibration) and then to temperature (Planck's law) without any further atmospheric interference calibration. NDVI is the normalized difference vegetation index; which is determined using reflectance values from the red (R) and near-infrared (NIR) bands. Surface albedo (α) was computed according to Brest and Goward (1987) as a function of R and NIR.

Heat flux source area (footprint) model

In an effort to understand and define the upwind area that contributes with heat fluxes to eddy covariance (or Bowen ratio) system 'flux area source' or footprint (FTP) models have been developed. The footprint models determine what area upwind of towers is contributing with heat fluxes to the sensors, as well as the relative weight of each particular cell (sub-area) inside the footprint limits. Different footprint models have been proposed, one-dimensional (1D), and tow-dimensional (2D) models. These models are the analytical solution to the diffusion-dispersion-advection equation (Horst and Weil, 1992 and 1994). Other models are Lagrangian (Leclerc and Thurtel, 1990). Studies using these models were able to prove that depending on the height of the vegetation, height of the instrumentation, wind speed, wind direction standard deviation, and atmospheric stability condition the shape and length of the footprint would vary upwind of the instruments, as well as the relative weights (magnitude of contribution), in each individual cell/area inside the footprint. Areas very close to the station contribute less to the total flux sensed by the instrument, areas further away (upwind) increasingly contribute more, up to a point where a peak is reached, thereafter the contribution decreases rapidly further upwind from the station (Verma, 1998). Similar behavior describes the crosswind flux distribution detected by the instruments.

In this study the FSAM (Flux Source Area Model) by Schmid (1994) was used to integrate and weight the TSM estimate ET values. The FSAM was based on the Horst and Weil (1992) model (coded in Fortran) generates the FTP weights for the source area and the approximate dimensions of the FTP area for an area that contributes up to 90% of the sensed fluxes by the instrumentation. It includes the crosswind-integrated flux as Horst and Weil (1992, 1994).

$$F(x,y,Z_m) = D_y(x,y).\overline{F^y}(x,Z_m) \qquad (10)$$

where, $F(x,y,Z_m)$ is the footprint weight function, $D_y(x,y)$ is the cross-wind distribution function, and $F^y(x,Z_m)$ is the cross-wind integrated function.

Results and Discussion

During DOY 178, the weather conditions where such, relative humidity (RH) was low and wind speed (H) was high, that the grass reference ET resulted in high rates (Table 1). Incoming short wave solar radiation (R_s) was slightly higher for DOY 178. However, on DOY 210, RH was higher and U lower thus ET_o was lower than on DOY 178. Further weather and crop parameter values can be found in Table 1 below. In this table note the difference in crop height (h_c) and leaf area index (LAI) for both DOYs. Wind direction (U dir) was from the south southwest direction; the direction of predominant winds.

Table 1. Weather and crop conditions on DOY 178 and 210.

	DOY	
	178	**210**
R_s, W m^{-2}	980	963
T_a, ºC	31.6	30.8
RH, %	31	44
U, m s^{-1}	7.6	4.9
U dir, º	206	214
U dir std, º	20	20
h_c, m	0.18	0.64
LAI, m^2 m^{-2}	0.1	1.3
ET_o, mm d^{-1}	10	8

In the process of correcting the surface aerodynamic temperature for atmospheric stability, the Monin-Obukhov stability length was computed (L), shown in Table 2. This parameter was also used in the FSAM footprint (FTP) to determine the extent of the FTP and the individual cell weight value within the boundary of the FTP. It worth noting that L was considerably large on DOY 210, which indicates that H was very small, consequently the cotton field was using most of the available energy (R_n – G) for the evapotranspiration process instead of for heating the air. Another terms used in the FTP model was the EC sensors' height (Z_m) and the friction velocity (u_*), Table 2, which was measured by the eddy covariance system.

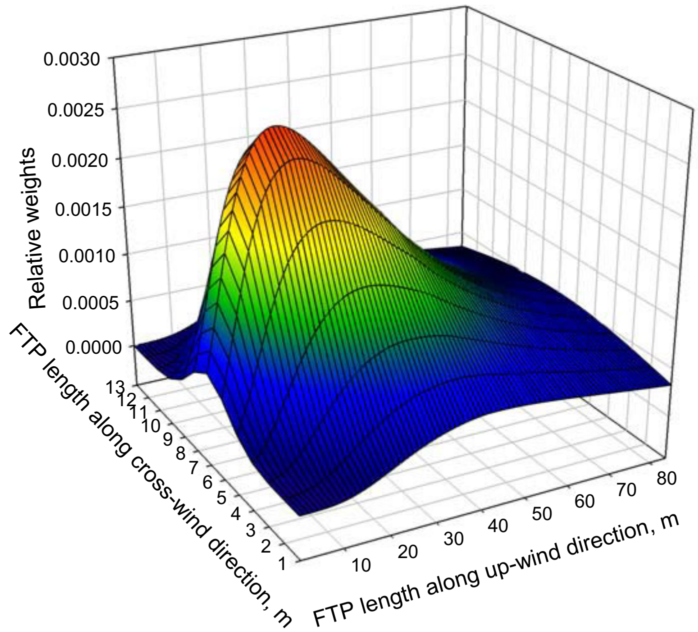
Table 2. Variables and parameters used in the footprint FSAM.

DOY	u_*, m s^{-1}	r_{ah}, s m^{-1}	L, m	Z_m, m
178	0.48	34.5	-65.2	2.5
210	0.53	25.5	-1071.5	2.5

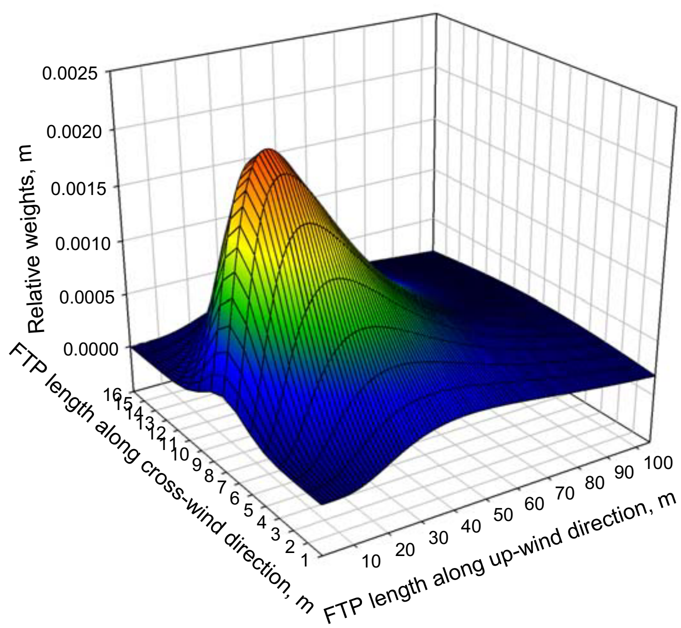
According to the FSAM, for DOY 178, 90% of the upwind FTP length (fetch) was 84 m and the crosswind length was only 13 m. The leading edge of the FTP started about 6 m (upwind) from the EC tower location. Even though the footprint dimensions were generated for 90% of the fetch, the weights integrated under the FTP function added up to 1, i.e. accounting for 100% of the weights. In the case of DOY 210 weather/crop conditions, the FTP fetch was a little bit longer, 105 m, and the crosswind extent was 17 m (not much wind direction variability), with the leading edge stating at 10 m from the EC tower. A graphical representation of the FTPs, for DOY 178 and 210, can be seen in Figure 3 (a) and (b), respectively. Note the effect of the stronger wind speed of DOY 178 in the FTP extent, i.e. small size. Figure 3 also shows the relative weights generated inside the FTP boundary. These weights were used to integrate the remote sensing based TSM ET estimation for comparison to the EC-based ET measurements. The ET weighting and integration procedure followed was that developed by Chávez (2005) and Chávez et al. (2005).

After generating the FTP weights, their text file was converted into an image. Subsequently, the weights image was geo-referenced (rectified) to the same coordinate system/projection/datum (UTM, m) as the reflectance/thermal imagery considering the FTP dimensions and leading edge from the EC tower location as well as the upwind wind direction.

Figure 4 depicts the superposition of the geo-rectified FTP weights image (black and white rectangles) over false color reflectance images of DOYs 178 and 210 respectively (two different days same northeast and southwest fields). The white color in the FTP image represents the concentration of larger (heavy) weights. Multiplying the geo-rectified FTP weights image by the TSM estimated ET image (ET map, Figs. 5 and 6) one obtains the FTP weighted ET values. These values were extracted from the image attribute tables and integrated according to the image pixel value histogram.



(a)



(b)

Figure 3. FSAM 3D footprint representation for DOY 178 (a) and 210 (b).

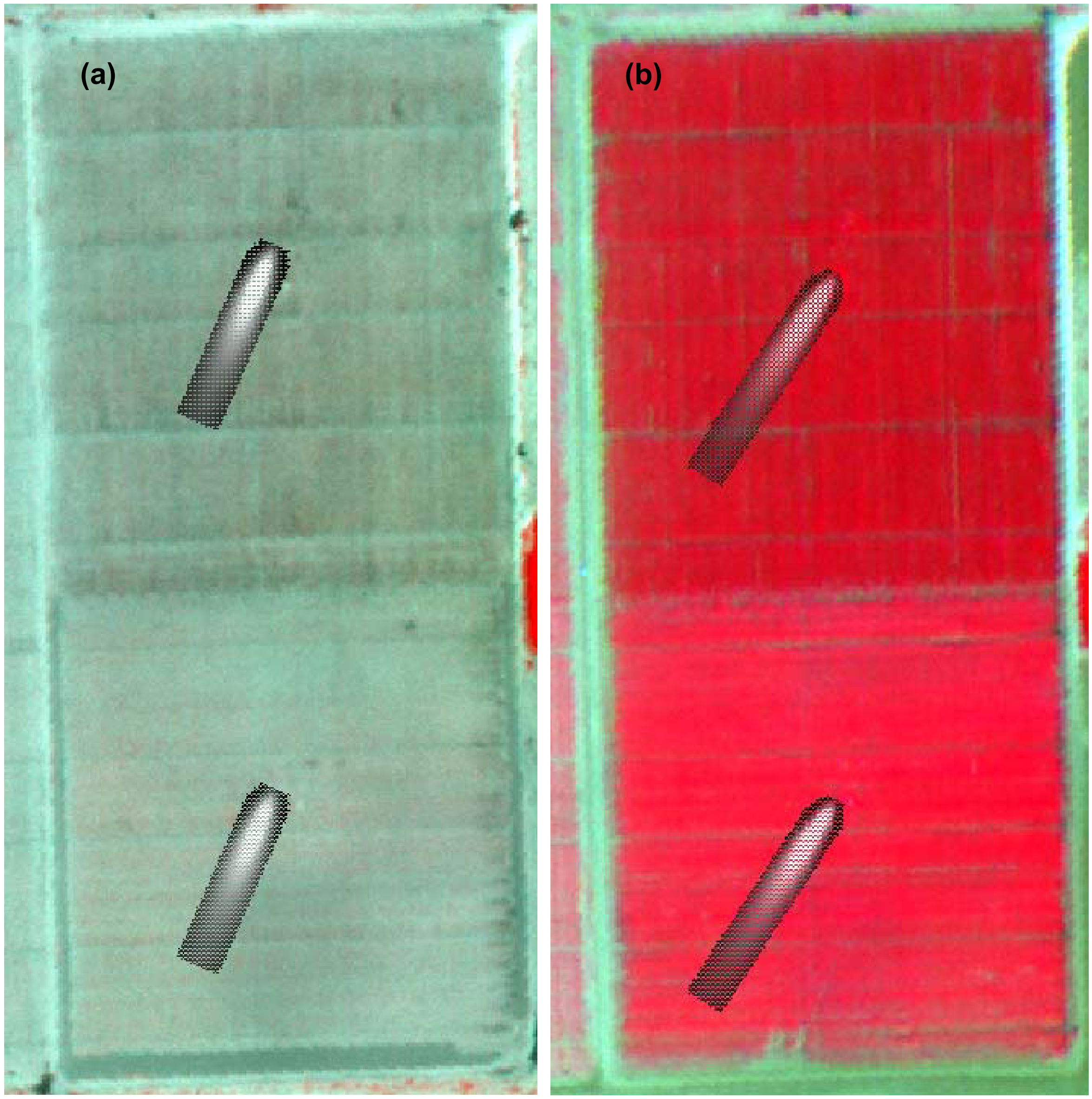


Figure 4. FSAM footprints on DOY 178 (a) and DOY 210 (b) over reflectance images. Both images (a) and (b) are the same northeast fields.

In the process of obtaining ET using the TSM, radiometric surface temperature values were partitioned into canopy (T_c) and background soil temperatures (T_s) using the modification in the calculation of the sensible heat flux originated from the soil. Results from the TSM ensemble surface temperature were reported in Table 3. These temperature values (Table 3) were used in the estimation of the composite sensible heat flux reported in Table 4. During DOY 178, the soil temperature was about 10ºC warmer than the canopy temperature, while on DOY 210 this difference was only 2ºC for the NE cotton field and almost 4ºC for the SE field. The much lower soil temperatures of DOY 210 were due to the higher biomass and greater ground cover presence (Table 1) on this day, even though solar radiation (R_s, Table 1) was slightly higher on DOY 178.

Table 3. Canopy and soil temperature from radiometric surface temperature.

DOY	**Site**	**T_{sfc}, ºC**	**T_c, ºC**	**T_s, ºC**
178	NE	42.2	31.6	42.6
178	SE	41.6	31.5	41.9
210	NE	29.2	30.5	32.5
210	SE	30.9	30.6	34.4

As previously discussed above, H resulted very low during DOY 210 (Table 4), lower for NE cotton field than for the SE field; an indication of higher ET rate at the NE field. In contrast H was very high during DOY 178, which indicates that the available energy was used to heat the air and the soil since the cotton plants were very short with not much biomass and probably due to limited soil water content. The resulting H was somewhat over estimated by the modified TSM algorithm. Sensible heat flux estimation error was 15 W m^{-2} (standard deviation, $\sigma_{d,}$ of 15.7 W m^{-2}), i.e. an error of 17.2 ± 15.5%. This H result is an indication of good canopy and soil temperature partitioning.

Soil heat flux was better estimated by the Bastiaanssen's model in a comparison with measured G by soil heat flux plates (accounting for heat storage). Bastiaanssen's model predicted G with an average error of only -9.9 W m^{-2} (σ_d of 20.2 W m^{-2}). In percent based on mean values these were -7.1% average error with a σ_d of 13.6%; while Chávez et al. (2005) model produced G estimates with large errors, in the order of 100%. This result was somewhat expected since the former was developed for a wider range of crops (including cotton), while the latter was developed using measured G values obtained on corn and soybean fields. In the case of the third G model, the errors were 46.6% in average, with a σ_d of 30.1%, thus not suitable for this study. Therefore, Bastiaanssen's G model was used in the TSM applied in this research. Soil heat flux values, using Bastiaanssen's model, can be found in Table 4, for individual fields and DOYs.

Net radiation was estimated accurately by the TSM, the average estimation error was only 39.8 W m^{-2} (σ_d of 7.9 W m^{-2}), or in percent 6.5 ± 1.6%. Table 4 shows the individual net radiation values for each DOY and field location.

Evapotranspiration, according to the FTP integrated TSM estimation, doubled on DOY 210 with respect to the ET rate of DOY 178 (Table 4). In addition, when the TSM ET values of Table 4 were compared to values measured by the EC systems it turned out that the TSM slightly under predicted ET by 0.5 mm d^{-1} (std of 0.6 mm d^{-1}), or by 5.1 ± 7.2%, respectively. This under prediction is relatively small if one considers that the uncertainty associated with the instrumentation, (for each term of the energy balance) in general ranges from

10-20%. Moreover, ET was better predicted than when a satellite image was used and no modification was made on the TSM for the calculation of H; in which case ET resulted in an under prediction error of 0.8 mm d^{-1} (std of 0.8 mm d^{-1}), or by 9.2 ± 9.0% respectively, Chávez et al. (2007). It is important to have in mind that in the latter case no footprint model was used and the pixel resolution was coarser.

This result was evidence that the modification proposed in Chávez et al. (2008) for the TSM to estimate H for the ground, under sparse/low biomass levels, is appropriate. Furthermore, the FSAM footprint seems to be a viable means to weight/integrate very high spatial resolution ET map pixels.

Table 4. Net radiation, soil/sensible heat flux and ET estimated by the TSM.

DOY/Site	**178/NE**	**178/SE**	**210/NE**	**210/SE**
R_n, W m^{-2}	625.9	619.7	719.9	690.4
G, W m^{-2}	109.3	114.6	73.1	78.1
H, W m^{-2}	261.8	247.2	17.0	24.0
ET, mm d^{-1}	4.1	4.2	8.9	8.2

Finally, maps of distributed ET are shown in Figures 5 and 6 for DOY 178 and 210 respectively. As per the distributed ET values in both Figs., the NE cotton field showed more ET heterogeneity (variability) for DOY 178 than for DOY 210. Also, Figure 5 shows the SE field bordering with a much drier fallow winter wheat field; which could have been an issue had the wind speed been calm because the heat flux source area would have extended into the drier fallow land, thus resulting in a probable lower ET measurement by the eddy covariance system.

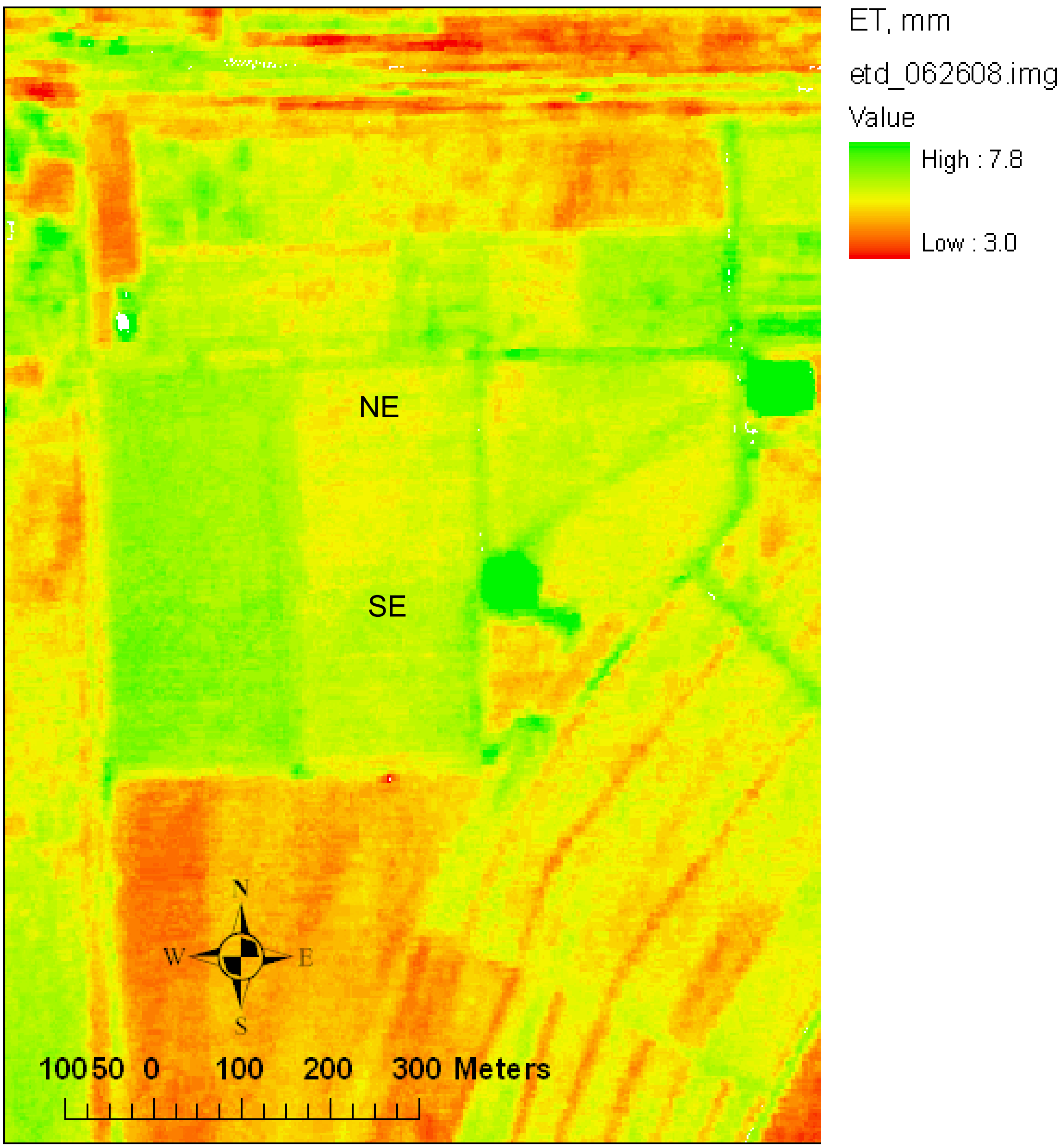


Figure 5. Map of distributed ET generated with the TSM for DOY 178

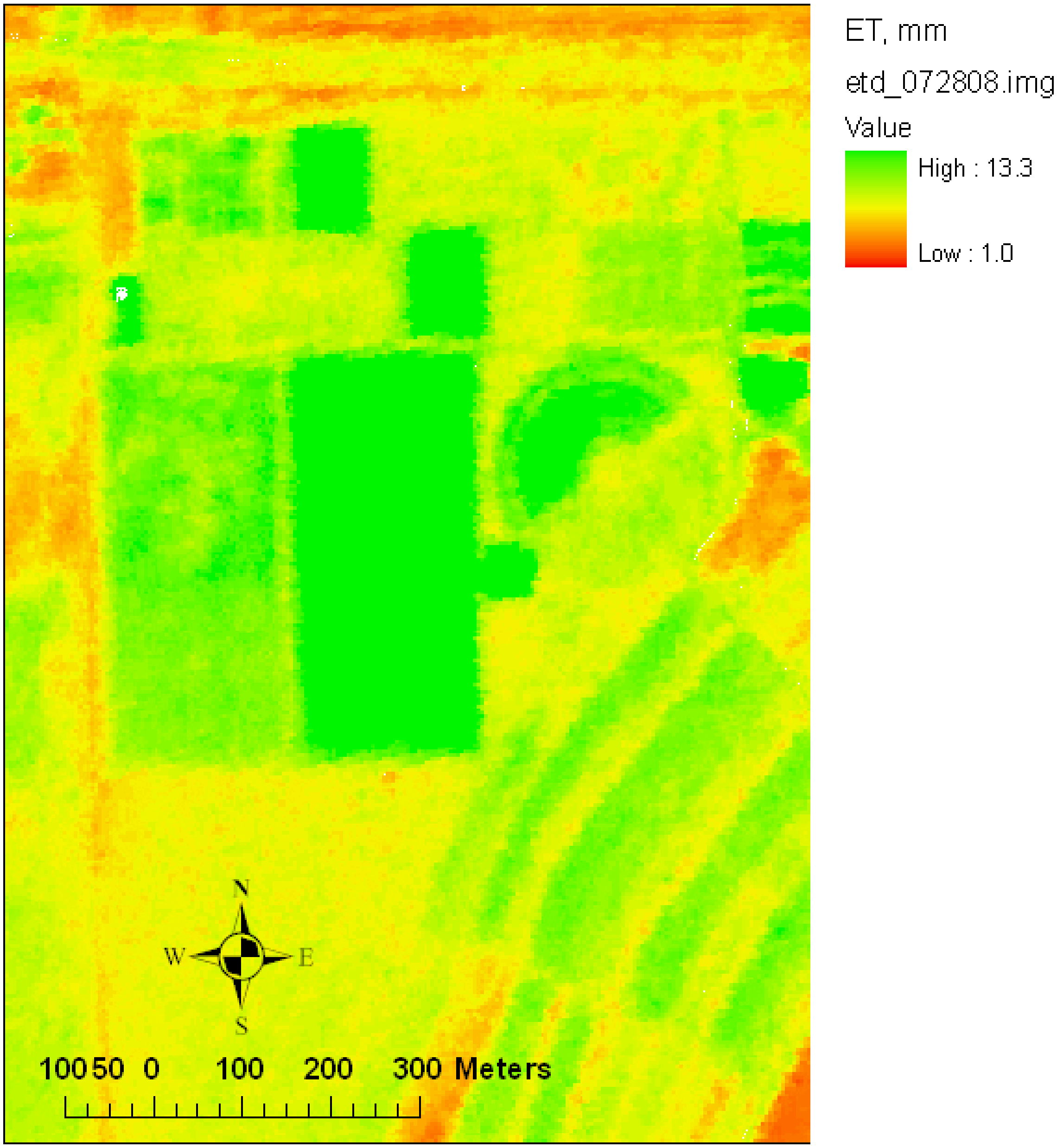


Figure 6. Map of distributed ET generated with the TSM for DOY 210

CONCLUSION

A modified two source energy balance model was applied to very high resolution airborne multispectral imagery to generate distributed ET values. And a 2D heat flux footprint model was used to weight and integrate the resulting ET values.

Results indicated that the modification proposed by Chávez et al. (2008) for the TSM sensible heat flux estimation originating from the ground (substrate), under sparse/low biomass levels, was appropriate. Furthermore, the FSAM footprint seems to be a viable means to weight/integrate very high spatial resolution ET map pixels.

In addition, soil heat flux needs to be estimated by a remote sensing-based model that is valid for the vegetation/background conditions encountered during the scene (image) acquisition. In other words, a soil heat flux model is needed which had been developed considering (is valid for) a wide range of crops, crop biomass level (range of LAI values), soil water content levels, sun zenith angle and sensor bandwidths.

Further research will include the incorporation of a number of airborne scenes to test the modified TSM under dense biomass presence where the resistance network modification suggests ignoring the sensible heat flux originated from the substrate when LAI is larger than 3 m^2 m^{-2}.

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APPENDIX

LE Conversion into ET Rates

Once the TSM has produced estimates of latent heat fluxes (LE, W m^{-2}), these need to be converted into an equivalent water depth or instantaneous ET rates (ET_i, mm h^{-1}).

LE is converted into ET as follows:

$$ET_i = \frac{(3{,}600\ LE)}{(\lambda_{LE}\ \rho_w)} \tag{11}$$

where, ET_i is hourly ET (mm h^{-1}) calculated from the TSM estimated instantaneous LE (W m^{-2}). λ_{LE} is the latent heat of vaporization (MJ kg^{-1}), equal to (2.501 – 0.00236 T_a), being T_a in º C units, and ρ_w is water density (~ 1 Mg m^{-3}). The 3,600 number is a factor to time conversion of s h^{-1}.

In addition, daily evapotranspiration (ET_d)) was computed as:

$$ET_d = \left(\frac{ET_i}{ET_{o,i}}\right) \times ET_o \tag{12}$$

where, ET_{oi} is hourly grass reference ET (mm h^{-1}), calculated using the ARS-Bushland weather station hourly data and the ASCE-EWRI (2005) standardized Penman-Monteith method. ET_o is the daily ET (mm d^{-1}) computed by adding up the hourly ET over the course of the entire day; and ET_i is the TSM estimated actual crop instantaneous ET (mm h^{-1}) values.

Basic Water Treatment: Theory & Practical Application

Micro irrigation systems are a wonderful invention for delivering water and fertilizer directly to plants with the least amount of water at a low cost. The biggest problem with micro irrigation systems is the “micro” part. Small emitters plug easier than larger emitters. The plugging of emitters is the biggest problem with “micro” irrigation systems. Emitter plugging can result many causes such as physical (grit), biological (bacteria and algae), or, as some claim, chemical (iron and calcium scale). Frequently, plugging is caused by a combination of more than one of these factors.

The rules for using water are the same for every industry that uses water. The practical applications of water treatment rules are the same for industrial cooling, fountains, agriculture, turf, and horticulture. There isn't any magic to the application and use of water. There are just some common sense rules to follow. There are several key factors for using water for irrigation: algae and bacteria, iron, and calcium. These factors are considered the most common problems encountered with irrigation systems.

ALGAE

Blockage caused by algae is the most common problem in irrigation systems. The reason why is that algae reproduces prolifically where there is moisture and warmth. The Ideal conditions for growing algae are the same conditions found in irrigation systems. And grow it does!

Algae (sing. alga) are a large and diverse group of simple organisms. They can be either unicellular or multicellular forms. Algae can use the sun to produce food through photosynthesis like plants, but they are "simple" because they lack the many distinct organs found in higher developed plants. Algae are eukaryotes (organisms whose cells are organized into complex structures enclosed within cell walls. Algae are distinguished from protozoa in that they can use photosynthesis to produce food. The process of photosynthesis produces oxygen as a by-product.

Algae reproduce asexually and the cycle of duplication is between 7 and 14 days depending on the strain and conditions. Because algae are asexual, their reproduction rates are not dependent on fertilizing eggs and their reproduction rate is continuous and exponential in numbers.

Think of a swimming pool as an example. Normal chlorine treatment is recommended at no less than every 7 days. Because on the 8th or 9th day, algae us usually visible. Preventive treatment is an attempt to keep the number of colonies low enough that they aren't visible. Algae in non-pathogenic to animals and plants, but it can make using the water difficult. Chlorine kills the algae, but it requires a filter is still required to remove dead cells from the pool water. Chlorine does not remove live or dead algae cells even when super chlorinated.

World-wide it is thought that there are over 15,000 separate species of algae which are: 5,000 species of red algae, 2,000 of brown algae and 8,000 of green algae.

You've probably heard a grower state "I have good water and I don't have any problems with algae". This is a common belief and hopefully it will hold true for those growers. However, there is a nursery in Louisiana that use RO water (similar to distilled water) and the algae still grow prolifically in their irrigation system. The overhead sprayers plug within weeks of being replaced.

Another statement that is made is "let's take a water sample and see what's in the water”. That's good to do occasionally, but there is no easy test for microorganisms that grow in these systems. The microorganisms are so small that it would take filtering several hundred gallons with very fine filtration to collect enough cells to run a culture. Almost all water will grow algae under the right conditions. Micro irrigation systems provide the optimal conditions for algae growth.

Treatments: No remedies have been effective for preventing the growth of microorganisms until recent innovations. Many treatments have been tried including chlorine (powder, liquid, & gas), chlorine dioxide, UV lights, ozone, mineral acids, quats (quaternary ammonium compounds), peroxide, and several others. None of these treatments has been effective to prevent or remove the microorganisms. The only treatment that has proven effective is a peracetic based product.

Chlorine only kills microorganisms, but it leaves the dead cells in the system which becomes food for other organisms. Chlorine has no residual effect. A continuous feeding of chlorine may allow organisms to become resistant to chlorine. Chlorine will then be less effective.

Being simple cell organisms, they don't have sophisticated defenses. One response they do have is reproduction. When algae colonies are attacked, they can immediately put an all out effort to reproduce. An algae bloom can occur. A bloom occurs when the reproduction rate grows dramatically and algae become visible. The colonies can become larger masses and are stringy.

Chlorine, at lower dosages of 1-15 ppm, will only kill the outside layer of a colony and has no ability to penetrate into masses. Chlorine added at a high enough dosage to remove colonies can be toxic to plants, corrosive to metals, and can even destroy plastic parts by removing the moisture (desiccating) the plastic. The plastic can then fracture which can cause the damage to emitters.

An example of how chlorine works is washing clothes. At a medium dosage (15 – 25 ppm) of chlorine, it will bleach out some organic stains (not blood). At a much higher dosage (super chlorination), it will destroy the fabric by burning holes in the clothing (and can do the same thing to plants). At lower dosages of 1-2 ppm of chlorine, it may kill a few organisms, but even at this dosage, slime can still form in the pipes of drinking water systems. In some municipal systems, non-pathogenic bacteria will grow in the system readily. Chlorine will not remove these organisms unless the system is super chlorinated.

Some “quats” (Quaternary Ammonium Compounds) are being used in an attempt to prevent blockage. An example of quats in common usage is Lysol. Quats work by attaching to the cells and bursting the cell walls, but a contact time of 10 minutes or longer is required. Dead cells are left behind which once again can be used as food for new colonies. Quats are very expensive and are rarely fed at the manufacturer's recommended rate of 25 to 50 ppm. Label directions clearly state to remove all organic matter before applying the quaternary compounds to the area.

Hydrogen peroxide is an effective cleaner, but requires a very high dosage. Peroxide isn't cost effective to use. It is effective at cleaning filters (particularly sand media). The high dilution rate makes using peroxide too expensive to use for preventing or removing organic deposits in micro irrigation systems on a large scale basis.

Another treatment method of cleaning irrigation lines is to use mineral acids (hydrochloric, nitric, n-furic, sulfuric acids). Mineral acid treatments are injected into the lines to remove either calcium or microorganisms. Mineral acids have no ability to kill microorganisms. They have no oxidizing or disinfectant properties, and have little effect. A very high dosage could physically destroy the cells, but that would take a huge amount of acid to fill the lines and just the fumes could kill plants. The mineral acids are very corrosion to most metals and could severely damage the plants. To remove calcium scale requires a pH of <2.5 which is deadly to plants and too expensive to use. A proposed dosage is 1-2 tons per acre. Reports indicate that it may be effective for a few days, but then the blockage returns. No study of their effectiveness has been reported.

A stabilized peracetic complex has been formulated that destroys organics. The pH is not affected. It leaves no residue, and, breaks down to water and carbon dioxide. Its low dosage results in low cost to use. It removes organics in irrigation systems. It is the only product we know of that removes blockage in micro irrigation systems. For more information, see http://www.lineblaster.com/.

BACTERIA

Bacteria work very similar to algae, but do not use photosynthesis for the production of food. They have more sophisticated structures. Sulfur slimes and sulfate reducing bacteria are probably the two types of bacteria that will cause most of the bacterial problems with micro irrigation systems. Both readily form colonies and can be pumped out of wells in great volumes. At times, the residue from the bacterial colonies looks like tissue paper when collected. They produce hydrogen sulfide gas (rotten egg smell) as a by-product and this can be used to determine their presence. Sulfur slimes and sulfate reducing bacteria are more difficult to remove than algae due to the tighter formation of colonies and the carbohydrate sheath of “chitin” that protect the cells. Chlorine has no effect on these bacteria at all. As a general rule, chlorine won’t even kill the sulfur slimes and sulfate reducing bacteria due to the carbohydrate sheath surrounding these organisms. Chlorine does not penetrate the sheath and can’t kill the bacteria. Peracetic acid compounds mentioned above has proven effective in penetrating the carbohydrate sheath to remove colonies.

IRON

Iron probably accounts for the second most problems in micro irrigation systems. Most water that contains iron is taken from wells. Iron is an element which means it can’t be eliminated with chemical treatment. Iron could be filtered or removed by RO, distillation, or other process, but the cost of eliminating iron is staggering. The volume of water is much too great to be treated by mechanical processes.

Iron is found in two states: ferrous (black) and ferric (red). The ferrous iron molecule is more soluble and is not visible when dissolved in water. The ferric molecule is formed when ferrous iron is combined with oxygen and converts the ferrous iron to ferric iron. This is called oxidation which is basically:

Ferrous Iron + Oxygen = Rust (Ferric Iron)

It is the ferric iron that causes the reddish-orange rust staining. The formula is listed below.

$$2Fe^{++} + O_2 = Fe_2O_2$$

Ferrous Iron + Oxygen = Ferric Iron

When this reaction occurs, the iron in the ferrous state converts to iron in the ferric state. It is still an iron compound and always will contain iron. The iron just changes the compound with the addition of oxygen. Once this reaction occurs, it cannot be reversed and there isn't any process outside of expensive mechanical processes to remove the ferric iron. The iron needs to be treated before it converts to the ferric iron state.

The ferrous iron is soluble and is dissolved in the water. Acid can be added to the water to keep the iron from coming out of solution, but the pH of the water after adding acid is too low for applying to plants. The ferric iron is a heavier compound and it is more likely to fall out of solution which can result in iron deposits.

One of the properties of this reaction (conversion) is that it takes from 4 to 12 hours to complete. It means the ferric iron is not visible for a few hours. To have a visible confirmation of iron in the water, collect a glass jar of water. When first collected, the water will appear clear and free of residue. The bottom of the container will be free of any iron particles. After a period of 4 to 12 hours, the iron will drop to the bottom of the jar. Iron normally will have turned to a dull brick-orange color and appear to be very light in texture. The iron particles are wispy-like when lightly swirled.

Although iron really does not cause plugging, there are several different ways that have been used for treating iron. One is to inject chlorine into water with iron to control the "iron deposits". The formula that has been proposed is "to continuously inject chlorine at the rate of 0.6 ppm of chlorine/ppm ferrous iron, and then adjust chlorine levels to a 1 ppm residual at the end of the line." This will accelerate the oxidation process. The idea is to not cause plugging. If the iron is induced to fall out of solution, there may be enough iron to actually cause plugging. Under normal operating conditions, iron does not cause plugging. Chemically inducing iron to precipitate may cause plugging.

Another treatment for iron that is being used is to dig a pond (or use a large tank). Pump the well water into the pond (tank) allow the iron to naturally oxidize and fall out of solution. The iron will naturally settle to the bottom of the pond or tank. The suction point of the irrigation pump must be raised off the bottom of the tank. This avoids pumping the iron through the system. There have been instances in which the iron builds up to such a level that the iron in the water being drawn from the pond is higher in iron content that the water coming directly out of the well. At that point, it may be a good idea to dig a new pond and start over. A factor to consider is the cost. This process requires two pumps (one pumping into the pond and the other out of the pond), the cost of digging the pond and the cost of the land.

Polyphosphates have been injected into irrigation water to bond with the iron to prevent the iron from converting to the ferric state. The iron bonds tighter with the polyphosphate and will not let the oxygen bond with the iron. This prevents the oxidation from taking place and is highly effective. However, this is usually reserved for horticulture and residential irrigation systems. As noted above, in agriculture the iron isn’t a real threat and iron on the ground does not hurt the product. In horticulture, no one wants to by a rust stained plant. In residential applications, the stains are unsightly and stain sidewalks, houses, cars, and plants. I’ve even seen red grass due to heavy rust stains.

When water containing iron is used in micro irrigation systems, the iron should have enough time to exit the system before oxidation occurs. The iron will convert to the ferric compound and precipitate on the ground. The amount of water left in the drip tape will leave a light dusting of iron residue, but will never be enough to cause blockage. Even In some of the worst situations, water with an iron content of 10 ppm or higher, plugging from iron doesn't occur. Consider a worst case scenario and how little iron is involved.

Example of Iron Distribution in Drip Tape

10 ppm iron in irrigation water @ 400 gpm

There is only 0.02 grams of iron per foot of Drip Tape in 299.8 hours of irrigation

This amount of iron is insignificant and won't cause plugging. Also this is considering that none of the iron passes out of the irrigation system.

IRON BACTERIA

The difference between iron bacteria and iron obviously is the bacteria. Iron-related or iron-precipitating bacteria (Crenothrix) are a diverse group of microorganisms widely distributed in nature. They are found in fresh and salt waters, in soils, and on desert rock surfaces. Iron bacteria do not normally cause diseases to humans or animals, but rather, they are a nuisance microorganism. These bacteria do not need light or air to proliferate or multiply. They flourish and they obtain energy by the oxidation of dissolved iron in the water from the ferrous to the ferric state. The ferric form is precipitated as ferric hydroxide ($Fe(OH)_3$

Usually surrounded by a tubular "mucilaginous" sheath that hardens and becomes impregnated with ferric hydroxide, iron bacteria can be difficult to control. Chlorination has been used for control in bulk waters for many years; however, there are inherent drawbacks in the use of these products. High chlorine demand due to organic matter and iron levels has shifted the emphasis for control to the use of non-oxidizing biocides, such as quaternary ammonium compounds, as well as organo-sulfur compounds. Both chlorine and quats are only temporary and the problem comes back in a matter of days.

Iron bacteria thrive on iron and use it as a food source. It occurs in pockets that are localized. Iron bacteria can be found in one place and 10 miles away, the water is free of iron and iron bacteria. These microorganisms combine dissolved iron or manganese with oxygen and use it to form rust-colored deposits. In the process, the bacteria produce a brown slime that builds up on well screens, pipes, and micro irrigation systems.

There are certain indications that your well may have an iron bacteria problem. These are:

Red, yellow, or orange color to the water

Slime on the inner walls of irrigation system

A smell that may resemble fuel oil, cucumber, or sewage

For several reasons, routine chemical disinfectants that effectively wipe out other bacteria are only modestly successful against iron bacteria. Iron bacteria build up in thick layers forming a slime that keeps disinfectants from penetrating beyond the surface cells. In addition, miner iron dissolved in water can absorb much of the disinfectants before they reach the bacterial cells. Also, because chemical reactions are slowed at the cool temperatures common in wells, bacterial cells need a long exposure to the chemical for treatment to be effective. Even if chlorine kills all the bacterial cells in the water, those in the groundwater can be drawn in by pumping or drift back into the well.

There are both chemical and mechanical methods for treating iron bacteria problems. The mechanical processes for iron and iron bacteria are too expensive due to the volume of water required. It is possible and has been used on a small basis, but it has very little acceptance due to the cost. Most current treatments consist of dumping chlorine or other chemicals into the well and “hope that works for a while”. Chlorine tablets have been in use since they are slower to dissolve and may give a longer contact time. Since bacteria tend to build up again a few day or weeks after treatment, well owners should be aware that this only controls rather than completely "cures" the problem. While this may be a common practice among well drillers, the legality may be under scrutiny by the environmental agencies.

The most effective product is the peracetic acid that penetrates and removes organic blockages. It can be used continuously or intermittently depending on the operation and the amount of time irrigating.

CALCIUM

Calcium has been identified as a culprit in plugging. Calcium does not precipitate (fall out of solution) in micro irrigation systems. Micro irrigation systems operate as once-thru systems at ambient temperature. If you collect a sample of water and allowed it to sit overnight, there won’t be any residue from the calcium in the bottom of the container. This is an example of the calcium remaining soluble. The calcium does not precipitate in the container. If it doesn’t precipitate overnight, the calcium will completely flow through the system and remain soluble during the irrigation cycle. Perhaps there may be little white specs of calcium are visible. After 20 years of research, we have learned that the real culprit is the microorganisms (algae, bacteria, etc.). They form layers and begin to act like a filter. The calcium deposit forms when the water on the surface of the colonies evaporates. What is seen in micro irrigation systems is the white crusty calcium. Underneath the calcium is a usually a colony of algae or other microorganisms. When calcium is observed, the water sits on the layers of algae and when the water evaporates, the calcium is visible. If you remove the organics, the calcium will pass through the system. In 34 years of water treatment experience, no plugging has been discovered to be caused by calcium. If the calcium were to form deposits, using micro irrigation systems in Florida would be almost impossible due to the extremely high calcium levels of Florida water.

PHYSICAL BLOCKAGE

Flushing irrigation systems is another method used to control algae. Flushing will remove the loose colonies that collect at the end of the rows, but will not remove the colonies that adhere to the micro irrigation systems. Automatic flush valves do not allow many of the colonies to flow out of the lines. The colonies are heavy and will settle to the bottom of the system without pressure to push them out of the lines. Flushing helps to an extent, but is labor intensive and expensive and does not remove many of the colonies.

Sand, clay, grit, insects, and other debris can cause blockage in micro irrigation systems. The blockage caused by physical debris is either a filter, well or insect control problem. These problems can be eliminated by proper operation of the system and careful checking of operations. Before the season starts, the system should be checked for problems. Filters should be inspected and cleaned. Sock filters can be used to look for problems that may arise from split casings, sand infiltration, or other problems. A sock filter should be installed to detect problems with physical matter that may be in the micro irrigation systems. Checking the sock filter weekly may prevent a disaster from occurring. Blockages caused by physical debris are almost impossible to remove. There are no methods that are effective in dissolving sand, clay, grit, or insect parts. A physical hand cleaning is about the only method of removing physical blockage. It usually is easier to replace the micro irrigation system.

Moisture-activated Kink Valves for the Hose-fed irrigation of individual trees, shrubs and vines.

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Abstract. *This paper explores the benefits of employing moisture-activated Kink Valves for remote irrigation, over conventional pinch valves and stopcock (end stop) valves. This new family of valves is manufactured from a combination of moisture-absorbing thermoplastic elastomers (TPE's) in a configuration that results in a bi-stable, mechanically-advantaged geometry. This enables the valve to 'flip' from a dry 'straight open-bore' state to a wetted 'kinked-closed' state and vice versa. These valves do not need filtered water, they operate from only inches of water-head and are self-purging. Data will be presented confirming their performance, energy and cost-saving benefits. Published International Patent Document WO 2008/068496 reveals how this is achieved and how Kink Valves provide an opportunity to expand 'Drylands' agriculture, using a minimum of irrigation water and without the need for electricity. Earlier patents for moisture-activated valves will be illustrated to show how advances in one industry make possible developments in another.*

Keywords. Moisture-activated irrigation valves, low head hose-fed irrigation for trees, shrubs and vines, kink valves, pinch valves, stopcock valves, earlier patents, commercial designs, moisture-swelling materials, some essential elements for a bi-stable bi-polymer valve, optimising hose system layout from a centrally positioned low head water supply tank, saving electricity, water and labor.

Introduction

It is felt that in remote low rainfall areas and where there is no electricity, horticulturalists could benefit from a simple design of water control valve to regulate the individual hose-fed outflows to widely spaced trees, shrubs and vines. Such a valve would have to be easily fitted to the open end of each hose lateral in a distribution system and rely solely for its operation on variations in local moisture. Given a practical and commercially viable solution Designers would be well placed then to provide horticulturalists with simplified 'on demand' irrigation systems on any scale, so reducing the costs of food production – this is our goal.

Table of Contents – in association with an animated Power Point® Presentation

Past experiences

Limited always by the *materials of their time* a great many people have devoted their energies to designing and producing moisture-activated valves. In the past there have been a number of very significant design proposals and some of these have reached the production stage and achieved success in niche applications. I personally owe a great deal, and empathize strongly with these pioneers, for signposting the way and demonstrating the scope of the two favoured design principles namely, the pinch valve and the stopcock. To date though, neither of these has been adopted for the large scale commercial growing of trees, shrubs and vines.

A new approach
With the very *latest materials* and a fresh approach it might be possible now to revisit the original 'constraints and opportunities' to establish a third basic design principle. For example, where previously only one moisture-swelling material was employed as the prime mover, it might be possible now to employ a combination of polymers to mimic some of the properties of the bi-metal thermostat.

This would introduce the prospect of serious animation to valve design, providing it with a snap open and close action, rather than the traditional slow hydraulic opening and closing. Such a valve would be bi-stable and perhaps exhibit different characteristics from pinch valve and stopcock designs.

With this in mind we have combined together up to three polymers (thermoplastic elastomers) in a special geometry to produce what we now call a moisture-activated Kink Valve. This bi-stable design is so radically different from earlier valves that we feel it represents a new, third design principle for the irrigation industry.

The future
Our work is not finished, as we still need to employ large numbers of these valves in the field, to better understand the size of the gains from simplifying hose-fed irrigation and reducing year on year operating costs. We are confident that these will be shown to be attractive to growers and sustainable for the long term, as energy costs rise and water supplies become more critical.

The evidence to date
The following text and illustrations are based around a Power Point® presentation of twenty slides some of which contain video clips and animations. They are reproduced here in a simplified form, starting at slide 3 in the series and concluding at slide 19:

Slide 3 What options do we have?

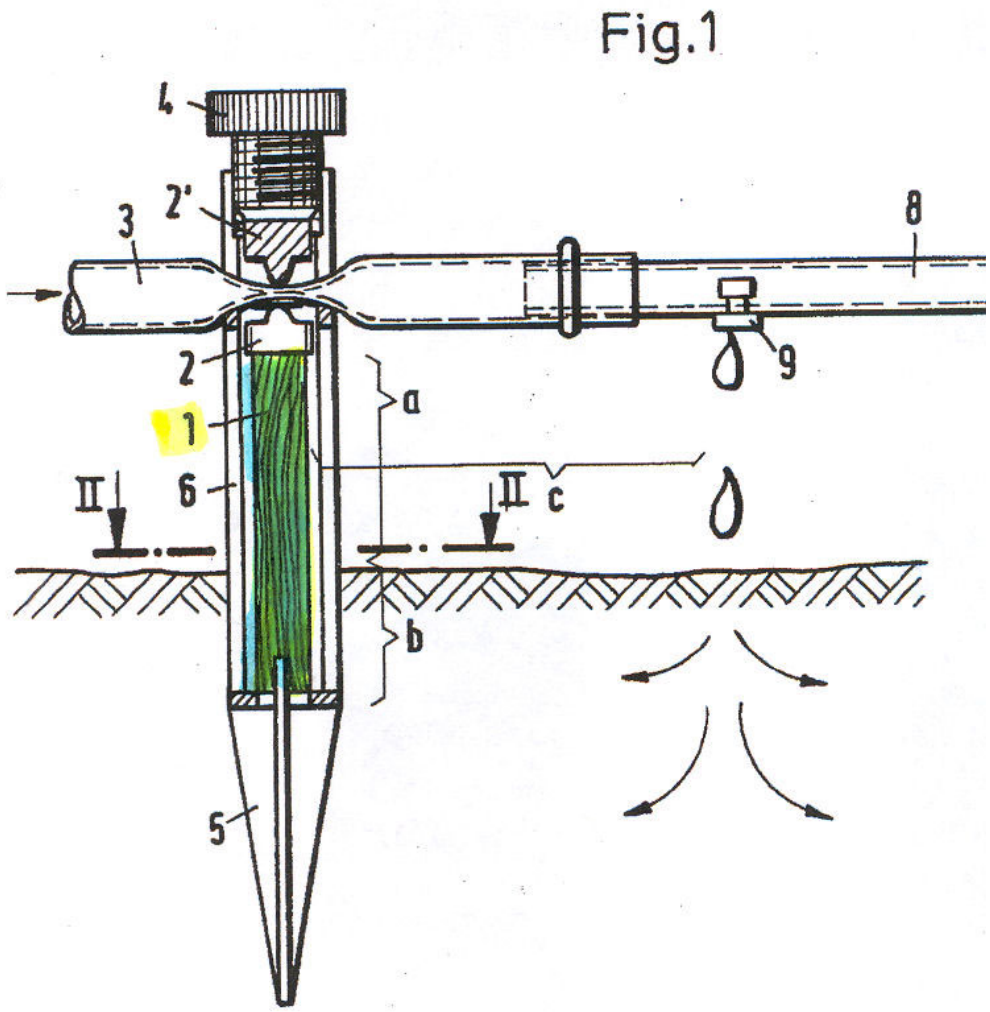
> For gravity-fed hose systems, individual outflows are controlled by one of two classic methods namely, moisture-activated, Pinch valves and Stopcocks. *Pressure-fed Dripper valves are not within the scope of this paper.* Kink Valves offer a third option perhaps with different benefits? But what has already been invented and what is available to buy?

*The **IP** year dates inside the brackets refer to the year that the **Intellectual Property** was filed as a patent application.*

Slide 4 The Patent Archives reveal (1): Pinch Valves: Top view

Irrigation valve device (IP 1978) Gerhard Beckmann, Patent US 4,214,701.

"The water swellable member 1 could be: wood – spruce, fir or pine, or a polymer – Polyurethane Gel."



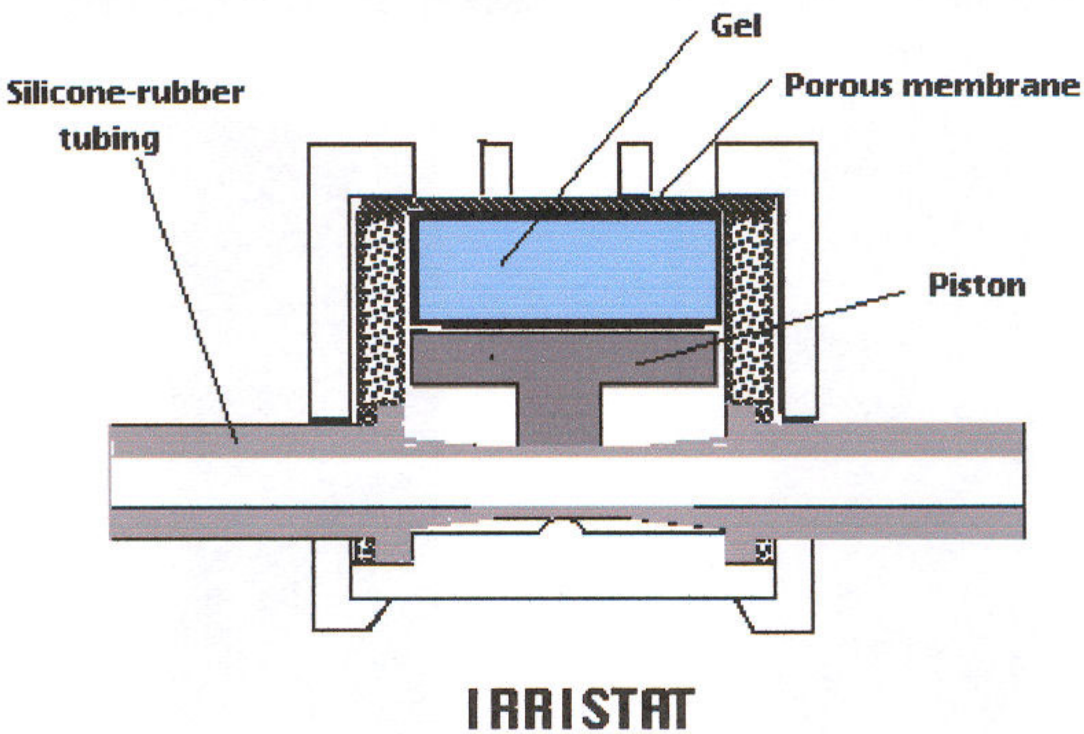
This 'general' configuration of a pinch valve which is spiked into the soil, appears many times in the Patent Archives and has been used ever since vulcanised rubber was first used to make hose pipes and tubing.

Slide 4
Lower view

Irristat™ (IP 1978) Leonard Ornstein, Patent US 4,182,357.

"A water swellable hydrogel, for example based upon polyacrylamide, polyvinyl alcohol, Formulations, etc."

Drawing reproduced with kind permission from: www.pipeline.com



The Irristat™ valve was used extensively in the field over many seasons and geared to controlling the water supply to individual fruit trees, etc. Preferably the product is sited below soil level.

Slide 5 The Patent Archives reveal (2): Stopcocks (end stop) valves: Top view

Moisture-activated valve (IP 1985) Gant, Patent US 4,696,319.

“Bentonite hydrophilic expandable material.”

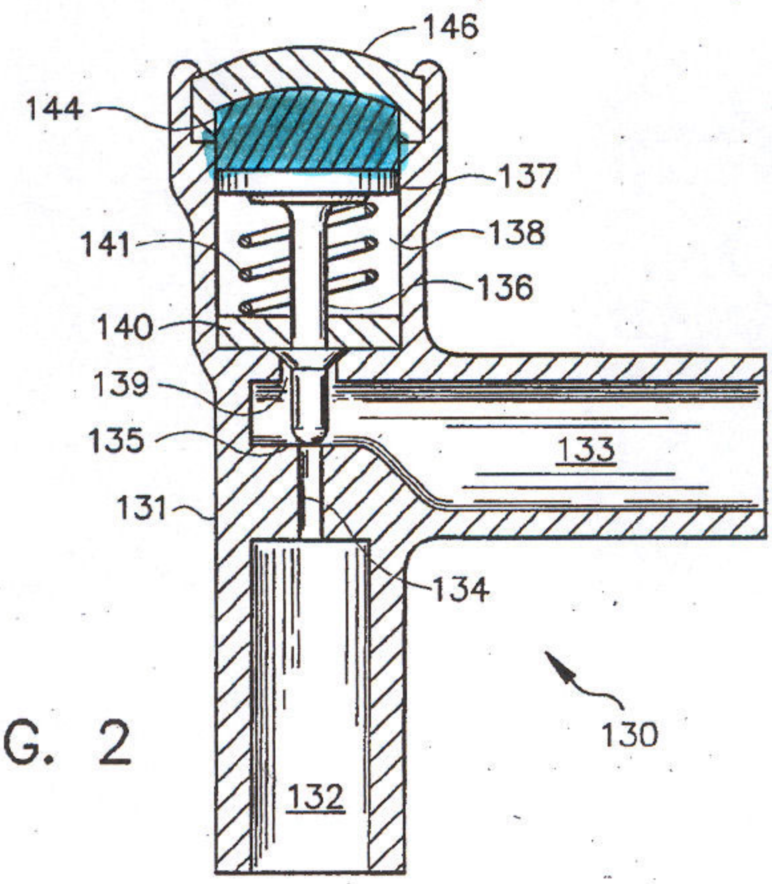


FIG. 2

This is an example of a stopcock type of valve, where the moisture swelling member 144 (shaded blue), working against a spring 141, is exposed to moisture entering and leaving through the top porous membrane 146 and generating hydraulic movement at the end stop 135. It is necessary for this type of valve to be in intimate contact with the soil.

Slide 5 cont'd
Lower view

SmartValve® (IP 1988) Graham et al. Patent US 5,382,270.

"Polyethylene oxide hydrogel."

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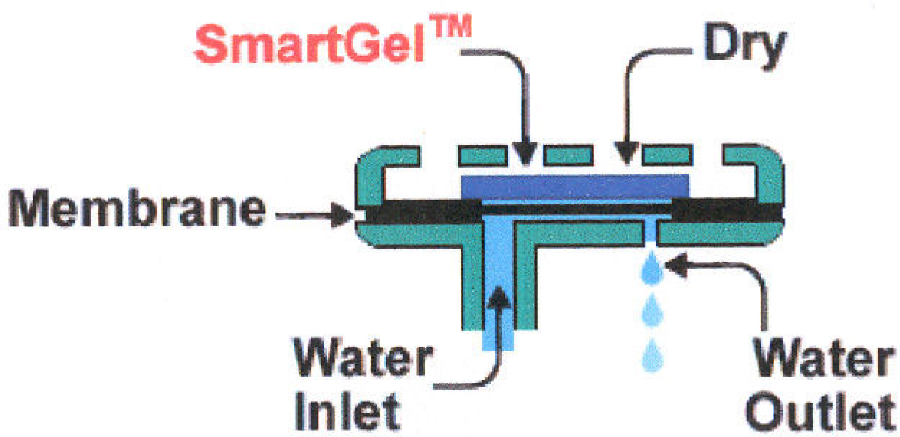
Web: www.smart-tech.uk.com
Smart Tech Ltd, United Kingdom.



This type of stopcock responds to being in intimate contact with the soil or growing medium.

Slide 6 The Market reveals:
Top view

SmartValve® Stopcock (IP 1988)
A moisture swelling Smartgel™ disc element which wets-up to press on a membrane to stop the flow of water through the valve.

slide 6 top view continued,

"particularly preferred is the use of a cross-linked, partially crystalline polyethylene oxide Hydrogel."

Web: www.smart-tech.uk.com
Smart Tech Ltd, United Kingdom.

Side/ front view

Rear/ side view

The activating moisture enters and leaves through the four apertures on the front face. The irrigation water from a push-on hose lateral, enters down the tubular stem, and when the valve is dry, passes across the internal membrane and exits into the soil through the recessed hole, arrowed (yellow).

It is worth noting at this point that the advent of new moisture swelling polymers has given the designer a new degree of freedom, which was not possible before with the limited-life, moisture swelling wood members and clay compounds.

slide 6 continued over page,

Slide 6 cont'd
Lower view

AquaSmart™ Stopcock (IP 1994)

A moisture swelling polymer (blue) takes the form of a piston and wets-up to stop the flow of water through the valve.

"Polyether block amide."

Moss Products Pty. Ltd, Australia
Web: www.mossproducts.com.au

This product is spiked into the soil so that the blue swelling polymer is in intimate contact with the soil or growing medium. The irrigation water enters the tubular stem on the left side, to which is attached a hose, and passes through the hole (arrowed yellow in the cut away view). Still inside the valve body the water is forced upwards and into the swivelling cowl which directs it back down again and onto the soil. By this means the valve can be adjusted to increase or decrease its delivery of water over time.

Slide 7 Moisture-activated Kink Valve.

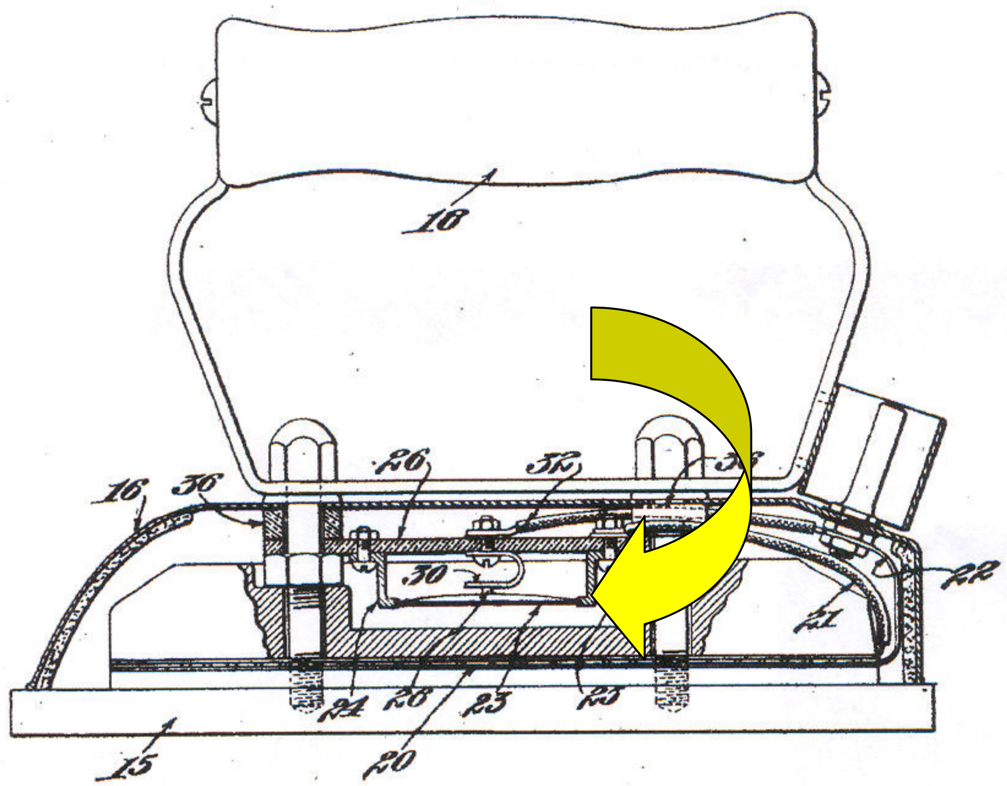
If we could make a Kink Valve using not just one but two or more thermoplastic elastomers (TPE's) with different moisture swelling properties, we might be able to make the Water Industry's equivalent of the bi-metal thermostat?

Slide 8 Elements of a bi-metal thermostat.

On 8th April 1921 John A Spencer of Massachusetts filed a patent application for a bi-metal thermostat device: Patent US 1,448,240.

*"to which is imparted a **sudden and rapid** movement when a substantially predetermined temperature is reached."*

Fig.1



The two special features of this switch (shown here in a smoothing iron) were that it was **able to convert the slow curling action** of the bi-metal element **into a sudden and rapid movement** by way of its special geometry to create a very positive bi-stable switching action – this minimised the arcing and burning of the contacts that was a normal occurrence when the circuit was made and broken repeatedly, to control the ironing temperature. At the time this was a very significant step forward for the Electrical Industry. Billions of these types of switch are in daily use around the world.

Slide 9 **Moisture-activated, bi-polymer Kink Valve.**

To make this new type of water ‘switch’ we need to accomplish the two steps as follows:

1. Initiate a curling action similar to that of the thermostat, but with moisture and not with heat, and

2. control the movement within a special geometry to create a mechanical advantage, to produce a bi-stable flip/ flop action.

Preferably the new valve will have a straight-through open bore with no restrictions to keep hose sizes to a minimum. The valve must also close positively and open again fully – to prevent blockages and leakage, i.e. it must be self-purging.

Slide 10 **Step 1: Make a moisture-activated, bi-polymer strip element.**

Two TPE’s with very different moisture swelling properties have been bonded together.

Underside view

Side view

This is a simple and effective demonstration.

Slide 11 Step 1: continued

From a dry state submerge the bi-polymer strip element in water and this is what happens after approximately 2 hours.

Side view

This reproduces the first condition – the curling action. How good is this material combination, what happens if we leave it in the water overnight?

Slide 12 Step 1: continued.

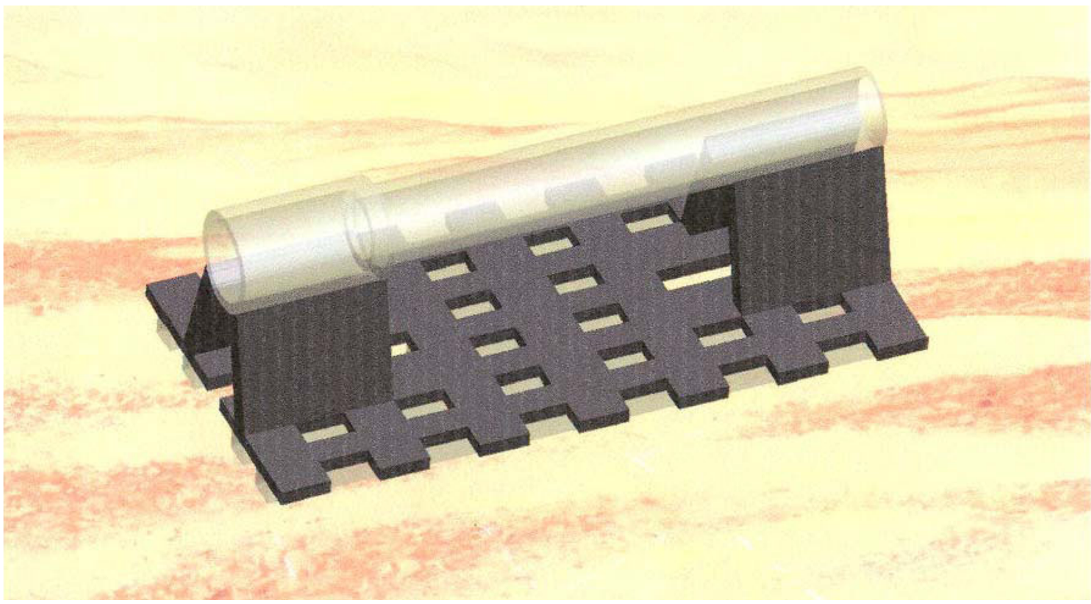
Sample strip element following an overnight soaking.

slide 12 continued

It is evident that this material combination has a very special property which we can put to good use. Note, it is only necessary to use a part of this potential for curling to create the basis for a kink valve.

Slide 13 The Moisture-activated Kink Valve features

There is a ten second animated E-Drawing on this slide which shows how the various features of the (2" long) Kink Valve have evolved.



1. At the base of the valve shown and underneath the dark waffle plate (perforated) there is a spider shaped web of high moisture-swelling polymer material.

2. The high moisture-swelling material is bonded to the underside of the dark waffle plate which is a low moisture-swelling polymer material, and in this example very elastic.

3. Four standoffs rise up from the waffle plate to form a cradle for the irrigation tube.

4. The irrigation tube is a very low moisture swelling polymer with the ability to kink repeatedly – in bore sizes: 5/32" (4 mm), 1/4" (6 mm) & 5/16" (8 mm).

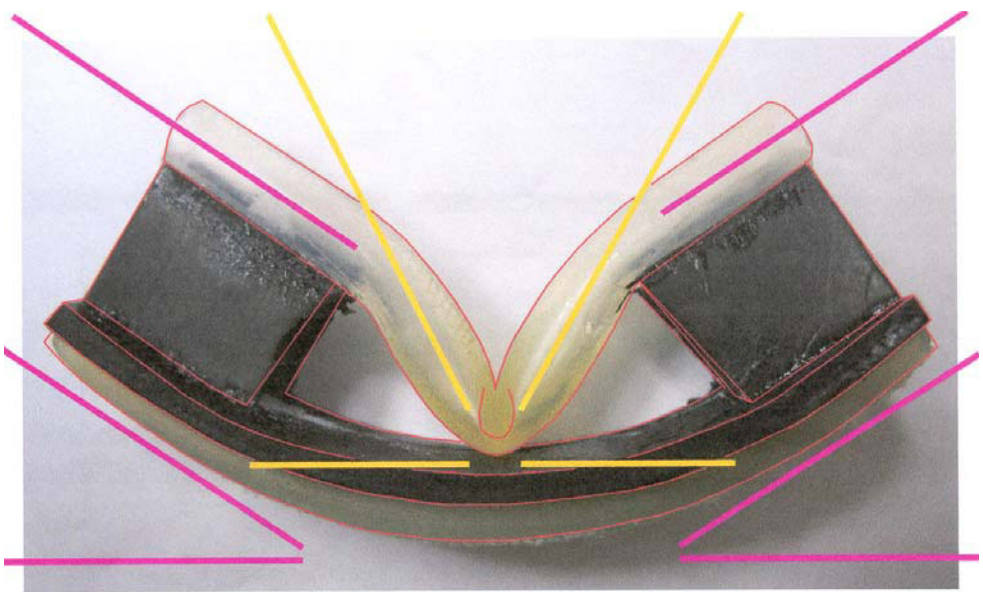
Providing water flows from, 1/2 gal. (2 litres) – 14 gal. (50 litres) per hour, and with water heads from as little as 20” (0.5 metre).

When these different materials are brought together in this special geometry and in a dry state the device can be connected to the free and open end of a hose lateral. In this dry state the valve will allow water to pass freely through its full open bore for as long as the valve remains dry and the water supply is available. For example from a supply tank providing anything from a two foot to a ten foot head of water. If at some point the valve is wetted up on the outside the subsequent swelling and stretching of the polymers will cause the valve base to curl inwards on itself to a point where the irrigation tube will suddenly collapse to form a kink. It is this action which closes off the passage of water.

Once the valve has had some time to dry out again and partially de-curl, there will come a point when the kink suddenly disappears and the water passage is opened up again to resume watering.

Slide 14 Step 2: Create the special geometry - the Mechanical Advantage.

The dramatic formation of a kink described above in slide 13 is shown here.



Note, the acute kink formed in the tube (yellow guide lines) as a direct consequence of the gentle curling of the high moisture swelling base element (magenta guide lines).

Slide 15 The Kink Valve in operation

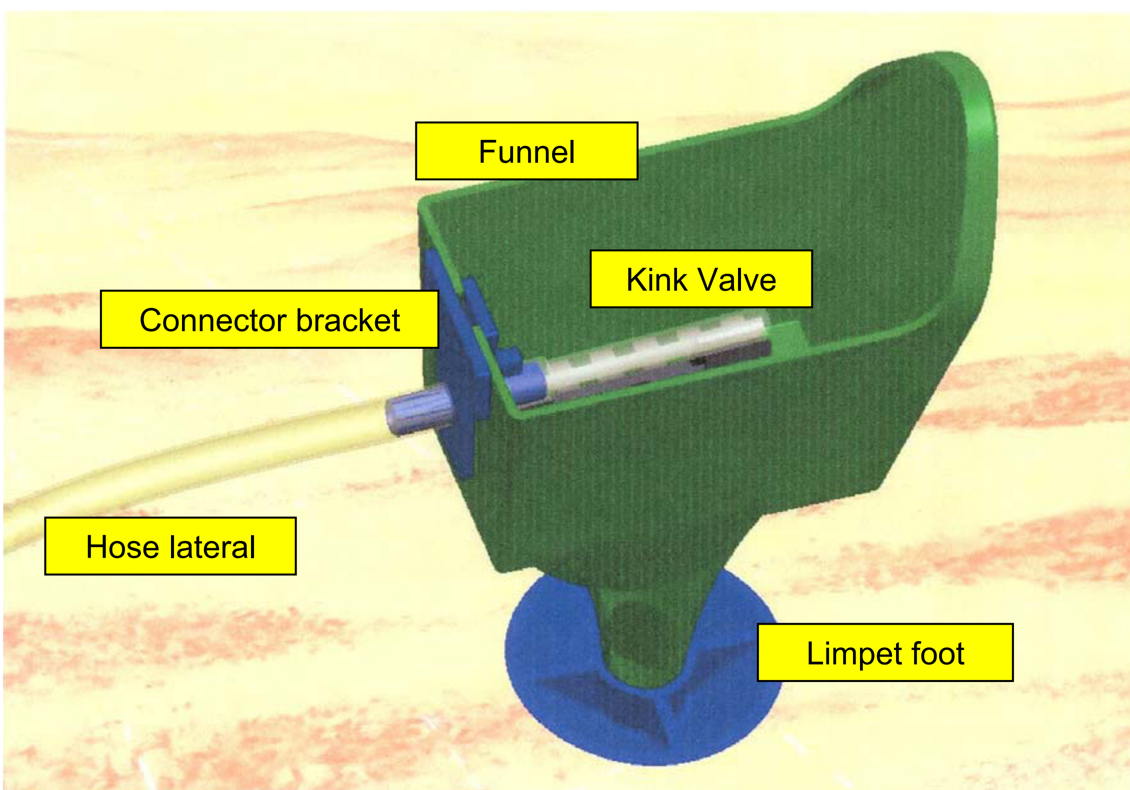
This is a twenty second video clip of the Kink Valve in operation, snapping shut and closing off the water flow.

Open – dry state

Closed – wet state

Slide 16 Kink Valve funnel assembly for field use.

This slide is a ten second animated E-Drawing showing the assembly of the Kink valve, its connector bracket, funnel and limpet foot coming together and attaching to the free and open end of a hose lateral.



slide 16 cont'd

The components are described as follows:

- **Funnel** – this is used as a housing and drainage point for the irrigation water.

- **Kink Valve** – this is used to switch the water on and off.

- **Connector bracket** – this is used to join the lateral hose to the Kink Valve and serves also to secure the sub-assembly to the funnel housing.

- **Limpet foot** – this acts as a ground anchor to prevent rodents and birds from uprooting the whole assembly.

In field use the funnel is partially buried with only the top one inch visible above ground level. The funnel has options for up to three drain holes, to cater for different watering needs.

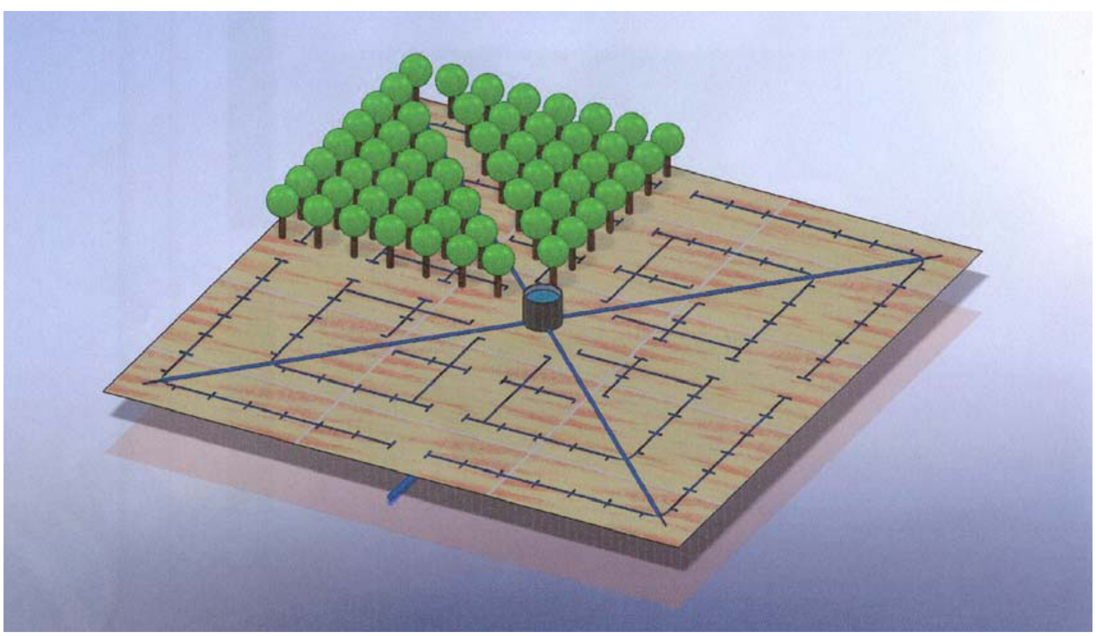
Slide 17 Kink Valve funnel assembly operating in the field.

This is a twenty second video showing the Kink Valve delivering water to a tree and then snapping closed when the watering is completed.

Slide 18 **The potential for gains employing moisture-activated irrigation valves in gravity fed hose distribution systems.**

- Costs less - simpler and smaller hoses
- Visible – not buried underground
- No electric power needed
- No pumping
- No pressurized filtration
- Optimum water usage
- Self purging
- Less maintenance
- Will fertigate.

Slide 19 **This slide is a twenty second animated E-Drawing of a citrus grove describing a tank-fed hose layout and its operation.**



Conclusion

A study of the patent archives and the commercial market confirms a long-standing and continuing interest in moisture-activated valves for controlling the individual outflows of hose-fed irrigation systems. This is particularly relevant where hose laterals are widely spaced for example in the cultivation of food producing trees, shrubs and vines.

There have been significant advances in the materials available for these special valves which traditionally fall into two classes of operation namely, pinch valves and stopcocks. New polymer based materials are providing Designers with the opportunity to refine existing configurations and to consider radical new designs based on Technology Transfer from other industries.

The new moisture-activated Kink Valves currently under development, exhibit animated properties similar to those of the electric thermostat. This adds a new dynamic to water-control valve design.

It is likely, in the very near future, that moisture-activated valves will come under the spotlight as growers seek solutions to overcome water and electricity shortages in the face of growing pressure to increase food production on ever more marginal land. It is hoped that the Irrigation industry will be well placed to supply a useful range of moisture-activated valves.

Acknowledgements

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2. AquaSmart™ is a Trade Mark of Moss Products Pty. Ltd, Australia. Further details available from web address: http://www.mossproducts.com.au

3. Irristat™ is a Trade Mark and invention of Leonard Ornstein of the United States of America. Further details available from web address: http://www.pipeline.com

4. SmartValve® is a Trade Mark of Smart Tech Ltd, Scotland, United Kingdom. The SmartValve is an invention by; Professor Neil B. Graham, Robert A. K.

Szmidt and Ralph C. Kirkwood all of Scotland, United Kingdom. Further details available from web address: http://www.smart-tech.uk.com

5. Kink Valve™ is the generic name for the Liquid Lever® irrigation valve. Rights reside with the charitable status company: Grow More Food – A limited company registered in England, United Kingdom, Reg. No. 6652992. Further details available from web address: http://growmorefood.org

6. Rights to use the Kink Valve technology are assigned to the company Liquid Lever Solutions Ltd – registered in England, United Kingdom, Reg. No. 6533540. Further details available from web address: http://growmorefood.org

7. The Intellectual Property relating to the Kink Valve is protected and published in the following International Patent Document: WO 2008/068496 A1.

ooOoo

Irrigation gate status recorder

Presented at the 2008 Irrigation Show, Innovations in Irrigation Conference, November 2-4 in Anaheim, CA

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Abstract
The flow of water down an irrigation ditch can be measured using a flume or by measuring the discharge from a well into the cannel. Water is diverted from the cannel into a field by opening gates in the cannel to each field. To calculate the depth of water applied to a field, it is necessary to measure the time duration that the flow in the cannel is diverted to each field and the area of the field. The time that a gate is open to the field can be measured with an irrigation gate status recorder consisting of standard magnet switch used in tipping bucket rain gauges and a Hobo event recorder that records the date and time that the switch is closed. An event is recorded each time the magnet on the gate passes the magnet switch as the gate is raised or lowered.

Introduction

Water conservation and proper irrigation timing and amount require knowledge about the amount of water applied during an irrigation to each boarder in a field. Ideally, the timing and amount of water applied to an irrigated field should be measured automatically without the need for a person to be present to record the flow rate and duration of the flow. Automatic control gate that opened and closed automatically were developed in the 1960 (Bowman , 1968, Calder and Weston. 1966, Humpherys , 1967), but these automated flood irrigation turnout gates were never adapted by the farming community because of the lack of reliability of the systems. Consequently, most flood irrigation control gates are operated manually. The flow rate of water down an irrigation ditch and the controlled turnout into a field through a gate can be measured using a flume or by measuring the discharge from a well into the cannel using a flow meter installed on the well discharge pipe. If the flow meter contains an output single proportional to the flow rate, it can be connected to a data logger to measure the accumulated flow over time and the total volume of water. Generally, the electronic propeller meter contains an electronic rate/totalizer that senses the propeller rotation via a magnetic pickup sensor located in the gearbox and translates these pulses to rate and total flow. The meters contain a 4-20 mA pulse output when the totalizer is connected to an outside power source. This output can be recorded by a data logger that can be an inexpensive single cannel data logger costing $400 or a multi cannel data logger costing up to $1,100.

However, when the irrigator changes the flow down the cannel from one boarder to another, a method of determining when that boarder gate is open or closed is needed to determine volume of water into each boarder or set of furrow irrigations. If a electronic sensor is not available on the flow meter but a total volume mechanical meter is read at the beginning and end of the growing season, and a gate recorder is used to record the time duration and date that each gate for each boarder is open then the proportional time duration that each gate is open can be used to prorate the total volume of water into each boarder at each irrigation assuming the discharge rate of the well into the channel is constant through out the growing season. If the well in use irrigate more than one field, then irrigation gate state recorders must be installed on all gates in all fields.

If the water comes from a main irrigation district cannel turnout then it can be measured using a flume in the field cannel. The depth of the water in the flume over time and thus the flow rate can be measured using a pressure transducer connected to a data logger. The S-M type flumes (Samani, Z. and Magallanez, H. 2000) can be installed quickly and at a cost of $100- $200 into a concrete or dirt ditch cannel. The pressure transducers range in price from $600 to $1000. Again the cost of the data loggers is from $400 to $1100. Water flow in a cannel is measured and the water is then diverted into a field by manually opening gates in the cannel to each boarder. Again, in order to calculate the depth of water applied to a boarder, it is necessary to know the time duration and flow rate that the flow in the cannel is diverted to each boarder and the area of the foarder. The boarder area can be determined by aerial photographs or using GPS equipment.

The objective of the research was to develop an inexpensive irrigation gate status recorder that when combined with knowledge of the flow rate or total flow down the cannel could measure the volume of water applied to each boarder in a field and in turn the depth of water applied at each irrigation date automatically.

Materials and methods

The time that a high flow turnout gate (Fig. 1) is open to irrigate a boarder can be measured with an irrigation gate status recorder. The gate data logger consists of an event recorder (Fig. 2) with an external magnetic switch (Fig 3) attached to the frame of the high flow turnout gate and a magnet attached to the slide portion of the gate.

Fig. 1 Irrigation gate with a data logger

Fig. 2 Irrigation event data logger.

The event recorder switch attached to the frame of the gate is activated as the slide portion containing the magnet pass the switch. The data logger records the date and time the magnet passes the switch each time the gate is opened or closed. The magnet switch and the magnet are attached to the gate using silicon rubber. The magnet switch used is a tipping bucket recording rain gages switch (Hamlin 5801 switch). The magnets used were acquired from a home alarm company. The switches used by the home alarm company can not be used because they are for indoor use and fail after a rainfall event even if covered with silicon rubber. The Hamlin switch is water proof. The event recorder is a Hobo h007-002. The magnet is raised when the gate is raised, closing the switch and recording an event. It is important that the magnet switch be placed closes enough to the magnet to be activated. This distance should be no more than 0.25 inch and do the operation check after installation by rising and lowering the gate several times to make sure the magnet is operating the switch. As long as the gate is open, no further events are recorded. However, a delay of 1 second is set in the Hobo data logger before another even can be recorded so that multiple recording do not occur when the magnet passes the magnet switch. When the gate is closed at the end of the boarder irrigation another event is recorded. This data along with the integrated flow over the measured time period is used to calculate the water amount diverted into the field.

Knowledge of the flow rate through the gate is required. In this study, the discharge from two wells was measured into the cannel using the Sparling meters installed on the wells outlet pipes. The gate flow rate was equal to the combined discharge rate of the two wells because only a single high flow turnout gate was open at a time. If sets of gates are open for an irrigation event, with each turnout gate supplying water to a different boarder in sequence, then one recorder is installed on each gate to determine when it was opened and closed. The total flow in the ditch must be diverted to one boarder at a time for the measurements to be accurate. The flow rate in the cannel if it is constant based on a upstream turnout setting can be measured using a inexpensive S-M flume (Samani, Z. and Magallanez, H. 2000) consisting of two half section of pvc pipe placed in a vertical channel or a single pvc pipe placed in the center of a trapezoidal channel. This flow rate must be recorded by the irrigator at each irrigation event or set to the same flow rate throughout the growing season.

Fig 3. Switch and magnet attached to a slide gate.

Field Experiment

A pecan orchard in the Messia Valley New Mexico was planted in 1970 on 9.7 by 9.7 m tree spacing with a average orchard tree height of 12.8 m and an average tree diameter at breast height of 30 cm. The soil type was a Harkey loam and the orchard was irrigated before the soil moisture reached a maximum allowable depletion (MAD) of 50% based on a tensiometer reading at 30 cm reached 0.6 bar or when more than 8 days would have occurred between irrigations. The study was started in 2003 and the gate recorder was installed on a gate in the first boarder of the field in March of 2003 down stream from a cannel that received its water from two irrigation wells containing Sparling meter with only totalizing water meters on them (Fig. 4)

The boarders had high flow turnout gates to take the total flow from the two irrigation wells that was around 3600 gpm. Flow measurement throughout the growing season determined that the flow rate from the wells varied less than 2% the accuracy of the flow meters. The event recorder data was downloaded using Onset cooperation Box Car Pro 4 software installed on a portable computer that was taken to the field to read the data logger every two weeks.

Fig. 4. Measuring discharge of the irrigation wells using Sparling meters.

Results and Discussion

Before the installation of the irrigation gate status recorder, in the first year of the research the two Sparling meters were read before and after each irrigation of the monitored boarder. However, because the farmer did not always inform the researchers when an irrigation event was to occur, many irrigation events were missed or more than one boarder in the field was irrigated between meter readings. Also, because it was necessary that the meters be read at the end of the irrigation before changing the gates to irrigate another boarder, a person had to stay at the field during the entire boarder irrigation even which could take 5 hr's.

After the installation of the irrigation gate status recorder, irrigation date, amount and depth were measured automatically (Fig. 5).

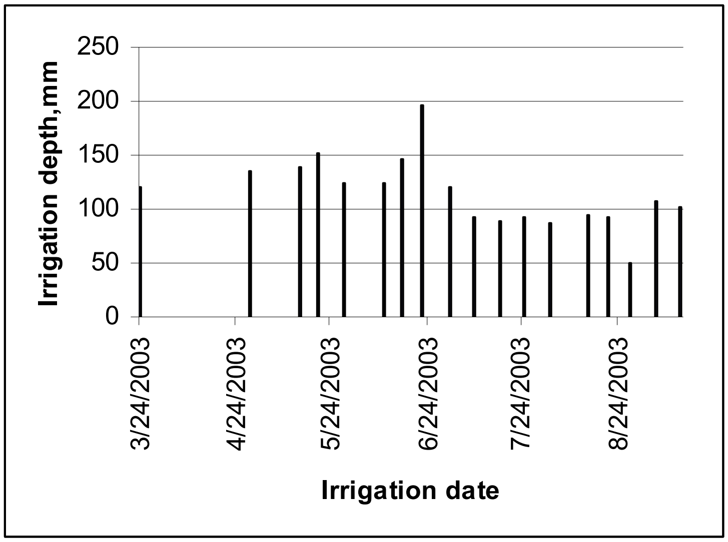

Fig. 5. Depth and amount of water applied to a Pecan flood irrigated orchard in 2003

Occasionally, the event recorder did not record an irrigation event for unknown reasons. Then, a second irrigation gate status recorder was installed on the other side of the gate, so if one failed the backup recorder would work. In a couple of times during the experiment (year 2004 and 2005) the irrigator broke and loosened the magnet switch from the side of the gate and one time the magnet came off the slide portion of the gate. It is recommended that a plastic cover be put over the magnet switch and the wires from the switch to the Hobo event data logger be put in protective pvc for long time installation. Also, it is important when using the Hobo event recorder to observe the battery status of the recorder and replace it when it shows 50% depletion.

Conclusion

A simple irrigation gate status recorder was designed and used to record the date and time a irrigation gate on a high flow turnout was opened and closed. This coupled with the flow rate in the cannel and the area of the boarder allowed for a calculation of depth of water application. The simple irrigation gate status recorder is reliable.Because of the low cost, two gate status recorders are recommended to be installed in case of instrumentation failure so that no irrigation events are missed.

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Measuring Soil Water Potential Using Dielectric Permittivity and Porous Ceramic

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Abstract. ***Irrigation control systems incorporating soils measurements to make "smart" decisions have not fully embraced soil moisture sensors because of difficulties associated with data interpretation. While soil water potential data are easier to interpret than soil volumetric water content data, the lack of a robust and inexpensive soil water potential sensor has prevented the irrigation industry from using water potential to control irrigation. The goal of our research was to develop a low cost, simple, and accurate water potential sensor that is easy to install and long-lasting in the ground. The water potential sensor (WPS) that we developed measured the dielectric permittivity of a well-characterized porous ceramic disc in equilibrium with the surrounding soil. We evaluated sensor performance over a wide range of water potentials using tensiometers and pressure plates. Sensor calibration showed high measurement sensitivity in range of soil water potentials that plants grow. In addition, confounding environmental factors like soil electrical conductivity and soil type did not appear to affect sensor output. Results suggest the WPS is a tool that makes irrigation scheduling as simple as regulating heating in a home.***

Keywords. Soil moisture, water potential, soil moisture sensor, smart irrigation

Introduction

"Smart" irrigation control is critical to conserving municipal water supplies. Among many control strategies, soil moisture monitoring has become one of the more promising irrigation control technologies because the measurement provides information about the availability of water in the soil (Campbell and Campbell, 1982). However, the majority of soil moisture technologies only determine the amount of water in the soil, not if irrigation is necessary. That decision is left to the user. Because most people do not know how to interpret soil moisture measurements, general integration of these devices into irrigation control systems has been slow.

The effects of soil particle size and soil density are at the heart of the challenge of interpreting soil moisture measurements. The size distribution of the particles in soil determines if water will be available to plant growth. The smaller the majority of the particles, the more tightly water is bound. Thus, a sand-sized soil and a clay-sized soil with the same amount of water in them will have completely different amounts of water available to the plant. For example, sand with 20% water by volume (VWC) may only bind 5% (by volume) tightly so 15% is freely available for uptake and use in biochemical processes and transpiration. A clay with 20% water by volume will exhibit completely different behavior. In this case, the water will be bound so tightly by the extensive surface area of the fine particles that 0% will be freely available and most plants will find it difficult or impossible to remove any water at all. Clearly, simply relying on the amount of water to determine the needs of the plant can lead to gross interpretation errors.

Ideally, the solution to "smart" irrigation control is similar to placing a thermostat in a house; people with no knowledge of thermoregulation can easily use their thermostat to keep their homes at a comfortable temperature. Instead, most irrigation control systems that integrating soil moisture measurements use an arbitrary "refill" point, set by the user, to make irrigation decisions. This is an imprecise technique, often relying on the knowledge of the user to define the level of soil moisture plants require. In fact, plant water requirements are better defined by a parameter called "soil water potential" (SWP) which defines the energy state, not the amount, of water in soil. Plants use a gradient in water potential to draw or literally suck water from the soil. Since healthy plants require a well defined range of water potentials for optimum growth, much the way people have a set range of temperatures for comfort, a SWP sensor could control irrigation with minimal knowledge of irrigation requirements.

Differences in water potential between the atmosphere and soils drive water movement from the soil through the plants and into the atmosphere. Water will always move from high water potential (less negative) to low water potential (more negative). However, if this gradient becomes too high (because of lack of soil moisture), plants can no longer pull water from the soil. The point at which the water potential is below optimal levels is typically < -100 kPa. This relationship is independent of soil type, and the optimal SWP growth ranges for specific plants are well tabulated in scientific literature.

Although SWP sensors have been available for many years, currently available sensors are either inaccurate, too expensive, or have short field life (Scanlon et al., 2002). The objective of this study was to design a low cost, high quality sensor to measure SWP *in situ*. To meet our goals, the sensor will show no soil type dependence, work over a wide range of SWP, have low salinity response, and agree well with existing technologies.

Sensor Design

When a porous material (ceramic) is put in contact with the soil, water will flow into or out of that material until the material's water potential is equal to the soil's water potential. As with any porous material, ceramic has a unique, static relationship between the amount of water in the matrix (water content) and its water potential, called a moisture characteristic. The WPS measures the water potential of the soil by equilibrating a ceramic matrix with the soil, measuring the dielectric permittivity of the ceramic to find its water content, then determining the water potential through the moisture characteristic relationship. Instead of converting the sensor output to dielectric and then water content, correlations are made directly between sensor output and water potential.

Laboratory Calibration and Characterization

1 and 5-bar pressure plates were used to create the moisture characteristic for the WPS. To determine points between 0 and 5 bars, we used a tensiometer for the wet range and a thermocouple psychrometer and a chlled miller hygrometer for the dry range. Sensors were packed into saturated soil on 1 and 5-bar pressure plates and allowed to equilibrate for at least 48 h at a variety of pressures. Two soil textures (sandy loam and silty clay loam) were tested to ensure sensor calibration was constant in differing soil types.
After calibration, sensors were installed in a silt loam together with tensiometers to show relative response time and water potential range. Wheat was grown in the soil under sodium grow lights to simulate field water use conditions.

Sensors were also tested to determine their sensitivity to electrical conductivity. To do this, the ceramic disks were vacuum saturated in solutions with a range of electrical conductivities. Data from the sensors in soils containing different electrical conductivities were not significantly different.

Results and Discussion

A time series of sensor equilibration on a pressure plate over a range of pressures is show in Fig. 1. The stair-step nature of sensor output shows repeated pressure changes and sensor equilibration. Although sensor output did not plateau for more than 24 h in some cases, it is likely that these long equilibration times are due to the equilibration of the entire pressure plate together with the soil and not the sensor themselves.

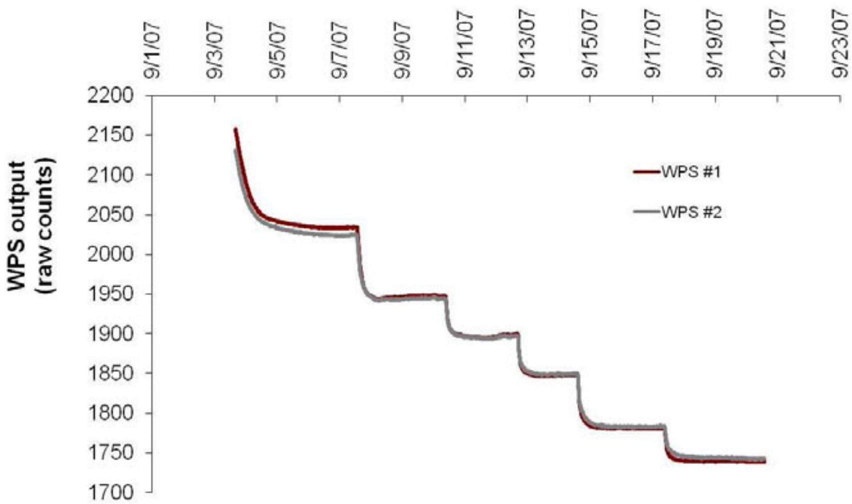

Figure 1. Time-series WPS calibration data collected in silty clay loam soil in 1 bar pressure plate apparatus. Chamber pressure settings are shown at each step.

Sensor calibration data were derived from the equilibrated sensor output at each chamber pressure (see plateau values in Fig. 1). Ideally, the WPS would have the same calibration curve, regardless of soil type. Indeed, Figure 2 (a&b) shows no difference between water potential readings on two different pressure plates and in the two soil types. Especially impressive is the way the calibration lines matchup between the one bar and five bar pressure plates, constituting entirely different measurement systems.

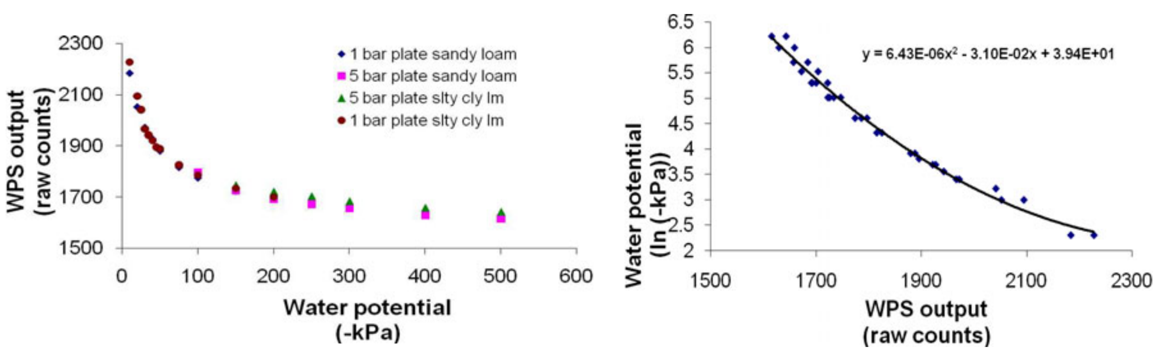

Figure 2. Calibration data collected from the WPS (a) plotted with linear axes and (b) plotted with water potential units in logarithmic increments. The derived calibration function for the semi-log data is shown in the upper right hand corner of Figure 2(b).

Semi-log plots of the calibration data show a quadratic relationship between sensor output and water potential (Figure 2b). The sensors were calibrated from these data, which requires both a natural log transformation and a subsequent quadratic conversion. More importantly, sensor data show high sensitivity in the most important range for actively growing plant, 0 to -100 kPa (1 bar = 100 kPa). However, the data also show the sensor will not measure to complete saturation; it reaches a maximum value at -9 kPa. This maximum is called the air entry potential of the ceramic and represents the potential that water begins to drain from pores in the ceramic matrix. At water potentials closer to zero, the soil will exert a pull on the water to drain the matrix but the binding strength of the ceramic will not allow water to flow out. Although an upper water potential limit closer to zero would be nice, it is not necessary for irrigation control. On the dry end, the WPS will work well down to SWP of approximately -500 kPa. This lower limit is more than adequate for actively growing plants although it does not reach the commonly accepted value for permanent wilting point of -1500 kPa.

Combined WPS and tensiometer data in a silt loam with actively growing wheat are shown in Fig. 3. Data from the WPS agree well across several dry-down events, marking heavy daytime wheat water uptake with steep declines in water potential and nighttime dormancy with plateaus. Response time of the WPS is consistent with the tensiometer, further supporting the hypothesis that long read times in the pressure chamber were due to system and not sensor equilibration. The abrupt end to tensiometer data during the last dry-down was caused by tensiometer cavitation, underscoring the challenges of maintaining that technology in functional condition (Young and Sisson, 2002).

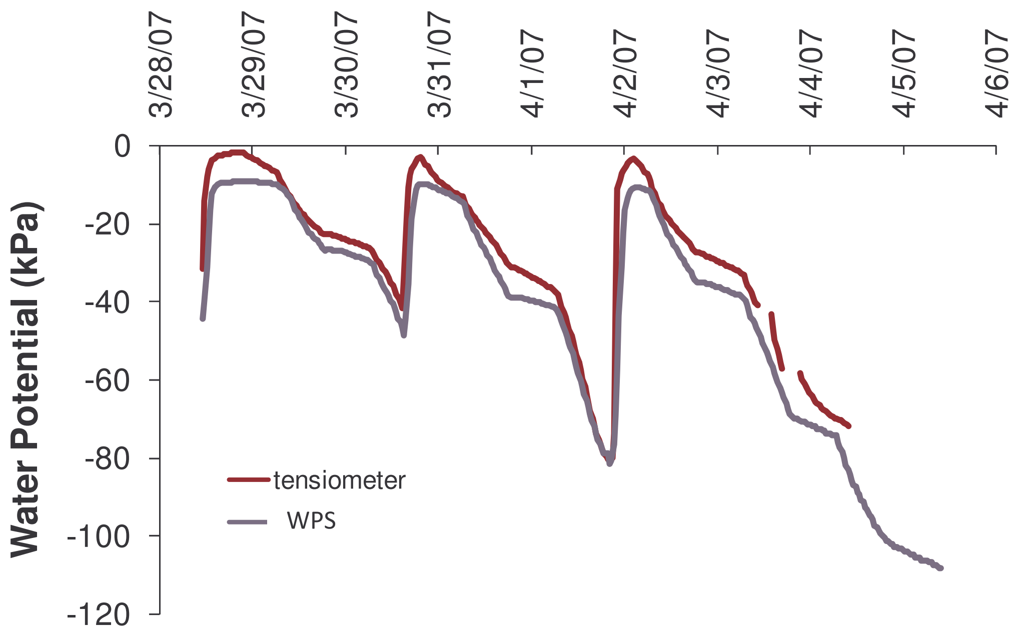

Figure 3. Time-series water potential measured with a calibrated WPS and a tensiometer over several drydown and re-wetting cycles in an agricultural soil under wheat.

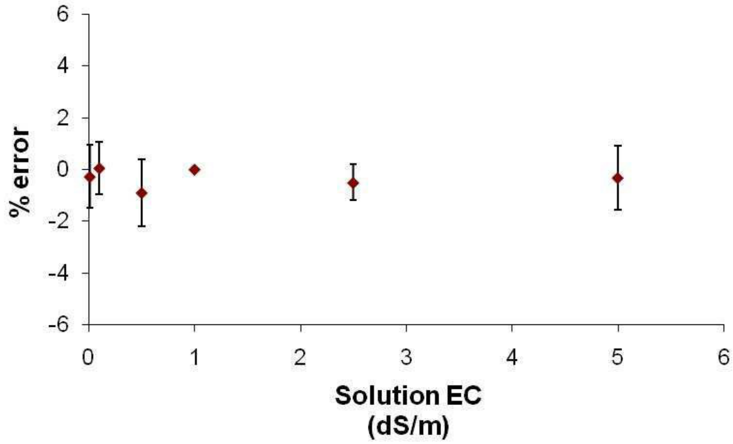

Figure 4. WPS sensitivity to soil solution to electrical conductivity. All values have been normalized to 1 dS/m solution values. Error bars are ±1 standard deviation from a sample of 10 WPS sensors.

Soil salinity did not appear to affect the sensor, changing < 1% over a range of ceramic solution electrical conductivies of 0 to 5 dS m^{-1}. The mechanism for the low sensitivity to salinity is unclear. The sensor's 70 MHz measurement frequency along with its no-contact measurement do reduce salt effects (Kizito et al., 2008). Still, there may be some salinity mitigation from the ceramic as well. With its extensive ability to bind charged ions, the clay ceramic may buffer salt effects by simply binding a portion of the ions in the water, thus reducing their deleterious effects.

Conclusions

The WPS performed well in our tests showing an extensive measurement range, fast equilibration, consistent readings in differing soil types, and low sensitivity to soil salinity. In addition, calibration was consistent between two soil types and with a variety of calibration techniques. Indeed, data suggest that the design objectives for the sensor were met. The broad range of water potential sensitivity will give irrigation controllers complete freedom to use literature values for healthy plants and simply control to an optimum value in the same way thermostats control temperature.

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Flow Conditioning for Irrigation Propeller Meters

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Abstract. McCrometer and the University of Nebraska recently studied the effects of flow conditioning on flow meter accuracy. The results of the study indicate that the incorporation of a flow straightener into the design of an irrigation propeller flow meter provides ±2 percent measurement accuracy while greatly reducing the instrument's typically required straight pipe run.

This advanced propeller flow meter's design reduces the straight pipe run required by up to 80 percent , which greatly reduces pipe material and installation costs for new irrigation well sites. In the retrofitting of existing well sites to add flow meters for the first time, this new meter design also alleviates the problems associated with crowded equipment configurations where adding the meter has often resulted in significant re-layouts at high cost.

Keywords. Agriculture, water, irrigation, flow meter, propeller flow meter, saddle meter, flow conditioning, flow conditioner, flow straightening, flow straightener, pipe straight run, mandatory water metering, measurement accuracy,

Introduction

Water agencies across the United States continue to require water flow meters for new agricultural irrigation well site installations and for existing well sites too. The need to balance the water needs of agriculture, other industries and residential use is driving water conservation as never before.

In agriculture, irrigation scheduling is the application of water to crops only when needed and only in the amounts needed. It involves studying, understanding, applying, then monitoring and controlling necessary instruments such as soil moisture analyzers, rain gauges, and flow meters to assure efficient use of energy and water in crop production. In turn, minimizing the waste of water and supporting water conservation while maximizing crop yields.

Good irrigation scheduling practices include knowing the volume of water applied to each field. Flow meters, when properly selected and installed correctly, accurately measure the water to verify the proper amount was applied. An *accurate* flow meter is essential to good irrigation scheduling practices.

Typical Flow Meters

Flow meters come in all shapes, sizes, and price ranges. Types of irrigation flow meters include: propeller, turbine, magnetic, and insertion. Propeller meters are durable, reliable, easy to install, economical to purchase, and therefore make up the majority of the installed base of irrigation water meters in the US.

The propeller meter consists of a rotating device, a helical-shaped impeller, positioned in the flow stream. When fluid passes through the meter it contacts the impeller causing it to spin. The impeller's rotational velocity is directly proportional to the velocity of the flow.

The impeller's rotation is transmitted through mechanical linkages, which drive a mechanical register that displays both instantaneous and totalized flow. The irrigator can look at his meter register at any given time to collect instantaneous and totalized flow rate data.

Propeller Meter Installation Requirements

To measure flow accurately, the installation of a typical propeller flow meter requires 5 to 10 pipe diameters of straight, unobstructed pipe run upstream from the meter inlet tube. The straight pipe run is necessary to provide a highly uniform liquid flow profile within the pipe that is stable enough for measurement.

Flow meter straight pipe run requirements are expensive in terms of pipe materials, installation labor and maintenance. In retrofit situations where a new flow meter is added to existing equipment, there is often not enough space to accommodate the straight pipe run necessary for accurate flow measurement.

This situation can result in costly redesigns and re-piping of existing sites that is time-consuming and costly.

Flow Conditioning

McCrometer and the University of Nebraska recently studied the effects of flow conditioning on the installation requirements for propeller flow meters. This study was designed to determine if integrating a flow straightener (FS) into the design of a new propeller flow meter would result in accurate flow measurement while significantly reducing the need for straight pipe runs.

The saddle-style propeller meter developed for this study features a patent pending flow straightener to condition water flow. This integrated meter/straightener design is expected to maintain the propeller meter's stated ±2 percent accuracy, while reducing the upstream straight run to 2 pipe diameters and the downstream run to 0 to 1.5 pipe diameters. The saddle-style propeller meter was selected for this test because it is easy to install as both a new and a retrofit device.

Statement of Problem

Irrigation plays a major role in the Nebraska farm economy. There are over 100,000 wells in the state that contribute to approximately 90% of the annual groundwater consumption. In order to practice good irrigation water management, it is important to accurately measure the amount of water being pumped from these irrigation wells. Currently, propeller flow meters are the most common devices used for irrigation water measurement in Nebraska.

When selected and installed correctly, propeller meters can be accurate within ±2 percent of actual flow. To achieve this level of accuracy, the propeller meters must be placed in an "undisturbed flow of water". Undisturbed flow is another way of saying that the velocity profile in the pipe has not been distorted causing swirl, secondary flows, asymmetrical profiles, or symmetrical non-reference profiles.

Propeller meters are designed to measure the flow rate in a full pipe that has an axially symmetrical, non-swirling, and parabolic reference distribution of velocity across the pipe (Figure 1). The flow measurement can be inaccurate when the water entering the metering section has been disturbed and the distribution of velocity across the pipe has been distorted (Figure 2). Apparatus in the pipeline, such as pumps, valves, and elbows, can cause distortions to the velocity profile. In Nebraska, common flow disturbances include pumps, chemigation check valves, and elbows.

One approach to obtain accurate water measurement in the vicinity of flow disturbances is to place the flow meter far enough downstream from the flow disturbance so that the water nearly returns to the normal expected velocity pattern, i.e., a fully developed velocity profile, before it enters the metering section. To achieve the desired pattern it is recommended that there be at least 10 pipe diameters (10D) of straight blank pipe between the disturbance and the metering section. However for many cases in the field there was not enough space built into the piping system to allow for the recommended 10D of distance. Thus, when retrofitting existing irrigation systems, the piping system must be altered significantly so that adequate distance is made available for metering. Since these alterations can be expensive it would be beneficial to the irrigation industry if the space requirements could be reduced.

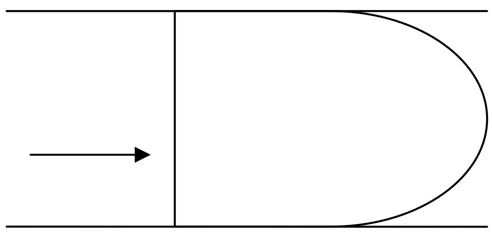

Figure 1. Symmetric-parabolic velocity distribution.

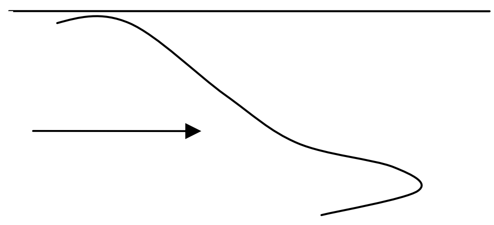

Figure 2. Distorted velocity distribution.

The use of flow conditioners is one approach for reducing the required distance of straight blank pipe. Straightening vanes are a common type of flow conditioner. McCrometer, Inc. uses a 6-vane arrangement for this purpose. McCrometer, Inc. recently developed a new flow conditioning and straightening device, the Mc SpaceSaver™ Flow Meter.

Project Objective

The objective of this project was to determine the impact of the flow straightener (FS) on the metering accuracy of propeller meters in the presence of flow disturbances. The flow disturbances considered were two elbows out of plane, vertical turbine pumps, and vertical turbine pumps equipped with a spring-loaded swing check valve.

Procedures

The project was conducted in the Biological Systems Engineering Water Hydraulics lab located in L. W. Chase Hall, University of Nebraska-Lincoln. A venturi flow meter system served as the standard for flow rate comparisons. The venturi size used for an individual test was based on flow rate. Flow rates less than 700 gpm were measured with a 6-inch venturi and flow rates greater than 700 gpm were measured with a 10-inch venturi. Our experience indicates that the venturi system measures flow within 1-2 percent of actual flow.

A redundancy meter, a McCrometer propeller meter, S/N 80-8-555, was used to verify the quality of the venturi data. The meter used in the test section, herein called the test meter, was a 6-inch McCrometer meter, Model Number MO 306-

675, S/N 07-06548-06. The meter was mounted in a 20 inch long metering section with flanged fittings. The flow straightener (FS), a McCrometer FS106-2, was mounted in a 12 inch long flanged spool. The spool length was considered as part to the straight pipe length between flow disturbances and the metering section. All distance measurements were taken from the downstream flange of each disturbance to the tip of the propeller. The piping used in all conditions was flanged 6-inch nominal Schedule 40 PVC pipe with an inside diameter of 6.065 inches.

The various testing conditions are shown in Tables 1 and 2. In addition, a baseline test was performed on the test meter. The baseline test was conducted with 32D of straight blank pipe located between a standard vane and the metering section.

The two elbows out of plane configuration is shown in Figure 3 and the vertical turbine pump and check valve is shown in Figure 4.

The volume totalizer of the test meter was timed with a stop watch for flow rate calculation. The timing period was for approximately three minutes. Each test was replicated three times.

Table 1. Two elbows out-of-plane test conditions.

Factors
Two flow conditioners – none and FS
Three distances – 2D, 4D, and 8D
Four nominal flow rates – 250, 550, 900, and 1200 gpm

Table 2. Vertical turbine pump test conditions.

Factors
Two flow conditioners – none and FS
Three distances – 2D, 4D, and 8D
Two check valve conditions – none and chemigation check valve
Two flow rates – 250 and 550 gpm

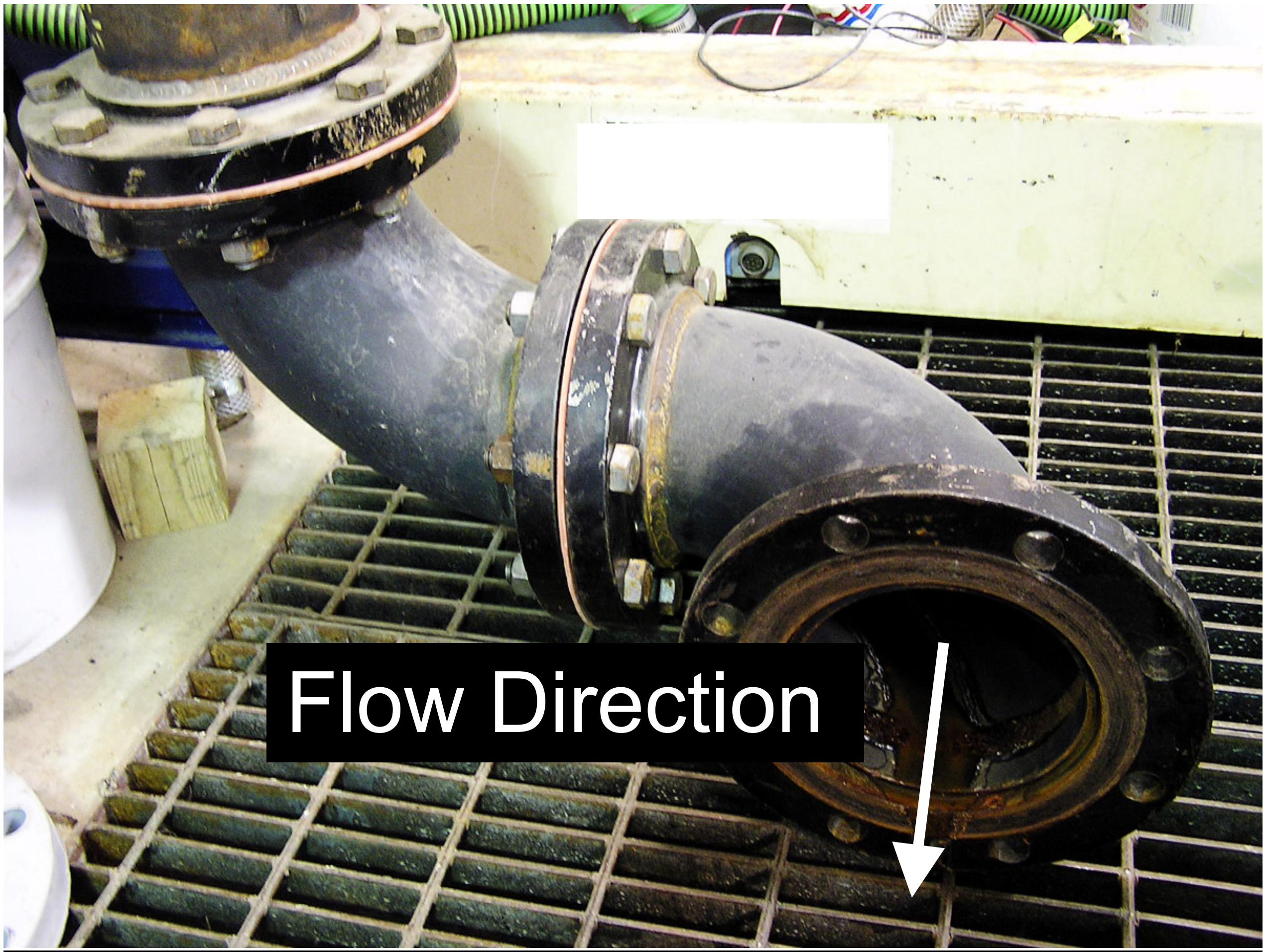

Figure 3. Two elbows out-of-plane configuration.

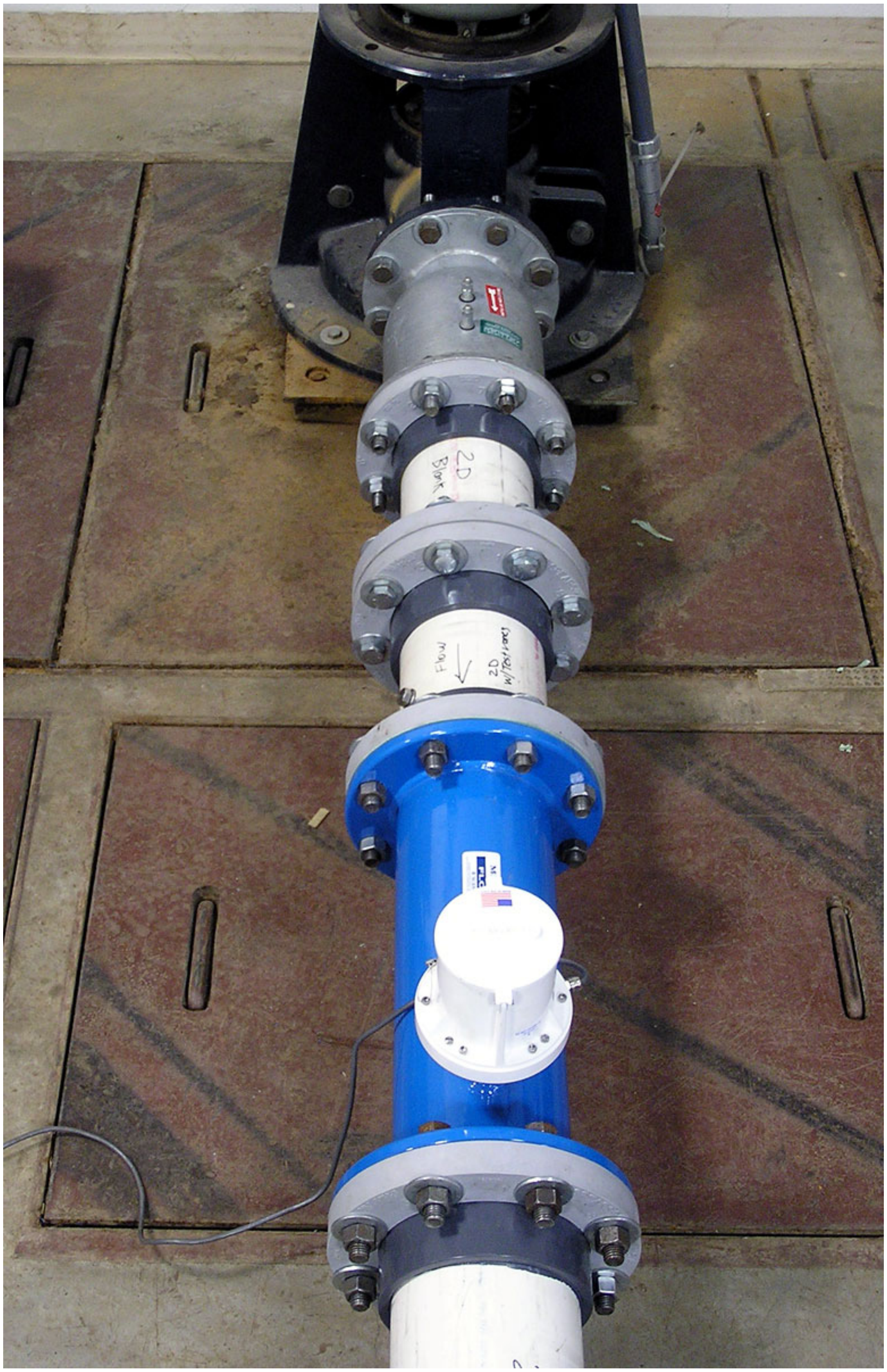

Figure 4. Vertical turbine pump with check valve configuration.

Results

The test results are summarized in Table 3 and are presented graphically in Figures 5-14. Actual flow rates were always very near to the planned nominal flow rates with all flows being within 20 gpm of planned and with the majority being within 5 gpm of planned. The metering accuracy or uncertainty was quantified by the flow ratio, the ratio of the test meter flow rate divided by the laboratory standard flow rate. A flow ratio of 0.98 indicates that the test meter registered 2 percent lower than the laboratory standard.

All data, except for the baseline test data, have been corrected for meter measurement bias, i.e., the baseline data were used to correct the test meter flow rates. The meter measurement bias is based on the difference between the test meter flow rate and the laboratory standard flow rate that was observed in the baseline test. It is caused by a combination of the laboratory standard bias and the test meter bias.

The test data were corrected for meter measurement bias by dividing the observed test meter flow rate by 0.98, the mean flow ratio of the baseline tests. The confidence intervals presented on the graphs are 95 percent intervals. The 95 percent confidence intervals were calculated by multiplying the standard deviation of the data by two and then adding and subtracting this number from the mean of the three replications. When calculated over all of the tests, the flow ratio of the laboratory redundancy meter (McCrometer S/N 80-8-555) was 1.00 with a range of 0.985-1.015 confirming that experimental errors did not lead to erroneous laboratory standard data.

Table 3. Summary of flow ratio results (data corrected for meter measurement bias detected in the baseline test).

	--- Flow Ratio---		
Flow Condition	Mean	Range[2]	Standard Dev.[3]
Baseline without vane @ meter	0.980	0.967-0.993	0.004
Two elbows, 2PD, w/o FS	0.892	0.879-0.899	0.010
Two elbows, 2PD, w/FS	0.984	0.972-0.989	0.003
Two elbows, 4PD, w/o FS	0.895	0.882-0.902	0.005
Two elbows, 4PD, w/FS	0.981	0.970-0.987	0.003
Two elbows, 8PD, w/o FS	0.904	0.891-0.908	0.005
Two elbows, 8PD, w/FS	0.982	0.969-0.988	0.003
Pump, no check valve, 2PD, w/o	0.954	0.949-0.959	0.004
Pump, no check valve, 2PD,	0.978	0.971-0.985	0.002
Pump, no check valve, 4PD, w/o	0.964	0.960-0.968	0.002
Pump, no check valve, 4PD,	0.981	0.974-0.988	0.001
Pump, no check valve, 8PD, w/o	0.973	0.971-0.975	0.004
Pump, no check valve, 8PD,	0.983	0.975-0.990	0.002
Pump, check valve, 2PD, w/o	0.937	0.920-0.954	0.004
Pump, check valve, 2PD, w/FS	0.980	0.978-0.982	0.002
Pump, check valve, 4PD, w/o	0.945	0.930-0.959	0.003
Pump, check valve, 4PD, w/FS	0.981	0.973-0.989	0.002
Pump, check valve, 8PD, w/o	0.951	0.943-0.959	0.002
Pump, check valve, 8PD, w/FS	0.981	0.975-0.987	0.002

[1]Mean flow ratio over all flow rates
[2]Range of the mean flow ratios for each flow rate
[3]Mean standard deviation over all flow rates

Baseline Tests

The results of the baseline tests are shown in Figure 5. The mean flow ratios varied from 0.967-0.993 with a mean of 0.980. As was true with many of the tests where the flow had been conditioned in this project, the lowest flow ratio occurred at the nominal flow rate of 550 gpm.

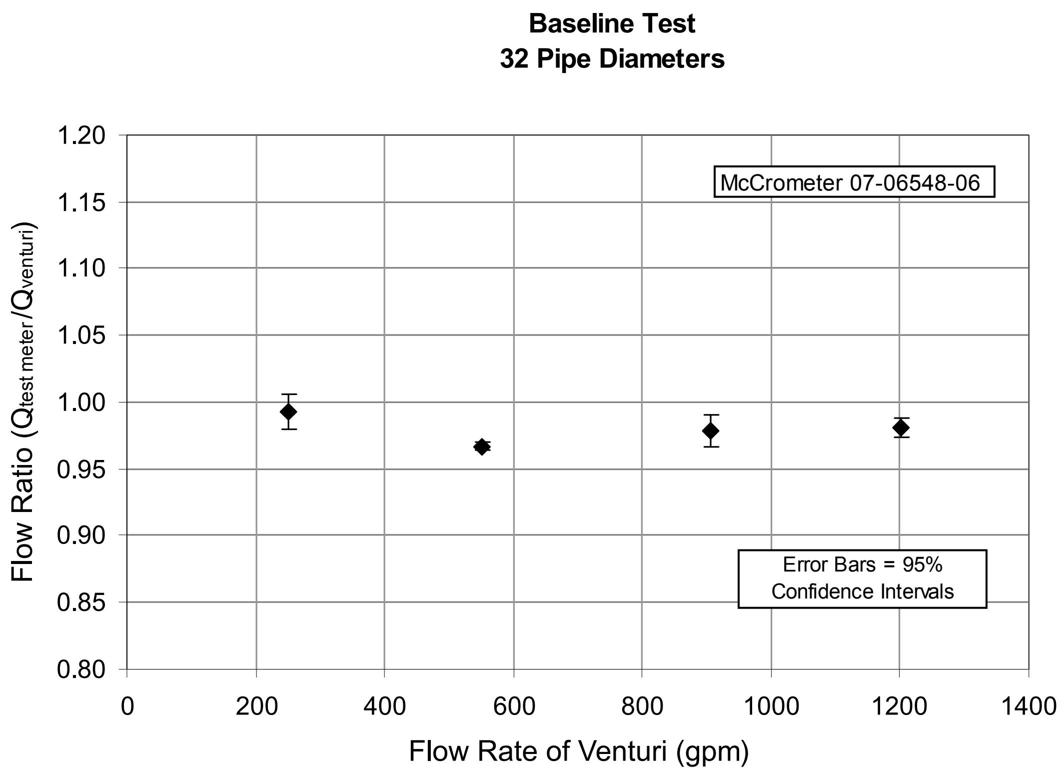

Figure 5. Flow ratios in relation to flow rate for baseline tests (data not corrected for directional meter bias).

Two Elbows Out-of-Plane

The two elbows out-of-plane results are shown in Figures 6, 7, and 8. The data shown have been corrected for the meter measurement bias. The two elbows out-of-plane was the disturbance that cased the most inaccuracy in flow measurement in our tests. Measured flow averaged about 11 percent low 2PD downstream of the elbows. At 8PD the meter still registered over 10 percent low. The FS significantly improved the metering accuracy with measured flows being within about 2 percent of the laboratory standard for all three straight pipe distances upstream. As can be noted by the error bars and the standard deviation data presented in Table 3, the FS greatly reduced the variability in the data.

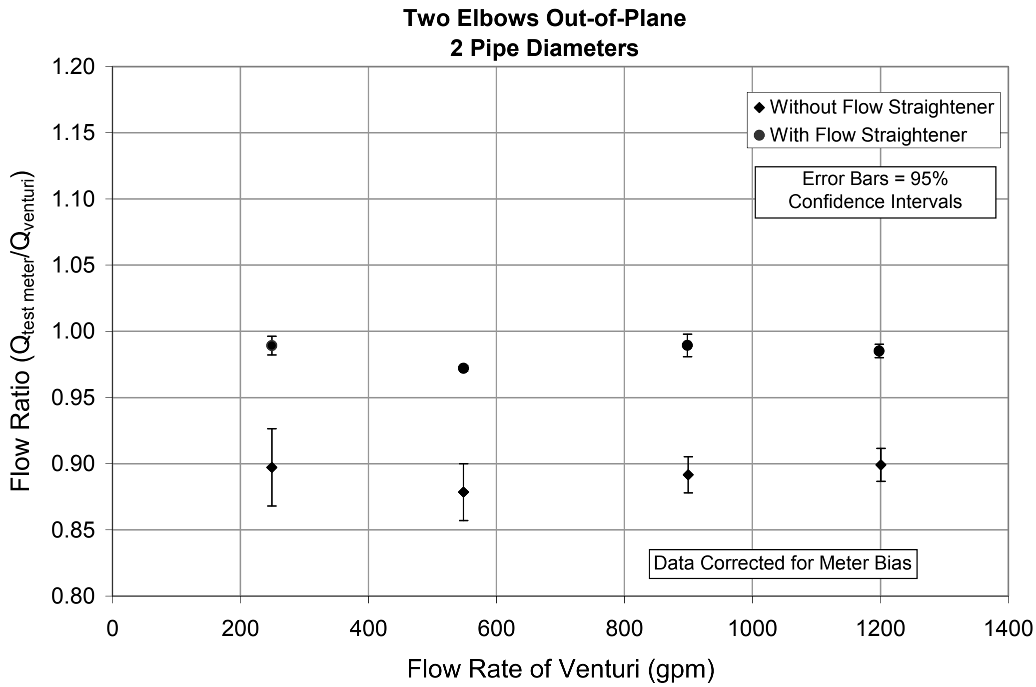

Figure 6. Flow ratios in relation to flow rate for two elbows out-of-plane, 2 PD upstream straight pipe (data corrected for meter measurement bias).

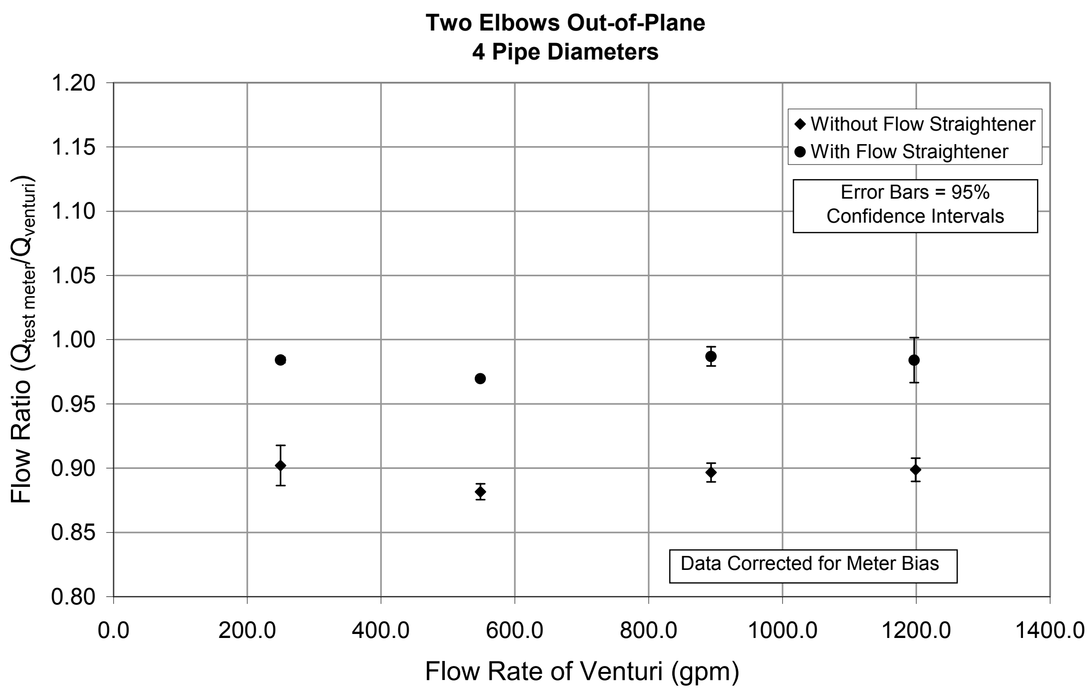

Figure 7. Flow ratios in relation to flow rate for two elbows out-of-plane, 4 PD upstream straight pipe (data corrected for meter measurement bias).

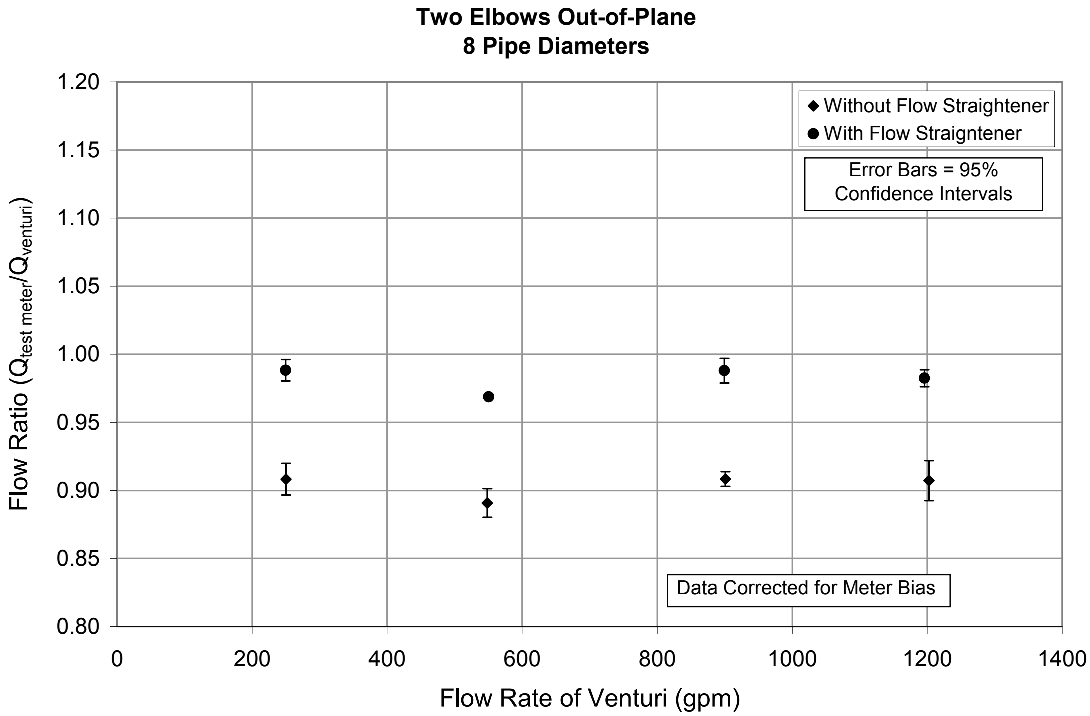

Figure 8. Flow ratios in relation to flow rate for two elbows out-of-plane, 8 PD upstream straight pipe (data corrected for meter measurement bias).

Vertical Turbine Pump/Check Valve Combinations

The results for the vertical turbine pump without the check valve are shown in Figures 9-11. Without flow conditioning the measured flow averaged between 2.7 and 4.6 percent low relative to the laboratory standard. The FS conditioned flow averaged 2.2, 1.9, and 1.7 percent low for the 2PD, 4PD, and 8PD of straight upstream pipe, respectively. Conditioning the flow with the FS reduced the standard deviation by approximately 50% for these tests.

When the spring-loaded check valve was in place downstream of the pump discharge and upstream of the test meter, the metered flow averaged 6.3, 5.5, and 4.9 percent lower than the laboratory standard for the 2PD, 4PD, and 8PD straight pipe upstream distances respectively. These inaccuracies were reduced to about 2 percent low by use of the FS. As was the case for the other tests, in general the variability in the data was also reduced by the FS as indicated by the reduction of the standard deviation.

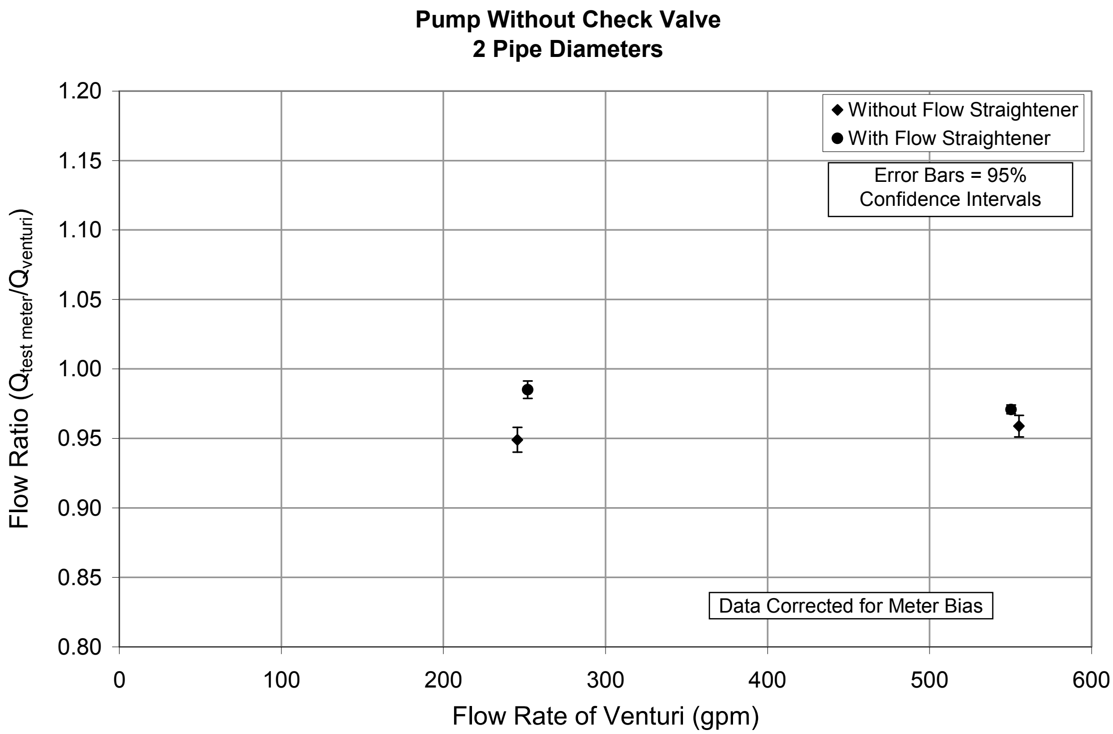

Figure 9. Flow ratios in relation to flow rate for vertical turbine pump without check valve, 2 PD upstream straight pipe (data corrected for meter measurement bias).

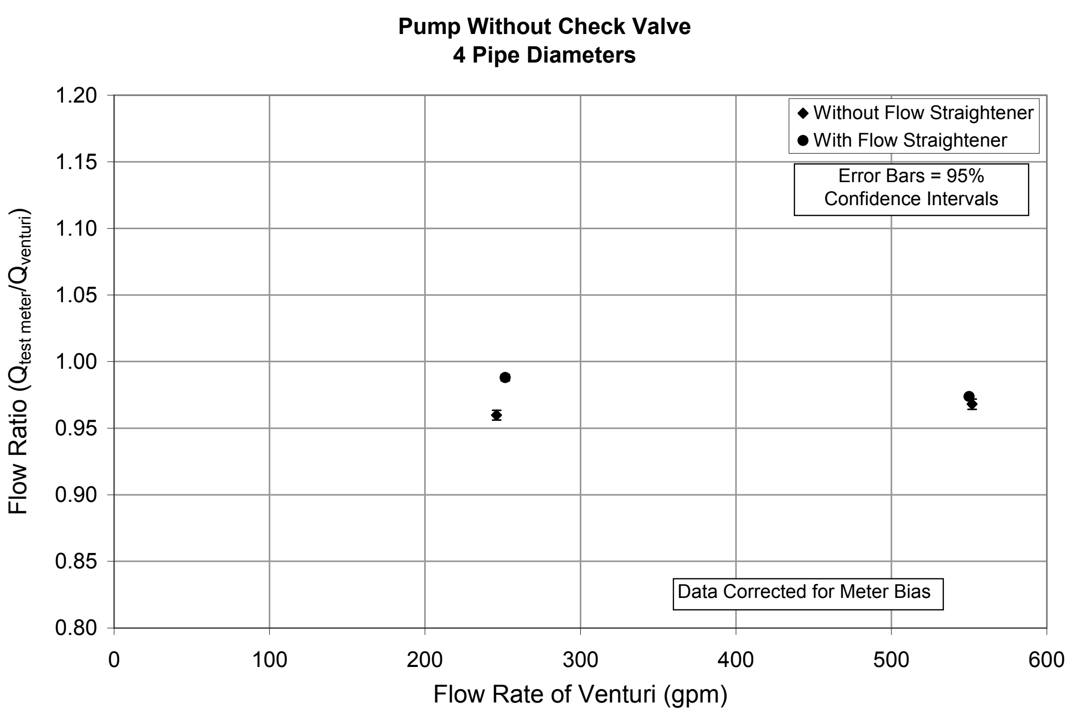

Figure 10. Flow ratios in relation to flow rate for vertical turbine pump without check valve, 4 PD upstream straight pipe (data corrected for meter measurement bias).

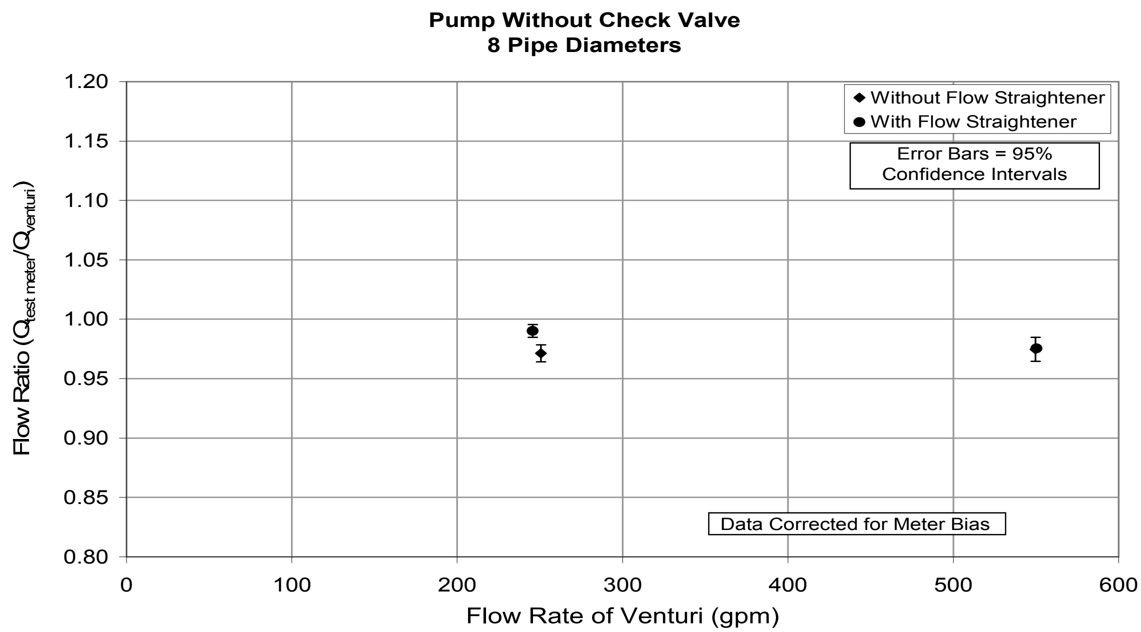

Figure 11. Flow ratios in relation to flow rate for vertical turbine pump without check valve, 8 PD upstream straight pipe (data corrected for meter measurement bias).

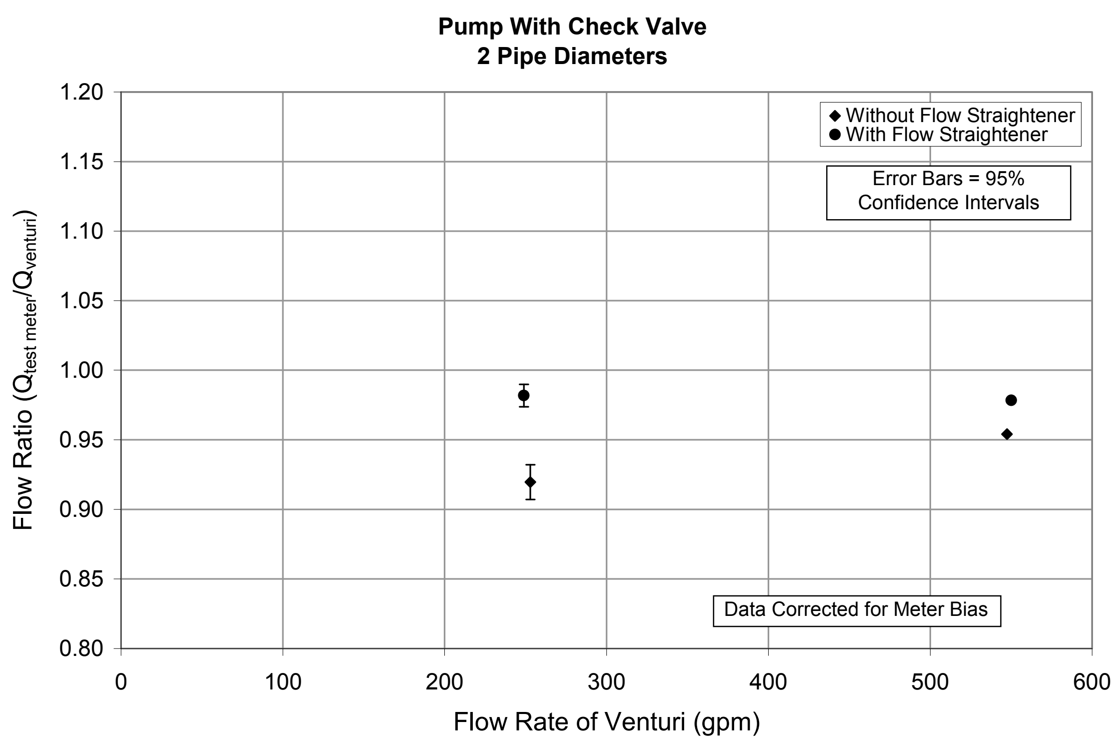

Figure 12. Flow ratios in relation to flow rate for vertical turbine pump with check valve, 2 PD upstream straight pipe (data corrected for meter measurement bias).

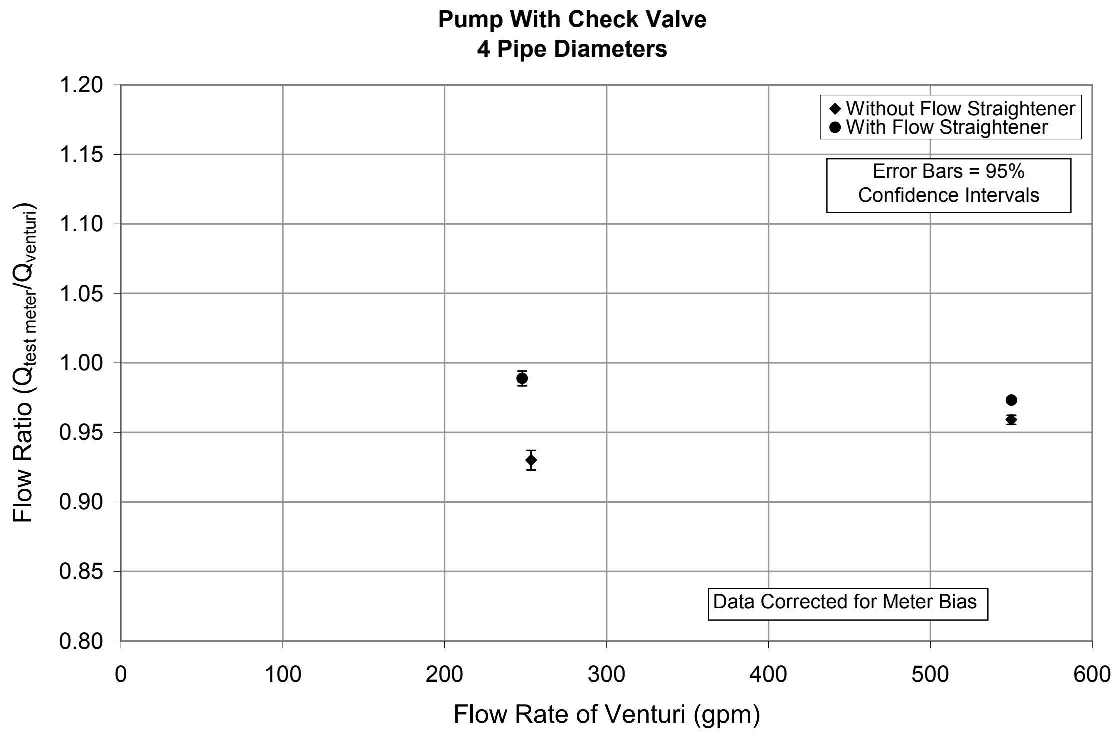

Figure 13. Flow ratios in relation to flow rate for vertical turbine pump with check valve, 4 PD upstream straight pipe (data corrected for meter measurement bias).

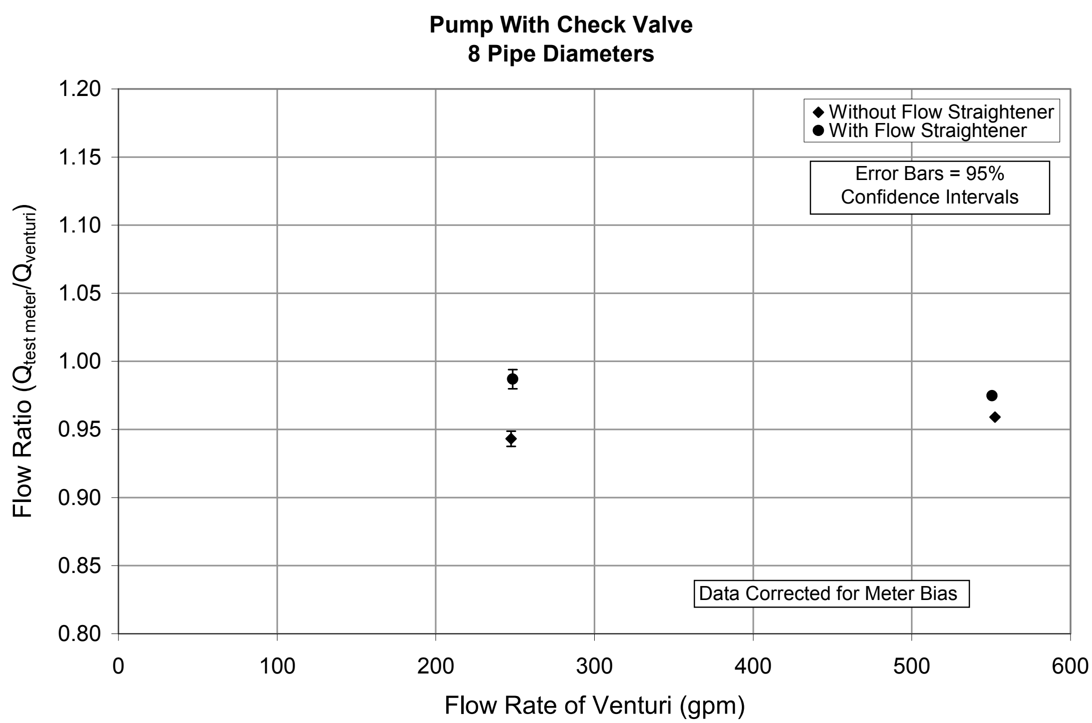

Figure 14. Flow ratios in relation to flow rate for vertical turbine pump with check valve, 8 PD upstream straight pipe (data corrected for meter measurement bias).

Conclusions

The objective of this project was to determine the impact of the McCrometer SpaceSaver Flow Straightener (FS) on the metering accuracy of propeller meters in the presence of flow disturbances. The flow disturbances considered were two elbows out of plane, vertical turbine pumps, and vertical turbine pumps equipped with a spring-loaded swing check valve.

In total, 34 tests, replicated three times, were conducted in the Hydraulics Laboratory of Biological Systems Engineering, University of Nebraska, Lincoln. All data were collected in 6-inch PVC pipelines. A venturi system was used as the laboratory standard for comparison. Measurement uncertainty was corrected for meter measurement bias. While the flow disturbances caused average uncertainties as high as 10.8 percent low, the FS conditioned the flow so that mean measured flow was within 2.2 percent of actual flow in all cases.

New inexpensive dendrometers for monitoring crop tree growth

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Abstract

A fast-responding dendrometer is needed for measuring tree growth responses (daily or hourly) to drought, fertilization stress and other stresses. This study reports on operational comparisons between new, inexpensive automatic point and band contact dendrometers. Eighteen point and five band dendrometers were installed on pecan tree trunks and branches during the 2005 growing season, and their performance and measurements were compared by analyzing data downloaded weekly. Data indicated that the point dendrometer was accurate. However, band dendrometers may underestimate tree growth (average measured value by a band dendrometer was half that measured by the point dendrometers), and they may not be able to measure the hourly diameter change of small-diameter branches over several days. Point dendrometers were found to be suitable for large-scale tree growth measurements and water and fertilizer stress monitoring due to their fast response (hourly or faster), ease of construction and installation, and low expense (<$40 each).

Keywords: Automatic, Branch, Dendrometer, Pecan, Point Dendrometer, Trunk, Radial Growth.

Introduction

Dendrometers have been used to measure the change in growth of forest trees (Clark et al., 2000) and fruit trees, notably apples (Link et al., 1998) and peaches (Goldhamer et al., 1999). Dendrometers measure the change in the diameter and growth of a tree. Clark et al. (2000) presented a complete review of the literature on dendrometer types and uses in forestry research and management. There are two categories of dendrometers: contact and noncontact. Contact dendrometers contact the stem physically to measure the diameter of a branch/trunk. A diameter tape (a kind of contact dendrometer) can measure the diameter of a trunk/branch by circling around the trunk/branch surface, assuming the trunk/branch shape is round. Contact dendrometers include calipers, dial gauges, diameter tapes, the Biltmore stick, sector forks, and the Samoan stick (Jackson, 1911; Brown et al., 1947; Tryon and Finn, 1949; Bower and Blocker, 1966; Dixon, 1973; Matérn, 1990; Keeland, 1993; Costella, 1995; Link et al., 1998; Goldhamer et al., 1999; Bitterlich, 1998).

Noncontact dendrometers can obtain measurements remotely. Optical dendrometers are the most commonly used noncontact dendrometers (Clark, 1913; Wheeler, 1962; Eller and Keister, 1979; Robbins and Young, 1968; McClure, 1969; Williams et al., 1999; Parker and Matney, 1999). An optical caliper uses two parallel lines of light to view points on a stem that represent the diameter. The distance between the two lines, which can be measured by a ruler on the optical dendrometer, is the diameter (Clark et al., 2000).

Noncontact dendrometers can be more efficient than contact dendrometers with a 35 to 40% time savings, and their diameter measurements are comparable in accuracy to measurements by calipers and diameter tapes (Binot et al., 1995). Data measured by non-contact dendrometers can be directly downloaded to a computer (Binot et al., 1995). Automated contact point and band dendrometers are also commercially available. However, instruments cost around $650, which limits the number that can be installed on a tree to measure branch growth (Agricultural Electronics Corporation, 2003).

Most dendrometers, except the automated ones, are “slow-responding” instruments, because they are typically used to measure tree growth monthly or yearly. To observe growth responses on an hourly or daily cycle (e.g., the responses to water and fertilizer stresses), a fast-responding electronic dendrometer is needed; and at least two sensors/branch must be installed and replicated three to four times (Andales et al., 2006). The minimum cost would be $20,800 to measure 4 trees, 4 branches per tree, with 2 dendrometers per branch, using commercially available automated fast-responding dendrometers. Consequently, there is a need for low-cost automated contact point or band dendrometers.

Point dendrometers have been criticized for being inaccurate compared to band dendrometers—a point dendrometer can only measure a point diameter growth, while measurements from band dendrometers represent an average of all diameters over all directions (Avery and Burkhart, 1994; Clark et al., 2000). Therefore, multiple point dendrometers are needed for branch/trunk growth measurements. In addition, an automatic point dendrometer is often installed with the LVDT or a linear potentiometer holder (LVDT: linear variable differential transformer) anchored to a measuring branch with two long anchor screws (Andales et al., 2006), so the LVDT or potentiometer will not move as the branch/trunk grows. Band dendrometers do not have this measurement problem; however, an LVDT/potentiometer band dendrometer must be held to the branch with a constant spring tension that allows the band to expand as growth occurs. If the interest is in measuring the expansion and contraction of the trunk diameter throughout the day in response to moisture stress, a band dendrometer may not be sensitive enough because a spring must contract the band, and to accomplish this contraction the spring force must overcome the force of friction as the trunk shrinks.

The objectives of this study were to design inexpensive automatic fast-responding point and band dendrometers and to compare the performance of these two systems to data found in the literature.

Materials and methods

Design

Automatic band dendrometer

The automatic band dendrometer consists of several parts, including a linear potentiometer sensor, stainless steel hose clamps, bolts and nuts, an aluminum channel, and a stainless steel spring (Figure 1). The potentiometer sensor is a Model 9605 BEI made by Duncan Electronics (http://www.beiduncan.com/html/products/linear/mini_sensors.htm). Clamps, bolts, nuts, and aluminum channel can be purchased from a local hardware store. The spring (model: LE 026 C 11s) can be ordered from Lee’s Spring Company (http://www.leespring.com/). The hose screw can be used to adjust the dendrometer perimeter to fit different branches and trunks.

The BEI 9605 sensor (Figure 2) gives a linear electrical response that can be converted to linear distance (e.g., diameter growth) when connected to a CR23X or a CR10X datalogger (Campbell Scientific, Inc., Logan, Utah) or to any data logger with the capability of measuring a half bridge circuit.

The 9605 sensor must be wired as shown in Figure 2 or the response curve will be non-linear. The sensor is a linear sliding resistor with terminal 2 connected to the resistor slider (plunger). Terminals 3 and 1 are connected to the resistor's end points. A datalogger measures the voltage (V1) between terminals 2 and 3 and the voltage (Vx) between terminals 1 and 3. The ratio of the resistance between 3 and 2 to the resistance between 1 and 3 is linearly related to the ratio of the length between 2 and 3 to the whole length between 1 and 3. From the ratio of V1 to Vx, the physical position of terminal 2 (plunger position) on the resistor can be determined. Consequently, the change in plunger length can be used to measure change in growth of the tree. The AC half bridge (P5) instruction set for the Campbell CR10X or CR23X is used in the data logger program to record the output from the sensor. Instruction P5 has eight parameters that need to be specified in the program. Appendix 1 shows an example program for a CR10X. Note that if more than one sensor is connected to the data logger, parameter 4 (excitation channel number) must be set to increment by 1 so that the excitation source can be rotated among the three available E (excitation) channels for consecutive sensors.

If two sensors per trunk (or per branch) are installed, a 6-wire cable (e.g, Belden Part No. 9745, 22 AWG, unshielded) can be used to connect the sensor to the data logger. However, a 3-wire cable also can be used to connect the dendrometer to the data logger (e.g., Belden Part No. 8443, 22 AWG, unshielded). Wire lead length should be less than 116 m in order to get accurate measurements of the change in resistance. Longer wire lengths can be used, but calibration should be done with the leads connected to the sensor to account for the connection wire resistance.

Construction of a band dendrometer requires two hose clamps (Figure 3, a, b and c). Each clamp perimeter should be longer than the half length of a branch perimeter to be measured. The clamps need to be unscrewed and then connected together (Figure 3, b and c). The screw at the open end is removed so that the other band end can go through the hole (Figure 3, d), and a new screw is inserted and held by a nut (Figure 3, e and f). The screw and nuts should leave some space around the band so that the band can freely move (Figure 3, f). The BEI 9605 is held in an aluminum channel segment which is held on the freely moving band end by two stainless screws (Figure 3, g and h). Appropriate holes on the aluminum channel are drilled and threaded before attaching the BEI 9605 sensor. The thread can be made directly by the screws instead of using threading tools since the aluminum is softer than the steel screw. One side of the spring is connected into the freely moving band end and the other side is connected into an appropriate point of the band (Figure 3, i). The spring choice was based on work by Keeland and Young (2007), who found that a spring length of 76.2 cm (3 inch), outside spring diameter of 6.35 mm (0.25 inch), and wire diameter of 0.66 mm (0.026 inch) work very well for band dendrometers. These springs provide an initial tension of 1.48 N (0.333 lb), a rate of 0.087 N/mm (0.5 lb/inch), and a maximum extension of 190.5 mm (7.5 inch).

Automatic point dendrometer

To build a point dendrometer, the BEI 9605 sensor is mounted in a 25.4 mm C–clamp (available at local hardware stores) that holds the 9605 sensor in place against the trunk or branch of the pecan tree (Figure 4). (We conducted intensive experiments on pecan tree water use [evapotranspiration] and growth; these dendrometers were initially used to measure pecan tree growth. However, in this paper, we report the dendrometers' design and comparison. These dendrometers can be used for other trees as well). Two holes are drilled at opposite sides of the clamp for the 100 mm hanger bolts. Two nuts on each bolt fix the clamp. Pre-drilling the trunk/branch for the two bolts is required to reduce resistance when driving the bolts into the wood. The BEI 9605 sensor is relatively inexpensive ($25), so the total cost for an automatic dendrometer (point and band) will be below $40.

Calibration of the 9605 linear position sensor

The 9605 sensor output V1/Vx ratio, which ranges from 0 to 1.0, is converted into the y-value (length of sensor, mm) using a linear calibration regression equation (Figure 5). The slope of the equation is the change rate of the sensor length to the variation of V1/Vx. When using new sensors, at least three sensors should be tested to verify that the same linear calibration equation can be used for all the sensors. The 9605 sensor attached to a CR10X or CR23X is easily calibrated using a digital caliper and viewing the response (V1/Vx) at various sensor lengths using Loggernet software (Campbell Scientific, Inc., Logan, Utah) or similar data acquisition software. One can also use a battery (e.g., AAA) to provide voltage to Vx and measure the V1 variation with a multimeter. Because of the inner structure of the sensor, the resistance between terminals 1 and 3 may vary when one changes the plunger length; therefore, measuring the resistance variation with plunger length across terminals 2 and 3 and then using the ratio of this resistance to a constant resistance across terminals 1 and 3 to infer V1/Vx may not obtain the true variation and is not recommended. The change of the sensor length over a specified time interval gives the measured linear growth of the radius (point dendrometer) or perimeter (band dendrometer) of the trunk or branch.

Thermal expansion and contraction—sensor resolution

For the point dendrometer, the thermal expansion/contraction variation of the bolt in the diameter direction will affect the diameter measurement. Steel has a thermal expansion rate of 1.2×10^{-5} °C^{-1} (Pesonen et al., 2004). The steel expansion rate was used for the point dendrometer thermal expansion correction. The length of the bolt was 100 mm. The bolt expansion/contraction was therefore 1.2×10^{-3} mm °C^{-1}. For this study, the measured annual diameter growth ranged from 0.47 mm to 7.1 mm. The annual growth measurement by the point dendrometers used data taken in the afternoon at 14:00. The temperature difference at 14:00 between day 87 (the beginning day of the growth calculation) and day 354 (the end day) was 10°C (temperature data were obtained from weather.nmsu.edu). Therefore, the thermal effect was about 0.012 mm for the annual point growth measurement, which appeared to be negligible compared to annual radial growth (>1 mm per year). However, for hourly growth measurement, thermal effects may be relatively large (e.g., 0.01 mm, because daily temperature change can be 10°C or more) in relation to the daily fluctuation (<0.05 mm per day) in radial growth. Therefore, the thermal correction must be made when using the point dendrometer for hourly measurements.

The thermal correction of the band dendrometer is related to the band effective length (the perimeter of the trunk/branch). The trunk/branch diameters ranged from 85.7 mm to 354.0 mm. The trunk/branch perimeters ranged from 269.1 mm to 1111.6 mm. Therefore, the thermal effect was about 0.13 mm for the annual growth measurement based on the expansion rate of

1.2×10^{-5} °C^{-1} (Pesonen et al., 2004), which is negligible compared to annual radial growth (>1 mm per year). However, for hourly growth measurement, thermal effects may be relatively large (e.g., 0.01 mm, because daily temperature change can be 10°C or more) in relation to the daily fluctuation (<0.05 mm per day) in radial growth. Therefore, the band dendrometers require thermal correction for daily measurements.

The working temperature limit of the BEI 9605 sensor is -40°C to 135°C. The published linear accuracy is 98%, i.e., the error will be 0.02 mm for a 1 mm measurement and 0.001 mm for a 0.05 mm measurement. The major specifications of the sensor are shown in Table 1. More detailed specifications can be found in the user manual (BEI Duncan Electronics, 2004). Sensor resolution (the shortest distance that the sensor can detect) was not provided in the manual. From the data measured in the study, the resolution of the sensor was estimated to be better than 0.01 mm (Figure 6).

Experiments

Dendrometer calibration

The BEI 9605 sensors may have different calibration slopes when new and after they are used for a certain period. Therefore, V1/Vx variation with sensor length was measured for five new sensors (randomly selected) and for five randomly selected sensors having been used for one year. Because the sensors had different lot numbers, V1/Vx variation with sensor length for five sensors from a second lot and three sensors from a third lot (only three sensors from the latter lot were available) were also measured.

Tree growth measurements

Dendrometer measurements

To compare point and band dendrometers, eighteen point dendrometers and five band dendrometers were constructed with BEI 9605 sensors from lot numbers 04-43, 3302, and 3362 and installed on four pecan trees at a 5.1-ha orchard south of Las Cruces, NM (N32° 16′ 34.37″, W -106° 49′ 4.14″) in March 2005 when the trees were dormant. The orchard was planted in 1970 at 10.0 m by 10.0 m tree spacing. In 2005, the average orchard height was 12 m and trees had a 0.3-m average DBH (diameter at breast height; the average diameter [outside the bark] of a tree 4.5 feet [1.35 m] above mean ground level.) The soil was a Harkey loam (coarse-silty, mixed, calcareous, thermic typic Torrifluvents). The farmer applied 320 kg ha^{-1} of nitrogen through the irrigation system throughout the growing season. The orchard was flood-irrigated from two wells; the water was discharged into the orchard through a high-flow turnout. Sparling Propeller flow meters (Sparling Instruments, Inc., CA) were installed on the pumps to measure irrigation amounts. Daily precipitation and hourly temperature were measured at the Leyendecker Plant Science Center Weather Station (N32° 12′ 3.89″, W -106° 44′ 33.0″), located 3.1 km from our experimental site, and the data are available from the New Mexico Climate Center Website (http://weather.nmsu.edu).

The dendrometer measurements were collected with a CR23X data logger. The sampling frequency was 1 hour. Measurements continued from March 28, 2005 (Julian day 87) through January 14, 2006 (Julian day 14). The trees broke dormancy in early April, 2005.

The dendrometers were installed on trunks, primary branches and secondary branches (the installation position and branch and trunk diameters are provided in Table 2). The band dendrometers were installed near (~1 cm) the corresponding point dendrometers.

Manual measurements

To check the dendrometer accuracy, the core samples of annual rings were taken at the corresponding dendrometer measurement locations using a borer tool (5-mm inside diameter, Suunto, Finland) in April 2008. For each trunk/branch, 4 core samples were taken, of which 1 or 2 samples corresponded to the point dendrometer measurement points (Table 2). Then the width (annual radial growth) of the 2005 annual ring on each core sample was measured using an electronic caliper (Model No. CD-6" CS, Mitutoyo Corp, Japan).

Data analysis

Calibration slopes

A calibration slope was obtained for each sensor from the V1/Vx and sensor length change data using a linear regression method (Figure 5). The slope and constant in a regression equation were evaluated using T tests to see if they were statistically significant. One-way ANOVA (analysis of variance) was used to test if the calibration slopes were different for new sensors, old sensors, and sensors from different lots.

Tree growth measured by dendrometers

Dendrometer measurements were converted to length using the average of all the calibration slopes, which were statistically similar (Table 3). The point and band dendrometer measurements were corrected for thermal effects (see the section *Thermal expansion and contraction and sensor resolution*). The temperature at the beginning of the growth season was used as the base temperature. Each length measurement then had subtracted from it the product of 1.2×10^{-2} mm $^{\circ}C^{-1}$ and the temperature variation (ºC) (the difference between the current and the base temperature). The length change (Lband for band dendrometers, Lpoint for point dendrometers, mm) during the growing season (from 14:00 day 87 to 14:00 day 354) was calculated. The Lband value measured by band dendrometers was divided by Pi (3.14) to obtain the diameter growth, and the resultant value was divided by 2 for comparison with the point dendrometer L point value, which was the radius growth.

Dendrometer accuracy

The annual radius growth measured by dendrometers was compared with the manual measurement. The point dendrometer measurements were divided into three groups: trunk, primary branch and secondary branch (Table 2). In each group, the radius growth data were used in one-way ANOVA analyses to test if the difference between measurements from point and manual measurement was significant. The Minitab (2000) statistical software package was used for all the statistical analyses.

For the accuracy analysis of band dendrometer measurements, the mean of each 4 manual measurements of radial growth on the corresponding branch/trunk was calculated. (The manually measured data were not available for the secondary branch on tree 2 [diameter =10.1 cm, Table 2] because the branch was removed by the farmer before 2008.) Then, all the measurements of annual radial growth (branch/trunk diameter ranged from 198.1 mm to 330 mm) by band dendrometers were compared to the manually measured means by one-way ANOVA.

In addition, the time series (daily and yearly durations) of band and point measurements were plotted against each other.

Results and Discussion

Calibration slopes

Good fits were obtained in the regression calibrations (see the sample calibration in Figure 5) (R^2>0.99, T>260, P<0.0001). The calibration slopes were statistically similar (F=0.63, P=0.605, and Table 3) for the three different categories of BEI 9605 sensors: new, old, and different lots. The average slope was 12.643 mm. The 95% confidence interval was 12.576 mm to 12.709 mm. Therefore, if the average slope (12.643 mm) is used, the possible error obtainable from the slope calibration would be within ±0.066 mm for the full scale (V1/Vx=1) and the relative error would be ±0.066 mm /12.643 mm (the full scale) = ±0.5%. To use these sensors to measure tree growth, several sensors (e.g., five in this study) would be enough to represent calibration for all sensors.

Daily measurements

Figure 6 shows the hourly measurements of point and band dendrometers in nine days (days 217 to 226). Branch or trunk growth usually occurred from sunset through morning, with peak growth occurring during the morning from around 7 a.m. to 12 p.m. From afternoon to sunset, the diameter of the tree shrank due to increased evapotranspiration drawing some water from the stems (Génard et al., 2001; Pesonen et al., 2004).

Band dendrometers were more sensitive to the hourly changes of trunks (dendrometer 9 in Figure 6) and larger branches (dendrometer 13 in Figure 6) than to changes in smaller branches (dendrometer 8 in Figure 6), because trunks and larger branches may undergo larger changes than do smaller branches over that period (Table 3).

Point dendrometers had different responses on different points of the trunk or branch (dendrometers 11 and 12 in Figure 6) because the radial change of each point was different. Point dendrometers can be sensitive to the radial changes of smaller branches (dendrometers 11 and 12 in Figure 6). Multiple (at least two) point dendrometers are required to measure growth of a branch/trunk accurately, which is feasible with a low-cost dendrometer.

Seasonal measurements

Figure 7 shows the seasonal radius growth measured by point and band dendrometers. The tree branch and trunk grew from day 87 to around day 260 (September 17). After day 260, the trunk and branches did not show significant growth. During wintertime (day 354, 2005 to day 14, 2006), the diameters of trunk and branches shrank because the trees had not been irrigated since day 276.

There are large oscillations shown in the graphs from days 149 to 272. This is the tree response to an irrigation cycle (compared with irrigation, precipitation provided a small amount of water). When irrigation occurred, branches and trunks started to grow and kept growing for about 7 days; then the diameters shrank as the trees experienced water stress.

Point dendrometer measurements may have large magnitude variations (point dendrometers 11, 12, and 20 in Figure 7), and point dendrometers on different points of a trunk or branch may give different measurements. However, band dendrometers always measure relatively smooth curves because the measurement represents an average of all diameters over all directions, eliminating variability caused by direction (Clark et al., 2000).

Dendrometer accuracy

Point dendrometer measurements were statically the same as the manually measured data (Table 4; all the one-way ANOVA P values were larger than 0.05). The annual radial growth measured manually and by point dendrometers was reasonable compared with data in Nelson et al. (1965), who found the average 10-year radius growth of unmanaged pecan (DBH= 150.2 mm to 304.8 mm) in the northeast Louisiana Delta to be 24.13 mm, i.e., an average annual radius growth of about 2.413 mm. The DBH of our measured trunk ranged from 295.4 mm to 354.0 mm and the average radius growth in 2005 was 2.50 mm (manual measurements, n=16) and 2.79 mm (n=5, measured by dendrometer) (Tables 3 and 4). The diameters of primary branches ranged from 198.1 mm to 273.4 mm and the average radius growth was 2.28 mm (manual) and 2.36 mm (dendrometer). The diameter of secondary branches ranged from 101.1 mm to 152.8 mm and the average radius growth was 1.70 mm (manual) and 1.64 mm (dendrometer).

However, the band dendrometer's measurement was significantly different than manual measurements (Table 4, F= 10.6, $P<0.05$). The measurements from band dendrometers (Table 4, mean=1.40 mm) were 42% lower than the manual measurements (mean=2.42 mm).

The underestimate of band dendrometer measurements may be caused by the slack between the band and the branch/trunk surface. Although the spring on the band forces the band tightly against the trunk/branch surface, the band may not touch the surface seamlessly, and this may cause some slack. If this is true, it is important to consider that measurements in the literature taken by automated band dendrometers may underestimate tree growth.

Further observations

The BEI 9605 sensor should not be held tightly by the screws and clamps; otherwise the plunger will not be able to move freely. The plunger should be evaluated after installation to ensure that it can move freely.

Thermal correction needs to be done for the point and band dendrometer measurements, especially for hourly measurements. The temperature data at a local weather station can be used for the correction, but onsite temperature data would be preferable.

Dendrometers can be installed in remote areas, but sometimes that makes it difficult to travel frequently to the site. It is possible to set up remote access using a local telephone line or a wireless phone line to connect to the datalogger (www.campbellsci.com). Even so, because the sensors may be affected by small animals and other environmental factors, routine physical checks would be required.

Conclusions

The high accuracy, fast response, ease of fabrication and installation, and low cost of automated point contact dendrometers make them suitable for tree growth measurements and for water and fertilizer stress monitoring. Multiple point dendrometers should be installed when making branch/trunk diameter growth measurements because the radial change at each point will be different. Band dendrometers underestimate tree growth, and they may not be able to measure the hourly diameter change of small-diameter branches (e.g., 10.1 cm in this study for pecan trees) over several days. Our data indicates that researchers should be careful when using growth data in the literature if measurements were obtained using automated band dendrometers.

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Appendix 1: A sample program (Instruction 5 setting) for a Campbell CR10X data logger to read the 9605 sensor.

Parameter	Setting	Note
01	4	Reps (i.e., 4 sensors connected to the logger)
02	15	2500 mV Fast Range (The voltage and scanning code for the readings)
03	1	First SE channel (i.e., 1st sensor is connected to single-ended channel 1, 2nd sensor connected to SE 2, 3rd sensor connected to SE 3, 4th sensor connected to SE 4)
04	11	Excitation begins at E1 and is incremented by 1 (i.e., E1 excites sensor 1, E2 excites sensor 2, E3 excites sensor 3, E1 excites sensor 4)
05	2500	mV Excitation voltage
06	1	Input (memory) location number for first measurement
07	1	Multiplier (This may be set to the slope of the calibration line)
08	0	Offset (This may be set to the y-intercept of the calibration line)

Table 1. Specification of 9605 sensor.

Total Electrical Travel (A) mm (inches)	12.7 (0.50)
Active Electrical Travel mm (inches)	10.0 (0.40)
Linearity Over Active Electrical Travel	± 2%
Mechanical Life	2,000,000 Full Cycles
Actuation Force Newtons (oz.)	4.0 (14.4) Maximum, supplied with internal spring to return actuator to extended position.
Temperature Limits °C	-40 to 135

Table 2. Dendrometer placement on pecan trees in the pecan orchard, and other trunk/branch parameters.

Tree No.	Trunk/branch information and dendrometer type	Sensor number and placement					
		Trunk		Primary Branch		Secondary Branch	
		SE*	NW	SE	NW	SE	NW
1	Trunk or branch diameter (mm)	327.6		218.4		85.7	
	Point dendrometer No.	#1	#2	#3	#4		#6
	Measured annual radius growth by the sensor† (mm)	3.57	2.85	2.87	0.57		1.3
	Band dendrometer No.			#5			
	Annual radius growth measured by the sensor† (mm)			0.88			
	Annual radius growth measured manually‡ (mm)	3.77	2.75	2.70	1.57	1.76	1.79
2	Trunk or branch diameter (mm)	354.0		198.1		101.1	
	Point dendrometer No.	#7			#10	#11	#12
	Measured annual radius growth by the sensor (mm)	1.54			0.91	0.24	0.23
	Band dendrometer No.	#9				#8	
	Annual radius growth measured by the sensor (mm)	1.39				0.33	
	Annual radius growth measured manually (mm)	1.72	1.93	2.2	1.31	N/A§	N/A
3	Trunk or branch diameter (mm)	295.4		273.4		152.8	
	Point dendrometer No.		#14	#15	#16	#17	#18
	Measured annual radius growth by the sensor (mm)		2.85	4.29	N/A	1.17	2.21
	Band dendrometer No.			#13			
	Annual radius growth measured by the sensor (mm)			1.8			
	Annual radius growth measured manually (mm)	2.26	2.75	3.48	2.08	1.47	2.01
4	Trunk or branch diameter (mm)	330.0		254.8		141.6	
	Point dendrometer No.	#19	#20		#22	#23	
	Measured annual radius growth by the sensor (mm)	3.28	N/A		3.16	1.88	
	Band dendrometer No.	#21					
	Annual radius growth measured by the sensor (mm)	1.56					
	Annual radius growth measured manually (mm)	3.13	2.78	3.21	3.33	1.83	1.39

*: SE = southeast side; NW = northwest side.

†: the growth during day 87 (March 28) to day 354 (December 20) in 2005.

‡: annual ring width in 2005

§: N/A: not available. Datalogger channel for dendrometer 16 had problems and did not record the data. Dendrometer 20 had outliers after day 188 and the annual radius growth could not be calculated.

Table 3. Mean and standard deviation (Std.) of annual radius growth (during day 87 [March 28] to day 354 [December 20] in 2005) for pecan tree trunk and branches measured by point and band dendrometers and measured manually.

	Automatic point dendrometer	Automatic band dendrometer	Measured manually
Trunk or branch diameter range	Mean/Std.	Mean/Std.	Mean/Std.
mm	mm	mm	mm
Trunk 295.4-330.0	2.818 / 0.776, n=5 [(a)]	1.475 / 0.120, n=2	2.50 / 0.71, n=16
Primary branch 198.1-273.4	2.36 / 1.576, n=5	1.340 / 0.257, n=2	2.28 / 0.69, n=16
Secondary branch 85.7-152.8	1.172 / 0.8187, n=6	0.330 / N/A[(b)], n=1	1.70 /0.20, n=12

[a]: n: sample number;
[b]: N/A: not available.

Table 4. One-way ANOVA test results for radius growth measured by point and band dendrometers vs. the corresponding manual measurements.

Dendrometer type	Point			Band
Branch diameter range (mm)	295.4-330	198.1-273.4	85.7-152.8	198.1-330
Sample number (n)	5	5	4	4
ANOVA F/P values	0.02/0.89	0.02/0.89	0.24/0.64	10.6/0.02
Mean radius growth (dendrometer vs. manual) (mm)	2.79/2.85	2.36/2.48	1.64/1.77	1.40/2.42

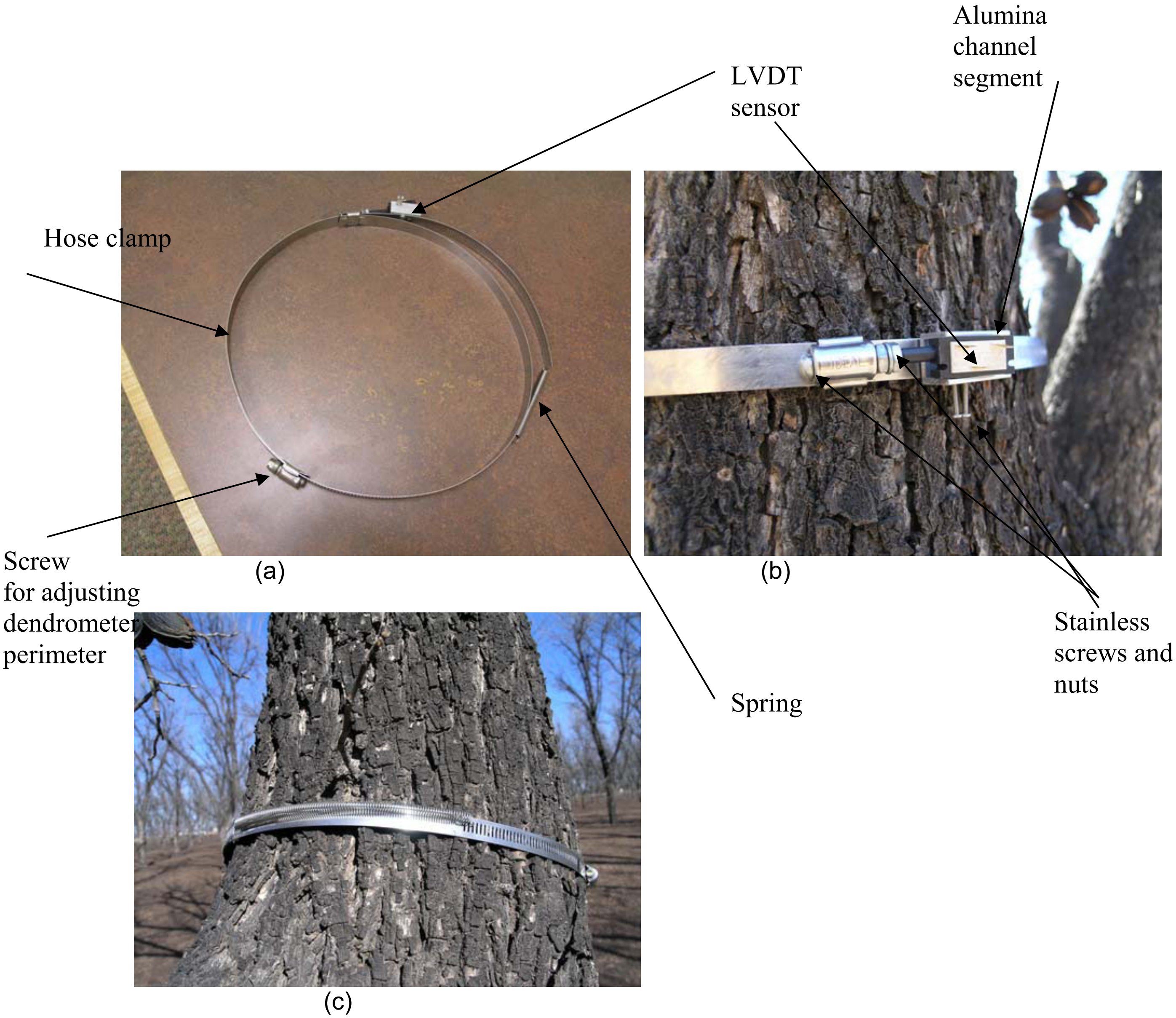

Figure1. A sample automatic band dendrometer. (a) a band dendrometer before installation; (b) the LVDT sensor side view after installation; (c) the spring side view after installation.

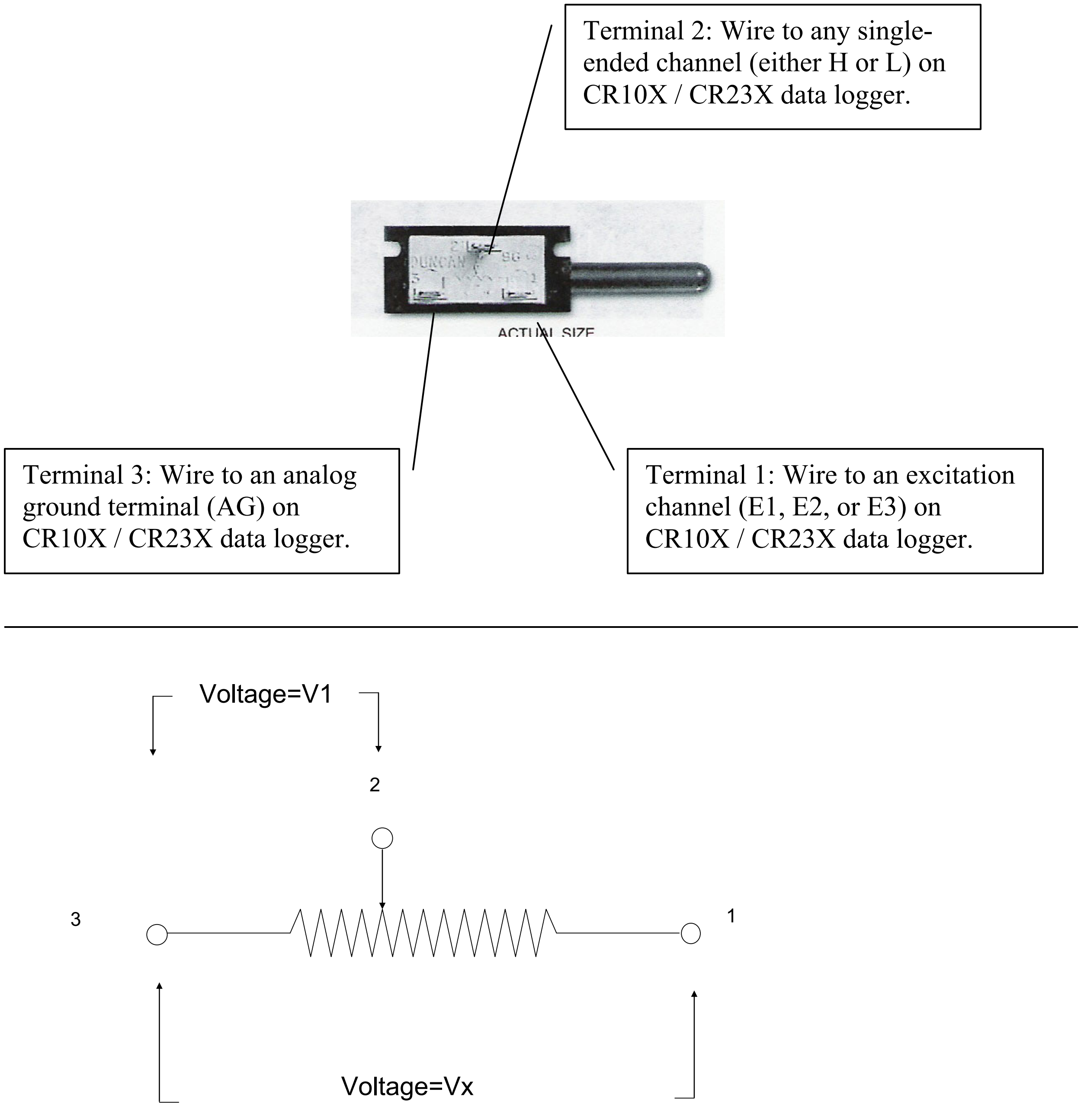

Figure 2. Wiring Diagram of a BEI 9605 linear motion position sensor to a CR10X or CR23X datalogger. Above: the sensor; bottom: the circuit diagram.

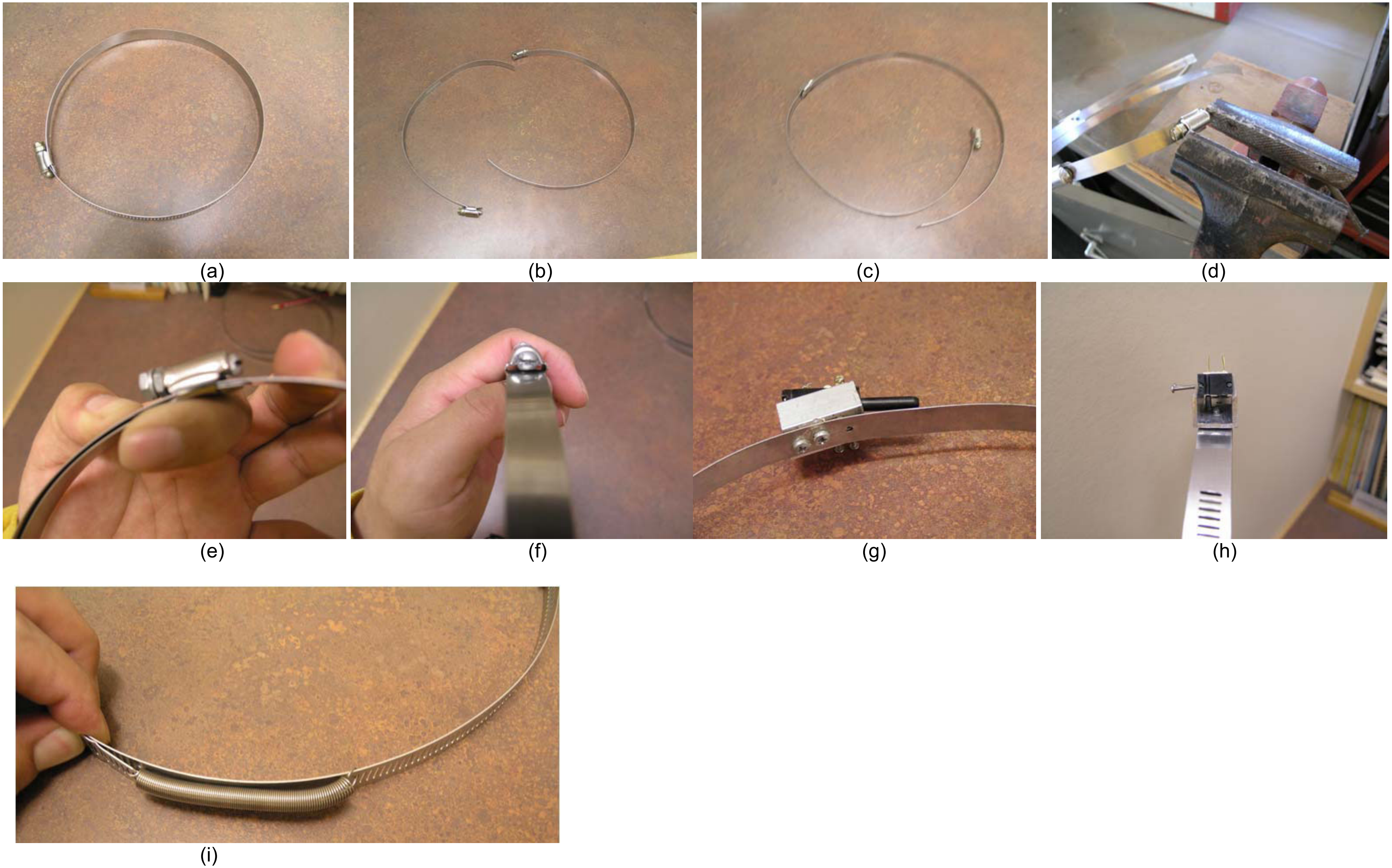

Figure 3. Automatic band dendrometer construction. (a) original hose clamp; (b) two unscrewed clamps; (c) two clamps are connected together; (d), (e), (f) replace the original screw (at the open end of the two connected clamps) with a smaller screw and insert the other camp band end into the hole; (g), (h) hold the sensor in a aluminum channel segment which is held on the freely moving inserted clamp end; (g) the bottom view; (h) one side view; (i) plug one side of the spring into the freely moving band end and the other side into an appropriate position of the band.

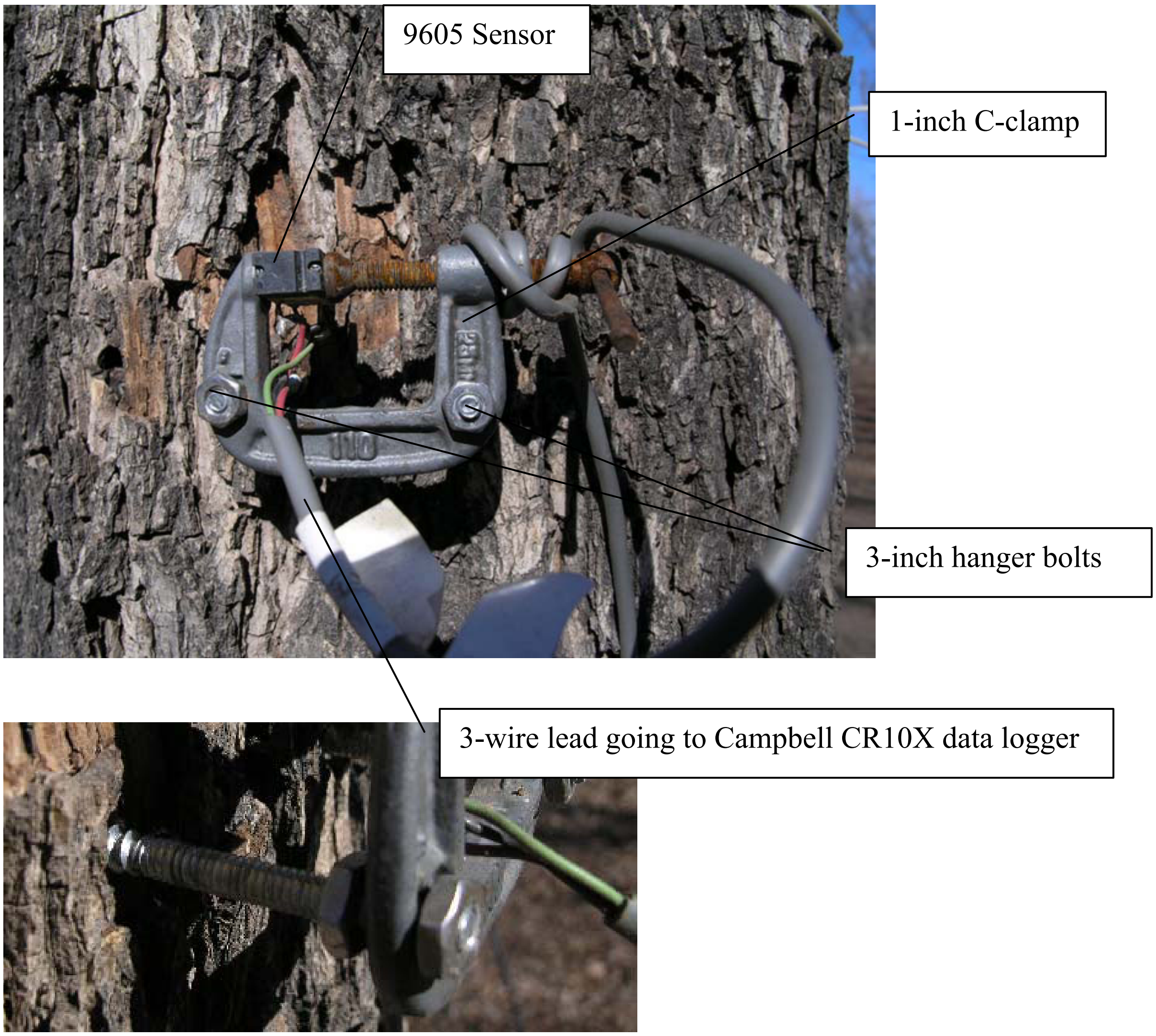

Figure 4. Mounting a 9605 sensor to a pecan branch. Top figure: the general mounting; bottom figure: the mounting bolt.

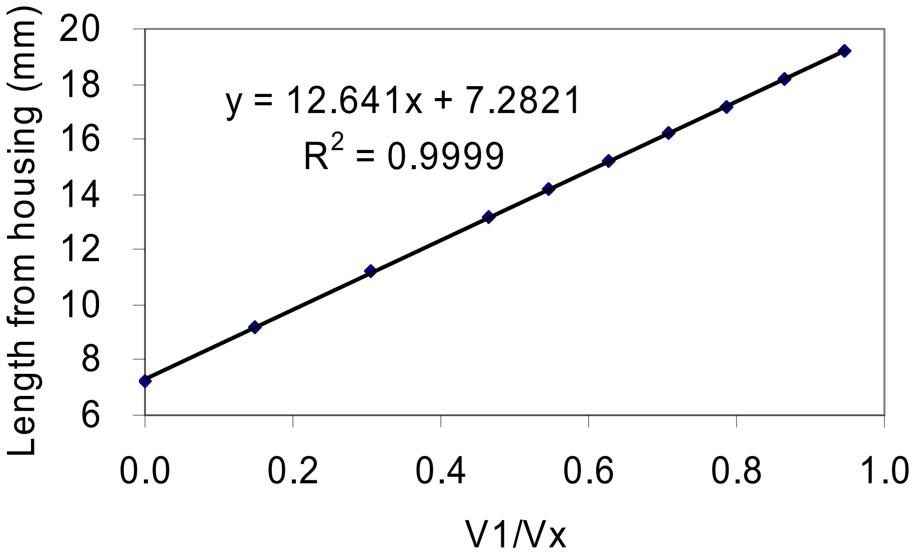

Figure 5. The linear response of a BEI 9605 sensor to change in length of the sensor. V1/Vx is the is the ratio of the voltage across terminals 2 and 3 to that across terminals 1 and 3 of the 9605 sensors (see Figure 2 for the terminals). 'Length from housing' refers to the sensor plunger length outside of the sensor box.

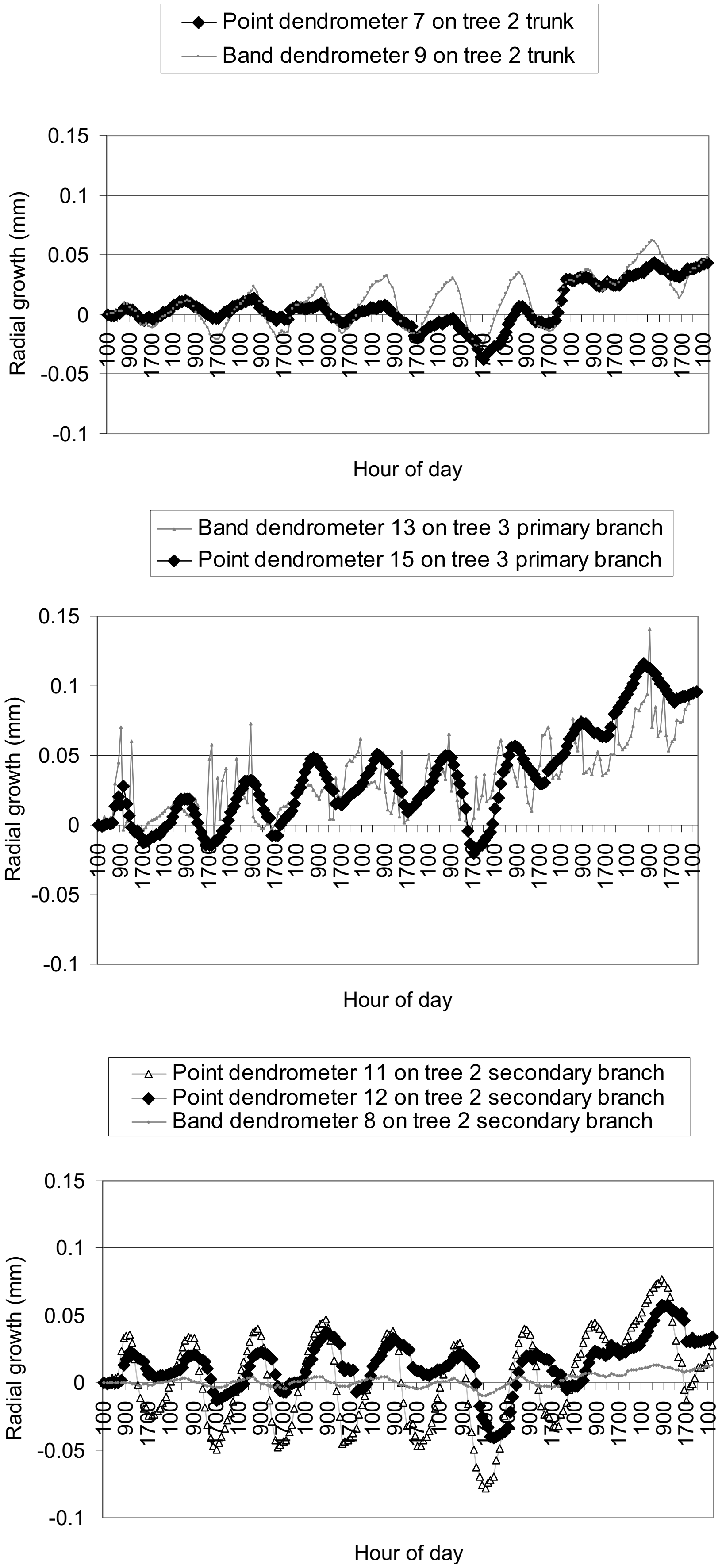

Figure 6. Hourly measurements of automatic point and band dendrometers during day 217 to day 226. Top figure: for tree 2 trunk (diameter=35.4 cm); middle figure:for tree 3 primary branch (diameter=27.3 cm); bottom figure: for tree 2 secondary branch (diameter=10.1 cm).

```
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level        N      Mean     StDev  --+---------+---------+---------+----
New 04-43    5    12.625     0.058     (----------*----------)
Old 04-43    5    12.593     0.124  (----------*----------)
Old 3362     3    12.726     0.081          (-------------*--------------)
Old 3302     5    12.660     0.211        (----------*----------)
                                    --+---------+---------+---------+----
Pooled StDev =     0.138          12.48     12.60     12.72     12.84
```

Figure 7. The mean, standard deviations (StDev), and confidence intervals (CIs) of calibration slopes (mm) for new and old BEI 9605 sensors (used for one year). The lot numbers are: 04-43, 3362, and 3302.

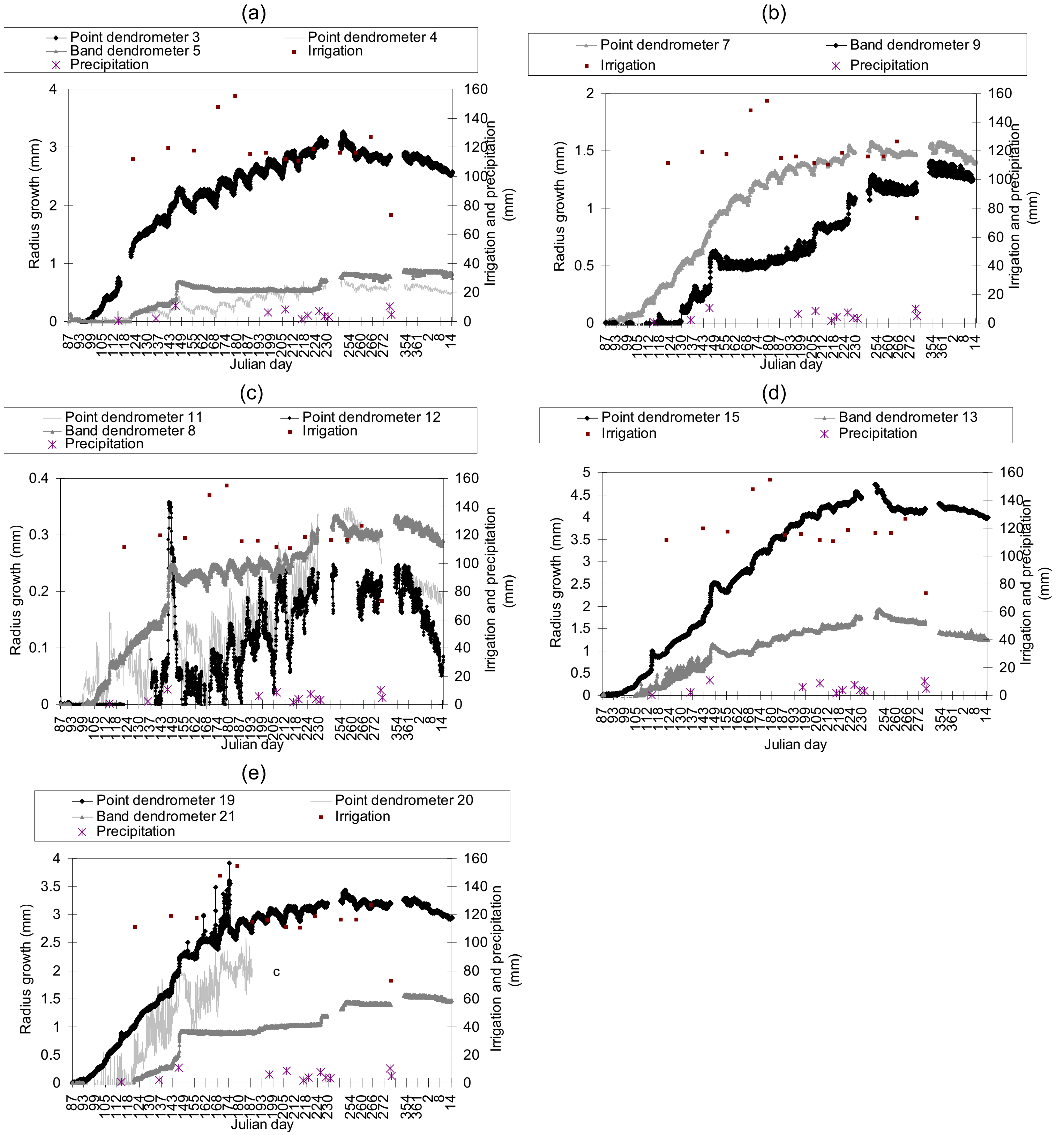

Figure 8. Measurements of selected point and band dendrometers of : (a) tree 1 primary branch (diameter=21.8 cm); (b) tree 2 trunk (diameter=35.4 cm); (c) tree 2 secondary branch (diameter=10.1 cm); (d) tree 3 secondary branch (diameter=27.3 cm); (e) tree 4 trunk (diameter=33.0 cm). Irrigation and daily precipitation were shown on the figure (daily precipitation amount smaller than 1 mm was not shown). The period was from day 87 of 2005 to day 14 of 2006. There were missed dendrometer data from day 231 to day 249 and from day 276 to day 353 because of datalogger power failures. Point dendrometer 20 had outliers (had negative 2-mm growth after day 188 because the transducer was tilted upward; the outliers are not shown on the figure).

Soil Water Repellency – Influence on Irrigated Apple Productivity

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Abstract. Soil water repellency (SWR) deleteriously influences soil hydrological properties, yet few reports on consequences to crop yield and quality exist. With global concerns on drought and water availability and the projected impacts of climate change, development of novel strategies to optimize efficient rootzone delivery of water are required. It is the objective of this study to utilize surfactant treatment to increase soil water content and wetting front depth in a precision irrigated, Goulburn clay loam soil in Victoria, AU, as a means of estimating potential crop losses to SWR in *Malus domestica* Borkh. [cv. Pink Lady (2006/07 and 2007/08) and cv. Gala (2007/08)]. SWR was mitigated using an alkyl polyglycoside - block copolymer surfactant co-formulation applied initially at 0 or 5 L ha^{-1} in November and followed by 3-4 monthly applications at 0 or 2.5 L ha^{-1}, respectively on mini-sprinkler irrigated *M. domestica* Borkh. Mitigation of SWR significantly increased soil volumetric water content at the 0-10 cm and 10-25 cm depths (p = 0.05) and increased fruit size by 17g – 41 g and total yield by 20% – 40% in the respective varieties (p = 0.05). The net difference in crop value was $6,000 - $9000 ha^{-1} for Pink Lady and $3,600 ha^{-1} for Gala. This is the first study to demonstrate the impact of SWR on productivity in apples.

Keywords: water repellency, soil water content, surfactants, crop yield, apples, irrigation efficiency

Introduction

Soil water repellency (SWR) reduces a soil's affinity to water and affects an array of hydrological processes including infiltration, runoff, soil erosion, heterogeneous wetting, the development of preferential flow, and accelerated leaching of agrichemicals (Doerr et al., 2000 Dekker et al., 2001). Heterogeneous wetting and flow results in deprivation of a consistent water supply to plants, decreased rootzone storage of water, and non-uniform soil distribution of crop production and crop protection chemicals.

The phenomenon of SWR is attributed to the accumulation of hydrophobic organic compounds as coatings on soil particles and aggregates, as well as, physiochemical changes that occur in decomposing soil organic matter of plant or microbial origin (Miller and Williamson, 1977; Hallett et al., 2001; Hallett, 2008). In most soils, SWR is a transient phenomenon appearing after the onset of dry periods with high evaporative demand. The impacts can vary widely and are highly influenced by environmental conditions and rainfall (Doer et al., 2000).

While it is recognized that SWR can influence irrigation efficiency, water conservation, and agricultural productivity, few studies have been published literature assessing the effects of SWR on productivity of agricultural and high value horticultural crops (Crabtree and Henderson, 1999; Robinson, 1999, Blackwell, 2000; Cooley et al., 2007).

Surfactants are commonly employed to ameliorate SWR in highly managed turf grass, improve infiltration, reduce runoff, and improve irrigation efficiency and turf performance (Cisar et al., 2000; Kostka, 2000; Park et al., 2005; Mitra et al., 2006). While this strategy is commonplace in turfgrass, application in agricultural crop production has been limited for two key reasons: the lack of recognition of SWR as a problem of agronomic significance and the lack of documentable evidence for surfactant enhancement of crop yields.

The sustainability of crop and biomass production is being impacted globally by depletion of water resources resulting in water scarcity and deteriorating water quality. As soil water repellency is now recognized as norm in agricultural soils rather than an exception, the use of surfactants may enable us to ascertain the potential impacts of this phenomenon on crop productivity. Hence, the objectives of this study were to utilize surfactant treatments to modify soil hydrological properties under precision irrigation as a means of estimating potential crop losses to SWR in a high value horticultural crop - apples (*Malus domestica* Borkh.).

Materials and Methods

Three trials were conducted in Victoria, AU on a clay loam soil with a history of poor wetting and water infiltration. Apple varieties included the cultivars Pink Lady planted at 1190 trees ha^{-1} on a trellis system and Gala planted at 100 trees ha^{-1} under a traditional central leader planting. The test design was a randomized complete block with each treatment replicated 5-6 times with each plot containing 5-6 trees, but varied by planting method (trellis versus single leader).

SWR was mitigated by applying surfactant [a blend of alkylpolyglycoside (APG) and ethylene oxide/propylene oxide (EO/PO) block copolymer surfactants (Kostka and Bially, 2005)] at initial rates of 0 or 5 L ha^{-1} in the spring as a 1 m band down the tree line. Applications thereafter were applied monthly at 0 or 2.5 L ha^{-1}, respectively for up to four months. Plots were irrigated by mini sprinklers and received the same irrigation volumes and management practices. Soil volumetric water content (VWC) was monitored at 0-10 cm and 10-25 cm using a Theta probe (Delta-T Devices, Cambridge, UK). At harvest, fruit weights were measured from selected individual trees and used for crop yield estimations.

Results and Discussion

At each of the three test locations differences in soil VWC were observed between the untreated control and soils where SWR was mitigated with surfactant treatments (p = 0.05).

Soil VWC was significantly lower in the untreated control than in soils where SWR was mitigated with surfactant treatments.

At Location 1, soil VWC was monitored at two depths (0-10 cm and 10-25 cm) throughout the test period. Statistically significant differences in VWC were observed between treatments, not only in the upper portions of the soil profile (0-10 cm) (Figure 1) but also deeper in the profile (10-25 cm) (Figure 2). On each measurement date, VWC was lower in the untreated control than in the SWR mitigated surfactant treatment. Water contents in the untreated controls were up to 25% lower than in soils where SWR was mitigated by surfactant treatments.

While not monitored systematically over the test period, statistically significant differences (p = 0.05) in soil VWC were observed between the untreated control and SWR surfactant mitigation treatment on each sampling date and depth at the remaining two locations (data not presented). Across all three test locations, surfactant mitigation of SWR resulted in higher VWC of the soil profile.

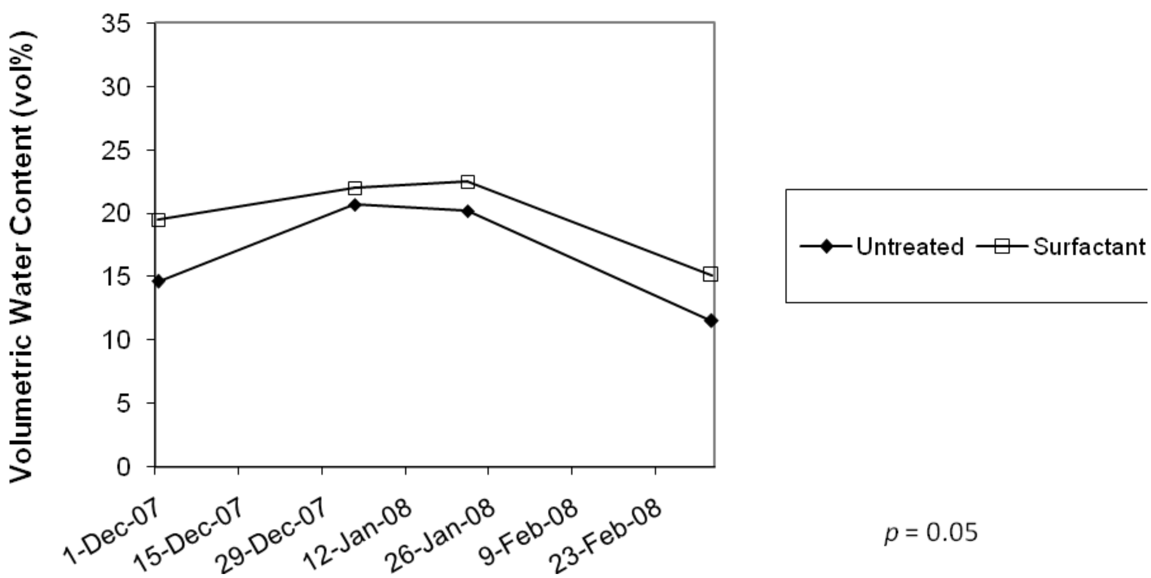

Figure 1. Soil volumetric water content (vol%) (10 cm depth) in untreated and surfactant-treated soils under precision irrigation in a clay loam soil.

During blossoming, plant growth regulators (thinners) were applied to manage fruit set resulting in statistically equivalent fruit numbers on a per tree basis. However, yields in the untreated controls were significantly lower (p = 0.05) on a hectare basis than with the SWR mitigation surfactant treatment (Table 1). The yield component most affected by SWR was mean fruit size - a difference of 24-32 g in the cv. Pink Lady and 43 g in the cv. Gala (p=0.05).

When examining the yield differences on a hectare basis, yield depressions of 3.7 – 6.1 Mg ha^{-1} (16-23% difference) solely attributable to WR were encountered in the two varieties tested. Mitigation of SWR resulted in increased net return of \$6,000 - \$9000 ha^{-1} for Pink Lady and \$3,600 ha^{-1} for Gala. This study is the first to provide an insight on potential crop losses in apples growing in a water repellent soil.

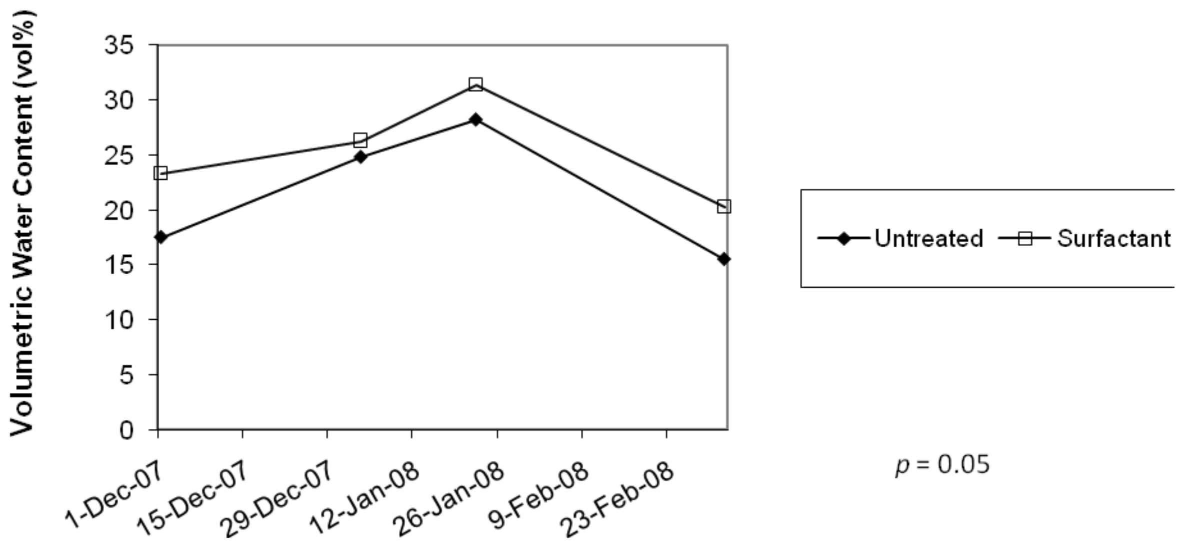

Figure 2. Soil volumetric water content (vol%) (25 cm depth) in untreated and surfactant-treated soils under precision irrigation in a clay loam soil.

Table 1. Effect of SWR on fruit size and yield in control and SWR-mitigated (surfactant treated) irrigated apples (*Malus domestica* Borkh.) in Victoria, AU.

		Fruit Size (g)		Yield (Mg ha^{-1})	
Location	Variety	Control	Surfactant	Control	Surfactant
1	Pink Lady	142.5 b[a]	175.3 a	29.3 b	34.9 a
2	Gala	81.3 b	124.3 a	7.9 b	11.8 a
3	Pink Lady	125 b	149 a	30.2 b	36.3 a

[a]Paired comparisons followed by the same letter are not significantly different, LSD (0.05).

Conclusions

The results from these studies provide evidence that SWR deleteriously impacts soil hydrological status resulting in reduced productivity, yield, and quality in apples (*Malus domestica* Borkh.), a high value horticultural crop. While irrigation practices and volumes were identical, water use efficiency was higher in the surfactant treatments and resulted in increased fruit size and yield increases in the apple cultivars Pink Lady and Gala.

In light of the severity of drought conditions experienced by growers in the Murray-Darling River Basin and projections that due to climate change such precipitation deficit conditions are becoming the norm, simple innovative management strategies such as the incorporation of surface active agents in irrigation programs can have profound effects on soil hydrological status, crop yield, and water use efficiency. Research is continuing to confirm these results in other high value horticultural crops.

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Improving Pump Performance

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Abstract. *Options can be specified to minimize power consumption by vertical pumps – both when new and over the life of the pump. Options discussed include bowl coatings, proper well development, improved suction screens, using closed impeller designs, increasing column size, using new bearings, providing proper bearing lubrication, impeller balancing, and polishing impellers. The proper TDH and flow rate must be specified, and the advantages of VFD controls are covered.*

Keywords. pump, efficiency, power, VFD, irrigation

Introduction

On the surface, the basics of good pump performance are relatively simple. They are:

1. Select a high quality pump.
2. Select a pump that operates at a high efficiency at your desired flow rate and pressure.

However, in practice, pump efficiencies are not as simple to achieve as it might appear. In December of 2003, ITRC published the report "California Agricultural Electrical Energy Requirements" (Burt et al, 2003) for the Public Interest Energy Research Program of the California Energy Commission that included the following two figures, demonstrating that average pump efficiencies are not as uniform they should be throughout California.

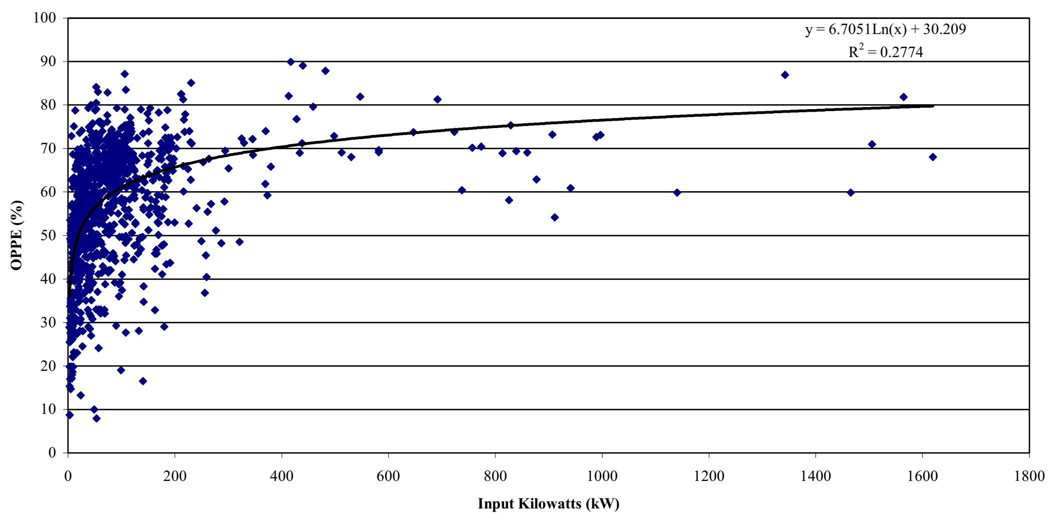

Figure 1. Pumping plant efficiency as a function of motor input kW for each pump tested – irrigation districts. Data collected by Cal Poly ITRC. Average efficiency is about 64%.

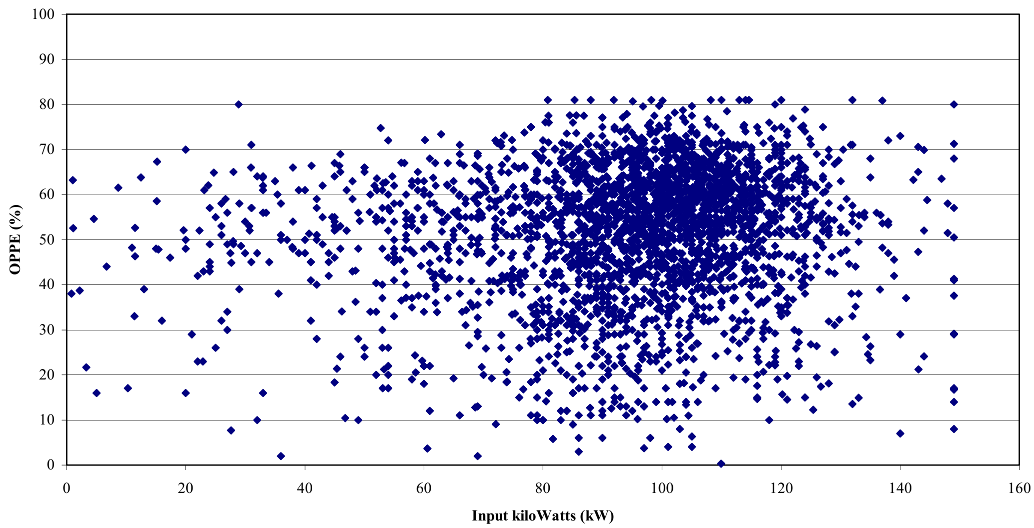

Figure 2. On-farm pumping plant efficiency as a function of motor input kW for each pump tested. Data collected by CIT. Average efficiency is about 48%.

So, if the basics of pump performance are so simple, why are overall pumping plant efficiencies so low? The answer includes a blend of the following factors:

- Energy prices have historically not been high enough (relative to overall farming costs) for farmers to pay more attention to obtaining higher efficiencies.
- Irrigation pump dealers appear to believe that agricultural customers will price-shop and therefore they will only be able to sell bare-bones equipment to farmers.
- Both farmers and pump dealers are often unaware of pump options that could be specified to improve or maintain high pump efficiencies.
- Some major pump companies have in recent years moved their foundries overseas and some of the previous "standard" options that were important for high efficiencies have been eliminated.
- There has not yet been widespread usage of variable speed drive controllers, which can be very helpful in (a) increasing well life, (b) reducing water hammer, and (c) perhaps most importantly for this paper, allowing the pump to operate without producing more pressure or flow than is needed on any particular day.

In agriculture, we typically use four general types of pumps:

1. Vertical line-shaft turbines in wells
2. Submersible motors for pumps in wells (usually called "submersible pumps" because the package often includes an impeller/bowl assembly that is custom-made for submersible motors).
3. Above-ground horizontal "booster" pumps – typically either end suction or split case.
4. Propeller pumps for low lift, often high volume applications.

Furthermore, there are two ways to power most pumps:

1. Electric motors (required for submersible pumps, obviously)
2. Engines

This paper focuses on one combination: **Vertical line-shaft turbine pumps with electric motors.** The authors address two important issues:

1. What options are important to include in a new pump purchase?
2. What options will help keep power consumption (per acre-foot pumped) low for 5 to 10 years after the initial purchase?

Minimizing Initial Power Bills with a New Well Pump

Note that the essence of the words above are "minimizing power bills" rather than "maximizing efficiency". It is always important to select an efficient pump, but putting an emphasis *only* on "maximizing efficiency" ignores several important concepts:

- Electric power bills can often be reduced if a farmer can avoid pumping during some hours of the day or week. Utilities offer special "time of use" electric rates for pumping during off-peak electrical usage hours only.
- A pump may be producing a pressure and flow rate with a very high efficiency, but if there is excess pressure that is being dissipated through pressure regulators, the "power utilization efficiency" (PUE – a new term by the authors) is much lower than the "pumping plant efficiency".
- The design pressure requirement may be greater than is necessary. For example, the column pipe diameter may be too small.
- Power can be minimized if the well is properly designed to minimize drawdown in the well.

Selecting an efficient pump

- It's not a question of whether or not the "pump is efficient". Rather, it's a question of whether the pump operates efficiently at the ***specified*** ***pressure and flow rate***. In other words, someone who understands hydraulics, well drawdown, and irrigation system pressure and flow requirements needs to get together with the pump supplier and provide the correct flow and pressure specifications.
- ***Use line shafts with enclosed oil-lubricated*** bearings rather than product (water) lubricated shaft bearings. If you are not allowed to use standard oil lubrication, instead select 10 weight food grade oil. The motor must provide the power to overcome the mechanical bearing friction, which is typically in the neighborhood of 1-2 HP per 100 feet of shaft with drip feed oil lubrication. This HP requirement can double with standard rubber water lubricated bearings – usually not at first but with time due to abrasion with sand. If there is no sand in the water, product lube can be fine.
- ***Coat the interior of pump bowls with Scotchkote 134 (SK134) fusion bonded epoxy*** per the manufacturer's specifications. It is approved for potable water, and will typically provide an improvement in efficiency of 2% minimum, with 4-5% reported in some cases. Costs vary from about \$500 - \$650/stage for 10" and 14" bowls, respectively.

Figure 3. SK134 fusion bonded epoxy application.

- Specify a C-10/C-20/C-30 polished finish on all impeller passages and removal of burrs. Some of the low-end agricultural market suppliers do not have the equipment necessary to do this. This should increase efficiency by 1-3%.

Figure 4. The thickness on the bottom of the vane is correct; the thickness must be reduced on the upper portion of the vane.

- Specify a sufficiently ***deep pump setting*** so that there will be at least 10-30 feet of water (while pumping) above the inlet to the pump bowls. One must take into account variations in well water levels from Spring to Fall, and between years. Some well pumps need even more submergence to avoid cavitation.
- Do NOT use semi-open impellers. Instead, use enclosed impellers. The performance of semi-open impellers is highly dependent upon proper adjustment of the lineshaft nut on the top of the motor, and incorrect "rules of thumb" for adjustment of the height are usually used.
- Obtain from the manufacturer the proper setting of the lineshaft for that particular installation – considering the lineshaft material and diameter, the bowls, the shaft length, and the pressure (total dynamic head). Make sure the installer uses that information.

Proper initial specifications that help *maintain* a high efficiency

- Specify that impellers be dynamically balanced to ISO 1940, Grade 6.3. The cost is about $100/stage for a 10" pump and $200/stage for a 16" pump. This minimizes the possibility of imbalance in the bowl assembly – and subsequent damage from vibrations.

- If you specify drip-oil lubrication of the shaft, make sure that the oil drips the way it should. This means you must specify a non-standard oil pot assembly. The design depicted below will maintain a fairly constant drip rate (a minimum of 6-7 drips/minute are needed) and provides a large reservoir – with the constant drip rate, the pot will empty out more quickly than standard pots with reduced drip rates over time. Another important feature can be a low wattage heater coil, covered with insulation, attached to the oil pipe above the adjustment valve.

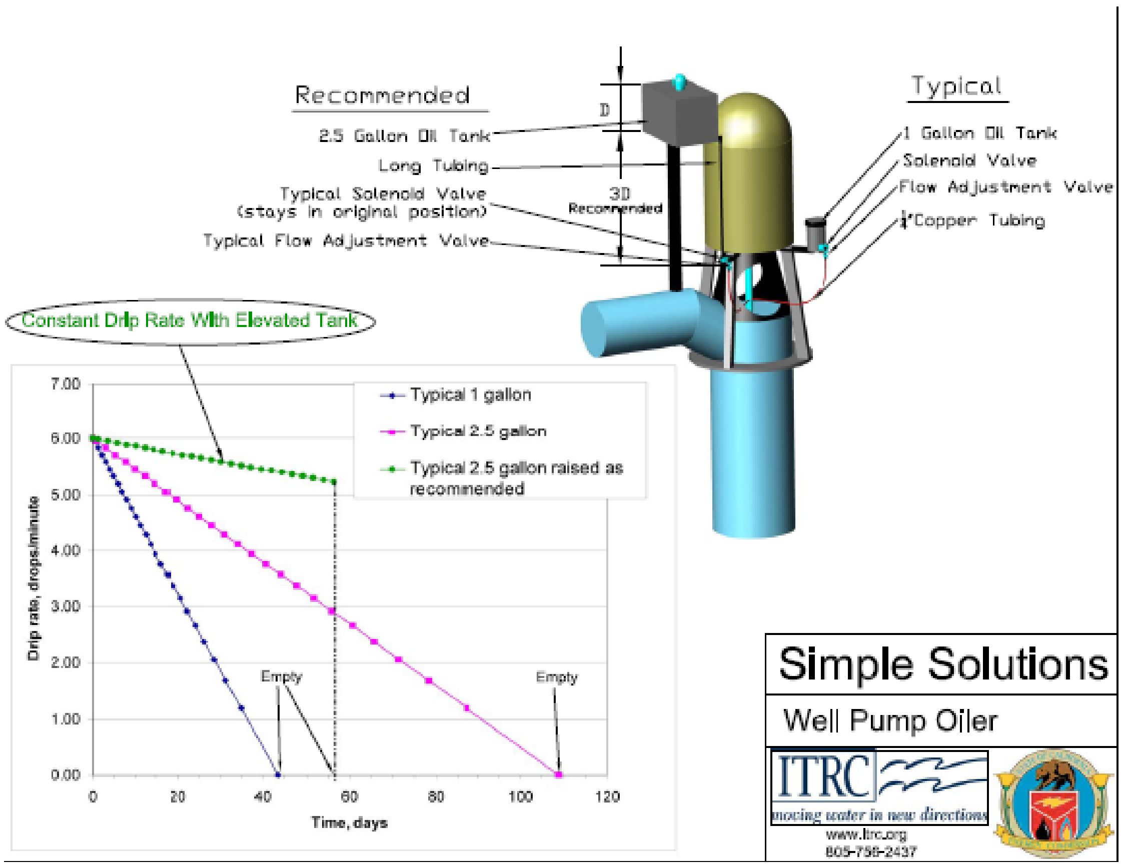

Figure 5. New well pump oiler

- Vertical hollow shaft motors require special attention. Premium efficiency motors should be specified on 150 HP or less. It is important to select the correct brand of motor. "Premium" efficiency motors by brand "X" may have a lower efficiency than standard motors from brand "Z." See later notes on motors for VFD installations.
- Motor life can be extended greatly in many cases if:
  - A space heater is provided in the motor housing to prevent condensation.
  - In areas of heavy fog, the motor is enclosed in some type of shed.
  - The motor is shaded from direct sunlight.
- A common misconception is that if a motor is oversized, the efficiency of the motor will drop. The figure below illustrates the result of ITRC testing of a variety of motors ranging from 20 HP to 100 HP.

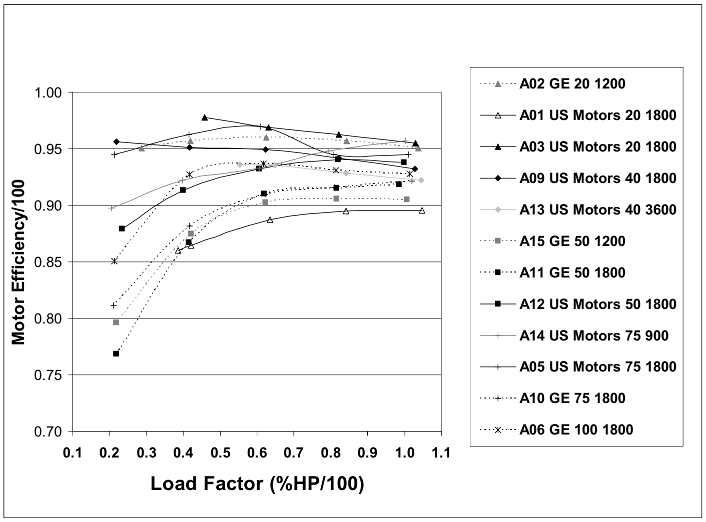

Figure 6. Efficiencies of ITRC-tested motors, across-the-line, at various relative loads.

- Install a flow meter that is robust and that is installed properly. Trying to estimate changes in pump efficiencies over time without a flow meter is problematic, to say the least.
- If there is any sand in the water, do not use bronze impellers. Instead, select Ni-Resist. Although this material requires more polishing than bronze and loses 1-2 efficiency points, it will last much longer (meaning the efficiency will not drop as much). Additional costs are about \$500 - \$1200 per stage for 10" and 14" pumps, respectively.
- If you want to use suction cone screens, be sure to use screens constructed of non-corrosive materials with no restriction of open area. The photo below indicates that, as screens fall apart, pieces of screen go into the impeller. Additionally, the flow opening can be drastically reduced. The reduced opening can cause pump cavitation and will always increase the Total Dynamic Head (TDH) of the pump – resulting in decreased flow rate and usually lower efficiency.

Figure 7. Corroded pump cone screen with missing sections.

Reducing the Total Dynamic Head (pressure) requirement

- Start with a well that has a good screen. Screens cost money up front. Holes poked in well casing are cheap, but a good screen has numerous initial and long-term advantages that save power in the long run. These advantages include:
  - They allow for good development of a well (see later section).
  - They have a large percentage of open area – easily 3-4 times as much as inexpensive slots or holes in casing. This means there is less head loss between the aquifer and the well (meaning less drawdown), and the lower velocities also help minimize corrosion and chemical blockage.
  - Good materials do not corrode. Corrosion blocks the entry of water into the well – increasing the TDH and decreasing the yield (flow rate).
- Have the well properly developed when it is initially drilled. Development is the process of cleaning out the soil immediately around the well casing to allow for free flow of water into the well (and thereby decreasing drawdown). Proper drawdown involves a lot more than just "overpumping" (the common practice), which just improves the opening of already-clean zones. See a well development specialist to learn about various techniques that are available.
- Use one larger size of column pipe and discharge head. Most customers don't know how much column friction they are paying for, but it can be substantial (a common number is about 1 foot per 100' of column). By going up one pipe size, the friction can often be cut in half. Another option is to coat the inside of the column pipe to increase the smoothness.
- Use a smart irrigation system design that does not require extra pressure for flushing filters, injecting fertilizers, or special valves.

Variable Frequency Drive Controllers

Advantages to VFD control

Power Savings. The key power savings advantage to using VFD control is simple – the speed of the pump will be adjusted so that the pump only provides the pressure or flow that is needed – no more and no less. For agricultural well pumps, this has huge implications because:

- Well water levels fluctuate during the year and between years.
- Irrigation systems may not always need a constant flow rate and/or pressure. For example, a drip system is typically divided into blocks that may be of different sizes and at different elevations, each requiring a different operating point.

How much savings does this represent? It is impossible to say without knowing the details of the aquifer and the irrigation system. There is an inherent extra 6% or so power requirement for VFD controllers (inefficiency plus air conditioning), so the savings have to be greater than 6% to break even. But "experience" seems to indicate that 10-15% overall savings are commonplace.

Ability to use Time-of-Use (TOU) Rates with Well Pumps. Every time a standard well pump is started, it has a very high initial flow rate (due to having a low initial pressure requirement). The water level in the well drops quickly, and the water on the outside of the casing takes time to "catch up" in dropping. Meanwhile, there are large inward pressures on the casing. This leads to premature well failure.

Many farmers correctly understand that their wells have a life measured in the number of startups, rather than in number of years. Therefore, these farmers will not start and stop their well pumps every day to take advantage of low power rates (TOU rates) – the risk of well failure in the middle of the summer is too great.

VFDs offer the advantage of being able to slowly start and stop the pumps – so that the well itself is not subject to violent stresses. This lengthens the life of wells. We do not have good field data on this, but it is clear that this is the case.

Reduction of Water Hammer. The slow start and stop of well pumps is a dream for minimizing water hammer problems that typically occur during rapid startup. Pipes fill up slowly.

Motor specifications for VFDs

Besides the general motor recommendations given earlier, VFD installations should include:

- Proper grounding to eliminate bearing corrosion due to stray currents. Specify a shaft grounding ring installed in the new motor.
- "Inverter duty" premium motors. These are designed to withstand the peculiar electrical stresses associated with simulated AC current.

Special lineshaft bearings for VFD applications

Because of the slow start, water lubricated bearings may spin some time before they become lubricated. If the water is very clean and and an open lineshaft is used, specify carbon bearings.

Purchasing a good VFD controller

There are large differences in quality between VFD controllers. ITRC provides guidelines for VFD specifications at www.itrc.org. A good VFD controller will:

1. Allow one to run electrical conduit more than a few feet between the controller panel and the motor.
2. Provide an excellent Power Factor.
3. Provide high quality power that helps ensure long motor life.
4. Have a very high efficiency – 98% or so.
5. Condition the power properly. For example, a good VFD controller will not be limited to the lowest voltage of the 3 leads of a 3 phase power supply.
6. Be capable of functioning with variations in voltage in the power supply.

ITRC has encountered two common VFD problems in the agricultural market:

1. The panel must be properly cooled and kept clean. Often this requires an air conditioner unit.
2. The VFD controller should usually be one size larger than the motor. For example, a 125-HP VFD controller is needed for a 100-HP motor.

Conclusion

Proper design and the addition of appropriate options can greatly maximize efficiency and minimize power bills associate with pump systems. Additionally, VFD controllers have not yet caught on in popularity, despite the powerful advantages that they bring when properly selected and installed. With rising energy prices throughout the country, it is important that farmers become aware of potential improvements to their systems.

Acknowledgement

The input of a large number of pump dealers and manufacturers is appreciated. Special thanks are given to Chris Lula of Layne/Verti-Line of Pentair and Bruce Grant of Floway. They have, of course, no responsibility for any errors in this paper. Support for ITRC's pumping activities is provided by the California Energy Commission's PIER program.

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Canal Pump Lift Station Modernization

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Abstract. *Case study of the Orchard Mesa Irrigation District's replacement of an old vertical turbine lift pump, and incorporating new technology in the station. Upgrading the pump station required a new: 75 horse power pump, 480 volt electrical service, a VFD, and a water level spread spectrum telemetry link. The new pump station has increased pumping capacity, improved the water delivery service to the growers, and has the potential to conserve both water and energy for the irrigation District.*

Keywords.

Grand Valley, Orchard Mesa Irrigation District, Colorado, Colorado River, Bureau of Reclamation, pumps, irrigation pumps, vertical turbine pumps, variable frequency drive, variable speed drive, water conservation.

Introduction.

The Orchard Mesa Irrigation District (OMID) is in the Grand Valley. The OMID is located south of the Colorado River and East of the junction between the Gunnison and Colorado Rivers, in Western Colorado. The OMID is part of the Bureau of Reclamation's Grand Valley Project. Irrigation water is transported to the OMID lands through the Orchard Mesa Power Canal, which transports 800 CFS to a Reclamation power plant and the OMID's hydraulic pumps, which serve 9,000 irrigated acres.

The Vinelands is a part of the OMID that straddles the Power Canal, before the canal reaches the power and pumping plants. One-hundred-sixty acres of trees and vines are located above the Power Canal. This acreage is served by a canal-side pump station and piped lateral.

Operation. The canal-side pump is referred to as the Vinelands Pump. The pump lifts water 103 feet, through a 12 inch diameter, 3,000 foot pipeline, to a concrete stand-pipe. The stand-pipe is the start of a three-mile gravity pipe lateral that supplies water to 160 acres of irrigated land.

The historic operation was to run the 60 horse power, 3 phase, 230 volt canal side pump continuously throughout the seven month irrigation season. About 3.3 CFS was continuously pumped from the canal to the stand-pipe. The gravity piped lateral from the stand-pipe to the farms, is a demand delivery system. There are no water orders and no limits on the duration of water deliveries. The delivery rate is somewhat controlled by the size of the on-farm irrigation systems. There is no standard water delivery measurement system on the lateral.

During low irrigation demand on the system, the quantity of water pumped exceeded the demand. The stand-pipe spilled into an overflow pipe that returned the excess water to the Colorado River. In normal operation the stand-pipe maintains a head on the lateral pipe, and no water is spilled to the river. When peak demand exceeds the 3.3 CFS delivered from the canal pump (9.2 gpm/acre), the water level drops in the stand-pipe and air enters the lateral pipe. The farm deliveries on the upper end of the lateral pipe loose their water. The ditch rider then negotiates with the users on the lower end of the lateral pipe to reduce their demand on the system, so that the upper end deliveries can resume. Under this operating strategy the pump was running in the service factor continually, and both the pump and motor had been rebuilt numerous times.

Modernization. The plan involved the replacement of the pump/motor combination and adding a Variable Frequency Drive (VFD) to maintain a somewhat constant water level in the concrete stand-pipe. The hydraulic calculation indicated that a two stage 75 horse power vertical turbine pump, with a 3.8 CFS maximum discharge (10.7 gpm/acre) would provide sufficient irrigation flexibility to operate the piped lateral without irrigation scheduling. To reduce the electric current requirement, a new three phase 480 volt power service replaced the existing 240 volt service. By using the higher input voltage, the wire size in the motor and the current requirements of the VFD are reduced.

The telemetry between the pump site and the stand-pipe use two spread spectrum 900 MHz radios. The Distance is only 3000 feet, but the line-of-sight is blocked by a ridge. The radio communication works fine, despite not having a clear line-of-sight. A 4-20 milliamp pressure transducer is mounted in a PVC pipe stilling well, that is attached to the high water level of the concrete stand-pipe. The controlled water level is about 2-inches below the overflow pipe inside the stand-pipe.

The VFD chosen for this application is an ABB-800 series. This VFD is actually two VFD mounted back-to-back within a single unit. One VFD manages the harmonics fed back to the power grid. The second VFD manages the power to the pump motor, and controls the pump speed. The combination of VFD's eliminates the need for a line filter, to cancel harmonics, and maintains the power factor at about .98. This coupled with a premium efficient motor makes for high electrical power efficiency.

Control strategy. For the on-farm delivery system to operate effectively, a constant water surface level in the stand-pipe is necessary. The pressure transducer generates a 4-20 milliamp signal that represents the water level in the stand-pipe. This signal is transmitted by spread spectrum radio to the VFD. A PID logic controller is used to control the pump motor speed in relation to the water level in the stand-pipe. A change in irrigation demand is signaled by a change in the water level in the stand-pipe, which in turn changes the pump speed to maintain the head on the lateral pipeline.

The old control strategy was to run the pump at the maximum speed and spill the excess water to the river. The new strategy is to adjust the pump speed to maintain the water level in the stand-pipe and during periods of low demand, run the pump at a minimum speed of 1300 rpm's and spill some water (up to 1 CFS) back to the river.

This strategy is not a no-spill operation, but it is a reduced spill from the constant flow strategy.

Results. There were no complaints of water shortages on the lateral this year. The demand for water on the Vineland's pipeline lateral will likely grow to match the available supply. With the new bigger pump, more water was pumped. Despite the improved electrical efficiency, more power was consumed by the pump. The irrigators experienced greater flexibility in their water delivery, but the speculation is that the annual on-farm irrigation efficiency may have decreased

Lessons Learned. The ABB field engineer, the integrator, and the electrician were all working on the VFD at various times. At one point an external PLC was added to the communication link, and the output from the PLC's PID algorithm was the analog input to the VFD's PID algorithm. That didn't work. There were too many cooks in the kitchen.

When this pump modernization proposal was presented to the OMID Board of Directors cost was a concern. The old pump didn't have a check valve on the discharge, or a flow meter; therefore, the new pump didn't "need" them either. Pump maintenance was a concern, so a flush water bearing system was used instead of the traditional product lubrication for the pump bearings. When the realization that domestic flush water was expensive, a canal water filtration system was substituted for domestic water. That didn't work. A flush water bearing system needs very clean water.

Conclusion. The pump station modernization was successful in that it increased the amount of water available to the irrigators. This may have resulted in more flexibility or it may have led to lower on-farm irrigation efficiencies. A power and water cost savings was not achieved, because the irrigation water delivery demand increased. Were the crops previously under irrigated? The crops were not stressed from an undersized irrigation delivery system. The new system will deliver water more efficiently (less spill), but the on-farm management may negate any cost savings.

Will Wetter Water Make Fatter Wallets? Evaluating Soil Surfactants in Irrigation

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Abstract. *Growers concerned with drainage, runoff, and localized dry spots in the Pacific Northwest are considering adding soil surfactants during irrigation based on claims that these wetting agents improve infiltration, water distribution uniformity, and soil moisture retention. Growers are requesting independent studies on the cost effectiveness of these materials. Experiments are being conducted at Washington State University in uniformly prepared soil columns to investigate the effects of surfactants on soil-water properties of sandy and silt loam soils. The infiltration rate, water holding capacity, and unsaturated hydraulic conductivity were compared for soil columns irrigated with and without several types of soil surfactants. To date, no statistical differences between treatments have been found. Capillary rise experiments remain to be conducted, and some sand columns are still being processd. Researchers have concluded that new tests will need to be designed with problem-soil conditions before results can help advise the irrigation practices of regional growers of difficult-to-irrigate crops such as high-value vegetables and beans.*

Keywords. Surfactant, wetting agent, soil penetrant, water saving, drainage, runoff, dry spot, water repellent, hydrophobic, surface tension, infiltration, hydraulic conductivity, moisture content, field capacity, capillary rise, Wet-Sol, WaterMaxx, Ad-Sorb, ADVANTAGE Formula One, anionic, non-ionic, block polymer

Introduction

Agricultural soil in the Pacific Northwestern states of Washington, Idaho, and Oregon is among the richest in the world for producing high-value crops such as potatoes, beans, and onions. Yet, growers face a number of costly irrigation problems. Not only does poor irrigation contribute to lowered yields and produce quality, but wasted water is costly and it can carry away topsoil or increase leaching of pollutants such as nitrates into groundwater.

Yet growers know that experimentation in the field with potential remedies is also costly and risky. Hence, this study investigates a frequently recommended method to improve penetration and distribution of irrigation water by "making water wetter," the application of soil surfactants with irrigation water.

The Need for Wetter Water

Whether center-pivot or surface irrigation systems are used, water fails to penetrate some soils due to surface crusting or hardpan conditions, leading to runoff or evaporation and poor irrigation distribution uniformity from surface ponding. In the opposite scenario, water often drains too quickly in sandy soils to provide adequate moisture content for plant uptake. While percolating, water may not distribute evenly, but instead take preferential pathways through the soil pores so that water and applied nutrients miss plant roots.

Localized dry spots (LDS), which may appear in patchwork patterns across a field, frequently occur when soils become water repellant, also known as hydrophobic. Naturally repellant soils include uncultivated sands of uniform particle size, clay soils with pore spaces too small for water droplets to enter easily, and various grasslands (Sullivan 2001, Doerr et al., 2000). Repellant soils can also be developed by burning fields or from frequent wet and dry cycles (Miller 2002).

Water repellency is believed to be caused by coating of soil particles with hydrophobic organic materials, which occurs when very wet soil dries quickly (Hallett, 2008; Doerr et al., 2000). Healthy soil is coated with wet organic compounds produced by beneficial fungi, other microbes, fluids excreted from plant pores, natural leaf waxes, and any plant residues tilled into the soil. When dry, however, these organic compounds cling to each other (i.e. adhere) and become hydrophobic (i.e. will not bond readily with water). Distribution of fungal species and organic matter will determine where dry spots develop. Water repellent soil layers may develop between layers of healthy, hydrophilic soil in response to burning, climate swings, or mineral profile (Hallett, 2008). LDS may be induced by uneven irrigation coverage that results in uneven wetting of organic compounds across a field (Karnok, 2001). Hence, growers' attempts to compensate for dry periods or new dry spots by temporarily increasing irrigation may unfortunately worsen water-repellent soil conditions over time. This problem only adds to the increased pumping and water costs and leaching of soil nutrients associated with over-irrigating.

An Advertised Solution

A remedy for all these problems is offered by manufacturers of surface-active wetting agents called soil surfactants. These topical treatments are advertised to change soil-water properties: if soil is impermeable, a soil surfactant will reduce crusting and compaction; if the soil is too dry, a soil surfactant will cause water to cling to the soil; if a soil is too wet, a soil surfactant will improve drainage. (These differ from surfactants applied in chemigation as spreaders and stickers.)

All soil surfactants on the market are designed to reduce the surface tension of water, and their main features are summarized in Table 1 from descriptions of various manufacturers. Since water molecules are bound to one another by surface tension (i.e. cohesive forces), then this reduction will make water less likely to bead, more likely to flow into air spaces in the soil, and more likely to spread over the surface of soil particles to adhere to soil. This theoretically should increase infiltration and uniformity of water distribution through the soil. Side benefits may include improvements in air movement (hence, better soil structure), microbial populations, seed germination, and root development.

Table 1. Chemical categories of soil surfactants.

	Common Ingredients	Main Use Characteristics
Anionic	Akyl aral polyethoxylate, ammonium lauryeth sulfate (used in bath products) or alkyl sulfate	• Reduce water surface tension. • Called "flash wetters," these low-molecular weight chemicals leach readily through soil. • May be toxic to some plants or affect some soil structures.
Non-ionic	Akyl -phenyl oxyethylene, phenol or alcohol ethoxylates, and/or organosilicones	• Reduce water surface tension. • Low-molecular weight flash wetters that leach readily. • Some used as spray adjuvants. • Most are chemically non-reactive and biodegradable.
Block Polymer	Alkoxylated polyols	• Achieve the least reduction in water surface tension of the types. • Designed as polar molecules for good residual effect: one end clings to hydrophobic soil, while the other end is hydrophilic and attaches to water molecules to draw them to the soil for long-lasting adsorption. • Biodegradable with low phytotoxicity.

Previous Evaluations of Soil Surfactants

Over the past three decades, studies on various soil surfactants have reported both positive and negative results, making it clear more investigation is needed. Studies have mainly focused on field trials over where soil conditions can vary greatly by local features, land use, and irrigation history. Cost analyses are not usually included in reports, and Sullivan's critique of alternative soil amendments cautions that applying soil surfactants adequately may prove costly (2001).

Positive results have been achieved with hydrophobic turfgrass. Severe LDS was reduced in 36 sand-based golf tees treated with a block polymer Aquatrols surfactant (Kostka, 2000). Another study with an Aquatrols surfactant on a putting green showed an increase in soil moisture uniformity, and overall water savings due to a moderation of soil moisture across different irrigation frequencies (Karcher et al., 2005; Aquatrols, 2005). However, timing is key: LDS reduction only persisted three months under a less costly one-time application of surfactants, while regular monthly applications consistently maintained low LDS levels (Miller, 2002).

Some striking successes have been realized with potatoes. In the Pacific Northwest, increases in potato yields and/or tuber yields were observed in 22 to 67% of the hydrophobic soil plots treated with Aquatrols' IrrigAid Gold block polymer surfactant (as cited in O'Neill, 2005). In more than one Wisconsin study, researchers have reported reduction of nitrate leaching and greater yields in surfactant-treated, hydrophic, sandy soils compared to no treatment (Kelling 2003; Lowery 2005). Although 50% increase in water content was seen throughout the growing season after an early surfactant application, further study into optimal timing was recommended (Lowery, 2005). In Colorado, the Platte Chemical Company was sure enough of nonionic surfactants' improvements in both potato yield and reductions in nitrate leaching that they applied for a patent on their own method of applying the surfactant to root zones (World, 2008).

Less promising results are found with other high-value vegetables and grains. A Texas A&M University review of soil surfactant use with corn, potatoes, soybeans, wheat, and grain sorghum cited several studies where no significant increase in yield or nutrient content was observed after applying surface wetting agents (McFarland et al., 2005). After their success on the golf courses, Aquatrols received a 2005 annual report on their IrrigAid Gold and Advantage surfactants that showed no significant differences in either soil moisture contents or pinto bean yields between treated and untreated sandy loam plots in the arid Southwest (O'Neill, 2005).

Surfactant vendors present results in promotional literature as well, which showcase their own trials, customer testimonials, and graphs and percentages taken from academic studies (without showing complete reports and references). These all share the bias that success was achieved in tests selected by the vendors. The soil conditions may have been optimal for that particular surfactant's mechanism of action, and may not exactly match the conditions in the field for which the surfactant is being considered by other growers. This present study differs from such approaches by seeking to level the field by using uniform soil conditions across the tests of different surfactants. The tests themselves attempt to isolate the effects of surfactants on the key physical processes that are behind the many advertised benefits of soil surfactants.

Objectives

This independent study evaluates advertised benefits of soil surfactants from the perspective of classic soil physics. The objectives are to determine if any statistically significant changes are seen in the following soil-water properties when a surfactant is added to irrigation water:

- Rate at which water vertically infiltrates the soil;
- Moisture retention of soil, measured as moisture content two days after irrigation;
- Unsaturated hydraulic conductivity (UHC) as a measure of water distribution in the soil;
- Rate of capillary rise, which is upward movement of a wetting front due to surface tension.

Methods and Materials

The experiments will determine whether surfactants added to irrigation water increase, decrease, or have no effect on the four properties of infiltration rate, field capacity, UHC, and capillary rise. For each experiment, each soil sample will receive one of the following treatments (applied randomly):

- Wet-Sol #233, a nonionic surfactant from Schaeffer Manufacturing Company (St. Louis, MO);
- WaterMaxx II, a block polymer surfactant from Western Farm Service (Fresno, CA);
- Ad-Sorb RST, a block polymer from J.R. Simplot Company – Plant Health Technologies (Boise, Idaho);
- ADVANTAGE Formula One, an anionic soil penetrant from Wilbur-Ellis Company (Fresno, CA);
- Irrigation water without additives (i.e. control treatment).

Each experiment will be performed in two types of soil from the Columbia River Basin: Warden silt loam and Quincy sand. Experiments will be replicated four times in each soil type, leading to 20 samples (5 treatments × 4 replicates) for silt loam and 20 for sand. Constants related to the soil water properties of infiltration rate, field capacity, UHC, and capillary rise will be derived from the measured data. Statistical differences among surfactant treatments and the control will be determined for each soil type by an Analysis of Variance (ANOVA) test on the means (average values) of the derived constants using Statistical Analysis System (SAS) software.

Surfactant Selection and Concentrations

The selected surfactants span the chemical categories and are all commonly used by Pacific Northwest growers and supplied by local distributers. Concentrations were determined for the tests of infiltration rate and moisture content based on the volume of surfactant V_s that the soil sample would see if it were irrigated as part of a larger field. Hence, the volume of surfactant applied to each sample was obtained by determining what fraction of the amount recommended for an acre would equate to the fraction of an acre taken up by a soil sample:

$$V_s \,/\, \textit{Recommended Volume for Acre} = \textit{Sample Cross-sectional Area} \,/\, \textit{Acre} \tag{1}$$

The median value from the manufacturer's range of recommended amounts was used so as not to bias the study toward lesser or greater chances of obtaining the advertised effects. Finally, the volume V_s of each surfactant was mixed with sufficient irrigation water (about 161 ml for these samples) to penetrate the soil sample to a 1-cm depth. UHC and capillary rise experiments were sample-volume independent, and hence used the same concentrations as for the infiltration rate and moisture content experiments. The surfactant volumes used were 0.271 ml, 0.181 ml, 0.090 ml, and 16.9 µl, respectively for Wet-Sol, WaterMaxx II, Ad-Sorb RST, and Formula One, and all were applied toptically in 161 ml of water.

Infiltration Rate Experiment

Infiltration rate was tested by siphoning irrigation water from a Mariotte-type reservoir into clear plexiglass columns filled with approximately 20.5 in. (52 cm) of air-dried, sifted soil to which the surfactant had been added in 1 cm of water (see Figure 2). A shake-cup-and-drop method of filling ensured uniformity across the columns and random particle distribution, while pounding the columns settled the particles. The bottom of each column was covered with wire mesh netting (0.2 cm holes) to allow drainage, while a slip of filter paper (150mm diameter pores) was placed on the mesh to hold the soil.

The water reservoir enabled air inflow through a tube (anchored by a rubber stopper on reservoir top) so that pressures could equalize after the siphon was released into a soil column open to the atmosphere as shown in Figure 1. The column was placed at a height that ensured (by the pressure head) that water would flow into the column until a pond formed on the soil surface that was level with the tube end. Thereafter, to keep the pond height constant, the reservoir continued to supply water to the soil column at just the rate necessary to replace the water that infiltrated the soil.

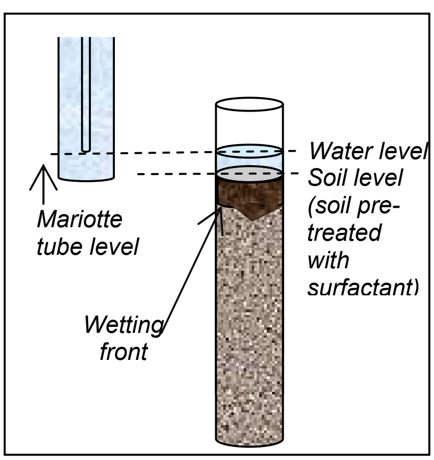

Figure 1. Mariotte principle is utilized in irrigating soil columns for infiltration rate experiments.

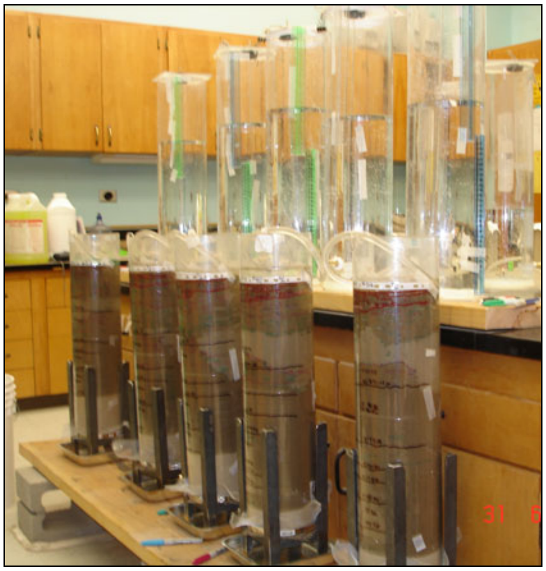

Figure 2. Irrigation of one treatment set during infiltration rate experiment.

Hence, the drops in the reservoir's water levels over time represented the infiltration rate. Water levels were recorded every 2 to 5 minutes for sand, and 3 to 10 minutes for silt until the soil column reached saturation and began to drip water. The infiltration rate decreased exponentially over time, as shown.

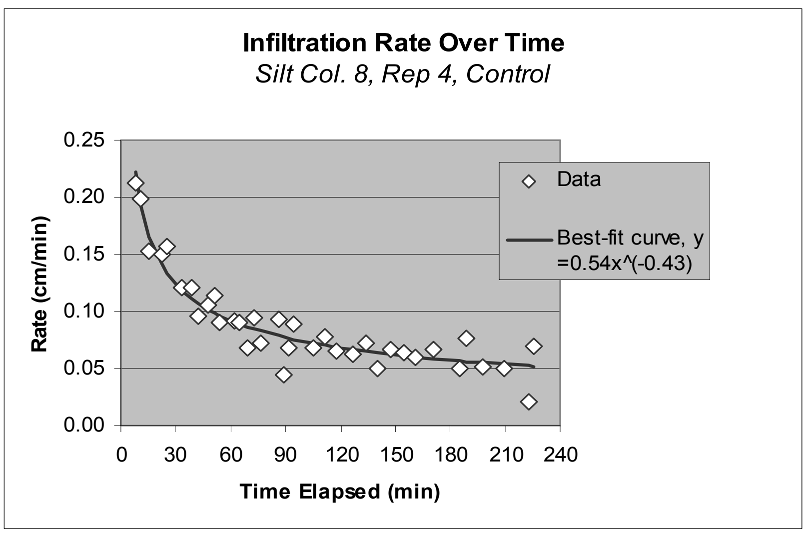

Figure 3. Typical infiltration rate curve obtained from experimental data.

Regression analysis showed that a power function of the form $y(t) = at^b$ best fit the infiltration rate curve. Hence, the data followed the form of the modified Lewis-Kostiakov equation for infiltration rate: $\bar{I}(t) = ak\ t^{(a-1)} + F_o$, with F_o always greater than or equal to zero. SAS ANOVA was finally applied to determine statistical differences in the Lewis-Kostiakov coefficients among the treatments.

Moisture Content at Field Capacity

The soil-moisture retention of the columns from the infiltration rate experiment was determined indirectly by collecting weight data and calculating gravimetric moisture content (θ_m), volumetric moisture content (θ_v), and bulk density (P_b). Columns were weighed just prior to irrigation and again after the soil had drained for two days (with columns covered with tin foil to prevent evaporation). This represented a field capacity condition, in which all the soil moisture that could be pulled by gravity had drained.

The equations for calculating θ_m, θ_v, and P_b are:

$$\theta_m = M_w / Ms \tag{2}$$

$$\theta_v = \theta_m \times P_b / P_w \tag{3}$$

$$P_b = M_s / V_t \tag{4}$$

where M_s is the mass of soil in the column, M_w is the mass of water in the soil at field capacity, V_t is the total volume of soil and water, and P_w is the density of water, known to be 1000 kgm^{-3}.

The masses can be represented by weights measured in the lab, as they relate directly through the gravitational constant. Hence, dry soil weight corresponds to M_s, while M_v is represented by subtracting the soil's weight from the total (soil plus water) weight at field capacity. Gravimetric water content is then approximated as follows:

$$\theta_m \approx (\text{wet weight} - \text{dry weight}) / \text{dry weight} \tag{5}$$

After determining θ_m for each column, the bulk densities were obtained using the soil height and column radius to calculate V_t, and θ_v was found from θ_m and P_b. Finally, the three values of gravimetric water content, volumetric water content, and bulk density for each column were statistically compared for variance across treatments using the same SAS ANOVA applied for infiltration rate constants.

Unsaturated Hydraulic Conductivity Experiments

Hydraulic conductivity is one of the most important soil-water properties, encompassing both lateral and vertical water movement in the unsaturated zone (i.e. still able to receive more water). In layman's terms, hydraulic conductivity accounts for the movement of water from wet to dry areas of the soil.

As shown in Figure 4, 100-ml mini-disk infiltrometers (Decagon Devices, Inc) were filled with a surfactant-water solution, of the same concentrations used previously, and then set on air-dried, sifted soil in shallow containers (5-in height, 9-in. diameter). Once the porous end of the infiltrometer contacted the soil, the solution spread freely out and down into the soil, while measurements similar to infiltration rate were taken. Water levels were recorded over time, every 10 seconds for silt and 5 seconds for sand. This time, cumulative infiltration was calculated as the drop in water level normalized by the cross-sectional area of the infiltrometer.

Figure 4. One researcher reads the water level on the mini-disk infiltrometer in the hydraulic conductivity experiment, while another records the readings at regular time intervals.

Cumulative infiltration data was fit to a simplified form of the Richard's Equation. Derived from the universal Darcy's Law, the Richard's Equation includes a theoretical UHC as a function of soil moisture content, denoted as *K(θ)*:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial K(\theta)}{\partial z} + \frac{\partial}{\partial z}[K(\theta)\frac{\partial \psi(\theta)}{\partial z}] \quad (6)$$

where *z* is the position variable (facing doward) and *ψ* is the matric potential, also a function of moisture content.
However, the Richard's Equation is difficult to solve in this form, so numerical solutions have been discovered as simplifications for irrigation over short time periods. The form used for this study is the same as described by Hallett (2008), and represents cumulative irrigation as a function of time, I(t), as being composed of a nonlinear term with coefficient C_1, related to sorptivity, and a linear term with coefficient C_2, which is proportional to hydraulic conductivity.

$$I(t) = C_1\, t^{1/2} + C_2\, t \quad (7)$$

Using this simplified model, hydraulic conductivity was indirectly analyzed through the constant value C_2. Regression was applied to determine values of C_1 and C_2 that gave the best I(t) curve-fit to the data. The results were analyzed with the SAS ANOVA program used previously to find any significant statistical differences in the C_2- coefficient across treatments.

Capillary Rise Experiments

Effects of the different surfactants on surface tension will be examined through a capillary rise test for the initailly-unsaturated soil condition. These tests were not yet conducted at the time of writing, but results will be announced in the presentation of this study at the November 2008 Irrigation Show in Anaheim, CA.

Clear plastic columns of 3-4 cm diameter and approximately 1 foot height will be filled with the same air-dried, sifted silt loam and sandy soils, then placed in 1-inch ponds of the treatment solution — a mixture of the same concentrations of surfactant and water used previously. A reservoir containing more of the treatment solution will be attached so as to resupply the pond at the same rate the water was taken up by the soil, according to the Mariotte principle. (Note: setup resembled an automatically-refilling watering dish for pets.)

Transparent rulers and transparent sheets will be attached to the clear columns for recording the heights of the wetting front and tracing its pattern at regular intervals of time. The rates at which the wetting fronts rise vertically will be statistically compared across the treatments with the same SAS ANOVA program used previously.

Results and Discussion

To compare the effects of different treatments, one or more key parameters were found for each of the soil-water properties of infiltration rate, moisture retention (at the field capacity condition), and hydraulic conductivity (in unsaturated soil condition). These parameters were statistically analyzed for the variance among their means with a SAS ANOVA (GLM) procedure. If the variance among the means was less than 5% (i.e. if a Pr-value of 0.05 was given by the SAS program), this variance was then considered significant. This meant that the surfactant showed a less than 5% chance of its key parameter's mean being significantly different from the key parameters' means of the other treatments.

Table 2 shows the key parameters that were analyzed, and the ANOVA Pr-values obtained. For the sand experiments, only 3 of the 4 planned replicates have been processed to date and soil columns are still drying from the unsaturated hydraulic conductivity experiments. Capillary rise experiments are also still underway. The remaining experiments will be completed and the results reported during the 2008 Irrigation Show held November 2-4, and the authors will be pleased to respond to requests for updated documents.

Table 2. Statitistical results from analysis of variance across the experimental treatments.

Soil Type	**Soil-water Property**	**Parameters Analyzed**	**Pr-values**
Silt	Infiltration rate	Rate constant *a*, for best-fit curve $\bar{I}(t) = ak\,t^{(a-1)} + F_o$	0.503
	Moisture retention at field capacity	θ_m, gravimetric moisture content θ_v, volumetric moisture content P_b, bulk density	0.763 (θ_m) 0.507 (θ_v) 0.194 (P_b)
	Unsaturated hydraulic conductivity	C_2 in best-fit curve, $I(t) = C_1\,t^{1/2} + C_2\,t$	0.443
Sand	Infiltration rate	Rate constant *a*, for best-fit curve $\bar{I}(t) = ak\,t^{(a-1)} + F_o$	0.411
	Unsaturated hydraulic conductivity	C_2 in best-fit curve, $I(t) = C_1\,t^{1/2} + C_2\,t$	0.620

As seen above, all the parameters showed greater than 20% likehood of having their means overlapping, so to speak, with the means of any other surfactants or the control treatment. Hence, this study showed no significant difference in soil-water properties across the treatments of 4 different types of surfactant and irrigating with no surfactant.

Nevertheless, one cannot interpret these results as proving that surfactants do not produce significant changes in soils. One must remember that the soils in these experiments used were sifted and uniformly settled into columns, without clods or uneven compaction. Also, though the soils were typical of Pacific Northwest fields where high-value crops are grown in furrows, they appeared free of some of the unique problems of water repellency that have been known to develop. Hence, these experimental soils are not actually the target customers for soil surfactants, which are advertised to ameliorate problem conditions in soils.

Researchers evaluating the success of numerous soil additive experiments have found similar results as achieved so far in this study: applying surfactants to normal (wettable) soils did not produce any noticeable changes (McFarland, 2005). Likewise, Sullivan's review of many soil amendments includes soils that already have good structure in his list of soils in which beneficial effects from surfactants should not be expected. Hence, the results from this study may be supporting a theory that soil surfactants have no effect on non-problem soils.

A balanced interpretation of these results would be to consider this type of study as a gateway to a full investigation of surfactants' physical effects. A full understanding of their activities during irrigation must begin with studies such as this that isolate the effects of the wetting agents on physicochemical properties of soil-water without soil problems in the picture.

Then for a study to be considered complete, it must proceed with a closer look at the effects of soil variations on the surfactants' action. The soil conditions should be varied in the lab, while still maintaining a controlled environment that assures uniform conditions across treatments, to investigate in more detail such scenarios as initial penetration in crusted or compacted soils, and moisture retention or distribution patterns in water repellent soils. Again, using classic soils physics methods will be applied, and perhaps digital imaging software can be used for observing wetting fronts (in case of preferential flows). Further helpful to understanding soil surfactant effects and still in the realm of soil physics, would be an examination of the surfactants more closely by measuring their surface tension; this would help explain the effects they may have on water and soil particles. The surfactant solution's critical mass should also be obtained or tested to verify that concentrations used in experiments (which, in this study, have been based soley on field applications) are appropriate for the surfactants' compositions.

Additionally, persistence experiments should also be conducted to see if accumulation of surfactant molecules in the soil may produce any effects on soil-water properties. If any of the above-mentioned experiments with problem soils should show improvements in soil-water properties after surfactants are applied, then the longer-term effects of surfactant treatments should be investigated to answer the question of how long the positive results will continue before the soil surfactants are drained away or biodegrade.

Conclusion

Again, no signficant statistical differences were noted among all surfactant treatments and the control, but the value of this study was to determine whether surfactants acted directly on the soil-water properties of two soil types typical in the Pacific Northwest for growing high-value crops. The results answered that adding soil surfactants to irrigation water did not produce any significant changes for the soil-water properties of infiltration rate, soil moisture content and bulk density, unsaturated hydraulic conductivity, and capillary rise, at least not for healthy and uniformly distributed soils immediately after the initial treatment.

Further studies with surfactants are needed. We recommend more tests on those properties of the surfactants that would influence their effects on soil-water, and experiments with varying soil conditions in the lab, especially water repellency.

In response to all the soil-improvement products being offered today, the North Central Regional Committee (NCR-103) was formed to investigate claims and advise consumers on a number of soil additives and conditioners, including surfactants (Iowa, 2004). NCR-103, which can boast Dr. Kelling of the Wisconsin potato studies as a member, cautions that reliable standardized procedures have not yet been developed to evaluate effects of various types of products on soil physical properties (North, 2004). Perhaps as further academic studies such as this one are conducted, new collaborations will be formed among universities and with industry partners that will lead to such standards, or at least, to an understanding of best practices so that growers can base their purchasing decisions on science-based evaluations of the effects of using these products in irrigation.

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Irrigation by Evapotranspiration-Based Irrigation Controllers in Florida

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Abstract. *Despite limited water resources, the need for irrigation will continually grow with increased population without change in the demand for aesthetically pleasing landscapes. The objective of this study was to evaluate the ability of three ET-based controllers to schedule irrigation compared to a time irrigation schedule representative of a homeowner. Twenty plots were partitioned into 65% St. Augustinegrass and 35% mixed-ornamentals to represent a typical Florida landscape plant composition. The five replicated treatments were: ET controller A, ET controller B, ET controller C, a time-based treatment determined by UF-IFAS recommendations and a time-based treatment that is sixty percent of the previous time-based treatment. Results showed that the ET controllers resulted in 35%-42% average water savings compared to a time clock schedule without a rain sensor while maintaining acceptable turfgrass quality. Also, average potential water savings by using a rain sensor at a 6 mm threshold was 21% over the study period.*

Keywords. Controllers, Evapotranspiration, Florida, Irrigation, Turfgrass, Water Conservation

Introduction

Similar to the water shortages seen in other parts of the United States, Florida has become increasingly aware of the limitations in the availability of its water resources. It is estimated that over half of total fresh water is used for irrigation (Hutson et al., 2004). It was found in recent research that 71% of residential water use was used for irrigation (Baum et al., 2003). As a result, new methods must be explored for outdoor water conservation to maintain the high demand for aesthetically pleasing urban landscapes from continually increasing populations in Florida.

Evapotranspiration (ET), defined as the evaporation from the soil surface and the transpiration through plant canopies (Allen et al., 1998), is the exchange of energy for outgoing water at the surface of the plant (Allen et al., 2005). The components used to estimate ET are solar radiation, temperature, relative humidity, and wind speed (Allen et al., 2005). Evapotranspiration-based controllers, also known as ET controllers, are irrigation controllers that use an estimation of ET to schedule irrigation. These controllers are typically programmed with landscape-specific conditions making them more efficient (Riley, 2005).

The objective of this study was to evaluate the ability of three brands of ET-based controllers to schedule irrigation by comparing irrigation application to a time clock schedule intended to mimic homeowner irrigation schedules. The controllers should also be able to maintain acceptable turfgrass quality regardless of water savings results.

Materials and Methods

This study was primarily conducted at the University of Florida Gulf Coast Research and Education Center (GCREC) in Wimauma, Florida. There were a total of twenty plots that measured 7.62 m x 12.2 m. Each plot consisted of 65% St. Augustinegrass (*Stenotaphrum secundatum* 'Floratam') and 35% mixed ornamentals to represent a typical residential landscape plant composition in Florida. This research reports on the turfgrass portion of each plot. Landscapes were maintained through mowing, pruning, edging, mulching, fertilization, and pest and weed control according to current UF-IFAS recommendations (Black and Ruppert, 1998; Sartain, 1991). Each plot contained separate irrigation zones for turfgrass and mixed ornamentals.

Five treatments were established and replicated four times for a total of twenty plots in a completely randomized block design. The irrigation treatments were as follows:

- ET controller A;
- ET controller B;
- ET Controller C;
- TIME, a time-based treatment determined by UF-IFAS recommendations (Dukes and Haman, 2002); and
- RTIME, a time-based treatment that is 60% of T4.

The ET controllers were as follows: Intelli-sense (Toro Company, Inc., Riverside, CA) utilizing the WeatherTRAK ET Everywhere service (Hydropoint Datasystems, Inc., Petaluma, CA), SL1600 controller with SLW15 weather monitor (Weathermatic, Inc., Dallas, TX), and Smart Controller 100 (ET Water Systems LCC, Corte Madera, CA). All treatments utilized rain sensors set at a 6 mm threshold.

There were five periods of data collection:

- 13 August, 2006 through 30 November, 2006 as fall 2006;
- 1 December, 2006 through 26 February, 2007 as winter 2006-2007;
- 27 February, 2007 through 31 May, 2007 as spring 2007;
- 1 June, 2007 through 31 August, 2007 as summer 2007; and
- 1 September, 2007 through 30 November, 2007 as fall 2007.

Data collected over these time periods included irrigation water applied per plot from totalizing flow meters and turfgrass quality measurements. More information on the additional results from this research can be found in Davis (2008).

The ET controller treatments were programmed with two days per week watering restrictions during fall 2006 and winter 2006-2007, Wednesday and Saturday, and no watering between 10 am and 4 pm. Also, the controllers were programmed with maximum system efficiencies over these periods that resulted in 95-100% efficiencies depending on the maximum efficiency value allowed by the individual controllers. All ET controllers were updated to allow irrigation everyday with an 80% efficiency determined from on-site uniformity testing from spring through fall 2007.

The time-based treatments were programmed with two days per week watering restrictions for all five periods. Fall 2006 and winter 2006-2007 applied 60% of the net irrigation requirement derived from historical ET and effective rainfall specific to south Florida (Dukes and Haman, 2002) and RTIME applied 60% of the irrigation depth calculated from TIME equaling 36% of the net irrigation requirement. TIME was increased to apply irrigation to replace 100% of the net irrigation requirement instead of 60% used during the first two periods. Once again, RTIME applied 60% of TIME resulting in the reduced treatment applying 60% of the net irrigation requirement. Irrigation runtimes for these treatments were adjusted monthly.

Results were quantified by comparing all treatments to a time-based treatment without a rain sensor (TIME WORS). The time-based treatment without a rain sensor was derived from TIME by including water application from irrigation events that were bypassed due to rain and was not an actual treatment. Turfgrass quality was measured monthly using the National Turfgrass Evaluation Program (NTEP) standards (Shearman and Morris, 2006). The turfgrass was rated on a scale from 1 to 9 where 1 represented dead turfgrass or bare ground, 9 represented an ideal turfgrass, and 5 was considered minimally acceptable quality for a residential setting.

SAS statistical software (SAS Institute, Inc., Cary, NC) was used for all statistical analysis, utilizing the General Linear Model (GLM) procedure with a confidence interval of 95%. Means separation was conducted using Duncan's multiple range test.

Results and Discussion

All treatments resulted in substantial savings compared to the TIME WORS treatment for fall 2006 (Table 1). RTIME showed the most savings at 55% due to an error in the October schedule for south Florida (Dukes and Haman, 2002) causing extremely low water application for this month. TIME had 28% savings also due to the low watering schedule in October. Savings from the ET controller treatments A and B fell between the other treatments by saving 38% and 39%, respectively. The ET controller C did not function during this period due to circuitry problems and results were not reported.

Fall 2006 average turfgrass quality ratings were below the minimally acceptable value of 5.0 for all treatments due to pest problems and fungal disease. All of the turfgrass plots suffered from an infestation of chinch bugs (*Blissus insularis* 'Barber') and a fungal disease known as Curvularia. Damaged turfgrass was replaced with new sod during the week following 26 September, 2006; no more than 25% of any plot was resodded and most of the damage was located along the edges of the plots where irrigation coverage was marginal.

Winter water application was less than any other period due to the reduced climatic demand. The ET controller A saved 50% and ET controller B saved 60% compared to TIME WORS (Table 2). TIME and RTIME respectively had savings of 20% and 49%. Both ET controller treatments, A and B, applied less water than RTIME unlike any other time of year. The ET controller C remained nonfunctional during this period. The ET controller treatments showed the potential to save over 50% of water applied in subsequent winter periods. Turfgrass quality ratings were above minimum acceptability ranging from 5.7 to 6.0 and were not different across treatments.

Spring 2007 water savings by all treatments compared to the TIME WORS treatment ranged from 9% by ET controller A to 50% by the RTIME (Table 3). The ET controller B and TIME had similar savings of 15% and 18%, respectively. The time-based schedules, TIME and RTIME, applied irrigation during every scheduled event for the months of March and May due to lack of rainfall. Irrigation savings by the ET controller treatments were based purely on their ability to match irrigation application with environmental demand and not affected by the variability of the rain sensor during these two months. All treatments maintained similar turfgrass quality ratings above the minimally acceptable level, averages ranging from 6.1 to 6.4, and were not different from each other (Table 3). Despite the reduced watering by RTIME in the spring 2007 period, the reduced time-based schedule still had an above average turfgrass quality rating.

The ET controller C resulted in 30% savings compared to TIME WORS (Table 3) in the Spring of 2007. The ET controller C frequently had poor signal strength and the irrigation schedule was not updated from 9 April, 2007 through 23 May, 2007 causing the 9 April schedule to continually apply until communication was re-established. Thus, the water application rate stayed constant throughout the spring period while the other treatments increased the irrigation rate (i.e., frequency) based on increased climatic demand and little rainfall. The 30% irrigation savings attributed to this controller was an over-estimate due to the constant irrigation rate in the spring. This controller also would not recognize a rain sensor despite repeated attempts with customer service to repair.

Water savings for summer 2007 by all treatments compared to the TIME WORS treatment (Table 4) ranged from 31% by TIME, to 63% by RTIME. Savings from the ET controller treatments, B and C, fell between the other treatments by saving 41% and 45%, respectively. Turfgrass quality ratings were not different across treatments ($P=0.933$) and remained above the minimally acceptable levels. A power outage caused by lightning occurring on 8 June, 2007 damaged the equipment associated with ET controller A, which resulted in a gap in calculated ET for that controller. Since ET controller A did not operate based on an ET schedule, data for this controller was removed for this period. The ET controller C continued to apply irrigation every day without a functional rain sensor.

Fall 2007 savings were once again seen by all treatments compared to TIME WORS (Table 5). The ET controller A saved 43% compared to TIME WORS while ET controllers B and C saved 59% and 50%, respectively. Both TIME and RTIME also showed water savings from 15% to 50%. Turfgrass quality was similar across all treatments and higher than the minimally acceptable value of 5, ranging from 6.4 to 7.1; quality was not different between treatments (P=0.170).

When operating properly, all ET controller treatments exhibited considerable savings compared to TIME WORS for every period except spring 2007. This occurred because the time-based treatments were developed considering historical effective rainfall. However, the spring 2007 period experienced very little rainfall and an increase in the demand for irrigation. Even though more irrigation occurred compared to the time-based treatments, the ET controllers were reacting to climatic demands based on real-time conditions and as opposed to historical weather data. Water savings by the ET controller treatments were similar between the brands when compared over the same periods.

TIME, developed from 100% replacement of the net irrigation requirement, consistently applied more cumulative irrigation compared to the ET controller treatments. Also, RTIME applied the least amount of water in all periods except winter 2006-2007 and fall 2007. However, turfgrass quality remained above the minimally acceptable level for both treatments with no statistical differences between the ratings. As a result, 60% replacement of net irrigation requirements is appropriate for effective water application assuming good uniformity and average weather conditions.

Conclusions

All treatments applied less water compared to TIME WORS. The average potential water savings across all periods averaged 35% - 43% for ET controllers. Maximum and minimum savings were seen over winter 2006-2007 and spring 2007, respectively, as responses to climatic demand. Also, average potential water savings by using a rain sensor at a 6 mm threshold was 21% over the entire study period. These savings occurred even during dry conditions due to scheduling only two irrigation events per week.

The reduced time-based treatment, T5, resulted in similar water savings as ET controllers with no differences in turfgrass quality. As has been shown in previous research in Florida, changing time clock settings throughout the year can result in substantial irrigation savings. The reduced time-based schedule (T5) only replaced 36% of the net irrigation requirement in Fall 2006 and winter 2006-2007, but still irrigated more in the winter compared to the ET controller treatments. Time-based treatments were developed from the historical net irrigation requirement for the area resulting in less water applied than if scheduled without using historical ET and effective rainfall. However, time-based schedules do not fluctuate with changing weather conditions and typical homeowners will not manually adjust on a regular basis. Thus, the ET controllers show promising results for consistent water savings.

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Table 1. Fall 2006 savings compared to the time WORS treatment[1] using cumulative period totals and turfgrass quality[2]

Controller	Savings compared to time WORS	Turfgrass quality[3]
A	38%	4.8 *a*
B	39%	4.9 *a*
C	--[4]	--
TIME	28%	4.7 *a*
RTIME	55%	4.8 *a*

[1]The time WORS treatment refers to the time-based treatment without a rain sensor theoretically derived from T4.
[2]Turfgrass quality ratings used a 1 to 9 scale where 1 was of lowest quality, 9 was of highest quality, and 5 was minimally acceptable.
[3]Numbers with different letters in columns indicated differences at the 95% confidence level using Duncan's Multiple Range Test.
[4]Indicates nonfunctional treatments.

Table 2. Winter 2006-2007 savings compared to the time WORS treatment[1] using cumulative period totals and turfgrass quality[2]

Controller	Savings compared to time WORS	Turfgrass quality[3]
A	50%	5.7 *a*
B	60%	5.9 *a*
C	--[4]	--
TIME	20%	6.0 *a*
RTIME	49%	5.7 *a*

[1]The time WORS treatment refers to the time-based treatment without a rain sensor theoretically derived from T4.
[2]Turfgrass quality ratings used a 1 to 9 scale where 1 was of lowest quality, 9 was of highest quality, and 5 was minimally acceptable.
[3]Numbers with different letters in columns indicated differences at the 95% confidence level using Duncan's Multiple Range Test.
[4]Indicates nonfunctional treatments.

Table 3. Spring 2007 savings compared to the time WORS treatment[1] using cumulative period totals and turfgrass quality[2]

Controller	Savings compared to time WORS	Turfgrass quality[3]
A	9%	6.2 *a*
B	15%	6.4 *a*
C	30%[4]	6.3 *a*
TIME	18%	6.2 *a*
RTIME	50%	6.1 *a*

[1]The time WORS treatment refers to the time-based treatment without a rain sensor theoretically derived from T4.
[2]Turfgrass quality ratings used a 1 to 9 scale where 1 was of lowest quality, 9 was of highest quality, and 5 was minimally acceptable.
[3]Numbers with different letters in columns indicated differences at the 95% confidence level using Duncan's Multiple Range Test.
[4]Savings were a partial result of low signal strength and no updates to the irrigation schedule.

Table 4. Summer 2007 savings compared to the time WORS treatment[1] using cumulative period totals and turfgrass quality[2]

Controller	Savings compared to time WORS	Turfgrass quality[3]
A	--[4]	--
B	41%	6.1 *a*
C	45%	6.1 *a*
TIME	31%	6.1 *a*
RTIME	63%	5.8 *a*

[1]The time WORS treatment refers to the time-based treatment without a rain sensor theoretically derived from T4.
[2]Turfgrass quality ratings used a 1 to 9 scale where 1 was of lowest quality, 9 was of highest quality, and 5 was minimally acceptable.
[3]Numbers with different letters in columns indicated differences at the 95% confidence level using Duncan's Multiple Range Test.
[4]Indicates nonfunctional treatments.

Table 5. Fall 2007 savings compared to the time WORS treatment[1] using cumulative period totals and turfgrass quality[2]

Controller	Savings compared to time WORS	Turfgrass quality[3]
A	43%	6.4 *a*
B	59%	7.1 *a*
C	50%	7.0 *a*
TIME	15%	6.6 *a*
RTIME	50%	6.5 *a*

[1]The time WORS treatment refers to the time-based treatment without a rain sensor theoretically derived from T4.

[2]Turfgrass quality ratings used a 1 to 9 scale where 1 was of lowest quality, 9 was of highest quality, and 5 was minimally acceptable.

[3]Numbers with different letters in columns indicated differences at the 95% confidence level using Duncan's Multiple Range Test.

Turfgrass Crop Coefficients in the U.S.

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Abstract. *Turfgrass crop coefficients are used for irrigation consumptive use permitting as well as the basis for irrigation scheduling in many areas of the U.S. However, there have been limited studies to determine crop coefficients for turfgrass. This paper summarizes crop coefficients available in the literature and indicates the need for future crop coefficient determination.*

Keywords: crop coefficient, warm-season turfgrass, cool-season turfgrass.

Introduction

According to a turfgrass industry survey, 18,207 km^2 (1,820,700 ha) of turf existed in Florida in 1991-92. Industry sales and services amounted to approximately $7 billion during that time (Hodges et al., 1994). In 2003, Morris estimated that there were 202,300 km^2 (20,230,000 ha) of turf in the U.S., with approximately 67% found in home lawns Florida has the second largest withdrawal of ground water for public supply in the U.S. (Solley et al., 1998). The most recent estimation of the turf area in the USA was presented by Milesi et al. (2005), reporting a total estimated turfgrass area of 163,800 km^2 (+/- 35,850 km^2 for the upper and lower 95% confidence interval bounds-equivalent to 16,380,000 +/- 3,885,000 ha), which include all residential, commercial, and institutional lawns, parks, golf courses, and athletic fields (Fender, 2006). The study was based on the distribution of urban areas from satellite and aerial imagery. If considering the upper 95% confidence interval bound, that would represent 199,650 km^2 (19,965,000 ha) and this estimate reasonably compares to the estimates of Morris (2003).

Estimates in Florida indicate that 30-70% (FDEP, 2001) of residential per capita water use is for landscape irrigation. Landscape ordinances and water conservation rebate programs from Texas, Arizona and California promote the use of water conserving plant species and the reduction in the amount of landscape area planted to turfgrass in urban landscapes. Little evidence was available to document the impacts of these ordinances and programs on reductions in water as of 2003 (Havlak, 2003). However, a study funded by Tampa Bay Water that suggests that landscape water conservation ordinances are not consistently enforced resulting in poor compliance in Southwest Florida. Thus, there are likely minimal water conservation benefits (Tampa Bay Water, 2005).

Turfgrass provides functional (i.e. soil erosion reduction, dust prevention, heat dissipation, wild habitat), recreational (i.e., low cost surfaces, physical and mental health) and aesthetic (i.e. beauty, quality of life, increased property values) benefits to society and the environment (Fender, 2006; King and Balogh, 2006). However, critics of grass maintain it not only wastes time, money and resources, but even worse, that efforts to grow grass results in environmental pollution. Critics recommend the total replacement with what are termed 'native plants' (Fender, 2006).

The water requirements of most turfgrasses have been established by scientific study (Beard and Green, 1994). Water use of turfgrasses is the total amount of water required for growth and transpiration plus the amount of water lost from the soil surface (evaporation), but because the amount of water used for growth is so small, it is usually neglected (Huang, 2006; Augustin, 2000). Most of the water transpired through the plant moves through openings in the leaves called stomates, which results in a cooling effect resulting from the evaporation process. The amount of water lost through transpiration is a function of the rate of plant growth and several environmental factors, such as soil moisture, temperature, solar radiation, humidity and wind. Transpiration rates are higher in arid climates than in humid climates because of the greater water vapor deficit between the leaf and the atmosphere in dry air. Thus, transpiration losses may be as high as 10 mm of water per day in desert climates during summer months; whereas in humid climates under similar temperature conditions, the daily losses may be only 5 mm of water per day (Duble, 2006). The application of water to turfgrass in amounts exceeding its requirements can be attributed to human factors, not plant needs (Beard and Green, 1994).

Crop coefficients (K_c's) used in irrigation are the ratio of actual evapotranspiration (ETa) to reference ET. Reference ET (ETo) is the ET that is calculated from a surface of actively growing grass that is maintained at 12 cm and is well-watered (Allen et al., 1998). Once K_c's have been generated, only estimates of ETo are required to estimate ETa needed for scheduling irrigation (Allen et al., 1998). Thus, using different ETo equations will generate different K_c values, which is one reason the ASCE EWRI Standardized Reference ET methodology was developed (Allen et al., 2005). Allen et al. (2005) stated "there can be considerable uncertainty in K_c-based ET predictions due to uncertainty in quality and representativeness of weather data for the ETo estimate and uncertainty regarding similarity in physiology and morphology between specific crops and varieties in an area and the crop for which the K_c was originally derived.

Crop coefficients can vary substantially over short time periods, so monthly averaged coefficients are normally used for irrigation scheduling (Carrow, 1995). These coefficients can be averaged to yield quarterly, semi-annual, or annual crop coefficients (Richie et al., 1997), although averaging K_c's reduces monthly precision and turfgrass may be under-irrigated during stressful summer months. Factors influencing K_c for turfgrasses are seasonal canopy characteristics, rate of growth, and soil moisture stress that would cause coefficients to decrease, root growth and turf management practices (Gibeault et al., 1989; Carrow, 1995).

Scientific irrigation scheduling regimes which calculate irrigation water requirements based on ETa have been suggested as one means of improving irrigation management of turfgrass (Brown et al., 2001). ETo data are available from public weather networks in different regions of U.S.; however, access to reliable K_c's becomes a limiting factor when implementing scientific irrigation scheduling systems for turfgrass.

The objective of this study is to perform a literature review showing reported crop coefficients for both warm and cool season grasses available in the U.S.

Methods

A review of the literature was performed to summarize K_c's determined for both warm and cool season grasses. Many studies have been conducted on turfgrass water use with a wide variety of methods. In most of the studies, weather data were not reported. Therefore, K_c values could not be calculated. In addition, turfgrass water loss data was assembled for Florida conditions.

Literature review

Many literature sources and agencies reference warm and cool season turfgrass K_c's developed in California in the early 1980's as reported by Gibeault et al. (1989). These K_c values were developed and documented in a series of publications, none of which appear in the peer reviewed literature, thus they are difficult to find in some cases. Turfgrass K_c's will exhibit considerable variation during the growing season which is due in part to plant cover, growth rate, root growth and stage of the plant development and turf management practices (Gibeault et al., 1989; Brown et al., 2001). K_c data for warm-season grasses included common and hybrid Bermudagrasses, St. Augustinegrass, Bahiagrass, Centipedegrass, Zoysiagrass, and Seashore Paspalum. K_c values for cool-season turfgrasses included Kentucky bluegrass, Perennial ryegrass, Tall Fescue, mixed grasses, shortgrass and sagebrush-grass.

One of the most comprehensive studies provided an estimate of Penman crop coefficients for various grasses grown in southeastern U.S. was presented by Carrow (1995), including Tifway bermudagrass (*Cynodon dactylon* X *C. transvaalensis*), common bermudagrass [*C. dactylon* (L.) Pers.], Meyer Zoysiagrass (*Zoysia japonica* Steud), common Centipedegrass [*Eremochloa ophiuroides* (Munro.) Hack.], Raleigh St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze], and Rebel II and Kentucky-31 tall fescue (*Festuca arundinacea* Schreb.). The study was conducted in Griffin, GA on research plots, during 1989 and 1990, where these seven turfgrasses (including warm-season and cool-season turfgrasses) are commonly used in the mid- to upper Southeast region. Reference crop evapotranspiration (ETo) was determined by the FAO modified Penman equation, which is described by Doorenbos and Pruitt (1984) as:

$$ETope = c[W \times Rn + (I-W) \times f(u) \times (ea-ed)],$$

Where ETope is reference evapotranspiration (mm), c is adjustment factor to compensate for the effect of day and night weather condition, W is temperature related weighing factor for the effect of radiation on ETo (mm), I is irrigation (mm), Rn is net radiation in equivalent evaporation (mm), f(u) is a wind function, ea is saturation vapor pressure of air at the mean daily air temperature (kPa) and ed is actual vapor pressure of air at the mean daily air temperature (kPa). Actual evapotranspiration (ETa) was derived from daily soil water extraction data from TDR soil moisture probes obtained during dry-down periods following irrigation or rainfall events when no drainage occurred. According to the author, the irrigation regime imposed moderate to moderately severe stress on the turfgrass but this would be representative of most home lawn irrigation regimes. ETa was determined by soil-water balance method. Therefore, K_c was calculated dividing ETa by the FAO modified Penman ETo. For all grasses, coefficients varied substantially over short time periods, but data was presented as monthly averages. Tifway bermudagrass exhibited the least variation (0.53-0.97 for K_c) and Meyer Zoysiagrass the most (0.51-1.14 for K_c). In general, warm-season species ranged from 0.67 to 0.85, while cool-season grasses were 0.79 and 0.82 (Table 1). A similar study using cool-season and warm-season grasses under warmer conditions (California) was presented by Meyer and Gibeault (1987). They developed a set of crop coefficients for Kentucky bluegrass, perennial ryegrass, tall fescue (cool-season grasses) and hybrid bermudagrass, zoysiagrass and seashore paspalum (warm-season grasses), that could be used by California turfgrass managers to determine on-site water use by both type of turfgrasses. Crop coefficients ranged from 0.60 to 1.04 for cool-season turfgrasses, and from 0.54 to 0.79 for warm-season grasses. ETc was calculated as the actual applied water divided by the extra water factor (EWF_{90}), which was 1.35. EWF_{90} is the amount of water needed to apply 1 inch

(2.5 cm) to 90% of the area. In this experiment the coefficient of uniformity, CUs – 87% and EWF90 =1.35:

$$EWF90 = 1/[1-(t^{\sigma}/X')$$

Where t = probability value from statistical table related to the number of cans in the test and the percentage of the area that must receive a unit amount of water (90%). Σ is a function of individual can value, the mean of all values (X') and number of cans. ETc was for the 100% ET regime, since 60% and 80% were also tested. ETo was calculated using the modified Penman equation (Doorenbos and Pruitt, 1977).

Meyer et al. (1985) used data from a study reported by Marsh et al. (1978) to develop the California K_c's. The authors report that the K_c values were developed by a Bureau of Plant Industry (BPI) evaporation pan measurement adjusted to a standard Class A pan and then adjusted to ETo based on factors presented by Doorenbos and Pruitt (1977). Thus, there were several adjustment factors based on generalized literature values rather than quantitative measurements. Furthermore, the ETc data reported by Marsh et al. (1978) were developed by measuring the irrigation application on tensiometer controlled field plots. This study was conducted during different years for warm and cool season grasses. Regarding the cool season grass study, the authors note "Evaporation was greater and rain less during these three years than during the previous study with warm season grasses". Thus, the California K_c values were developed with uncertain and general ETo values and it is likely the plots were not "well-watered" during the entire study.

Another study using bahiagrass (*Paspalum notatum* Flugge) was presented by Jia et al. (2007). Daily K_c values were determined for July 2003 through December 2006 in central Florida, where the eddy correlation method was used to estimate crop evapotranspiration (ETc) rates. ETo was calculated using the standardized reference evapotranspiration equation. Monthly K_c values were low in the winter time (dormant grass status) although the K_c values also decreased in the summer time from peak values in May (Table 1). In the southern area of Florida, the water budgets of a monoculture St. Augustinegrass (*Stenotaphrum secundatum* Waltz Kuntze cv.

‘Floratam’) and an alternative ornamental landscape were compared (Park and Cisar, 2006). ETc was determined by a water balance equation and ETo was estimated using the McCloud method. The average wet season crop coefficient for St. Augustinegrass was 0.30; however, for the dry season the crop coefficient increased to 0.51. These values are much lower than other literature values for warm season grass likely due to the over-estimation of ETo by the McCloud method (McCloud, 1955).

A study carried out in the humid northeast (Rhode Island) using Kentucky bluegrass (*Poa pratensis* L., ‘Baron’ and “Enmundi’), Red fescue (*Festuca rubra*), Perennial ryegrass (*Lolium perenne*) and hard fescue (*Festuca ovina*) during 1984 and 1985 showed that the mean crop coefficients ranged from 0.97 for hard fescue to 1.05 for Baron Kentucky bluegrass, as shown in Table 1 (Aronson et al., 1987). And, as a conclusion, an averaged K_c value of 1.0 would be appropriate for irrigation scheduling on all the grasses studied. K_c values were obtained dividing ETc data from weighing lysimeters, and ETo computed from two predictive methods, the modified Penman equation (Burman et al., 1980) and pan evaporation. The exact form of the equation used was:

$$ETo = [\ \Delta / (\Delta + \gamma)] + [\gamma / (\Delta + \gamma)] 15.36\ wf(ea - ed)$$

Where ETo is reference crop ET in J m^{-2} day^{-1}; Δ is the slope of the vapor pressure – temperature curve in kPa/^{o}C; γ is the ppsychometer constant in kPa/ ^{o}C; Rn is net radiation in J $m^{-2}day^{-1}$; G is soil heat flux to the soil in J $m^{-2}day^{-1}$, wf is the wind function (dimensionless); and (ea-ed) is the mean daily vapor pressure deficit in kPa.

Monthly crop coefficients for bermudagrass (*Cynodon dactylon* (L.) Pers.) overseeded with perennial ryegrass (*Lolium perenne* L.) were presented by Devitt et al., 1992. Lysimeters were installed at two golf courses and at a park in Las Vegas, NV. Each site was equipped with an automated weather station. Crop coefficients were calculated by dividing monthly ETa by Penman calculated ETo values. The greatest variability in the K_c values (all sites) occurred during the winter months (December to February) and only during this period did both the high management turf (golf courses) and the low management turf (park) have similar K_c values (Table 1). Significant differences were observed the rest of the year as the K_c values for the golf course sites were fit to a bell-shaped curve; the park site had a somewhat flat K_c response. Since the same mixed grass was grown at each site and because the soil type and water quality were similar, differences on Kc values were attributed to cultural management input, especially the fertilizer input. Nitrogen was applied at a rate 3 to 5 times higher, iron 6 to 8 times higher and phosphorus 13 to 24 times higher on the golf courses than on the park site.

Brown et al. (2001) developed Penman Monteith crop coefficients for warm-season 'Tifway' bermudagrass (*Cynodon dactylon* L. X *C. transvaalensis* Davy) in summer and overseeded 'Froghair' intermediate ryegrass (*Lolium perenne* X *L. multiflorum*) in winter at Tucson, AZ. Froghair is a new intermediate ryegrass which is designed for the overseeding market in the Southern regions of the U.S. Intermediates are genetic crosses using annual ryegrasses and perennial ryegrasses in the parentage (www.turfmerchants.com/varieties/TMi_**Froghair**.html). They related daily measurements of ETa obtained from weighing lysimeters to reference evapotranspiration (ETo) computed by means of the simplified form of the FAO Penman Monteith Equation (Allen et al., 1994, 1998):

$$ET_o = \{[0.408\Delta\ (R_n - G)] + [\gamma\ 900/(T+273)\ U_2\ (e_s{}^o - e_a)]\}/\ \Delta + \gamma(\ 1 + 0.34\ U_2)$$

where ET_o is the reference evapotranspiration rate in mm d^{-1}, T is mean air temperature in ^oC, and U_2 is wind speed in m s^{-1} at 2 m above the ground (and RH or dew point and air temperature are assumed to be measured at 2 m above the ground, also). Equation 3 can be applied using hourly data if the constant value "900" is divided by 24 for the hours in a day and the R_n and G terms are expressed as MJ m^{-2} h^{-1}.

For overseeded bermudagrass, a constant K_c of 0.8 would be effective for estimating ETa during the summer months, but not for non-overseeded bermudagrass, which has extended periods of slow growth and lower ETa during the spring and fall. Monthly K_c's for overseeded 'Froghair' intermediate ryegrass varied from 0.78 (Jan) to 0.90 (Apr), which showed that winter K_c's were dependent upon temperature (Table 1). Another study reporting K_c values for Tifgreen and Midiron hybrid bermudagrasses

(*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Davy), and Texturf-10 common bermudagrass (*Cynodon dactylon*) growing at plot level from sod in Tucson, Arizona (Garrot and Mancino, 1994), showed average K_c values ranging from 0.57 to 0.64 with Midiron being lowest and Texturf-10 being highest. Irrigation was made only when the turf showed symptoms of wilt. Time periods between irrigation events were referred to as soil dry down cycles (DDC). Turfgrass water use (ETa) was determined using two methods: (i) through the determination of gravimetric soil moisture from soil cores (0 to 90 cm depth, using 30 cm intervals) taken at the beginning (48 h after irrigation) and end of each DCC. The K_c's were calculated by dividing the actual consumptive use (derived from the gravimetric samples) by the cumulative ETo [modified Penman equation (Doorenbos and Pruitt, 1977)]. Daily K_c values varied, however, from as high as 1.50 to as low as 0.10. As soil water became limiting during the course of a DDC, K_c values declined, sometimes to < 0.10. These values depended mostly on the availability of water but very high values always occurred when solar radiation was low. This study implemented deep and infrequent irrigation regime under fairway conditions, when the turf showed symptoms of wilt and keeping the overall turfgrass quality above acceptable. Thus, the stress imposed during this study likely violated the "well-watered" concept.

A similar experiment applying deficit irrigation but using cool-season turfgrasses was presented by Ervin and Koski (1998) in Fort Collins, CO. Kentucky bluegrass (KBG, *Poa pratensis* L.) and tall fescue (TF, *Festuca arundinacea* Schreber) turfs were subjected to increasing levels of drought through the use of a line-source irrigation system with the idea to develop water-conserving crop coefficients (K_c) to be used with Penman equation estimates of alfalfa (*Medicago sativa* L.). Their research indicated that water conservation can be encouraged while still maintaining acceptable turfgrass quality by irrigating every 3 days with K_c values in the range of 0.60 to 0.80 for KBG and 0.50 to 0.80 for TF (Table 1).

Crop coefficients for rangeland were also determined (Wight and Hanson, 1990). This study used lysimeter-measured ET to determine K_c's under non-limiting water conditions from mixed grass (*Agropyron smithii* as dominant species), shortgrass

(*Bouteloua gracilis* as dominant species), and sagebrush-grass (*Artemisia arbuscula* as dominant species). From seasonal plots of daily ET/reference ET, lysimeter-measured ET, and daily precipitation, time periods were identified, following periods of precipitation, that met the conditions for determining K_c. The sites were South Dakota, Wyoming and Idaho, respectively. The K_c values were relatively constant among the 3 study sites and over most of the growing season ranging from 0.75 to 0.90 (Table 1). According to the conclusions, these are crude estimates because the soil water requirements necessary for the determination of K_c are seldom fully met, and it is difficult to determine when these conditions occur.

Results and discussion

Available K_c data for cool-season and warm-season turfgrasses for different locations in the U.S are presented in Table 1. The study period length, the methodology to determine K_c and the reference are specified. K_c data were plotted on graphs according to the turfgrass type (cool- or warm-season). Monthly K_c values for the summer months (May to October) and for the winter months (November to April) are shown in Figures 1 and 2.

Table 1: Summary chart showing turfgrass species, average K_c, methodology used to determine ET and K_c and respective references.

Turfgrass species	K_c	Study period length	Methodology	Reference/ Location
Bahiagrass	Jan (0.35) Feb (0.35) Mar (0.55) Apr (0.80) May (0.90) Jun (0.75) Jul (0.70) Aug (0.70) Sep (0.75) Oct (0.65) Nov (0.60) Dec (0.45)	July 2003 through December 2006	ETc: Eddy correlation method. ETo: Standardized reference ET equation. K_c: ETc/ETo	Jia et al., 2007. Central Florida.
St. Augustinegrass	Wet season (0.30) Dry season (0.51)	4 years	ETc: Water balance. ETo: McCloud method. K_c: ETc/ETo	Park and Cisar, 2006. South Florida.
Overseeded froghair ryegrass (Nov-May) – Winter (3-yr avg.)	Nov (0.82) Dec (0.79) Jan (0.78) Feb(0.79) Mar (0.86) Apr (0.90) May (0.85)	Nov. 1994 to Sept. 1997.	ETc: lysimeters (water balance). ETo: Penman-Monteith equation. K_c: ETc/ETo	Brown et al., 2001. Tucson, AZ.
Tifway bermudagrass (Jun-Sept) – Summer (3-yr avg.)	Jun(0.78) Jul (0.78) Aug (0.82) Sep (0.83)			
Kentucky Bluegrass Tall fescue	0.60 to 0.80 0.50 to 0.80	1993 to 1994	ETr: (Kimberly-Penman combination eq.) Eta: 80% ETr K_c: Eta/ETr	Ervin and Koski, 1998. Fort Collins, CO.
Tifway bermudagrass Common bermudagrass Meyer zoysiagrass Common centipedegrass Raleigh St Augustinegrass Rebel II tall fescue Kentucky-31 tall fescue K_c values are annual	0.67 0.68 0.81 0.85 0.72 0.79 0.82	First season: from 26 June to 10 Oct 1989 (data on the left) Second season: from 5/4/90 to 11/2/90 (data on the right)	ETc: soil moisture content (TDR_s) during dry-down periods when no drainage occurred. ETo: Penman equation. K_c = ETc/ETo	Carrow, 1995. Griffin, GA.

Turfgrass species	K_c	Study period length	Methodology	Reference/ Location
Bermudagrass/ Perennial rye	Jan (0.44) Feb (0.43) Mar (0.67) Apr (0.76) May (0.74) Jun (0.89) Jul (0.89) Aug (0.82) Sep (0.82) Oct (0.77) Nov (0.81) Dec (0.51)	1987 to 1989 (two golf course sites)	ETc: lysimeters (water balance). ETo: Penman equation. K_c = ETc/ETo.	Devitt et al., 1992. Las Vegas, NV.
Hybrid and common Bermudagrass: Texturf-10 Tifgreen Midiron	 0.64 0.60 0.57	1989 to 1991 These are annual K_c s	Water use determined by gravimetric method. ETa=actual water use ETo (mod. Penman) K_c =Eta/ETo	Garrot and Mancino, 1994. Tucson, AZ.
Bermudagrass/ Perennial rye	Jan (0.40 Feb (0.33) Mar (0.45) Apr (0.54) May (0.48) Jun (0.58) Jul (0.52) Aug (0.60) Sep (0.56) Oct (0.54) Nov (0.60) Dec (0.45)	1987 to 1989 (park site)	ETc: lysimeters (water balance). K_c = ETc/ETo	Devitt et al., 1992. Las Vegas, NV.
Mixed grass, shortgrass and sagebrush-grass	0.82 0.79 0.85	46 days at Newell (1969,1971) 86 days at Gillete (1968-1970) 121 days at Reynolds (1977-1984)	ETc: lysimeter (ETc was separated into an evaporation component [EP] and a transpiration component [Tp]. ETref: Jensen-Haise K_c = ETc/JHET	Wight and Hanson, 1990. Newell, SD. Gillette, WY. Reynolds, ID.

Turfgrass species	K_c	Study period length	Methodology	Reference/ Location
Kentucky bluegrass	July (1.03) Aug (0.84) Sept (1.0)	From July to September, 1984-1985	ETc: weighing lysimeters K_c: 1) Modified Penman equation	Aronson et al., 1987. Kingston, RI.
Red fescue	July (0.98) Aug (0.83) Sep (0.99)			
Perennial grass	July (1.05) Aug (0.88) Sept(1.02)			
Hard fescue	July (0.98) Aug (0.80) Sep (0.94)			
Cool season grasses	Jan (0.61) Feb (0.64) Mar (0.75) Apr (1.04) May (0.95) Jun (0.88) Jul (0.94) Aug (0.86) Sep (0.74) Oct (0.75) Nov (0.69) Dec (0.60)	Aug. 1981 to Dec. 1983	ETa: equals the actual applied water divided by the extra water factor (EWF90), which was 1.35 for this case. ETo= calculated using modified Penman equation. K_c: ETc/ETo	Meyer and Gibeault, 1987. Riverside, CA.
Warm-season grasses	Jan (0.55) Feb (0.54) Mar (0.76) Apr (0.72) May (0.79) Jun (0.68) Jul (0.71) Aug (0.71) Sep (0.62) Oct (0.54) Nov (0.58) Dec (0.55)			

In general, all grasses had substantial changes in crop coefficient values during the respective study periods (Figures 1 and 2). In Florida, bahiagrass K_c's varied throughout the year with a peak in May, when wind was strongest, cloud cover is lightest, and vapor pressure deficit was highest (Jia et al., 2007, Figure 2). They decreased in the summer due to weakening of these three variables with respect to ET. K_c's developed by Carrow (1995) showed increases in September (Figure 2), in spite of the moderate severe stress to the turf in the field plots. Apparently, the prolonged dry-down periods in August and early September resulted in a proliferation of roots within a moist soil zone deep in the soil profile and resulting in high ET values. An average of August and October coefficients may be better than the September coefficients for scheduling irrigation in September. Brown et al. (2001) concluded that within season K_c's may be relatively constant. They noted that K_c's were more variable in the summer season where cloud cover became more frequent, which supports findings by Jia et al. (2007). Also, different climates will have different green up and dormancy periods and these differences are reflected on the K_c values. These differences are evident in the comparison of K_c's developed by Brown et al. (2001) in Tucson and values developed by Devitt et al. (1992) in Las Vegas using bermudagrass. In summary, the results are mixed but it does appear that cool-season turfgrasses use up to 20% more water than warm-season turfgrasses.

Warm-season turfgrasses exhibited lower K_c values compared to the cool-season turfgrasses, reflecting their low water-use rates. Both types of turfgrasses overlapped ranges of K_c values in some circumstances; however, a uniform crop coefficient cannot be used for all grasses since every species does not perform in the same way, according to most of the references. On the other hand, Aronson et al., (1987) recommended a K_c value of 1.0 for irrigation scheduling on all the grasses they studied (Kentucky bluegrass, Red fescue, Perennial ryegrass and Hard fescue.

Some K_c values in the literature were developed under limited irrigation and it is likely the plots were not "well-watered" during the entire study as part of their objectives. These K_c values may be appropriate for water conservation in the location of the study, but should not be extended to other regions of the U.S. (Carrow, 1995; Garrot and Mancino, 1994; Meyer and Gibeault, 1987).

According to the ASCE manual (Allen et al., 2005) the calculation of crop evapotranspiration (ETc) requires the selection of the appropriate crop coefficient (K_c) for use with the standardized reference evapotranspiration, either for a short crop

(ETos) of tall crop (ETrs). New recommended abbreviations for crop coefficients developed for use with ETos would be denoted as K_{co}, and K_{cr} if ETrs is used.

$$ETc = K_{co} * ETos \qquad \text{or} \qquad ETc = K_{cr} * ETrs$$

Grass-based crop coefficients should be used with ETos. K_c values that can be used with ETos without adjustment are reported in FAO-56 (Allen et al., 1998) and ASCE Manual 70 (Jensen et al., 1990)

Finally, there is a need for seasonal adjustments when using K_cs for irrigation scheduling. So, to effectively use weather-based irrigation scheduling, turfgrass managers must select crop coefficients based on month and turfgrass species.

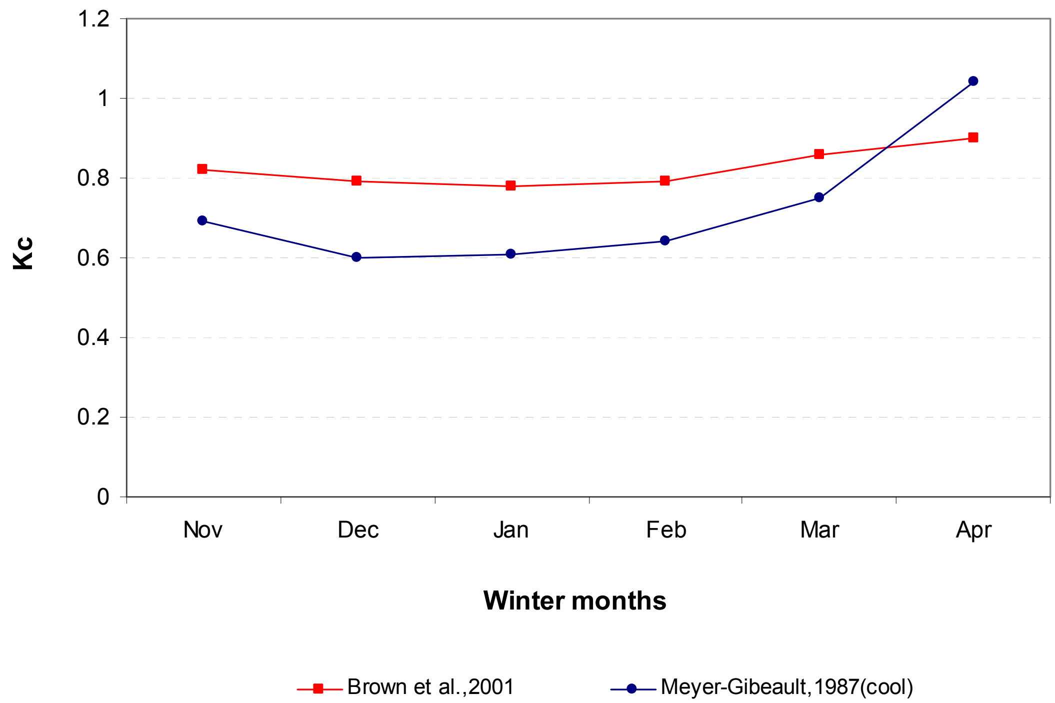

Figure 1: K_c values for cool-season turfgrasses according to different references.

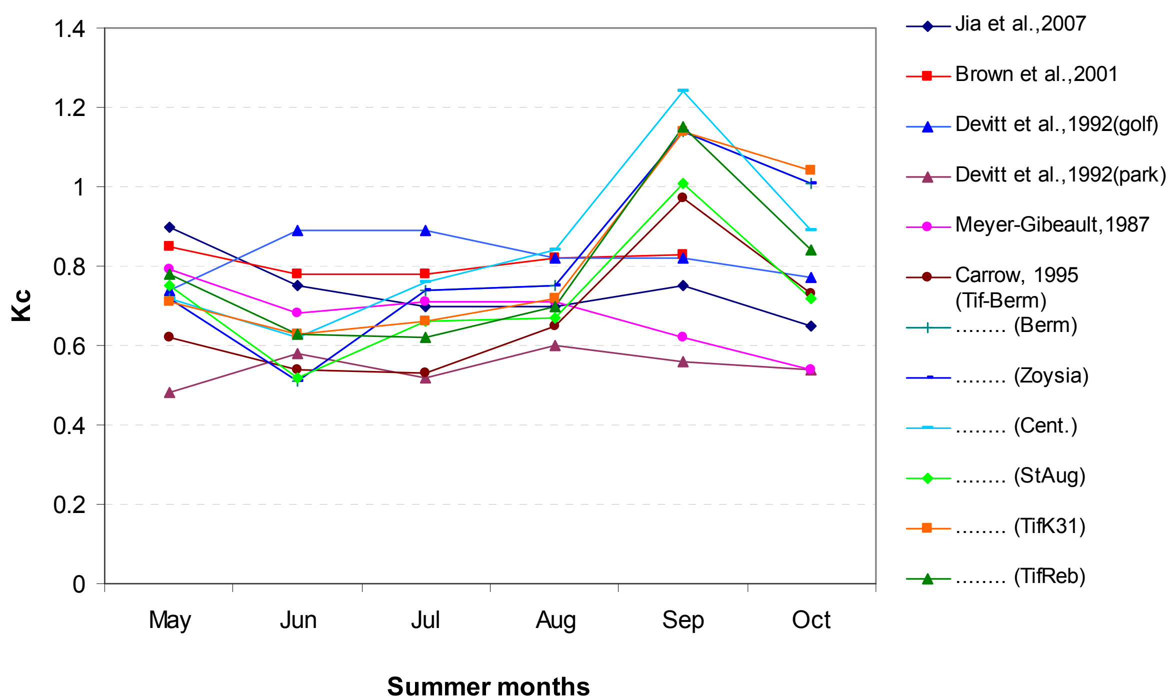

Figure 2: K_c values for warm-season turfgrasses according to different references.

Conclusions

- Crop coefficient values for warm-season and cool-season turfgrasses can be found in a wide variety of literature. Those published in peer reviewed literature were available and discussed in the present paper; others, however, published in other sources were difficult to find and access.

- A variety of methods were used to determine turfgrass K_c values across the various studies reviewed here. Many of these varying methods impact the resulting K_c values. For example, differences in ET_o estimation impact many of the literature K_c values; however, the Penman methods will likely agree the closest. In addition a number of studies used slightly stressed turfgrass conditions for K_c development and these values should be avoided.

- For warm season grasses, K_c values developed by Jia et al (2007), Brown et al (2001), and Devitt et al. (1992) appear to follow accepted methodology for K_c determination of warm-season turfgrass.

- In general, all turfgrasses (warm-season and cool-season) had substantial changes in crop coefficient values over the time period when measurements were conducted.
- The results are mixed but it does appear that cool-season turfgrasses use up to 20% more water than warm-season turfgrasses when water is not limiting.
- It is important to understand the seasonal water use over a period of repeated years rather than relying only on short study periods. Seasonal water use differences can be attributed to different green up periods in the spring and dormancy periods in the fall and winter across grass varieties. The different growth periods across different climatic regions impact the K_c values.
- Crop coefficients based on month and turfgrass species must be selected to effectively use weather-based irrigation scheduling.

Acknowledgements

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Monitoring and Control of SMART Irrigation system.

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Abstract

The U.S. Department of Agriculture has identified water management improvements as a primary agricultural policy objective. Water savings of 20-30% through improved water use efficiency in landscape and turf industries could offset the ever-increasing water demand. Evaluating water use through monitoring devices is a necessary component of any SMART irrigation system. Over the last 5 years, the Center for Irrigation Technology has been involved in testing a number of soil moisture sensors and climatologically based Evapotranspiration (ET) controllers in an effort to evaluate their accuracy, reliability and repeatability under different soil types, salinity and temperature conditions. Additionally, some of these devices were installed in the field for continuous monitoring of soil moisture/tension and were linked to a web based portal that allowed access from PC/PDA/Cell phone. Our results to date indicate that these technologies can be very efficient in monitoring and controlling water usage and thereby improving water use efficiency.

Introduction

The development of Smart Water Application Technologies™ or SWAT™ was initiated by water purveyors who wanted to improve residential irrigation water scheduling. SWAT™ is a national initiative designed to achieve exceptional landscape water use efficiency through the use of irrigation technology. SWAT™ identifies, researches, and promotes technological innovations and related management practices that advance the principles of efficient water use.

It is estimated that typical residential landscapes apply 30 to 40% more water than is required by the plants. It has been noted that much of the over-irrigation occurs during the fall season when plant/water demand is dropping off and the corresponding irrigation run times are not reduced accordingly. The widespread adoption of “smart” controllers and soil moisture sensors should conserve a significant portion of the excess water applied. Most in-ground irrigation systems are operated by a controller which requires frequent input from the operator (homeowner) to adjust irrigation run times during the year. A first step in ensuring that irrigation run times are optimized is to ensure that the soil water holding capacity is not exceeded, thereby reducing water losses via leaching and run off. In order to achieve this, it is important to have some kind of kind of devices/technology like soil moisture sensors or Evapotranspiration (ET) based controller.

Over the past couple of years, the Center for Irrigation Technology (CIT) has been working closely with water purveyors statewide and the Irrigation Association (IA) as part of SWAT™ in an effort to establish a testing protocol standard to verify the accuracy of commercially available soil moisture sensors and ET controllers. The next step would consist of having the ability to continuously monitor and control these controllers- preferably with remote access too.

Historically farmers have had to physically inspect crop conditions to determine if an action is needed to be taken, that is, “When to irrigate and how long to irrigate?” With the new and advanced controllers this physical inspection can be eliminated as the controller will make the intelligent decisions with respect to irrigation. But as we all know automation in an agricultural setup is much more different from an industry floor. Agricultural fields are susceptible to weather and other natural disturbances.

The objectives of this proposed study is:

a) Achieve real time data acquisition from the field (this data can be moisture data, plant stress, temperature etc.)
b) Based on changing field schedule/conditions, be able to remotely monitor and control switch, pumps or similar devices.
c) Collect the data in a portal such that the end user (farmer/irrigator) can access the data from any part of the world.
d) Based on the incoming real-time data from the field, provide recommendations to the farmer.
e) Send alerts to the farmer (email/text message to cell-phone), in case something goes wrong in the field. Example, send alert to the farmer if the line pressure drops all of a sudden due to a line break in the field or if the sensor signal fails due to line break.

Summary and Future work

So far we have been able to finish and test the beta version of the web portal. Data was remotely collected, stored, processed, tabulated and presented in a graphic dashboard format in our web portal from four remote locations (Idaho, Fresno (CA), Riverside (CA) & Chile). These data included soil moisture data, soil temperature data and electronic flowmeter readings.

We are currently testing the control components, recommendation module and the efficiency of a crop model that has been incorporated into our control module, the crop model is supposed to control the soil moisture thresholds automatically throughout the growing season for the particular crop. We are currently running our tests on a 0.8 acre plot, which has been divided into 12 beds of 400 feet length. A relatively smaller field allows us to better quantify inputs like water usage, fertilizer treatment and manpower inputs. At the end of the growing season this fall, we will take all the inputs into account and look at the yields to do a return on investment. Of the 12 beds, 6 are being irrigated manually using traditional farmers practice and the other 6 beds are being managed by the SMART controller for irrigation, the results of water usage from these tests beds will help us quantify water use efficiency.

Minimum Cup Quantity: An Update

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Introduction

For many years there has been discussion among auditors as to what is the minimum number of catch devices (cups) needed to perform an accurate and/or acceptable audit to determine DU_{LQ} —the measure of an irrigation system's distribution uniformity. There has been difficulty in reproducing consistent results on calculated DU_{LQ} when auditing the same area by different auditors. Cup spacing, the amount of water to capture, and other test procedures are standardized by the Irrigation Association.

This paper seeks to answer the question: "is there a minimum number of catch cups required for an audit to acquire an acceptable level of approximation on DU_{LQ}"? Given an actual audit data set, does DU_{LQ} change significantly the fewer cups one uses? By creating a random exclusion simulation of real data, iterative methods of forecasting and scenario generation are used to find the error in DU_{LQ} calculation by randomly throwing out real catch cup data points and recalculating DU_{LQ}. The process is repeated 1,000 times and statistically analyzed for each catch cup quantity scenario.

Theory

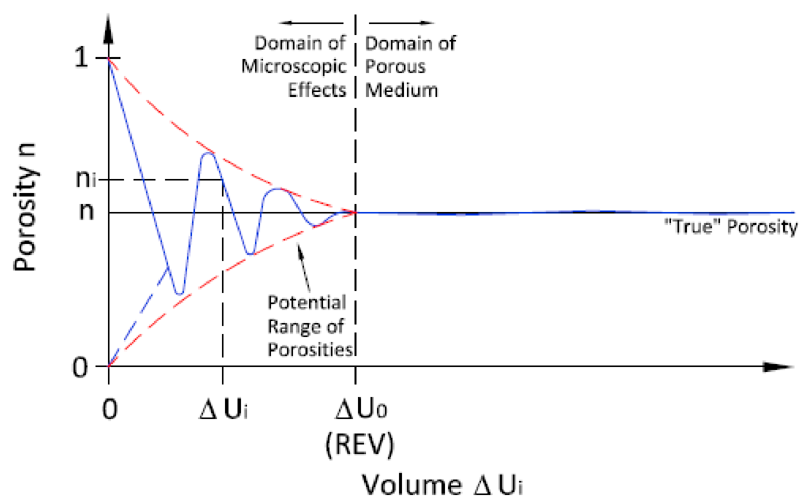
In order to determine if a minimum number of catch cups accurately describing the DU_{LQ} for an irrigation system exists, an understanding of what this represents is needed. For a given irrigation system, the DU_{LQ} is used to assess its uniformity. While there is a numerical value association (a percentage), this value is really just a qualitative estimate on how uniformly the system applies water. Audits, by definition, are just a small sample of the overall system performance. To get a "true" DU_{LQ}, an auditor would need an infinite number of catch cups covering the entire irrigation system, i.e., they would need to catch all the water. Obviously, this scenario is not feasible and auditors collect data from select areas within the irrigation system from a finite number of catch cups spaced appropriately. Therefore, DU_{LQ} is an "estimator" for system performance and is inherently variable. For example, if an auditor calculates the DU_{LQ} for an irrigation system to be 72.5, it would be acceptable for a designer to calculate uniformity and net precipitation rate from this result. One system that has a DU_{LQ} of 72.5 and another that is, for example, 67.4, in reality, have no appreciable difference in performance. The Irrigation Association (IA) provides general guidelines for distribution uniformity in that rotor systems around 80 are classified as "excellent", around 70 as "good", and closer to 55 as "poor". The goal of the audit is to ascertain whether a system is applying water uniformly or not. While quantitative data is collected during an audit, the end result should be interpreted as a qualitative assessment on system performance.

DU_{LQ} from an audit is an estimate of uniformity of water distribution for an irrigation system. If an infinite number of cups are required for the true value, and audit programs that are appropriate in size and coverage can closely approximate this value, then there exists a relationship between the number of catch cups and the representative DU_{LQ} value. Therefore, if for a given audit one increases the number of catch cups to better approximate the actual value, is the converse true? In other words, if one reduces the number of catch cups, does the DU_{LQ} deviate further from the real DU_{LQ}? Experience, and perhaps intuition, tells us that the answer to these questions is yes. But, DU_{LQ} from an audit is not required to be an exact or perfect representation of the truth: it is intended to be an estimate. So, we arrive at the original question laid out more specifically: is there a minimum number of cups required for an audit to acquire an acceptable level of approximation on DU_{LQ}?

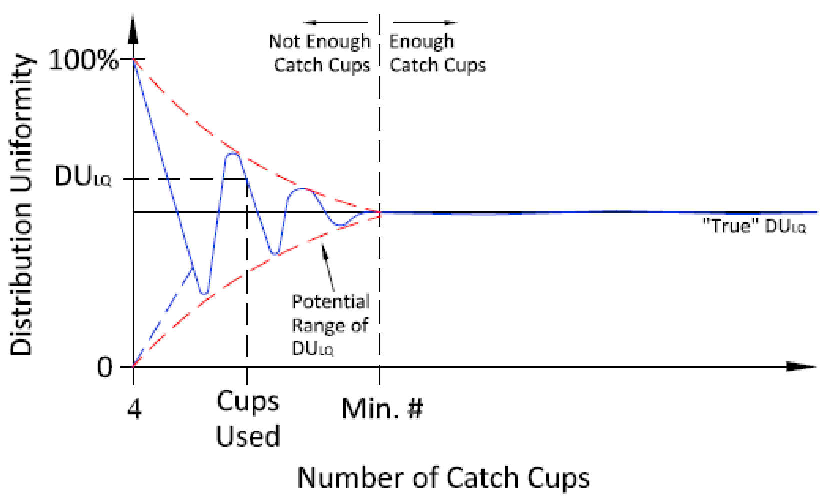
This question has been asked in other fields of science and engineering for different index parameters and estimators. Bear (1972) provides a robust discussion on the continuum approach and the concept of a Representative Elemental Volume (REV) for soil properties such as porosity as shown in Figure 1a. For example in production well design, if one could perform testing on the entire aquifer volume, the true porosity, n, would be known. Yet, a very good approximation (n_i) could be made if only 10 cubic yards of aquifer material were tested, or one cubic yard, and so on (each represented by some volume ΔU_i). Testing for porosity is generally limited to a few split-spoon samplers—the total volume of which would be, at most, on the order of one cubic foot. However, for example, if one split-spoon sample, or a cup, or a teaspoon of aquifer material is taken for testing, then the variations due to sample location, grain-size distribution, etc., can skew the resulting porosity values. "Microscopic effects" would begin to provide results that would not be "representative" values of the true porosity. In the examples described by Bear, there exists a minimum volume that can still represent the true value of the desired parameter (ΔU_0). This concept is crucial to testing design and construction management as minimizing testing minimizes costs. The same concept can be applied to irrigation auditing in determining a minimum number of cups to represent the entire system. The following research verifies the behavior of audits correlated to a REV in Figure 1b.

Analysis

The IA provides guidelines for auditing procedures in that cup spacing is somewhat standardized—relative to the spacing of the irrigation heads. Generally, cups are placed at regular and appropriate intervals at and in between heads. Cup spacing and the number of cups are related to one another when considering a fixed audited area such as a golf green or lawn. As it will be further explained below, this analysis takes actual audit data, randomly removes some of the cup data, simulates a new audit, and notes the effects on the calculated DU_{LQ}. It is assumed that the simulated audit (with less data points) have catch cups that are evenly spaced between each other. So, when data are removed from the original audit, we are, technically, changing the spacing, as the catch cups will spaced further apart. However, the simulated audits as a whole will still make an assessment on the entire area in question. This paper is not a study on cup spacing, per se: it is a study on the level of discretization required to properly calculate DU_{LQ}. As more catch cup data points are taken away, the spacing would be one cause for uncharacteristic uniformity calculations. The authors recognize that audits of rotary and fixed-arc spray sprinkler heads may differ and have included both types in the following analysis.



a) Representative Elemental Volume (ΔU_0) for Porosity



b) REV Concept for Irrigation Audit Catch Cups

Figure 1: The Representative Elemental Volume Concept (from Bear, 1972)

Actual Data DU_{LQ} Analysis		Random Exculsion Simulation Analysis	
Cup Count	**36**	*Cup Count*	**32**
Cups in LQ	**9**	*Cups in LQ*	**2**
Total Collection (mL)	**1497**	*Total Collection (mL)*	**287**
LQ Collection (mL)	**149**	*LQ Collection (mL)*	**25**
Average Total	**41.58**	*Average Total*	**35.88**
Average LQ	**16.56**	*Average LQ*	**12.50**
Actual DU_{LQ}	**39.81%**	*Random Data DU_{LQ}*	**34.84%**

a) Sample RES Program Simulation Output for an Actual Audit

Number of Catch Cups used from Actual	4	8	12	16	20	24	28	32	36
Actual Field DU_{LQ}	39.8%	39.8%	39.8%	39.8%	39.8%	39.8%	39.8%	39.8%	39.8%
Average Distribution Uniformity, DU_{LQ}	49.2%	43.4%	42.3%	41.0%	40.8%	39.9%	40.0%	39.8%	39.8%
Standard Deviation, s, of DU_{LQ} Sampling	18.1%	10.8%	7.9%	6.3%	5.2%	3.9%	3.1%	2.0%	0.0%
Minus 1 Standard Deviation	31.1%	32.6%	34.3%	34.7%	35.5%	36.1%	36.9%	37.8%	39.8%
Plus 1 Standard Deviation	67.3%	54.2%	50.2%	47.3%	46.0%	43.8%	43.2%	41.8%	39.8%
% Difference of Sampling DU to Actual DU	23.5%	9.0%	6.2%	3.0%	2.4%	0.3%	0.6%	0.1%	0.0%
Maximum Random Sampling DU_{LQ}	97.6%	90.3%	79.1%	61.6%	57.3%	53.1%	50.8%	47.6%	39.8%
Minimum Random Sampling DU_{LQ}	17.2%	21.3%	25.3%	26.0%	28.5%	31.3%	33.0%	36.0%	39.8%
Difference Between Max and Min DU_{LQ}	80.4%	69.0%	53.8%	35.6%	28.8%	21.8%	17.8%	11.6%	0.0%
Simulation Iteration	4	8	12	16	20	24	28	32	36
1	90.9%	27.2%	50.9%	32.8%	52.2%	42.6%	36.3%	38.7%	39.8%
2	58.8%	34.6%	42.2%	50.5%	38.8%	33.1%	42.6%	41.7%	39.8%
3	47.1%	44.4%	40.6%	47.4%	39.1%	39.5%	41.0%	42.7%	39.8%
4	43.9%	41.4%	50.0%	41.6%	42.4%	31.7%	39.7%	38.1%	39.8%
5	44.9%	48.6%	40.3%	33.9%	32.7%	41.3%	42.3%	39.3%	39.8%
6	46.2%	36.5%	55.1%	44.8%	34.4%	37.7%	36.0%	41.3%	39.8%
7	64.5%	31.1%	41.8%	35.9%	35.9%	38.7%	37.7%	38.5%	39.8%
8	35.7%	27.7%	49.6%	38.5%	36.5%	43.9%	37.5%	37.8%	39.8%
9	40.7%	54.3%	40.4%	55.2%	53.0%	38.6%	40.3%	40.2%	39.8%
10	20.7%	23.0%	28.9%	45.2%	46.5%	32.5%	41.8%	41.4%	39.8%
995	55.6%	30.2%	49.9%	29.2%	44.2%	36.9%	36.1%	38.4%	39.8%
996	24.5%	29.4%	40.4%	35.4%	34.8%	39.9%	37.6%	39.5%	39.8%
997	60.2%	44.2%	35.3%	50.0%	41.3%	36.9%	43.8%	37.7%	39.8%
998	31.0%	47.1%	49.6%	40.4%	48.4%	33.9%	38.0%	42.3%	39.8%
999	77.3%	45.7%	34.6%	42.6%	48.4%	32.9%	34.9%	39.6%	39.8%
1000	55.2%	69.3%	32.1%	48.6%	31.8%	35.3%	39.8%	42.2%	39.8%

b) Abbreviated Output of 1,000 Simulations of RES Data Sorted and Analyzed

Figure 2: Random Exclusion Simulation Analysis for Audits

Using the random number generator in Excel, a method was developed to take actual audit data, randomly remove a user-specified number of catch cups, and recalculate the new DU_{LQ}. A simulation was run for a specific number of catch cups 1,000 times each. For example, if an original audit had 40 catch cups, then 1,000 simulations were performed for a 36-cup audit, 1,000 for a 32-cup audit, etc. The average, minimum, maximum, and variance of the DU_{LQ} for the 1,000 simulations were calculated. These were compared to the actual distribution uniformity that was calculated in the effort to show the progressive degradation of reliability of using too few cups. The computer analysis performed is a Random Exclusion Simulation (RES) of real data to acquire a new DU_{LQ} calculation. Figure 2 displays excerpts from the program's interface to show how the analyses were executed. Note that these analyses adhere to IA guidelines for DU_{LQ} calculation by only using audits with a total catch cup count as a multiple of four. This way (as the IA intended it) when dividing data into quartiles, they are evenly grouped and no interpolation is required. The method of taking real data and generating simulated scenarios is not new in analytical studies. This "re-sampling" analysis method is almost identical to bootstrapping—a common statistical practice. However, bootstrapping requires that the re-sampled size be identical to the actual size. By using actual data in the simulations, we are utilizing the same distribution of catch cup volumes found in the field to apply it to a simulated run—giving a sense of reality in the synthesized audit and validating the analysis. A sensitivity study as to the number of simulations to run was also carried out. RES program runs for 5,000 and 32,000 (the maximum Excel could handle) simulations were performed. It was determined that there was no appreciable difference in the number of iterations used between 1,000 and beyond. The computing time was about 10 times greater with 5,000 simulations (10 minutes) while 32,000 simulations took over an hour (when the PC used didn't crash). Therefore, the accuracy level and computing time were found acceptable for 1,000 simulations.

Results

Figure 2b shows an abbreviated output for a typical RES program run. 1,000 simulations were performed for each new catch cup total. The actual audit data removes no cups in the simulation and, therefore, retains its actual data in the simulation (39.8 DU_{LQ} in all simulations). As the number of catch cups is reduced to 32, 28, etc., the DU_{LQ} changes for each simulation. The average DU_{LQ} for the each new catch cup count begins to slightly deviate from the actual field result by trending higher. What becomes noteworthy in the example shown in Figure 2 is that while the simulated DU_{LQ} stays very close to the actual value, the standard deviation of the simulated average grows larger. Moreover, the minimum and maximum ranges DU_{LQ} become larger by decreasing the number of catch cups. Graphically, these phenomena are shown in Figure 3.

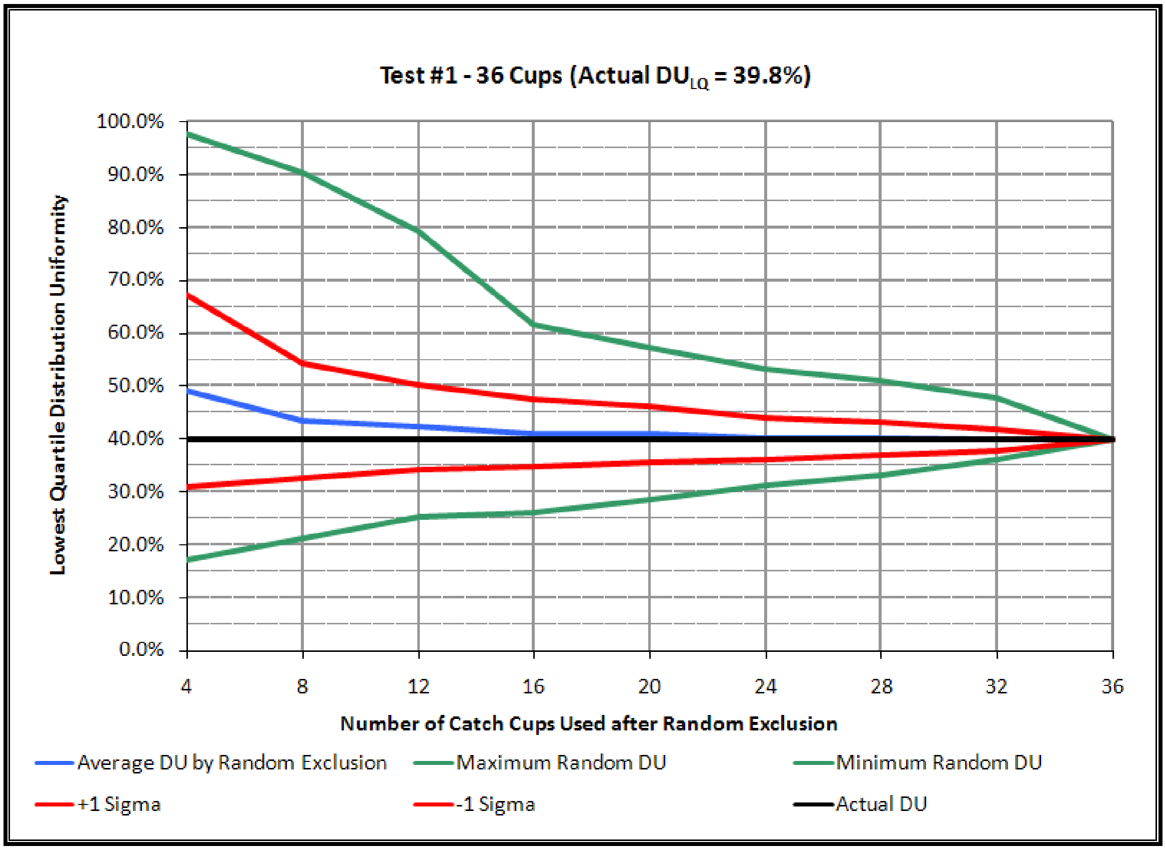


Figure 3: Graphical Results of Sample RES Program Output for an Actual Audit

The actual DU_{LQ} for this test (black line) is assumed to be the "true" DU_{LQ} of the system. If one reduces the amount of catch cups in an audit, on average, one should calculate almost exactly the same DU_{LQ}. However, the variations in results become greater, as shown by the standard deviations (red lines) and extreme values (green lines). If another auditor goes out to this site and re-tests the system with, for example, 20 cups, the probability becomes greater that he or she will come up with a DU_{LQ} that is not representative of actual conditions. The effects of low discretization levels become evident as fewer cups are used similar to the "microscopic effects" on porosity in Figure 1a.

To illustrate how the issue of using too few catch cups becomes a probability issue, consider Figure 4. This chart tabulates the number of occurrences out of 1,000 simulations that the simulated DU_{LQ} falls within a bandwidth of 2.5. Note that the bar graph for 36 cups, the number of cups used in the actual field audit (DU_{LQ} = 39.8), have 1,000 occurrences that fall between 37.5 and 40.0. The black vertical lines indicate the +/- 5 range on actual DU_{LQ} (34.8 - 44.8). The results of each catch cup scenario run 1,000 times are overlaid on each other to show the distribution of occurrences. The key visual aspects to understand from this figure are that when there are a sufficient number of cups in the simulated audits, the average DU_{LQ} of all iterations stays close to the actual DU_{LQ} and that the band of DU_{LQ} calculated is narrower and stays symmetrical around the actual DU_{LQ} value. On the other hand, when there are an insufficient number of cups used in simulation, the average DU_{LQ} trends away from the actual value, the distribution loses symmetry about the field DU_{LQ}, and the values are scattered about all ranges in a wide band of possible values. Based on the tabulated data, if, for example, one were to perform a new audit for the area analyzed and spaced out only 20 cups for the test, there is only 75% chance that the DU_{LQ} obtained will be between the +/- 5 range on actual DU_{LQ}. The probability drops to 43% when that number drops to 8 cups. However, this chance increases to 99% when 32 cups are used. Therefore, if the number of cups used in an audit goes down, there is a greater the chance that the audit will provide non-representative results.

This type of analysis with trends and probabilities on simulated DU_{LQ} calculation was performed using 13 actual audits on large spaced rotor sprinkler systems. These audits range from 32 – 128 cups and took place in locations all over the contiguous United States. The resulting data were combined in order to ascertain the key parameters in determining a minimum number of catch cups to accurately represent distribution uniformity. Five parameters were calculated from the combined analyses and shown in Figure 5:

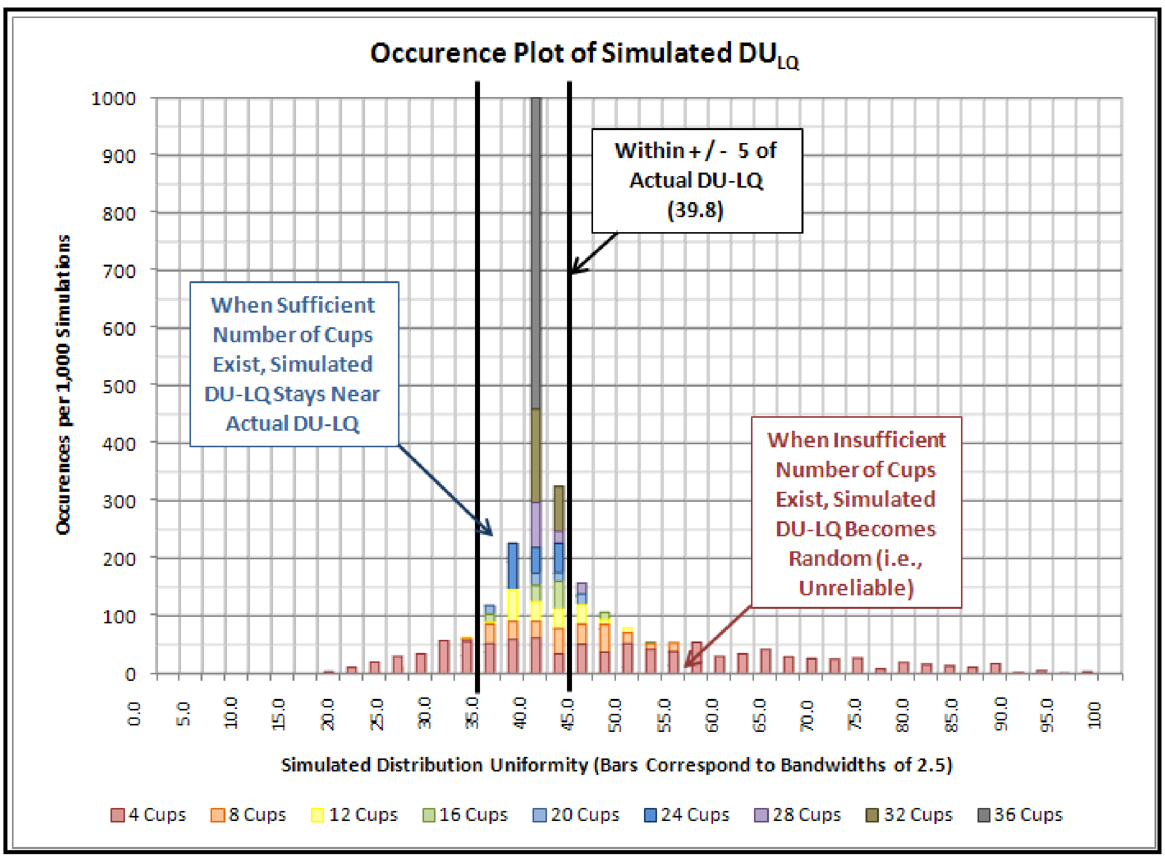


Figure 4: Number of Occurrences DU_{LQ} falls within bandwidths of 2.5 in 1,000 iterations of Random Exclusion Simulation data (Actual Field Audit has 36 Cups)

1.) Average Actual DU_{LQ} = 46
2.) Average on DU_{LQ} Simulations
3.) Change of Average Simulated DU_{LQ} to Average Actual DU_{LQ}
4.) Average Standard Deviation on DU_{LQ} Simulations
5.) Average Number of Occurrences (out of 1,000) Simulated DU_{LQ} is within +/-5 of Actual DU_{LQ}

Average Field DU_{LQ} = 46.3	Number of Catch Cups in Random Exclusion Simulations (All Data Analyzed)									
	4	8	12	16	20	24	28	32	36	40
Average Simulated DU_{LQ}	56.4	51.2	49.1	48.0	47.6	47.3	47.0	46.8	46.7	46.6
Difference Between Average and Simulated DU_{LQ} From Field DU_{LQ}	10.1	4.9	2.8	1.7	1.3	1.0	0.7	0.5	0.4	0.3
Standard Deviation of Average Simulated DU_{LQ}	18.5	12.1	9.2	7.4	6.1	5.0	4.2	3.2	2.5	1.5
Occurrences per 1,000 Simulations of DU_{LQ} Within +/-5 of Field DU_{LQ}	218	378	502	599	695	776	852	912	952	965

Figure 5: Combined Statistical Data on Large Spaced Rotor Sprinkler Audits

These calculated parameters were selected because it allows the experienced auditor to make some global sense on the sensitivity on catch cup totals. In trying to sift through this data and make some assertions, design judgment is used to try to narrow down a minimum number of catch cups to use. The criteria set forth for group averages were:

1.) The difference in average simulated DU_{LQ} is within +/- 1.25 of the actual DU_{LQ}. This would place the simulated DU within the bandwidth of 2.5 encompassing the actual DU in the Occurrence Plot of Simulations shown in Figure 4.
2.) A standard deviation of 5 in simulated DU_{LQ}. There is not much difference *qualitatively* between a DU_{LQ} of 41 and 51. A range of 10 is a sensible estimator for comparing audits.
3.) Greater than 75% of all occurrences (out of 1,000) are within +/- 5 of the actual DU_{LQ}.

These criteria should not be considered completely arbitrary. Given the analysis the authors have described, the IA guidelines for audits, and auditing experience, they are a feasible starting point to consider a minimum number. The number of catch cups where the averages for all 13 audits with large rotor sprinklers meet all the given criteria is 24.

When examining medium rotor sprinklers and applying the same criteria previously described, a similar result is found when averaging 5 audits. Figure 6 replicates the summary in Figure 5, except for medium throw rotors.

Average Field DU_{LQ} = 48.7	Number of Catch Cups in Random Exclusion Simulations (All Data Analyzed)									
	4	8	12	16	20	24	28	32	36	40
Average Simulated DU_{LQ}	57.3	53.2	51.6	50.6	50.0	49.6	49.3	49.2	49.0	48.9
Difference Between Average and Simulated DU_{LQ} From Field DU_{LQ}	8.6	4.5	2.9	1.9	1.3	0.9	0.6	0.5	0.3	0.2
Standard Deviation of Average Simulated DU_{LQ}	17.9	11.4	8.9	7.0	5.7	4.7	3.7	2.4	3.0	1.4
Occurrences per 1,000 Simulations of DU_{LQ} Within +/-5 of Field DU_{LQ}	245	412	543	647	742	817	885	924	924	958

Figure 6: Combined Statistical Data on Medium Spaced Rotor Sprinkler Audits

With the analysis above, again 24 cups is the minimum number of cups where all criteria are met. To this point, it would appear that initial spacing for audits would have very little effect on the minimum number of catch cans. In both the large and medium rotary sprinkler analyses, more audit data should be included to statistically strengthen these assertions. Nonetheless, Figures 5 and 6 show that when fewer cups are used in an audit, the calculated DU_{LQ} diverges from the true DU_{LQ}. These analyses attempt to pinpoint a minimum number of audit catch cups that minimize the amount of acceptable divergence from a representative value, i.e., to minimize error.

Spray sprinklers are generally much closer and in greater numbers within an irrigation system compared to rotors. Unlike rotary sprinkler audits where all sprinklers are operational at the same time over a given audit area, spray sprinkler audits generally require that individual zones are run sequentially due to flow restrictions and/or water availability. The same analysis above was applied to 6 spray zone audits ranging from 192 – 600 cups on outdoor testing facilities.

Average Field DU_{LQ} =64.3	Number of Catch Cups in Random Exclusion Simulations (All Data Analyzed)									
	4	8	12	16	20	24	28	32	36	40
Average Simulated DU_{LQ}	70.5	67.5	66.5	66.0	65.6	65.3	65.1	65.0	64.9	64.7
Difference Between Average and Simulated DU_{LQ} From Field DU_{LQ}	6.2	3.2	2.2	1.7	1.3	1.0	0.8	0.7	0.6	0.4
Standard Deviation of Average Simulated DU_{LQ}	13.7	9.7	7.9	6.9	6.1	5.6	5.1	4.8	4.4	4.2
Occurrences per 1,000 Simulations of DU_{LQ} Within +/-5 of Field DU_{LQ}	295	452	547	608	677	714	758	778	797	813

Figure 7: Combined Statistical Data on Spray Sprinkler Audits

When applying the same criteria to spray audits as in the rotor audits, only one of the 3 criteria is met at 24 catch cups (difference between simulated and average). The standard deviation criteria is met at 32 catch cups, while 750 occurrences or greater per 1,000 is met at 28 catch cups. While the desired result of 24 cups as a minimum to meet all criteria was not realized for spray data alone, at least as importantly, the same trends of increasing divergence from actual DU_{LQ} values with fewer catch cups remain intact.

Conclusions

In all analyses, the authors recognize that more audits are required to make a definitive answer as to what the minimum number of catch cups for an audit should be. The results presented above begin to point strongly towards 24 as a minimum number. The criteria for passing acceptability are based on total number of catch cups was synthesized from experience, design judgment, and basic statistics. For a more robust statistical analysis, involving confidence intervals, exceedance probabilities, etc., more audits would be required.

Average Field DU_{LQ} = 51.3	Number of Catch Cups in Random Exclusion Simulations (All Data Analyzed)									
	4	8	12	16	20	24	28	32	36	40
Average Simulated DU_{LQ}	60.1	55.7	54.0	53.0	52.6	52.3	52.0	51.9	51.7	51.6
Difference Between Average and Simulated DU_{LQ} From Field DU_{LQ}	8.8	4.4	2.7	1.7	1.3	1.0	0.7	0.6	0.4	0.3
Standard Deviation of Average Simulated DU_{LQ}	17.2	11.4	8.8	7.2	6.0	5.088	4.3	3.4	3.1	2.2
Occurrences per 1,000 Simulations of DU_{LQ} Within +/-5 of Field DU_{LQ}	243	404	522	611	700	769	835	881	907	926

Figure 8: Combined Statistical Data on All Audits

In essence, a prudent auditor should have in mind what their minimum level of error and variation is. Using the data presented above, it may be evident that "somewhere between 24 and 32 cups" would be acceptable. It would have been desirable to have the minimum number be 24 in each independent audit analysis based on sprinkler type. However, if a minimum number had to be selected from the data above, as a final analysis, all audits (coincidentally, 24 total) are averaged together and tested against the criteria described above.

Figure 8 displays the results of all audits averaged together regardless of sprinkler type. If we are to adhere strictly to the criteria for acceptable error presented above, then the difference between simulated and field DU_{LQ} would be met at 24 cups, the number of occurrences criterion would be met at 24 cups, but the standard deviation of simulated DU_{LQ} would be met at 28 cups. However, since the criteria presented above are based mostly on experience and judgment, both would indicate to the rational auditor that at a standard deviation of 5.088, 24 catch cups could be within the realm acceptability for error in irrigation auditing.

More catch cups in an audit lead to less error and a more realistic sense as to the “true” DU_{LQ} of an irrigation system. However, based on the data and ideas presented above, with time and money as constraints for set up, testing, and analysis of audits, the minimum number of catch cups to have the best chance of finding a “representative” value for DU_{LQ}, and thereby ascertaining the “true” efficiency of an irrigation system, is 24.

Maximizing Irrigation Distribution Uniformity with Catch-Can Performance Data

J. J. Gilbert, CLIA, CGIA

Abstract. *Continued demand for high quality sports and recreation turf facilities has driven many innovations in the irrigation industry. Increasing irrigation distribution uniformity has been a major goal behind many design and management decisions. Using scheduling coefficients to compensate for poor irrigation uniformity increases water use and extends application times beyond what may be practical or safe. Knowing the actual precipitation rates of every individual zone in an irrigation system can provide the information needed to increase distribution uniformity and reduce over or under watering.*

An irrigation audit of a 12-zone, block design, NCAA men's baseball field was completed to address non-uniformity issues. All zones were tested separately and individual precipitation rates determined. Two hundred fifty-three catch cups were used in the analysis. Distribution uniformity was determined as operated by the groundskeeper and after inputting the correct precipitation rates of all zones.

Distribution uniformity was improved nearly 9% compared to groundkeeper controlled irrigation management practices and was 20% greater than a typical audit outcome using this technique. In addition, actual measured precipitation rates were determined allowing for more precise irrigation scheduling and optimization of overall irrigation system performance.

Keywords. *Optimization, distribution uniformity, precipitation rate, RTM, sports turf.*

Introduction

Currently audits are done after all known problems with an irrigation system have been addressed. Performing an audit after everything has been fixed makes it impossible to document any changes, positive or negative, as a result of repairs. Also, audits are usually only conducted once and overall performance and irrigation scheduling based on this single event. Current guidelines suggest that, for rotors, each sprinkler stream pass over an individual cup at least five times. This may not be adequate to truly represent the performance of an irrigation system. In personal examination of this observation, I believe that an audit should be conducted over multiple days (~3), and values from individual test runs added together (pooled) to calculate overall performance. In performing an audit three separate times, differences in predominant wind direction (even when very calm), operating pressure, sprinkler rotation speed, and even air humidity tend to normalize. Distribution uniformity always improves when pooled data from multiple audits on an individual sprinkler system are compared to single event testing.

Most audits are not used to determine sprinkler precipitation rates, but water management decisions are decided based on the outcome of an audit. By using the Low-half Distribution Uniformity (DU_{LH}) as determined by an audit to calculate a run-time modifier (RTM) and relying on catalog precipitation rates, misapplication of water will result. Even if precipitation rates are based on audit results, these values can represent an average across several individual irrigation circuits. Slight differences in water pressure, sprinkler spacing, nozzle wear, sprinkler orientation and any obstructions to the water stream from the nozzle can influence irrigation delivery rates. These small differences are missed when precipitation rates are represented by using the average catch cup volume across adjacent zones.

To follow the recommended procedure for conducting an audit (IA, Recommended Audit Guidelines), the precipitation of all zones involved, must be known in advance. Since any number of factors can influence actual sprinkler performance, being able to predict the real precipitation rate of an irrigation system may be impossible. Determination of the precipitation rate for complex irrigation systems like those found on baseball fields, makes actuate prediction much more difficult.

A more comprehensive approach to irrigation system testing is warranted and would involve an audit "as is" prior to any repairs. Actual run times would be those that the irrigation manager normally uses during a regular scheduled irrigation event. From this test, the current irrigation system parameters could be determined. Distribution uniformity and actual applied water depth could be calculated from the "as is" audit and documented. The next step would be to make **<u>all</u>** repairs to the system. Check and adjust sprinkler arcs, measure pressure, make sure all sprinklers have the correct nozzles installed, adjust sprinkler orientation to surrounding grade, and remove anything that may obstruct the spray pattern (e.g. tall grass). Once all repairs are complete, test the system one zone at a time and determine individual precipitation rates for each zone. Then, conduct a final audit that reflects the differences in run times between zones to apply the same depth of water (Table 1.). The outcome of this procedure optimizes the sprinkler system, increases the distribution uniformity, and reduces potential water waste.

This technique is possible on all spray head or rotor irrigation systems, from those that have multiple sprinklers on a single circuit to valve-in-head rotor-type sprinklers commonly used on golf courses. Optimizing the performance of an irrigation system can reduce water use by minimizing the need to “cover up” deficiencies using large run-time modifiers. Operating an irrigation system that has been optimized makes both economical and ecological sense and should be seen as being more “green” and environmentally responsible.

Materials and Methods

An irrigation audit of a 12-zone, NCAA men’s baseball field was conducted to address irrigation non-uniformity. Each zone consisted of five to eight individual sprinklers in a block configuration. Each zone had water that was contributed to it from as many as three to four adjacent zones. All zones were operated separately so that individual precipitation rates could be determined. Two hundred fifty-three catch cups were used in the analysis.

Catch Can spacing was approximately 15’, which allowed for 3 catch cups between the individual sprinklers and 1 cup next to each sprinkler (IA, Recommended Audit Guidelines). Cups were laid out in a grid pattern. Gear driven rotor-type sprinklers were spaced at approximately 55-60’ with full-circle sprinklers occupying the center of the infield and part-circle heads along all perimeters.

Prior to zone-by-zone analysis of the entire field, an audit of a large central area in the outfield was conducted **(see figure 1.)**. In this audit 60 catch cups were used and spaced in a square grid pattern at 15 feet. Runtimes for all zones were controlled by the groundskeeper with a desired application of 0.25 inches. The irrigation in the center area of the outfield was audited on three separate nights and data pooled for calculation of distribution uniformity (DU) and total volume applied (aka. precipitation). This audit allowed for the determination of observed conditions under current management practices.

Results and Discussion

The DU (low quarter) as operated by the groundskeeper was approximately 65%; low half distribution uniformity (DU_{LH}) was 76%. The average applied water depth was 0.21”per night, 19% lower than intended. After the initial audit, both the number and size of the overly wet and dry areas were noted and reconfirmed initial concerns regarding uniformity.

The zone-by-zone audit was then conducted, one morning to measure and mark all locations for the catch cups and a second morning to operate each of the 12 zones and record catch volumes. After calculation of the individual zone precipitation rates and reprogramming the irrigation controller, the “center” area which was tested prior to runtime adjustment was re-tested. Low quarter DU was now 74% an increase of 9%, and DU_{LH} increased by 4%**.** Distribution uniformity for the entire field was also determined and averaged 71% (DU_{LH} = 80%).

Evaluating how an audit is typically done and using this technique are possible by ‘virtually’ comparing the expected catch volumes from each procedure. In a usual audit, all zones would be operated a set time based on either the catalog precipitation rates or by summing the expected total gallons per minute over a given area. With the proposed technique, recorded catch volumes would reflect zone-by-zone runtime adjustment based on measured precipitation rates. Fair comparison between these two procedures can only be made in the “center” square area which was initially tested. This area was irrigated by full-circle sprinklers and the water applied by 5 separate zones (Figure 1.). Had all 5 zones been run for 21 minutes with the intent to apply 0.25 inches (based on a catalog precipitation rate of 0.72) so that there would be about 25 ml or more in each catch-can (Table 1.), the DU_{LQ} would have been approximately 54% and the average hourly precipitation rate would be approximately 0.43 inches (Table 2.). Compare these results with a DU_{LQ} of 74% and an average hourly precipitation rate of 0.59” (5 ‘center’ zones) after optimizing the runtimes. By using a ‘set’ runtime for all full-circle sprinkler zones an underestimation of the potential distribution uniformity and precipitation rate would result. A runtime modifier (RTM) calculated using the DU_{LH} value determined by using a ‘set’ runtime would result in 21% more water being applied compared to a RTM determined after using the zone-by-zone optimization technique (table 2.). Additional over-application (approximately 37%) of water would also be made using the lower precipitation rate supplied by the ‘set’ runtime procedure compared with the zone-by-zone optimization technique.

Additional benefits to this type of an audit are the determination of actual precipitation rates. Catalog precipitation rates for the sprinklers tested ranged from 0.67-0.77, depending on square or triangular spacing (both of these sprinkler arrangements are used on this site) with an average of 0.72. Tested IPH values for the ‘center’ area averaged 0.59”. Catalog inch-per-hour (IPH) values have a difference of 13-30% or average approximately 22% greater than actual measured precipitation rates. Using catalog precipitation rates to schedule irrigation would result in a general under application or deficit irrigation.

Another advantage to zone-by-zone testing is being able to make changes in a single sprinkler and not having to re-test the entire field. For example, a nozzle change to one or more sprinklers may increase overall DU. Testing the possible improvement would involve operating only the affected zone(s), making sure to maintain the same cup grid as was used in the initial audit. Once the new data has been collected, replace the old data for the same zone in the original matrix and recalculate the precipitation rates and DU.

Conclusion

Improvements in overall irrigation distribution uniformity are possible using the zone-by-zone determination of sprinkler precipitation rates prior to an audit. Overall DU compared to that applied by the groundskeeper at this baseball field was improved using this technique. This is a highly maintained facility with a relatively small amount of turfgrass and irrigation is frequently monitored and adjusted. All sprinklers on this site were at an ideal orientation to the surrounding grade and had nothing obstructing the spray patterns. Greater improvements in DU have been observed using this technique on other landscaped turf areas (data not shown). Additional improvements in DU at the baseball field are possible and would involve the relocation of select sprinklers, changing some nozzles and making sure there was adequate water pressure on all zones.

This technique can be another tool available to the irrigation manager along with; 1) making sure the sprinkler system has adequate water pressure, 2) there is proper spacing between individual heads, 3) matched nozzles are used within any given zone, and 4) making sure there is nothing obstructing the spray pattern. This technique requires no physical changes to the sprinkler system other than adjustment of runtimes as dictated by the measured precipitation rates. In addition, improvements to an existing sprinkler system can be measured if an 'as is' audit is performed prior to making any changes to the system. In this way it makes it possible to document positive changes to an irrigation system and optimize performance. The other benefit to using the zone-by-zone audit is in only having to re-test smaller areas within a lawn area if changes are made to a single sprinkler. Data from a re-test area can be substituted with data from a previous test and new precipitation rates and increased DU often result.

Figure 1. Catch cup placement and large central area location at The University of Arizona Men's Baseball field.

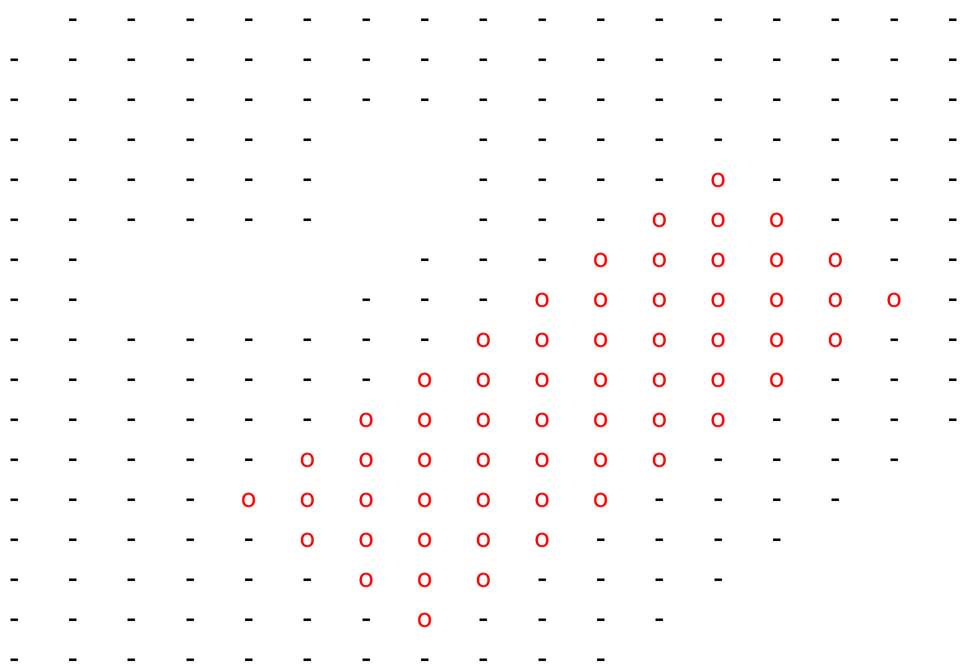


Table 1. Precipitation rates of all irrigation circuits as determined by zone-by-zone testing.

station #	IPH	min./0.25"	in./21 min.
1	**0.71**	21	0.25
2	**0.81**	19	0.28
3	**0.57**	26	0.20
4*	**0.71**	21	0.25
5	**0.59**	25	0.21
6*	**0.65**	23	0.23
7*	**0.56**	27	0.20
8*	**0.46**	33	0.16
9*	**0.59**	25	0.21
10	**0.66**	23	0.23
11	**0.71**	21	0.25
12	**0.58**	26	0.20

*Stations that contribute to 'Center' square.

Table 2. Distribution uniformity and precipitation rates for Men's baseball field at the University of Arizona.

	Large 'central' area		
	Pre	Post	'Virtual'
Low quarter DU	65.2%	73.6%	53.7%
Low half DU	76.0%	80.4%	66.2%
Inches applied (desired/actual)	0.25/0.21	0.25/0.24	-/0.11
IPH (avg.)	-	0.59"	0.43"
RTM	1.31	1.24	1.51
		Entire field	
Low quarter DU	-	71.4%	-
Low half DU	-	80.0%	-
Inches applied (desired/actual)	-	0.25/0.25	-
IPH (avg.)	-	0.63"	-
RTM	-	1.25	-

References

Irrigation Association. 2007. Recommended Audit Guidelines.

A Comparison of Fairway Distribution Uniformity Computed with Catch Can Data and with Soil Moisture Data from Three Sampling Depths

Douglas L. Kieffer[1], Mike Huck[2]

Paper presented at the 29th Annual Irrigation Show
Anaheim, CA
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Abstract

Distribution uniformity and precipitation rate are important for determining base irrigation schedules. Currently, uniformity is calculated using catch can data. There is interest in using soil moisture data instead because of ease of collecting data and because it measures root-zone moisture. Data were collected at 3 fairways identified as high, medium, and low-traffic areas. Catch cans were placed according to IA recommendations for auditing a fairway. Additional catch cans were placed to give a surplus of data locations. Soil moisture measurements were taken adjacent to each catch can with a portable wave reflectometer before and after irrigation. Sampling depths were 1.5, 3, and 4.8 inches. Distribution uniformities and net precipitation rates were computed for the full data sets and on pre-selected subsets. The reduced data set results were analyzed to determine minimum sampling points necessary to calculate a representative distribution uniformity and precipitation rate.

Introduction

Golf courses are very conspicuous consumers of irrigation water. It is estimated that U.S. golf courses use 2.1 billion gallons of water per day (Ostmeyer, 2008). And, in the southwestern U.S., golf courses average 149 million gallons per year and spend an average of nearly $108,000 per year for water (Ostmeyer, 2008). As water becomes an increasingly scarce and valuable commodity, there is increased pressure on superintendents to manage this resource prudently and efficiently. A golf course, however, consists of 5 main categories of irrigated area; greens, tee boxes, fairways, roughs and landscapes. Although the greens are the most visible and intensely managed features on the course, fairways and rough may offer the best opportunity to realize savings in irrigation water use. The reasons for this are twofold. First, fairways and rough constitute a much greater percentage of the total irrigated turf area on a course. Second, the turf quality threshold for fairway irrigation can be much lower than for the greens. So, there is a greater margin for error when managing these areas.

Evapotranspiration, which represents the amount of amount removed from the soil by the atmosphere and roots, is one way in which the timing of irrigation events can be determined. This data can be accessed from local weather networks or calculated from on-site weather stations. It has been shown that irrigation at 100% ET is not necessary to maintain acceptable turf quality on fairways planted to bentgrass (DaCosta and Huang, 2006), Kentucky bluegrass (Feldhake et al., 1984) and fescue (Feldhake et al., 1984; Fry and Butler, 1989).

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Deficit irrigation has been shown to promote deeper root depths and increased drought tolerance (Jiang and Huang, 2001). Conversely, excess water, whether from heavy rain or over-irrigation can yield anaerobic soil conditions and a moist environment that is conducive to the spread of fungal pathogens. Incidents of over-irrigation are more likely to occur late in the season, assuming irrigation schedules have not been adjusted to reflect shallow root systems resulting from summer heat stress. Lacking the root depth typical of early season, the turf can no longer access the same depth of soil-held water. Consequently, turf water consumption decreases without a corresponding decrease in applied water.

One technique for scheduling and determining if a sprinkler system is performing as expected is to perform an irrigation audit. Currently, this is most commonly done with catch cans placed in a pre-determined pattern depending on the sprinkler configuration and whether the area being audited is a green, tee box or fairway (IA, 2007). The catch cans capture the water applied during a typical irrigation cycle. Net precipitation rate and lower quartile distribution uniformity (DU_{lq}) of the system can then be computed from the volumes collected (Kieffer and O'Connor, 2007). The calculations are as follows:

$$PR_i = \frac{V_{avg} \text{ x } 3.66}{TR \text{ x } CDA}$$

Where:
PR_i = Precipitation rate for an individual catch can, (in./h)
V_{avg} = Average catch can volume (milliliters)
3.66 = Constant that converts milliliters to in.^{3} and minutes to hours
TR = Testing run time (minutes)
CDA = Catch device throat area (square inches)

To calculate net precipitation rate (PR_{net}), the average the catch device water volume must be calculated by dividing the total water volume of all catch devices by the total number of catch devices.

$$DU_{lq} = \frac{\overline{V}_{lq}}{\overline{V}_{total}}$$

Where:
DU_{lq} = Lower quartile distribution uniformity
$\overline{V}_{lq}$ = Average of the lowest 25% of catch can volumes (or soil moisture readings).
$\overline{V}_{total}$ = Average of all catch can volumes (or soil moisture of all readings).

Table 1 - Estimated DU_{lq} for golf systems by sprinkler type and system quality

Sprinkler Type	**Excellent** (achievable)	**Good** (expected)	**Poor** (if lower than this, consider not scheduling or improving irrigation system)
Rotary Sprinklers	80%	70%	55%
Spray Sprinklers	75%	65%	50%

This method is useful for evaluating the performance of the irrigation hardware (Mecham, 2001) as well as determining the precipitation rate. Table 1 lists a standard for using DU_{lq} to rate the quality of the irrigation system (IA, 2003). The catch can audit can be a time consuming process and its accuracy can be affected by wind, number of cups, cup placement and cup spillage. Further, it gives no information on whether the water reaches the soil or how the water distributes itself in the soil. For making irrigation decisions, there is an increased interest in using soil moisture data to calculate the distribution uniformity (Mecham, 2001; Dukes et al, 2006; Miller et al, 2005; Kieffer and O'Connor, 2007; Vis et al, 2007, Li and Rao, 2001). Miller et al (2005) found no correlation between the catch can DU and soil moisture DU. Warrick and Gardener, (1983) found that the uniformity of the irrigation played a major role in soil moisture uniformity, especially for subsurface systems. Li and Rao (2001) found water redistribution to be more important than irrigation uniformity, while Hunsaker and Bucks (1987) determined that soil texture was a more important factor. The volumetric water content (VWC) at field capacity, which is soil texture dependent, is a parameter that has been found to have a similar pattern of spatial variability to other stable landscape parameters (Krum et al, 2007). Therefore, spatial maps of VWC, provide useful information for managing turf grass. Krum et al (2007) used maps of VWC and the normalized difference vegetative index (NDVI) to create site-specific management units for precision agriculture applications.

Portable or in-situ soil moisture data can direct a turf grass irrigator when to irrigate and the amount of water necessary to replenish the root zone. And, while a soil moisture audit gives information on how to adjust the irrigation run-time to account for the uniformity of moisture in the root zone, it gives no information on the irrigation system's precipitation rate. In a 2-year study in Florida, Miller et al (2005) found little change in the precipitation rates measured by catch cans despite using fewer catch cans in the second year of the study. Vinchesi et al. (2007) performed a study with 133 catch cans on a 3600 sq. ft. putting green. They systematically computed precipitation rates on subsets of the full data set. They found that cup configurations consisting of as few as 4 to 9 cups gave precipitation rates similar to that of all 133 cups. Cup placement and the output characteristics of the sprinklers play a role in the minimum number of cups necessary to calculate an accurate precipitation rate.

This paper looks at a comparison of soil moisture and catch can audits on three portions of a golf course fairway in selected high-, medium-, and low-traffic areas. Soil moisture measurements were taken at 3 depths. Subsets of the catch can data set were examined to identify the minimum number of catch cans necessary to calculate an accurate precipitation rate.

Materials and Methods

All data were taken on the 12th hole at the North Shore Country Club in Glenview, IL on July 14 and August 11, 2008. The fairway for hole twelve is composed of Bentgrass and Poa Annua on silty clay loam soil. Three fairway areas, identified by the assistant superintendent as low-, medium-, and high-traffic areas, were evaluated in the study. The fairway has single-row irrigation with a 65 ft. spacing between Toro Model 835 sprinkler heads equipped with 80 PSI pilot valves with nozzle pressures operating between 74 and 80 psi. A rectangular measurement area (figure 1) approximately 65 ft. by 90 ft. was laid out in each treatment.

The longer side is perpendicular to the direction of play. The main sprinklers for each treatment were located near the center of each of the longer sides of the measurement area. Additionally, on the high- and medium- traffic sites, there were 7 additional sprinklers that operated simultaneously

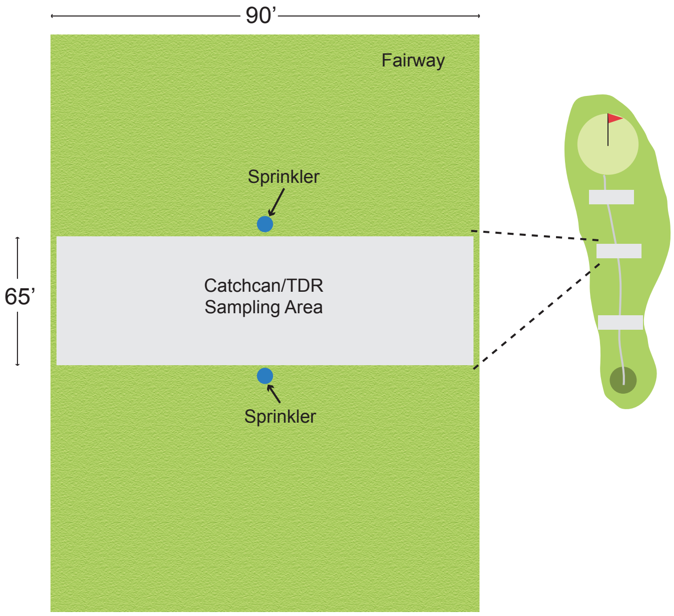


Figure 1. Diagram of sampling area within the fairway for hole 12.

with the fairway sprinklers and could potentially contribute water to the sampling area. Due to narrowing of the fairway near the green, the high-traffic area had only 6 additional sprinklers. Within each sampling area, 81 nails were used to mark out a 9 x 9 grid pattern. Catchments were placed 11 and 8 feet apart in the long and short direction respectively. A small plastic bowl (d = 5.9 inches) was placed at each nail (figure 2). Volumetric water content (VWC) readings were taken with a TDR300 soil moisture probe (Spectrum Technologies, Plainfield, IL) at each grid point (figure 3).

Figure 2. Catch cans laid out in 9 x 9 grid pattern.

Figure 3. Sampling soil moisture with TDR300.

In July, data sets were collected with 1.5, 3, and 4.8 inch rods connected to the meter. In August, only the 4.8 inch rods were used. Soil moisture data was geo-referenced with a Garmin 72 (Garmin International, Olathe, KS) connected to the TDR300. After the soil moisture data was collected for each treatment, the irrigation system was run in that zone for 12 minutes (figure 4).

Figure 4. Irrigating the sample area.

Wind speed was recorded with a hand held anemometer during each irrigation event. The volume of water captured by each bowl was measured after irrigation. The TDR300 measurements were then repeated at each site approximately 1 – 2 hours after the irrigation.

The lower quartile distribution uniformity (DU_{lq}) was calculated for both the soil moisture and catch can data sets. Visual assessment of spatial variability was done using 2-dimensional color plots of soil moisture and catch can data created using the SpecMaps ProTurf mapping utility (Spectrum Technologies, Plainfield, IL). Precipitation rates were calculated using the 81 catchments and pre-selected subsets (Appendix 2). The number of cups in each subset ranged from 4 cups to 41 cups. These subset precipitation rates were then compared to the precipitation rate estimated by the full data set to identify the minimum number of cups necessary to estimate an accurate precipitation rate.

Results and Discussion

Distribution Uniformity

In the weeks preceding data collection, northern Illinois received above-average rainfall. In the Chicago area, 1.85 inches fell from July 6 to July 13 and 2.43 inches from August 3 to August 10 (National Weather Service data for O'Hare International Airport). Additionally, prior to the August sampling date, the irrigation system had been run over the weekend. Therefore, the soil profile was fairly saturated at sampling time. This has likely contributed to somewhat higher soil moisture uniformity data than might otherwise have been recorded in a dry season. However, under normal management practices, the fairway would be receiving regular water applications so the data represent realistic conditions.

Table 2. Summary of lower quartile distribution uniformity (DU_{lq}) calculations.

Date	Traffic Level	CC	5Pre	5Post	3Pre	3Post	1.5Pre	1.5Post	Wind speed (mph)
			Audit Type						
July 14	High	*62*	92	88	89	86	90	88	5
	Medium	*78*	87	87	88	85	89	86	5
	Low	*65*	83	84	83	83	85	84	2
August 11	High	*76*	89	88	-	-	-	-	4
	Medium	*66*	84	83	-	-	-	-	6
	Low	*70*	81	81	-	-	-	-	2

CC, results from catch-can audit; Pre, data taken prior to irrigation; Post, data taken following irrigation; Numbers in Audit Type columns (5, 3, 1.5) refer to data from TDR300 connected to 4.8", 3", and 1.5" rods respectively.

The results of the lower quartile distribution uniformity (DU_{lq}) calculations are summarized in table 2. Distribution uniformity for the catch cans is always lower than that calculated from the soil moisture data. The wind speeds for the high- and medium- maintenance sites were a bit high but within the maximum threshold of 8 mph recommended by the Irrigation Association. So, wind alone does not account for the differences in uniformity. One or two cups near the sprinklers on the high- and low-maintenance sites tipped and spilled on each sampling date. But, considering the large number of cups involved in this study, this will have a minimal effect on the DU_{lq} computation. Lower half distribution uniformity, DU_{lh}, was also calculated and compared to DU_{lq}. A linear regression of these two parameters yields a relationship between the two as $DU_{lh} = 0.663\ DU_{lq} + 34.5$ which compares well with the equation given by the Irrigation Association, $DU_{lh} = 0.6143\ DU_{lq} + 38.6$.

The soil moisture uniformities are all very high. There is no difference between the uniformity seen before and after the irrigation system is run. This could be due to the fact that the initial soil moisture content was already very high. Consequently, the additional water added by the irrigation did not redistribute as much as it would in a drier soil profile. The expectation would be that the uniformity would increase as moisture is sampled deeper in the profile. This is because the near-surface soil moisture will evaporate at a faster rate and reveal the spatial variability in soil moisture. However, there is no difference or trend seen in the uniformities at the different sampling depths. Again, high soil moisture contents could be masking this effect.

There is a trend for soil moisture DU_{lq} to increase with increasing traffic level. A possible explanation could be that, as traffic increases, the likelihood of the traffic being more evenly spread across the site increases as well. Factors such as compaction and turf wear that impact the infiltration of water will be more evenly spread as well. These differences translate to greater uniformity in soil moisture content.

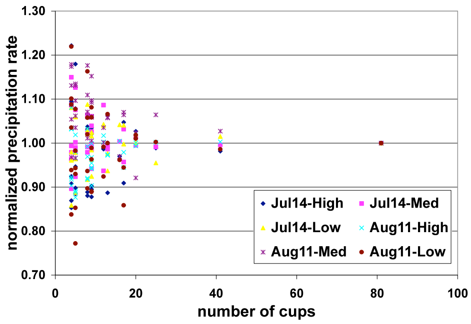
Map Analysis

Appendix 1 shows 2-dimensional maps of each soil moisture and catch-can data set. The overall pattern of soil moisture variability is very similar across sampling date, sampling depth, and for the pre- and post-irrigation sampling. For each sampling date, a uniform data range is used for all the maps. This allows for easier discernment of differences in location and sampling depth. The patterns can be summarized as follows:

-High Traffic - Wet in the southeast corner, dry in the southwest corner, dry in the north central portion.
-Medium Traffic - Wet in the south and north central portions (near the sprinkler heads). Dry in the east and west central sections.
-Low Traffic - Wet in the southern section. Dry in the northwest and north central portions.

As expected, there is a slight increase in the overall soil moisture content after the irrigation cycle. Therefore, the wetter areas in the post-irrigation maps have a darker blue color than the corresponding pre-irrigation map. There are no visible similarities between the distribution pattern in the soil maps for a given sampling site, and the map of catch can data. For example, comparing the catch can and soil moisture maps for the high traffic area for July shows that the southern part of the maps are opposite one another. The soil moisture maps show it wet in the southeast and wet in the south east. The catch can map is opposite this. This could be related to surface runoff from rain events such that the soil moisture map is evidencing the slope characteristics of this part of the fairway. For the medium- and low-traffic areas, there are noticeable bands of soil moisture that could also indicate variation in slope. These bands are more discernible in the data from the 4.8” rods where the overall range in soil moisture values is smaller.

Precipitation Rate



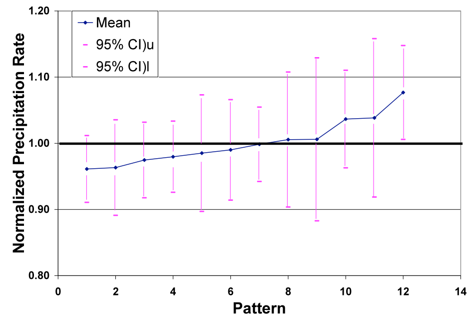


Figure 5. Normalized precip rates as function of number of cups.

Figure 6. Mean precip rates for 4/5 cup combinations (by pattern).

Although the portable soil moisture measurements can be used to measure and evaluate the uniformity of the fairway, they can not be used for determining the precipitation rate. The precipitation rate and uniformity are both necessary for computing the run-time for the irrigation system. So, catch cans will still need to be part of the audit process. But, the quantity necessary to compute a DU may not be necessary to get a reasonably accurate precipitation rate. In this study, more catch cans were used than would be practical for a typical audit. We calculated the precipitation rate for the full 81-cup data set. Then, following the work of Vinchesi et al. (2007), precipitation rates for a number of pre-selected subsets of the full set were calculated (Appendix 2). There were a total of 6 data sets (3 sampling sites x 2 sampling dates). The precipitation rates were normalized by dividing each subset precipitation rate by the 81-cup precipitation rate. This allowed all 6 data sets to be compared with each other. The data are summarized in Figure 5. It is evident that as the number of catch cans used to calculate precipitation rate is reduced, the greater the variability in the estimated precipitation rate. However, with even as many as 41 catch cans, the calculated value can over- or under-estimate the precipitation rate by 3%. Table 3 shows the normalized precipitation rates for 4 and 5 cup patterns. The means and corresponding 95% confidence intervals are plotted in figure 6. For certain patterns, the estimated precipitation rate is acceptably close to the 81-cup value. For this data set, the “4-square medium” gave the best estimate.

Table 3. Summary of precipitation rates calculated using pre-selected 4- and 5-cup subsets of the full 81-cup data set.

	July			August				
Pattern	Hi	Med	Low	Hi	Med	Low	Mean	StDev
5 Diamond Large	0.93	1.08	0.89	0.97	0.97	0.94	**0.96**	**0.06**
5 X-cross Small	0.88	0.98	0.96	0.89	1.13	0.93	**0.96**	**0.09**
5 X-cross Medium	0.95	0.99	0.98	1.02	1.06	0.85	**0.97**	**0.07**
5 X-cross Large	0.90	0.92	0.96	0.98	1.04	1.08	**0.98**	**0.07**
4-Square Small	0.85	0.96	0.96	0.92	1.17	1.04	**0.99**	**0.11**
4-Diamond Large	0.91	1.09	0.86	1.03	0.97	1.09	**0.99**	**0.09**
4-Square Medium	0.92	0.98	0.98	1.08	1.09	0.94	**1.00**	**0.07**
4-Square Large	0.87	0.90	0.96	1.03	1.05	1.22	**1.01**	**0.13**
5 Diamond Small	1.18	1.00	1.06	0.89	1.13	0.77	**1.01**	**0.15**
5 Diamond Medium	1.08	1.13	1.06	0.88	1.10	0.98	**1.04**	**0.09**
4-Diamond Small	1.22	0.99	1.08	0.92	1.18	0.84	**1.04**	**0.15**
4-Diamond Medium	1.09	1.15	1.08	0.90	1.13	1.10	**1.08**	**0.09**

Hi, Med, and Lo refer to data from the High-, Medium- and Low-Traffic areas respectively. Patterns are described in Appendix 2.

Conclusions

Our data, again, demonstrates that distribution uniformity calculated using soil moisture data is greater than for those calculated with catch can data. These results however may have been skewed by pre-existing soil moisture due to rainfall occurring between catch can evaluations. Additional evaluation in an arid location may provide more consistent data. Additionally creation of a DU_{lq} table (similar to Table 1) that correlates specifically to soil moisture data may need to be developed in order to rank acceptable distribution when measured by soil moisture data. The spatial pattern of soil moisture variability was not greatly influenced by the depth of sampling. However, the effect of depth may not have been evident because of the high pre-irrigation soil moisture levels. The pattern of spatial variability of SM did not vary significantly from one sampling time to the next and was not greatly affected by overall soil moisture content. This suggests that SM variability (and thus SMDU) is mainly a feature of permanent soil features such as texture, structure, and slope than application pattern. Precipitation rate can be estimated from as few as 4 or 5 cups on a site to expedite the audit data collection process. Placement of 9 or 10 cups, however, will be less vulnerable to the possibility of being placed in an unusually low or high application area.

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Appendix 1: Spatial Variability Maps

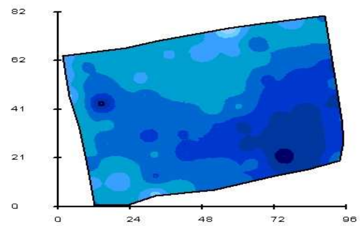
July 14 Data

VWC (%)		
30	to	34
34	to	38
38	to	42
42	to	46
46	to	50
50	to	54
54	to	58
58	to	62

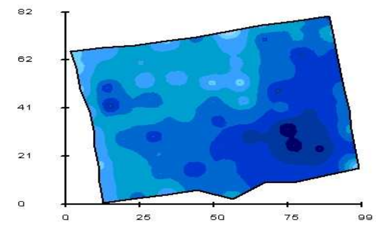
Legend for TDR data

Catch Can Volumes (inches)		
8	to	18
18	to	28
28	to	38
38	to	48
48	to	58
58	to	68
68	to	78
78	to	88

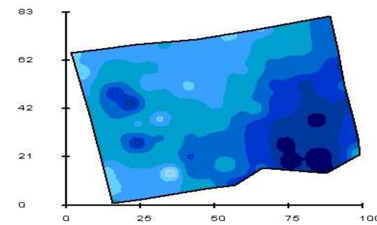
Legend for catch can data



High Traffic area
1.5” rod length
Pre-Irrigation
DU= 90



High Traffic area
1.5” rod length
Post-Irrigation
DU= 88



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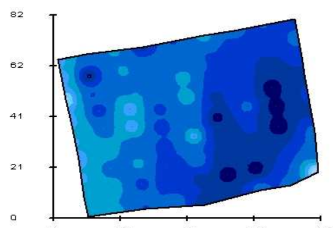
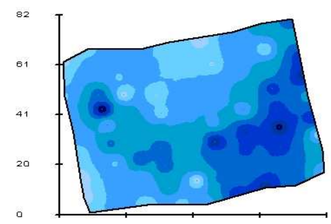
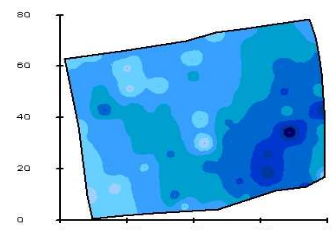
Pre-Irrigation
DU= 89



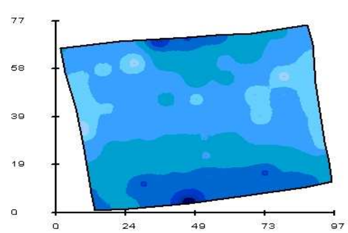
High Traffic area
3.0” rod length
Post-Irrigation
DU= 86



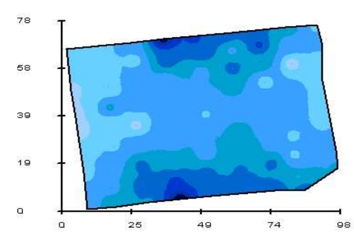
High Traffic area
5.0” rod length
Pre-Irrigation
DU= 92



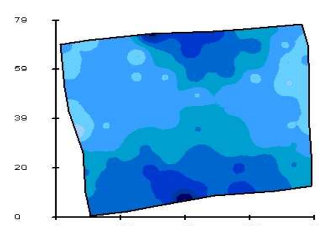
High Traffic area
5.0” rod length
Post-Irrigation
DU= 88



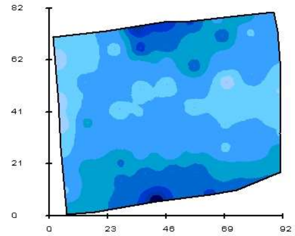
Medium Traffic area
1.5” rod length
Pre-Irrigation
DU= 89



Medium Traffic area
1.5” rod length
Post-Irrigation
DU= 86



Medium Traffic area
3.0” rod length
Pre-Irrigation
DU= 88



Medium Traffic area
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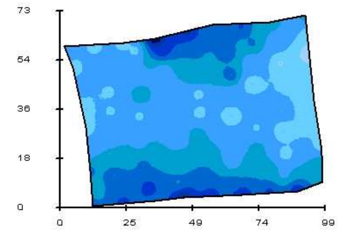
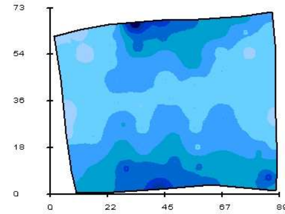
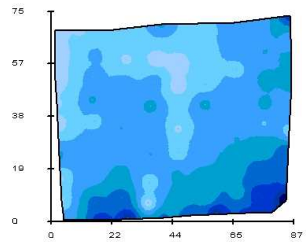
Post-Irrigation
DU= 85



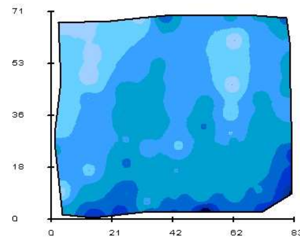
Medium Traffic area
5.0” rod length
Pre-Irrigation
DU= 87



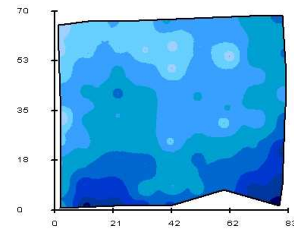
Medium Traffic area
5.0” rod length
Post-Irrigation
DU= 87



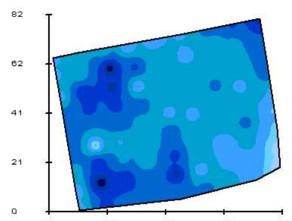
Low Traffic area
1.5” rod length
Pre-Irrigation
DU= 85



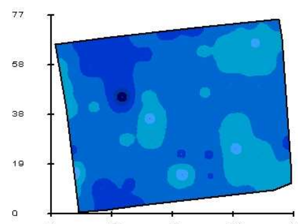
Low Traffic area
1.5” rod length
Post-Irrigation
DU= 84



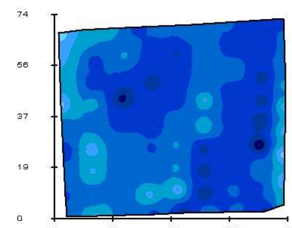
Low Traffic area
3.0” rod length
Pre-Irrigation
DU= 83



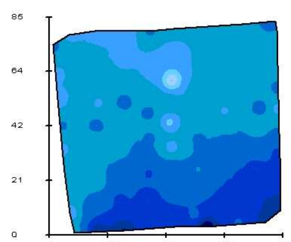
High Traffic area
Catch Can
DU= 62



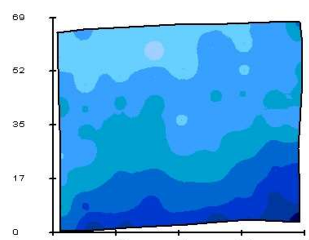
Medium Traffic area
Catch Can
DU= 78



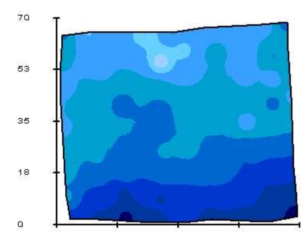
Low Traffic area
Catch Can
DU= 65



Low Traffic area
3.0” rod length
Post-Irrigation
DU= 83



Low Traffic area
5.0” rod length
Pre-Irrigation
DU= 83



Low Traffic area
5.0” rod length
Post-Irrigation
DU= 84

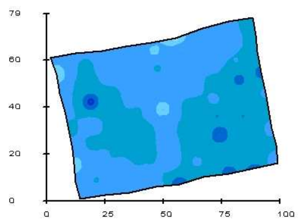
August 11 Data

VWC (%)		
25	to	29
29	to	33
33	to	37
37	to	41
41	to	45
45	to	49
49	to	53
53	to	57

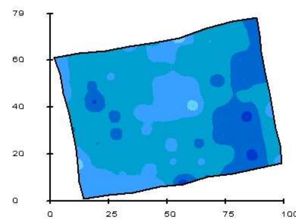
Legend for TDR data

Catch Can Volumes (inches)		
27	to	35
35	to	43
43	to	51
51	to	59
59	to	67
67	to	75
75	to	83
83	to	91

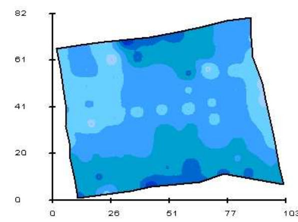
Legend for catch can data



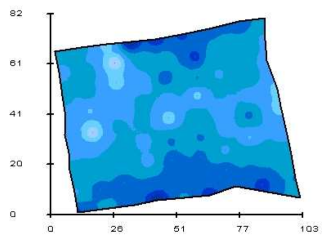
High Traffic area
5.0” rod length
Pre-Irrigation
DU= 89



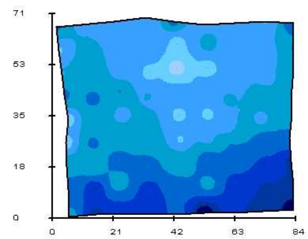
High Traffic area
5.0” rod length
Post-Irrigation
DU= 88



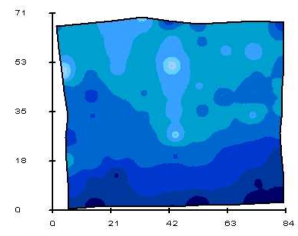
Medium Traffic area
5.0” rod length
Pre-Irrigation
DU= 84



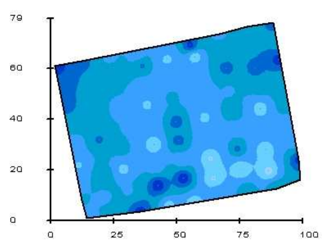
Medium Traffic area
5.0” rod length
Post-Irrigation
DU= 83



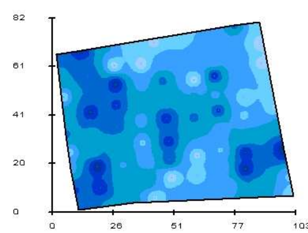
Low Traffic area
5.0” rod length
Pre-Irrigation
DU= 81



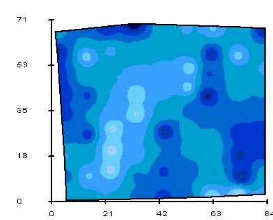
Low Traffic area
5.0” rod length
Post-Irrigation
DU= 81



High Traffic area
Catch Can
DU= 76

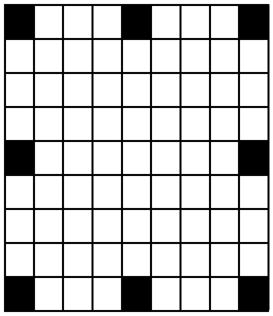


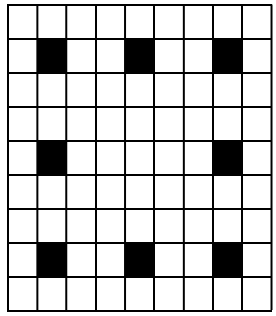
Medium Traffic area
Catch Can
DU= 66

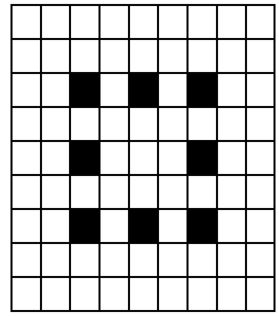


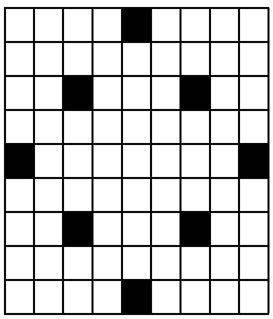
Low Traffic area
Catch Can
DU= 70

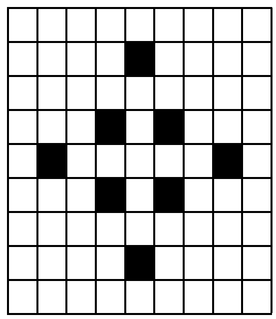
Appendix 2: Pre-selected cup configurations used in precipitation rate study


8 Square Large


8 Square Medium


8 Square Small


8 Diamond Large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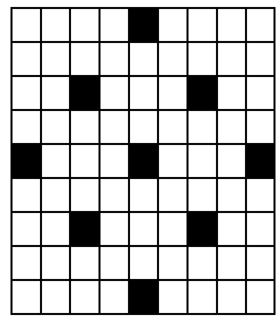
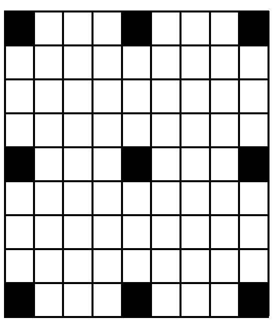
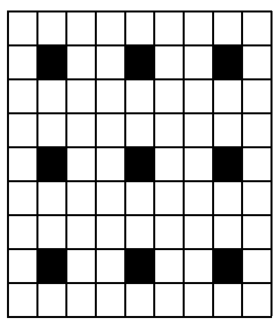

9 Diamond


9 Square Large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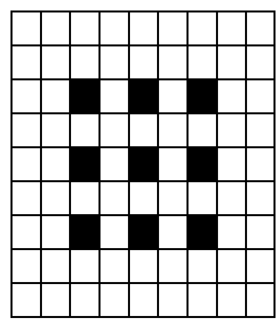
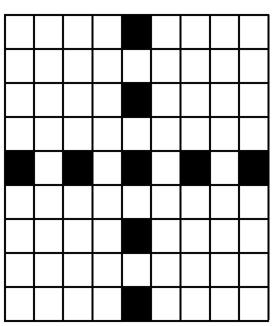
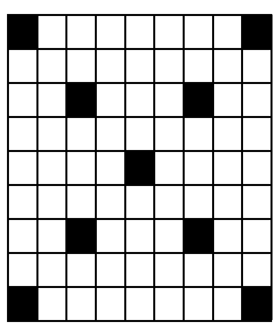
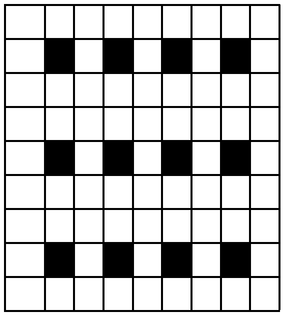
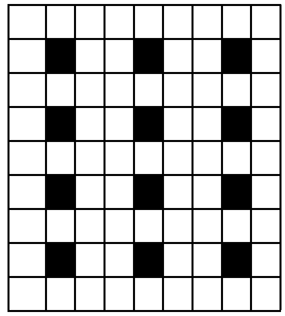
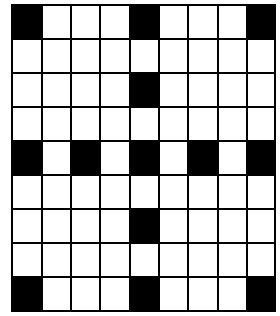

9 Square Small

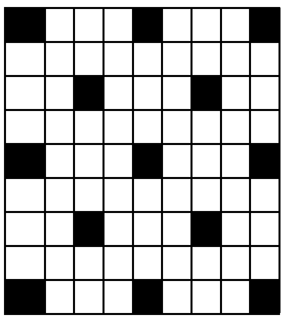

9 Diamond +-Cross

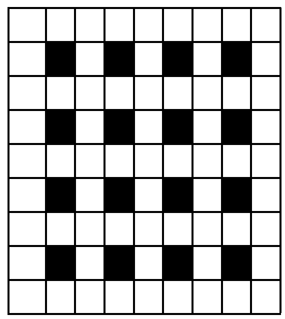

9 X-Cross

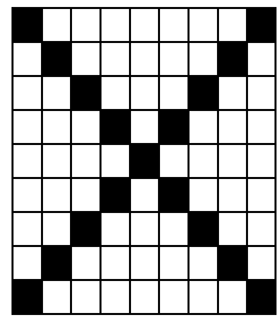

12 Square Horizontal

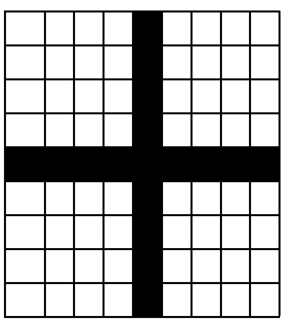

12 Square Vertical

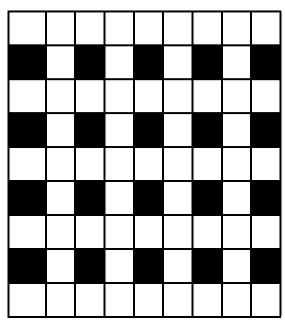

13 +-Cross/Corner

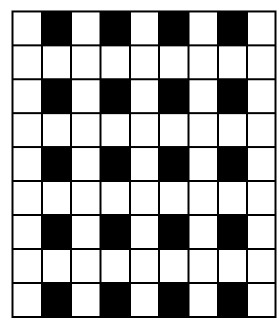

13 X-cross/middles

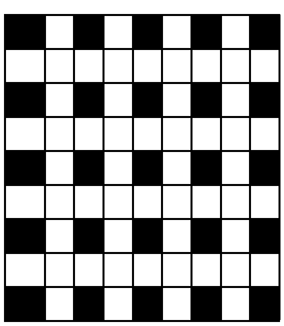

16 Square

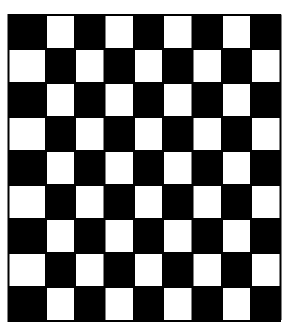

17 X-cross


17 +-cross


20 horizontal


20 vertical


25


41

Survey of Residential Water-wise Irrigation Practices and Perceptions

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Abstract. *Much research has been conducted proving the effectiveness of technology in reduction of lawn/landscape water use. However, studies are primarily conducted in controlled settings. When attempting to incorporate recommendations into residential arenas, savings are not as significant. The results of this study will identify unique barriers with regards to residential irrigation water use. In order to effectively change behavior, factors that contribute to perceived attitudes of homeowners must be considered. A mail-out questionnaire was used to determine public awareness, if/why watering restrictions are followed, and influence of water source. The results presented here represent the initial survey analysis (n=157). Seventy-five percent of the respondents reported to having automatic systems using irrigation timers and with 16% running an automatic system manually. Fifty-six percent of the homes reported having mixed head types within the zones. Homes using some form of low-volume irrigation to water their landscape account for 31%; with drip-tubing as the most commonly selected choice. Forty-seven percent of the homes have rain-shutoff devices, of these, 54% of them were reported to be connected and functioning. Significant differences were observed between the number of irrigation events per week and automation of the system as well as water source.*

Keywords. Behavior, conservation, irrigation, landscape, rain sensor, residential irrigation, survey, turfgrass, water use

Introduction

The desire for a lush landscape often requires irrigation and fertilization, both which are commonly over applied (Mayer et al. 1999). Research has shown that residential in-ground automatic irrigation systems can account for over 50% of the customer's total monthly water consumption and that residential customers in Florida tend to over-irrigate (Haley et al., 2006). While Water Management Districts (WMDs) have implemented allotted irrigation days and times, as well as the requirement of rain shut-off devices for newer systems (Florida Statutes 2007), anecdotal evidence suggests that customers may not be following watering regulations and restrictions (Whitcomb 2005). It has also been seen that domestic irrigators do not understand plant water needs related to irrigation. Domestic irrigators rarely choose alternative, low-input methods, because of aesthetic desirability which does not allow for lawn heterogeneity (Bormann et al. 1993), time, effort, and perceived expense for individual households (Templeton et al. 1998).

Water use efficiency has become a growing concern on both the local and national level. The water used for residential irrigation can be separated into three unique water categories: potable (drinking) water, domestic well water, and reclaimed water. Reclaimed water as an irrigation source is a practical use for treated effluent, however this source requires available additional infrastructure. The most accessible water for the homeowner to use for outdoor purposes is the treated potable water line that is already supplying water to the residential property. This is a costly source with water rates steadily increasing due to the considerable amount of energy it takes to treat and deliver this source. Depending on the aquifer composition, groundwater from an on-site well may lead to some savings in energy costs, but not a decrease in the depletion of reservoirs and groundwater aquifers. Decreasing the water table can lead to saltwater intrusion, higher concentrations of natural contaminants (e.g. radon and arsenic), and human pollutants (e.g. fertilizers and pesticides). Over irrigation can specifically contribute to nonpoint source pollution by increasing runoff containing such pollutants from the suburban landscape.

In 2000, Florida's population was nearly 16 million which ranked Florida as the fourth most populous state in the United States (USCB 2001). In Florida, 88% of the state's population receives their potable water from the public supply. The public supply is that water which is withdrawn by either public or private suppliers and delivered to multiple users. In Florida, the public supply is made up of 90% ground water (2nd highest in U.S.) and 10% surface water withdrawals. Over half, 53%, of the total public supply comes from the Floridan aquifer (Marella 1992). The public supply is usually treated ground or surface water, which is used for both domestic (indoor and outdoor) and public uses (e.g. firefighting and street washing). This sector of the water supply is critical when ensuring that the total water demand can be met.

The domestic self-supply refers to quantities of potable water withdrawn, via well or pumped from surface water, small enough that a permit is not required from the WMD. Although individual household wells fall under this definition, they are only included when water is used for both indoor and outdoor purposes. When the water is pumped solely for irrigation purposes it is not accounted for in this category (Marella 1999). Pinellas County Florida has initiated rebate programs for the installation of a shallow well for outdoor water use (PCU 2007a). The contemporary attitude is that the best way to decrease the need from irrigation water on the potable water demand is to encourage the use of alternative water sources. This avenue gains further support from Florida's Legislature which has allocated funds to the WMDs for the promotion of alternative water sources for irrigation water.

The overall objectives of this study are to quantify the outdoor water use practices and level of community knowledge of water conservation technologies and policy through a mail out survey questionnaire. It will be assumed that the survey respondents will fill out the questionnaire honestly. Since some of the questions will be asking about excessive outdoor water use practices or practices not incompliance with local policy, participants may be reluctant to disclose truthful information. A limitation of this study is that typically homeowners with more water conservative practices have a greater interest in participating. To substantiate this, actual water use statistics will be performed on the non-respondents as well. The ability to generalize these results prove to be another limitation because the dissemination of the instrument will only be in one county within Florida. Therefore the information will not be truly generalized across the entire state.

Previous Work

Previous surveys in Southwest Florida have looked at homeowner concern relating to water cost (Whitcomb 2005) and participation in Cooperative Extension Service yard care programs

(Israel and Hague 2002). Through previous residential irrigation cooperator studies it was observed that the homeowners did not have a clear understanding of when and how much to irrigate (Haley et al. 2007) and that watering day ordinances are recurrently ignored (Haley and Duke 2007)

Residential irrigation research, in Florida, has indicated that the use of technology can decrease outdoor water use without causing plant/turfgrass stress or degradation of appearance (Haley et al. 2007; Haley and Dukes 2007). However, there is reluctance on the part of the domestic irrigator to incorporate this new technology. One such device is an automatic rain shut-off sensor for irrigation systems. In Florida, it is required for homes with automatic in-ground irrigation systems installed since 1991 to have a functioning rain shut-off device (Florida Statutes 2007). However, this ordinance is not enforced and many homes, including new construction, do not use rain sensors (Whitcomb 2005).

There are two aspects which affect the functionality of the irrigation system: technology and user interaction. The technological components include weather-based controllers, soil moisture, and rain sensors, which will electronically bypass unnecessary irrigation events. The regulations stated by the local WMD have an influence on the use of bypass technology as well as the time and day settings for the automatic irrigation timer.

Research has been conducted proving the effectiveness of technology in reduction of outdoor (lawn and garden) water use. However, these studies have been primarily conducted in controlled settings. When attempting to incorporate the recommendations of the research into the residential arena savings are not as significant (Campbell et al. 2004; Geller et al. 1983). In order to effectively change behavior, factors that contribute to perceived attitude must be considered.

Baumann (1990) established three factors which affect the intensity of water use by residential users. The first two are economically derived; the consumer's ability to pay for and the willingness to pay for water at a given price. The non-economic factor is the consumer's conservation behavior. This reflects the motivation to employ effort or technological innovations for water conservation. Weather plays a major role in conservation practices as well. During periods of drought, consumers are more willing to employ conservation techniques than during wet years (Baumann 1990). According to the *Florida Water Rates Evaluation of Single-Family Homes*, completed in 2005, the main concern of homeowners with respect to increased costs is outdoor use (Whitcomb 2005). The current rate for potable water from Pinellas County Utilities is $4.16 per 1000 gal (3780 L) as of December 19, 2007 (PCU 2007c).

Methodology

The project target area is within the Pinellas-Anclote River Basin which is under jurisdiction of the SWFWMD. This area is located in the Southern Water Use Caution Area, meaning the expected demand may be larger than the supply. According to the U. S. Census Bureau's 2006 estimates, Pinellas County has 924,413 residents. This population is 52.4% female and 47.6% male with an average age of 43 years (USCB 2001). The response population will include a representative sample of homes that reflect this demographic data and which use both potable and alternative water sources (reclaimed and well water). Previous surveys in Southwest Florida have looked at homeowner concern relating to water cost (Whitcomb 2005) and participation in Cooperative Extension Service yard care programs (Israel and Hague 2002).

Surveys were mailed following the Multi-wave Method (Dillman 2000), advertising 1,000 mail-outs. Although municipal customers have the most significant impact on potable water demand, the sample population also includes customers who draw water from alternative water sources (i.e. reclaimed water or private wells). Mailing lists were acquired with the assistance of Pinellas County Utilities to ensure representative samples of customers using both public supply and alternative water sources. The sample population was selected randomly with the aid of the local water purveyor. To promote increased response rate, the survey process included a cover letter, survey packet with a water conservation kit as an incentive, and a reminder postcard.

This new survey specifically targets lawn (turfgrass) and landscape (bedded areas) watering practices, knowledge of water conservation ordinances, motives for water conservation/overuse, and perception of community water conservation/overuse. Water conservation ordinances include watering days and percentage of allowable turfgrass. To investigate technological advances, such as the inclusion of a functioning rain shut-off device (e.g. rain sensor, soil moisture sensor, weather-based (ET) controller with rain bypass switch), it is assumed that the irrigation system is operated by an automatic time-based controller. Socio-demographic variables will include income, lot size, education, swimming pool, homeownership, level of water conservation technology, and automation of irrigation system. Latent attitudinal variables will be lifestyle, recreation, landscape interest, conservation attitude, and social desirability towards conservation. The independent variables include irrigation system type, outdoor water source, ownership and economic profile.

Univariate data analysis was used to describe the data set sample with mean, standard deviations, and percentages. The level of measurement was the range of response from frequency statistics. The bivariate analysis was used for the evaluation of the independent variables and the hypothesis testing between the independent and dependant variables. For this data set, control variables were not considered because there was no known relationship between any variable which could be considered control variables and the dependant and independent variable.

Results

The results presented here represent the initial analysis of the outdoor water use practices and perception survey. Thus far, a 27% response rate was achieved and this initial data analysis was performed on first 157 surveys. The property, irrigation system, and demographic attributes of questionnaire respondents are presented in Tables 1 and 2. Water source can be categorized into three types, potable, reclaimed, and well/surface. Well water users made up the largest percentage (36%) of the respondent sample. Three quarters of the respondents reported to having automatic systems using irrigation timers and 16% utilize an automatic system manually. The percentage of irrigatable area was normally distributed. The reported average irrigatable area was approximately 54% of the total lot area with turfgrass making up approximate 38% of the irrigatable area. Luxury attributes such as the homes having lawn maintenance service and additional water features were also evenly distributed across the sample. Ninety-one percent of those who reported having water features selected swimming pool.

Looking at the design of the irrigation system, 56% of the homes reported having mixed head types within a zones. Homes using some form of low-volume irrigation to water their landscape account for 31%; with drip-tubing as the most commonly selected choice, followed by micro-irrigation. Forty-seven percent of the homes have rain-shutoff devices, almost exclusively rain sensors; seven homes reported having a soil moisture sensors and only one having a weather-based controller. Of the homes with rain shutoff devices 54% of them were reported to be connected and functioning.

Table 1. Attributes of the respondent's property and irrigation system.

	Percentage
Water Source	
Potable	32%
Reclaimed	32%
Well/surface	36%
Irrigation type	
Automatic system set	75%
Automatic system used manually	16%
Hose end sprinkler	5%
Hose or watering can	3%
Do not apply any water	1%
Percentage of lot that is lawn/landscape	
0-25%	11%
26-50%	37%
51-75%	37%
Over 75%	14%
Has a lawn maintenance service	
Yes	55%
No	45%
Has additional water features on property	
Yes	57%
No	43%
Has mixed zones (spray and rotor)	
Yes	55%
No	40%
Don't Know	5%
Use of low volume irrigation	
Yes	31%
No	63%
Don't Know	6%
Use of rain shutoff device	
Yes	54%
Connected and functioning	*66%*
Not connected and functioning	*20%*
Don't know	*14%*
No – turns off system manually	25%
No	21%

There is a significant difference between the three water sources (potable, reclaimed and well/surface) and how often the respondent admits to watering their lawn/landscape ($p<0.0001$). The homes that receive reclaimed water for irrigation use had a mean response of irrigating 3.1 times per week; this was statistically significantly higher than the other two water sources. While well/surface and potable users did not have significantly different responses from each other, the mean response for well users was slightly higher reporting 1.2 times per week.

Table 2. Respondent demographics and residency information.

	Percentage	Mean (Std. Dev.)
Owns the house	95%	
Number of years living in Florida		24 (15) yrs.
10 or less	27%	
More than 10	73%	
Number of months of the year in Florida		11 (3) mo.
1-3 months	13%	
4-9 months	11%	
10-12 months	76%	
Age		59 (11) yrs.
40-65 yrs.	77%	
66-81 yrs.	23%	
Educational level		
Completed high school	10%	
Some college	15%	
Completed college	42.5%	
Advanced degrees	32.5%	
Household income		
Under $30,000	10%	
$30,000 - $49,999	10%	
$50,000 - $74,999	15%	
$75,000 - $149,999	47.5%	
Over $150,000	17.5%	

Other attributes that affected irrigation frequency included timer location and the inclusion of a rain shutoff device. Timer location resulted in significant differences with p=0.0295. The homes with the statistically highest irrigation frequency, which are those who reported to irrigate more than three times per week, had timers either in the garage or on an exterior wall of the house. Concurrently, homes that reported having a rain shutoff device also reported to having an irrigation schedule that is set to run less frequently (p= 0.0062). In this category, homes that do not have a rain shutoff device but reported that they manually turn off the system following a rain event resulted in more irrigation events scheduled per week versus those homes that did not report any rain interaction.

Three indexes were developed from Likert scale attitudinal questions. The Likert scale asks the respondent to rate his/her agreement to statements based on an interval scale. In this questionnaire the scale ranged from “strongly agree” to “strongly disagree” in five even intervals with an additional “don’t know” option. Indexes were developed statistically based on Eigen value criteria. Indexes serve as a means to group strongly related questions together resulting in a numeric score than can be used for statistical analysis.

Index of conservation attitude:

- When watering with reclaimed water, outdoor water use conservation is not necessary.
- When watering with well water, outdoor water use conservation is not necessary.

- We are all responsible for water conservation in out community.

Index of conservation knowledge:

- I am not aware of watering restrictions in my area.
- I am aware of lawn appearance requirements in my neighborhood.
- New irrigation systems are required to have shutoff devices.

Index of personal lawn/landscape interaction:

- I spend a lot of time outside in my lawn/landscape.
- I am very concerned about the appearance of my yard.
- I am familiar with seasonal water needs of my lawn/landscape plants.

The index for knowledge has a correlation with education level, having a Pearson correlation coefficient of 0.60. There was also a moderate correlation between the knowledge index and the statement that the "homeowner would like to consider changes but [does not] have the money." The strongest correlation (0.87) existed between the conservation attitudinal index and the statement that the homeowner would "prefer more lawn (turfgrass) and would like to increase the lawn area of [their] yard." There were only weak correlations between the personal lawn/landscape interaction and the attitudinal preferences about the present landscape and the desire to make changes.

Conclusions

This paper presents the initial analysis of the outdoor water use practices and perceptions survey, distributed summer 2008. From the reported irrigation system attributes, approximately one third of the homes use some form of low-volume irrigation to water their landscape and half of the homes have rain-shutoff devices. Further, according to the respondents the majority of these devices were reported to be connected and functioning. These percentages of conservation technology and equipment incorporated into the system were much higher than expected for the area based on previous studies. However, the percentage of homes with mixed head types within the zones was 55%, which concurs with visual inspection of similar homes in the County.

The significant difference between water source and how often the respondent admits to watering their lawn/landscapes concurs with the watering day restrictions within Pinellas County. According to Pinellas County Code 82-1, homes using county water or wells, lakes, and ponds are allocated one day of irrigation a week for established lawns and landscaping. The homes surveyed using well/surface or potable water fell within the once per week categorical level. However, it should be noted that although the respondents reported once per week irrigation, previous research in the target area has observed far great irrigation frequencies for potable users. Irrigation using reclaimed water is on a voluntary schedule (Resolution No. 01-329) permitting up to 4 days of irrigation per week. The mean response for homes receiving reclaimed water was 3.1 times per week.

There were also significant differences observed between the number of irrigation events per week and automation of the system. Homes which allow the rain shutoff device to bypass irrigation following rain events reported less weekly irrigation event scheduled. Although a homeowner may suspect conservative irrigation practices when manually turning off the automatic controller after rain events, these homes also seem to have their timers set to higher frequencies. Additionally, homes without irrigation time clocks irrigate less often than those homes with automatic systems, this concurs with previous findings about residential end use by the AWWA.

The correlation between water use knowledge level and the educational level of the respondent was not surprising. Furthermore, an increased knowledge index score correlates with the attitudinal factor of money affecting the desire to change the landscape. This would infer that the homeowners are aware of the expected costs for changes to the lawn/landscape when adding or removing turfgrass or conservation technology devices. What was most interesting about the correlation between conservation attitude and the desire for increased turfgrass area was that the correlation was positive. Recall, the questions that make up this index were contrary, meaning the questions were negative resulting in a reverse code. What this could imply is that the homeowners' attitude toward alternative water sources is that they do not require irrigation conservation practices and in turn provide the additional water needed for an increased turfgrass lawn area.

Unexpectedly, there were no obvious correlations between the personal lawn/landscape interaction, which is the index that attempts to quantify the level of time spent in the lawn/landscape, and any of the attitudinal choices about the present landscape, which express the homeowner's satisfaction or want to make changes. It would have been expected for this index to have a more defined opinion clearly observable. This may require additional investigation, as these interactions may be masked by spurious effects.

Further analysis will be performed to quantify the outdoor water use practices and level of community knowledge of water conservation technologies and policy. Continued analysis will also consider actual water use data from the local water purveyor records to find out how accurate the responses are. The ultimate goal of this research is to determine a means to promote knowledge of water conservation related to residential irrigation by understanding why people over irrigate.

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Abstract: Landscapes are losing sustainability and are placing greater demands on municipal and natural resources. Contaminated stormwater runoff from developed land is the leading cause of water quality problems, accounting for 70% of water pollution in urban areas. Approximately 80% of rainwater runs into storm sewers versus soaking into the ground.

Utilizing rainwater for gardens and lawns reduces the strain on municipal systems. Stored rainwater alleviates water shortages during periods of drought and helps alleviate flooding that typically occurs when heavy rains follow a drought. Consumers want an aesthetically appealing solution to environmental problems.

Used in conjunction with a decorative water feature, a rainwater harvest storage system captures polluted rainwater before it enters the sewer system, and then filters and stores the water to be accessed for future use in both residential and commercial applications.

In addition, ecosystem ponds can be implemented to further aid in providing sustainable environments for wildlife habitat.

Keywords: Decline in Biodiversity, Rainwater solutions, Urban Runoff, Polluted Runoff, Water Issues, Coastal pollution, Clean Water Act, Problems with Combined Sewer Systems, Stormwater runoff and Coastal Health Issues, Hydrologic Cycle, Riparian habitat degradation

Report:

A summary of the hydrologic cycle and facts about water, we're known as the blue planet, the majority 97.5% of all water is salt water the remaining water is made up of glaciers, groundwater, lakes, rivers and streams and water vapor in our atmosphere. The water cycle is a process in which water is evaporated and rises up into the atmosphere where it condenses and cools it then falls back to the earth as precipitation, it will soak into the ground replenishing our groundwater or runoff into a lake or river or it's absorbed by plants for photosynthesis. This cycle has been going on for eons unchanged until man and development.

Urbanization has altered our watersheds through the process of construction and development, this occurs in several ways:

- Impervious surface installation, roofs, roads, asphalt, etc…
- Removal and compaction of native soils
- Use of potable water for irrigation
- Pollutant and contamination from stormwater runoff

The effects of urbanization on our environment and biodiversity, this is a critical component for future generations which include: Clean water for drinking and healthy water for native inhabitants: amphibians, insects, fish, birds, mammals etc… all living things need water and the proper habitats to survive.

The changes associated with development have negative impacts on their immediate surroundings and global impacts from a watershed perspective as all water leads to the sea. During this process the increased volume, velocity and quality of the water is responsible for the degradation of all the associated riparian habitats. According to the EPA urban runoff is the #1 cause of coastal pollution.

The combination of impervious surface construction (blocking the natural infiltration of water to the aquifers), increasing usage of water through improper irrigation techniques and population growth in water stressed areas is causing a decline in our freshwater reserves. The effects of these are forcing the implementation of water restrictions and regulations limiting consumption and usage of this resource. Aquifers (subterranean water reserves), continue to decrease in volume forcing policy makers to make hard decisions for the sustainability of their communities. Simply put we're taking out water faster than we're allowing it to fill back up, this is not sustainable!

This process is not only destroying lakes, rivers and streams but also overburdening our storm sewer systems requiring costly repairs and upgrades to handle the increasing volumes. Just moving water from underground reserves, from surface lakes and reservoirs, filtering it and delivering it to our homes and businesses is responsible for up to 5% (estimate) of our countries electrical consumption! Add to this the carbon dioxide production and use of other resources needed to produce the energy.

Summary:

The answer is simple rainwater capture and reuse on a micro scale, capture water where it falls and use it in and around the landscape instead of using filtered potable water. This will alleviate the stress on the overburdened storm systems, less flooding, slowing the volume and velocity down so it does not harm the natural stream corridors which will save drinking water for drinking. Less energy consumption equals better air quality and more energy available for other uses. Rainwater also has some benefits over tap water for plant productivity, water as nature intended it.

Resources:

(California Natural Heritage Program)
(Clean Water Act, 1972)
(Coastal Zone Act Reauthorization Ammendments, 1990)
(Environmental Health Science and Policy Program, University of California)
(The Endangered Species Act, 1973)
(Gallup Poll, Princeton New Jersey, March 2008) Environmental concerns with water
(International Herald Tribune, April 2008) Droughts and Rainwater solutions
(The Millenium Ecosystem Assessment, 2005) 1,360 scientists in 95 countries on Biodiversity Impacts
(Natural Resources Defense Council) Stormwater runoff and health issues
(Newsweek, April 2008) Rivers Running Dry
(The New York Times, June 2008) California drought information
(Pacific Institute) The electrical cost of water
(Tucson Citizen, July 2008) Rainwater harvesting policies
(Surfrider Organization) Stormwater and health/coastal issues
(UNESCO) Global Hydrology and Water Resources
(The United Nations World Water Development Report) World wide water facts

Irrigation Runoff from Narrow Turf Areas for Sprinkler and Surface Flow Systems

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Abstract.
Landscape irrigation runoff may contribute to contamination of streams, lakes and oceans, and some municipalities' enforce runoff ordinances. The objectives of this study were to measure and analyze runoff from small turf plots on a slope with Surface Flow irrigation, and sprinklers with spray and rotary nozzles. Under the tests conditions Surface Flow had less runoff than sprinklers with spray nozzles. Approximately 1 - 7% of applied water from sprinklers with spray nozzles became runoff; nearly 75% of this runoff was caused by wind. Replacing spray nozzles with rotary nozzles reduces runoff caused by wind.
Keywords. Landscape irrigation, irrigation runoff, sprinkler wind drift

Introduction.

Prevention of runoff from irrigated landscapes is important to prevent pollution due to the runoff, decrease demand for water, minimize irrigation cost, and decrease damage to hardscapes.

Legislation and ordinances affect irrigation practices. California Assembly Bill 2717 has a recommendation for a model landscape ordinance to include "provisions to minimize landscape irrigation overspray and runoff." This provision would impact methods of irrigation and operation of irrigation systems that result in runoff.

One area of regulatory interest for runoff from landscapes is runoff during the dry weather irrigation season. These surface flows, generally labeled nuisance flows, occur during the March through November irrigation season in Southern California. The quantity of runoff in an ideal world should be zero. However, the norm for many urban communities with irrigated landscapes is that significant runoff does occur in the summer unto hardscapes, gutters and storm drains that may ultimately degrade rivers and coastal waters. With Southern California water supplies stressed, any runoff from landscape is considered a waste of this limited resource.

A recent study by Municipal Water District of Orange County (Anonymous. 2004) showed a 49% reduction results in watershed runoff with the installation of ET controllers on residential sites. The city of Tustin and the Irvine Ranch Water District (Anonymous. 2004) installed a WICK irrigation system on a large street median, which virtually eliminated runoff that had previously occurred at the same site with sprinkler irrigation.

A study (Vis, 2006) reported both surface runoff and runoff due to wind drift on turf plots with 8% slope irrigated by rotary sprinklers on 50 x 50 spacing, and sprinkler precipitation rate near one inch per hour. Approximately twice the required irrigation water requirement was applied for the runoff data for the study. Under these conditions up to 9.5% of the applied water became runoff at the lower end of the plot. Surface runoff, if the irrigation runtime had been correct, was estimated at less than 0.2% of applied water. However, runoff due to wind drift under correct irrigation scheduling and moderate wind conditions (less 5 mph) was a substantial volume of water. This study showed that for the given soil, slope, and wind conditions, up to 3.3% applied water could become wind spray runoff if the irrigation runtime had been correct.

Replacement of spray nozzles with rotary multi-stream nozzles on existing landscapes improved the distribution uniformity (Kissinger 2005). Before and after catch can tests showed a distribution uniformity improvement of 18 percentage points.

Surface Flow, also identified as WICK and other names, was developed as an alternate irrigation method for landscape sprinkler irrigation for certain applications. This method has emission points spaced to achieve 100% wetted area. Flow is controlled by 2 gph or higher flow emitters with a micro tube emission point between the soil surface and turf cut height. The author's observations and experience with surface flow (WICK) systems suggest that with attention to detail in system design, site preparation, and installation, that good turf quality can be achieved. Potential advantages of surface flow irrigation are more uniform distribution of water, more control of water around landscape boundaries and curbs, and no wind drift. These factors could result in high irrigation efficiency, and the potential of reduced or no runoff from urban irrigation sites where wind is a major factor in runoff.

This study was initiated to measure runoff from turf plots irrigated by conventional popup with spray heads, conventional popup with rotary multi-stream nozzles, and Surface Flow irrigation. Each set of tests will be described in the following sections.

Conventional spray nozzles and Surface Flow

Methods and Procedures

There were eight turf plots for this project, four plots with sprinklers spray heads and four plots with surface flow irrigation. Plot dimensions were 20 feet by 5 feet. Native soil from the field was used to construct plots on 10% slope. Soil texture was sandy clay loam (58% sand, 18.4% silt, 23.6% silt). The 20 foot dimension of the plots was approximately 45 degrees from North. Runoff was collected from all plots during four irrigations in June 2007.

Jardinier Planter Systems Inc., manufacturer of some Surface Flow components, assisted with the design of emitter spacing and emitter flow rates for the plots. Emitters were installed on triangular spacing, 3 feet on the lateral and 3 feet between laterals with the lower lateral 1.5 feet from the lower edge of the plots. Emitters on this lower lateral had a flow rate of 3 gph. The top lateral was 0.5 feet from the top edge of the turf with emitter flow rates of 5 gph; this lateral had one additional emitter at each end. Average precipitation rate with this design was 0.98 inches per hour.

The sprinkler irrigated plots were designed and installed using traditional 6 inch popup spray heads with 5 foot nozzles (5^{o} trajectory) on 5 foot by 5 foot spacing operated at 30 psi. Manufacturer rated precipitation rate for the sprinkler nozzles in this design was 1.58 inches per hour. The lower row of sprinkler heads was installed approximately 4 inches up the slope from the lower edge of the turf. Sprinklers at each corner of the rectangular plots had 90^{o} arc nozzles, and 3 sprinklers at 5 foot intervals along the 20 foot side had 180^{o} arc nozzles. A-G Elite sod from A-G Sod Farms, Inc was installed.

Figure 1. Left photo shows runoff collection system for surface runoff and wind drift. Right photo shows 5 by 20 foot plots and wind drift collection barrier.

The irrigation runtimes were based on available water of 2 inches per foot of soil and targeted irrigation near 40% depletion of available water. For a rooting depth of 4 inches and an assumed 75% irrigation efficiency which resulted in a 14 minute runtime for the sprinkler plot. The same volume of water was applied to the Surface Flow plots in a 22 minute runtime.

The actual runtimes and volume of applied water are shown in Table 1. The volumetric moisture content was measured with a TDR with 4.8 inch probes as means to maintain surface moisture condition similar for all plots. The moisture contents in Table 1 are based on 3 reading per plot , one reading 0.5 feet up from the lower end of the slope, the second was 2.5 feet up the slope, and the last one 4.5 feet (0.5 feet from the top of the slope) up the slope. The TDR reading in the Surface Flow plots were sensitive to distance from an emitter where a reading was taken.

Table 1. Test dates, irrigation information, and volumetric soil moisture.

	Irrigation Runtime		Water Applied		Volumetric Soil Moisture*	
Date	minutes		gallons		%	
	S.F#.	spray@	S.F.	spray	S.F.	spray
June 1, 2007	22	14	22	22	51	48
June 5, 2007	22	14	22	22	44	39
June 8, 2007	22	14	22	22	38	41
June 12, 2007	22	14	22	22	36	40

Note: S.F. is Surface Flow
* Volumetric soil moisture measured with TDR before irrigation
# Surface Flow method of irrigation as described above
@ Six inch popup sprinklers with 30 psi PRS stems and 5 foot nozzles

Runoff from the sprinkler plots was collected in two components, surface runoff and wind drift runoff. All runoff was collected at the lower end of the plots only (Figure 1)
The plastic barrier directed any wind drift into one collection trough. Surface runoff from each plot was collected in a second trough at the lower edge of the plot. Both troughs drained into containers for runoff volume measurements. Turf was mowed one day before irrigation events.

Results and Discussion

Runoff collected after each irrigation event is shown in Table 2 for both irrigation treatments on four dates. The collected runoff was 100% surface flow for the Surface Flow method and a combination of surface flow and wind drift for the sprinkler plots. Sprinkler plots had some overspray on the sides and top of the rectangular plots; overspray was collected only from one side in this experiment. Likewise some Surface Flow irrigated plots had minor surface flow off the plot sides and some subsurface flow near the lower end. The total collected runoff was only the water collected at the lower end of each plot, and it should be consider the minimum potential runoff.

Significant differences were shown for mean collected runoff for Surface Flow and mean collected runoff sprinkler plots for each date (Table 2).

There was no overspray, as defined for this study, with Surface Flow method since water from the 3 and 5 gph emitters is not projected into the air. There was no measured runoff for the Surface Flow plots, but there was some subsurface water flow that will be discussed later.

Table 2. Surface runoff and overspray collected from plots.

	Mean of 4 plots per treatment			
	Surface Flow Emitters	Sprinkler Spray Nozzles		
Date	Collected Surface Runoff, Liters	Surface Runoff, Liters	Overspray Runoff, Liters	Total Collected Runoff, Liters
6/1/2007	0.0a	0.8	2.6	3.4b
6/5/2007	0.0a	0.9	2.9	3.8b
6/8/2007	0.0a	0.6	2.7	3.3b
6/12/2007	0.0a	0.6	3.0	3.6b

Mean values in rows followed by different letters are statistically different at the 95 % level by Duncan's Multiple Range Test.

Runoff as a percentage of applied water is important for using test data and projecting potential runoff from a larger site with irrigation systems operated under similar conditions. Runoff from the sprinkler plots ranged from 3.9 – 4-5% of the applied water (Table 3).

Average hourly wind speed was obtained from a CIMIS weather station (height 2 meters) approximately 0.25 mile from the site. Average hourly wind speeds ranged from 2.9 to 6.5 mph with a mean of 4.6 mph. Instantaneous wind speed measured at the site with an anemometer approximately 1 foot above grade had mean values of 2.2 mph. Wind direction was generally 45 degrees toward the runoff collection device at the lower end of the plots.

The sprinklers for the sprinkler irrigated plots were new, head to head spacing, new nozzles, and no turf interfering with nozzle spray. Therefore, volume of runoff is probably the minimum expected for these general irrigation conditions.

Table 4 reports the sprinkler runoff in two components of surface runoff and overspray. The mean wind speeds of 2.2 mph were moderate, but accounted for 76 – 83% of total runoff for experiment. Surface runoff was 17 – 24% of total collected runoff; this runoff potentially could be reduced or eliminated by cycle and soak irrigation scheduling or extending the irrigation interval. Runoff due to wind may be more difficult to reduce since the time of the irrigation event with respect to wind is normally not controlled.

Table 3. Runoff as percentage of applied water.

	Mean of 4 plots per treatment, % of Applied Water			
	Surface Flow Emitters	Sprinkler Spray Nozzles		
Date	Collected Surface Runoff	Surface Runoff	Overspray Runoff	Total Collected Runoff
6/1/2007	0.0	0.9	3.1	4.0
6/5/2007	0.0	1.1	3.4	4.5
6/8/2007	0.0	0.7	3.2	3.9
6/12/2007	0.0	0.7	3.5	4.2

Table 4. Surface runoff and overspray components of runoff from sprinkler plots.

	Sprinkler Spray Nozzles		
Date	Surface Runoff, %	Overspray Runoff,%	Total Collected Runoff,%
6/1/2007	23.6	76.4	100.0
6/5/2007	24.3	75.7	100.0
6/8/2007	18.0	82.0	100.0
6/12/2007	17.4	82.6	100.0

As discussed earlier in this report, the water measured in the runoff collection should be considered the minimum runoff expected. The pit at the end each plot where the buckets were installed collected some subsurface flow. These flows were not considered in the above data since we were primarily interested in runoff from the irrigated plots. In a commercial site, subsurface flows may become surface runoff down slope from the site, or it may become deep percolation.

We conducted one test with a 32 minute runtime to create measurable surface runoff from the Surface Flow plots. Surface runoff was measured and the subsurface flow into the collection pit was also estimated. This total runoff was compared to total runoff from the sprinkler plots.

Under these irrigation conditions, there was substantial variation in the volume of runoff, but the Surface Flow had less runoff in each pair of plots (Figure 2).

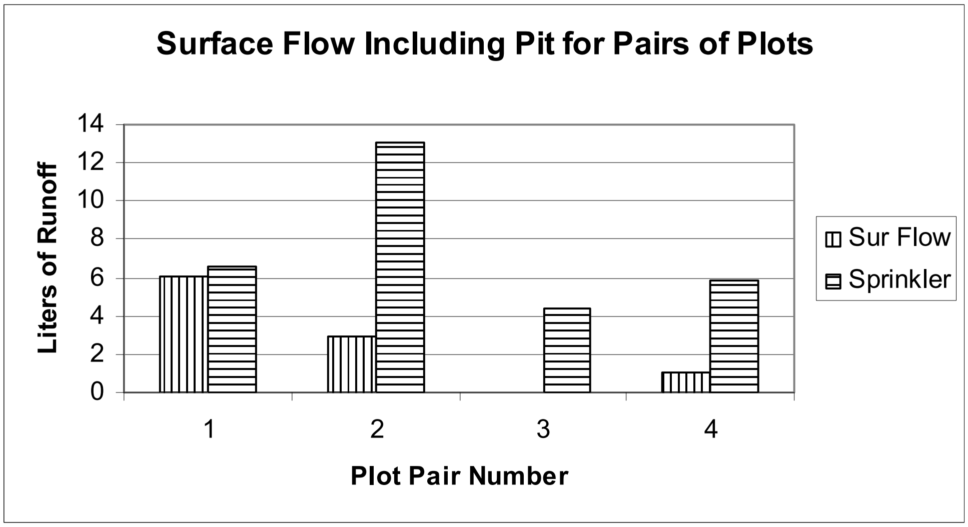

Figure 2. Comparison of potential runoff off perimeter of plots from Surface Flow and sprinkler irrigated plots.

Runoff with Cycle Soak Irrigation and Two Nozzles Types

Surface Runoff with Cycle and Soak Schedules for Sprinklers with Spray Nozzles

There is the question whether surface runoff for sprinklers with spray nozzles can be reduced with cycle and soak programming of the irrigation runtime. Cycle and soak is commonly recommended for irrigation on soils with low infiltration rates. The results of one test run of each sprinkler plot had surface runoff for the irrigation with one cycle more than twice the runoff than any of three cycle and soak irrigation schedules.

The water collected in this test was surface runoff from the 10% slope and any overspray that landed in the 5 inch wide trough at the lower end of the plots.

Surface Runoff Comparisons Between Spray and Rotary Nozzles

The same four plots were used in this study. Six inch popup sprinklers in two plots had spray nozzles and two plots had sprinklers with rotary multi-stream nozzles, all on 30 psi PRS heads. Catch can tests were conducted to determine the distribution uniformity and precipitation rate. Irrigation runtimes were calculated for the soil type, 4 inch root zone, 40% management allowable depletion, and DU_{lh} which determined runtimes of 20 minutes for the spray heads and 27 minutes for rotary nozzles. Runoff was collected in a 5 inch trough at the lower end on the 10% slope. Runoff was measured for10 irrigations over approximately 2 months was determined to be 0.27% of applied water for spray nozzles and 0.29% for rotary nozzles.

Comparisons Wind Drift between Spray and Rotary Nozzles

The same turf plots and sprinklers were used as for the previous study. Wood frame panels with plastic covers were installed around the plot to collect water due to wind drift on all four sides of each plot. The width of the collection panels ranged from 3 to 5 feet to fit the available space. The systems were run early morning, late morning, and early afternoon times; early morning had lower wind speeds.
Overspray accounted for 2.4 to 7.9% of the applied water for the spray nozzles, and 0.8 to 2.7% for the rotary, multi-stream nozzles.

Comparison of Potential Runoff with Spray and Rotary Nozzles after Arc and Radii Adjustment.

This part of the study was conducted to determine if overspray could be decreased by further adjustment of the arc and radius of the sprinkler nozzles. Rotary nozzles had adjustable arcs and radii while the spray nozzles had fixed arcs and adjustable radii. After adjustments there was some overspray visible but it was best that could be done under these field conditions. There were two plots for each type of nozzle.

Wind drift was collected by plastic covered panels surrounding the 10 by 20 foot plots. Surface runoff was also collected at the lower end of each sloped plot. Catch can tests performed on each plot showed DU_{lq} decreased from 38 to 35%for the spray nozzles and 68% to 60% for the rotary nozzles. DU_{lh} was used for scheduling purposes.
Total runoff was 6.3% of applied water for plots with spray nozzles and 1.0% for the rotary nozzles

Summary

A summary of the results are as follows:

- Surface Flow method of irrigation had less runoff than sprinklers with spray nozzles and was not affected by moderate wind conditions.
- Sprinklers with spray nozzles had 3.9 to 4.5% of applied water became runoff surface runoff. Seventeen to twenty four percent of the runoff was surface runoff which can be minimized by proper irrigation scheduling.
- Sprinklers with spray nozzles had 76 – 83 % of the total runoff due to wind drift. It is difficult to reduce with current spray nozzles and controller technologies.
- Sprinklers with spray nozzles had wind drift that ranged from 2.4 to 7.9% of applied water when wind drift is collected from all four sides of plot, and wind in the 0 – 5 mph range.
- Sprinklers with spray nozzles had wind drift that ranged from 0.8 to 2.7% of applied water when wind drift is collected from all four sides of plot, and wind in the 0 – 5 mph range.

General Conclusions

Irrigation systems such as Surface Flow and subsurface drip may have application in narrow turf areas where wind causes runoff, and where design of sprinkler systems in curved areas that

border hardscapes may be difficult. It was possible to control surface runoff from sprinkler irrigated turf on 10% slope with proper runtimes sprinkler.
Wind was an uncontrolled variable in these tests, and wind speed ranged of 0 – 5 mph. Under these conditions total runoff ranged from 1 – 7% of applied water. Runoff due to wind drift was in the range of 70-98% of the total runoff even with wind speeds of 5 mph or less.

Increased use of ET controllers, soil moisture sensors, and good irrigation scheduling practices may minimize surface runoff with sprinkler system near curbs and hardscapes. But to minimize total runoff, the system management must take into account wind speed and direction. The other alternative is to consider methods of irrigation such as Surface Flow and subsurface drip for landscapes near curbs and hardscapes that are affected by wind.

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Improving Soil Hydrological Behavior for More Efficient Irrigation

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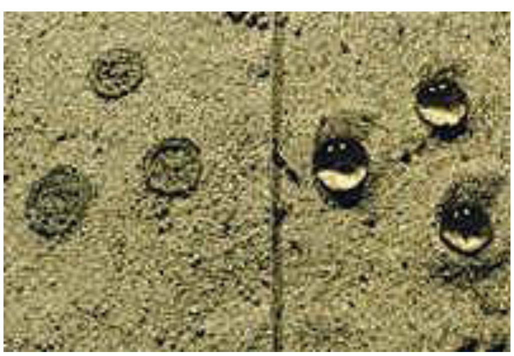
Abstract. *Irrigation efficiency depends largely on irrigation system performance (distribution uniformity), scheduling and the ability of soils to absorb and retain water for optimal use by plants. While many technological advancements have been made with irrigation systems and controllers, less attention has been given to how the soil system is functioning. Factors affecting soil hydrological behavior, especially the development of soil water repellency, can lead to significant reductions in irrigation efficiency. Even low levels of repellency can cause reduced infiltration and retention, increased runoff, variable wetting, preferential flow, and suboptimal growing conditions, all leading to reduced irrigation efficiency and increased water requirements. This has lead researchers to the view that soil water repellency seems to be more the norm than exception. Soil surfactants are capable of improving soil hydrological behavior by correcting or preventing water repellency, resulting in more efficient irrigation and significant water conservation. Examples and results from recent studies around the world are presented.*

Key words. Soil water repellency, soil surfactants, irrigation efficiency, water conservation, runoff, preferential flow.



Water drop penetration in wettable and repellent soil. Preferential flow in repellent soil. Courtesy Alterra,

Introduction

Irrigation efficiency depends largely on irrigation system performance (distribution uniformity), scheduling and the ability of soils to absorb, retain and release water for optimal use by plants. By definition, irrigation efficiency is “the ratio of the average depth of irrigation water beneficially used to the average depth of irrigation water applied” (Rochester, 2006). Simply put this translates to the percentage of the water applied that was beneficially used in the crop management program. Regardless of what the irrigated crop may be, maximizing irrigation efficiency is a desirable goal agronomically, environmentally and economically.

While many technological advancements have been made with irrigation systems and controllers, less attention has been given to how the soil functions with regard to irrigation efficiency. Soil water holding capacities and intake rates, based on generally accepted values, are taken into account in irrigation scheduling and run times. However, changes in soil conditions or behavior, which may compromise expected performance, is often not considered. Increased awareness of changes in soil functionality, the impact of these changes on irrigation efficiency and the practices available to manage them can narrow the gap between theoretical efficiencies and the actual efficiencies achieved by practitioners.

Factors affecting soil hydrological behavior, especially the development of soil water repellency, can lead to significant reductions in irrigation efficiency. Soil water repellency causes at least temporal changes in the hydrological properties of a soil which result in, among other things, increased irrigation requirements. Restoration of soil wettability will improve the hydrological behavior of soils allowing increased irrigation efficiency and significant water conservation in irrigated crop and landscape systems.

Soil surfactants can be used to improve the wettability of soils. Soil surfactants are materials that lower the surface tension of water and, depending upon formulation, can also restore wettability to water repellent mineral or organic soils. Since the invention of the original soil surfactant, AquaGro, in the 1950’s, there have been many advances in surfactant formulation making their use more economically viable for a variety of cropping systems. Where soil wettability is less than optimal, the use of soil surfactants in combination with appropriate irrigation and soil cultivation practices, improves soil hydrological behavior resulting in improved irrigation efficiency and water conservation (Kostka et al., 2007).

An growing body of research shows that soil water repellency and associated preferential flow are more common than previously thought - and that application of soil surfactants is an effective remediation strategy (Dekker et al., 2005). However, until recently, the impact of these findings on irrigation efficiency has not yet been widely recognized. This paper and its related presentation summarize the findings as they relate to efficiency of irrigation and water consumption citing some of the recent research results

Soil water repellency and preferential flow

Soil water repellency is a condition that develops in soils causing the soil to resist wetting. It is caused by the accumulation of water repellent/hydrophobic coatings on the soil particle surface (Dekker et al., 2001; Hallett et al., 2001; Karnok and Tucker, 2002), and triggered when a soil drops below a certain critical soil moisture content for that particular soil (Dekker and Ritsema, 1994). A direct consequence of soil water repellency is a reduction in a soil's ability to wet and retain water (Hallett, 2007).

The development of water repellent behavior in soils is more wide-spread than previously thought. Among the first to mention water repellency in North America were Schreiner and Shorey (1910) who wrote in a USDA bulletin: '*…there was found in California a soil which could not be properly wetted, either by man, by rain, irrigation, or movement of water from the subsoil, with the result that the land could not be used properly for agriculture. On investigation it was found that this peculiarity of the soil was due to the organic material, which when extracted had the properties of a varnish – repelling water to an extreme degree."* Since that time, water repellent soils have been identified in a wide variety of soils worldwide and studied in 35 countries on six continents, including in more than 20 states in the United States (Dekker et al., 2005). Dekker et al. (2001) and Karnok and Tucker (2002) also report that soil water repellency develops under a wide range of different plant systems. All of this has lead researchers to the view that soil water repellency seems to be more the norm than exception (Wallis and Horne, 1992; Ritsema and Dekker, 2005).

Preferential flow refers to the movement of water and solutes through specific pathways in only a portion of the soil matrix rather than in a more uniform wetting front as expected from lateral diffusion of water in the soil. Because soil water repellency reduces the wettability of portions of the soil, it leads to the development of preferential flow paths (Dekker et al., 2001). The preferential flow paths often carry applied water and solutes past the active root zone, reducing efficiency of both precipitation and irrigation, and increasing environmental risk.

As noted, soil scientists and hydrologists now consider water repellency and preferential flow to be more the norm than the exception in a wide variety of soils (Dekker et al., 2005). Water repellency in soil and the associated preferential flow are like "barriers" and "leaks" in the soil plumbing system respectively. Their occurrence interferes with the soils ability to effectively capture and distribute rainfall or irrigation water for plant use. It has been observed as well that, even after extended wet periods, soil water repellency and preferential flow paths recur (Oostindie et al., 2005). Even low levels of repellency can cause reduced infiltration and retention, increased runoff, variable wetting and preferential flow. These lead to, among other things, reduced irrigation efficiency, suboptimal growing conditions and increased water requirements.

The development of water repellency in soil can be detected by a variety of methods, the most common of which is the Water Drop Penetration Time (WDPT) test. There are advantages and disadvantages to the various approaches (Hallett, 2007). To quickly and easily determine the presence of soil water repellency for applied purposes like irrigation management, the WDPT test has many advantages. This method is spelled out in detail in the new Soil Science Society of America publication, Soil Science – Step-by-Step Field Analysis (Ritsema et al., 2008).

Soil surfactants are capable of improving soil hydrological behavior by correcting or preventing water repellency, and reducing and preventing preferential flow. The result is more efficient irrigation, reduced environmental risk from preferential flow and water savings of up to 30% or more. This has been extensively studied and documented in turfgrass management (Cisar et al., 2000; Karnok and Tucker 2002; Park et al., 2004; Dekker et al., 2005; Oostindie et al., 2005; Karcher et al., 2006; Aamlid et al., 2007; Hallet, 2007; Leinauer et al., 2007) and is now being explored in agricultural crops as well (Cook et al., 2005; Speth et al., 2005; Rowland et al., 2007).

Runoff

Runoff of irrigation or rainfall results in a loss of water which is wasteful, raises the risk of pollution and erosion, and increases irrigation requirements. Runoff is increased when water is applied at excessive precipitation rates or when infiltration is reduced. While compaction has long been recognized as a cause of reduced infiltration, soil water repellency is another cause of reduced infiltration and increased runoff. This has been verified in numerous studies (Dekker et al., 2005). And while this consequence has been recognized for some time in the case of severe water repellency, it has more recently been discovered to occur with very low levels of repellency as well (Hallet et al., 2001).

Soil surfactants have been shown to increase infiltration into soils and accordingly reduce runoff significantly. Morgan, Letey and others observed this in early research with surfactants in the 1960's (Morgan et al., 1966). More recent research has documented reductions in runoff on a variety of surfactant treated soils under a variety of slope angles. A 19.4% reduction in runoff on a surfactant treated clayey Crosby soil with a 4% slope was documented by Sepulveda (2004). Oostindie et al. (2005) recorded reduced runoff and increased soil moisture on a water repellent sand in a sloped fairway that had been treated with a soil surfactant. On a loamy sand with an 8% slope, Mitra et al. (2006) found that soil surfactant applications doubled the time to runoff, from 20 minutes to more than 40 minutes, and total runoff was reduced more than 30%. By reducing runoff, soil surfactants increase efficient irrigation, reduce irrigation requirements and lessen the potential for contaminants to enter surface waters or storm water systems.

Infiltration and root zone wetting

Infiltration and root zone wetting are fundamental to effective irrigation and irrigation efficiency. When soils are functioning well, as is still so often expected, infiltration and root zone distribution of applied water will both be fairly uniform. This will result in relatively high distribution uniformity (DU) in the soil as well as on the surface as is generally expected. However, soil water repellency can interfere with infiltration and water distribution in the soil resulting in significant variation in moisture content throughout the root zone (Dekker and Ritsema, 1994; Park et al., 2005). This has been found to be true in many soils such as sand, loam, clay and peat (Dekker et al., 2001; Dekker et al., 2005). Hallett et al. (2004) have also found this to be true even at low, "subcritical" levels of soil water repellency. When infiltration is compromised by soil water repellency, root zone DU will be lower than irrigation DU on the surface, leading to reduced irrigation efficiency.

In addition to reduced efficiency in water distribution in the root zone, the aforementioned preferential flow paths will form. This occurs as the repellent parts of the soil, which are not wetted, become drier and the wettable areas become the channels through which water and solutes are transported (Dekker et al. 2001). As a result, a significant portion of the water and solutes intended for the root zone will bypass it instead (Dekker and Ritsema,1994; Ritsema et al., 2001). This increases waste, irrigation need and the risk of environmental contamination by solutes reaching groundwater faster than expected.

Since soil surfactants reduce soil water repellency and facilitate wetting, their use in soils with even subcritical water repellency can lead to significant improvements in infiltration and root zone DU. Park et al. (2004), among others, report significantly reduced repellency and improved wettability when surfactants are applied with some regularity. In a very water repellent sand, Oostindie et al (2005) report significantly more consistent moisture levels and, correspondingly much lower coefficients of variation, in surfactant treated soils (average variation 10.4%) compared to adjacent untreated soil during the same period (average variation >50%). Reducing water repellency and increasing soil wettability and root zone moisture distribution uniformity reduces irrigation requirement, preferential flow and associated environmental risk (Oostindie et al., 2005; Park et al., 2005; Karcher et al., 2006; Aamlid et al., 2007) significantly increasing the efficiency of irrigation.

Plant available water

The Irrigation Association definition of irrigation refers to intentional application of water to provide water to plants for crop production or sustained growth (Rochester, 2006a). Plant available water (PAW), the available water located in the root zone, is therefore an important aspect of irrigation management and efficiency. As PAW values for use in irrigation scheduling are calculated from expected soil water holding capacity and plant root zone depth (The Irrigation Association, 2003), the actual behavior of the soil will affect the effectiveness and efficiency of the irrigation events. When PAW is compromised plants do not have access to expected amounts of water with the result that crop quality will suffer and/or excess water will be required.

Soil water repellency reduces actual PAW because it “locks out” part of the soil’s water holding potential. In severe cases it can render soils non-usable for crop production as the soil is unable to accept or hold water necessary for plant growth (Hallett et al., 2001). In less severe cases, because water is not available in parts of the root zone, it can cause reduced plant performance (Cisar et al., 2000; Cook et al., 2005; Leinauer et al., 2007). Unaddressed, this reduced PAW also reduces irrigation efficiency.

The use of soil surfactants to restore soil wettability and increase infiltration, soil water contents and root zone uniformity results in improved soil behavior with regard to PAW. This has been documented by an increasing number of researchers working with a variety of different crops. Significant increases in soil water contents after treatment with surfactant have been documented by many researchers (Karnok and Tucker, 2001; Cook et al., 2005; Mitra, 2005; Oostindie et al., 2005). Improved crop performance with the same or reduced irrigation, indicating improved PAW, has also been reported in turfgrass maintenance by Cisar et al. (2000), Karnok and Tucker (2001), Mitra (2005), Oostindie et al. (2005), and Park et al. (2004, 2005) among others; and by Cook et al. (2005) with potatoes and Rowland et al. (2007) with peanuts. Managing soil behavior to ensure expected levels of PAW is fundamental to achieving efficiency in irrigation.

Water conservation through efficient irrigation

Clearly, efficient irrigation is impossible without well designed, installed, operated and maintained irrigation systems. Nonetheless, it is also true that how water moves in the soil is key to overall irrigation efficiency, crop performance and water conservation. When water movement into and through soils becomes erratic, even the most well designed and managed irrigation system will fall short of expected and desired goals. Consequently, more irrigation is often applied because plants exhibit stress, which increases consumption and reduces the efficiency of the irrigation program. In addition to well designed and operated irrigation systems, water can be conserved by increasing the efficiency of water delivery to the soil through management practices that ensure desirable soil hydrological behavior.

Soil surfactants ensure that soils are wettable so that irrigation applied at appropriate precipitation rates, as well as rain fall, will move quickly and uniformly into soils. An increasing amount of research by scientists of varying disciplines is showing that more effective delivery of water to the root zone, especially where soil water repellency is a factor, can result in very significant reductions in water use or requirements. In turfgrass management, reductions of at least 20% (Kostka et al., 2005; Oostindie et al., 2005) and in some cases more than 50% (Park et al., 2005; Karcher et al., 2006) have been reported. A summary of research in this regard was published by Kostka et al. (2007). The use of soil surfactants allows conservation of water and greater irrigation efficiency.

Conclusion

When soil hydrological behavior is affected by water repellency, efficiency of irrigation declines leading to either increased water consumption to meet plant needs, or reduced “crop” performance. Soil water repellency is more common than previously recognized and, even at very low levels, significantly impacts soil hydrological behavior. Correction or avoidance of soil water repellency keeps soils wettable, improving hydrological behavior and, therefore, irrigation efficiency, crop performance and efficiency of water use.

The development of water repellency can be detected using the Water Drop Penetration Time test. Once detected, water repellency can be managed with the use of soil surfactants to improve efficiency of irrigation. Although scientists do not yet know exactly why, soils that have a critical water content threshold for water repellency seem to remain susceptible to water repellency below that moisture level, even after long wet periods or remediation efforts. Therefore, especially during drier periods, water repellency can be expected to recur in areas where it has been previously detected.

Soil surfactants are a reliable management technology for restoration for reducing, and possibly avoiding development of, water repellency and associated preferential flow. The result is maintenance or restoration of soil wettability and improved infiltration and root zone distribution uniformity. Research worldwide is increasingly indicating that certain soil surfactant formulations significantly improve soil hydrological behavior allowing more efficient irrigation, improvement in crop response and significant reductions in water consumption. Further research regarding the relationship between managing soil hydrological behavior with surfactants and irrigation system design and operation holds promise for allowing irrigators to achieve new levels of irrigation and water use efficiency in irrigated crop and landscape systems.

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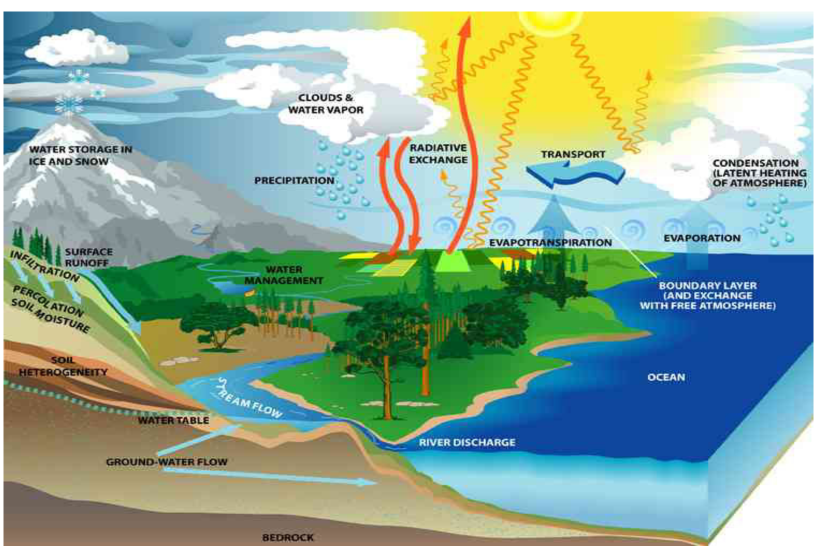
Drip vs. overhead on large slopes and landscapes

By Ron Stuart

"When the well's dry, we know the worth of water." – Benjamin Franklin

What is Water?



Water is unique – Water is the only substance found on earth in three forms solid, liquid and gas. Water is relatively incompressible. Water regulates the earth's temperature. Unlike other liquids, water expands in freezing.

Water is quality of life – We use water to bathe, cook, clean, recreate, add ambiance. Water causes us to travel to it just to look at it i.e. the ocean, a lake, a fountain. Water is used for a multitude of manufacturing processes and waste removal.

Water is property value – Property values are typically higher in areas located near lakes, streams or other bodies of water or where water is readily available through import or processing. They sharply decline in areas where water is not available.

Water is economy – The nursery and landscape industry employs over 600,000 workers during peak seasons. The nursery and landscape industry revolves solely around the application, channeling and management of water in a given area. The multi-billion dollar industry creates controllers, piping, sprinklers, filters and a multitude of other devices for the given purpose of keeping plant material alive and healthy.

Water is life – The human body is made up of 66% water, the human brain is 75% water. Water is essential for the flow of blood, absorption of nutrients and division of cells. Water is the most precious resource on earth and the only one we readily throw down the gutter.

Introduction

The landscape industry as a whole is quite unique. No other single industry has as large an impact on the direct property values in California. Aside from this, no other industry has been entrusted with the only resource in our world that we literally cannot survive without. It is also has one more unique quality. It is the only industry of it's kind that requires no formal education or experience to participate in, in fact it is often looked upon as the job people find when they are uneducated and cannot get a "real" job. When was the last time you heard of a person looking for the lowest bid for open heart surgery? Even the workers at your favorite fast food restaurant are required to study and pass a test just to serve your food. As an industry, we need to bring the value of our positions and abilities back into the market so others do not dictate the future of our careers. Lack of education is the single largest waster of water in the world! We simply do not fully understand it's value.

As our communities grow and water becomes a more precious resource, we are looking to innovative ways of irrigation to meet the changes in legislation and off set the increases in water use and water costs. Even though, the concept of point drip irrigation is little used in the ornamental landscape industry it has been effectively used for years in both the nursery and agricultural industries. This type of irrigation has been successfully used in Middle East countries where water is very scarce and extremely expensive for years. The design of the irrigation layout is just as important as plant selection. Although certain plants do not perform as well under this type of irrigation in our desert climates, many plants perform even better than under a traditional style of overhead irrigation.

Background

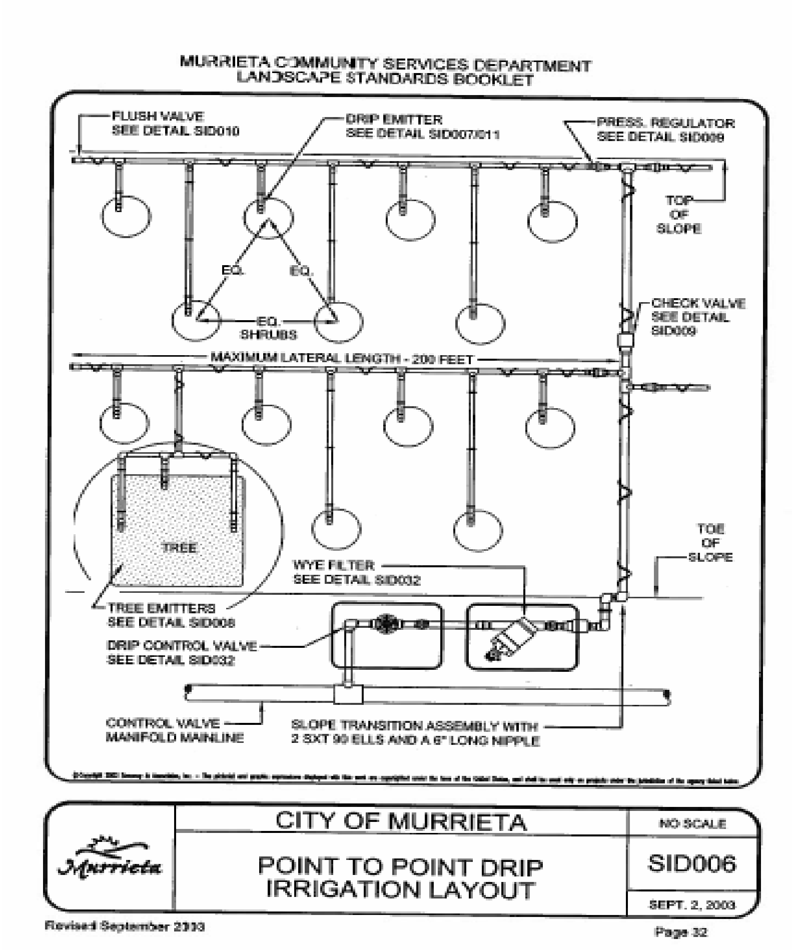
Back in 1999 we ran into a dilemma regarding budgeting and power shortages to our projects, since 1997 with the passage of proposition 218 we were no longer able to just raise assessments to cover year to year increases as they occurred from local utilities. By 1999 the State of California was experiencing shortages in electrical power and electricity costs were expensive and increasing. Around this same time, a Developer submitted a plan for review and approval which incorporated the use of multiple controllers, 3" mainlines and the use of two booster pumps to irrigate the 8+ acres of hillside landscape around two new communities. With the ability to charge for fluctuations in assessments being locked, the costs of electricity going up, the uncertainty of available power and the long term costs of using and maintaining these booster pumps we decided to meet with the Irrigation Designer, Sweeney and Associates. We wanted to see if we might be able to explore any non-conventional solutions to the impending money pit.

The designer told us of another design he ran across that incorporated the use of a "point drip" type irrigation system, (irrigation that is installed on a predetermined grid pattern to cover a specific area rather than laying out the irrigation to a preinstalled plant layout), and we asked him to draw it up. The original idea seemed to work well and considerably reduced the installation costs by alleviating the need for booster pumps, mechanical joint restraints on the larger pipe (smaller mainlines now worked hydraulically), the total number of valves was reduced enough to use single controllers and all the piping was downsized. It even resolved issues with water window conflicts. A few modifications and the plans were approved.

Before we began the physical installation of the project, the installing contractor stopped the development stating that the design wouldn't work. Since neither our department nor the irrigation designer had extensive knowledge in this type of application, we chose to listen. The original design showed piping going both uphill and downhill off the horizontal lateral lines or branch lines. This was changed to prevent siphoning back into the lines when the system was off and draining through the downward facing lines, as well as a few other key elements and off we went again with the design and installation. Eight years later we discovered some amazing data that was not even considered during the initial design and installation.

The Design

The design is based on a preset on center spacing that is held constant across a system or valve, typically we used either three or six feet on center spacing dependent on plant variety. The original installations were installed in soils which ranged from course sandy loam to clay to heavy sand. The average PH was about 7.5-7.7.



Critical elements for long-term maintenance consist of a large variety of other considerations. Because visual verification of system performance can be difficult to obtain, a controller capable of reading accurate flow was used. This allowed for personnel to check valve performance at the controller and also alert them to any potential problems. Although this is a useful tool, it doesn't alleviate the need to walk the systems on a regular basis as is done for traditional systems. Once an average flow was obtained for each valve, pre-set high and low numbers should was used. This prevented the controller from continuing to "learn down" flow rates if the system slowly plugs over time.

Obviously, with the usage of a controller that reads flow, a flow meter was used. The flow meter was compatible with the controller and able to read within the ranges used by the system. Accurate control of the system by the use of a flow meter allowed for larger systems to be designed because the potential for an unseen failure was great. Examples of these were the large 2:1 slopes in the back open space areas.

Along these same lines, the system was designed with a pressure regulator and master valve to shut the system down if there was a high flow reading. Even though the point drip system releases at a lower flow rate (typically 16-23 GPM's), than a traditional system, a stuck valve can run unnoticed longer and saturate a slope to the point of potential slide. A master valve properly used greatly reduced the opportunity for this scenario to take place. The master valve was used with a pressure regulator, this allowed for the pressure to begin lowering in the system reducing the ultimate stress to the mainline over time. The pressure regulator should also be of a type that will effectively regulate within the given system parameters.

Every RCV was also a pressure regulating type. This continued to adjust the pressure down in steps and also allowed for more site-specific regulation according to each zone condition. All valves were designed as 1" size for consistency in zone size and to reduce overhead.

Contamination from debris is the number one cause of failure in a commercial drip irrigation system and the usage of proper filtration is critical to the long-term effectiveness of the system. At the POC, a basket/flushable screen was used. After each RCV the use of a disc strainer was also incorporated. Every emitter installed on the system was also individually able to flush debris through their orifices. If it cannot perform this action than a filter at the emitter should be installed. This allowed the individual emitters to not clog as easily and has given years of satisfactory performance to the system.

Immediately after the RCV assembly area, the piping was installed at 1 1/4" along the main lateral or "trunk lateral" of the grid pattern, larger than the hydraulic needs required. This allowed the system to "reserve" a larger mass of water creating a quicker charging of the system, which reduced the total run time for each station. The reserve of water in this column was maintained through the usage of either swing check valves or spring check valves. These check valves were placed at the toe of slopes and one foot uphill of any tee or tee assemblies off this line. This allowed for a maximum amount of water to be reserved and also gave ease in the locating of these check valves.

One foot off the main lateral from the transition tees, a low flow pre-set in line pressure regulating valve was used on each branch line. This allowed for the continual step down of the pressure and for even pressurization of each line eliminating the need for compensating emitters. By using the low flow in line regulating valves, we found that in the case of a break, they reduced the flow of water by shutting down and kept erosion to the landscape at a minimum.

Drip layout shown on slope

All the branch laterals were designed to be only a ½" size in diameter and laid horizontally to grade. This not only reduced the total cost for the installation and the maintenance of the system but also reduced the total time for charging and discharging the lines, giving more accurate irrigation control. These lines were also made from rigid PVC piping to reduce the incidence of breakage and also alleviate damage from digging or rodents. At the ends of these pipes a flush cap was installed.

After the initial design using hard PVC piping and street ell assemblies to the plant, a flexible PVC lateral change was made to irrigate each individual plant from the rigid branch lateral line to the emitter. These "stick lines" all generally placed in a downhill format to create a positive draining of the system and reduce back siphoning when the systems are turned off. This flexible line allowed for a better attachment to any variations in the grade and could be moved aside to either work on the emitter or dig around the plant. The flexible PVC lengths were sized according to design and final plant spacing and pre-assembled by a manufacturer for consistency and quality control. All the flexible PVC laterals were Teflon taped to reduce the chance of undesirable leakage in the system. All of the piping from the valve to the emitters was j-hooked into place on a ten foot spacing.

The emitter was a ½" threaded type. These not only sped the process of installation and repair but also tended to be more durable, lasting longer in a commercial application without leaking through a punched hole. Every emitter had the same flow rates. This prevented the maintenance personnel from having to decide which emitter goes where and changing the distribution uniformity through lack of knowledge.

Because the field conditions and square footages varied from the drawings, all the laterals were installed prior to any actual plant layout and the irrigation grid determined the final plant placement. ***We did not irrigate by the planting plan!*** The planting plan was considered diagrammatic for purposes of uniform bidding and concept only. This greatly reduced any confusion and cost to the installation personnel with regards to the final layout of the irrigation. It also ensured a more uniform, higher efficiency system. Although, the irrigation design can be considered “inappropriate” by conventional design standards, we have found that the end result was significant enough to consider it an absolute success.

At the completion of the first location we had two different emitter manufacturers do some catch can testing and they found that the design met with their performance standards. We also invited two different landscape architects, a maintenance contractor, an installation contractor as well as several other municipalities. We wanted to find what flaws would be discovered from the different disciplines. Everybody felt that all the difficulties with irrigating large areas on drip in a commercial application had been addressed. When all was said and done the entire area was mulched with a 4” layer of rough grade tree trimming mulch, which had a good balance of both leaf matter as well as wood fiber.

Results

The following was our findings in both installation costs and water usage over the past seven years.

As you can see by the tables below, there has been a significant reduction in water usage compared to actual budget amounts. The numbers provided were the water usage as provided by the Rancho California Water District from a history search. The water rates as well as the energy costs were generated from the actual charges found on a typical potable water bill at the time of the calculations, water rates have gone up since this study. As is apparent the water savings vary from approximately 63% to as high as 90% depending on year and maintenance practices. An overall average of low to mid 70% savings has been experienced over the past seven years.

These numbers are reflective of an uncontrolled real world environment. This area was under the control of the installing contractor and developer in the first two years, the County of Riverside CSA143 and it’s maintenance contractor for a few years, the City of Temecula as well as the Redhawk Communities Homeowners Association currently. The pattern showed no control over usage, typical of the average contractor’s knowledge and abilities to irrigate the area. The only constant is the usage remains around 70-75% and the landscape continues to grow as seen in the pictures.

Drip Usage vs. Overhead Usage Comparison Tuesday, September 30, 2008

Project Name: Vintage
Meter #: 1561966 Account #: 01-0000067-2
Square Footage: 365,237 *MAWAB: 18,186

	Base	2008	2007	2006	2005	2004	2003	2002	2001	2000
Unit costs:		$0.6607	$0.6607	$0.6607	$0.6607	$0.6607	$0.6607	$0.6607	$0.6607	$0.6607
Energy Costs:		$0.1021	$0.1021	$0.1021	$0.1021	$0.1021	$0.1021	$0.1021	$0.1021	$0.1021
January	673	543	362	326	7		306	60	283	
February	920	203	224	124	0	153	300	64	79	
March	1251	0	282	219	0	114	395	72	9	
April	1329	163	247	332	0	116	110	127	22	
May	1964	808	274	407	644	390	507	329	34	
June	2273	699	440	300	172	731	312	376	103	
July	2546	784	793	420	644	1747	551	449	122	257
August	2437	634	794	643	841		667	532	259	225
September	1964	808	848	595	1037	1156	729	778	383	287
October	1329		797	607	715	990	775	772	349	291
November	837		733	440	825	663	575	466	313	363
December	618		929	187	320	12	426	381	146	359
Yearly Total	18,186	4,642	6,723	4,600	5,255	6,092	5,576	4,426	2,102	1,782
Amount Saved		13,544	11,463	13,586	12,931	12,094	12,610	13,760	16,084	16,404
Percent Saved		74.48%	63.03%	74.71%	71.10%	66.50%	69.34%	75.66%	88.44%	90.20%
Percent Used		25.52%	36.97%	25.29%	28.90%	33.50%	30.66%	24.34%	11.56%	9.80%
$$ saved		$10,331.67	$8,744.29	$10,363.70	$9,864.07	$9,225.61	$9,619.21	$10,496.43	$12,269.18	$12,513.27

Total Saved: $90,427.42 Average: 72.68%
Units Saved: 122,460 * MAWAB (Maximum Annual Water Allocation Budget)

Drip Usage vs. Overhead Usage Comparison Tuesday, September 30, 2008

Project Name: Eastridge
Meter #: 2658784 Account #: 01-0000066-2
Square Footage: 224,018 *MAWAB: 10,576

	Base	2008	2007	2006	2005	2004	2003	2002	2001	2000
Unit costs:		$0.6607	$0.6607	$0.6607	$0.6607	$0.6607	$0.6607	$0.6607	$0.6607	$0.6607
Energy Costs:		$0.1021	$0.1021	$0.1021	$0.1021	$0.1021	$0.1021	$0.1021	$0.1021	$0.1021
January	391	0	214	183	0		52	24	257	
February	539	52	338	68	0	102	194	28	41	
March	751	16	212	307	0	31	198	27	10	
April	772	64	129	143	0	53	31	70	16	
May	[illegible]	174	[illegible]	[illegible]	[illegible]	195	[illegible]	[illegible]	19	
June	1322	184	334	239	65	286	160	173	59	
July	1481	512	369	307	156	404	289	241	77	0
August	1417	509	388	278	181	330	296	279	74	0
September	1142	471	462	331	20	754	485	395	222	69
October	772		180	223	193	588	514	451	247	13
November	486		416	150	165	249	443	379	191	174
December	360		508	102	223	0	315	151	90	248
Yearly Total	10,576	1,972	3,682	2,549	1,040	2,991	3,270	2,420	1,303	504
Amount Saved		8,604	6,894	8,027	9,536	7,585	7,306	8,156	9,273	10,072
Percent Saved		81.35%	65.18%	75.90%	90.17%	71.72%	69.08%	77.12%	87.68%	95.23%
Percent Used		18.65%	34.82%	24.10%	9.83%	28.28%	30.92%	22.88%	12.32%	4.77%
$$ saved		$6,582.76	$5,258.37	$6,122.63	$7,273.69	$5,785.47	$5,572.65	$6,221.03	$7,073.06	$7,682.56

Total Saved: $57,552.23 Average: 76.69%
Units Saved: 75,449 * MAWAB (Maximum Annual Water Allocation Budget)

How much does all this cost? The average cost per square foot is comparable to slightly higher than a traditional overhead design. A typical installation cost for traditional overhead system of a 33,750 square foot project in 2005 was $0.8637 per foot. A 332,134 square foot drip project in 2006 was rated at $0.8382 per square foot and a 94,519 square foot project in 2007 was only $0.9638 per foot. Even if the costs were identical, the water savings alone for the drip, soon tips the scales in it's favor.

Benefits

The water savings was tremendous. Between the initial two installations, a savings in excess of more than 203,512 units of water has been realized. According to statistics provided by the Environmental Protection Agency, the average adult requires 64 ounces or a half gallon of water a day to survive. Given these statistics the saving from these two projects equates to enough water to keep over 834,118 people healthy for one year.

Water savings also translates into energy savings reducing the carbon footprint as well as a very real financial benefit both through the water costs and a reduction in maintenance costs by as much as 20%.

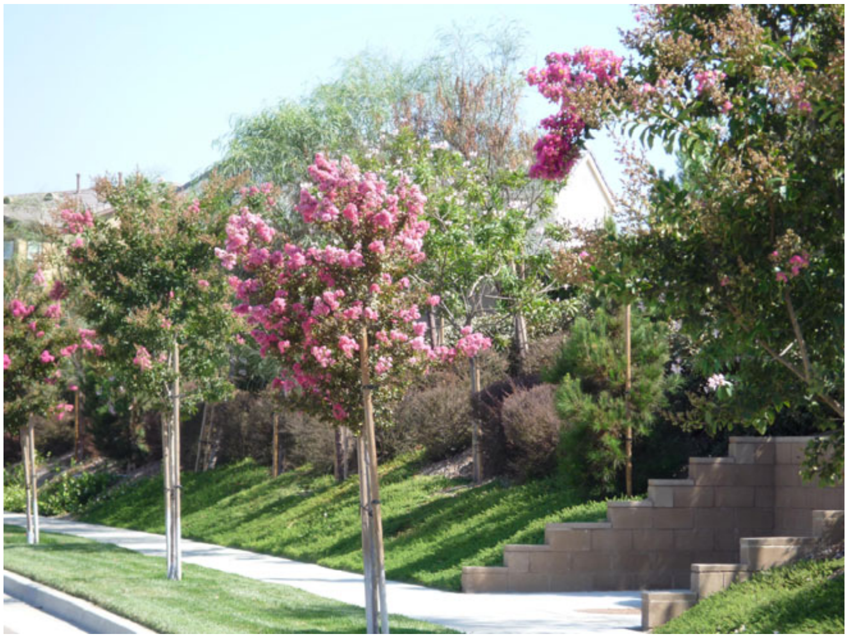
Based on water costs alone, these two developments have produced a savings of over $155,248.36 since initial installation. These numbers will vary based on water costs and increases within a given district.

As landscapes mature and fill in drip systems do not require the raising of heads or trimming back of plant material which are blocking the spray patterns, causing dieback in the interior of the landscape and exposing the systems to increased vandalism.

The mulch acted as a short term fertilization program that amended the soil and stimulated the bacterial activity in the soil matrix. It also became a quite effective erosion control and brought aesthetic integrity to the job.

Drip designs eliminate Storm Water Pollution Prevention concerns. This photo depicts a low volume stream spray system. Overhead systems all have this inherent problem.

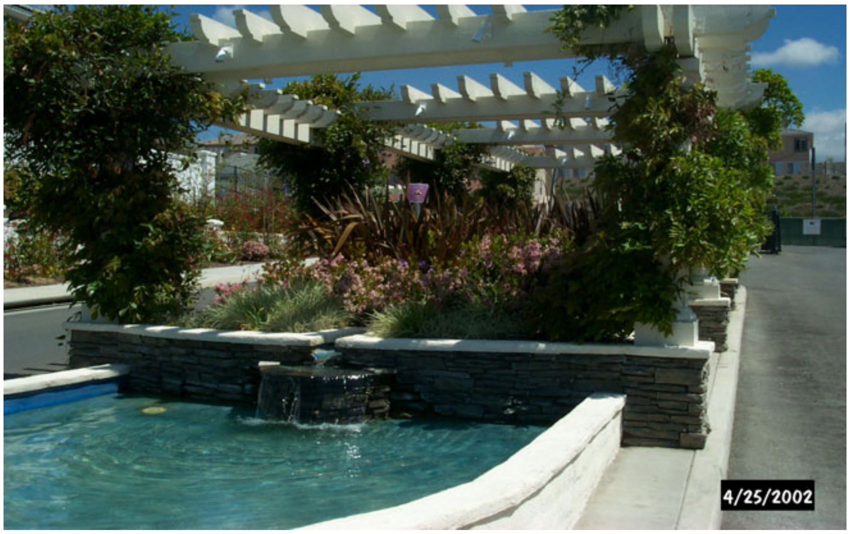
These benefits do not come at the cost of aesthetics either. The plant palette was typical of those found within our region and not only have they performed as well as in any other landscape but many outperformed the traditional overhead system. Based on a six foot grid pattern, we have experienced plants touching as soon as six months and areas completely filling in by eighteen months. We have planted drought tolerant plants such as Pyracantha and Acacia spp., as well as higher water users such as roses, Raphiolepis and Myoporum. With very few exceptions, most plants performed better under the drip environment. Baccharis is one exception.



We quickly created this to be a standard within the County of Riverside which was followed by the City of Temecula, the City of Murrieta and Valleywide Parks and Recreation Department. More municipalities may have adopted the design that we are not aware of. Each entity has taken the original design and performed slight modifications and product preferences but the concept remains the same.
We have successfully installed millions of square feet of this system into the landscape and development areas including 1:1 granite hillsides that required rappelling equipment to install the irrigation and plant material, sandy slopes that fall apart when they get too wet, in parks, parkways, medians and retrofits.

As a follow up with Lance Sweeney of Sweeney and Associates, he states that some clients have increased the number of emitters per plant to provide additional water. Rudy

Adame with Adame Landscape who is in charge of much of the Valley Wide designs keeps their designs to no further than 4’ on center spacing. Kevin Herrington of the Temecula Community Services Dept., has stated their only problem is they don’t have enough systems and the maintenance contractors continually need to be reminded to clean the filters. Maintenance practices are slightly different for this type of system. Keeping the filters clean on a regular basis greatly increases the long term success of the system.



Although there are many great ideas for water management, we have never seen any so consistent in its performance. With the water saved in the non turf areas, perhaps we will be able to still maintain healthy full dimensional gardens and landscapes. There are course other solutions to our water crisis that are suggested but less than desirable.


This can be our future if we don’t consider what we are doing and start to react in a more positive approach.

This paper is dedicated to the memory of Sam Toby of Salco products, whose inspiration, encouragement and help have all been tremendous driving forces in the long term success of this endeavor.

References

Tim Barr, Resource Planner, Rancho California Water District, 42135 Winchester Road, Temecula, Ca 92590

Lance Sweeney, President, Sweeney and Associates, 38730 Sky Canyon Drive, Suite C, Murrieta, Ca 92563

Rudy Adame, President, Adame Landscape, 41863 Juniper St., Murrieta, Ca. 92562

Kevin Herrington, Parks Superintendent, City of Temecula, 43200 Business Park Drive, P.O. Box 9033, Temecula, Ca 92589-9033

Environmental Protection Agency, Facts web page

Eastern Municipal Water District, Water Budget Formulator

Injection of Urea-Sulfuric Acid Fertilizer to Improve Water Quality

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Abstract - *This paper proposes an additional component to traditional fertilizer and irrigation water management. The continuous management of irrigation water pH has been developed over the past two decades in production agriculture. The same principles for its applications are equally important for horticulture and turf management.*

All water used for irrigation contains some dissolved salts. The suitability of water for irrigation generally depends on the kinds and amounts of salts present. All salts in irrigation waters have an effect on plant-soil-water relations, on the properties of soils and indirectly on the production of plants. (Stromberg)[i]

One of the hazards of irrigated horticulture is the possible accumulation of soluble salts in the root zone. Some plants tolerate more salts than others, but all plants have a maximum tolerance. Most plants are more sensitive during early seedling growth and then become increasingly tolerant during later states of growth and development. Ordinary irrigation methods result in some leaching so that the accumulation of salts in the soil is reduced but not eliminated. Before a critical assessment of the salinity hazard of any irrigation water is made, it is necessary to know how much salt a plant can tolerate and how much leaching is needed to reduce the salt in the soil or growing medium to an acceptable level. (Western Fertilizer Handbook)[ii]

Of the salts that may be present in irrigation waters, this paper will focus on bicarbonates and carbonates. These two anions are similar in its adverse effects. Appreciable amounts of carbonate ions can be present only at pH values of 9.5 or higher. The relative amounts of bicarbonates and carbonates present are a function of the pH value of the solution. (Agricultural Handbook No. 60)[iii] All references to bicarbonates in this paper are assumed to include both carbonates and bicarbonates. Bicarbonate is routinely analyzed in water analysis tests. Acids act upon bicarbonates and carbonates, resulting in the formation of carbon dioxide and water, as shown in the following equation, using sulfuric acid: [ivv]

$$2HCO3 + H2SO4 \rightarrow SO4 + 2H20 + CO2$$

Traditional management of horticultural landscapes and lawns are to broadcast soil amendments and/or fertilizers once or twice a year.

Many of the soils in the Western United States are highly calcareous and high in pH. Often irrigation water is high in pH and high in bicarbonates. These irrigation waters are adding salts to the landscape. High pH will restrict the nutrient uptake, depending on the nutrient.

It has been demonstrated that adding urea-sulfuric acid fertilizers, at a controlled rate, on a continuous basis, to achieve an adjusted water pH of 6.5 to 7.0, under the right conditions, has significant response. The landscape maintenance person is required to have a hand held pH meter to monitor the pH. The pH of the irrigation water, downstream of the injection point of the urea-sulfuric acid fertilizer, determines the rate of injection of the fertilizer. The higher the salt content and pH of the irrigation water, a higher rate of injection of urea–sulfuric acid fertilizer is needed, and the results are expected to be more dramatic.

The benefits of continuous injection of urea-sulfuric acid fertilizer include:

- Deeper soil penetration of the irrigation water
- Less surface water runoff
- Decrease of total amount of irrigation water required
- Increased leaching fraction, with more salts leached below the root zone, than what would be leached by water alone
- As the water pH is reduced, the bicarbonates in the water are reduced
- Continuous application of nitrogen as a nutrient, in small controlled amounts
- Continuous application of sulfur as a nutrient, in small controlled amounts
- Continuous application of sulfuric acid to lower the water pH to a neutral pH level
- Urea-sulfuric acid is a relatively safe fertilizer to handle in the event of skin contact

Different ratios of urea-sulfuric acid fertilizers are available, to balance the nitrogen and sulfuric acid ratios, to meet the optimum response of the water and plant nutrient requirements. This liquid fertilizer is available from different fertilizer manufactures and retailers under different trade names.

The systems require back-check protection if the water comes from a public water supply, to assure all interested parties that fertilizer is not backing up and potentially contaminating the upstream water supply.

The fertilizer injection systems have an up-front cost to the user. However, under the right soil and water conditions, and with proper management, the response by the landscape can be dramatic.

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[i] Stromberg, Les K., "Water Quality for Irrigation," University of California Cooperative Extension, Fresno County, CA, 1975

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[iii] Richards, L.A. (editor), USDA Handbook No. 60, Diagnosis and Improvement of Saline and Alkali Soils, 1954

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Understanding the Varying Viewpoints of the Water Utility Provider and Landscape Contractor

Debra Lane, CLIA, Water Conservation Representative

City of Santa Rosa, CA

Introduction

Water agencies in the Western States typically experience more than a 200% increase in water use during the summer months due to landscape irrigation. Fostering effective partnerships between water purveyors and landscape contractors is critical to reduce demand of this resource. For many water purveyors, it remains difficult to get the landscape contracting community to participate in programs and support services targeted toward landscape water conservation. Conversely, although free rebate money and support services are available, many landscape contractors avoid working with their local water supplier – even though this could strengthen their water management skills and increase sales opportunities. Why is this occurring?

This paper explores the viewpoints, goals and objectives of each party and examines the common barriers, as well as avenues to cooperation. Specific examples are used that highlight the growth and success of the landscape water conservation programs at the City of Santa Rosa.

For this study, the region of surveyed water purveyors and landscape contractors included areas within the Greater San Francisco Bay Area. The region typically exemplifies a Mediterranean climate with hot dry summers and mild, wet winters. Rainfall amounts average 30” between November – April, while summer temperatures range from 70 – 90 degrees.

Methodology

In order to obtain viewpoints from the landscape contractor, a fifteen question survey was developed. Hard copies, including a postage paid, return envelope were mailed to 295 landscape contractors throughout the Greater San Francisco Bay Area. Forty surveys were completed. Fifty surveys were also sent out via e-mail to water purveyors throughout the Greater Bay Area. Nine purveyors responded with answers. Questions were targeted toward the large landscape (commercial) programs although some data does include residential landscape programs.

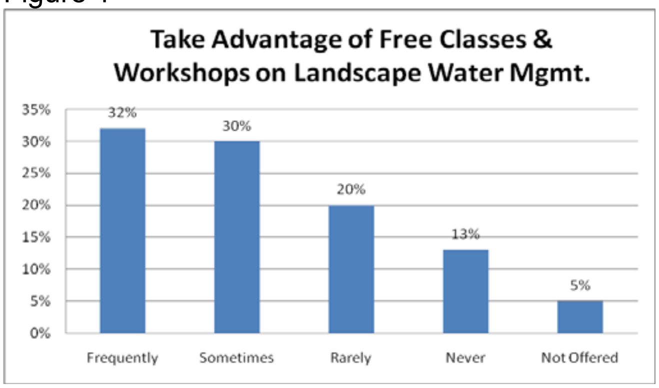
Results and Discussion

The landscape contractors who completed the survey represent a broad range of company size. Of the responding companies, 38% employ less than 5 people, 32% employ 5-25 people, and 30% employ 26 or more people. The water purveyor respondents included large water wholesalers and small to moderate water retailers. These respondents represent approximately 50% of all water purveyors throughout the Greater Bay Area and their corresponding geographical footprint.

The following results are calculated based on respondents who answered each respective question. Some questions allowed for multiple answers. Discussion points are provided to highlight learning opportunities:

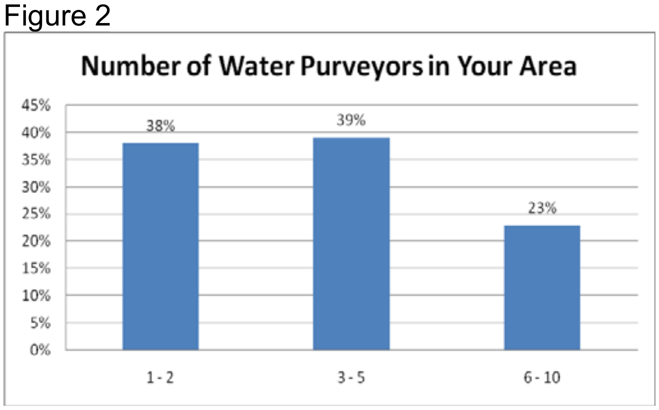
Of the landscape contractors who completed the survey, 62% attend free water management classes and workshops offered by the water purveyor while only 18% never attend (see figure 1). With adequate outreach and marketing efforts, water purveyors attract most of the landscape contracting community through offering educational events developed specifically for water management in the landscape. These events also provide an added opportunity to establish and strengthen relationships between the water purveyor and landscape contractor:

Figure 1



The Greater Bay Area is host to a large number of landscape contractors. Because of the relatively close county lines, even a small landscape maintenance contractor may service an area that encompasses several counties and multiple water purveyors. Of the landscape contractors who completed the survey, 62% have 3 or more water purveyors in their service area (see figure 2):

Figure 2



Having multiple water purveyors within the landscape contractor's service area demands more time on the landscape contractor's part in order to understand, track and implement the varying services and rebate programs offered by water purveyors. This potentially unbillable time could lead to a lack of participation by the landscape contractor (see Figure 5). Water purveyor efforts to create regionalized rebate programs could simplify the compliance process which would decrease the time required by the landscape contractor and therefore increase program participation.

Of the landscape contractors who replied to the survey, 61% assist their customers in taking advantage of irrigation hardware rebate programs (see figure 3a); 52% stated that they take advantage of the turf removal rebate programs provided by the water purveyor (see figure 3b).

Of the water purveyors who replied to the survey, 67% offer a rebate for large landscape upgrades (see figure 4a) while only 33% offer a turf removal program (see figure 4b):

Figure 3a

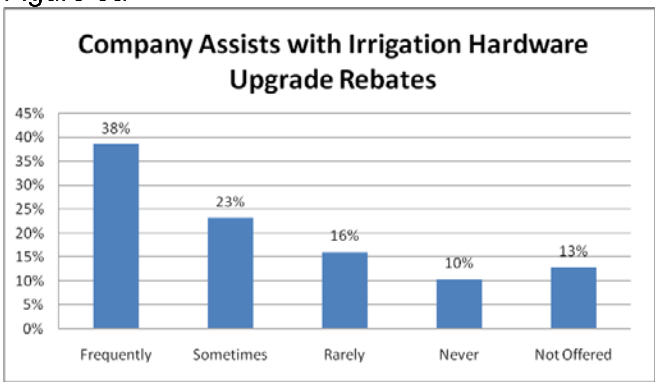


Figure 3b

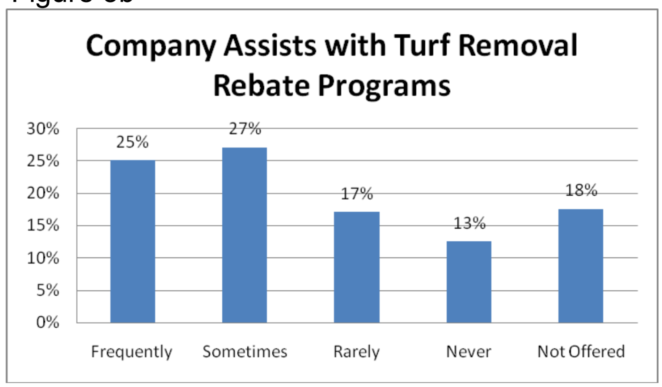


Figure 4a

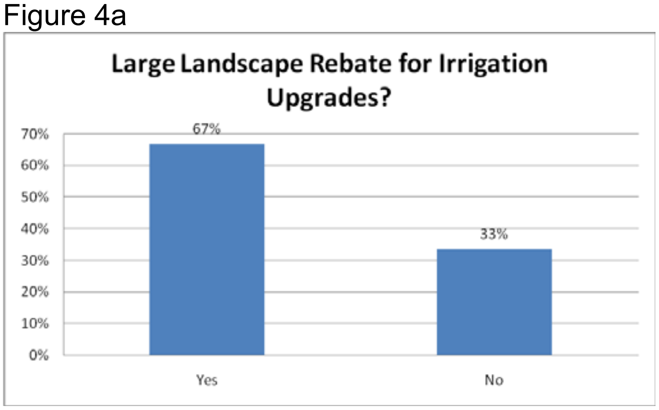
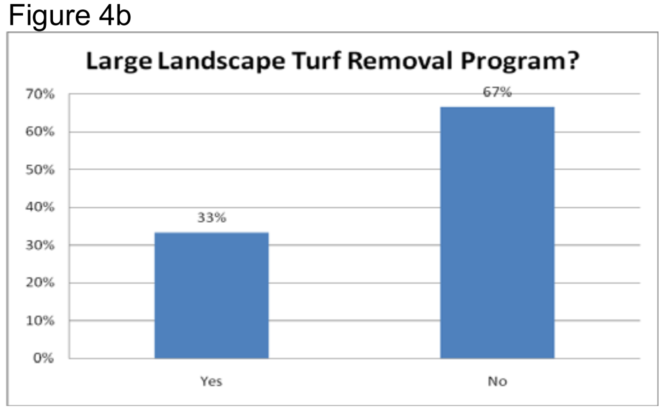


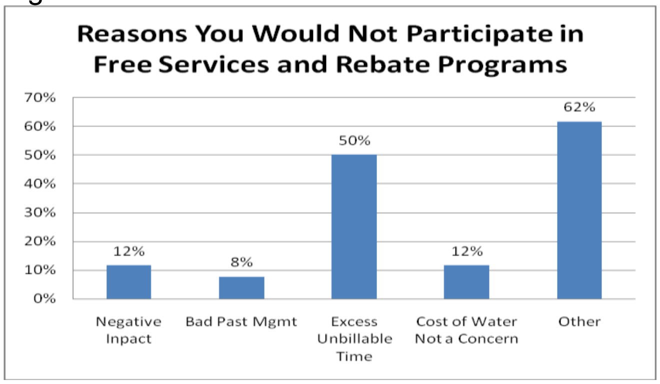
Figure 4b



Irrigation hardware rebate programs are both offered and taken advantage of the majority of the time. However, it is interesting to note that while there is a much smaller availability of turf removal programs offered by the water purveyor, over half of the landscape contractors are taking advantage of these programs. Implementing and marketing a turf removal rebate program is likely to increase landscape contractor participation. Additionally, early results from the City of Santa Rosa's Green Exchange Program show that more cost-effective water savings can be achieved as a result of implementing a turf removal program vs. implementing irrigation upgrades.

The landscape contractor survey listed several reasons why landscape contractors would not participate in free services and rebate programs (see figure 5):

Figure 5



Unbillable time was the #1 reason why landscape contractors would not participate in free services and rebate programs. The less time-consuming that a rebate program can be in terms of contractor compliance, the more likely there will be landscape contractor participation. In addition, a landscape contractor may want to consider charging for their time to assist the customer in taking advantage of a rebate.

The most cited "other" category comment was that the customer was not willing to spend money on upgrades. In terms of the customer's unwillingness to spend money on upgrades, any tool or educational service that the water purveyor can provide to assist the landscape contractor in illustrating the value of the investment in implementing landscape and irrigation upgrades will be of help to both the landscape contractor and the customer. An example of this type of tool will be displayed in the case study section.

Of the landscape contractors who replied to the survey, 45% reported that they spend 10% to 25% of their time training and implementing landscape water management practices (see figure 6a). Additionally, 46% of landscape contractors are using rebate programs and water use consumption analyses to sell extra work (see figure 6b). Extra work typically refers to any work that is not part of the regular maintenance contract. This usually includes irrigation upgrades, turf renovation and turf removal:

Figure 6a

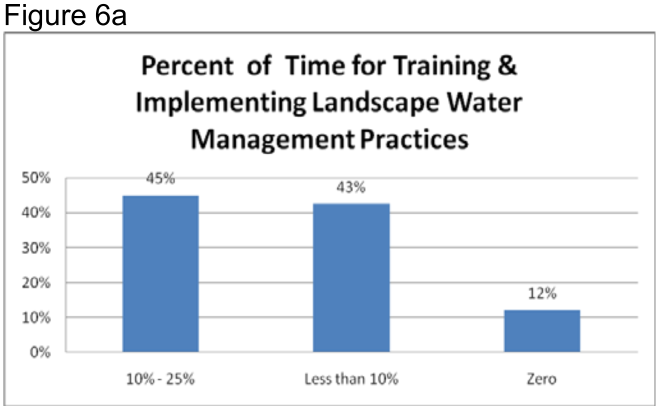
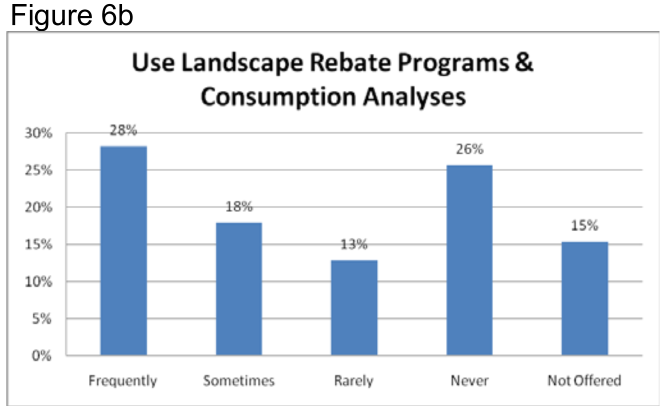


Figure 6b



Water management is gaining acceptance and momentum within the landscaping industry. Landscape contractors are beginning to commit company resources to training in water management as well as utilize their water purveyor(s) to increase business results.

Survey Summary

Based on these survey results, landscape contractors will participate more in services and programs offered by the water purveyor if: they know about the free classes and workshops that are offered on water management; the programs are designed to minimize time needed for compliance; both irrigation hardware and turf removal rebates are available; water consumption analysis tools are offered that assist the landscape contractor and their customers in measuring the investment value of implementing water conserving landscape renovation and irrigation upgrades.

Traditional water purveyor conservation programs focus primarily on ways to assist the water customer. In order to be successful, programs in landscape water conservation should also consider the landscape contractor. The following is a water purveyor case study that incorporates a programmatic approach which addresses both the water customer and the landscape contractor (see Table 1).

Case Study

Santa Rosa is located approximately 50 miles north of San Francisco in the County of Sonoma and has a population of approximately 158,000 people. There are a total of 1,832 dedicated irrigation meters and roughly 400 commercial mixed use meters within City limits. Santa Rosa water use reaches its peak during the summer months of June through September when half of water consumed is used to irrigate urban landscapes. Water use during the winter months averages 13 million gallons per day (mgd) while water use during the summer months increases to as high as 33 mgd. As a result, water use is the highest during the month of July and is considered to be the “peak demand” month.

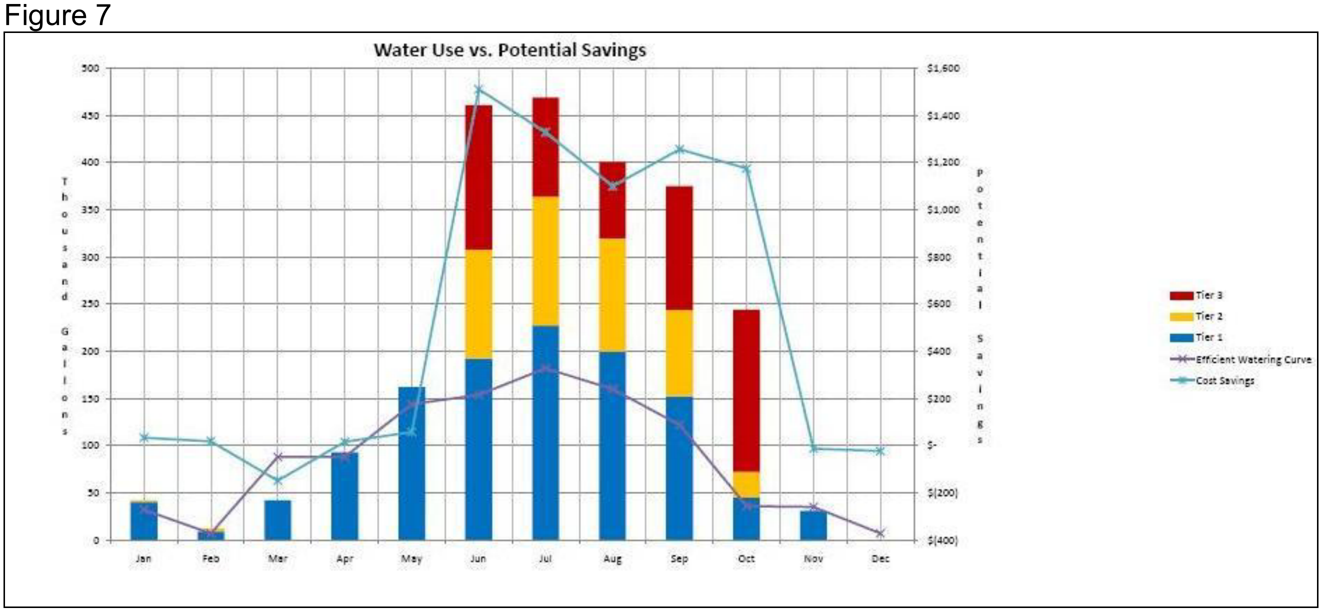
The City of Santa Rosa (City) has implemented several policies and programs throughout the years as a way to focus on reducing peak demand and improve outdoor water use efficiency. In 2007, the City implemented landscape water budget based tiered rates. Budgets for all dedicated irrigation meters are calculated using landscape square foot measurements and real-time evapotranspiration (ET) data for the billing period. Tiered rates are based on the amount of consumption in relationship to the landscape water budget. Also in 2007, the City requested voluntary conservation due to supply impairment conditions. (This may have contributed to higher program participation rates.)

A rebate program called the Green Exchange was also implemented by the City in 2007. The program offers cash incentives for turf removal and/or irrigation efficiency improvements for residential and commercial properties. Both a pre and post inspection is required for program compliance. A rebate check is sent to the customer upon successful completion of the project. In prior City programs, a rebate was given after the customer had complied with a required amount of water consumption savings (i.e., irrigating below water budget) for a period of one year. This placed much of the responsibility and more investment in time needed for compliance on the part of the landscape contractor and water customer. The Green Exchange Program does not require a water savings requirement or a monitor period in order to qualify for a rebate. Providing the money up front has increased program participation as compared to prior programs; which has also been validated by other water purveyors. Additionally, the pre and post inspection requirements serve as an opportunity for relationship building between the landscape contractor, their customer and the City's water conservation staff.

As part of an implementation plan to support the City's Water Waste Ordinance that was adopted in 1999, the City's Water Conservation Program developed a "Water Watch Patrol." In 2007, the City initiated the Water Watch Patrol in response to a request for voluntary conservation by the City's wholesaler, the Sonoma County Water Agency. While the service was created to identify and notify customers of water waste, it has proven to be an effective tool for identifying irrigation related water waste (which is almost always the source of the problem). While a report of water waste can be considered a "slippery slope" for the landscape contractor and water purveyor, it is the City's position to be supportive rather than punitive, even if the water waste is a result of excessive controller programming or a poorly maintained irrigation system. It is an opportunity to both establish a working relationship with the landscape contractor and to offer the customer a free irrigation audit in order to help eliminate the water waste. Any audit then serves a dual function of education and outreach, and as a pre-approval for participation in the Green Exchange rebate program. This has increased the number of irrigation audits performed and rebate program participation.

The City's Water Conservation Program has offered free large landscape audits since its inception. These audits are performed by qualified staff members who are all Certified Landscape Irrigation Auditors through the Irrigation Association. Many of the staff members have a strong working knowledge of irrigation product technology and can assist the landscape contractor and water customer with site specific recommendations. During the audit, a consumption analysis showing annual actual vs. budgeted consumption is provided and discussed. Potential savings that could be achieved by irrigating to budget is broken out by tier in a spreadsheet and graph (see figure 7).

Figure 7



Some additional landscape services offered by the City's Water Conservation Program that have helped build a comprehensive landscape program include:

- Turf-Time lawn watering information. This information is updated weekly to reflect current lawn and shrub watering requirements for the Santa Rosa area, and information is available via a recorded phone message and a web page.
- Landscaper Training Program. The City co-developed the "Qualified Water Efficient Landscaper" program (QWEL). Designed to educate the professional landscaping community on landscape water management, this program is recognized by WaterSense as a water auditor course and is available in both English and Spanish (www.qweltraining.com).
- Workshops and classes on water management. Topics have included irrigation efficiency, Smart controllers, drip irrigation and low water use plant selection.
- Monthly water use vs. water budget information. This information is printed on each customer's dedicated irrigation bill; referred to as a "report card."
- High water use customer calls. Courtesy calls are placed to customers whose dedicated irrigation meter account shows excessive tier three consumption.
- End of Year analysis for dedicated irrigation customers. This analysis illustrates how much the site was above budget in gallons and dollars. A letter and chart is sent to each customer to encourage the customer to take advantage of the free audit service and invest those dollars in sustainable improvements.

Table 1 illustrates which party (water customer and/or landscape contractor) the City water landscape programs assist:

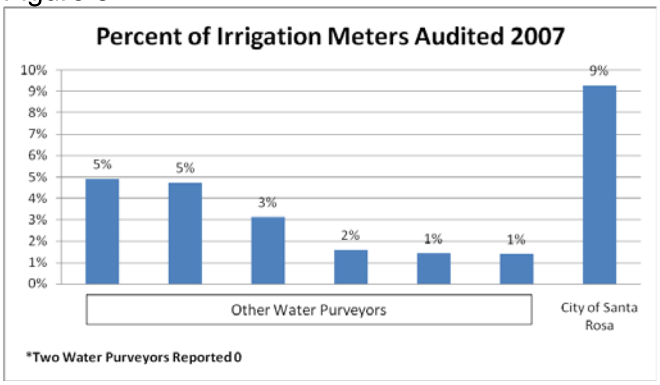
Table 1

Water Customer	**Landscape Contractor**
Turf-Time	Turf-Time
Residential Workshops	Contractor Workshops
Green Exchange Program	Green Exchange Program
Consumption Analysis	Consumption Analysis
Irrigation Audits	Irrigation Audits
Water Use Report Card	QWEL
High Water Use Calls	
End of Year Analysis	

The combination of rate structure, programs and services offered at the City are producing excellent results:

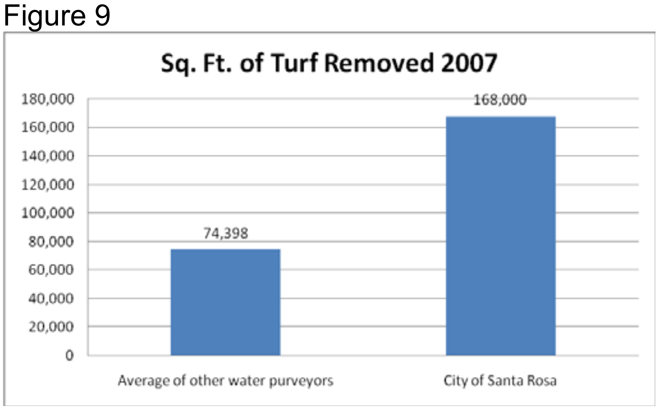
In 2007, the City's Water Conservation staff audited 9% of all dedicated irrigation meters. This is roughly 2 to 9 times the amount of audits that were performed in 2007 by other water purveyors in the surveyed area (see figure 8).

Figure 8



In 2007, the City's turf removal program resulted in the removal of 168,000 square feet of turf removed. The average square feet of turf removed by other water purveyors in the surveyed area was 74,398 (see figure 9).

Figure 9



Having real-time ET landscape water budget based tiered rates drives interest in the City's Water Conservation Program. A site specific landscape water budget allows an accurate analysis of water consumption and, as already illustrated, can show the potential cost savings as a result of irrigating to budget. This analysis, combined with the increase in water costs due to tier two and tier three consumption, has created more customer demand for programs and services.

Prior to the introduction of the tiered rate structure, the total number of large landscape audits averaged 15-20 per year. After the introduction of the tiered rate structure in 2007, 170 large landscape audits were performed by the City.

The success of the City's turf removal program illustrates the combined effect of the City's efforts to improve outdoor water use efficiency and design programs that attract both the water customers and landscape contractors.

Conclusion

Landscape water management is gaining prominence in the landscaping industry. In order for the landscape contractor to be successful, they need the technical water management skills and they also need to know how to sell water management and water conservation related landscape and irrigation upgrades. Time is money and increased sales drive success for their bottom line.

Landscape services and programs offered by water purveyors that take the water customer (decision maker) and the landscape contractor's paradigm into consideration will be most successful. Providing free rebate money up front and a rate structure to encourage the change will help transform the market. Creating regionalized programs will minimize the time needed for program compliance. Implementing a turf removal program will not only attract both water customer and landscape contractor participation, but also it is likely to achieve more cost-effective water savings than an irrigation hardware rebate.

All of this combined with outreach efforts designed to build supportive relationships with all stakeholders will provide a win win win combination. The customer is going to save money on their water bills and have a healthier landscape; the water purveyors will be saving water from unnecessary water usage, reduce peak demand and minimize potential runoff pollution from fertilizers and other contaminants entering into the storm drains; and the landscape professionals will bring a new revenue stream into their company while protecting the environment and a valuable resource.

Acknowledgements

Thank you to all of the landscape contractors and water purveyors who were kind enough to take the time to complete the surveys that were used in this report. Many thanks to Stacie Hatfield for her excellent assistance with the statistics and graphs and to Janette Morris for her help with final editing. A special thanks to Sean McNeil and Daniel Muelrath for their expertise, guidance and support with content review and refinement. Additional thanks to the following individuals: Randall Barron, Jennifer Burke, Gail Chavez, B Jay Turpel, Glen Wright and all of the City of Santa Rosa Water Conservation Interns.

Secondary Water Systems for Landscape Irrigation: Issues and Opportunities

Stephen W. Smith[1]

ABSTRACT

Secondary or dual water systems are described as those providing pressurized raw water for landscape irrigation. Often, the native water supply that was historically used for agriculture irrigation can be successfully "repackaged" for landscape irrigation as urbanization occurs. There are numerous examples of secondary systems throughout the western United States, primarily in Utah, Idaho, Washington, and California. Some of these systems have been successfully implemented and continue to expand with new housing projects. Other systems can be shown to be problematic in various ways and might be implemented differently in hindsight. Successes and failures will be generally described to include both engineering and organizational issues. Case studies will be referenced based on personal visits and interviews with system managers.

INTRODUCTION

In various regions around the western U.S., secondary water supply systems or dual systems are common and readily acknowledged as a benefit to the region and the community. Often times, the availability of raw water for the landscape is perceived to be an amenity for a housing project because it is considered to be the right thing to do and the cost of raw water is generally lower to the homeowner than the cost of potable, culinary water.

In 2001, the Colorado Water Conservation Board funded a project at Colorado State University to do an in-depth study of dual systems in other states and attempt to understand the benefits of such systems for Colorado. The results of this particular, detailed and comprehensive study of secondary supply systems were completed in the fall of 2003. Both the executive summary and the full report can be found on-line at:

http://waterlab.colostate.edu/DualStudy/dualstudy.htm

The purpose of this paper is not to review or describe secondary supply systems in great detail but to make observations as the underlying reasons why larger regional systems have not come about to date in northeastern Colorado.

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CONCEPTS OF SECONDARY SUPPLY

Under the prior appropriation system as utilized by 19 of the western states, water is generally decree for a given use, in a given quantity, and as diverted from a decreed point in the river system. The original decreed use is very commonly “irrigation.” As urbanization occurs and farms are turned into housing projects, it makes good sense to continue using the native water supply for the decreed purpose – namely, irrigation, but for landscapes instead of agricultural crops.

The mutual irrigation companies that often hold significant decrees can benefit from secondary supply systems by becoming a participant in some manner. Changes in use wherein a municipality is buying, or being provided with, native water and altering the decreed use to municipal and industrial use are common but these changes are time consuming and costly. In Colorado, it can take three or four years to change a water right and the legal and engineering costs grow in proportion to the number of objectors in the water court case. The return flows on the changed shares are likely accounted for and stay in the canal so there is no injury to other shareholders in the mutual irrigation company or downstream to other water rights.

The hard engineering details of secondary supply systems are many and varied. The resolution of questions and the approach to secondary supply implementation is important but these engineering aspects of the project are, in the author’s experience, generally easy to resolve. Organizational and sociological issues may trump engineering issues overall.

Prevalent technical questions and engineering issues include:

- Pipe burial depths.
- Standard installation details for all primary components such as the point-of-connection.
- Standard specifications for equipment and installation for the secondary system (overall system uniformity).
- Landscape irrigation standards and potential for review by the secondary supply system entity.
- Design criteria.
- Suitable water window and approach to scheduling (daytime irrigation allowed or not?).
- Meters versus no meters.
- Potential for self-adjusting irrigation control systems.
- Piping offsets with the potable pipes or any utilities of others.
- Drought response plan.
- Minimum and maximum operating pressure at the point-of-connection.

- Level or primary filtration.
- Demand management plan and prediction of maximum and peak period flows.
- Back of lot versus front of lot points-of-connection.
- Point-of-connection size.

SUCCESSFUL AND EXEMPLARY BUILT PROJECTS

Projects that have survived the test of time and continue operating effectively are described in the literature (Wilkins-Wells 2003) but two projects are briefly described here as to the elements of those projects that have relevance to the topic at hand. These two projects exemplify what can be and has been accomplished when the sociology, politics, and engineering moons can come into alignment.

Davis and Weber Counties Canal Company

The Davis and Weber Counties Canal Company in Sunset, Utah was established in 1894. In modern times, the Company delivers agricultural water to shareholders but also secondary water to approximately 8,000 customers in the area around Kaysville, Utah. The secondary supply project is now almost 25 years old and was originally funded via concessionary loans made available by the State of Utah. It is notable that the community accepts and very much appreciates the raw water availability for landscapes since this source of water is so much less costly than the potable, culinary water. Billboards for housing developments in the area often cite secondary supply as a key benefit of that project. Further, it is notable that the Company enjoys a revenue stream from the secondary supply customers that has allowed the Company to make substantial improvements to the canal infrastructure over time. These improvements include canal lining, pump stations, equalizer reservoirs, and supervisory control and data acquisition (SCADA) implementation. An important part of the success of this secondary supply project is that there was strong cooperation between the ditch company supplying the raw water and the municipal water departments supplying the culinary water.

Kennewick Irrigation District

Another example of an older and successful built and building project is found with the Kennewick Irrigation District in Yakima, Washington. The following quote can be found on KID’s home page website:

> “The Kennewick Irrigation District began ninety years ago as an agricultural water supply system. Today it still supplies water, but more and more of it goes to keep lawns green and gardens growing. Farms are turning into residential subdivisions at a surprising rate around the Tri-Cities. More and more cropland is going into vineyards, too. Things keep

changing, but the Kennewick Irrigation District still sticks to its main job: they keep the water moving!"

At present, KID had more than 14,500 customers to which raw water is delivered for landscape irrigation. KID's web site can be found at: http://www.kid.org/

The District has 88 miles of canal, four ditch riders, and a maintenance crew of six. Local improvement districts, known as "LIDs" used to take water from the District at the historic headgate. But as the demands on the KID organization grew they ultimately came to accept the operation and maintenance of the distribution system downstream of the headgate as long as it was designed and built to KID standards. Currently, KID has 153 LIDs to which KID delivers raw pressurized water.

One success of the KID secondary supply system was the staff and Board acceptance of the opportunity to serve the new customer base as a suitable extrapolation of their mission and an opportunity.

RECENT CIRCUMSTANCES IN NORTHESTERN COLORADO

Following completion of the dual systems study (Wilkins-Wells 2003) in the fall of 2003, several mutual irrigation companies undertook and commissioned more specific feasibility study efforts so that the potential for dual system projects could be fully understood for their circumstance, initial and annual costs estimated, revenues forecast, and so on. These feasibility level studies were accomplished by working directly with the boards of the companies and the study generally resulted in:

- Estimates of construction costs that allowed for an understanding of the loan commitment.
- Analysis of the water right or rights on a seasonal basis.
- A drought response plan.
- Analysis of housing growth rates to understand phasing and growth of the secondary supply system.
- Analysis of rate structures and revenues.
- Analysis of cash flows and cash position over the term of the loan.

HINDSIGHT ANALYTICAL COMMENTS

From 2003 to the present, the author participated in multiple regional secondary supply feasibility level projects and numerous (several hundred) mutual irrigation company board meetings where options were discussed, analyzed, or debated. As noted earlier, the technical questions, in the author's experience, can likely be solved in a series of workshops. Resolution of the technical questions is not particularly difficult especially when successfully built and operating projects can be toured and so much can be learned from the successes or failures of others. A key question in this regard for the managers of existing systems is "what would you do differently if you had it all to do again?" Answers to that question are easily obtained.

The difficult lessons learned from participation in various northern Colorado feasibility-level studies can be summarized as follows:

1. **Cooperation between the various players:** the synergy and cooperation between the potable water purveyor and the secondary supply entity is paramount. If these two entities can mutually support one another, then success can be assured. (The concept for one potential secondary supply entity stalled because the intent was to be "for profit" and the potable water entity was "not-for-profit". This philosophical disconnect could not be overcome.)

2. **Development agreements:** generally the housing developer has an agreement with the municipality or the county. This agreement identifies the source of all utilities. If the municipality communicates to housing developers in a directive way as to where the potable versus raw water sources come from, the long term success and expansion of a regional system becomes more predictable.

3. **Project cash flow:** negative cash flow in the early years is probable due to over-sizing of project elements but housing growth tends to create a positive cash flow in a financially reasonable period of time. If state water development money can be obtained at concessionary interest rates, then the negative cash flow period tends to be short and predictable.

4. **Understanding the concept and the future:** many mutual irrigation companies, even though they have been in business for 100 years or more, operate in a low-key and often volunteer way. If the vision of the managing board is to "roll" under the pressures of urbanization and development, then the likely outcome of discussions concerning provision of pressurized raw water delivery are predictable – the no action alternative will likely prevail. Under these circumstances, secondary supply is an "insurmountable opportunity."

5. **Water rates:** financial models can generally predict a successful venture when initial and annual operating costs are known and the intent is to cover those costs and gradually move into a stable and positive cash flow position. The financial aspects of a project can be greatly enhanced when a raw water rate is set more or less artificially as a percentage of the potable water rate. Homeowners in northern Colorado are generally accepting of raw water rates that are 80% of the potable water rates.

6. **Water share ownership and control:** the issue of who actually owns the raw water shares that are dedicated to secondary supply has been a difficult issue. The secondary supply entity wishes to own the shares if the water is to be delivered through a raw water system. The potable water entity may insist on owning the water shares to ensure unequivocally that the water is there into perpetuity. This question is not easily resolved.

SUMMARY

Successful regional secondary supply or dual system projects can be found in several western states. Provision of raw pressurized water for landscape irrigation is a sound concept and means continued use of the decreed water supply without administrative or water court changes. Pitfalls or fatal flaws associated with intended regional systems are often more related to sociological and political problems as opposed to engineering problems.

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Dispelling Myths Associated with Spread Spectrum Radio Technology in the Irrigation Industry

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Abstract. *Each year, the irrigation and drainage industry deploys an increasing number of Spread Spectrum communication solutions. As recently as five years ago, the use of wireless telemetry in irrigation and drainage SCADA systems was almost exclusively in the licensed radio realm. The scarcity of available licensed channels as well as its improved technology has made the Spread Spectrum radio an increasingly popular choice. With the install base of Spread Spectrum devices rapidly increasing, many urban legends, superstitions and myths have circulated. As with the introduction and advancement of any new technology, misconceptions and misunderstandings will always surface. Spread Spectrum can be a valuable tool when used in the correct environment and with correct network deployment. This paper will explore these "myths" and provide a better understanding of how to use Spread Spectrum technology in irrigation and drainage applications and also show where you can succeed with Spread Spectrum communication solutions.*

Keywords. SCADA, Spread Spectrum communication solutions, irrigation and drainage industry, FreeWave Technologies, Spread Spectrum radio

Introduction

Every year the irrigation industry deploys more Spread Spectrum communication solutions. As recently as five years ago, the telemetry of irrigation data was almost exclusively in the licensed radio realm. However, the scarcity of available licensed channels as well as its improved technology has made the Spread Spectrum radio an increasingly popular choice. With the install base of Spread Spectrum devices rapidly increasing, there have been a number of "Urban Legends" or "Superstitions & Myths" that have circulated. Among the more prevalent of these are the following:

Myth	Summary
Security	Spread Spectrum is not secure; someone can steal your data.
Saturation	Spread Spectrum radios will shut down when there are too many radios on the same frequency.

Range	Spread Spectrum radios are only one watt and won't perform as well as licensed radios.
Compatibility	If you have licensed radios you have to buy only licensed radios for expansion.
Interference	If you mix licensed radios and Spread Spectrum radios or different brands of Spread Spectrum in the same system they will cause interference and data will be lost
Obstructions	You must have clear line of sight, or Spread Spectrum will not communicate.

With the introduction and advancement of any new technology, misconceptions and misunderstandings will always surface. Spread Spectrum, like any technology, can be an extremely valuable tool when used in the correct environment and with correct deployment. The objective of this paper is to explore these "myths" and provide a better understanding of how to use Spread Spectrum technology and also show where you can expect to succeed with Spread Spectrum communication solutions.

Security

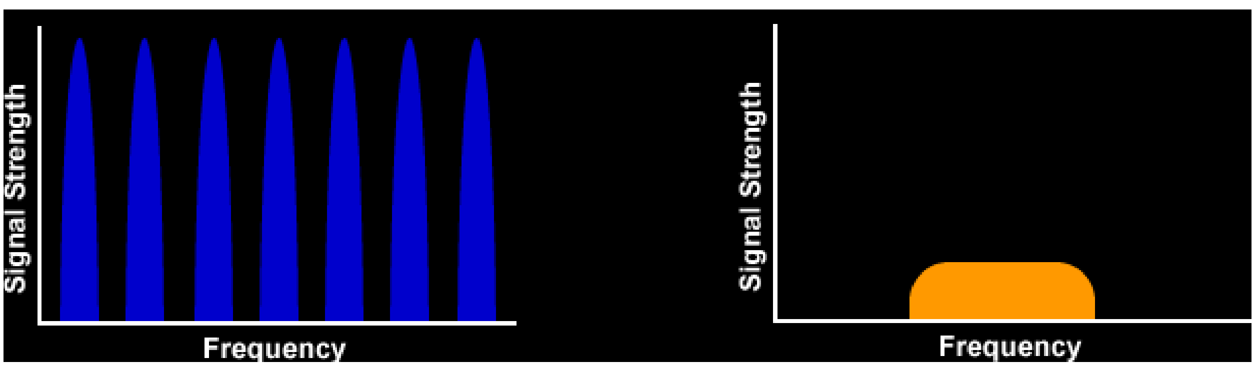
Spread Spectrum was originally designed for security purposes. It was invented for the US Navy during World War II to prevent the Germans from "jamming" American radio transmissions for radio guided torpedoes. The technology was invented by Hedy Lamar, a famous movie star of the 1940's. The original radios contained a roll of paper slotted like a player piano to cause channel switching. Lamar's close friend Inventor/Musician George Antheil designed the first successful synchronization device that brought Lamar's idea to fruition. In 1941 Lamar and Antheil were granted a U. S. patent for the first "Secret Communications System." This original system used merely 88 frequencies. Today, the switching is controlled in embedded software code that enables a radio to change frequencies in excess of 200 times per second and use more than 100 channels.

The technology behind spread spectrum radio is complex enough that anyone trying to intercept a signal would have to match more than 186,000 possible parameters to be on the same channel with the radio and then would only be in sync for about 1/100th or possibly 1/200th of a second. In addition to matching parameters, the entity attempting to intercept data would find that today's Spread Spectrum radios also utilize advanced encryption protocol to insure additional security.

Saturation

The common fear in Spread Spectrum is that as more and more companies go to this "shared" frequency, it will become saturated and unusable. However, if there is a saturation point, it has not yet been reached. In many areas of the country, thousands of Spread Spectrum radios are delivering data to multiple end-users without conflict or data loss. Examples of these networks can be found in various regions around the country and in other industries. In Wisconsin, a major generation and transmission utility is using more than 100 radios in the field with another 300 radios to be deployed over the next year. The end-users' offices and their base stations are in a proximity where repeater towers can be shared by multiple networks, as appropriate. If there were any potential for "saturation," it would happen at these repeater sites where the wireless traffic is at its highest, and the antennas are installed very near to one another.

Over the past several years, considerable research and development has gone into developing Spread Spectrum radios that can work in close proximity to one other and share the same frequency bands. To accomplish this goal, radio networks are programmed to share common bands, but use separate frequencies. Each radio network is programmed to "hop" to a different frequency than the other radio networks in the area. This hopping allows users to build distinct communication networks that will not conflict with other networks in the immediate area. An analogy to this is your car radio in which there are multiple channels available, but you only hear the channel you are actually tuned to. When you change channels, you no longer hear the old channel, only the channel you just switched to. The same is true of Spread Spectrum networks: multiple users can share the Spread Spectrum band as long as they are all set up to use different frequencies at different times.



The FCC allows two methods for building spread spectrum radios: Frequency Hopping Spread Spectrum (FHSS) or Direct Sequence Spread Spectrum (DSSS)

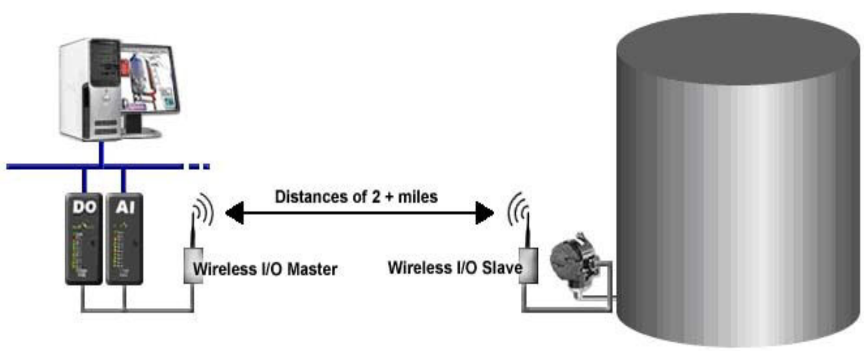
In the previous Wisconsin example, there are many other organizations in various industries using Spread Spectrum radios. The combined total of radios is growing each day as these companies continue to add more radios to expand their communication networks. It is highly unlikely that this or any other area will achieve "saturation" so long as the networks are managed and deployed properly.

Range

Another common myth associated with Spread Spectrum is that it is good only for short-range communication. To the contrary, Spread Spectrum can be deployed as a complete (long-range and short-range) communication network solution. This technology is a result of the lower maximum output power of a Spread Spectrum radio. By federal regulation, a Spread Spectrum radio can only have an output of 1 Watt of radiated power at the radio and 4 Watts at the antenna. Licensed radios, by contrast, can have higher output power, typically 5 Watts at the radio and 20 Watts at the antenna. In a contest of which radio will broadcast the furthest in a straight line, the licensed radio will clearly win the distance contest, however it is extremely rare to have a line of sight range exceed 20 miles. Typically, an obstruction such as a building, valley, hill, or vegetation will interrupt a signal in longer-range applications. Spread Spectrum radios can easily establish links of 20 miles and they have even been able to link at distances greater than 60 miles. Spread Spectrum radios have been used in relay protection schemes and for utility SCADA applications where data must be passed accurately over many miles of obstructions. At great distances, the curve of the earth becomes one of the major obstacles to overcome. In order to establish a 30-mile link in an application, the end user will have to have radio antennas mounted at least 100 feet above the ground to compensate for the curve of the earth.

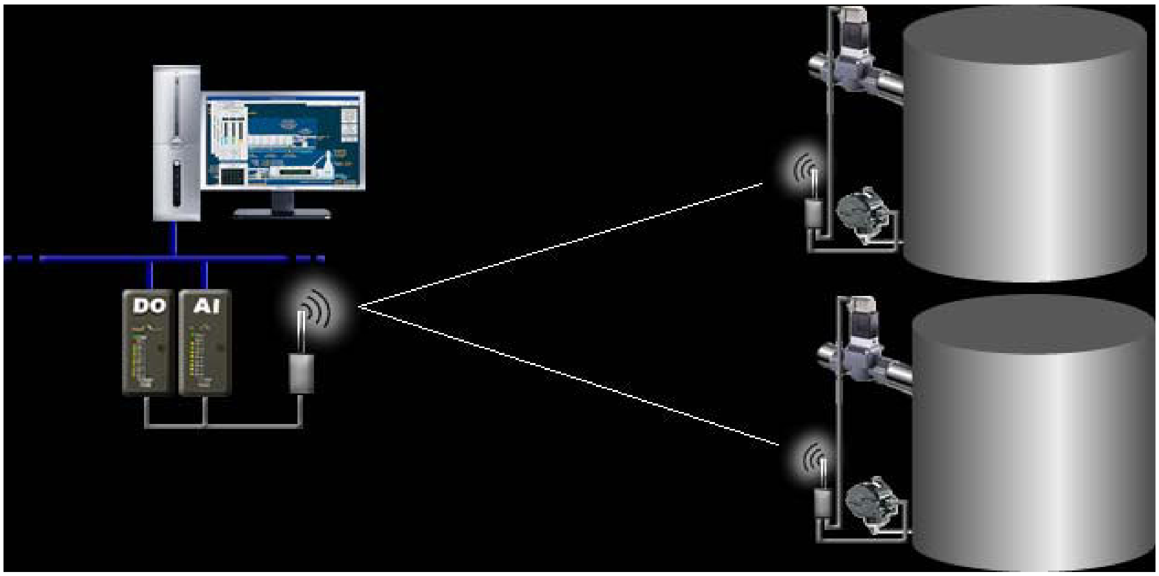
Mountains often create the opposite challenge. In mountainous regions, Spread Spectrum radios have been used to establish radio communication at distances of 60 miles. This link is from a mountain top at a 9500 feet elevation down to a valley floor where the elevation was 5000 feet.

Another factor influencing complete long-range communication is repeaters. With a licensed radio system, there is only one repeater in a network. All slave sites must communicate to either the Master unit directly or though a maximum of one repeater.



However, with Spread Spectrum technology, it is possible to have multiple repeaters. These repeaters can either be arranged in series (serial repeater) to extend the range or in parallel to improve coverage around obstacles such as hills, buildings, or vegetation. It is also possible to mix repeaters in parallel and series to provide the benefit of all capabilities in large systems. Some manufacturers produce products where the use of repeaters is unlimited, meaning there are no limits to the number of repeaters you can have in a single network. Some complex networks actually use more than 100 repeaters in a single network.

Another Spread Spectrum feature offered by a limited number of manufacturers is the ability to have the radio to operate as a slave and repeater simultaneously. This feature provides both a network extended capability and a cost reducing tool. The slave/repeater function eliminates the need for multiple dedicated repeaters while also reducing installation costs.



The "magic" here is that any PLC (programmable Logic Controller), RTU (Remote Terminal Unit), or other intelligent devices can multitask as both a slave unit, sending data back to the host and as a repeater for other devices further down the network hierarchy. Spread Spectrum radio systems can track and control Utility SCADA systems and/or delivery systems for hundreds of miles using a wireless "daisy chain" to bring data through a series of repeaters back to the host in a distant location. Spread Spectrum can also move data in a "micro-network" that is set up to work around a mountain or any other obstruction and ultimately deliver data to a host that is not within line of site.

Compatibility

Many people believe that if they install a base of licensed radios, they must use the same manufacturer and model of radio they originally purchased. However, it is possible to mix Spread Spectrum radios into an existing licensed radio system enabling features such as multiple repeater functionality and reduced deployment costs. This network can be accomplished by placing a new repeater in the existing system. You simply need to take an existing slave site and put a Spread Spectrum (Master) radio back-to-back with the licensed slave and join the two radios together by using a 'Null Modem" cable between their respective RS-232 ports.

When the licensed master transmits to the licensed slave, the request is passed through the licensed slave's RS 232 port to the Spread Spectrum radio's RS 232 port. The Spread Spectrum Master will then retransmit the message to the Spread Spectrum “network extension” down stream from the Spread Spectrum master. This “Hybrid” system offers many advantages over any single system network.

It is also possible to create hybrid systems by combining CDPD (Cellular Digital Packetize Data), Satellite, Cell Phones, and landline telephone modems individually with Spread Spectrum. The beauty of these systems is that the end user can use a communication device, such as a landline, to cover a long distance of 100 miles and then “mate” to a Spread Spectrum network to gather data over a wide area network (WAN). This configuration would allow an end-user to gather data from 100 devices through a single telephone connection. Since landline telephones, cell phones, and satellite communication come with monthly charges, it is much more cost effective to spread these cost over multiple devices in the field. Combining these technologies will produce the most efficient and cost effective solution.

Interference

Another common misconception is that Spread Spectrum and other radio communications will interfere with each other. The most common Spread Spectrum band in the United States is 902 Megahertz to 928 Megahertz. This frequency band is set aside by the federal government to be allocated for Spread Spectrum devices and the rules are structured to allow the band to be shared by multiple users. The official designation for this band is ISM, which implies this was established for Industrial, Scientific, and Medical usage.

The Licensed radios utilize frequencies outside of this band. No licenses are granted for any frequencies inside the ISM band. Consequentially, there will be no overlap between licensed systems and Spread Spectrum systems. These two technologies will always broadcast on separate frequencies and thus cohabitate without negative results.

The closest frequencies to the ISM bands 902 Megahertz to 928 Megahertz range are cell phones and microwave signals. If the power of one of these two communication devices is high enough and the device is not precisely tuned to its licensed frequency, it is possible for the signal to “bleed over” into the ISM band. The cure for this occurrence is an inexpensive Band Pass Filter. This filter will block any noise or interference that is outside the 902 MHz to 928 MHz range.

Obstructions

Many times you might hear that radios must have clear “Line of Sight” (LOS). It is also a common myth that Spread Spectrum radios are more restricted by line of sight than other communications devices. However, while line of sight is always preferred, Spread Spectrum radios will indeed pass data through obstacles such as buildings, trees, and in many cases over hills. What happens to a radio signal in these environments is that the obstacles introduce “attenuation” into the signal path. Attenuation is a resistance that reduces the strength of the signal. Attenuation occurs over a distance: the greater the distance the greater the attenuation. Attenuation also increases with the presence of tree branches and foliage. A radio may transmit for 20 miles with clear line of sight, but it may not be able to do so if the 20 mile path is through a dense forest. The signal loss over the distance combined with the signal loss or attenuation of the forest would be too great. While the radio can often transmit through one or the other obstacles, the combination of the two may be too great to overcome.

Buildings offer a challenge similar to that of a forest. Radio signals will often transmit through buildings, but not through both a building and then a distance of 20 miles. There are many applications where Spread Spectrum radios are used to gather data from multiple floors in a building and bring it to a central collection point in the basement or lowest level. The signal is weakened with each concrete floor that is penetrated. After some finite number of floors, the signal will become so weak that it will not penetrate any more floors. Even in this case, the radio may sometimes find a path (elevator shafts) that allows the signal to continue.

This illustrates an example in which there is no clear “Line of Sight” for the transmitted signal, yet the signal still reaches its destination. A radio will communicate through multiple floors depending on the environment and the antennas being used; the limitation may be 5 floors, 6 floors, or even more than 10 floors. The common term for this degradation of signal is “Path Loss” or “Signal Fade.” In outdoor field applications, this point can be computed by the use of software programs. The common mistake many end-users make is not preparing a ‘Path Study” prior to starting installation. This is the quintessential case of “an once of prevention being worth a pound of cure”.

Performing a “path study” prior to starting a project will create a network design that allows you to work around any obstacle and insure a solid robust communication system, regardless of “line of sight” in the area.

Conclusion

Spread Spectrum is a relatively new technology for data communication. As with any new technology, there are many misconceptions about the best way to utilize its features. In the case of Spread Spectrum radios, there are still many people who are quick to tell the myths, yet have never actually used the product. In practical application, Spread Spectrum can be used in almost any data acquisition system that would work with licensed radios. Spread Spectrum systems are designed to perform and be trusted, but they are dramatically different from licensed systems.

Remember that the use of multiple repeaters and slave/repeaters allows for long-range, flexible, and secure networks. When you add the option of “Hybrid” communication to the mix, you now have the opportunity to match the “best fit” technologies for your data network.

In building a communication system, its effectiveness will increase with the more tools you have at your disposal. Spread Spectrum radios enable both a reduced communication cost while also increasing both the reliability and throughput of any system.

It was only a few years ago that radio systems used Bell 202 modems and a 1200-baud throughput was commonplace. Spread Spectrum radios are capable of delivering data at speeds up to 115 K-baud. Speed and error-free results (accomplished by utilizing CRC up to 32-bit) provide a viable communication option for applications never before thought to be within the realm of wireless communication.

The natural evolution of data communications has brought us to understand the benefits of Spread Spectrum radios and the power of their versatility. Spread Spectrum’s ability to be coupled with other communication mediums adds yet another layer of versatility never before imagined.

It is reasonable to foresee the day when Spread Spectrum radios and their closest relative, the Ethernet radio, will be the dominant communication device in data collection for the irrigation industry.

Software is the Future of Irrigation Design

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Abstract. *The future of irrigation design is in software, with highly-specialized CAD tools that dramatically speed the process of producing irrigation plans.*
The first, and most crucial element of irrigation design software, is the equipment database: all the varied manufacturers, with new and updated models, and wildly varying performance specifications. Further, all these pieces of equipment have to be matched with appropriate symbols to represent them on the plan. There needs to be tools to rapidly and easily place sprinklers and equipment, calculate their flow and pressure needs, indicate how they are to be piped, generate a legend, and most importantly, perform the flow hydraulics calculations to determine thie sizes of pipes required.
Programs such as Land F/X offer this, as well as advanced error-checking, resulting in the production of a plan in a fraction of the time it normally takes, and verified accurate to a degree never possible before.

Keywords. Irrigation software CAD

Why Use Technology?

I'd like to start with a brief story about the adoption of technology. A good example of this would be to go all the way back to the late 1800's. Those times saw the heyday of inventions, yet for the railroad industry, advancements in railcar coupling mechanisms and automatic brakes were not adopted. Even after a tragic crash that killed 29 passengers, it still took an act of Congress to mandate the use of such simple safety mechanisms. And after all the complaining from the railroad industry that such standards would bankrupt them, the new technology saw them benefiting with record profits and much-increased efficiency and safety after adopting the innovations.

In the same vein, some irrigation designers claim that they can produce a design quicker by hand than with software. While this may or may not be true, the indisputable gains from using software are in areas such as error-checking, revisions, redesigning the system for differing requirements or equipment, all done nearly instantly and perfectly accurate.

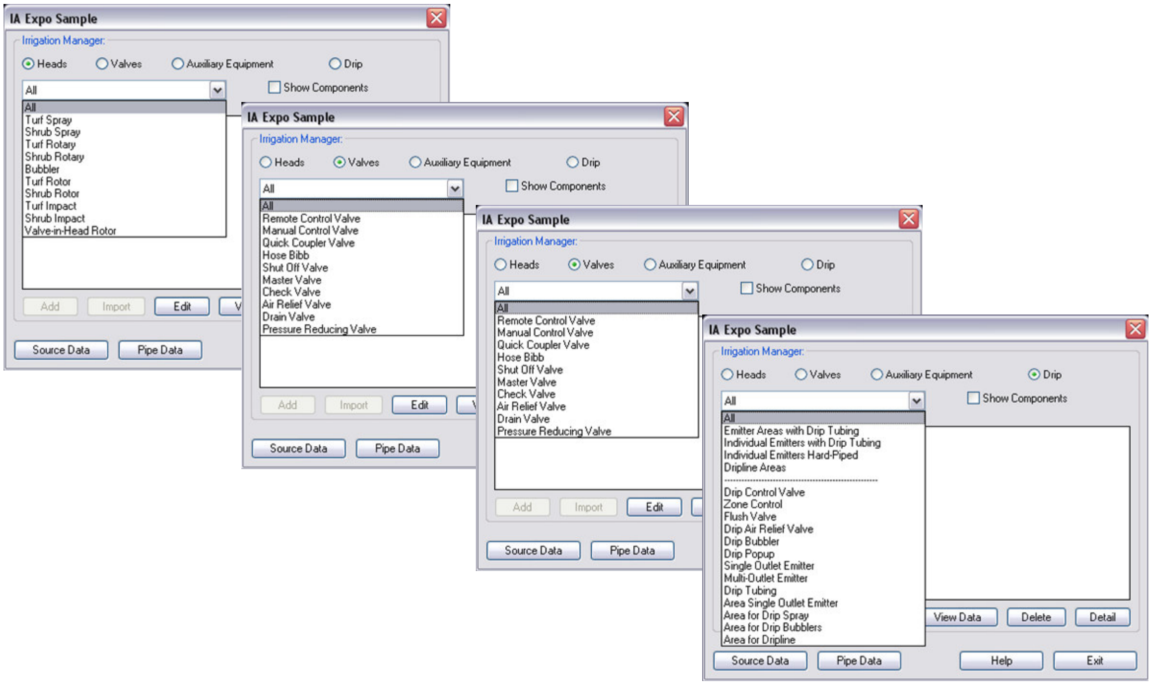
There are a number of irrigation software design programs out there – I am going to demonstrate the one I am most familiar with – in fact so familiar with it, I wrote every line of code in there. But let's suffice it to say that there are several programs which accomplish the same basic goal – that of the computer aiding the irrigation designer in the management of the many technical calculations necessary. Let me show you how computer software can automate and radically speed up the typical steps in developing an irrigation plan.

Selecting Equipment

The first stop is in equipment selection. Many irrigation designers can fall into the habit of continuing to specify the same equipment over and over. One reason for this, of course, is because they have seen the equipment in action and think it's a good product, but, more often than not, it's because it is too difficult to design with equipment they are not used to and don't have the performance data memorized.

This is just one of the many things that software can help with. These software companies spend vast hours updating their product with the latest models from each manufacturer, folding them into the system, logging the vast performance-related data, and creating graphical symbols to represent each piece of equipment.

Correctly designed software can allow you to quickly place any type of equipment, and not bother you with data and symbol requirements. First, is just managing the many various types of irrigation equipment, broken up into four overall categories: Heads, Valves, Auxiliary Equipment, and Drip Irrigation.

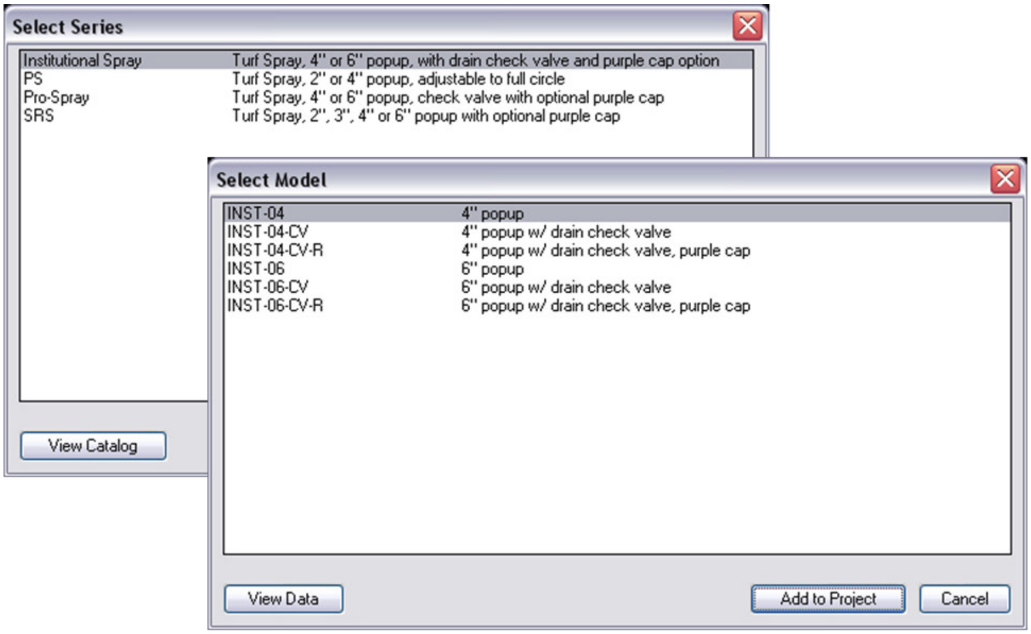


The four basic categories – Heads, Valves, Auxiliary Equipment, and Drip – with the various associated types of equipment.

If I want to use a turf spray head on a project, I first see a list of manufacturers that have this type of head.

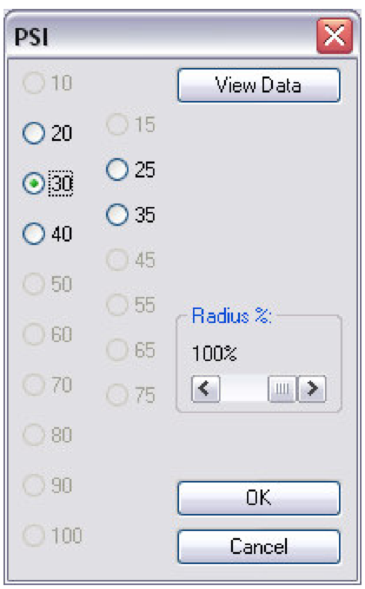
Selecting a Turf Spray head.

I just pick which manufacturer I want, and then decide which model I want that is offered by that manufacturer. I am able to view the page from the manufacturer's catalog for any piece of equipment, and am able to make a decision based up the model options I wish to use, leaving the software to determine the exact model number for me.



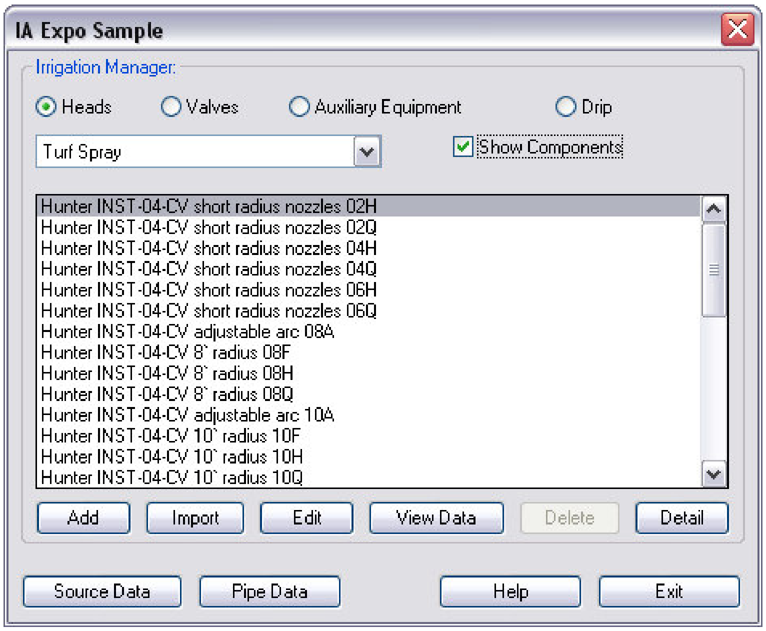
Selecting a Series and Model of Turf Spray head.

After selecting a model I will need to decide which Design Pressure I want the head to perform at, and a good program will allow you to select from any of the design pressures and performance options that the manufacturer lists for that head type. Again, I can view the performance chart from the manufacturer's catalog with one click, to see how the Design Pressure will affect the gallonage and radius of the selected head.



Selecting a Design Pressure for the Turf Spray head chosen.

As I add a spray head, again I am just picking out the model options, and the design pressure – note that the software has assembled all the fixed-arc nozzles for me, as well as the variable-arcs, the strip sprays, the low-flow nozzles, and the specialty nozzles. All of these have unique symbols assigned to them, and their correct gallonage associated with them.

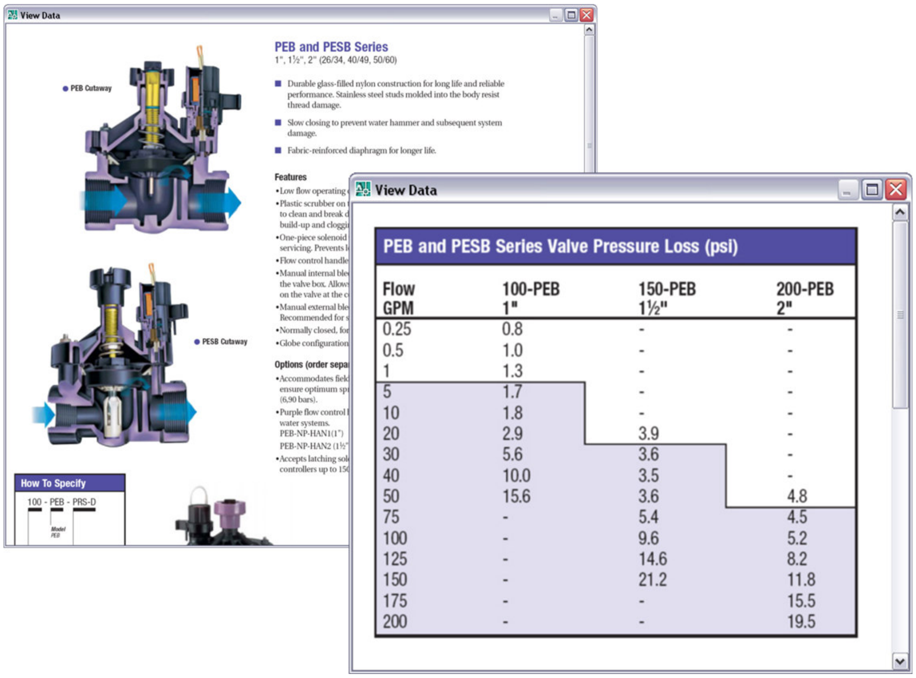


The selected Turf Spray has been added to my project, with all available nozzles assigned symbols and ready to be placed.

So already, if I was in a situation where I had to use a head I had never used before, such as a short-radius strip spray, coupled to a valve the client wants to use, the fact that I don't have the manufacturer's catalog, or any experience with the equipment is irrelevant. The software is action as an information channel, much like the internet, making it easy for me as a designer to access and utilize product information I am unfamiliar with.

Viewing the manufacturer's catalog pages for various equipment.

In selecting other equipment, such as valves, again I can view catalog pages instantly, see performance curves, and make my selection without having to figure out the model number myself.



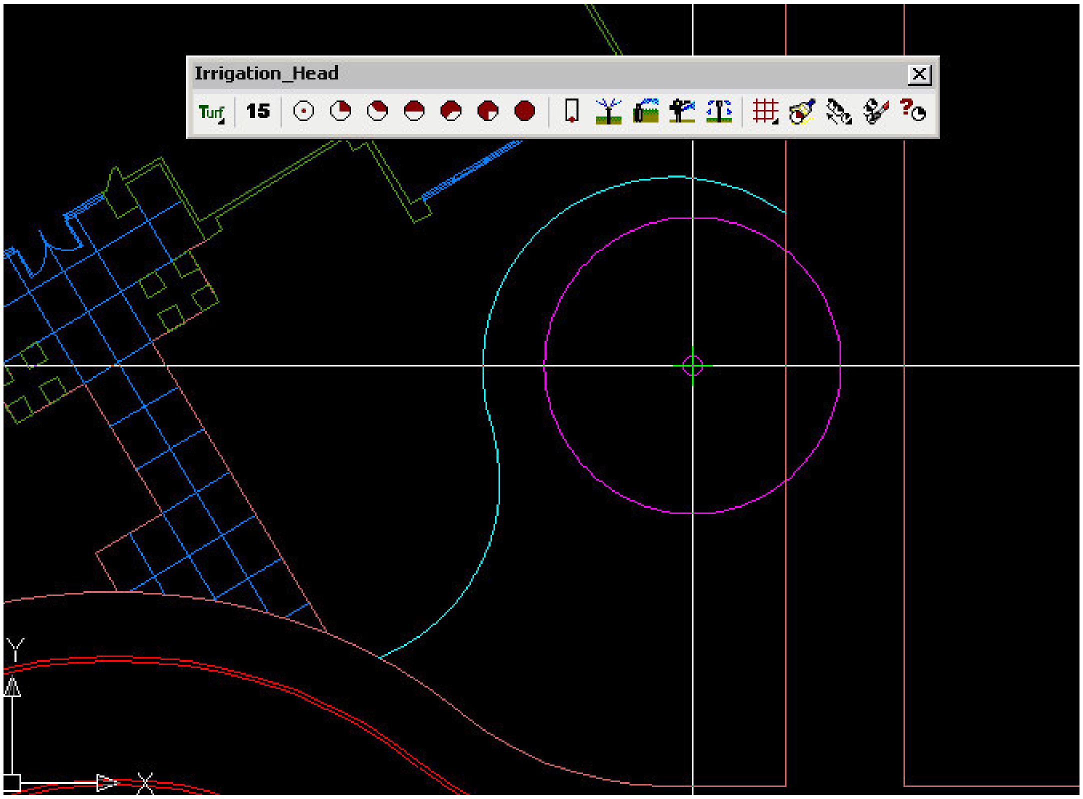
PEB and PESB Series Valve Pressure Loss (psi)

Flow GPM	100-PEB 1"	150-PEB 1½"	200-PEB 2"
0.25	0.8	-	-
0.5	1.0	-	-
1	1.3	-	-
5	1.7	-	-
10	1.8	-	-
20	2.9	3.9	-
30	5.6	3.6	-
40	10.0	3.5	-
50	15.6	3.6	4.8
75	-	5.4	4.5
100	-	9.6	5.2
125	-	14.6	8.2
150	-	21.2	11.8
175	-	-	15.5
200	-	-	19.5

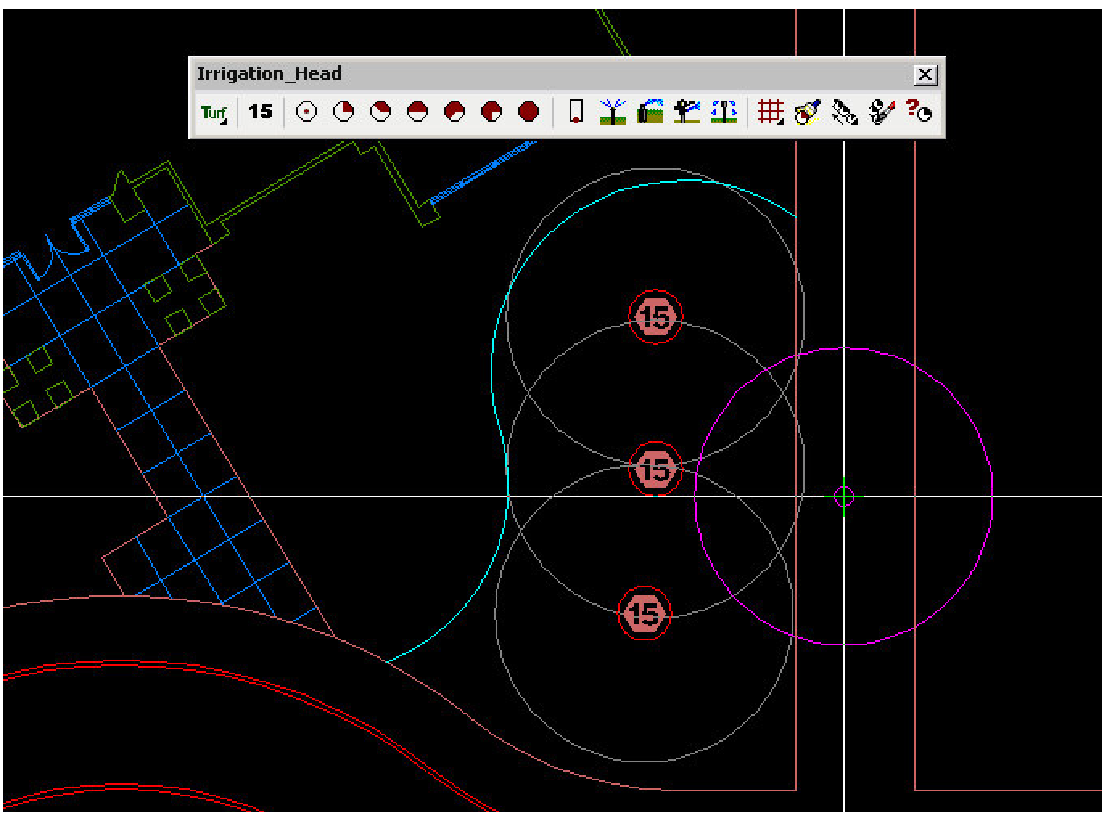
Viewing catalog pages for a valve.

Head Placement

When placing heads, it is easy for me to place from a palette of up to six different spray types, and any number or rotors, rotators such as the MP Rotator, bubblers, impacts, etc., with the system automatically placing the correct symbol, and scaled automatically for me no matter what scale I will be plotting the drawing at. Keyboard commands let me toggle among the various radiuses and nozzles. In this way, the traditional method of using a circle template to design a system is mimicked by the system, yet is much faster.

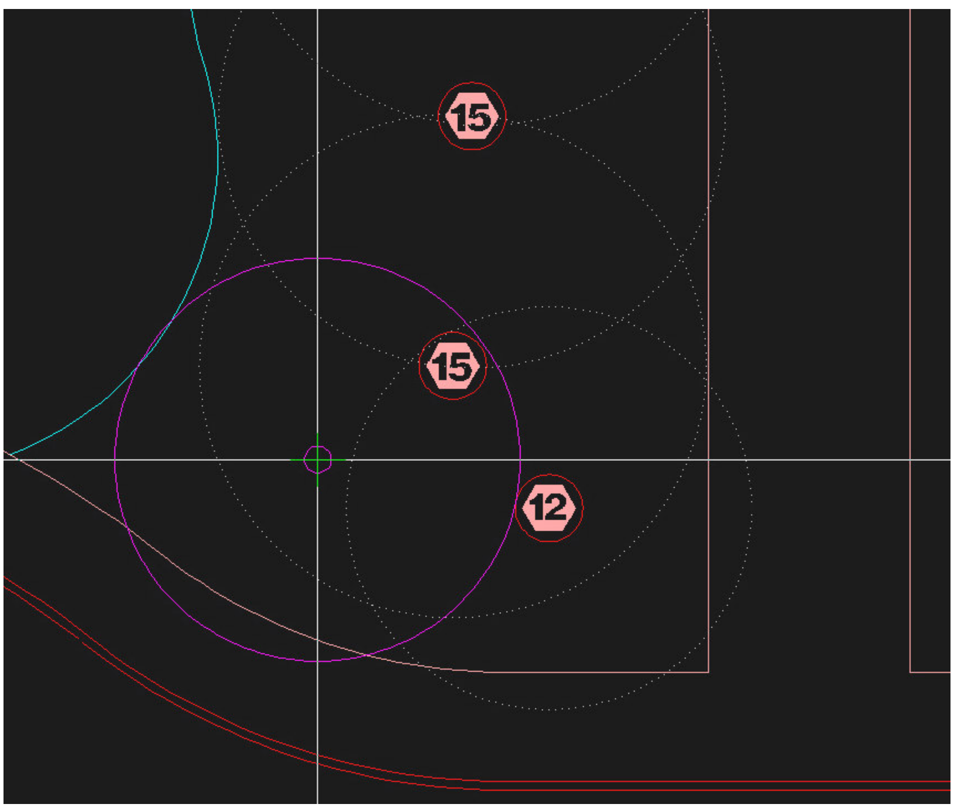


Radius preview as I place my 15′ Turf Spray head.



Spray symbols are automatically sized for the scale the drawing will be plotted at.

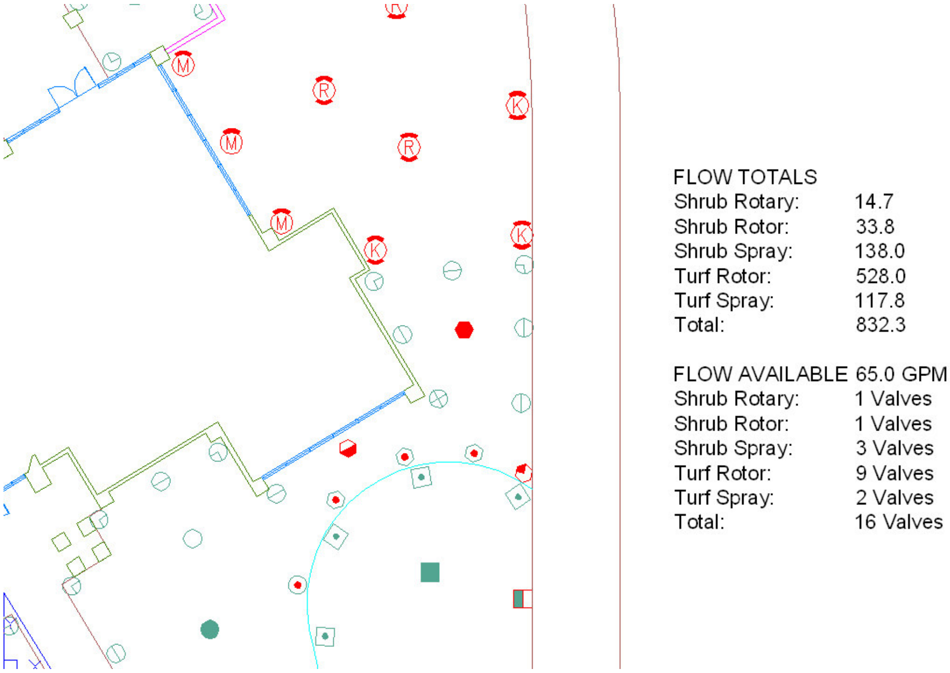
Using keyboard commands, I instantly toggle to a 12' radius preview.



I also have keyboard commands to decrease the radius, as if adjusting the radius screw on the nozzle.

GPM Total and Zoning

Now that I have placed the heads for my design, it is time to get into the GPM calculations, the area where the software provides the most dramatic improvements in speed and accuracy. I can total the GPM in the project with a single click.



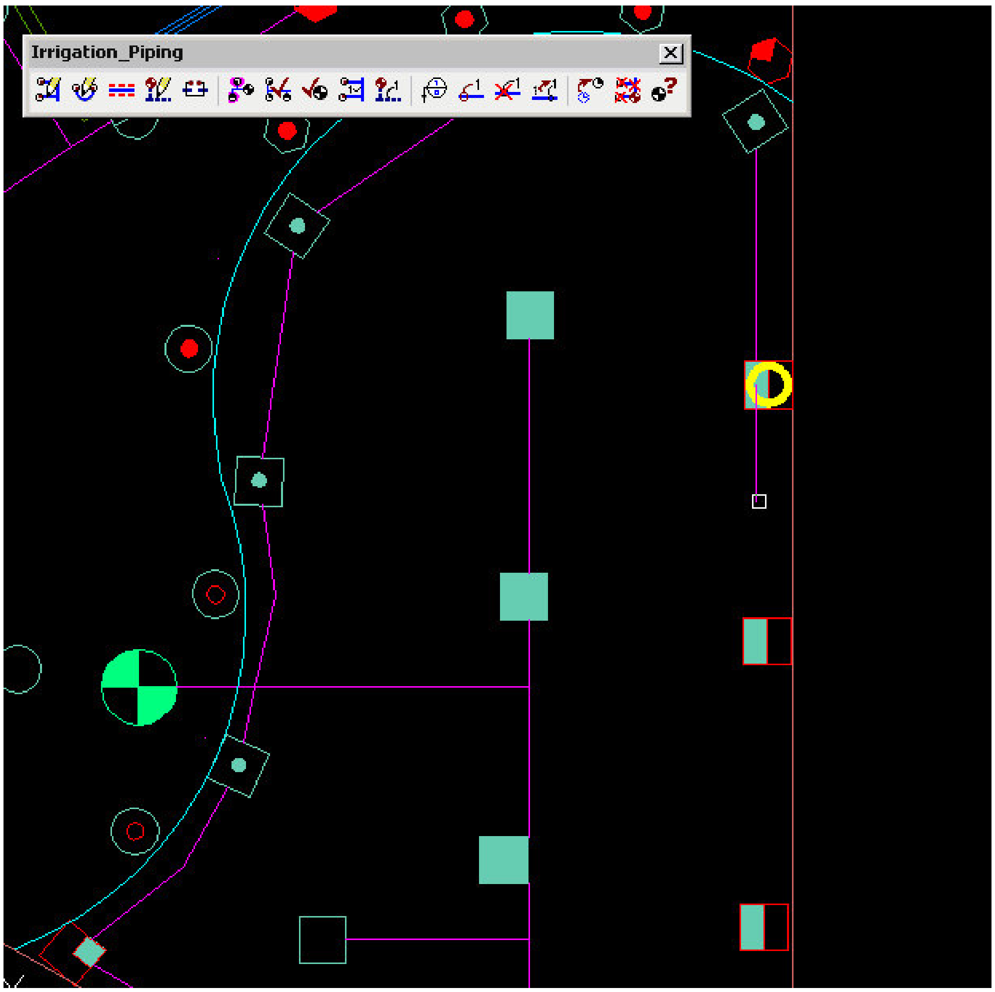
GPM Total for the entire project.

As I zone the various areas, the totals are not prone to human error, I can easily adjust the zone boundaries to be instantly recalculated, and not to mention I am even saving paper by keeping this process entirely electronic.

Zoning the various areas of the site.

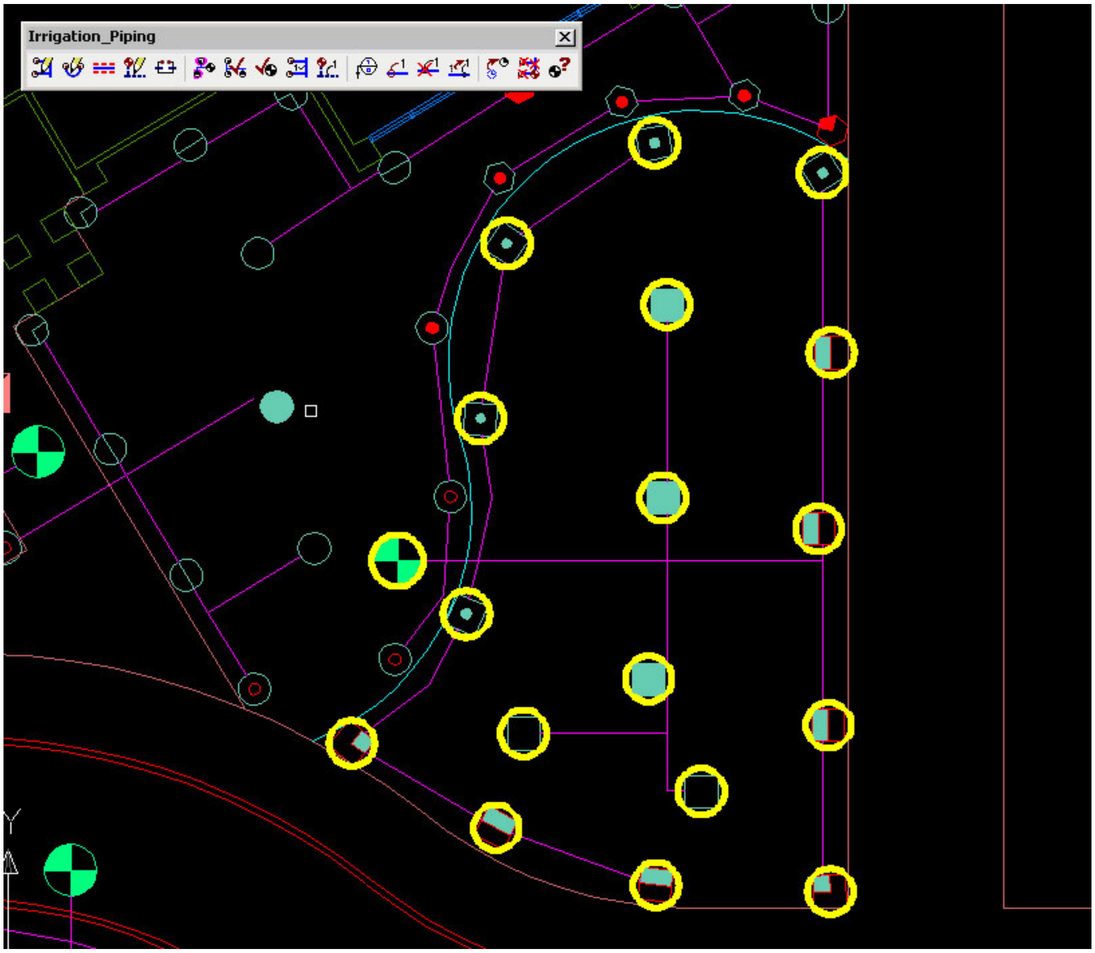
Piping and Error Checking

In order for a computer system to do my flow hydraulics and pipe sizing for me, it needs to know the order the heads are connected – this is essentially just an internalization of the pipe layout, as if we are teaching the computer the artificial intelligence of visual recognition. I draw the pipe as I would any line in the CAD system, yet the system is doing several things for me: it highlights the object I clicked on, so that I can easily see if I missed clicking on my target, and it also offsets the drawn pipe perfectly from the head symbol, for clarity of the plan.



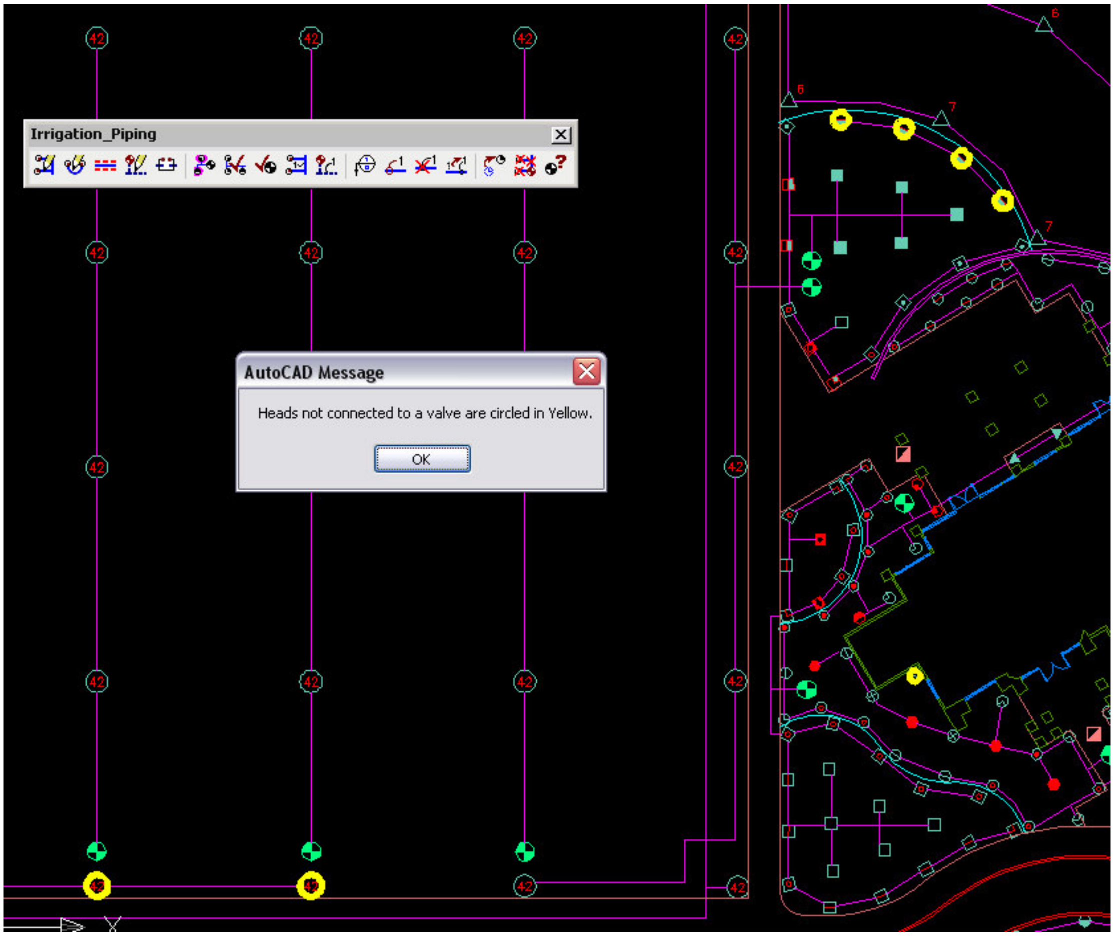
Piping to heads, the pipe is offset perfectly from the head symbols, and the Yellow highlight lets me know that I click on the head.

In using a software system, I now have abilities I could never dream of doing any other way – for instance, I can click on any head, and the system will highlight all connected items, so that I can verify that the system is correctly piped, or just to see what system a head is a part of.



Highlighting all the connected items in a system.

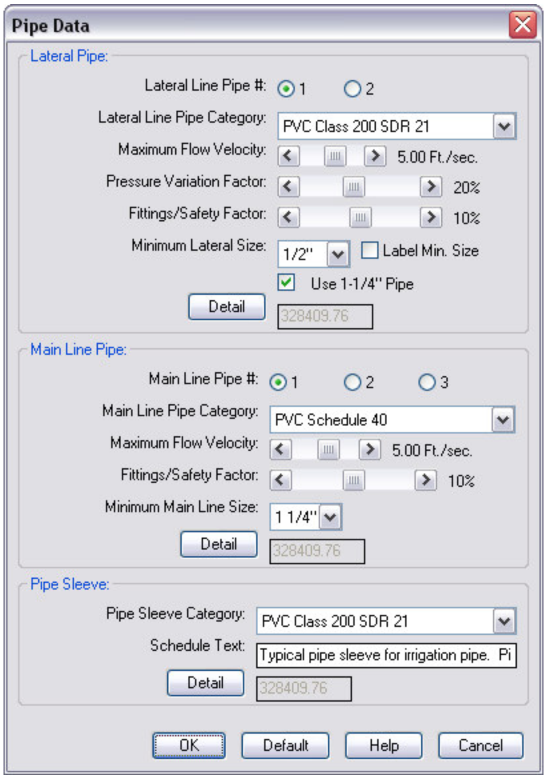
And of course I will use the ultimate in error-checking – having the system automatically highlight for me any heads that are not connected to valves. This is a classic example of replacing a lengthy manual process with something that is not only instant, but 100% accurate.



Highlighting any heads that are not connected to a valve.

Pipe Sizing

Having a computer perform the intensive calculations for automatically determining the pipe sizes is very much the holy grail of irrigation design software. My input is reduced to determining a few simple factors, such as the type of pipe I am using, the maximum velocity of the flow I would like to use, and what the Pressure Variation between the first and last head is to be.

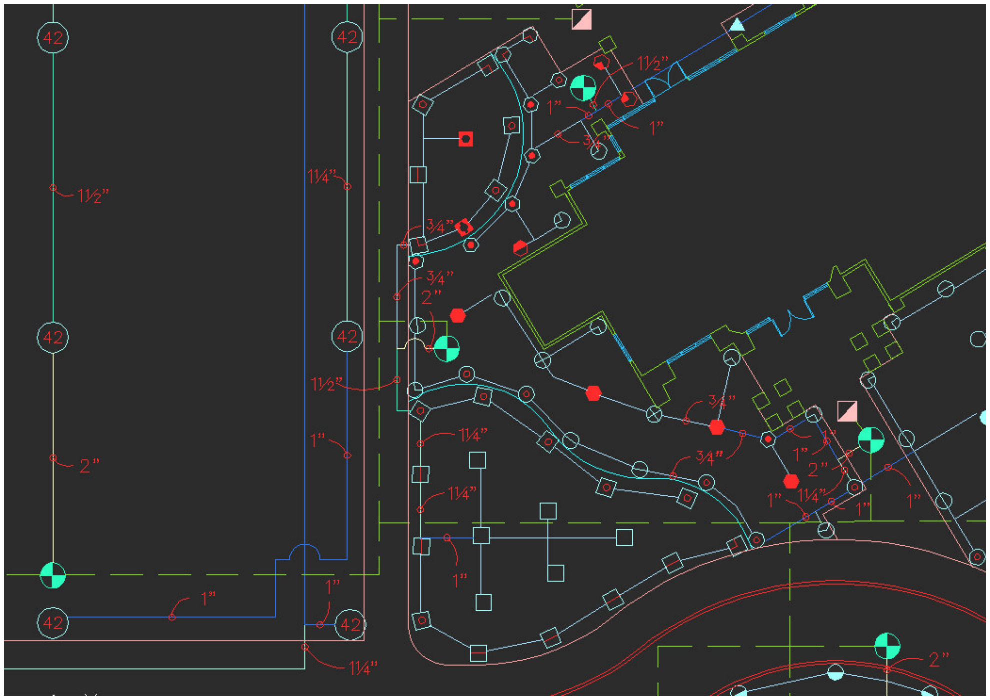


The factors used in sizing the pipe – note that for both lateral and mainline, my primary control is simply a slider to determine the maximum velocity of the water.

When you size a lateral system the software will do far more calculations than one would ever have the time or inclination to do manually. Since it knows the gallonage of each head, the desired Design Pressure, and the exact distance between heads, it can perform the actual flow hydraulics according to the Hazen-Williams equation considering the flow, the inside diameters and coefficient of the type of pipe you indicated, and the maximum water velocity selected. It also has the ability to perform this calculation over and over again as necessary, adjusting the velocity of water until the required sizes of pipe result in the system having balanced pressure (within the Pressure Variation Factor determined by the user).

In fact, the system is even able to calculate the exact precipitation rate for each station. For spray heads it uses the aggregate area of the station divided by the exact gallonage. And for rotor heads it can automatically determine if my rotors are at square or triangular spacing, and even factor in the effect of similar rotor heads from a different lateral that are spraying onto this station's areas.

Nothing will ever replace the seasoned design professional, who has viewed different types of heads in action, and can make the best determination of what kind of water to apply to different situations. Let the human do what a skilled human does, and let the computer do the intensive mathematical operations and organize the vast amount of data.

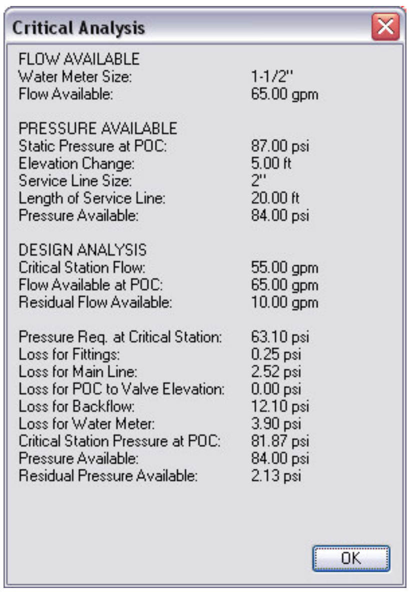


The system has sized all the appropriate pipe, and placed labels as necessary.

Sizing Mainline

As we get to sizing the mainline, again we have to leave the intelligent designer in the loop. It is up to the designer to know an appropriate maximum velocity they wish to use, or, if they are sizing for multiple valves to operate at once, to select an appropriate fixed GPM to size all pipe consistently.

The system can automatically detect how a valve will be receiving water, even automatically detecting a loop and determining the exact correct ratio to split the flow. It again will size the pipes using the Hazen-Williams formula for the type of pipe and desired velocity, but is able to adjust the velocity if necessary and resize all pipes, in a seemingly instant process. When complete, it can provide me with a Critical Analysis showing all pertinent data.

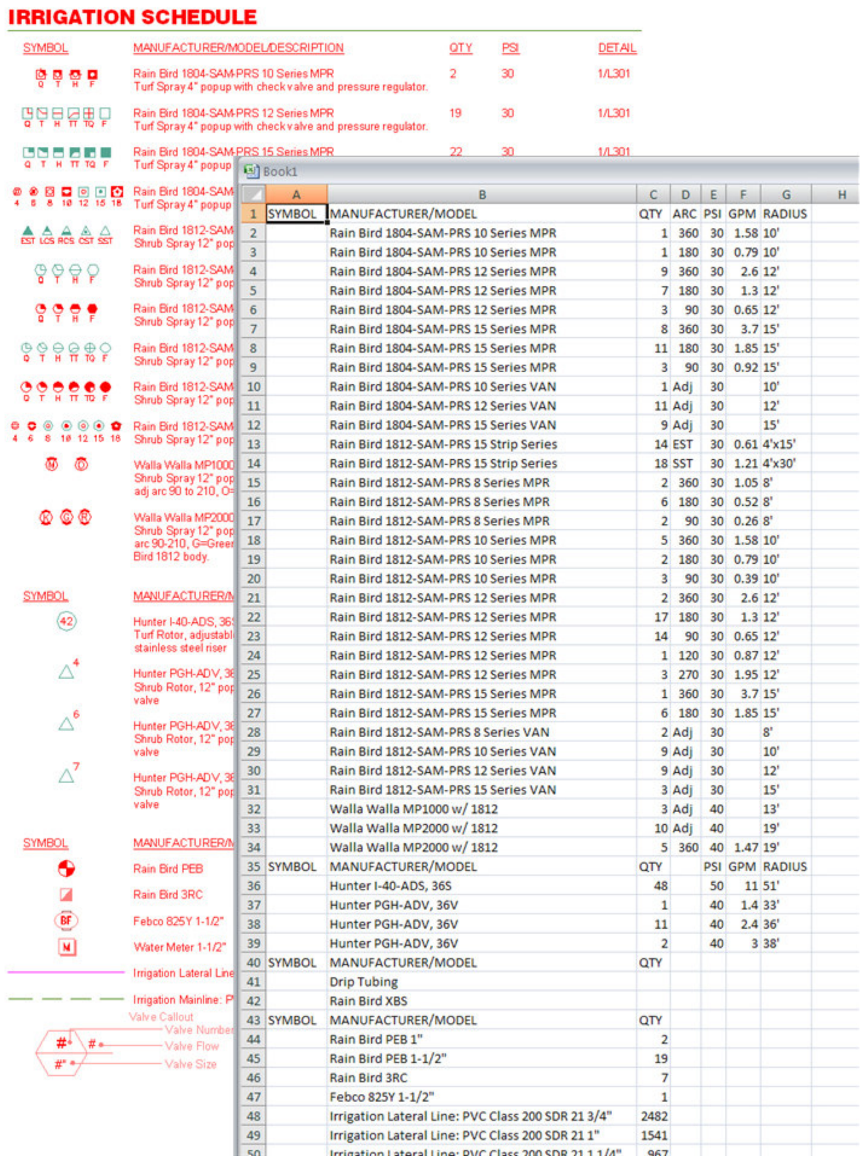


The Critical Analysis is able to show every piece of data used in sizing the Mainline.

The great thing about advanced software is that you can quickly adjust to a system that ends up being short on pressure. Suppose that after sizing your mainline, your distant rotor valves are now short 3 or 4 psi. Rather than add a booster pump, simply slow your water down and decrease your Pressure Variation. Slow your velocity on lateral lines from 5 ft/sec. to 3.75 ft/sec., and change your Pressure Variation from 20% to 10%. Both of those will result in larger pipe sizes, but that also means less pressure loss. Thus a complete resizing of several systems, and resizing the mainline, updating dozens if not hundreds of labels, is done by clicking a couple buttons in mere seconds.

Creating a Legend

When I generate a legend or schedule with a software system, I have the benefit of exact quantities, for whatever equipment was actually used in the project. I am able to instantly adjust to any variety of equipment, even if I have never used it in a project before. My lineal feet quantity of pipe is even far more accurate than any other possible method, as it is totaling the length between each insertion point of connected item. Again, my accuracy at this point is near perfect, and the time comparison is from a couple hours traditionally, to instantly by using an advanced software system.



	A	B	C	D	E	F	G	H
1	SYMBOL	MANUFACTURER/MODEL	QTY	ARC	PSI	GPM	RADIUS	
2		Rain Bird 1804-SAM-PRS 10 Series MPR	1	360	30	1.58	10'	
3		Rain Bird 1804-SAM-PRS 10 Series MPR	1	180	30	0.79	10'	
4		Rain Bird 1804-SAM-PRS 12 Series MPR	9	360	30	2.6	12'	
5		Rain Bird 1804-SAM-PRS 12 Series MPR	7	180	30	1.3	12'	
6		Rain Bird 1804-SAM-PRS 12 Series MPR	3	90	30	0.65	12'	
7		Rain Bird 1804-SAM-PRS 15 Series MPR	8	360	30	3.7	15'	
8		Rain Bird 1804-SAM-PRS 15 Series MPR	11	180	30	1.85	15'	
9		Rain Bird 1804-SAM-PRS 15 Series MPR	3	90	30	0.92	15'	
10		Rain Bird 1804-SAM-PRS 10 Series VAN	1	Adj	30		10'	
11		Rain Bird 1804-SAM-PRS 12 Series VAN	11	Adj	30		12'	
12		Rain Bird 1804-SAM-PRS 15 Series VAN	9	Adj	30		15'	
13		Rain Bird 1812-SAM-PRS 15 Strip Series	14	EST	30	0.61	4'x15'	
14		Rain Bird 1812-SAM-PRS 15 Strip Series	18	SST	30	1.21	4'x30'	
15		Rain Bird 1812-SAM-PRS 8 Series MPR	2	360	30	1.05	8'	
16		Rain Bird 1812-SAM-PRS 8 Series MPR	6	180	30	0.52	8'	
17		Rain Bird 1812-SAM-PRS 8 Series MPR	2	90	30	0.26	8'	
18		Rain Bird 1812-SAM-PRS 10 Series MPR	5	360	30	1.58	10'	
19		Rain Bird 1812-SAM-PRS 10 Series MPR	2	180	30	0.79	10'	
20		Rain Bird 1812-SAM-PRS 10 Series MPR	3	90	30	0.39	10'	
21		Rain Bird 1812-SAM-PRS 12 Series MPR	2	360	30	2.6	12'	
22		Rain Bird 1812-SAM-PRS 12 Series MPR	17	180	30	1.3	12'	
23		Rain Bird 1812-SAM-PRS 12 Series MPR	14	90	30	0.65	12'	
24		Rain Bird 1812-SAM-PRS 12 Series MPR	1	120	30	0.87	12'	
25		Rain Bird 1812-SAM-PRS 12 Series MPR	3	270	30	1.95	12'	
26		Rain Bird 1812-SAM-PRS 15 Series MPR	1	360	30	3.7	15'	
27		Rain Bird 1812-SAM-PRS 15 Series MPR	6	180	30	1.85	15'	
28		Rain Bird 1812-SAM-PRS 8 Series VAN	2	Adj	30		8'	
29		Rain Bird 1812-SAM-PRS 10 Series VAN	9	Adj	30		10'	
30		Rain Bird 1812-SAM-PRS 12 Series VAN	9	Adj	30		12'	
31		Rain Bird 1812-SAM-PRS 15 Series VAN	3	Adj	30		15'	
32		Walla Walla MP1000 w/ 1812	3	Adj	40		13'	
33		Walla Walla MP2000 w/ 1812	10	Adj	40		19'	
34		Walla Walla MP2000 w/ 1812	5	360	40	1.47	19'	
35	SYMBOL	MANUFACTURER/MODEL	QTY		PSI	GPM	RADIUS	
36		Hunter I-40-ADS, 36S	48		50	11	51'	
37		Hunter PGH-ADV, 36V	1		40	1.4	33'	
38		Hunter PGH-ADV, 36V	11		40	2.4	36'	
39		Hunter PGH-ADV, 36V	2		40	3	38'	
40	SYMBOL	MANUFACTURER/MODEL	QTY					
41		Drip Tubing						
42		Rain Bird XBS						
43	SYMBOL	MANUFACTURER/MODEL	QTY					
44		Rain Bird PEB 1"	2					
45		Rain Bird PEB 1-1/2"	19					
46		Rain Bird 3RC	7					
47		Febco 825Y 1-1/2"	1					
48		Irrigation Lateral Line: PVC Class 200 SDR 21 3/4"	2482					
49		Irrigation Lateral Line: PVC Class 200 SDR 21 1"	1541					
50		Irrigation Lateral Line: PVC Class 200 SDR 21 1 1/4"	967					

Irrigation Schedule, placed into the drawing with symbols, or sent to a spreadsheet for cost takeoff purposes.

Making Changes

The last portion of a project that a software system can assist with is in making changes. I have tools at my disposal to easily move heads along with any connected pipe, or to delete all the pipe for a system, or to replace symbols or equipment. And of course after making any number of changes, no matter how complicated, resizing my pipes and regenerating my schedules is instantaneous.

Conclusion

Other software tools that we use daily have the convenience of things such as Find and Replace, and Spellcheck – now advancements made with standardization of CAD software, and advanced database technologies have allowed the creation of highly specialized software tools for irrigation design.

Incorporating advanced technology such as this will allow us to not only be more accurate, efficient, and allow more flexibility, but will make our profession more productive and profitable.

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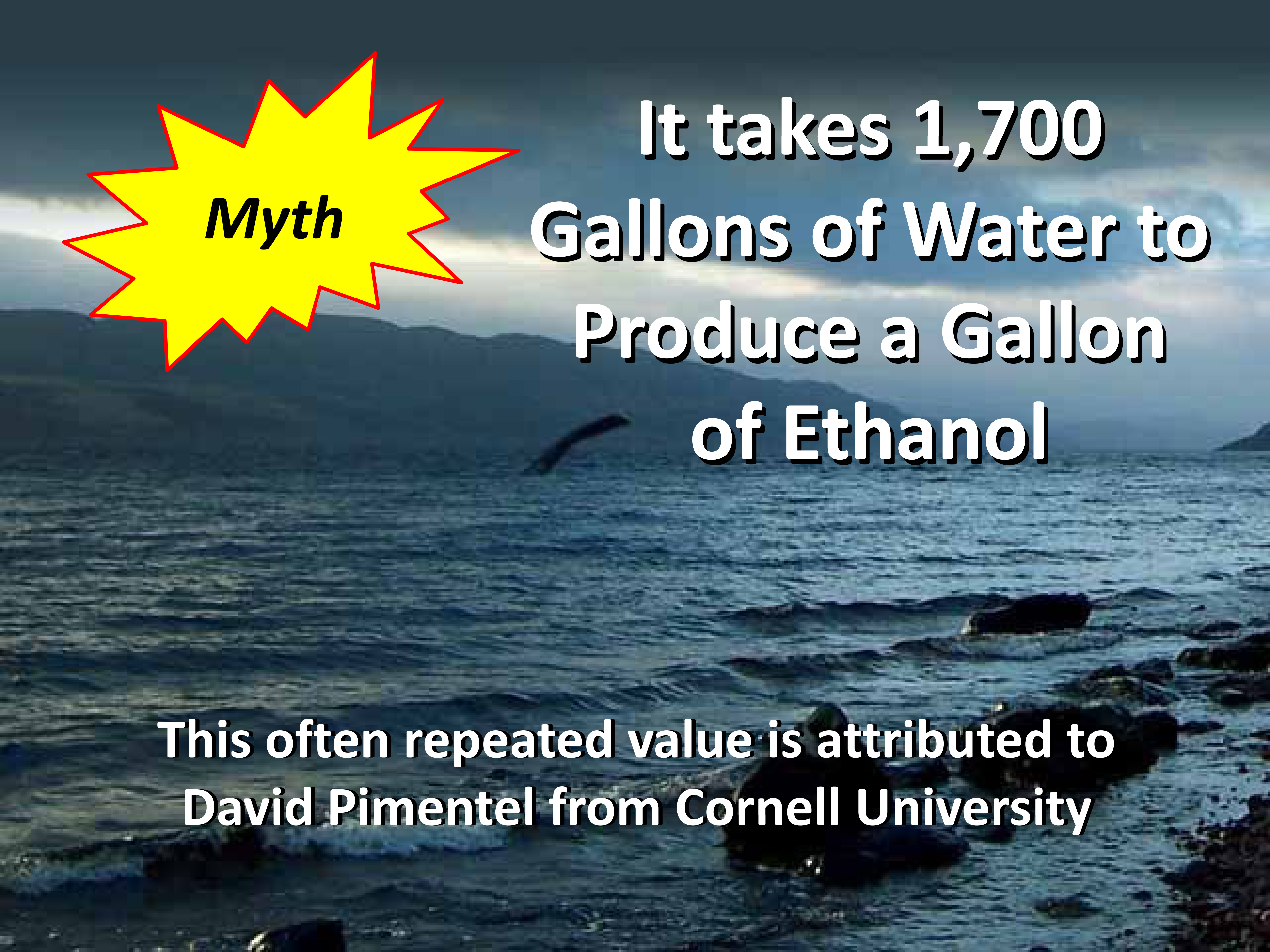
Dispelling the Myths about Water use in Ethanol Production

Presented by Myke Feinman

Biofuels Journal


Myth
It takes 1,700 Gallons of Water to Produce a Gallon of Ethanol
This often repeated value is attributed to David Pimentel from Cornell University

FACT

It takes less than 4 Gallons of Water to Produce a Gallon of Ethanol

This value from the
American Coalition for Ethanol (ACE)

FACT

Water used in the Production of Ethanol at Dry Mill Plants Decreased 26% from 2001 to 2006

Some plants have reduced water consumption to less than 2.8 gallons per gallon of ethanol

Source: Argonne National Laboratory

If the production of one gallon of ethanol actually uses less than 4 gallons of water, then how are the remaining 1,696 gallons of water in Mr Pimentel's value used and where does the water come from?

FACT

Over 96% of the corn grown in the United States is grown with natural rainfall. The remaining 4% is irrigated

Source: ACE

FACT

Of the corn that is actually irrigated, it requires 785 gallons of water to produce feedstock to produce one gallon of ethanol

Source: American Coalition for Ethanol (ACE)

FACT

An acre of corn also gives off 3,000 to 4,000 gallons of water per day through transpiration

Source: US Geological Survey

Myth Dispelled

One gallon of ethanol requires 785 gallons of irrigation water to grow the corn for feed stock + 4 gallons of water to manufacture =
789 gallons actual water use.

A difference of 911 gallons when compared to the widely quoted 1,700 gallon value.

How does less than 4 gallons of water required to manufacture one gallon of ethanol compare with other water uses?

FACT

Water usage to produce a gallon of gasoline is 2 to 2.5 gallons.

There is no recovery of water from the refining process of gasoline.

Source: National Renewable Energy Laboratory (NREL)

FACT

Over 1/3 of the water used in the manufacture of ethanol is recycled in the process.

One trend is to achieve <u>zero waste water discharge</u> from plants - VeraSun's Plant in Welcome, MN has met this goal.

Municipal waste water plants treat gray water drained from sinks and showers at water treatment plants.

FACT

Many ethanol plants are finding value in gray water as a replacement for fresh water in the manufacturing process.

One such facility is the POET plant in Corning, Iowa which uses gray water for its cooling tower saving 40% of their fresh water requirements.

In addition to having the ability to utilize “gray water” in the manufacturing process, ethanol production yields many useful by-products as well.

FACT

Production of ethanol produces these useful by-products further adding to the value of the water used in the manufacturing process.

- Dried Distillers Grains with Solubles (DDGS) which are used a livestock feed
- Carbon Dioxide which, if captured can be used in a number of industrial and food applications
- Corn Oil extracted from DDGS which is a prime feedstock for biodiesel production

FACT

Additional uses:

- Food grade corn oil can be extracted with reduction in yield of ethanol.

- Fiber can be fractionated from the corn kernel and be used as a fuel source in lieu of natural gas or used as a source of cellulose for cellulosic ethanol production.

The Food versus Fuel Question Surrounds Ethanol

FACT

The Primary Uses of Corn in North America

- 47% Livestock Feed
- 17% Export
- 17% Ethanol
- 8% Surplus Stock
- 4% High Fructose Corn Syrup
- 7% Other Uses

Source: National Corn Growers and USDA

Is Ethanol Production a Wise use of Water Resources - A Financial Perspective -

FACT

- Ethanol Production 2007: 6.5 billion gallons
- Employment for 238,000 People
- GDP Contribution $47.6 billion
- Federal Tax Revenue: $4.6 billion
- State and Local Revenue: $3.6 billion
- Reduction in Farm Subsidies: ($8 billion)
- Saved Import of Oil: 228 million barrels or

$16 billion dollars

Source: Bob Dinneen - Renewable Fuels Association Feb 2008

Is ethanol production a wise use of water resources?

Given the facts, I believe it is!

Thank You for Your Attention

Questions?

Rainwater Recovery Systems for Commercial Irrigation: Do's and Don'ts

Brian Vinchesi, CID, CIC, CLIA, President, Irrigation Consulting, Inc.
Jeffrey Bowman, Project Engineer, Irrigation Consulting, Inc.

Introduction

For many years the majority of commercial irrigation systems have relied on potable water supplies as their source of water. The advantages to potable supplies are many and include: "unlimited" use, pressurized delivery, superb water quality and reliability. However, as water resources have become more critical and competition has increased for its use, using potable water as an irrigation source has come under more and more scrutiny. This has resulted in water withdrawal permits, water restrictions and all-out bans. As "green" and "sustainability" have become the buzz words of the decade, alternative water sources for irrigation systems have become necessary and in some cases rewarded. There are a number of different alternative sources that can be considered for an irrigation system and include: gray water, reuse, water, effluent water, and rainwater. This paper will concentrate on one of these sources, rainwater and considerations that should be undertaken when using it with commercial irrigation systems.

Planning, Codes and Laws

First, codes and laws need to be investigated. In some states most notably, Colorado and Utah, rainwater cannot be collected, stored and used for irrigation by law. Due to water law (prior appropriations) and downstream user rights, the water cannot be collected. In Utah the law is not as restrictive as in Colorado so there may be instances where rainwater can be used. Plumbing and health codes also may need to be considered. Some health codes, especially local ones, do not allow non-potable water to be piped through a building. Others may not allow irrigation of interior plantings with non potable water. Lastly, code may effect how and where the water can be stored, for example it may not be allowed to be stored inside a building, only outside.

Second, it is important that the irrigation designer be involved from the inception of the building planning and design, including the site work. Tank sizes and location, wire and conduit routing, and rainwater collection routes cannot be add-ons to an already designed building—it will be too late. In rainwater systems the water balance inputs and outputs need to be determined very early in the process, long before the irrigation system is designed. Inputs consist of roof area, rainfall data and collection efficiencies. Outputs consist of ET data, evaporation data and irrigation efficiencies. Once this balance is undertaken, the storage tank can be sized and located.

Storage

There are a number of different storage scenarios that can be undertaken and will be based on location, how much storage is needed and the cost of the storage. Storage can be above ground, below ground, in a building or as a water feature. Materials can be concrete, fiberglass, certain types of plastic or specialty materials made just for storage of rain or stormwater. In its simplest form storage is just 55 gallon rain barrels, but they are a bit small for commercial systems. It is important to remember that not 100% of the storage is usable, i.e. you can never get all of the water out. So for example, if you require 20,000 gallons of usable storage the tank more realistically will need to be 25,000 gallons. The amount of unusable storage will be determined by the shape of the tank, the size of the tank and what type pumping system is installed. You also want to leave some buffer in the bottom in case you get some settling of containments. Concrete tanks are easily obtainable from pre-cast companies. Ganged together septic tanks work well and the cost is low. Fiberglass tanks are also available, but are not always cost-effective. Plus with fiberglass, you need to worry about buoyancy, which is usually not a problem with concrete. There is prefabricated storage also made of plastic such as the Trident system. Above ground tanks can be of all shapes, sizes and materials. The trick is to make them aesthetically pleasing to the eye and to blend into the building and landscape. Storage costs range from $1.00 to $2.00 per gallon (for material costs), with the price getting lower with size.

On some sites multiple tanking may be required to maximize the collection of the rain water by gravity. In these cases several smaller tanks may transfer water into one larger tank to pump into the irrigation system. An economic analysis needs to be performed to determine if it is better to pump from one tank or several tanks into the irrigation system. Although transfer pumps are required in the other tanks, the cost of controls and the more sophisticated pumping system for irrigation is usually more economical than pumping from multiple locations directly into the irrigation system.

The tank will need an overflow pipe in case it gets too full. The configuration of the overflow system will depend on the inputs and where the overflow water will be going. Usually just a properly sized pipe towards the top of the tank will suffice as an overflow. If the controls are properly set up and working, then the overflow pipe is essentially just a safety measure.

Pumping

The type of pump associated with the system to pump out of the tank can be accomplished in many different ways, from the cheap to the expensive. The pump can be in the tank or out of the tank. The pump system can be submersible, flooded suction or suction lift. Keep in mind the serviceability of the pump system and the controls required. You also want to maximize the available storage. Submersible pumps lain horizontally (never vertically without a deep sump if you want any usable storage) in the bottom of the tank will work. You need to make sure from the pump manufacturer that the bearings on the pump are rated for horizontal installation. The submersible pump is probably the simplest way to pump out of the tank, but if something goes wrong, someone is going into a dark, wet tank. A centrifugal pump can be installed on top of the tank and a suction line installed down into the tank. This will be better for maintenance as the pump is out of the tank but will minimize useable storage as their will be a minimum submergence level over the foot valve and the foot valve will have to be installed some distance off the bottom to prevent contamination. This type system also will have the inherent problems of any suction lift application. It's always preferable to avoid suction issues when possible. A flooded suction type pump system works best from our experience. The pump is installed in a manhole beside the tank and a suction pipe of the proper size cored through the wall into the tank. The only part of the pumping system in the tank then is the intake screen. The manhole allows for easy access to the pump and all its controls. The chamber is dry but you may want a sump pump in the bottom as a safety in case it starts to take in water for some reason. Since it is a dry well, all of the electricity can be installed in close proximity to the pump. As with any irrigation pumping system on a diversified landscape the pump system will work best if it includes a VFD drive. Otherwise the pump system should have standard equipment: isolation valve, check valve and maybe a filter depending on the water quality although it is preferable to filter the water going into the tank not out.

If transfer pumps are required, a simple submersible or trash/sump pump can be used as long as there is not a high head required and piped directly to the main irrigation storage tank.

Controls

The brain of any rainwater recovery system is the controls. There needs to be logic with these systems which inherently raises the cost. Without logic in the system it can be a disaster as it is very important to be able to control levels, inputs and outputs. As a result of the required logic, either some mechanical logic (float or pressure switch) and/or some sort of programmable logic controller (PLC) will be used. The simple part of the controls turns the pump on and off – on a very large system there could be multiple pumps – in conventional ways. Either buy a flow switch, pressure switch or pump start relay from the irrigation controller. The pumps will the stop on a similar signal. The VFD depending on its sophistication and the logic controller in combination with it may require a flow and pressure signal. In these cases a flow meter and pressure transducer will be needed. Keeping track of the water pumped is always a good idea any way. Water level sensors for the tank will be required to make sure it does not get too empty or too full. They will also protect the pump and signal make up water or other transfer pumps to add water to the tank. Because the level controls have different tasks at different heights in the tank, i.e. water in at one level, pump off at another, and one pressure sensing level indicator usually is better than multiple probes. The sensor then, in combination wit the logic, can be used to perform its various functions. This makes for a neat control package at an economical cost with reduced maintenance. If there is a sump pump, it will just start and stop with a float switch.

Make Up Water
Unfortunately, when irrigation water is needed the most, it is when it has not rained for awhile. Rarely can a system balance between ET requirements and rainfall received over the whole year, unless there is very sizable storage and that gets expensive quickly. Calculations can indicate the percentage of time the system could be out of water based on historical weather data and a climate analysis. However, most clients do not want a dry landscape so make up water is required. There are systems that rely 100% on rain water either because another source of water is not available or local restrictions do not allow for make up water. Make up water can be a groundwater source, a potable source or from other storage if water is available. The make up water into the tank needs to be sized and controlled. If it is a pumped source, transfer or groundwater, a signal is sent to the pump starter when the tank reaches a certain level. If it is a potable source a properly sized electric solenoid valve can be installed and signaled to come on. Make sure proper backflow prevention is employed which in a tanking case may be an air gap. In some systems there may be two or three make up sources and that logic needs to be programmed through the senses. For example, the tank level drops to a certain point and the transfer pump or pumps turn on, the tank level continues to drop and the well turns on, but the tank continues to drop so then the potable supply turns on. To reduce the dependence of make up water, an efficient irrigation system with weather-based controls works best—if economically feasible.

Coordination
Rainwater recovery systems require a great deal of coordination with other disciplines. As mentioned previously, this needs to be done early in the process, not late. The roof leaders and drainage need to be run to the tank or tanks, tanks need to be sized and located, power needs to be run to pumps and controls and monitoring coordinated. This will require coordination engineers, building and landscape architects. A level of design detail, that you are not use to may also be required. Because of the timeline, sophistication and coordination required on these systems they do not lend themselves to design-build scenarios and need to be engineered.

Conclusion
Rainwater recovery systems are becoming more popular and in some cases mandated by authorities. Coordination and engineering of these systems early in the process is imperative to have them operate correctly. Tanking, pumping and controls need to be customized for each system and a water and climate analysis performed. As potable and groundwater sources come under increased scrutiny rain water systems will be common place and an understanding of there requirements is a must.

WATER REUSE FILTRATION FOR GOLF COURSE IRRIGATION

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Abstract. *One of California's most impressive golf courses is demonstrating a high degree of conservation by utilizing highly treated recycled water for irrigating the grounds. With today's emphasis on water conservation, irrigation nozzles and emitters are getting smaller and smaller increasing the importance of a reliable filtration system. Effluent from a local wastewater treatment plant has unique qualities that must be considered when thinking about using it as a source for irrigation. After switching over to this reuse source the original filtration system at this golf course began rusting away and the control system was not adequate for the application. This paper will investigate the parameters to consider when looking at reuse water for irrigation and how they influence the design. Only if the filtration system works properly can the sprinklers stay free of debris keeping the greens green.*

Keywords. Filtration, Filters, Automatic Filters, Self-cleaning Filters, Water Reuse, Irrigation, Golf Course Irrigation, Effluent Reuse

Introduction

The Links at Bodega Harbour in Bodega Bay, CA is located just an hour north of the Golden Gate Bridge. This Scottish style links has whitecaps from the roaring Pacific Ocean as a backdrop to the lush green grass of the course and a deep blue sky overhead as shown in Figure 1.

Densely manicured turf, as highly desired on golf courses today, requires vast amounts of water to replace moisture lost to the atmosphere through evapotranspiration. Historically, this water came from the same surface or ground water supplies utilized for potable needs. With the growing population and industrialization of areas such as Northern California, human and recreational water needs start to compete. While The Links is known as one of California's premier golf courses, the general public may not know how this course is "green" in more ways than the obvious. Conservation minded management uses highly treated reuse water from a municipal wastewater treatment plant to meet the high water demands of actively growing turf. Reusing water from this source is becoming more and more popular (and necessary) in many parts of the world. Not only does it provide a much needed resource for recreational areas but also helps preserve estuaries and coastal regions from changes in salinity and nutrients that can degrade or at least alter such environments. Along with noble actions however, come secondary problems.

Figure 1. The Links at Bodega Harbour

Operation

Wastewater in a nearby urban area is treated at a wastewater treatment plant in a contemporary fashion. However, instead of simply being discharged to the ocean or a stream leading to the ocean, the effluent from the treatment plant undergoes additional filtration to remove organic and inorganic solids and extensive disinfection. The effluent then is piped to a 33 million gallon reservoir and stored as reuse water until needed for irrigation at The Links. Water is then withdrawn from the reservoir by the golf course's irrigation system for application to all the turf and landscaping on the course. A good system maintains the uniformity needed to see that every square foot of turf gets its share of water and nutrients.

Problem

With today's emphasis on water conservation, orifices in nozzles and emitter in irrigation systems are getting smaller and smaller. No longer do we have the luxury of being able to apply excessive amounts of irrigation water to recreational sites. Reuse water in the reservoir picks up wind-blown debris, small fish, snails, algae, insects and other critters. Pumps transfer water loaded with solids to the irrigation system. Once in the irrigation system these solids can quickly plug the fine orifices causing "brown" greens and other turf problems. Costly labor is required to clean and often replace plugged emitters. Fine robust filtration systems are a necessity today to prevent such happenings. The Links had an old irrigation filtration system but in 2004 the filters were rusting away and the control system was no longer reliable. Something had to be installed to replace the old system as soon as possible while using more appropriate materials of construction to prevent premature failure.

Solution

A dependable long term solution was found using three filters with weave-wire 316L stainless steel screens as positive barriers to organic and inorganic suspended solids. The manufacturer offered a complete line of automatic self-cleaning filters with the capability of fabricating manifolds and filter connections to fit right into the existing piping system. To prevent future corrosion problems, filters with stainless steel bodies were selected off the shelf. The Links at Bodega Harbour needed immediate action so three all stainless steel filters with high-performance multi-layer screens were shipped the day after they were ordered. Actual installation and start-up took only a day resulting in the system shown in Figure 2.

Figure 2. Three High Performance Stainless Steel Filters

Operating in parallel, the three filters easily handled the 1500 gpm flow rate using less than 1% of the flow for the self-cleaning operation. Even during the cleaning process water is provided downstream at all times since individual filters do not have to come off-line to clean themselves. The control system was specifically designed to clean each of the three filters sequentially taking only 8 seconds per filter. The cleaning cycle is initiated by either a differential pressure switch with a preset threshold or an adjustable timer inside the control panel. A solenoid control valve is a key component in the cleaning process used by many filter manufactures. If this valve plugs with debris, such as algae or sand, the filters will fail to operate properly. This problem was eliminated by using only solenoid control valves having large 5/8 inch openings that are virtually clog-free. The automatic flush cycle eliminates a lot of maintenance work and the new controller provides flexibility and dependability. A full description of how the filter operates is given in the Appendix and diagramed in Figure 3.

Conclusion

The earth's hydrologic cycle is the ultimate water reuse system. However, societal demands can no longer wait on "nature's way." We are learning to accelerate this cycle in ways that are safe for humans and non-detrimental to the environment of which we are a part. By utilizing wastewater effluent in non-potable ways, we can prolong the time, perhaps indefinitely, before much more drastic steps are required to provide safe water for human consumption. Irrigating golf courses with reuse water is one positive step in the right direction. As the praxis changes, new problems must be addressed. The Links at Bodega Harbour saw finer filtration needs, accelerated corrosion problems and a need for more sophisticated controls when switching to reuse water. These problems were solved with the installation of a new filtration system with greater capacity, more appropriate materials of construction, greater control capabilities, better reliability and expedient service. Automatic self-cleaning screen filters are proving themselves as desirable options for treatment of reuse water for many applications including membrane pretreatment. As more of these applications for reuse water become apparent, new problems will need addressing in unique ways.

Appendix

The operation of the filters used at this site is simple yet effective. Dirty water enters the ***inlet*** flange as shown in Figure 3 then passes through the ***coarse screen*** from outside-in removing large hard objects. The pre-screened water then flows to the inside of the ***fine screen***. As water passes from inside-out in the ***fine screen***, suspended solids are stopped if they are too big to pass through the screen openings. Clean filtered water then leaves the filter through the ***outlet*** flange. As more and more material builds up on the inside surface of the fine screen a pressure drop in the system begins to build. When a preset pressure drop threshold (7 psi) is reached across the fine screen, the controller is signaled to initiate a cleaning cycle. The first step in the cleaning cycle is to open the ***rinse valve*** to atmospheric pressure which quickly drops the pressure in the ***hydraulic motor chamber***. Because the hollow ***dirt collector*** connects the end openings in the ***nozzles*** to the ***hydraulic motor chamber***, water quickly moves from the ***nozzle*** openings, through the ***dirt collector*** into the ***hydraulic motor chamber*** and out the ***rinse valve*** to a drain. Since the ***nozzle*** opening is touching (optional self-adjusting nozzle) or nearly touching (standard nozzle) the screen surface, water rushes backward through the screen (outside-in) in a small area (about the size of a "dime") at a velocity exceeding 50 ft/sec. This intense energy pulls off the stickiest material and expels it from the system though the ***rinse valve***. The ***hydraulic motor*** then rotates the ***dirt collector*** while the ***piston*** moves the ***dirt collector*** linearly. The tight spiral movement of each ***nozzle*** on the ***dirt collector*** assures that every square inch of ***fine screen*** surface is sucked clean of all debris in 5 to 12 seconds. The next cleaning cycle will begin when the pressure drop threshold is met again or until a preset time interval has been reached.

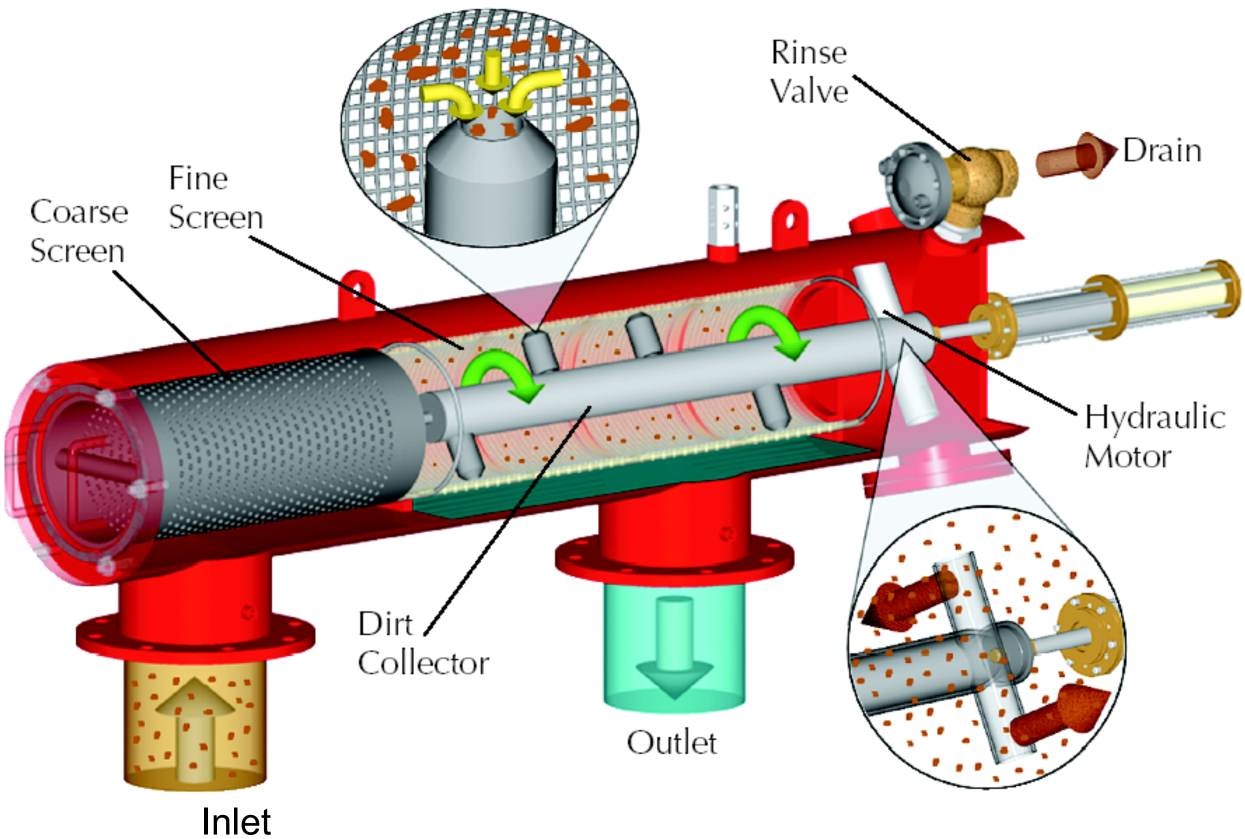

Figure 3. Automatic self-cleaning screen filter.

Acknowledgements

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Importance of spatial information in irrigation management

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Abstract. Soil water tension is a widely used parameter to manage irrigation. The collection of simultaneous information on soil water tension from many locations in a field is now made possible through wireless tensiometers. Such automatic spatial data collection results in a better assessment of the field-average tension. Additional gains in water management efficiency can be obtained if some spatial patterns can be identified which represent zones large enough to be irrigated independently. When such conditions exist, excess water is often applied if subzones of high variability are not independently managed. In this case, important excess water and energy may be used. Hence, important water savings can be obtained by recognizing spatial variability patterns in soil water tension and managing such patterns as sub-units instead of as a whole field. This paper summarizes observations obtained from different studies investigating the presence of independent zones and their effect on irrigation needs.

Keywords: tensiometer, wireless, spatial variability, precision irrigation,

Tools for measurements of plant and soil water status

Irrigation water accounts for about 2 / 3 of drinking water consumption on the planet and irrigated areas increase year after year in order to improve overall land productivity. Adequate irrigation management remains an important factor for many crops, as any water application excess leads to energy waste. In general, with appropriate irrigation management, there is increased growth, reduced production times, a more efficient use of fertilizers and pesticides, and reduced water and nutrient losses to groundwater (or to runoff). Finally, there is a decreased risk of developing certain foliage and root diseases.
Various tools exist to manage water (Table 1). Atmospheric, plant and soil based measurements do exist. Timers can also be used.

Timers are very basic and generally do not add the appropriate amount of water. The cost is low, but for more precision the preference has been to control the application of water based on the amount of water evaporated and transpired by

Table 1 : Different tools used to evaluate water status

Measurement level		Plant	Atmospheric	Soil
Type of measurements	direct	Yield Photosynthesis Xylem potential		Matric potential
	indirect	Temperature Fluorescence	Evapotranspirative demand (ETP)	Water content

the plant [evapotranspiration (ETP)]. This involves estimating how much water to apply to the soil according to meteorological parameters such as temperature, net radiation, wind speed, the stage of growth. These data can be calculated from public software, mathematical formulas on Excel or forecasting weather stations. This approach is widely used in North America, although some authorities now require the addition of measurements in the soil to increase accuracy.

The ETP approach goes one step further than timers by trying to estimate the appropriate amount at the field scale. Although a very significant improvement over timers, it does not sense, however, the real need at the plant level at a particular site. Hence, despite the fact that irrigation can be recommended from atmospheric measurements, sufficient storage of water may already exist and water may be applied in excess. Also, ETP recommendations provide an assessment on a large scale but do not provide any information on local irrigation needs.

Therefore, a better assessment, at the plant or at the soil level would be provided by multiple measurements taken at the plant or soil level. Plant measurements (photosynthesis, stomatal conductance, leaf temperature, xylem potential) are widely used in research. However, for field applications, they remain expensive and required highly skilled people to operate the equipment and interpret the results. While still viewed as promising (Jones, 2004), they remain limited to research applications; however growers tend to rely more on soil-based measurements, which are easier to use and interpret.

Among the measurements taken in the soil, it has long been recognized that measuring matric potential (or water tension) is preferred as it is regarded as the best direct measure of water availability to crops (Van Pelt and Wierenga, 2001). It is more directly related to uptake than soil water content, since the tension is a measure of the ease with which water can be withdrawn from the soil by the plant. Matric potential determines the amount of water transpired, according to the principles of thermodynamics, in the absence of the significant effects of salinity. When the ground dries, that is what the plant "sees". As the water tension increases (the plant may begin to suffer) while its water content is lowered. The tension reference value for initiating irrigation is fairly well known and published values for different soil types and irrigation methods can be found (Werner, 2002). However, tensiometers do have problems as they require maintenance and calibration, which has sometimes limited their use in the field.

With respect to water content, advances in time (TDR) and frequency (FDR) domain reflectometry have renewed interest in using soil-based measurements to manage irrigation. Measuring water content requires specific soil calibration because the water content observed at the critical tension set point will vary with soil properties and the soil salinity (for FDR and capacitance probes). Moreover, the differences between the dry (start of irrigation set point) and the wet (stop) are very small in coarse soil (sand, structured clay and organic soils) and a very high accuracy is needed, which cannot be obtained with all water content probes.

Whatever type of approach is used (measuring soil water content or water tension), these approaches have shown performances superior to those based on evapotranspiration or on visual inspection to manage irrigation in the greenhouse and/or in field. This has lead to significant water and energy savings. In the future we expect to see the proportion of measurement tools in the soil increase. Moreover, some sensors can be combined with wireless transmission systems to yield real time data originating form different spatial locations.

In the near future, as was the case in precision agriculture, these tools will be used at different locations in the field to estimate local irrigation needs. In the United States, this approach has been termed "hydrozoning". By obtaining information about the spatial distribution of soil water tension, as well as additional measurement like salinity, soil oxygen content and temperature, significant gains in productivity and irrigation efficiency are to be expected.

The main problems associated with tension measurements are the small volumes of soil that are measured (an advantage with drip irrigation), the need to fill the tensiometer with water if the soil gets too dry, and the need to calibrate the equipment for the water height within the tensiometer. Moreover, an additional limitation for collecting spatial information data is the need to scout (physically read) the systems at regular time intervals. Several companies nowadays have introduced wireless communication systems that can be installed in the field to transmit data in real time using radio frequency units. Real time transmission of data using wireless tensiometers with reduced maintenance now exist. They allow real time collection of tensiometer data to properly manage irrigation.

This new possibility raises new questions: how many tensiometers do we need and where should we place them? The first obvious response is based on the number of crops to be managed, their growth stage, the existence of different irrigation zones and the influence of topography. For the same crop and within a same irrigation zone, two questions remain: where should they be located and how many of them should we use?

Where should the tensiometers be located? The answer varies: it really depends on spatial variability. We need to know whether or not the tension varies in a soil, if the variability of these zones is important, and if the variability is caused by differences between patches of uniform properties (in which case the variability is manageable if these zones can be grouped into adjacent subzones).

Field studies have indicated important variability in irrigation needs based on soil parameters and that of irrigation dosage (Warrick and Gardner, 1983). Additional information is also needed on local plant water uptake (Cyr, 1990). Therefore, adequate estimation of local irrigation needs should be based on real time data, as it allows for the integration of irrigation distribution uniformity, local drainage and storage properties and local effect related to plant water uptake. Abundant data can be found in the literature on water content and have shown the existence of patches and the persistence of these patches in time (temporal stability).

Little data exists for water tension (Van Pelt and Wierenga, 2001). These authors have shown though the temporal stability of such measurements at different locations in the field. Additional information on spatial distribution of water tension is illustrated in the cases below.

Case 1: Spatial variability in a potato field. Data were collected in the summer of 2007, at thirty different locations, from May to October. Soil water tensions were collected using wireless tensiometers every five minutes, at the 15 cm depth (30 cm once hilling was performed) for the whole duration of the experiment. Nitrate contents were collected at different periods and depths in the profile, at a total of 30 different locations.

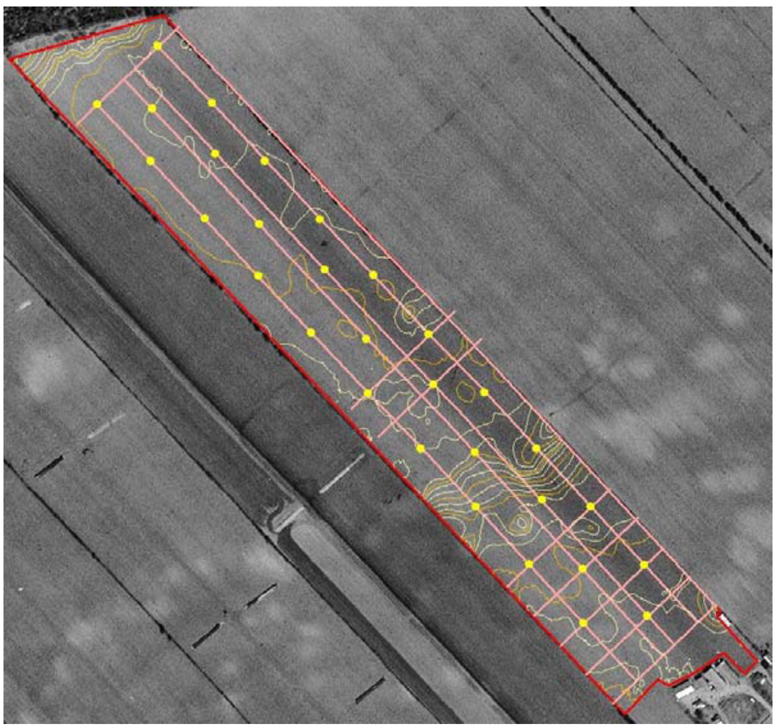

Figure 1. Position of the 30 different tensiometers and soil samples, in a 20 ha potato field along with the topographic lines

Patterns were observed in the interpolation maps. They confirmed the presence of a spatial structure for soil tension, zones being grouped into sizes about 250 m long (Figure 2). These zones were constant in time, with drier areas (on the higher surfaces), more humid areas in depressions and a wet spot in the bottom right corner (Figure 3). These patterns were directional and were longer in the direction of the slope. This meant that the similarity in tension was closer along than across the slope, an effect that might be due to tillage which tends to smooth out differences over time, since ploughing may be moving particles in the direction of the slope. The pattern also corresponded to the fact that the irrigation was carried out in four distinct zones, separating the field in four sections of equal size.

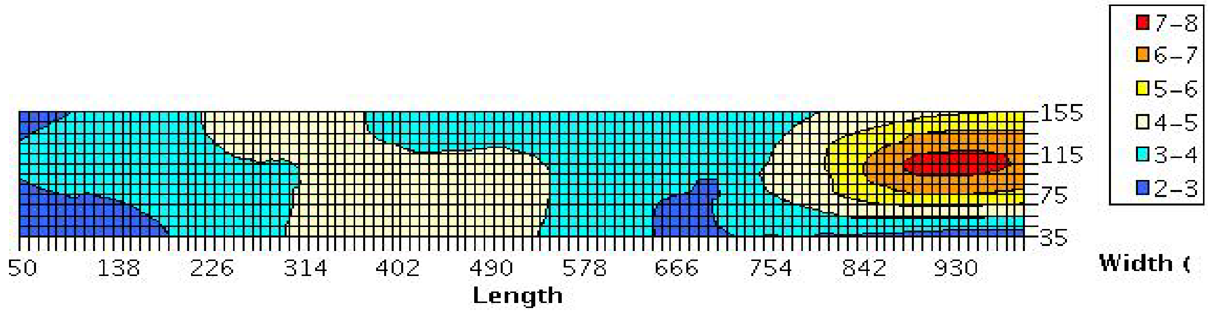

Figure 2. Mapping of the different zones for soil water tension during the wet period (in kPa or cbars)

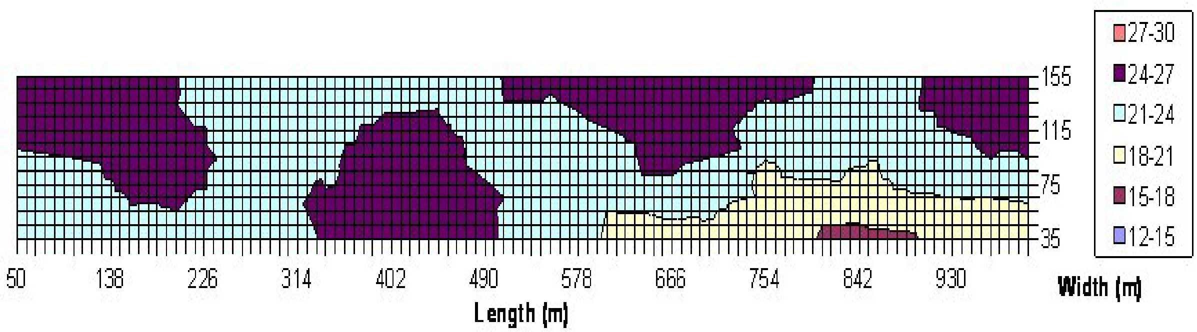

Figure 3: Mapping of different zones for marketable yields (T ha^{-1}).

Similar results were observed for potato yields (Figure 3). A positive and significant correlation was observed between potato yield and tension during wet events (Figure 4), suggesting that the yield decreased with decreasing tension (wetter soil). This correlation was consistent with similar behavior observed for cranberries (Bonin, 2008) and most likely occurred because the grower tended to over irrigate in the bottom right corner of the field, which most likely increased nitrate leaching. In this case, at least a quarter of the whole area was found to be over irrigated, resulting in net yield decreases. The results indicate that most of the irrigation could be largely reduced in that zone, hence generating about a 20-25% savings in water. Experiments are ongoing to confirm this conclusion.

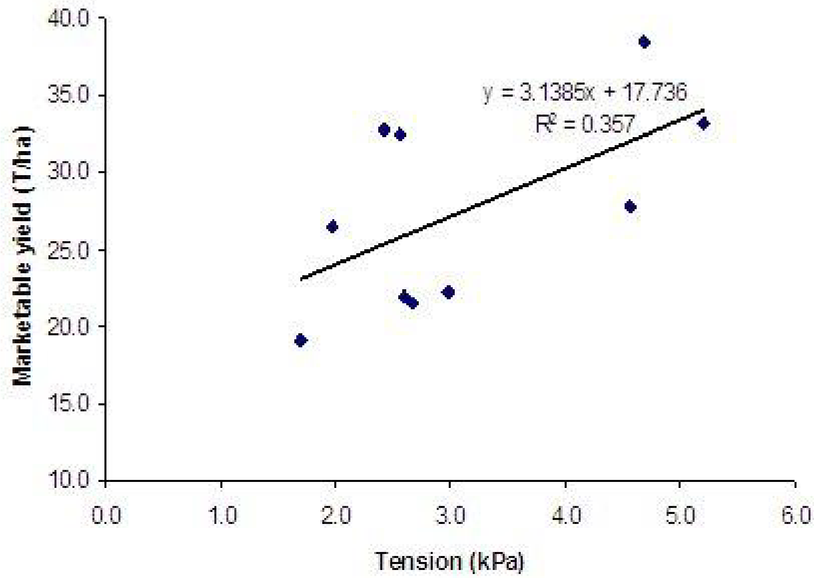

Fig. 4. Relationship between soil water tension during the wet period and potato marketable yield.

Case 2: A cranberry field. The second example came from a farm instrumented for three years with tensiometers (one per three fields), having a total of 60 fields. Preliminary measurements indicated a consistent spatial pattern of dry and wet zones in these fields and a relationship could be established between water tension during wet periods and crop yields (Figure 5).

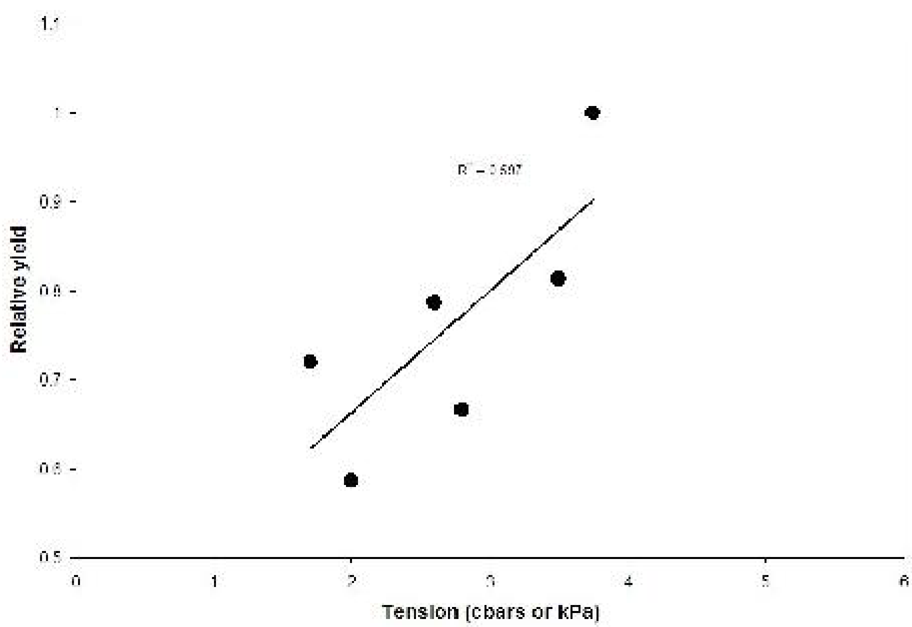

Figure 5. Soil water potential and cranberry relative yield.

Tensiometers were installed at the 8 cm depth, over an area of about 1.5 km^2. They were left to equilibrate for a total of two days and measurements were recorded within 2 hours at the end of May. Additional details can be found in Bonin (2008). Like the potato results, the data indicated the presence of a spatial structure, i.e., the data were not random. Hence, contour maps for water tension were generated by kriging, a statistical data approach found appropriate for regional (non random) variables. From this map, patches of low and high water tensions were observed that were consistent with observations made by the grower, with zones of about 400m in length showing changes in tension (Figure 6). This should be expected as it corresponded to the average length of a field, with each field being more or less independent of its neighbors. Indeed, each field has its own drainage and irrigation system. These differences were large enough though to have a significant effect on cranberry yield (Figure 5) and helped the farmer to assign different irrigation zones. Later work showed that one third of the fields gave the same yield with no irrigation at all, generating water savings of about a third relative to previous practices at the whole farm scale

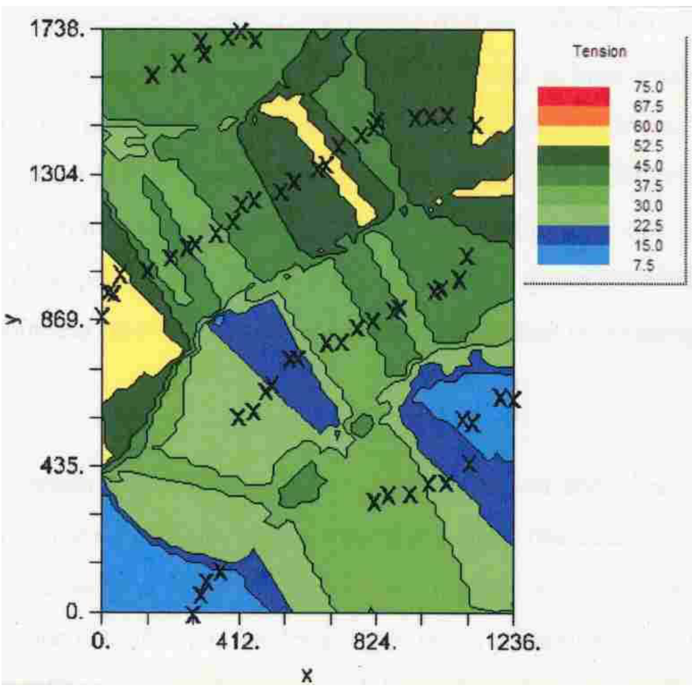

Figure 6. Tension variation (in mBars or hPa) found in 60 cranberry fields at the end of May.

Case 3. The Greenhouse case. The data were taken from Cyr (1990). They investigated the variation in water tension from a plastic greenhouse tomato experiment by taking tension measurements prior, between and after irrigation, for a total of 36 tensiometers. The tensiometers were located at 36 different locations within a Latin square design. Measurements were performed on actively growing plants over a full month period in the fall. Obviously, measurements that were carried out after irrigation were less variable than those measured before irrigation, but again, the data showed spatial variations that were stable in time, over the whole course of the study.

Their data clearly indicated that most of the variation (evaluated by calculating the standard deviation of the water tension) was observed for tensions between plants and then between the different patches found in the greenhouse (location). Measurements errors were found to be small relative to the other two sources of variability (Table 2). After irrigation, the standard deviation was the same between locations as that between growing slabs.

Table 2. Summary of the variation (standard deviation) of tension, in cm of water (1 cm=0.1 cbars)

Effect	Before irrigation	After irrigation
Location within the greenhouse	4.5	3.8
Between growing slabs within the same location	9.0	3.8
Measurement error	2.1	0.8

The pattern was expected to show more local variation than field data as growing slabs are truly independent when compared to soil zones. Therefore, little water redistribution should occur between growing slabs. In terms of water savings in a greenhouse operation, efficient leaching is critical. In this case investigations have shown that with 5 tensiometers within a greenhouse, instead of 1, the proportion of growing slabs efficiently leached goes from 8% to 31%. Because adequate leaching is performed, better growth is often observed and this leads to an improved water use efficiency of about 14% (Lemay, 2006).

How many tensiometers should we use? From all three examples, it becomes obvious that patches of large sizes exist in a different kind of growing environment and that they should be grouped and managed separately. Now, the second question remains. Once you have identified humid and dry zones, which are temporally stable, how many sensors should you used to detect those zones? From a purely statistical point of view, the answer is related to the maximum yield differences we can have between dry and wet zones. In both the greenhouse and field experiments, relationships can be drawn between tension and crop yield (Figures 4 and 5). Then a calculation can be carried out to determine the number of tensiometers needed in a zone. Obviously, the conclusions are site specific as they are dependent on the soil, irrigation distribution uniformity, type of crop and the expected tension effect on crop yield on top of the economical constraints linked to the cost of establishing and managing a new zone.

Case 1. The potato field. At least some calculations can give an indication and can be compared with the common statement made that 3 tensiometers in a zone should give a good estimate. For potatoes, calculations were based on the fact that a decrease of tension of 2 kPa would result in a yield drop of 20%. Then, we based the calculation on a T-test where

$$T = \frac{differences\ between\ two\ zones}{(SD * (NuT)^{1/2})}$$

where *SD* is the standard deviation and *NuT* , the number of tensiometers. This clearly suggest that at least 4 tensiometers per zone would be required in that field.

Number of tensiometers	T value	Probability level 5%	10%	Significance
2	2.00	12.70	6.31	Non significant
3	2.45	4.30	2.92	Non significant
4	2.83	3.18	2.35	Significant (10%)
5	3.16	2.77	2.13	Significant (5 and 10%)

Case 3. The Greenhouse case. In this case, real data were used to generate, using a Monte Carlo simulation, the effect of the number of tensiometers on the proportion of the total tomato plants of the greenhouse suffering from water stress (Table 3). The effect on yield is then expected to be very direct, as wilted tomato plants also show important yield losses due to blossom end rot. Obviously, growers will tend to over irrigate to avoid having stresses, resulting in more water and fertilizer use. It is clear in Table 3 that an adequate number of tensiometers could help avoiding over leaching, but it would require at least 3 tensiometers with a zone to reduce the percentage of stressed plants from 63% down to 33% and 5 tensiometers to reduce them to 15%.

Table 3. Results of Monte-Carlo simulation on the effect of the number of tensiometers on the percentage of greenhouse tomatoes plant showing sign of water stress.

Number of tensiometers	Percentage of the tomato plants suffering water stress
1	63
3	33
4	23
5	15

Conclusions

- With the coming of wireless technologies, soil tension measurements collected in real time at different location within fields or greenhouse make new information on the spatial and temporal distribution of this parameter available.

- All examples clearly indicated that the spatial patterns of large size (patches of same tension value) could be identified in all three examples and those patterns were constant in time, consistent with results of van pelt and Wierenga (2001) for soil tension and those of others for soil water content.

- Recognizing those zones and managing them individually could lead to important water savings (field case) or to an improve water use efficiency (greenhouse case).

- Results suggest that at least 3 tensiometers per zone are needed to detect a 20% yield drop 90% of the time in the potato field or 5 to detect 20% yield drops 95% of the time. For greenhouse operations, a minimum of 5 tensiometers per zone is necessary to have less than 15% of the greenhouses with less than 10% of the tomato plant in water deficit without detecting it.

- Recognizing those zones has lead to water saving up to about 30% so far.

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Sprinkler irrigation for site-specific, precision management of cotton

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Abstract. Fluctuations in cotton yield in the Tennessee Valley region in North Alabama are common and are usually due to irregular rainfall or drought. A sprinkler irrigation scheduling study was initiated in 2006 at the Tennessee Valley Research and Extension Center to test cotton yield response to six irrigation treatments ranging from 0% (rainfed) to 125% of calculated pan evaporation adjusted for percent canopy cover. The study was conducted in a randomized block design with eight replications. The 2006 and 2007 growing seasons were the driest growing seasons since 1954 at the research site. Rainfall was less than 7 inches during both 2006 and 2007 seasons, with total pan evaporation exceeding 23 inches each year. All irrigation treatments significantly increased seed cotton yield over rainfed. Irrigation at 100% and 125% gave the highest yields in 2006 (3.0 bales/acre) and in 2007 (4 bales/acre). Average sprinkler irrigated cotton yields were 2.3 bales in 2006 and 3.5 bales in 2007. The increase in yields in 2007 was likely due to change in irrigation management to longer, deeper irrigations compared with 2006. Although the two irrigation managements were not replicated across each season to obtain a verifiable cause-and-effect, the two growing seasons were similar enough to draw strong inferences about the irrigation management used during these two drought years. Results from both years provide clear differences between yield responses to overhead irrigation schedules during drought conditions. These results quantify the benefit of irrigation to increase cotton yield during sporadic periods of drought.

Keywords: cotton yield, rainfall, irrigation, canopy cover, evapotranspiration

Introduction

Water is the main limiting factor in crop production. Limited water resources mandates that agricultural researchers find alternate ways to increase the water use efficiency of irrigation while maintaining optimum economic crop productivity. Excessive application of irrigation water to crops not only worsens water scarcity, but also causes runoff and leaching of fertilizer nutrients and pesticides to ground and surface water, leading to environmental pollution and unnecessary costs in crop production. While the southeastern U.S. has abundant rainfall on an average annual basis, large inter-annual variability in rainfall and frequent dry periods during the growing season make purely rain-fed agriculture a poor competitor to the efficiency of irrigated agriculture (Dougherty et al., 2007). Under such periods of drought, irrigation is critical to avoid potential yield loss.

Steger et al. (1998) reported that water stress caused by delaying post-planting irrigation reduced cotton lint yield. Similarly, in field studies conducted under rainfed and irrigated conditions, Pettigrew (2004) found that moisture deficit reduced cotton lint yield by 25% in rainfed cotton. Other studies have shown that both drip and sprinkler irrigation increased seed cotton yield compared to rainfed treatments (Camp et al., 1994; Camp et al., 1997; Bronson et al., 2001; Pringle and Martin 2003; Sorensen et al., 2004; Curtis el al., 2004; Kalfountzos et al., 2007).

The objective of this study was to test cotton yield response to six overhead sprinkler irrigation treatments ranging from 0% (rainfed) to 125% of calculated pan evaporation adjusted for percent canopy cover.

Materials and Methods

The research presented in this paper was conducted at the Tennessee Valley Research and Extension Center, located in northern Alabama, an area of widespread cotton production. Treatments included five overhead sprinkler irrigation schedules and a non-irrigated, rainfed treatment. These irrigation treatments were 0 (rainfed), 25, 50, 75, 100, and 125% of calculated pan evaporation adjusted for percent canopy cover. The target depth of irrigation water was derived using pan evaporation (PAN) and percent canopy cover (CC) according to the equation:

$$\text{Irrigation (inch)} = \text{PAN (inch)} \times \text{CC\%} \times \text{irrigation treatment \%}.$$

Canopy cover for each treatment was measured on a weekly basis. Pan evaporation for Belle Mina station was downloaded daily from the Alabama Weather Information Service (AWIS, 2008). Treatments were applied to plots arranged in a randomized complete block design and replicated eight times. Each plot was 39 feet x 39 feet and was irrigated with four quarter-throw sprinklers located head to head in each corner of the plot programmed with a “soak-and-cycle” feature to limit runoff. The flow rate of each sprinkler was 3.5 gpm and the application rate in each plot was 0.89 inch/h. According to irrigation equation above, maximum soil water depletion due to evapotranspiration (ET) and before irrigation was set at 0.10 inch in 2006 and at 0.30 inch in 2007. In 2006, sprinklers in each plot were turned on to irrigate for a minimum of 7 minutes, but only after the accumulated ET depletion reached 0.1 inch. In 2007, the threshold for minimum ET depletion was increased to 0.3 inch, resulting in a minimum 21-minute water application.. This change in irrigation management was due to concerns that irrigated water was not adequately wetting the root zone and benefiting plants.

Cotton (*Gossypium hirsutm*, L.) variety, DPL 445 BR, was planted in the second and third week of April in 2006 and 2007, respectively, using a 4-row John Deere 1700 vacuum planter set at

40-inch row spacing and a seeding rate of 4-5 seeds per foot. Each irrigation treatment was applied to a plot with eight rows of cotton, using the four middle rows as yield rows. The other four rows in each plot were treated as border or guard rows (two rows on each side). Cultural practices were carried out according to conventional cotton production practices in the Tennessee Valley region. Harvesting was carried out in the third week of September in 2006 and in the first week of October in 2007. Each treatment was harvested individually and then weighed.

Yield data were analyzed statistically with Statistix 8 using Tukey method for means separation at $\alpha \leq 0.05$ (Analytical Software, 2003).

Results and Discussion

The 2006 and 2007 growing seasons were progressively dryer at the Tennessee Valley Research and Extension Center (TVREC), Belle Mina, AL, with decreasing precipitation and increasing evaporation during both years (Figure 1). The most recent 10-year average rainfall at Belle Mina for June through August is 10.5 inches; and the 78-year average is 11.5 inches. Comparable season rainfall in 2006 and 2007 was less than 7 inches. Only four previous years on record had such low rainfall during these months; and only one year on record, 1954, had less rainfall than 2007. Not only was rainfall low, but evapotranspiration (approximated by pan evaporation) was extremely high throughout the growing season of both years (Figure 1), with estimated pan evaporation surpassing 23 inches each year.

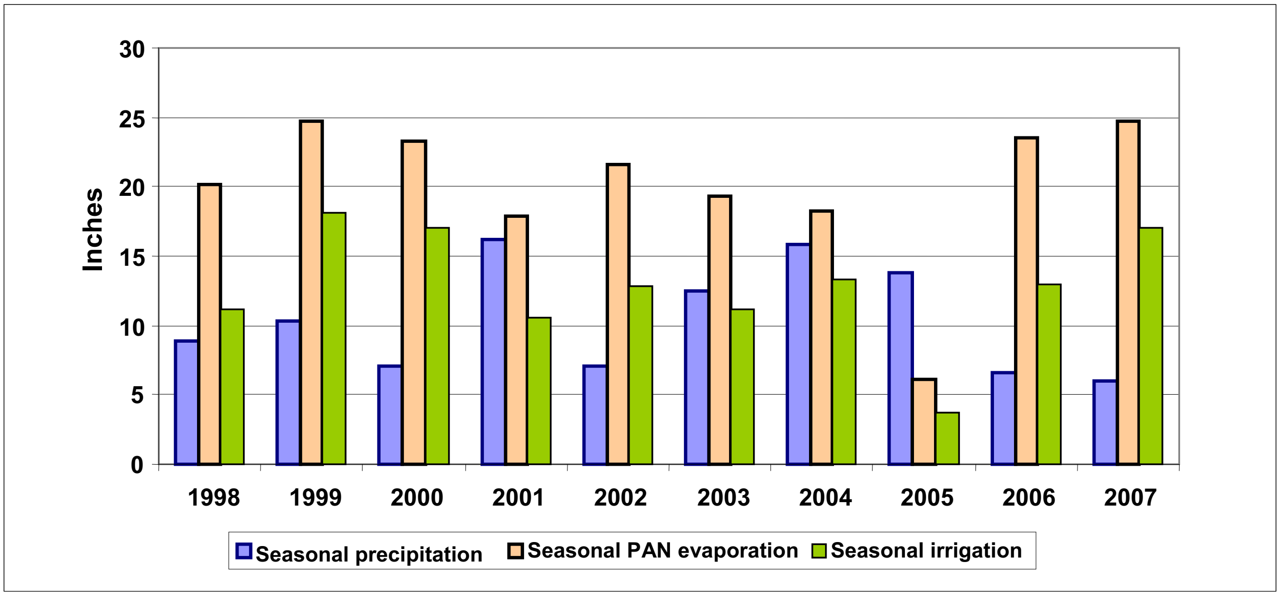

Figure 1. Ten-year seasonal water balance (June through August only), TVREC, Belle Mina, AL. Annual seasonal irrigation is calculated as 90% x seasonal pan evaporation x crop canopy factor.

Yield results from 2006 and 2007 (Table 1; Figure 2) provided benchmarks that clearly indicated the significant ($\alpha = 0.05$) response of various overhead irrigation schedules on seed cotton yield over rainfed treatments. Sprinkler irrigated cotton yields averaged 2.3 bales in 2006 and 3.5 bales in 2007 (Table 1). The highest yielding sprinkler treatments in both seasons were 100 and 125% of pan evaporation (adjusted to crop canopy percent), resulting in approximately 3.0 and 4 bales per acre in 2006 and 2007, respectively. Similar cotton yield responses to irrigation under rainfed conditions were reported in several studies (Camp et al., 1994; Camp et al., 1997; Bronson et al., 2001; Pringle and Martin 2003; Curtis et al., 2004; Sorensen et al., 2004; Balkcom et al. 2006; Kalfountzos et al., 2007; Balkcom et al. 2007). However, other studies reported the absence of response to irrigation in cotton and attributed that to root growth restriction by soil compaction or insufficient irrigation (Bauer et al., 1997; Camp et al., 1997; Camp et al., 1999). The increased sprinkler irrigated yields in 2007 season was most likely due to the change in the irrigation threshold used to trigger irrigation events. In 2007, soil moisture depletion, estimated by daily pan evaporation, was allowed to reach 0.3 inch before an irrigation event was scheduled, while in 2006 irrigation events occurred once estimated soil moisture depletion reached 0.1 inch. The larger soil moisture depletion in 2007 resulted in less frequent, but beneficial deeper irrigations (Figure 3).

Table 1. Effect of different sprinkler irrigation treatments on cotton yield.

	2006		2007	
Treatment	**Seed Cotton (lb/acre)***	**Bales (bales/acre)**	**Seed Cotton (lb/acre)***	**Bales (bales/acre)**
125% pan evaporation x canopy cover factor	**3703.9[a]**	**2.9**	**4612.1[a]**	**3.9**
100% pan evaporation x canopy cover factor	**3520.4[a]**	**2.8**	**4692.1[a]**	**4.0**
75% pan evaporation x canopy cover factor	**2748.2[b]**	**2.2**	**4436.5[a]**	**3.8**
50% pan evaporation x canopy cover factor	**2491.0[cb]**	**2.0**	**3969.6[b]**	**3.4**
25% pan evaporation x canopy cover factor	**2098.0[c]**	**1.7**	**2612.5[c]**	**2.2**
0% pan evaporation (rainfed)	**1492.3[d]**	**1.2**	**1151.3[d]**	**1.0**

***Different superscripts denote statistical difference (α = 0.05). Turnout in 2006 and 2007 were 38% and 41%, respectively.**

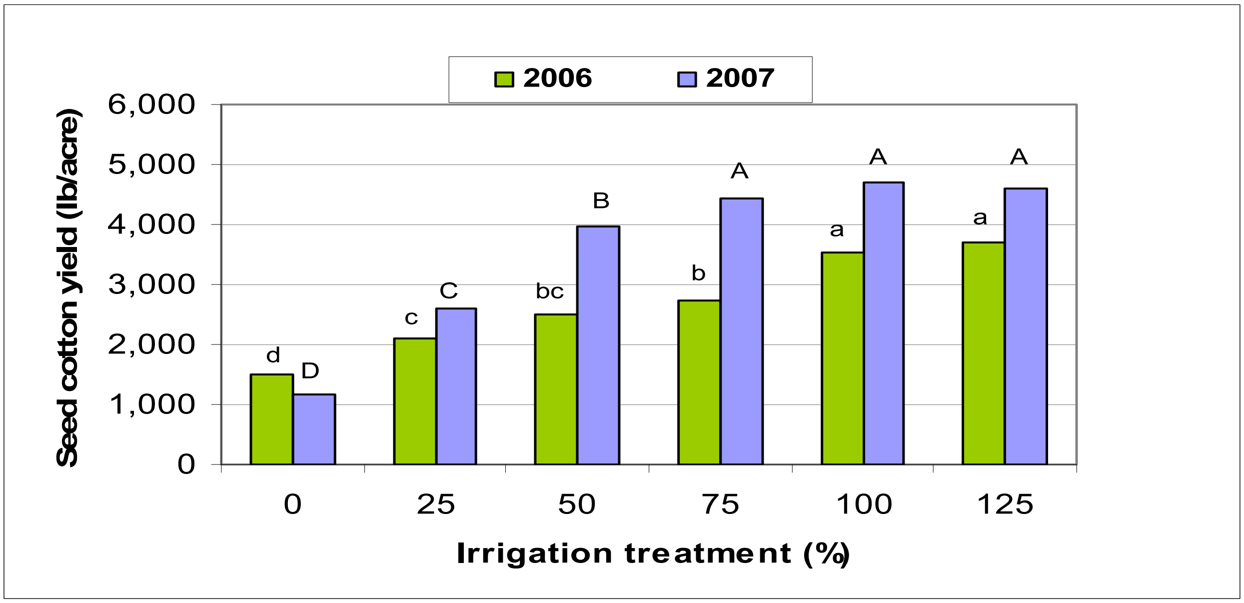

Figure 2. Precision sprinkler irrigation cotton trials, lb/acre, 2006 and 2007. Different letters denote statistical difference ($\alpha = 0.05$) within a year.

Table 2 and Figure 3 revealed that although nearly identical seasonal depths of irrigation were applied in 2006 and 2007 (approximately 20 inches for both 100% irrigation treatments), almost 100 irrigations were required out of the 111-day growing season in 2006 versus only 52 irrigations out of the 97-day growing season in 2007 because of the different irrigation management. Figure 3 shows the resulting irrigation schedule for the 100% treatment using the 2006 and 2007 irrigation set points or thresholds. The observed two-year result was less frequent, but heavier irrigation events in 2007. Marked yield improvement in 2007 suggests the higher allowable depletion management is beneficial because of more efficient water use. Although the two irrigation managements were not replicated across each season to obtain a verifiable cause-and-effect, the two growing seasons were similar enough to draw strong inferences about the irrigation management used during these two drought years.

Table 2. **Total irrigation amounts for 2006 and 2007, sprinkler scheduling trials.**

Treatment	Irrigation depth (inch)	
	2006	2007
125% pan evaporation x canopy cover factor	25.17	24.42
100% pan evaporation x canopy cover factor	20.44	19.31
75% pan evaporation x canopy cover factor	15.24	14.71
50% pan evaporation x canopy cover factor	10.07	9.63
25% pan evaporation x canopy cover factor	4.87	4.29
0% pan evaporation (rainfed)	0.00	0.00

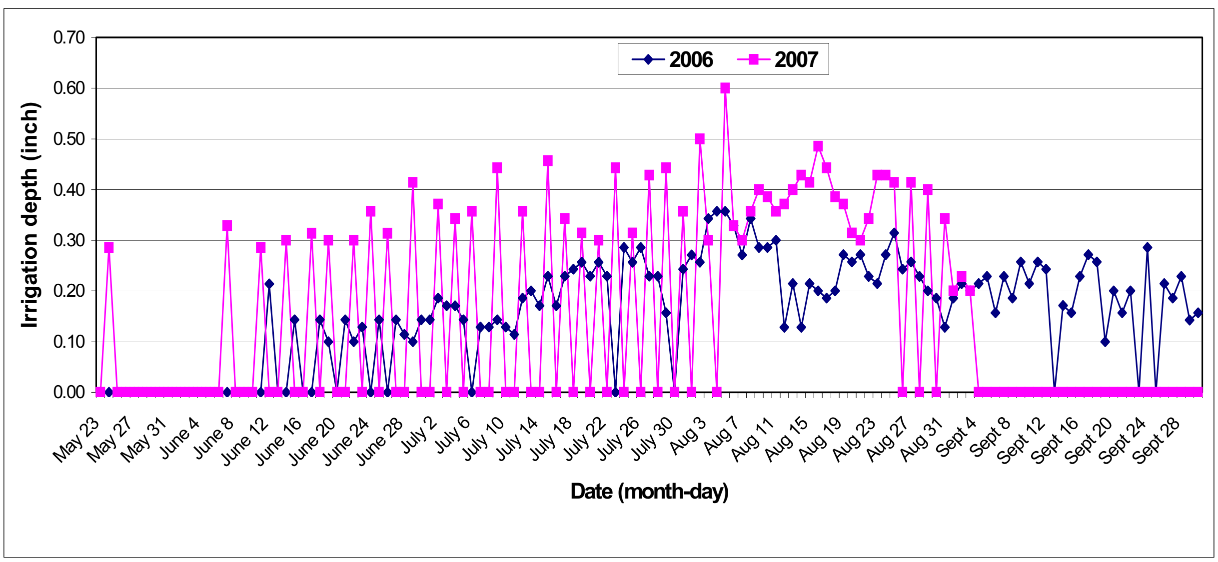

Figure 3. Daily irrigation record for 100% irrigation treatment, sprinkler irrigation trials, TVREC, Belle Mina, AL, 2006-2007.

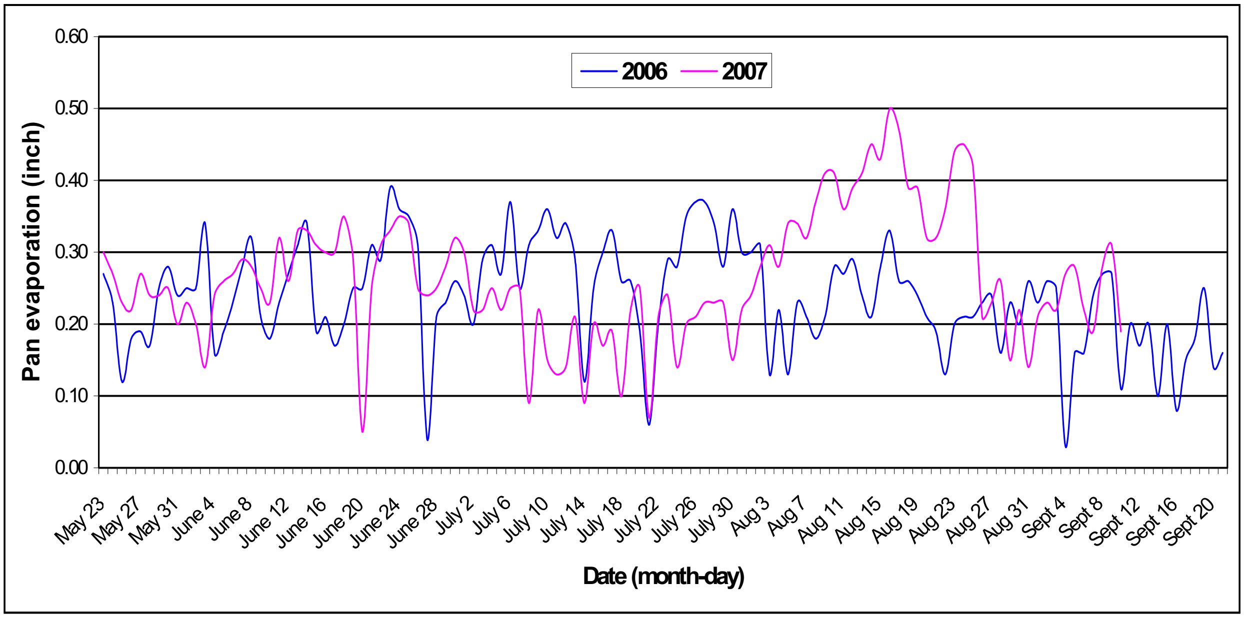

Figure 4. Daily PAN evaporation during growing season, TVREC, Belle Mina, AL, 2006-2007.

Figure 4 illustrates the differences in daily pan evaporation between 2006 and 2007 growing seasons that, along with changes in irrigation management, may also have influenced seasonal yield differences. Daily PAN evaporation was similar in 2006 and 2007, except for the months of July and August. Higher pan evaporation was observed in July 2006 compared to July 2007, with the opposite observed in August of both years. Since July is the peak flowering time in Tennessee Valley, it is possible that the higher evaporation combined with shallow irrigation in 2006 decreased flower setting and thus cotton yield. Guinn and Mauney (1984a, 1984b) reported that water deficit during cotton flowering decreased flower production and yield.

Summary and conclusions

Five sprinkler irrigation treatments significantly increased seed cotton yield in the Tennessee Valley region during two years of drought. The highest yields were obtained at 100 and 125% irrigation treatments in both seasons, resulting in approximately 3.0 and 4 bales per acre in 2006 and 2007, respectively. Although irrigation management was changed over the two-year study, the two back-to-back growing seasons were similar enough to draw strong inferences regarding the yield benefits of less frequent, deeper irrigations during low rainfall years. Overall results indicate that cotton producers in this region with adequate irrigation facilities have the potential to realize significant yield gains over rainfed cotton. A third season of this study is currently underway to corroborate these findings across a wider range of seasonal rainfall and temperature conditions.

Acknowledgements

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How do you obtain necessary funding for an irrigation audit program when water is in abundance?

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Abstract. *The Grand Valley of Western Colorado is flush with irrigation water. The Water Rights of Grand Valley irrigators prior to 1922 account for 2260.28 cubic feet per second (close to 900 thousand acre-feet per 200 day growing season. This is more than adequate for the needs of the Grand Valley(even if the lower states dry up). Due to the abundance of water and the "use it or lose it" attitudes of the area's population, obtaining local, state and federal funds for water conservation programs is nearly impossible. This paper explains why an irrigation audit program in the Grand Valley of Western Colorado is difficult to fund and the problems resulting from a lack of such a program. Background information and data are provided.*

Keywords.

Grand Valley, Colorado, Mesa County, Grand Junction, Colorado River, Gunnison River, Ute Water Conservancy, Palisade Water, Clifton Water, City of Grand Junction, water conservation, funding, Colorado Water Conservation Board, Bureau of Reclamation, water rights, selenium, salt loading, run pumps, deep percolation, salinity loading.

Introduction.

The Grand Valley is a populated valley approximately 30 miles (48 km) long and 5 miles (8 km) wide, located along the Colorado River in Mesa County in western Colorado. The valley contains the city of Grand Junction, as well as the smaller communities of Fruita, Orchard Mesa, Clifton and Palisade.

Six irrigation companies provide raw water for the Grand Valley. [1] In 2007 they diverted 1,648,985 acre-feet of water from the Colorado River. The 982,964 acre-feet diverted for the production of electricity or run pumps, was returned to the river. The remaining 666,021 acre-feet was diverted for irrigation or domestic use. [2]

Four water providers (City of Grand Junction, Clifton Water, Palisade Water and Ute Conservancy District) serve the domestic needs of the residents and businesses.[3] As a result of state-wide drought conditions during the 2001-2002 Water Year, the Grand Valley domestic water providers drafted a response plan in case domestic water supplies were threatened.[4] Their water delivery systems are joined to permit the sharing of water in case of drought. They also developed a tiered pricing schedule to be implemented when their water supplies are threatened.

[1] http://www.irrigationprovidersgv.org/
[2] Information provided by Rham Dan Khalsa, Bureau of Reclamation, Western Colorado Area Office.
[3] http://www.thedripwebsite.com/
[4] http://www.thedripwebsite.com/PDF/DroughtResponsePlanApril2003.pdf

The Concept.

Improper irrigation in the Grand Valley is an issue documented by several years of irrigation audits conducted by Mesa County Colorado State University Extension staff. [5]

Table 1. Grand Valley Irrigation Audit results for 2005 through 2008

Year	Acres Audited	Water Savings [6]	
		Gallons	**Acre-Feet** [7]
2005	18.7	14,015,281	43.01
2006	28.8	21,585,032	66.24
2007	27	20,235,968	62.10
2008	23.5	17,612,787	54.05
Total	98	73,449,069	225.40

It is estimated that 7.6 square miles [8] or 4,864 acres of the Grand Valley consists of high water-using landscapes. If the water application on all 4,864 acres was reduced by 40% [9], a savings of 11,187 acre feet or over 3.6 billion gallons of water per year would be expected. As the population of Mesa County, Colorado increases from 134,189 [10] to an estimated population of 209,628 in 2020 [11] and 224,820 by 2025 (92.3% growth from 2000), this amount of landscaping is likely to double [12] and the water needs of the Grand Valley significantly increase.

An irrigation audit program in the Grand Valley would help reduce per capita water use, help prevent future water restrictions, and ensure adequate water is available for domestic, agricultural and industrial uses.

The benefits of a Grand Valley irrigation audit program include:

- The reduction of water use and fewer dollars spent on irrigation water
- The reduction of runoff and associated contamination of the Colorado River with pesticides, fertilizers, etc.
- The reduction of deep percolation
- The reduction of fertilizer and chemical requirements to maintain the lawn
- The reduction of insect and disease problems

[5] Irrigation Audit reports 2005 – 2008 at http://WesternSlopeTurf.org
[6] The estimates provided are based on an annual ETo of 49 inches and sprinkler system efficiency of 70%.
[7] An acre foot of water contains 325,861 gallons.
[8] Personal conversation with Rick Corsi, Mesa County GIS Specialist
[9] Irrigation audit programs can reduce the water use by an average of 40%.
[10] 2006 estimate http://quickfacts.census.gov/qfd/states/08/08077.html
[11] http://www.mesacounty.us/administration/adminpopulationdata.aspx
[12] http://www.mesacounty.us/about_mesa_county.aspx

- The improvement of irrigation system performance
- The improvement of landscape appearance; fewer saturated and dry spots
- The reduction of salinity and selenium problems for down-stream users

Salts flushed into the river by excessive irrigation cause extensive economic impacts to water users in the lower Colorado River basin. Estimates by the US Bureau of Reclamation indicate these costs exceed $300 million annually to include reduced crop yields, limiting the types of crops that can be grown, plumbing and appliance corrosion, and high water treatment costs. [13]

Over-irrigation flushes 580,000 tons of salt into the Colorado River from the Grand Valley soils each year. [14] These salts negatively impact plant and animal health throughout the Colorado River basin. Proper irrigation of lawns significantly reduces deep percolation and flushing of salts into the river system.

Selenium is a trace element widely found in the Mancos shale soils that underlie much of the populated valleys of Western Colorado. "Selenium is a trace metal that bioaccumulates in aquatic food chains and has been known to cause reproductive failure, deformities, and other adverse impacts in birds and fish, including some threatened and endangered fish species." [15] Drainage from the Uncompahgre Project and the Grand Valley may account for as much as 75% of the selenium load to the Colorado River near the Colorado-Utah line. [16]

As population growth occurs, the need to develop previously un-irrigated Mancos soils for new housing, shopping malls, and industries will result in increasing problems with higher levels of salt and selenium being flushed into the Colorado River.

The Belief.

Many who live in the Grand Valley believe irrigation and treated water will always be available. There are a number of reasons for this.

Eighty percent of Colorado's population resides on the East Slope of the Continental Divide and 80 percent of the water is on the West Slope. [17]

The canals are kept full during the irrigation season to ensure those at the end of the canal always have access to their full allotment. Some of these canals are 12 feet deep and all run at full flow

[13] Sonja Chavez de Baca, Coordination, Gunnison Basin & Grand Valley Selenium Task Force. Letter dtd September 18, 2008 to Barbara Sharrow, Bureau of Land Management, Montrose, CO.
[14] Colorado River Salinity Control Program, Grand Valley Colorado, Bureau of Reclamation Report http://www.usbr.gov/dataweb/html/grandvalley2.html
[15] USGS Publication "Characterization of selenium concentrations and loads in select tributaries to the Colorado River in the Grand Valley, western Colorado"
[16] http://www.seleniumtaskforce.org/indexold2.html
[17] Eric Hecox, Manager, Interbasin Compact Process, Department of Natural Resources, September 2, 2008. Memorandum to the Basin roundtable Chairs and IBCC Members.

from the first of April to mid-October. These canals run by major roads throughout valley giving area citizens "proof" the availability of water is not and never will be a problem.

During the 2002 drought only 6.2 million acre-feet flowed down the Colorado. By mid-July the Ute Water Conservancy District's primary water source and the Lower Molina power plant were out of water. Even during this period the domestic water providers did not implement drought restrictions. This provides further "proof" the Grand Valley does not need to conserve water.

"If we don't use it, we'll lose it" and "If we don't use it, Denver or California will take it" are common sayings of valley residents. Even with the many negatives related to excess irrigation, as delineated previously, this engrained mind-set further compounds efforts to implement water conservation efforts.

The cost of water in the Grand Valley is relatively inexpensive. Raw water delivered through the irrigation canal system ranges anywhere from $77 for 7.8 million gallons ($3.35 per acre foot), to $212 for 1.3 million gallons ($53 per acre foot) depending on the irrigation company.

Homeowner Associations in western Colorado provide raw water to home sites for as little as $75 a year for all the water the resident can use. As a result of the low cost, western Colorado residents with access to raw irrigation water do not consider water conservation important. Why spend the money to upgrade your irrigation system and reduce deep percolation when water is so inexpensive?

Even treated water is relatively inexpensive. Domestic treated water costs as little as $3.00 for one-thousand gallons [18] as compared to $5.93 per thousand gallons of water for the eastern Colorado city of Arvada. [19]

Even if the lower Colorado River states called for more water, the water rights held by the Grand Valley water providers prior to 1922 (Table 2) would continue to provide for the water needs of the Grand Valley. These rights are for 897 thousand acre-feet of water, more than adequate for the needs of the valley. [20] With this amount of water guaranteed for the Grand Valley, why should the farmers and residents of the area conserve water?

Table 2. Water Rights in the Grand Valley by Priority.

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[18] http://www.utewater.org/rates.htm
[19] http://www.denverwater.org/rateinfo/pdf/frontrange_09.pdf
[20] Based on a 200 day irrigation season and 2260.28 cfs water rights.

Year	Agency	cfs [21]
1882	Grand Valley Irrigation Company	520.81
1889	Palisade Irrigation District	80
1898	Orchard Mesa Irrigation District	10.2
1903	Mesa County Irrigation District	40
1907	Orchard Mesa Irrigation District	450
1908	Grand Valley Water Users' Assoc.	730
1908	Bureau of Reclamation	400
1914	Grand Valley Irrigation Company	119.47
1918	Palisade Irrigation District	23.5
Total		**2260.28**

Why aren't funds available for a Grand Valley irrigation audit program?

With the exception of the City of Grand Junction, other water providers in the Grand Valley see no benefit in supporting water conservation programs. The City of Grand Junction has helped fund this irrigation audit program during the last three years. Requests for funds from Mesa County to support the Grand Valley irrigation audit program have been denied. [22]

Monies are available from the Colorado Water Conservation Board's (CWCB) Water Efficiency Grant Program (established through HB 05-1254) for an irrigation audit program. These grants require a 25% match which Grand Valley water providers and governmental entities are not willing to provide. [23] In addition, CWCB requires proof of water savings. [24]

Meters have never been installed at raw water points of delivery. Since much of the Grand Valley is irrigated with raw water, providing the CWCB their required proof of water savings, is not possible. Treated water is metered, but many of these sites have dual systems. These systems are set up to use treated as well as raw water for irrigation.

In addition, a water provider must first develop a water conservation plan and have it approved by CWCB in order to be eligible to receive a grant from CWCB for water conservation purposes. Since a water shortage in the Grand Valley is not an issue, why should these water providers, domestic or raw, spend the money and devote the time to develop such a plan?

The Bureau of Reclamation grant program also has restrictions the Grand Valley can't fulfill. The "*Water 2025* Challenge Grant Selection Criteria" requires identifying the "direct benefits of

[21] Cubic feet per second
[22] See the annual irrigation audit reports at http://WesternSlopeTurf.org for funding partners
[23] CWCB GUIDELINES FOR THE WATER EFFICIENCY GRANT PROGRAM Revised November 14, 2006
[24] Personal phone call with Veva McCaig, CWCB.

the proposed work, i.e. acre-feet of water conserved" [25] which as indicated previously is not possible.

Conclusion.

On July 31st 2008 the Irrigation Audit program in the Grand Valley of western Colorado was discontinued due to a lack of financial support.

[25] http://www.usbr.gov/water2025/criteria.html

THE "SUPER DITCH": A TEST OF COOPERATION FOR COLORADO FARMERS

MaryLou Smith[1]
Jay Winner[2]

ABSTRACT

Colorado's Statewide Water Supply Initiative (SWSI) shows that the state has only enough water to meet about 70% of its needs by the year 2030, with most of the gap occurring in the front range urban areas of the state. The SWSI report forecasts that a majority of the water needed for cities will transition from agriculture, which currently uses more than 80% of the state's water. Agricultural communities are concerned what such a transition could mean to their viability. The second phase of SWSI investigated such alternatives to the traditional "buy and dry" as interruptible supply agreements, rotational fallowing leases, water banks and cropping changes.

The Lower Arkansas Valley Water Conservancy District (LAVWCD), inspired by the Palo Verde Irrigation District in California, set about to see if ditch companies in the lower Arkansas Valley might agree to form a "super ditch" whereby they would cooperatively pool part of their water to gain operational flexibility and make it available for lease to cities. By working together in a rotational fallowing scheme, they conceptualize that they will have greater bargaining power. Perhaps by converting part of their land from growing hay or corn to growing "water" they could actually benefit financially, and keep their agricultural communities viable.

Those attempting to transform the concept into reality are finding that "the devil is in the details." This paper is presented as a sociological case study in the making. The authors detail the steps Super Ditch organizers went through to determine if their scheme is feasible, as well as the hoops they are now going through to try to bring it to fruition.

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BACKGROUND

LAVWCD, formed in 2002, encompasses five counties from Pueblo to the Kansas state line. While most conservancy districts were formed to *develop* water resources, the Lower Arkansas District was formed to *protect* water resources. Its mission is to insure the continued availability of water resources for long term economic viability of the Lower Arkansas Valley. What is threatening these water resources?

Buy and Dry

Since 1950, more than 60,000 irrigated acres have been sold to municipalities—primarily Aurora, Colorado Springs, and Pueblo. 20% of one of the largest canals in the lower basin, the Fort Lyon Canal, was purchased by High Plains, now PureCycle, for transfer to the Colorado Front Range. Temporarily defeated in Colorado water court because of the state's anti-speculation law, PureCycle is poised to move the water off the farms once they have a customer.

For several reasons, permanent transfers, frequently referred to as "buy and dry," have historically been the preferred mechanism for municipalities to transfer water from agriculture. Owning the water allows municipalities to enjoy the appreciation of its value as an asset, but more importantly gives them certainty and control of the supply. These transfers carry a lower risk than developing new trans-basin supplies—an option which has become highly difficult in recent years given environmental and other concerns and with curtailment of federal funds for such projects.

However, despite some municipal mitigation in the form of revegetation and payment-in-lieu-of taxes to schools and other taxing districts, these "buy and dry" deals have contributed to economic difficulty, if not disaster, for the rural communities from which the water was transferred. Those irrigators selling their water enjoy immediate benefits and options for use of cash, but the community and region suffer overall economic loss.

Politically Motivated Alternatives to Buy and Dry

At this point, cities are politically motivated to seek water deals other than "buy and dry" and have begun to think in that direction. The City of Aurora, for instance, in 2004 negotiated a deal with shareholders of the Rocky Mountain High Line Canal, under the terms of which farmers would lease part of their water up to 3 out of 10 years in an "interruptible supply" arrangement to help Aurora meet demand in drought years. Farmers, many of whom could not have realistically farmed in such a dry year anyway, reaped cash benefits which kept them and their bankers happy. More than 80% of eligible farmers signed on to participate, and most of those who did not wish they had.

With the first SWSI report projecting that another 72,000 acres would likely be transferred from Arkansas Basin agriculture by 2030 (and commensurately large amounts from the state's South Platte Basin), the state commissioned a SWSI 2 Technical Roundtable to investigate ways that water could be transferred without permanently drying up those irrigated acres. Their report, released in November 2007, details benefits and shortcomings of such alternatives to buy and dry as:

- interruptible supply agreements
- long term rotational fallowing agreements
- water banks
- reduced agricultural consumptive use without reducing return flow (through efficiencies or cropping changes)
- purchase-leaseback (a form of delayed buy and dry)

Current Investigations into Buy and Dry Alternatives

A number of efforts are currently underway in Colorado related to the issue of "ag to urban water transfers." A committee of the Arkansas Basin Roundtable has brought together urbanites and agricultural folks to hammer out ways to "get it right" if water is to be transferred from agricultural to urban uses.

Colorado State University's Colorado Water Institute is working with the Colorado Ag Water Alliance to investigate ways water can be conserved in agricultural practices to provide additional water for cities without infringing on water rights of downstream users or jeopardizing Colorado's compact with Kansas.[3]

The City of Parker has contracted with researchers at Colorado State University to study cropping changes such as deficit irrigation and different crops to determine if farmers can in effect add to their crop mix a new crop called "water." A survey of farmers is being conducted to determine the willingness of farmers to lease water under a variety of circumstances.

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[3] Of particular import is that Colorado water law allows a farmer to "save" from only the CU portion of water diverted—the crop's consumptive use. For example, a farmer with 30 acres of corn to irrigate and a decree for 1000 acre feet of water cannot use any more water than a farmer with 30 acres of corn to irrigate and a decree for 100 acre feet of water. The first farmer can divert the full decree, but every drop not consumptively used he must "give back" as return flow.

THE SUPER DITCH

The Super Ditch is undoubtedly the most talked about alternative being investigated in Colorado for moving water from agriculture to cities without drying up agricultural lands.

What Is the Super Ditch?

The Super Ditch is not a ditch at all. Instead, it is conceptualized to be a company formed by shareholders of multiple ditch companies who would lease water to municipalities by fallowing a portion of their land in a rotating fashion. Specifically, irrigators who own shares in participating ditch companies would voluntarily offer to fallow part of their land and lease the corresponding water for other uses. Municipalities and other users would lease the water instead of purchasing it outright. The idea is for shareholders to pool their water, lease it, make money, then distribute the money to shareholders through dividends, providing an additional, predictable revenue source which farmers could use for farm improvements, debt reduction, new equipment, or capital for launching new agri-business endeavors.

LAVWCD would not be the administrator of the Super Ditch; they are only serving as the instigator to get it organized. District funds totaling close to $600,000 have been expended for engineering and economic studies as well as legal research to determine the feasibility of the concept

Roots

Peter Nichols is one of the prime characters in the Super Ditch story. He helped conceptualize it and he is helping move it forward. Nichols is one of the authors of *Water and Growth in Colorado—A Review of Legal and Policy Issues,* published in 2001 by the Natural Resources Law Center at the University of Colorado School of Law. In this book Nichols said “moving water from the agricultural to the urban sector has the potential to solve projected municipal water shortages” but, he said, there are a host of difficult legal and policy issues to be considered, including the effect on the viability of rural communities. He proposed that temporary transfer mechanisms such as leases, dry year options and water banking might provide municipalities with drought protection while maintaining rural economies.

Now, six years later, Nichols is deep into a major experiment to see if his theory will “hold water.” Hired as special counsel to the LAVWCD, Nichols is part of the Super Ditch team made up of District personnel as well as engineering and economic consultants, actively working with farmers to work out the myriad of questions and issues which must be answered and resolved if the Super Ditch is to come to fruition.

The District began talking about alternatives to buy and dry immediately upon its 2002 formation. But others had been thinking along the same lines for some time. Bill Hancock knows the farmers and ranchers of the lower Arkansas Valley. He was lured to LAVWCD to assist with the Super Ditch effort, after 38 years working in Rocky Ford for Colorado State University Extension Service. Hancock remembers that even as far back as the mid-90's, right after the permanent "buy and dry" sale of the Rocky Ford Ditch, [4] extension service was trying to plant a seed for farmers to consider interruptible supply as an alternative to buy and dry.

First Steps

Identification of Potential Participating Ditches The first concrete task LAVWCD undertook was to contract with an engineering firm to investigate how much water might potentially be available for lease and from which ditch companies. Diversion and stream flow data from sixteen ditches between Pueblo and John Martin Reservoirs was collected, and seven ditches were subsequently found to have sufficient supplies to be carried forward in engineering and economic studies. Elimination of ditches from consideration was for a variety of reasons, including negligible potential yield because of large previous transfers, limited water rights, or dedication of water as an augmentation supply. Other ditches were eliminated because of head gate issues or extreme exchange concerns.

Trip to California "Seeing is believing" has long been a motto employed by extension service agents working with agriculturalists. Demonstration projects, models, and field trips enable farmers to get a hands-on feel for how something works. In keeping with this approach, LAVWCD organized an early 2007 trip to California so that irrigators could see for themselves a rotational fallowing arrangement undertaken by the Palo Verde Irrigation District (PVID) with Metropolitan Water District (MWD). Irrigators had first heard about the Palo Verde deal when Ed Smith, general manager of PVID, had spoken about it at an April, 2006 workshop funded by LAVWCD in cooperation with several lower basin ditch companies. John Wilkens-Wells, a sociologist from Colorado State University's Sociology Water Lab organized the workshop, which was titled "Innovative Approaches to Water Leasing and Canal Company Cooperation in Face of Municipal Demands for Agricultural Water Supplies."

Smith's picture of how Palo Verde farmers were improving their financial situation while supplying water to Los Angeles and other Southern California coastal communities intrigued the District—and the ditch companies. The District

[4] Rocky Ford Ditch should not be confused with the Rocky Ford High Line Canal discussed elsewhere.

funded a delegation of representatives from the seven selected ditch companies to travel to California and meet with Smith and his PVID shareholders.

Delegates came back to Colorado variously "pumped up" but also aware of the considerable obstacles which stood between them and realizing a similar deal in the lower Arkansas. Unlike the Palo Verde circumstance in which there was one water right and one ditch company, the Super Ditch would be made up of seven ditch companies and many different water rights. Exemplary of the dozens of questions the delegation came back with were "how can equity be achieved when point of diversion, decree date, and yield all affect the relative value of water to be provided from various ditches?" Can ditch companies not known for having a tradition of cooperation put aside their differences to make this work? Are farmers willing to commit to a lease as long as 40 years? Are municipalities willing to commit to a lease as short as 40 years? Will the state engineer allow farmers to fallow their least productive lands? Can they get "credit" for fallowing the part of their land which has historically taken up water non-beneficially?

Forming a Steering Committee Shortly after the California trip, the District invited delegates and other interested parties to convene to discuss the experience, and to determine if there was collective will to proceed with the Super Ditch. Despite misgivings on the part of some, there was enough enthusiasm that the District asked each of the seven ditch companies to appoint two representatives to a steering committee which would either move the concept forward or determine it was not feasible.

CONSIDERATIONS

Organization

Steering Committee meetings have provided opportunity for ditch company representatives to hear reports of further study engaged in by the engineering and economic consultants hired by LAVWCD and to discuss a variety of issues and concerns, including recommendations by legal counsel as to what legal form the Super Ditch might best take. Steering Committee members are currently meeting to make decisions about constitution of its governing board as well as preliminary bylaws and articles of incorporation which would later be adopted by the governing board. Though decisions about board constitution have not yet been made, it is clear that shareholders from participating ditch companies will be well-represented on the Super Ditch governing board, which will be tasked with protecting the interests of the shareholders and indirectly the lower Ark valley. It will be the governing board, not LAVWCD who will make critical decisions such as whether out of basin entities will be allowed to lease water from the Super Ditch.

Forming the organization before all the pieces of the puzzle are in place has been difficult—a sort of "chicken and egg" dilemma. As one steering committee member said "We can't work out the final details until we know who the players will be. But the players aren't willing to commit until they know the final details." Legal counsel has recommended an approach whereby potential shareholders can take two steps, the first to pledge willingness to participate contingent on final details, the second to actually commit. Even still, it appears that participating stakeholders don't have to sign a particular lease, even after the organization is put together, if they don't like the price being offered.

Ditch Company Bylaws

As a direct reaction to earlier buy and dry deals, some ditch companies have adopted clauses in their bylaws which limit the use of water to lands served directly by the ditch. This clause is frequently referred to in Colorado as "catlinization" of the bylaws, because the first ditch company to enact such a clause was the Catlin Ditch. All but two of the ditch companies being considered for the Super Ditch have this clause, which is seen to be an obstacle for shareholders' participation in the Super Ditch. Ditch companies appear to be reticent to change their bylaws to allow their shareholders to participate in the Super Ditch until all the details are clear, yet details cannot be clear until it is known which ditch companies will allow their shareholders to participate. Again, a chicken and egg dilemma.

Laterals

Another consideration has to do with how a ditch company can ascertain that everyone on the ditch stays whole, assuming that since Super Ditch participation will be voluntary on behalf of each shareholder some shareholders may not be participating. (In fact, for planning purposes, it has been assumed that only 65-85% of shareholders would participate.) Each ditch company will still have to maintain its headgates in order to deliver water to those not participating. On the surface, this would not seem to be a problem, since each participating irrigator would be fallowing only a portion of their land at any given time. But from a practical standpoint, having enough "push" remaining in the laterals could be problematic if some laterals participate and some do not. The Rocky Mountain High Line Canal resolved this issue when they signed the interruptible supply deal with the City of Aurora by requiring that a whole lateral be either "in or out" even though that meant some folks who wanted to participate weren't able to. Indeed, conversations with various steering committee members seems to indicate they are concerned about lack of measurement devices at the lateral level that would allow for proper measurement if even a whole lateral chooses to participate.

Storage, Transmission, Water Quality

Storage vessels to hold water from year to year and a pipeline(s) to take water at a point downstream and send it upstream are important considerations in making the Super Ditch work optimally. It is generally understood that those leasing the water would be responsible for constructing a pipeline, and in fact one potential user, Pikes Peak Regional Water Authority is already undertaking a pipeline feasibility study.

Conveyance losses/exchange factors and water quality all vary from ditch to ditch. Those shareholders low on the river have less "paper water" to contribute because of exchange factors figured due to conveyance losses. In addition, those lower on the river have lower quality water which will require more expensive treatment by municipalities. Though on the surface it would appear that their water quality should decrease their lease revenue compared to revenue from irrigators providing water from points further upstream, the point has been made that it is all those folks upstream using the water and sending it along downstream whose use has caused the water quality to worsen!

Utilizing storage will increase firm yield—and maximize revenues. Storage will also help smooth out year to year variation in demand for the water. As one steering committee member said, "With storage, you can sell wet year water in a dry year." One of three storage options in the system is Timber Lake which holds 38,000AF and has been virtually empty the past nine years.

Which Land to Fallow?

Some steering committee members dislike the term fallowing. They point out that the terminology used should be "not irrigating." They contend that an ideal piece of land to fulfill the "fallowing" qualifications under the Super Ditch plan may be an old hay crop you don't water—but from which you can still get a first cutting. It's not exactly fallowed; it's just not irrigated! But others bring up the issue of sub-irrigation that could be an issue with deep rooted crops like alfalfa. If you are dry land farming fallowed ground, how do you prove it isn't taking up any subsurface water? Would participants have to kill deep-rooted alfalfa?

Another question relates to whether when a participant agrees to fallow or not irrigate 25% of his land, can it be the same land every year or does he have to rotate to new ground? This brings up the wish of some to take out their worst land permanently, a practice with which the state engineer might have problems, especially if that land was not earlier consuming much water anyway. Complicating the situation is that in some cases permanently fallowing certain portions of land could improve water quality. The law does not currently give credit for this side benefit, however.

Collective Benefits

Why shouldn't individual irrigators and/or ditch companies make their own leasing arrangements with municipalities? The Rocky Mountain High Line Ditch/City of Aurora deal referred to above is, indeed, a successful example of such. The Super Ditch model, however, allows for the possibility of greater bargaining power than if individual ditch companies are played against each other by municipalities attempting to get the best price. Another factor is that more irrigated land can be included in the arrangement when multiple ditches work together, because each ditch has some advantages to bring to the table. Some ditches have better water quality, some have more senior rights, others have most ready access to storage and piping facilities. A third advantage is the opportunity to apply economies of scale to high transaction costs for both lessor and lessee.

Benefits accruing to municipalities from a Super Ditch lease include drought protection; minimal environmental impact; high reliability, since most irrigators have senior water rights which deliver even in dry years; avoidance of capital costs; and not having to deal with the uncertainties of developing new supplies or negotiating transmountain diversions. In addition, economic reports show that municipalities can often do better financially by leasing over buying. The downside has to do with not having control of the water, not owning it as an asset, and the chance that the supplies might not be available after the initial or subsequent 40 year lease.[5]

Rural Community Viability

By annually rotating the impact across the region and across the involved ditch companies, Lower Arkansas Basin farm economy would be expected to stay more or less "as is" under the Super Ditch. Lease revenues would generate much needed financial infusions into the local agricultural economy, resulting in an overall beneficial impact. The only adverse impacts which might accrue would be to those handling farm output, such as custom harvesters and local elevators. It is generally assumed that Super Ditch leases would prompt an "averaging up" of earnings and income in the lower basin. LAVWCD economic consultants reported that "when compared to straight dry up transfers, leasing shows a $10-$30 million gain for the valley." Providing anecdotal evidence, Ed Smith, manager of Palo Verde Irrigation District reports that Blythe, California, the local town impacted by their lease to MWD, "is looking much perkier these days."

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[5] Bureau of Reclamation leases are typically for 40 years with an option to renew for another 40 years but they typically contain language about having to comply with endangered species situations which may have subsequently come up. This language makes them less certain than the leases being contemplated under the Super Ditch plan.

ISSUES

Dry Year Options

One issue the steering committee has wrestled with is whether pricing should be on a dry year, average year, wet year basis or whether it should be priced without such distinction. Engineering and economic consultants used the tiered approach in their investigations, based on their understanding that the three major municipalities in the basin are looking for dry year supply and would be more likely to pay a premium for it. Other potential lessees, such as the Pikes Peak Regional Water Authority, currently meeting its water needs by drawing down non-renewable groundwater, would be interested in a relatively constant supply year after year. The model built for examination by the steering committee assumed that revenues would be maximized by planning on a mixed portfolio.

Sentiment among the steering committee, however, has leaned away from a tiered approach toward a "take or pay" concept. They want each irrigator to be guaranteed a minimum return year to year, regardless of what kind of year it is. These members insist that cities would be leasing the right to take delivery of the water, whether they need it that particular year or not. "My tractor lease has to get paid no matter if it's a wet year or a dry year!" Some members, on the other hand, believe the tiered system would get them higher overall prices. Here's a sample of the dialogue:

> Herb: *In California, the cities paid for the water every year whether they need it or not.*
> Lee: *But the pricing has to take into consideration whether they need it or not. They will pay a lot more in a dry year.*
> Curtis: *No, they are paying for an insurance policy.*
> Burt: *It's like fire trucks. They have to buy them and have them available whether they use them or not. A farmer's costs don't go down whether it's a wet year or a dry year.*

Another consideration regards how to account for water under a tiered pricing system. One member raised the question, "If the Fort Lyons ditch puts water in storage in a wet year then delivers it in a dry year, is it valued as wet year or dry year water?" Another member stated that if in a wet year a farmer could only get a small amount for his water, he would not want to commit, because he could put his land into "preventative planting" and do better.

Is the Price Right?

Another stumbling block—another of the chicken and egg dilemmas—has to do with pricing. Potential shareholders don't want to commit to the Super Ditch concept until and unless they like the price they can expect to get for their water. But the Super Ditch concept cannot go forward and into pricing negotiations with potential lessees until the organization is formed. Some of the sentiment of farmers can be seen in these comments:

On length of lease "If I am locked into only leasing 30% of my land and committed to a thirty year term, I would have to get big money. 30 years is too long. 5 or 10 years is all I would do." Response from another farmer: "But you can't expect a city to put in a pipeline without a long term commitment."

On percent of land to be fallowed each year, fixed or variable? "Seems like in dry year folks might want to fallow all their ground—since they can't get a crop up anyway." Response from another farmer: "It would be hard to get folks to sign up if they don't know more than year to year how much of their water is to be taken. How do bankers know how much credit for collateral to give you if they don't know how much land you will be leasing year to year?" Another farmer: "The revenue amount should stay level plus inflation year after year to keep your banker happy."

On price "It's hard to propose this whole thing to your ditch company if you don't know what the price is going to be. Farmers aren't going to do this without knowing where they are at. They want to know that each year they can only irrigate X percent of their land and every year they get a check for X amount." And another farmer: "Everybody is going to have to see a check every year to sign on. If it's not any more than I can farm for, then forget it. It has to be a premium over what we get from farming. My commitment and expenses are still there for farming. I am not here for a 1 to 1 trade. I want a 4 to 1 trade. You will have to have damned good returns to get farmers interested."

On needing more particulars One steering committee member put it in most forthright terms. He said "Right now I wouldn't get into this for nothing. People need to have something for every year. You have to sell this to the farmers. You need to start talking money or you're going to lose your potential market."

Super Ditch organizers, realizing the chicken and egg dilemma, decided to ask the economic consultant to draw up some scenarios that would help steering committee members better understand what the possibilities might be, even though it would be impossible to guarantee any particular price.

Pulling together a number of variables to consider, the economic consultant was able to show steering committee members enough to move the organization process forward. Based on what water is selling for on various ditches, and given a proposed lease price of $500 per acre foot in an average year and $750 per acre foot in a dry year, it appears that a typical shareholder would come out better leasing his water through the Super Ditch than either selling it or continuing to farm. Steering committee members agreed that it is important to keep moving on the concept, even given the uncertainty of exactly what price they will get in a given lease.

CONCLUSION

U.S. Senator from Colorado, Wayne Allard, is reputed to have said several years ago, "If you can ever get the farmers in the lower Ark basin to work together, they will make a fortune." Whether or not there is a fortune at the end of the rainbow called the Super Ditch, there is definitely an opportunity worth pursuing. Various members of the steering committee have phrased it this way:

- "This is the best chance we have to get the true value of our water."
- "It's useless to talk dollars at this stage. When they realize there's no one else, the numbers will be a lot higher."
- "This is our one and only chance to get this done."
- "It's not going to be a perfect deal. Every ditch is going to have to give a little."
- " A lot of our board members are in good shape financially so they aren't motivated to see a change. But we have to appeal to their sense of community. We all know what buy and dry does to Main Street."
- "This thing is helping us build relationships between ditches. But it took a trip to California to kick it off."
- "The folks in Palo Verde told us we would have to stay united or they would pick us off one by one. They were right. We have to buck up and make this work or the Front Range is going to pick us off ditch by ditch."

Many people throughout the Arkansas Basin and for that matter all across Colorado are watching to see if Super Ditch organizers will be successful working out the details with farmers (and later with Colorado water court) in order to make what some call a pipe dream a reality. The answer to the question is seen by most to be far more sociological than technical. As Dypak Gyawali, a Nepali engineer and political economist working on water issues as part of the European Commission says, "the most critical need is not for technical solutions, but for socio-political solutions to water problems." And those solutions, to paraphrase Delph Carpenter, prime negotiator on the 1920 Colorado River Compact, will take "time, time, time."

Evaluation of Deficit Irrigation Strategies for Corn

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Abstract. *Competition for water is increasing while a growing world population requires more food production. It is critical to develop and implement efficient deficit irrigation strategies, and to predict the impacts of deficit irrigation on yield. South Dakota State University Management Software was used to simulate center pivot irrigation and corn yield at seven locations across the Great Plains with historical weather data. Thirty irrigation strategies were evaluated across three soil water holding capacities and three pumping rates. Yield ratio was calculated based on a normalized transpiration ratio. Strategies with high water use efficiencies performed well across all treatments and locations. The recommended maximum yield strategy is 30-60-30 (strategies were defined by the minimum available soil water (%) for early, middle, and late season). Recommended deficit strategies are 15-50-0, 0-30-0, and 0-15-0 for minimal, moderate, and severe water restrictions. Annual variation in yield is greatest when water is most limited.*

Keywords. Deficit irrigation, corn, center pivot irrigation, irrigation modeling, irrigation management, water conservation.

Introduction

Competition for water is increasing while a growing world population requires more food production. One study predicts that in the year 2050, there will be an annual water shortage of 640 billion cubic meters (Spears, 2003). Some irrigators are already faced with limited water supplies. Drought in western South Dakota has reduced water supplies for several irrigation projects, and low water flows in the Missouri River have restricted irrigation from the reservoirs in the system. Since irrigation is the largest consumptive use of water in many places, accounting for 65% of the fresh water use in the 22 western states (calculated from USGS, 2000), proper irrigation water management is critical to make the best use of the water available.

As competition for irrigation water supplies becomes greater, it will be necessary for irrigators to optimize the use of the water available to them and reduce the risk of large yield losses. The benefits of scientific irrigation scheduling have been documented (Stegman, 1986; Steele et al., 1994; Steele et al., 1999). Corn yield response to limited irrigation has also been studied (Klocke et al., 2004; Klocke et al., 2007, Lamm et al., 2008). However, specific deficit strategies have not been developed for use with center pivot management software. English et al. (2002) calls for "more detailed models of the relationships between applied water, crop production, and irrigation efficiency."

Center pivot irrigation became popular in the 1960s, and now accounts for nearly 75% of sprinkler irrigation in the United States (Werner, 2000). Center pivots provide a high-efficiency and low-labor alternative to surface irrigation. South Dakota State University (SDSU) Management Software was developed by Oswald (2006) to account for the complexities of center pivot irrigation while simulating irrigation water use and estimating yields for various crops. Heeren (2008) modified the software with an improved ET routine and yield model.

Using the SDSU Management Software, the objectives of this research were, 1) to develop a method for evaluating deficit irrigation strategies; 2) to recommend deficit and full irrigation strategies for various locations, soil types, and system capacities; and 3) to increase understanding of yield-water relationships in these situations.

Methods

SDSU Management Software, developed by Oswald (2006) and modified by Heeren (2008), was used to simulate center pivot irrigation and corn yield. Simulations were performed on seven locations across the Great Plains, for 16 to 24 years of historical weather data for each location, 30 irrigation strategies, three soil types, and three pumping rates. A total of 40,000 simulations were performed. Output files included data for ET, soil water levels, irrigation amounts, and yield.

The SDSU Management Software was set up to simulate a center pivot irrigator with an effective length of 418 meters (1370 feet) , covering 55 hectares (135 acres). The maximum speed was set to one full revolution in 12 hours. Irrigation application efficiency was assumed to be 90%. Evapotranspiration was calculated with the tall reference Penman-Monteith equation (Allen et al., 2005) and dual crop coefficients for corn (Allen et al., 2007). The yield ratio was calculated with a normalized transpiration ratio (Steduto et al., 2006).

The locations and their associated planting dates for corn are shown in Table 1. All simulations ended on September 30th. Years of available weather data (downloaded from the High Plains Regional Climate Center, 2007) are also shown.

Table 1. Locations where simulations were performed.

Location	Planting Date	Season Length (days)	Years
Akron, CO	April 1st	180	1983 – 2006
Brookings, SD	April 15th	165	1983 – 2006
Nisland, SD	April 15th	165	1988 – 2006
Oakes, ND	May 1st	150	1990 – 2006
Ord, NE	April 1st	180	1983 – 2006
Rock Port, MO	April 1st	180	1991 – 2006
St. John*, KS	April 1st	180	1985 - 2006

*weather station at the Sandyland field station.

Pumping rates included 37.9, 50.5 and 63.1 L/s (600, 800, and 1000 GPM). Three soil types were selected to represent a range of soils. Soil types included available water holding capacity (WHC) values of 37.9, 50.5, and 63.1 mm/m (1, 1.5, and 2 in/ft), as defined in Equation 1.

$$WHC = (\theta_{FC} – \theta_{WP}) * 1000 \qquad (1)$$

Here, WHC is in mm/m, θ_{WP} is the volumetric water content at the wilting point, and θ_{FC} is the volumetric water content at field capacity. For irrigation scheduling purposes, it is helpful to define soil water content as a percentage, with zero being the soil moisture at the wilting point and 100% being the soil moisture at field capacity. This plant available water (AW) is the amount of water available to the crop and is calculated by Equation 2.

$$AW = (\theta – \theta_{WP}) / (\theta_{FC} – \theta_{WP}) * 100 \qquad (2)$$

Here, AW is the available water (%), and θ is the actual volumetric water content. An irrigation strategy offers a guideline for making irrigation decisions. A method was needed to numerically describe an irrigation strategy so that strategies could be changed and tested easily. An irrigation strategy was defined by the minimum available water (MAW) as it varies throughout the season. This concept is similar to the maximum allowable depletion (MAD), with MAW = 100 – MAD. Irrigation events were triggered when the soil directly in front of the pivot dried to the MAW.

Thirty strategies were defined for the simulations. These were inputs for the SDSU Management Software, which ran center pivot simulations for each strategy. The general shape of most of the strategies required higher AW levels mid-season and lower AW levels early and late-season. This is based on the observed effects of stress timing, showing that corn is more sensitive to water stress during flowering than the vegetative and yield formation phases of development (Doorenbos and Kassam, 1979).

Each strategy was defined by timing parameters (defining the early and middle stages of the season) and correlating MAW parameters. A strategy can be conveniently labeled by the MAW values for early, middle, and late season. Many strategies have similar timing parameters, although “30-60-30 extended” has a longer peak than normal. Based on the parameters, the MAW for any point in the season can be determined, as illustrated in Figure 1.

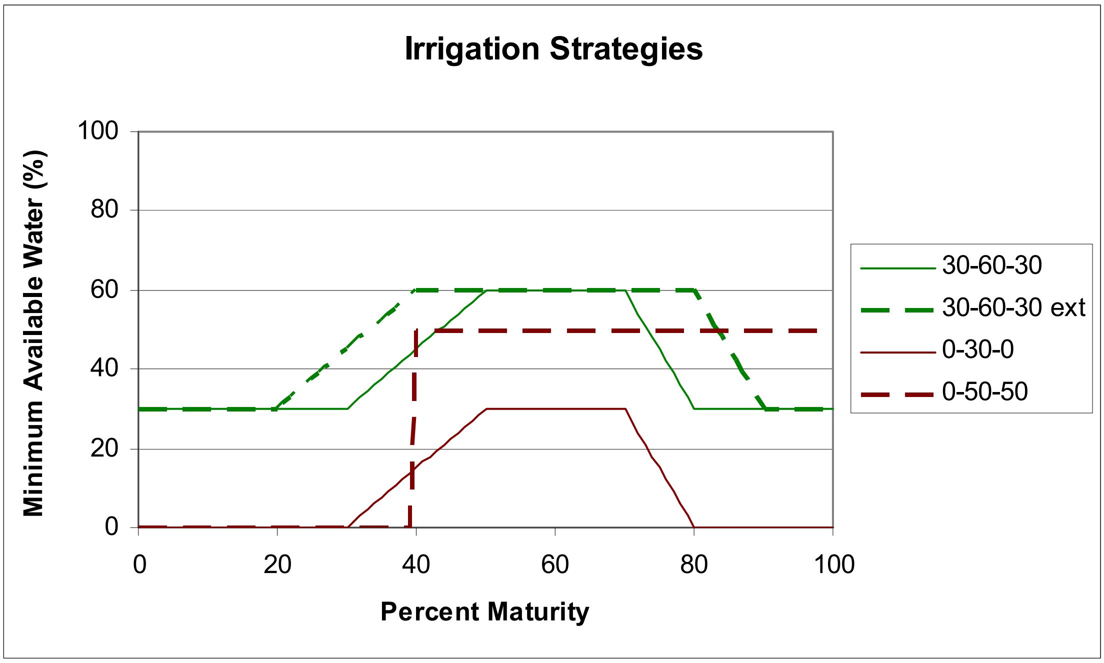

Figure 1. Selected irrigation strategies. Percent maturity expresses the ratio of days after planting to total days in the growing season.

The center pivot SDSU Management Software divides a circular field into 60 sections, each a 6˚ pie shape with its own water balance. Initial AW was set to 80% at the beginning of each season for each location. (This assumption was tested against a 20% initial AW at a dry site. While seasonal irrigation changed slightly, the shape of the yield-irrigation graph remained the same.)

The SDSU Management Software was modified to graph the mean, mean +/- one standard deviation, and the maximum/minimum AW for the 60 soil water balances. Figure 2 illustrates the variability in AW throughout a corn field for a particular season at Rock Port, MO. To account for this spatially variability, yield was calculated for three equidistant locations within the field and the results were averaged for each simulation.

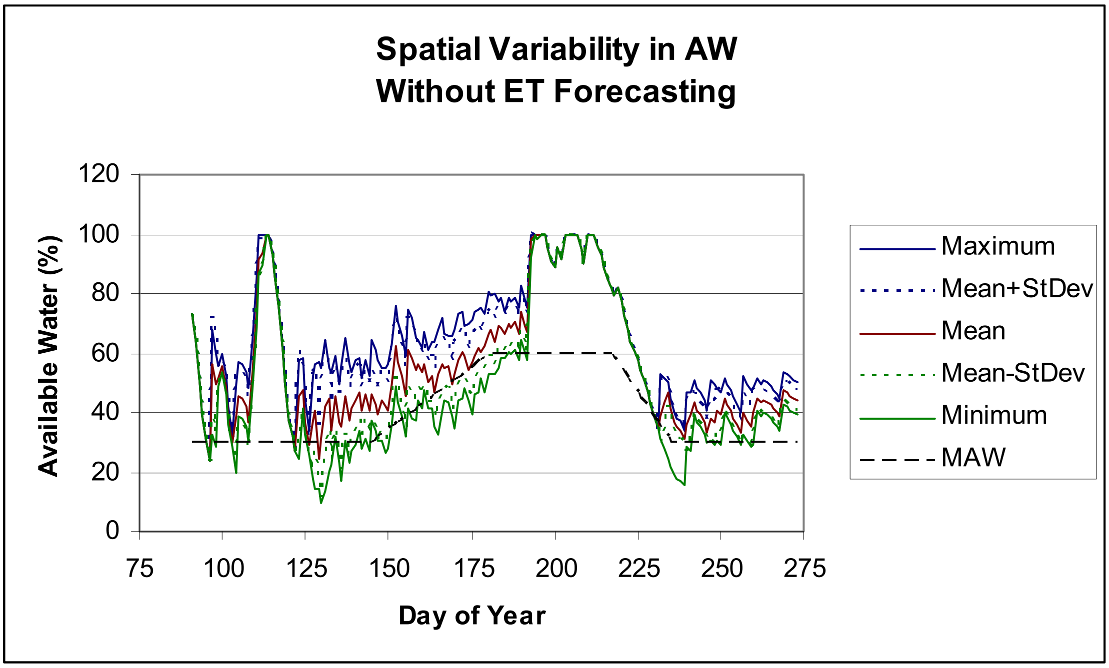

Figure 2. Example of spatial variability in AW without ET forecasting. Rock Port, MO, 1992 (driest year in dataset: 370 mm seasonal precipitation), 125 mm/m WHC, 63.1 L/s pumping rate, 30-60-30 irrigation strategy.

It was noted that ET forecasting, originally included in the SDSU Management Software, was not necessary for good irrigation management. While the drier portions of the field are often below the MAW line, high enough MAW values can be selected to achieve a desired result. The mean AW is maintained above the MAW line, if the system is able to keep up with ET demand.

Results

Water Relationships

For each site, the yield ratio is generally proportional to transpiration (Figure 3). Crops at sites with greater evaporative demand have a smaller increase in yield for each unit increase in transpiration.

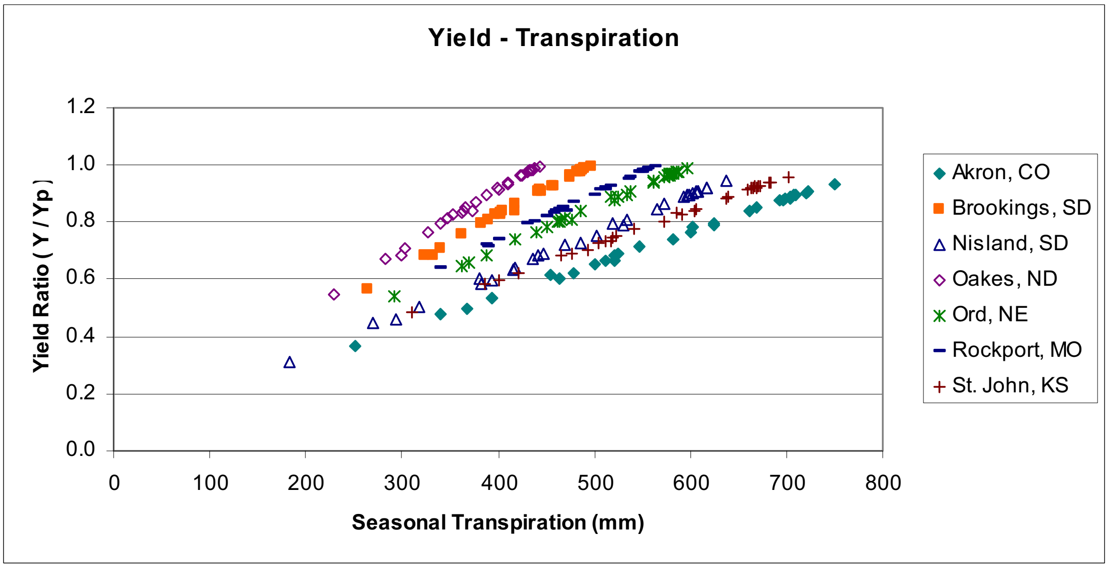

Figure 3. Yield-transpiration relationship for each site. Each point represents an irrigation strategy. Data is averaged across all WHCs, pumping rates, and years.

Yield ratio was also plotted against seasonal irrigation values in order to evaluate irrigation strategies. Figure 4 shows the summary of the results, with all 30 strategies represented for each location.

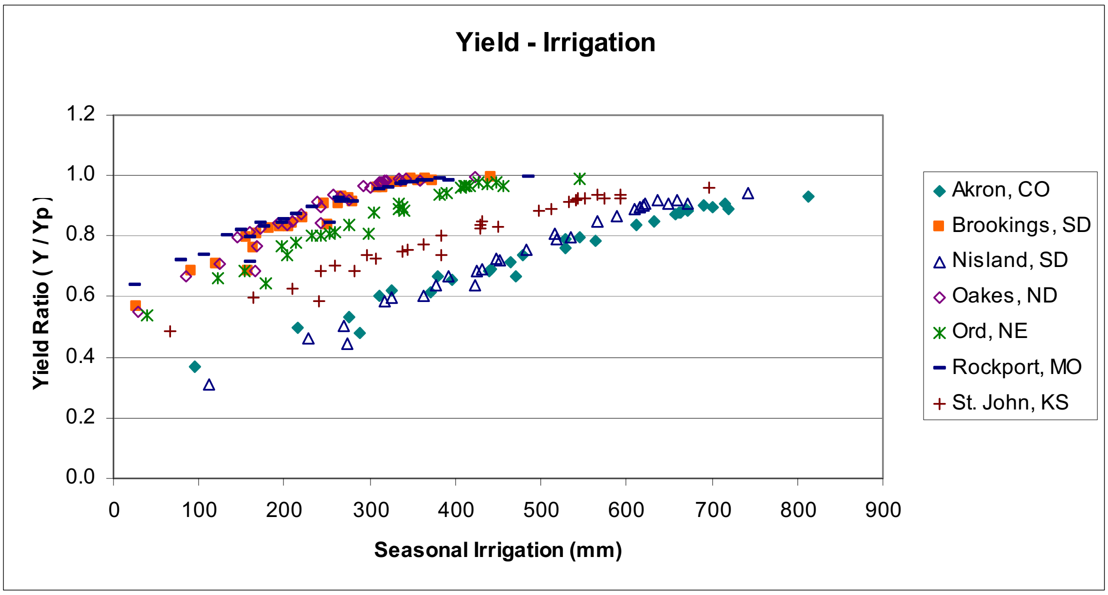

Figure 4. Yield-irrigation relationship for each site. All WHCs, pumping rates, and years. Net seasonal irrigation is used, based on a 90% application efficiency.

Sites with lower rainfall and higher ET demand showed greater yield loss for deficit irrigation strategies and required more water for high yields. The yield-irrigation relationship is relatively linear for each location until maximum yield is approached.

Figure 5 illustrates the differences among three yield-water relationships. The yield-transpiration line was nearly linear. Evaporation introduced more variability, which was shown in the yield-ET relationship. The precipitation plus irrigation was substantially different from ET. This difference was likely due to runoff and deep percolation losses. The amount of water loss generally increased with the amount of irrigation applied, and some strategies had more loss than other strategies with similar yields.

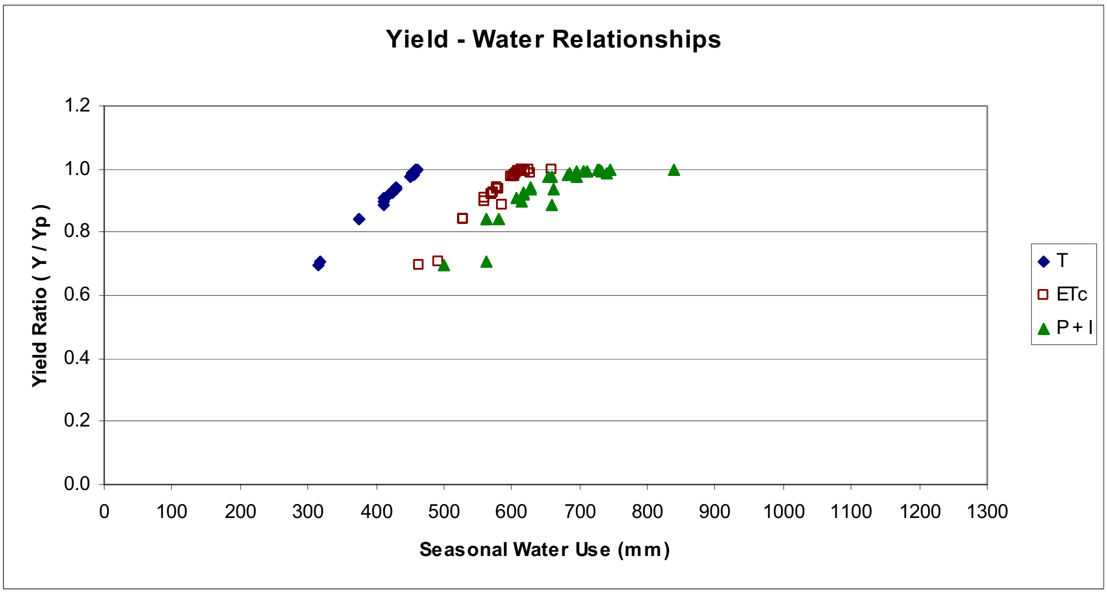

Figure 5. Yield-transpiration, yield-actual crop evapotranspiration, and yield-precipitation/irrigation relationships. Oakes, ND, 2005, 83 mm/m WHC, 63.1 L/s pumping rate.

Besides total seasonal precipitation, the timing of the precipitation is also important when considering crop water stress. Figure 6 shows climagraphs comparing average monthly reference ET to rainfall during the growing season for each location (based on weather data used for this project). While the curve for precipitation follows the ET curve for Rock Port, MO; Nisland, SD, and Akron, CO, reach peak rainfall two months before peak monthly ET. Climate trends can indicate the potential for mid to late-season water stress for a given location.

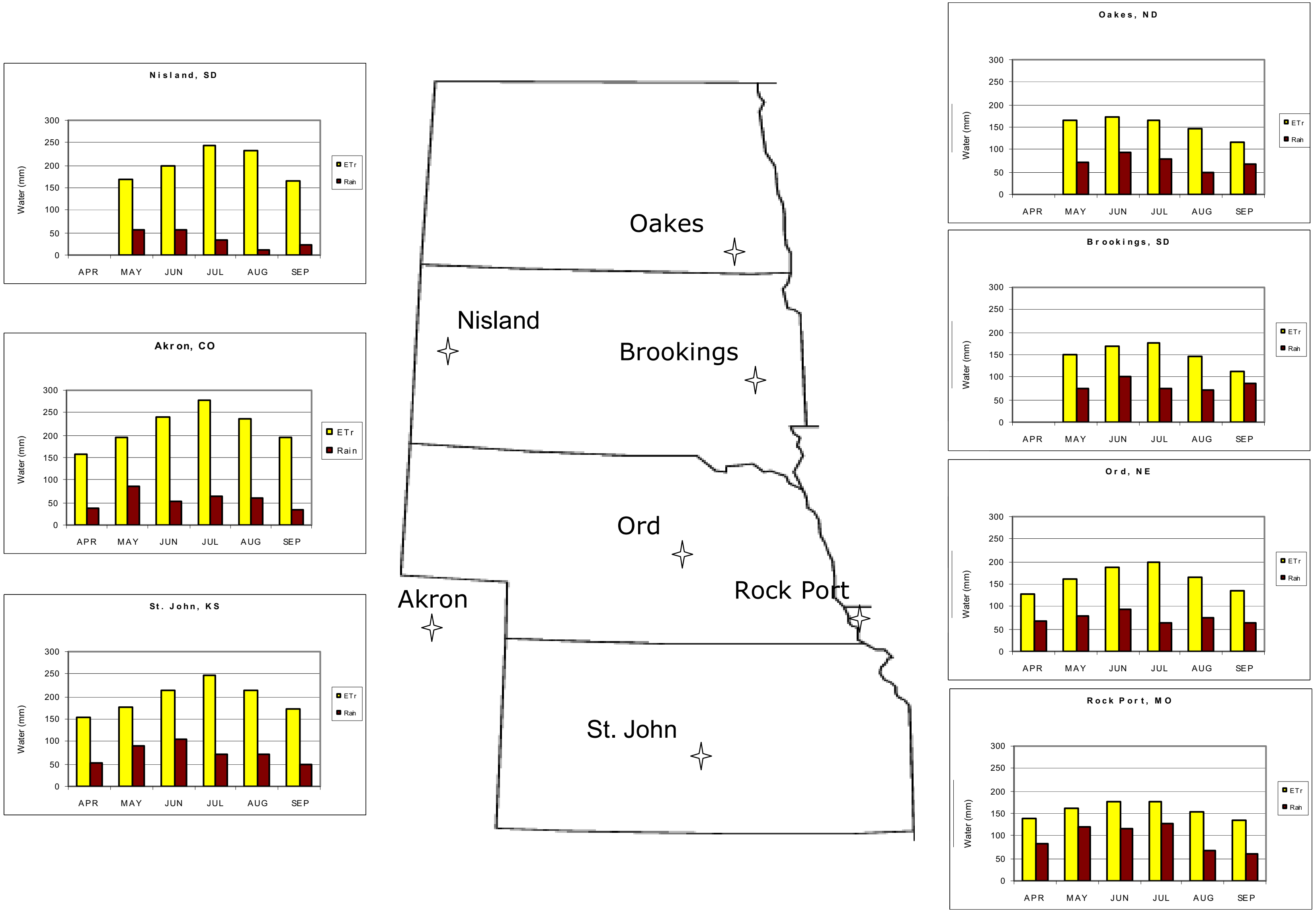

Figure 6. Climagraphs showing average monthly reference ET and rainfall (mm) for each location.

Recommended Strategies

The yield-irrigation relationship is the most relevant of the yield-water relationships for evaluating irrigation strategies. An example yield-irrigation graph is show in Figure 7, with strategies of interest labeled.

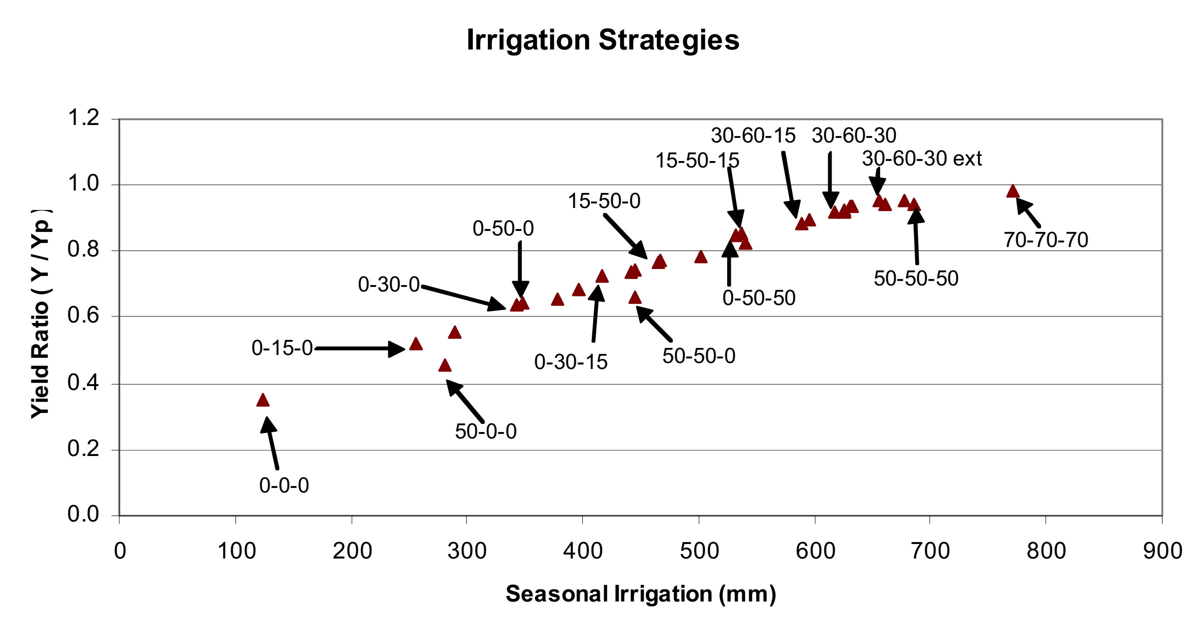

Figure 7. Example of yield-irrigation relationship with selected strategies labeled. Nisland, SD, all years, 83 mm/m WHC, 63.1 L/s pumping rate.

The basic shape and distribution of points (in relation to each other) in Figure 7 is representative of plots for all simulations. The 0-0-0 strategy, which irrigated only when the wilting point was reached, provided a lower bound on the data set. The 70-70-70 strategy, providing an upper limit on the data set, produced a minimal increase in yield (compared to similar strategies) for the large amount of applied water it required. The 30-60-30 strategy was the original strategy in the SDSU Management Software.

The historical strategy of 50-50-50 resulted in high yields, but it also consistently used more water than other strategies with similar yields. The 50-0-0 and 50-50-0 strategies, representing situations where available irrigation water was used up before the end of the season, consistently performed poorly. This indicates the benefit of good irrigation management, resulting in higher yields for a given supply of water.

Water use efficiency (WUE) is a concept that compares crop production to water used, and has been defined in numerous ways. For pragmatic reasons, WUE here will be considered relative grain yield per unit of irrigation. The best irrigation strategies result in high WUE; that is, they result in a large yield for a given amount of irrigation. On a yield-irrigation graph, "High WUE" strategies are the points above and left of the trend. The High WUE strategies in figure 12 performed well across locations, soil types and pumping rates.

The 0-50-50 and 0-30-15 strategies resulted in High WUE. This indicates that delaying irrigation early in the season (unless wilting point is reached), a deficit strategy that is relatively easy to implement, results in good water use efficiency. Yield and irrigation data for these and other strategies are shown in Table 2.

Table 2. Yield ratio and seasonal irrigation (mm) for High WUE strategies. Data is averaged over all soil types, pumping rates, and years.

Strategy	Akron, CO	Brookings, SD	Nisland, SD	Oakes, ND	Ord, NE	Rock Port, MO	St. John, KS
30-60-30 ext	0.903	0.987	0.920	0.988	0.976	0.986	0.937
	691	348	637	333	428	362	567
30-60-30	0.875	0.976	0.891	0.977	0.960	0.974	0.913
	656	328	610	311	406	336	533
30-60-15	0.838	0.959	0.848	0.963	0.939	0.953	0.886
	611	308	567	293	381	312	497
15-50-15	0.797	0.929	0.806	0.936	0.908	0.927	0.847
	544	268	516	257	335	264	432
0-50-50	0.791	0.906	0.793	0.897	0.888	0.920	0.839
	530	264	519	243	334	269	429
15-50-0	0.740	0.906	0.728	0.914	0.878	0.897	0.805
	480	246	447	238	305	231	383
0-30-15	0.668	0.827	0.668	0.826	0.801	0.841	0.736
	380	183	392	172	232	172	297
0-50-0	0.622	0.810	0.594	0.812	0.781	0.820	0.705
	326	167	325	159	213	149	260
0-30-0	0.605	0.794	0.584	0.794	0.764	0.801	0.687
	312	156	318	146	197	134	244
0-15-0	0.498	0.682	0.463	0.670	0.659	0.720	0.596
	215	91	228	86	123	79	163

Data from Table 2 (or yield-irrigation graphs) can be used for long term planning. As a simple example, consider a corn producer in Nisland, SD, with enough irrigation water to apply 320 mm (13 in) of irrigation water on 55 hectares (135 acres) with his center pivot irrigator. Would it be beneficial for him to apply 640 mm on half of his field, and leave the other half fallow? According to the table, yield ratios of 0.92 and 0.58 could be expected on average. Since 0.58 * Y_p * 55 hectares is greater than 0.92 * Y_p * 27.5 hectares, deficit irrigation is preferred to full irrigation in this case. In fact, similar results to this question would be found for all locations in this study, where average seasonal precipitation exceeds the amount of water typically lost to evaporation (when planting more acres, the benefit from rainfall outweighs the increased evaporative losses). Planting one half the field to a dryland crop (instead of fallow), however, could change the results.

For practical management purposes, the many strategies in Table 6 are not necessary. Of the High WUE strategies, four were selected that resulted in good spacing and covered a range of deficit and full irrigation conditions. Recommended deficit irrigation strategies are 15-50-0, 0-30-0, and 0-15-0 for minimal, moderate, and severe water restrictions. The recommended maximum yield strategy is 30-60-30 extended for Akron, CO, Nisland, SD, Ord, NE, and St. John, KS. For Brookings, SD, Oakes, ND, and Rock Port, MO, where the 30-60-30 extended provided little yield benefit for the extra water required, the recommended maximum yield strategy is 30-60-30. These strategies will be incorporated into the SDSU Management Software. Producers can select the best strategy based on the amount of water available to them, and have the option of changing strategies mid-season due to atypical rainfall or other factors.

Simulation data from the recommended maximum yield strategies were compared to results from a traditional strategy (50-50-50). Water savings and changes in relative yield are reported in Table 3.

Table 3. Benefit of recommended maximum yield strategies. All WHCs, pumping rates, and years.

		Akron, CO	Brookings, SD	Nisland, SD	Oakes, ND	Ord, NE	Rock Port, MO	St. John, KS
I (mm)	Traditional	720	372	671	359	456	392	593
	Recommended	691	328	637	311	428	336	567
	Change	-29	-44	-34	-47	-27	-56	-26
Y / Y_p	Traditional	0.892	0.983	0.910	0.984	0.968	0.981	0.924
	Recommended	0.903	0.976	0.920	0.977	0.976	0.974	0.937
	Change	0.011	-0.007	0.011	-0.007	0.008	-0.007	0.013

Annual Variation

Each irrigation strategy resulted in a different yield ratio and irrigation use for each year. Figure 8 shows error bars (standard deviation) on a yield-irrigation plot for both an arid and a sub-humid climate. There was more annual variation in irrigation use for strategies with higher water use. There was more annual variation in yield for strategies with lower water use. This information is valuable for risk management. For example, a deficit irrigation strategy may be economically beneficial on average, but the producer would have to be willing to accept greater variability in yield from year to year.

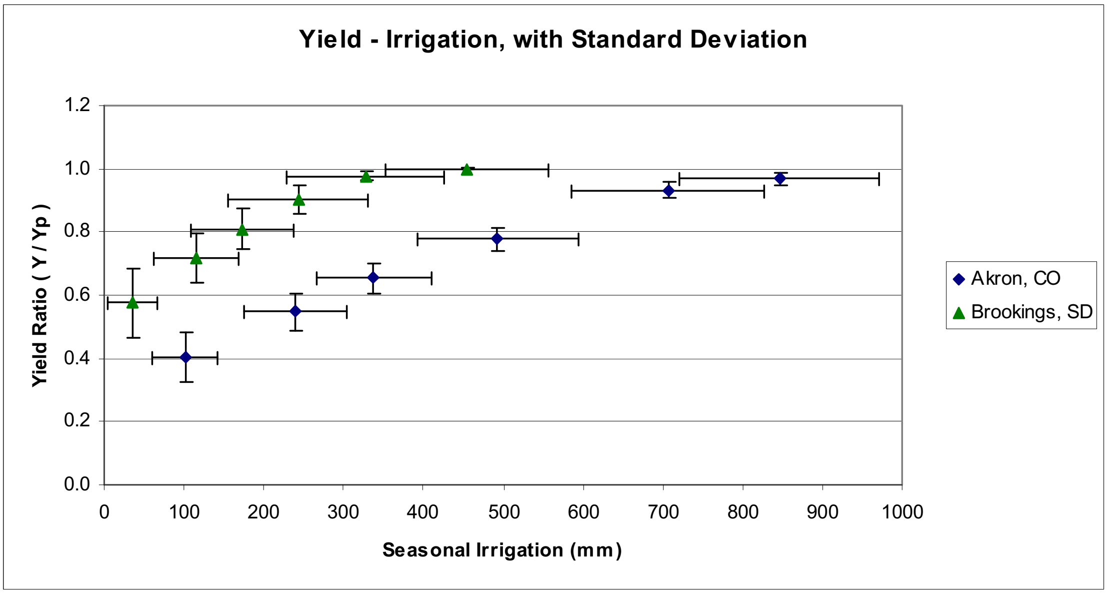

Figure 8. Example of standard deviation (for annual variation) shown on a yield-irrigation plot. 83 mm/m WHC, 63.1 L/s pumping rate, all years, 0-0-0, 70-70-70, and recommended strategies.

Soil Type and Pumping Rate

The effect of soil type was also evaluated. Soils with a high WHC had less water loss (i.e. runoff and deep percolation) since they were able to store more of the rain from large rain events. However, Rock Port, MO, was the only site to have increased water use efficiency for heavier soils. Rock Port had the highest mean annual precipitation (573 mm), and, perhaps more importantly, it had the most large rain events (greater than 25 mm) per season (Table 4).

Table 4. Large rain events and their impact on benefits of high WHC.

Location	Large rain events per season	WHC with best WUE
Akron, CO	2.1	83 mm/m
Brookings, SD	3.8	minimal difference
Nisland, SD	0.8	83 mm/m
Oakes, ND	2.7	83 mm/m
Ord, NE	4.2	minimal difference
Rock Port, MO	6.1	167 mm/m
St. John, KS	4.4	minimal difference

A high WHC allowed a soil to take advantage of large rain events, so it is reasonable that Rock Port, MO, would benefit the most from this. According to these simulations, Brookings, SD, Ord, NE, and St. John, KS, showed a minimal difference in WUE among WHC treatments. For Akron, CO, Nisland, SD, and Oakes, ND, however, the 83 mm/m soils performed the best, with 167 mm/m showing the smallest yield for a given irrigation amount. This was due to the increased evaporation loss in heavy soils, which is illustrated in Figure 9 (evaporation loss is indicated by the horizontal space between the ET and T lines).

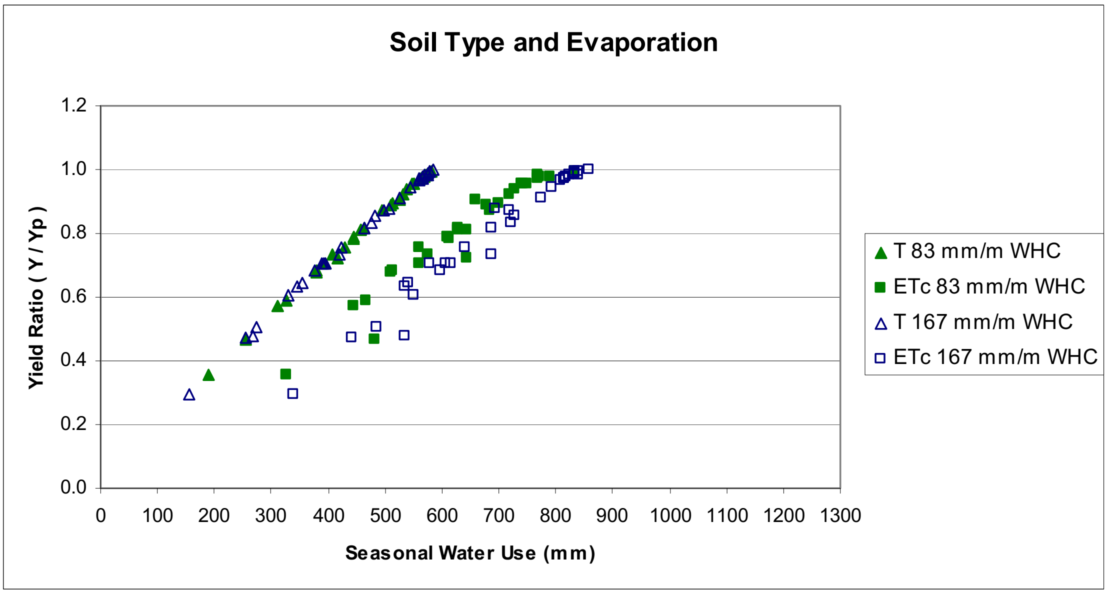

Figure 9. Example of soil type impact on yield-transpiration and yield-actual crop evapotranspiration relationships. Nisland, SD, 1997 (seasonal precipitation near the mean: 210 mm, zero rain events greater than 25 mm), 63.1 L/s pumping rate.

In medium to small rain events (and irrigations), drainage and runoff were small. For a high WHC soil, more of the moisture was held in the surface layer and lost to evaporation; less of the water made it deeper into the root zone to benefit the plant. For locations with few large rainfall events, this drawback overrides the benefits of a heavy soil. Two notes of caution are in order here. Soils with very low WHC, 42 mm/m (0.5 in/ft) for example, were not simulated. It is doubtful that the trend would continue and show such a soil to be desirable. Also, these results are highly dependant on the method for calculating evaporation from the topsoil (Heeren, 2008). Soil parameters describing the amounts of water that topsoil can hold and readily evaporate should be verified with laboratory tests in order to strengthen this observation.

The above analysis regarding WHC and WUE is especially appropriate from a deficit irrigation perspective. It should be noted, however, that if water is not limiting and the maximum yield is desired, a high WHC is preferable. The highest yields from maximum irrigation strategies were consistently obtained by the 167 mm/m WHC soils.

Pumping rates had a negligible effect on which strategies performed best. The same strategies are recommended for all pumping rates. However, for a particular strategy, pumping rate did impact yield. Figure 10, showing the four recommended irrigation strategies, provides an example of the effect that pumping rate has on the yield-irrigation relationship.

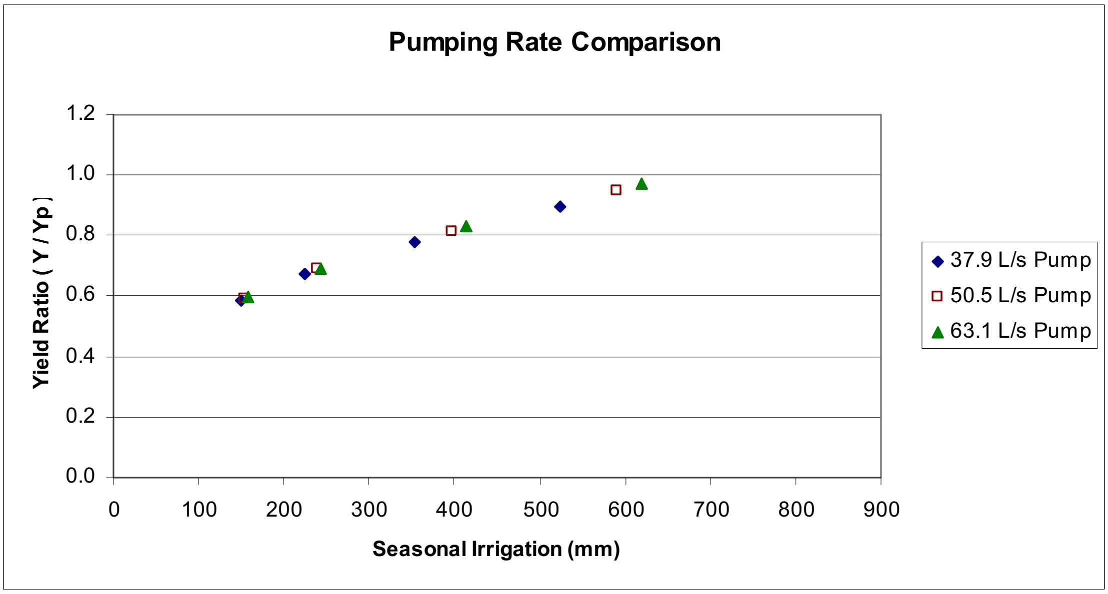

Figure 10. Example of the effects of various pumping rates. St. John, KS, 125 mm/m WHC, all years, recommended irrigation strategies.

Pumping rate appeared to have a small effect on water use efficiency; the points above form a fairly smooth irrigation-yield curve. The primary difference is where they lie on the curve. All sites showed at least a slight reduction in yield when the pumping rate was limited to 37.9 L/s. Akron, CO, Nisland, SD, and St. John, KS, showed substantial yield losses with a pumping rate of 37.9 L/s, and small losses with 50.5 L/s compared to 63.1 L/s. It is not surprising that the sites with the greatest middle and late-season difference between monthly ET and precipitation (Figure 5) showed the largest yield reductions from limited water delivery rates. From a design standpoint, a 50.5 L/s pump may be sufficient to achieve maximum yield in Brookings, SD, Oakes, ND, Ord, NE, and Rock Port, MO. Another implication involves situations where the pumping rate is being reduced due to declining aquifer levels. These data provide indications of the effects on water use and yield in those scenarios.

Conclusions

The recommended maximum yield strategy for corn is 30-60-30 for Brookings, SD, Oakes, ND, and Rock Port, MO, and 30-60-30 extended for Akron, CO, Nisland, SD, Ord, NE, and St. John, KS. Recommended deficit irrigation strategies (for all sites) are 15-50-0 for minimal water restrictions, 0-30-0 for moderate water restrictions, and 0-15-0 for severe water restrictions. Recommended irrigation strategies did not depend on soil type or pumping rate.

Variability in yield from year to year is greatest for strategies that use the least water. Pumping rate had a small effect on the general yield-irrigation relationship, but a rate of 37.9 L/s substantially limited maximum yields in Akron, CO, Nisland, SD, and St. John, KS. The benefit of soils with high WHC may be limited to locations with a high frequency of large rainfall events.

Acknowledgements

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Optimizing Crop Water Use Efficiency with AirJection® Irrigation

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Abstract
Evaluating the addition of ambient air via subsurface drip irrigation system, referred to as AirJection® Irrigation, has been the focus of our research over the past seven years. In the most recent phase our research we examined the potential of this system to enhance crop water use efficiency (WUE). First, we compared the "agronomic" WUE, calculated as the ratio of crop yields to water inputs, for conventionally and organically grown vegetables. Secondly, by measuring the rates of photosynthesis, transpiration, and stomatal conductance, we determined the "leaf scale" and "intrinsic" WUE. Our results to date indicate that AirJection® Irrigation had a significant ($P<0.05$) on crop WUE. In the case of the organically grown vegetables, this effect was enhanced by Nitrogen fertilization. These findings would be of benefit to vegetable growers as they continue to optimize their irrigation systems in an effort to maintain the sustainability of their farms.

Introduction

The world population is estimated to increase from 6.1 billion in 2000 to 9.1 billion by the year 2050 (UN, 2005). With this increase in population, there exists a challenge to feed the people by producing crops on relatively less arable land and limited water resources. In addition to urbanization, there is a decrease in agricultural land due to soil erosion, reduced soil fertility, and desertification of soils (Carvalho, 2006).

California is known to be one of the largest and most diverse economies in the United States. Industries such as agriculture, mineral extraction, telecommunications, and computer technology have made California a mixed economy (DWR, 2005). It is estimated that California's population may reach up to 48 million by 2030, as projected by the California Department of Finance, and by 2050, it may grow to a total of 55 million. With an increasing population, the state's demand for water, either for domestic use, or for agricultural purposes, would invariably enhance the importance of water conservation recycling strategies (DWR, 2005). The present water situation in California has to be seen as a critical need to improve the irrigation practices further but not as a limitation to farming practices.

Sub-surface Drip irrigation (SDI), has been reported to be a very effective way of applying water and nutrients to the crops (e.g. Camp et al., 2000; Ayars et al., 1999). In the San Joaquin Valley (SJV), the leading agricultural production region in California (CDFA, 2003), SDI is a major component of agricultural production systems as farmers continue to compete with municipalities and other industries for decreasing water resources. Over sixty five years ago, Durell (1941) wrote, ‘‘a study of suitable oxygen carriers, which could be applied as fertilizer, and which would release oxygen slowly to the soil during the growing season, may be worthwhile”. More recently, through work in other areas, the Mazzei® Corporation has developed high efficiency venturi injectors capable of aerating water with fine air bubbles. The combination of the venturi system with SDI has been patented as AirJection® Irrigation. Researchers in Australia have also adopted this technology and refer to it as oxygation (Bhattarai et al., 2005). The concept of modifying the root zone by injecting air into the subsurface drip irrigation system (SDI) could be an alternative for tillage operations. The hypoxic condition which might be induced due to the alternate wetting and drying using SDI can be avoided by injecting air into the irrigation water supplied through SDI (Bhattarai et al., 2004). When air alone is supplied to SDI system, it emits a vertical stream moving above the emitter outlet directly to the soil surface. As a result, the air moves away from the root zone due to chimney effect (Goorahoo et al., 2001a,b).

The major goal of our research is to evaluate the technical and economic feasibility of AirJection® Irrigation, as a best management practice for crop production. Ideally, the technology should be applied to and tested on as many crops as possible. Realistically, we plan on assessing the practice on as many vegetable and fruit crops commonly grown in the SJV. In this presentation, we review the basic concepts of AirJection® Irrigation and then describe some of the research our group has conducted to date which has focused on estimating the impact of AirJection® Irrigation on water use efficiency (WUE).

Material and Methods

Details of the design and theory of operation of the air injection system employed in the research is described above and can be found in Goorahoo et al., (2001a,b). Briefly, the injector/ drip tape assembly operates on the following principle: As water under pressure enters the injector inlet, it is constricted in the injection chamber (throat) and its velocity increases. The increase in velocity through the injection chamber can result in a decrease in pressure below the atmospheric in the chamber. This drop in pressure enables air to be drawn through the suction port and can be entrained into the water stream. As water stream moves towards the injector outlet, its velocity is reduced and the dynamic energy is reconverted into pressure energy. The aerated water from the injector is supplied to the irrigation system. The fluid mixture delivered to the root zone of the plant is best characterized as air/water slurry.

Commercial scale experiments were located in Firebaugh (tomatoes) and Mendota (cantaloupe and honeydew melons, and peppers) in the SJV, CA. Soils in this region range from sandy loams to clay loams. Crops were grown on 5 feet wide beds and an experimental plot consisted of at least 4 alternating replications of air-injected and no-air treatments (control). Each replicate was made up of seven beds to accommodate the width of the tractor-drawn trailers during harvesting. For example, the honeydew experimental plot comprised of four replicates of each treatment for a total of 56 beds (2 treatments x 4 reps per treatment x 7 beds per rep = 56 beds). The drip tape run length for the beds in the honeydew plots was 390m (1280 feet). The cantaloupe and pepper experiments were conducted on relatively larger plots than those used for the honeydews. For these crops the experimental plot consisted of 13 alternating replicates of AirJection® and control treatments for a total 182 beds with a drip tape run length of 400m (1,312 feet). The tomato experiment was a completely randomized design with four replicates of each of the aerated and water only treatments. Each replicate comprised of 12 beds which were serviced by an irrigation manifold. The drip tape run length for the tomato plot was 300m. Based on observations from our concurrent experiment in which we noticed that for air treated plants there were greater yields from the plants located at the "head" of the drip line versus the plants down at the "tail", experimental plots were blocked along the beds as Head, Middle and Tail. This was done by dividing the length of the bed into three equal sections and labelling the section closest to the irrigation manifold as the "Head" and that furthest away as the "Tail". For example in the 300m long tomato beds, the section from the inlet manifold to 100m along the direction of the water flow was designated as the "Head", the section between 100 to 200m was referred to as the "Middle" and between 200 to 300m was the "Tail" section.

One constraint of conducting the experiment on the commercial farm is that an excessive destructive plant sampling was not possible during the growing season to examine the impact of the air injection on the roots. Hence, we set up a bell pepper research plot (0.25 ac) at CIT on our campus farm, in which the destructive sampling was carried out.

In addition to the scientific studies mentioned above, we have done some observational studies on Strawberries planted in Oxnard, CA (Goorahoo et al., 2008). Air injectors were installed on drip lines serviced by one valve such that 38 beds received

AirJection® irrigation. Then six test subplots containing 40 plants from three of aerated and non aerated beds were used to collect yield data.

Both the Non-Aerated Control and AirJection® Aerated plots used the following design:

- Two lines of sub-surface drip tape (0.667 gpm / 100 ft) per row;
- 64" bed x 15" spacing x 4 rows per bed x 315' row length (25,500 plants per acre); and,
- Drip tape was operated with approximately 10 psi of inlet pressure

The AirJection® aerated test plot used the following configuration to supply the air/water mixture:

- Model A-14 Mazzei AirJection® Irrigation units
- 100% of the water for each row flows through the injector.
- The AirJection® units were operated with approximately 25 psi of inlet pressure.
- The gas to liquid ratio was approximately 11%.

All routine agronomic practices and irrigation scheduling were conducted by the growers. However, periodic growth observations, soil moisture measurements and irrigation flow meter readings were collected. In addition to the flow meters, to insure equal amounts of water were being applied to the air-treated and control plots, the irrigator regularly checked and adjusted the inlet pressure to the air injector to verify and maintain that the pressure downstream the injector was the same as that of the drip tape for the control plots.

For each of the crops in the commercial plots, the following measurements were performed:

1. Pre-Plant Soil sampling
2. Crop Growth and Irrigation Monitoring
3. Harvest and Yield Data Collection
4. Photosynthesis and transpiration
5. Plant Height and width measurements
6. Root and Shoot Post Harvest
7. Post Harvest Soil Sampling

Data collected for the various parameters were analyzed for statistical differences using the SPSS statistical package to conduct either independent-samples *t- test* or ANOVA. Yield data were to determine the agronomic WUE as a ratio of the marketable product yield to the amount of water applied.

To determine the leaf scale and intrinsic WUE, which relates the amount of photosynthesis to the transpiration rate, we used a "CIRAS-2"portable photosynthesis and soil respiration instrument. Leaf photosynthesis (Pn), transpiration (T), stomatal conductance (g_s), and soil respiration (SR) were determined for various crops. The CIRAS-2 instrument works on the principle of detecting CO_2 levels with an infrared gas analyzer (IRGA). Basically, the instrument measures the relative change in CO_2 for the volume of air in contact with the leaf or soil. Any decrease in CO_2 values is used to calculate photosynthesis rates using series of equations (PP Systems. 2002). In the case of the soil respiration, an increase in CO_2 concentration was used in the calculations. Leaf measurements for Pn, T, and g_s were taken on clear days between 0900-1200 h in order to minimize the photo-inhibition due to greater light intensity (Barth et al., 2001). 33

Results and Discussion

For melons harvested in Summer 2004, for the number of cantaloupes harvested per 20 feet section of a bed (i.e. 20' x 5' = 100 sq ft.) there was no significant difference ($t(86) = 1.164$, $p > 0.05$) with mean number of melons from the aerated and non aerated plots being 17.32 (sd=6.26) and 15.82 (sd=5.82), respectively. However, there was a statistically significant difference in the weight of the melons harvested ($t(82)=2.105$, $p<0.05$). The mean weight of AirJection® irrigated melons (m = 27.18 kg/100 sq.ft, sd= 9.54) was significantly higher than the mean weight of the melons receiving water only (m = 23.06 kg/100 sq.ft, sd= 8.38). When the cantaloupes harvested from seven of the 100sq.ft sections were categorized into grades used for packing and shipping, there was a 43% increase in the number of large melons and, a 39% increase in the weight of large melons harvested due to air injection (Tables 1 and 2). This increase in the number and weight of large air–injected melons, which are shipped in 9 per box, is important since the larger melons are the most desirable grade for the grower. While there was no significant difference in root dry weight per plant, the mean shoot dry weight of plants from the aerated treatments (m=308g, sd=179) was significantly higher ($t(28)=2.972$, $p<0.05$) than the mean shoot dry weight of plants from the non aerated plots (m=207, sd-81).

For tomatoes, our findings seem to indicate that in the case of the tomato crop, there may have been earlier fruit maturity for the air treated plants. This statement is based on the relative amounts of mature "red" and "breakers" harvested at 80 and 93 DAT (days after transplanting). Traditionally, at the commercial scale, fresh market tomatoes are harvested as mature "Green", with "reds" and "breakers" considered as either being too late for picking or marginally harvestable, respectively. These colour maturity grades are based on guidelines provided by the USDA. For the variety of tomatoes grown in 2004, the anticipated date of harvest was at 93DAT. However, at 80DAT, it was obvious that there were a number of red and breaker tomatoes on plants from both treatments. Hence a preliminary harvest was conducted in which only the red and breaker tomatoes were picked. While there was no significant difference in the number of red tomatoes at 80DAT, there was a significant difference, in both the number ($t(126)=2.492$, $p<0.05$) and weight ($t(126)=2.354$, $p<0.05$), between the breakers from ten air injected and non aerated plants. The mean number of breakers from the air injected plots comprising of 10 plants (m=24.94, sd =13.97) was significantly higher than the mean number of breakers from the control plants (m=19.50, sd=10.47). In terms of weight, the mean value of 2.54 kg (sd=1.39) for the breakers from the aerated plants was significantly higher than the mean value of 2.03 kg (sd= 1.07) for the breakers harvested from the plots receiving no aeration.

At 93 DAT, the following results were obtained from the t-test analyses of tomatoes harvested:

(i) The mean number of red tomatoes from air-injected plants (m=246,sd=38) was significantly higher (t(62)=2.939, p<0.01) than the mean number of red tomatoes from plants receiving water only (m=212, sd=53);
(ii) In the case of breakers and green tomatoes, both these categories demonstrated significant weight differences (t(62)=1,59) at the p<0.05 probability level. However, unlike the harvest at 80 DAT, at the 93 DAT harvest the mean weights of the non aerated breakers (m=13.22, sd=2.81)and greens (m=27.12 kg, sd=5.31)were significantly higher than the breakers (m=11.56, sd=2.81)and greens (m=24.34 kg, sd=5.31) from the ar injected plots.

In the 2003 experiment with peppers grown on 40acres with run of over 400m, we observed that although there was a trend of decreasing yields in terms of both numbers and weights. Generally, in moving away from the source of the air and water injection, there was still a positive effect of the air injection towards the tail end of the irrigation tape (Table 3). We are currently conducting additional research using specialized drip tape in an effort to minimize the yield variability observed along the run length of the drip tape.

For the peppers grown in the relatively smaller plots at CIT location, there has been no significant difference in the dry weights of the above ground portion of plants. However, for root dry weight, the mean weight per plant from the air injection treatment (m=11.55g, sd=1.33) was significantly higher (t930)=4.326, p<0.001) than the mean weight of the water only plants (m=8.73, sd=2.24).

The strawberry results analyzed to date indicate that there was a 18.3% increase in #1 Grade fruit in the Aerated plot vs. the Control plot. There was a 6.9% increase in #2 Grade fruit in the Aerated plot vs. the Control plot. There was a 33.7% increase in Freezer Grade fruit in the Aerated plot vs. the Control plot.

Increased yields with the similar amount of water being applied as that in non aerated crops will suggest that AirJection® Irrigation resulted in increased agronomic water use efficiency. At the leaf scale WUE for peppers, we have observed that there ia lot of variability as o whether the air injected plots show increased WUE or not with both the DAT data and the location along the drip irrigated beds (Figure 1). For example, in the case of the peppers at CIT, we observed that during the early vegetative growth stage (30 DAT) the WUE in the water only plots were 3.9 compared to 3.2 for the air inljected plants. However, by the time of fruit formation (65DAT), the air injected plots had a WUE of 3.8 versus the 3.2 value for the water only plants. At full maturity (100DAT), the air injected plants were showing a leaf scale WUE of 4.4 compared to 4.1 for the control plots. Similar analyses are currently being conducted for the other crops.

Concluding Remarks

Our recent and on-going research has shown that the incorporation of high efficiency venturi injectors in SDI systems can increase root zone aeration and add value to grower investments in SDI

From the data analyzed to date in our current research, we have observed that generally, there was a decrease in transpiration rates in the plants subjected to AirJection® Irrigation. For the majority of crops examined, the net photosynthetic rate, stomatal conductance and leaf scale water use efficiency (WUE) increased considerably with the use of AirJection® Irrigation. These findings imply that AirJection® Irrigation has great potential for optimizing water usage as farmers continue to seek out innovative practices aimed at increasing yields with relative less water being allocated to the agricultural sector.

The work conducted to date on fruits and vegetables have been aimed at evaluating AirJection® Irrigation on conventional farms. However, because the air injection system with the venturi devices uses ambient air, there exists the potential to use this system on organic farms. Hence, in summer of 2007 we began evaluating the effect of the AirJection® Irrigation on organic vegetable production at California State University-Fresno.

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Table 1: Comparison of Count for Melons per 700 sq ft- 2004

Treatment	Large	Medium	Small	Total Harvestable	Non Harvestable
Air	96	203	447	746	696
Water	67	180	411	658	667
*Difference	29	23	36	88	29
**% increase	43%	13%	9%	13%	4%

* Difference = Air count minus Water count
** % Increase = (Difference ÷ Water count) × 100

Table2: Comparison of Weight (kg/700 sq. ft.) for Melons-2004

Treatment	Large	Medium	Small	Total Harvestable Weight
Air	207.4	331.6	603.0	1142.0
Water	149.31	325.44	491.56	966.3
*Difference	58.05	6.13	111.49	175.66
**% increase	39%	2%	23%	18%

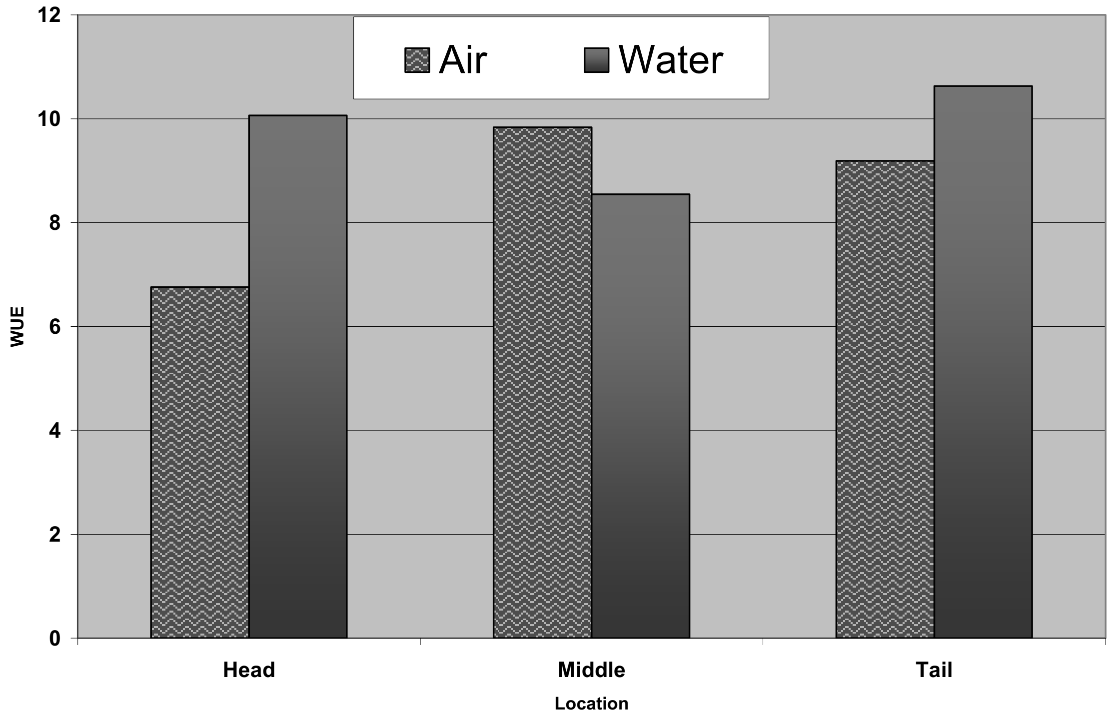
* Difference = Air weight minus Water weight
** % Increase = (Difference ÷ Water weight) × 100

Table 3: Summary of Pepper yield for 10 plants along the drip lines grown in 2003.

Relative distance from drip tape inlet	No. of Peppers	No. of Peppers	Wt. of Peppers (kg)	Wt. of Peppers (kg)
	Air	Water	Air	Water
Head (West)	100	57	13	10.72
Middle	80	84	12.26	14.03
Tail (East)	47	45	7.18	7.52
Total	**227**	**186**	**32.44**	**32.27**
***Difference**	**41**		**0.17**	
****% Difference**	**22.04%**		**0.53%**	

* Difference = Air value minus Water value
** % Increase = (Difference ÷ Water value) × 100

Figure 1:WUE along Head , Middle and Tail, in Air vs. Water Treatments at CIT Pepper Trail.



Boom-Type Carts vs. Big-Guns in Northwestern Washington

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Abstract. *Agricultural producers in Northwestern Washington need an irrigation system that is low-cost, non-permanent, and highly mobile to provide supplemental irrigation water to certain crops. Big-guns on reels fill this need. Recently a few progressive growers have been experimenting with boom systems. These can work with the existing reels but use long "booms" cantilevered over both sides of the cart to distribute water through drop tubes similar to a center pivot. This paper will discuss the system performance comparison evaluations for efficiency and uniformity for both of these systems. The economics and practical considerations of converting from a big-gun to a boom are also discussed along with how this will impact the environment.*

Keywords. Big gun, boom, economic comparison, efficiency, uniformity

Ag. and Natural Resources Extension Agent, Don McMoran measuring the volume in a catch can with a boom irrigation system in the background.

Introduction

Irrigation in Northwestern Washington is done on a supplemental basis. Although there have been years in the past when farmers have not used their irrigation equipment, (1996 growing season) these years are becoming fewer and further in between. Using the WSU Skagit County Extension Agriculture Statistics, WSU extension personnel have noticed a rise in supplemental irrigation in Western Washington using what is referred to as a traveling, or reel big-gun system (Picture 1). This system of irrigation is effective at supplying water to the crop but applies water inefficiently. High pressures are required to propel the water long distances. Therefore it is highly vulnerable to wind drift and evaporation. Addition tests have shown that big gun systems have poor distribution uniformity when compared with other systems.

Picture 1. A big-gun irrigation system in operation.

Improved irrigation efficiency and distribution uniformity are important because they can improved crop yields, crop uniformity and quality, and can facilitate fertigation or chemigation. These improvements can also lower input costs of irrigated specialty crops in Northwestern Washington such as high value vegetable seed crops, small fruit and potato production while addressing environmental concerns for conserving water and energy.

Recently manufacturers have adapted the reel big-gun to a boom system (Picture 2). Similar to a reel big-gun, a "boom" system is mounted on a traveling cart that is reeled in slowly over a length of a field. However, "booms" (supported pipes) are cantilevered over both sides of the cart and micro sprinklers are spaced along the length of the pipe to evenly distribute water over the soil similar to center pivot or linear-move irrigation systems. Because of the different mode

Picture 2. A boom irrigation system in operation.

of operation, a boom system operates at lower pressures and the water travels less distance through the air. This should make the irrigation system more efficient (less water is evaporated as it travels to the soil surface) and should make it less susceptible to wind redistribution. Therefore one would expect higher distribution uniformity.

The objectives of this project were to compare uniformity and water application efficiency of typical big-gun irrigation systems with a new boom type irrigation system and to look at the cost advantages or disadvantages of each system.

Materials and Methods

Evaluations were done on two big-gun systems, and on two boom systems. All of the evaluations were done in potato fields. Standard procedures for doing irrigation system evaluations were followed. A line of catch cans was laid out at equal intervals ahead of the traveling sprinkler perpendicular to its path in an un-irrigated area of the field. The cans were placed on the top of the bed of every third row in line with the plants. The can's position in relation to the center line of the traveling sprinkler was noted. The cans were placed as level as possible and the plant canopy was laid down away from the can if it was likely to interfere with the trajectory of the sprinkler drops as they traveled from the sprinklers to the catch cans. The system was allowed to pass completely over the row of cans until water was no longer being caught in the cans. The volume of catch was then measured in each can and recorded along with the can's position. This volume was converted into an application depth using the cross sectional area of the can opening.

The travel speed of the sprinkler was measured using a long survey tape, marked beginning and ending locations, and a timer. This measured speed was compared with the travel speed information on the reel controller as a back-up check. The pressure was noted at the sprinklers as well as at the reel and if possible at the pump. Wind conditions were recorded. The water flow rate going into the reel was measured using a portable transit time ultrasonic flow meter. The catch depth, the spacing between the cans and the travel speed of the cart was used to calculate the water application rate at the soil surface. This was divided by the measured inflow rate to calculate irrigation application efficiency. Application efficiency is the percentage of the water leaving the nozzle that makes it to the ground to be stored in the soil (assuming no runoff).

The catch depths from the border cans were added to simulate overlap from previous and subsequent pulls. These catch depths are ordered and the average of the lowest 25% is divided by the overall average catch to give the distribution uniformity of the low quarter (DULQ). DULQ is a number between zero and one that reflects how evenly the irrigation system applies water. The lower the DULQ the more water must be applied to adequately irrigate all areas of a field to compensate for the fact that some areas aren't receiving adequate water.

Results

Big Gun Evaluation 1

This was done on a Baur reel and gun. Wind speed of about 10 mph out of the northwest was estimated. The rows are oriented in a north-south direction. The pressure at the pump was 140 psi. Because, the reel was run by a hydraulic drive the pressure was reduced across the drive. The pressure at the nozzle was 100 psi. The big gun was pulled from the south towards the north. Potatoes were grown on 36 inch centers and the grower was irrigating 90 rows per pull for a total an irrigation width of 270 ft per pull. The depth of water caught in each can at various distances from the center line is shown in figure 1. During the evaluation, the wind had a large effect on the uniformity and efficiency of the gun. The wind was likely responsible for not only distorting the pattern to one side, but also tightening the pattern so that the outer edges didn't receive as much water as they should. If the exact same application pattern is seen every pull, then the current overlap strategy of 90 rows would result in the pattern shown in figure 2. An improved overlap strategy of irrigating only 65 rows per pass is shown in figure 3. This overlap strategy would give a much better water distribution uniformity. In general narrowing the distance between passes assures good irrigation uniformity regardless of the wind condition. This would result in improved yields and crop quality. The efficiency of this system was estimated at 58%. In other words, 58% of the water that left the nozzle made it to the soil surface.

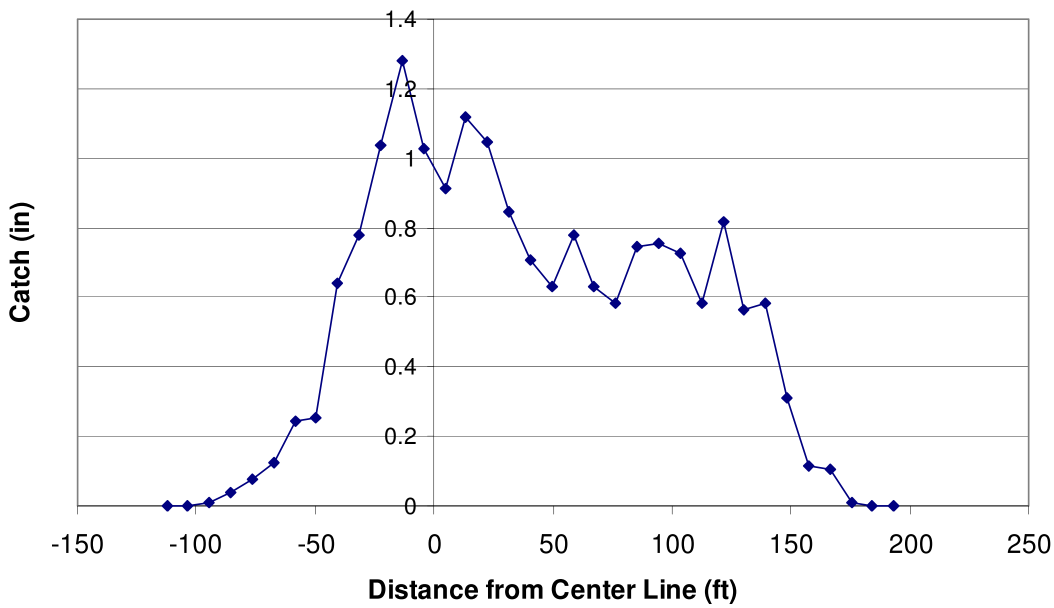

Figure 1. The catch of big-gun #1 at various distances from the center line.

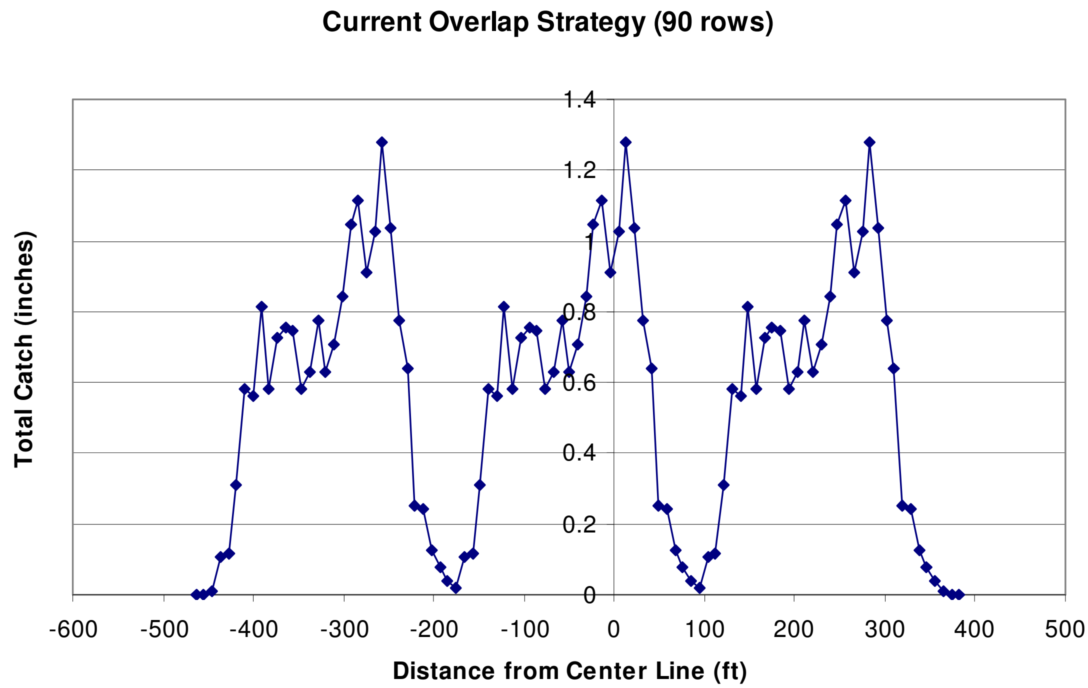

Figure 2. Three overlapping pulls if the exact pattern is replicated on a 90 row spacing resulting in a DU_{LQ} of 0.20.

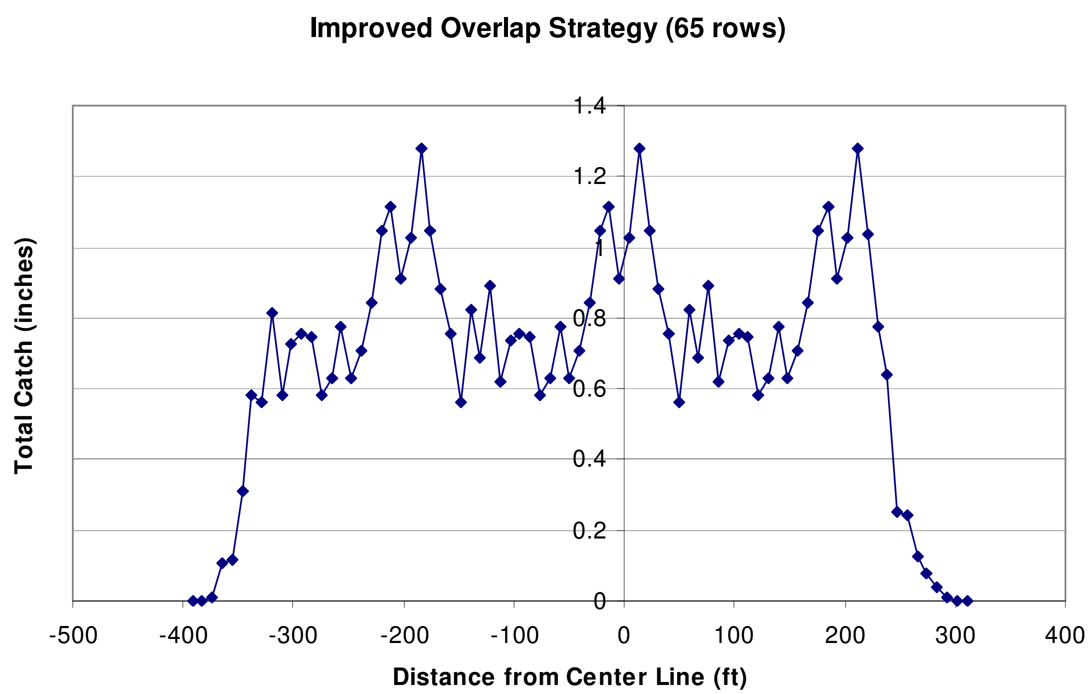

Figure 3. Three overlapping pulls if the exact pattern in replicated on a 65 row spacing resulting in a DU_{LQ} of 0.75.

Big Gun Evaluation 2

This evaluation was done on a Rainstar reel (Model E51) and a Bauer gun. The application rate was set high on this gun such that too much water was caught in the cans, resulting in lots of splash-out and overflow. Because of this inaccuracy we can't report the results from this evaluation. Another similar evaluation was done earlier in the year on a big gun by Tom Walters in which he reported a DULQ of 0.73 for the overlapping portions of his evaluation.

Boom Evaluation 1

A Baur Rainstar reel (model E31) was used in this evaluation. The boom was also manufactured by Bauer. The reel was driven by a small gasoline engine. The system pressure was 58 psi at the pump and 45 psi at the reel. This was regulated at the boom nozzles to 20 psi. Instead of just one row of cans, two rows were used to improve the accuracy of the catch estimates. The catch can results are shown in figure 4 and the current overlap strategy would result in the application pattern in figure 5. The grower was struggling with the pressure regulators plugging up. This was apparent from the evaluation data. The low catches next to the center line were the results of partially plugged pressure regulators. A low catch followed by a high catch was also observed at the ends of the boom. The grower subsequently changed the nozzle configuration at the ends of the booms to decrease the over application at the ends and improve the uniformity underneath the ends. Figure 6 gives the potential application efficiency and uniformity of this system after these two minor issues were corrected. The efficiency of this system was estimated at 86%.

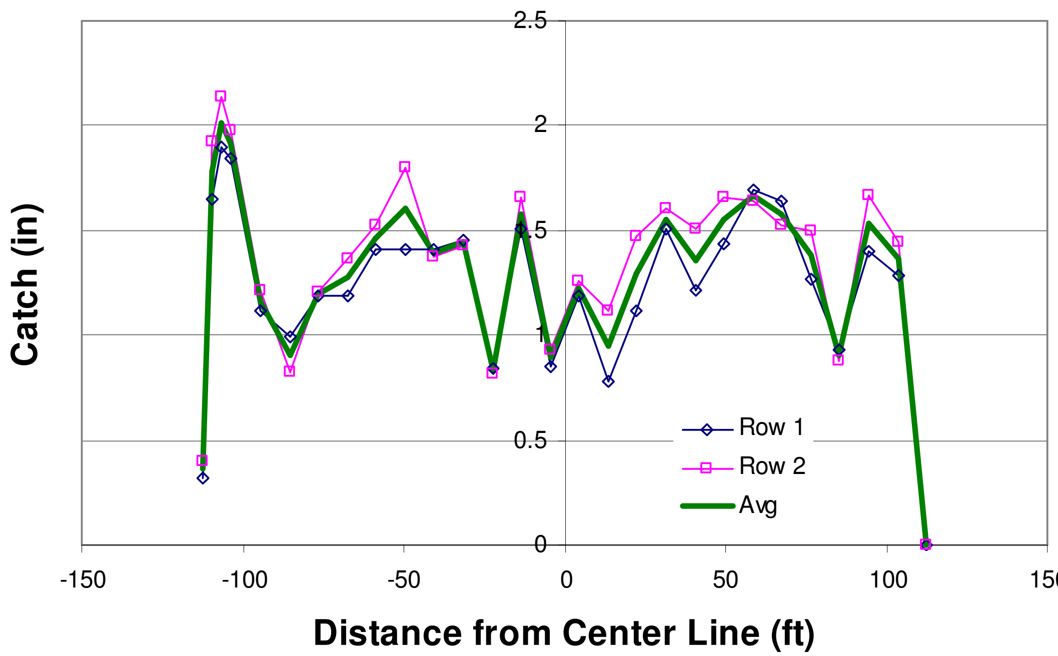

Figure 4. The catch of boom system #1 at various distances from the center line.

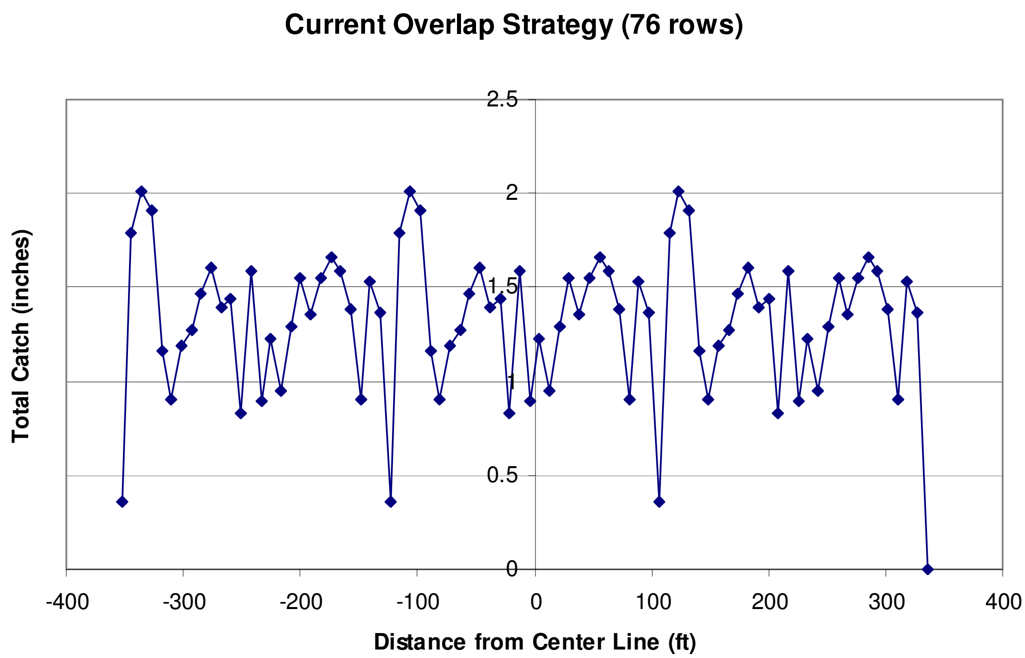

Figure 5. Three overlapping pulls of Boom 1 if the exact pattern is replicated on a 76 row spacing resulting in a DU_{LQ} of 0.64.

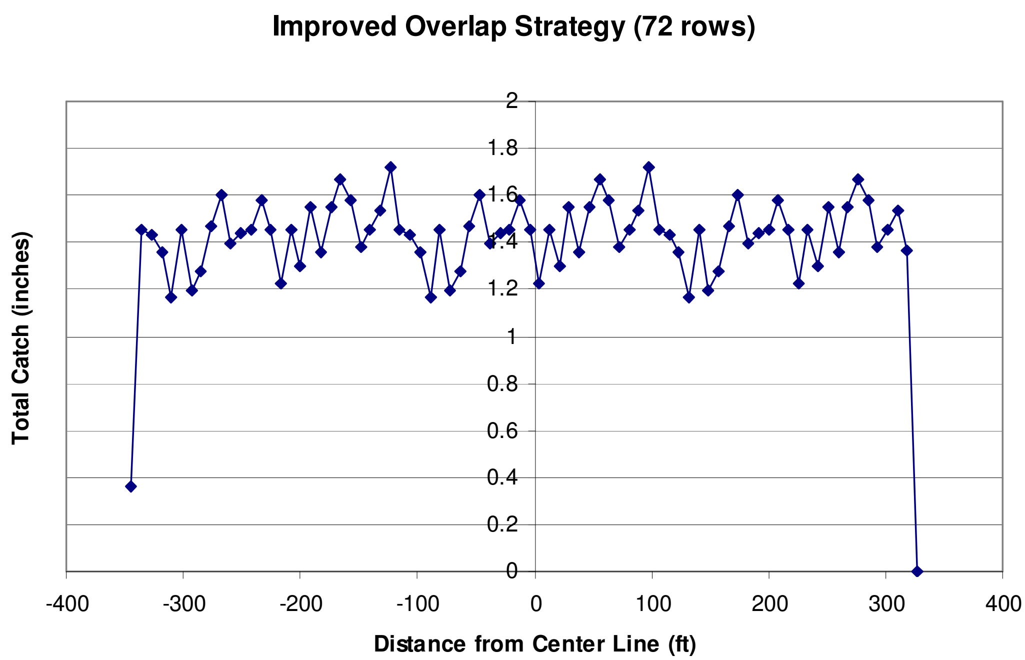

Figure 6. An improved overlap strategy for Boom 1 of 72 row spacing and with the fixing of plugged nozzles resulting in a DU_{LQ} of 0.88.

Boom Evaluation 2

This was done on a Greenseeker reel and the boom was manufactured by Briggs. The reel was driven by a small gasoline engine. Pressure at the pump was 100 psi (much more than necessary) and was regulated at the boom nozzles to 20 psi. The catch can results are shown in figure 7 and the current overlap strategy would give the application pattern in figure 8. Figure 9 gives the potential application efficiency and uniformity of this system on a 78 row spacing. The efficiency of this system was estimated at 85%.

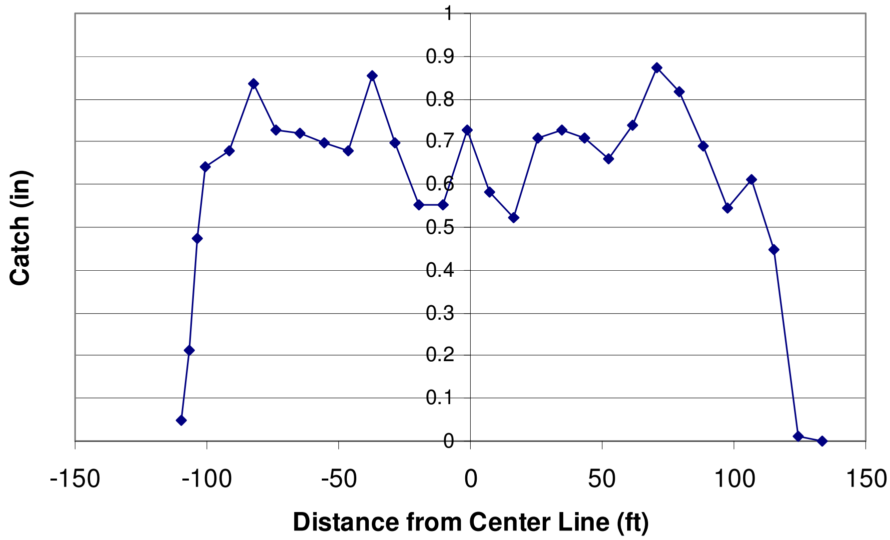

Figure 7. The catch of boom system #2 at various distances from the center line.

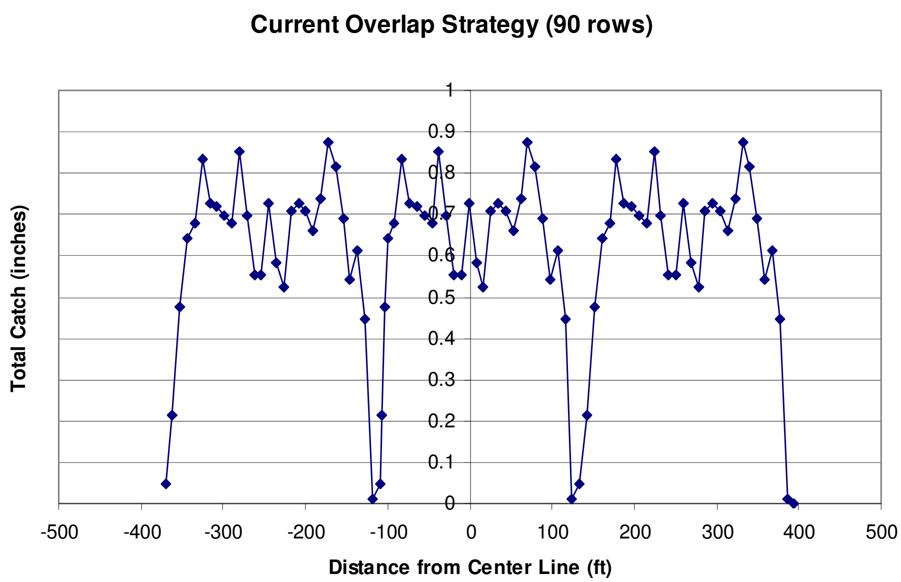

Figure 8. Three overlapping pulls of Boom 2 if the exact pattern is replicated on a 90 row spacing resulting in a DU_{LQ} of 0.53.

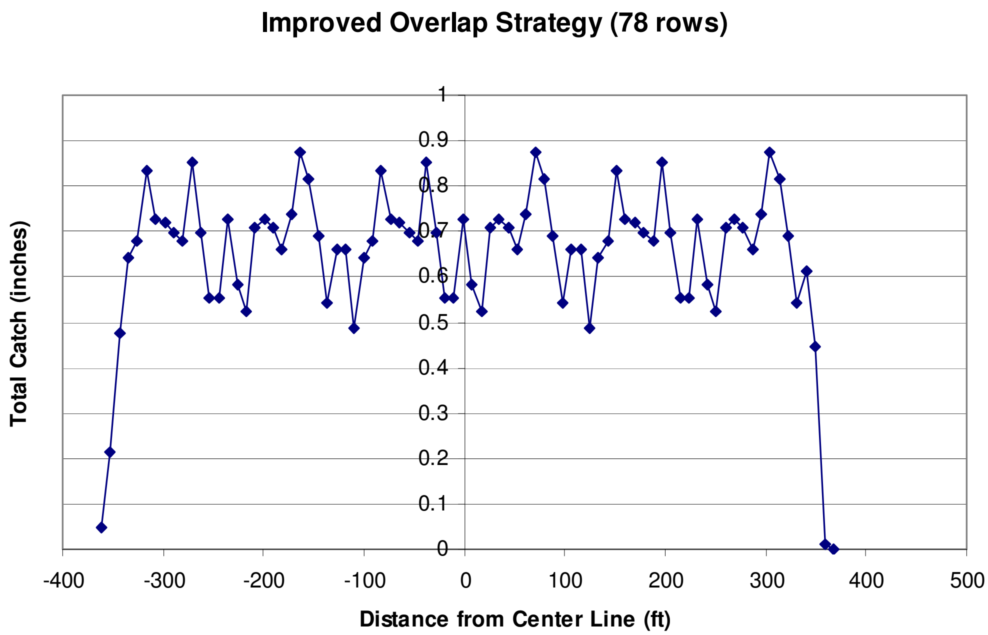

Figure 9. An improved overlap strategy for Boom 2 of 78 row spacing resulting in a DU_{LQ} of 0.81.

Summary of Results

The results and comparison of the results is summarized in Table 1. Since the objective of the study was to compare a big-gun to a boom system the DULQ that would have been possible with good overlap and without plugged nozzles is also given for both systems and should be the basis for making comparisons between the two systems.

Table 1. Summarized Results

	Big-gun 1	**Big-gun 2**	**Boom 1**	**Boom 2**
Efficiency	58	60	86	85
Evaluation DU_{LQ}	0.20	0.57	0.64	0.53
Possible DU_{LQ}	0.75	0.86	0.88	0.81
Pump Pressure (psi)	150	130	55	100
Possible	150	130	55	35

The efficiencies and distribution uniformity numbers for the big-gun evaluations and boom systems are consistent with what was expected. A typical efficiency for a big-gun irrigation system is about 60%. Since their water application method is essentially the same as a center pivot a boom was expected to have efficiencies in the same range as a center pivot (80-85%) which is what was measured. Therefore, on a boom system 42% more usable irrigation water is delivered to the soil compared to a big gun. A big-gun is inherently less efficient because the water spends so much time traveling through the air before it reaches the soil. Water droplets from a big-gun typically spend about 3 seconds traveling through the air. This gives much more opportunity for water to evaporate on its way to the soil. It also gives the wind more opportunity to distort the application pattern. Although under ideal conditions the distribution uniformity of both systems was comparable, the big-gun is much more susceptible to poor uniformity due to higher wind conditions than the boom system was. It was also interesting to note that in all cases (big-gun and boom) uniformity could be very significantly improved by increasing the overlap by just a few rows. This may be equivalent to one or two extra pulls per field.

Economic Comparisons

Although a boom cart costs significantly more than a big-gun cart, there are potential cost savings because it runs at lower pressure. Energy costs are directly related to pressure and flow rate. If the pressure is cut in half then the energy costs can be cut in half (assuming that the pump is changed so that equivalent pumping plant efficiencies can be obtained). Not only will this result in lower seasonal energy bills but it will require less expensive pumps (lower horse power). Pump horsepower can be reduced since less water must be pumped per unit area irrigated due to higher application efficiency of the boom system.

An analysis was done to compare potential costs of both a big-gun and a boom system for a typical grower in North Western Washington. An electrical pumping plant was compared with a diesel engine pumping plant. The following assumptions were made for both systems regardless of whether it was a big-gun or a boom:

- Water lift from the water source to the pump of 20 ft,
- Flow rate of 350 gpm,
- 100 acres are irrigated per system,
- Seasonal irrigation requirement of 6 inches,
- Power transmission efficiency from motor to pump of 95%,
- Water pump efficiency of 80%, and
- Electrical motor efficiency of 85%, diesel motor efficiency of 33%.

Electricity rates used were the current irrigation power rates (summer 2007) from Puget Sound Energy of 5.74 cents/KWH for consumption less than 20,000 kilowatt-hours (KWH) and 5.08 cents/KWH for consumption exceeding 20,000 KWH. In the most extreme case 38 kilowatts (kW) was demanded which is less than the 50 kW cutoff for a demand charge so no demand charges were applied. Diesel was assumed to cost $4.00/gallon and have 130,500 British thermal units (BTUs) of energy/gallon. It was assumed that 150 psi was required at the pump to adequately operate a big-gun system and that the application efficiency was 60%, while a boom required 50 psi at the pump and had an application efficiency of 85%. Because of a big-gun's lower efficiency more water must be pumped to meet the crops irrigation water needs. The results are given in Table 2.

Table 2. Comparison of typical annual energy costs for the big-gun and boom systems in Skagit and Whatcom Counties.

	Electric		Diesel	
	Big-gun	**Boom**	**Big-gun**	**Boom**
Energy Cost per Season	$ 2,585	$ 723	$ 13,014	$ 3,396
Cost per acre-in	$ 2.59	$ 1.02	$ 13.01	$ 4.81
Reqd Motor Size (hp)	43	16	43	16

Running a boom system instead of a big-gun resulted in a total season energy savings (difference between the energy costs of big-gun and boom) of **$1,862** for an electric pumping plant, and **$9,618** for a diesel pumping plant.

Although a boom system has obvious pumping energy savings it can require more labor to move than a big gun and would therefore result in higher labor costs. If an additional 30 minutes per move (interviewed growers reported 15 minutes additional time required or less) is allocated for moving a boom system for 160 moves per season at a skilled labor rate of $15/hour, there will be an additional labor cost of **$1,200** per season in labor costs to move a boom compared to a big-gun.

If we further assume that energy rates will escalate at 11% per year (conservative estimate), that a grower could get a 10% return on otherwise saved money (unsecured investments), and that the boom system will last 15 years with no salvage value, then *the net present value of converting from a big-gun to a boom* (including energy, additional labor costs, and subtracting annualized equipment costs) is **$9,623** for an electric pumping plant and **$122,390** for a diesel pumping plant. This net present value of converting should be compared to the additional upfront cost of the cart to determine whether it is cost effective to convert. At the time of publication a new boom cart costs approximately $40,000. Since $122,390 is much larger than $40,000, in this scenario a grower using a diesel powered pump would save a significant amount of money over the life of the system by purchasing a boom cart and replacing their big-gun. A grower using an electrical pumping plant would not save money by converting, however.

These cost differences are the results of *only* energy savings. Things that were *not* considered that will also *have very real effects on the economics of converting from a big-gun to a boom type system are:*

- Return to the producer due to increased crop yields and quality that will result from better uniformity of booms (especially under windy conditions). Although very difficult to predict or quantify, these differences will likely have the greatest effect on a grower's bottom line.
- The differences in the purchase and maintenance costs of lower horse-power pumps needed for boom systems compared to big-guns. These differences will be significant. For comparison, the initial cost of a 6 cylinder diesel pump that will run two guns at 150 psi will be in the neighborhood of $28,000 while a 4 cylinder diesel pump to run two booms at 50 psi will be closer to $20,000.
- To compensate for poor uniformity additional water must be applied to adequately irrigate all areas of a field. This additional water and pumping costs were not included. These differences can be significant.

All of these unconsidered factors provide further (in addition to the energy cost differences calculated above) economic incentives to convert from big-gun carts to booms.

Practical Considerations

- A big-gun nozzle is large enough to pass most debris moving in an irrigation line. However, boom system nozzles and pressure regulators have significantly smaller orifices and will plug with much smaller diameter debris. A filter will likely be needed if converting from a big-gun to a boom system, depending on how clean the source water is.

- High wind conditions appear to not only push an application pattern to one direction, but also to tighten it up as well. This means that under windy conditions growers can improve uniformity by decreasing the spacing between pulls. Unfortunately this will increase the number of "pulls" required to adequately irrigate a field. This is complicated by the fact that wind conditions often change over the course of a day.
- Despite any irrigation systems' inherent advantages and disadvantages, good irrigation scheduling and management have a large effect on energy cost savings and crop yield and quality.
- Proper pressure at the nozzles is important for uniform and efficient water application. Saving pumping energy costs by operating sprinklers at pressures below manufacturer recommendations can result in poor irrigation uniformity and poor yields, crop uniformity and crop quality. This may actually hurt a grower's bottom line.
- Maximizing the spacing between "pulls" is attractive because it decreases labor requirements, but irrigation uniformity and therefore crop yields and quality can suffer greatly.

Conclusion

Under ideal conditions and optimal spacing, boom systems had similar distribution uniformity to big-gun systems. However big-guns were much more susceptible to poor uniformity in higher wind conditions and the overlap should be increased (fewer rows between pulls) under high wind conditions. In general, the uniformity of all the systems measured could be improved greatly by increasing the overlap. The application efficiency of the big-guns was about 60% compared to 85% for booms. This means that with a boom system, 42% more irrigation water makes it to the soil compared to a big gun. The lower pressures required by a boom and the water savings would likely make the transition to a boom system cost effective due to energy savings alone for those using diesel pumping plants. Those using electric pumping plants will likely see less economic benefits due to energy savings by converting. Although an irrigation system may have very real limitations, good management of existing systems is as important if not more important, to good crop uniformity and quality.

Canal Seepage Reduction by Soil Compaction

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Abstract. *Large-scale tests were conducted of in-place compaction of irrigation district earthen canal bottoms and sides. Five canal pools with sandy loam soils were compacted, with four results presently available. Seepage reduction of about 86% was obtained when the sides and bottoms were compacted; reductions of 12 – 31% were obtained when only sides were compacted.*

Keywords. irrigation, canal, compaction, seepage, irrigation district

Introduction

Irrigation districts that rely upon long, open canals share a common problem: canal seepage. Canal seepage can create difficulties including:

- Reduced water deliveries to farmers
- Increased pumping costs if the water in the canals is lifted by pumps
- Increased drainage problems, possibly causing crop yield and health problems
- Loss of water supply in a basin if the seepage goes to a salty aquifer or into the ocean
- Increased diversion from rivers, resulting in decreased in-stream flows

The two most common solutions for reducing seepage are lining canals or replacing them with pipes. These options bring along with them additional benefits, such as stabilization of banks (canal lining) or reduced need for access and fewer drownings (pipelines). However, these solutions are expensive. A typical piping cost in California for an irrigation district is in the neighborhood of $120 - $200/foot for pipe sizes in the 4' – 5' range (flows in the 20 – 30 CFS range). Canal lining costs are often in the neighborhood of $1 million per mile, which is prohibitive for most irrigation districts.

Therefore, the Irrigation Training and Research Center (ITRC), with support from CALFED and the California Agricultural Research Initiative, has experimented with an uncommon method of seepage reduction – in-place compaction of canal banks and canal bottoms.

Concepts of Soil Compaction

The general concepts of soil compaction for seepage reduction and soil consolidation are well documented in civil engineering, under the category of "soil mechanics". Everyone is familiar with compaction of soils for roadways, even if they do not understand the technical details. Additionally, many people are aware that two of the major dams in California (Oroville Dam and San Luis Dam) are earth-filled dams rather than concrete structures.

Soil laboratory tests for compaction (Proctor and Modified Proctor) have specified procedures by ASTM. Samples of soil are compacted by specified layer thicknesses, by specified weights dropped a specified number of times from a specified height. In a compaction test, this is typically done with a number of samples, each of a different moisture content. A graph such as Figure 1 is developed, illustrating what the moisture content should be during construction.

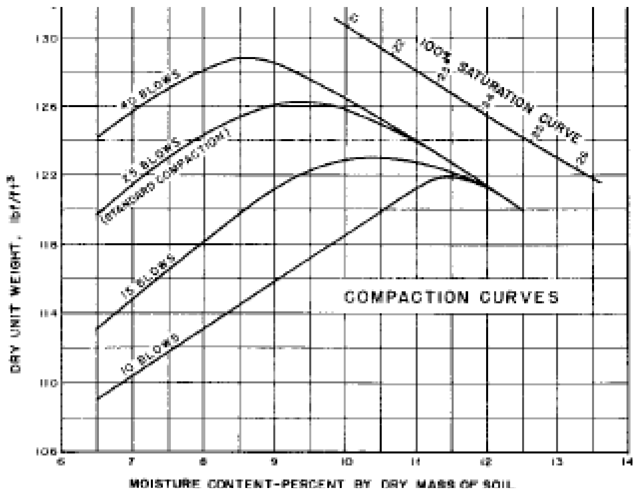

Figure 1. Compaction curves (USBR, 1998)

It is relatively common knowledge that some soils compact better than others and that as the level of compaction increases, the soil hydraulic conductivity (seepage rate) decreases. Optimum compaction will also depend upon the moisture content during compaction. If the soil is too moist or too dry, it will not achieve the "optimum bulk density". Different compaction techniques are suited for one soil or another, as shown in Table 1.

Table 1. Compaction equipment (Bader, 2001)

Effect of Soil Type on Equipment selection				
		Vibrating Sheepsfoot Rammer	**Static Sheepsfoot Smooth Roller**	**Vibrating Plate Vibrating Roller**
	Lift Thickness	*Impact*	*Pressure*	*Vibration*
Gravel	12 in.	Poor	No	Good
Sand	10 in.	Poor	No	Excellent
Silt	6 in.	Good	Good	Poor
Clay	6 in.	Excellent	Very Good	No

Additionally, the optimum moisture content for high bulk density does not necessarily translate to the optimum moisture content for reduced seepage. There are differences between laboratory and field activities and results. Some engineers believe that a slightly-moister-than-"optimum" soil in the field provides the best seepage reduction.

Soil Compaction for Sealing Canals

Perhaps the best source for information on earth lining of canals is a publication by ANCID (Australian National Committee on Irrigation and Drainage, 2001) entitled "Open Channel

Seepage and Control". This publication, as well as others, focuses on bringing soil material to the site one layer at a time and compacting each layer. The publication does mention "in situ" compaction – which is in-place compaction of existing canal banks and bottoms. The senior author has talked to engineers from dozens of irrigation districts in California about this, and has not encountered anyone who has tried it before this experiment.

Field Experiments in California

ITRC contacted four irrigation districts in the San Joaquin Valley of California who were experiencing seepage problems:

- Panoche WD
- Chowchilla WD
- San Luis Canal Co (also known as Henry Miller Reclamation District)
- James ID

Seepage tests were conducted on two Panoche WD canals, and it was determined that the seepage rates were very low. Plus, the soil was a heavy silty clay loam and it would have been impossible to dry the soil out enough for compaction without just making mud.

The other three districts had sandier soil, so compaction trials were conducted there. The results of one canal compaction effort in Chowchilla cannot be reported because the well that would have supplied the water for post-compaction seepage tests failed and was not repaired.

All the compaction work was "in-situ", meaning that there was no addition of soil, and no over-excavation and replacement of compacted soil layers. The compaction was performed on the soil surface "as-is" with the exception of some smoothing of canal banks.

Seepage Tests. Prior to, and after compaction, ponding tests were conducted to determine the seepage rates. The ponding tests involved the following:

- The entire canal pool that was compacted was filled with water to the normal operating depth.
- The ends of the pool were sealed to prevent water from entering or leaving the pool.
- Weather data was recorded from the nearest CIMIS station, to estimate evaporation losses.
- Redundant water level sensors were installed to measure the change in water depth versus time.
- The water was replenished occasionally with a metered supply to maintain a fairly constant water level.
- Water temperatures were measured, to correct for different viscosities in pre- and post-compaction tests.
- Measurements began after water had been standing in the pool for several days, and continued for 1-3 days.

Figure 2. James ID Main Canal during pre-compaction seepage test.

Figure 3. James ID Main Canal during side compaction

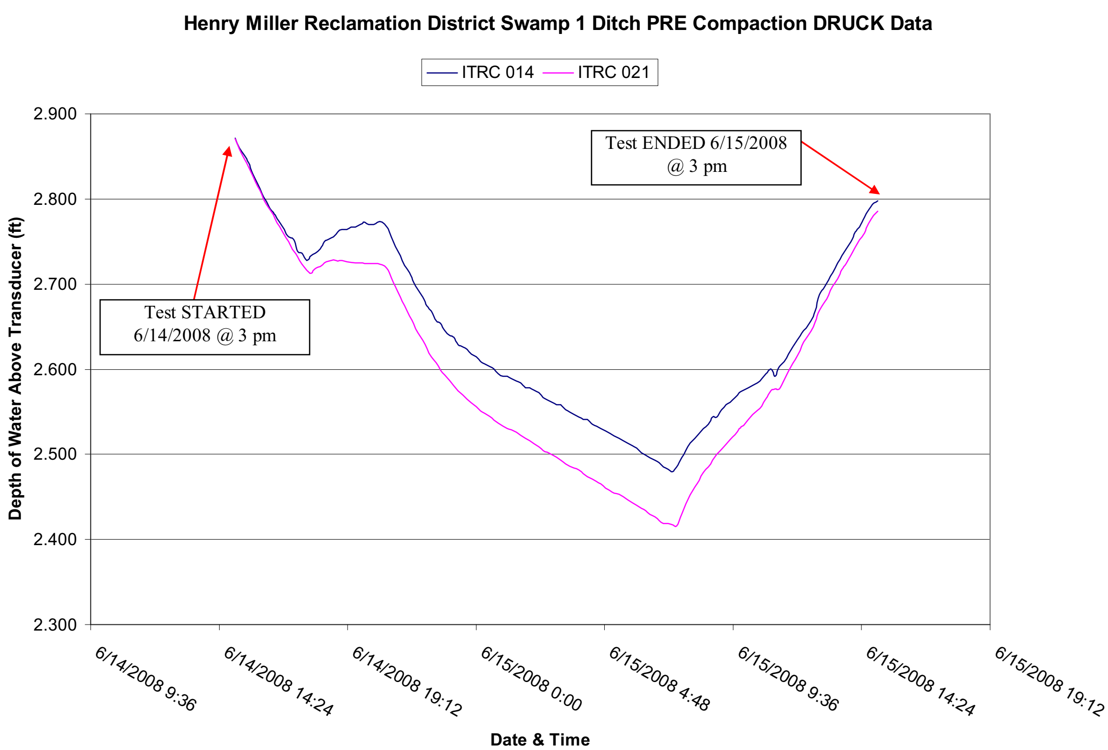

Figure 4. Pressure transducer data for ponding test – San Luis Canal Co (Henry Miller RD)

Soil Preparation. During the first compaction work at Lateral H in James ID, it was learned that if the canal banks were smoothed off, the compactor could operate much more quickly. Subsequent locations were therefore lightly smoothed off. There was no opportunity to obtain the "optimum" moisture content for compaction. Field conditions and availability required that the compactor begin work as soon as the canal had dried down enough to use the equipment without making mud. Certainly, moisture contents were different at various depths in the bands and bottom.

Laboratory Tests. Soil samples were taken in the field for a number of reasons. In some cases, undisturbed core samples were taken to measure bulk density before and after compaction. Texture samples (about 20 per canal section) were taken at various depths. Laboratory experiments were run with the modified Proctor test to determine optimum moisture contents for compaction, and the effects on hydraulic conductivity. Those laboratory results and their correlations with the field results have not yet been completed.

Equipment and Costs. The soil was compacted using a 45-thousand pound Kobelco excavator with an MBW 36-inch roller attached to the end of the boom. Installed immediately between the UVW-36 roller and the end of the excavator boom was a UV-10K exciter. This exciter is a hydraulically driven vibration mechanism. Since the vibratory exciter was hydraulically driven, the excavator operator could engage and disengage the exciter when he felt it was necessary.

The compaction accessories cost about $25,000 (not including the cost of the excavator) installed. An experienced operator was able to compact the sides of 1 mile of canal (both sides, meaning 2 miles total) in about 8 days. The cost for the operator, transport of the excavator, and the excavator rental was about $1.20/foot of canal, with about 10 feet of compaction on each side of the canal (cost = $1200 for 1000' long pool).

Figure 5. MBW 36" vibratory roller attached to the end of an excavator arm.

Figure 6. Compacting the sides and bottom of Lateral H at James ID

Figure 7. Compacting the canal banks on the James ID main canal with an MBW vibratory roller

Results

Table 2 shows the results of the in-situ compaction. Seepage reduction varied from 12% to 89%. Clearly, the two sites at which the canal bottom was compacted had much better results than the two sites at which only the sides were compacted. The seepage differences were probably due to additional factors, but this appears to be one possible explanation.

Table 2. Compaction results

Irrigation District	Location	Compaction		Cost, $	L, ft	Canal width, ft	Texture	Pre-Seepage, GPM	Post-Seepage, GPM	% Seepage Reduction
		Sides	Bottom							
Chowchilla WD	Site #2 – Ash Main Canal, between roads 11-12	Y	N	4,845	4,240	27	Loamy Sand	143	126	12*
James ID	Lateral H, from Main Canal to TO	Y	Y	3,240	1,010	15	Sandy Loam	86	12	86
James ID	Main Canal	Y	N	15,800	10,238	58	Sandy Loam	252	173	31
San Luis Canal Co.	Swamp 1 Ditch, between Turner Island & Deep Well	Y	Y	1,945	1,730	27	Sandy Loam	130	14	89
San Luis Canal Co.	East Delta Canal	Y	Y – with ride-on	Pending	3,020	19	Loam	80	Pending	Pending

*The Chowchilla WD site had sections of rip-rap along the canal banks that could not be compacted, resulting in a lower % seepage reduction

Conclusion

For sandy loam soils, in-situ compaction with a vibratory roller reduced seepage. The seepage reduction was significant (86 – 89%) when both the sides and bottom were compacted. The compaction extended to a depth of about 2 feet, so it is suspected that the seepage reduction will withstand normal maintenance activities from year to year.

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CONSIDERATIONS WHEN CONVERTING TO PRECISION IRRIGATION

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Summary

Decisions to make when considering converting from surface irrigation to another form can be overwhelming. What type of irrigation should I to switch to? What changes will I need to make to my management? How do I make this as easy as possible?

This paper will focus on suggested steps and the irrigation equipment considerations that will make the transition easier, more efficient, and more cost effective when a farmer decides to change from surface to mechanical move irrigation.

Introduction

The profitability of converting from surface irrigation to precision irrigation has been discussed many times in the central plains states (Dhuyvetter, 1996) with the focus on differing pumping capacities on crop yield and revenue. In most of these cases, the items considered include the cost of the pumping and irrigation systems, changes to production costs, and potential on yield. To a lesser extent, some discussion has focused on potential labor savings. The studies date back for years and include, but are not limited to, Dhuyvetter 1996, Lamm, et.al. 1997. These studies focused on the impact of sprinkler irrigation capacity on corn yield potential, as well as economics. Some manufacturers offer information for the conversion (Lindsay, 2003 and Valmont, 2003).

In recent years, with the help of the EQIP program, economics have changed and farmers are considering conversion from surface flooding to other forms of irrigation, in order to reduce farm water use. Another incentive for conversion is water limitations, either through availability or regulation. This is becoming more of a consideration throughout the central plains states. Grain prices also have a significant impact on conversion considerations Corn futures are now closing over $5.00 per bushel, as compared to corn prices in past studies of $2.50 per bushel (O'Brien, 1998).

For a grower today who is considering conversion to a form of precision irrigation, the following questions need to be taken into consideration: What steps can be taken to ensure the best long-term solution? How might a I proceed? What should be part of the considerations when making a major irrigation change in my operation?

Discussion

To begin the process, one should consider the following steps before talking with an irrigation supplier. This prepares the grower, and helps them focus on the items of particular importance to their operation. Also, the irrigation dealer and/or consultants should help encourage the grower to follow through a decision-making process to reach the optimum decisions regarding conversion. The crop consultant may be of assistance at several points throughout the decision-making process in order to provide data and/or recommendations about the production plan.

1) Start with a review of current management and cropping plans
    a. Does conversion fit into the long-term plan for the operation?
        i. Cropping/rotation plans
        ii. Expansion
    b. What are the primary reasons for making a change?
        i. Labor availability
        ii. Water availability
        iii. Overall profitability

2) Perform a field resource inventory (the crop consultant may have good input at this stage)
    a. Available water supply
    b. Available power supply
    c. Soil types
    d. Field size and shape
    e. Field "problems" – is there an area that has never yielded the way the grower would like? Do challenges that would hinder a conversion such as buildings, power lines or topography exist?
    f. Changes that will be needed to existing farm equipment if conversion is completed

3) Consider irrigation equipment options that may be a best fit. (At this stage, do not rule out any options.)
    a. Drip or SDI
    b. Mechanized irrigation

4) Select a partner to help with the conversion process
    a. Interview potential irrigation equipment suppliers
        i. Explain what is being considered and your needs

        ii. Show the information that has been collected
    b. Look for a partner who:
        i. Is open to listening to you
        ii. Understands your needs and your field
        iii. Understands the value of converting to your operation
        iv. Has product options for consideration
        v. Does not immediately jump to make a quotation
        vi. Has finance options and understands cost share programs
    c. Consider more than just the sales person of the dealership
        i. Long term support in service and parts
        ii. Experience with the options presented
        iii. Talk with your neighbors about their experiences with the dealer
    d. Request a proposal to use as part of the comparison. Look for:
        i. Does the proposal offer options?
        ii. Is financing and cost share information presented?
        iii. Is operating cost addressed?
        iv. Is the proposal addressing the overall farms needs?

5) Once the partner is selected, review goals. Is it to:
    a. Maximize the area covered in the field?
    b. Maximize returns from the field?
    c. Maximize returns for the farm?
    d. Minimize investment?
    e. Minimize labor?
    f. Minimize operational expense?

6) Review the management plans and agricultural practices anticipated for the new precision irrigation system
    a. Crops
    b. Application of crop production products such as nutrients, herbicides, insecticides, etc
    c. Tillage practices

7) Review the options presented by the irrigation dealer
    a. Type of irrigation equipment
        i. Area covered
        ii. Options on the equipment
        iii. Ease of use
    b. Initial investment
        i. Financing plans
        ii. Cost share programs
    c. Operating costs
    d. Life expectancy of the equipment
    e. Labor requirements
    f. Ability to automate

8) Take the time to consider the long term impacts of the decision
    a. Well manufactured, designed and applied mechanized irrigation equipment should last for at least twenty years
    b. Conversion to precision irrigation should make life easier and not harder
    c. Realize it may take two years to begin to reach your goals

At this point, a grower should be ready to make a decision on how they want to proceed. But before proceeding, consideration should be given to the specific type of irrigation equipment. Many times, one automatically assumes the best solution for their situation is a center pivot, as it may well be. But a grower should consider other options, and look for an irrigation equipment supplier who is open to considering such options.

Whether the primary goal is maximizing the area irrigated, minimizing operating costs, or maximizing profits, several options are available for consideration:

- Drip and SDI
    - Advantages
        - Maximizes area covered in irregularly shaped fields
    - Disadvantages
        - Initial investment
        - Germination of crop
- Towable center pivot
    - Advantages
        - Maximizes the area covered by using one center pivot over multiple fields
        - Can always add a fixed pivot in the future
    - Disadvantages
        - Labor – will require time to go to the field, prepare the center pivot for towing, actual towing and switching back from tow to operation
        - Pumping rate – flowrate needs to be more than what is required for the areas irrigated to allow for downtime and towing

- Center pivot with corner arm
    - Advantages
        - Maximize the area covered – corner arm can be folded in and out to dodge obstructions
        - Uniform watering over the entire field
    - Disadvantages
        - Initial investment
        - In some situations may have more wheel track issues

- Linear
  - Advantages
    - Will maximize the area covered in a square or rectangular field
    - Wheel tracks may fit cropping plan better
  - Disadvantages
    - Initial investment
    - If a hose drag, may require labor to switch the hose
    - If a ditchfeed, ditch maintenance is required

- Options to consider for all mechanical move irrigation equipment
  - Floatation options (not available for towable machines) – to minimize the wheel tracks and avoid getting stuck
  - Sprinkler package – to maximize productivity from the crop and the soil
  - Pipeline materials – different options available depending on the crop production products used
  - Automation capabilities
    - Control panel for off-peak operation
    - Automatic changes to manage water applied for different sectors of the field
    - Remote monitoring and/or control options
  - High speed operation to allow for minimal water applications for germination and application of crop production products.

Conclusions

Decisions to make when considering converting from surface irrigation to another form of irrigation can be overwhelming. What type of irrigation should I to switch to? What changes will I need to make to my management? How do I make this as easy as possible?

This discussion has focused on eight steps to consider in order to help make the decision-making process simpler. It is critical for the grower to have a goal in mind, such as why to convert, and then follow through to see that this goal is achieved. Options need to be considered in order to determine the best equipment solution for the situation. Remember depending on the grower's specific situation, numerous options exist to meet the farmer's expectations and goals.

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EFFECTS OF EARLY-SEASON WATER STRESSES ON CORN PRODUCTION

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ABSTRACT: The corn vegetative stage is often considered the least sensitive stage to water stress and could provide the opportunity to limit irrigation water applications without severe yield reductions. The vegetative stage begins at crop emergence and ends at tasseling when silks begin to emerge. Nine years of research was conducted at the Kansas State University Northwest Research-Extension Center in Colby, Kansas on a productive, deep, silt loam soil where irrigation was delayed in one-week increments, typically ranging from about June 10 to July 20. Delaying irrigation only statistically affected the yield components in three of the nine crop years. Overall, these results suggest that corn grown on this soil type has great ability to handle early-season water stress, provided the water stress can be removed during later stages. In addition to the statistical results, graphical representations indicate that the pertinent yield components are related to measured July crop water use, available soil water, evaporative demand and to the ratio of well-watered evapotranspiration to the sum of irrigation and precipitation.

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KEYWORDS: Corn, irrigation macromanagement, yield components, irrigation scheduling, water stress.

INTRODUCTION

Producers are well aware of the needs of corn for water during the critical reproductive periods, but may want to delay the first irrigation during the vegetative stages. A decision about when to start the corn irrigation season is called a macromanagement decision, which is different than the day-to-day irrigation scheduling decisions during the season. This macromanagement decision can result in significant amounts of water either being used or saved, but does affect corn grain yield. Some yield-limiting stresses that were tolerable at the lower yield level of 30-40 years ago are probably less tolerable today. Additionally, there are irrigation system constraints concerning water application that may confound the understanding of what abilities the corn has to withstand vegetative-period water stress. For example, many irrigation systems cannot apply sufficient amounts of water to replenish depleted soil water reserves during the peak corn water-use periods. A renewed understanding of the biological effects of vegetative-period water stress on corn production appears warranted because there can be solutions to the irrigation system constraints.

The corn vegetative stage is often considered the least sensitive stage to water stress and could provide the opportunity to limit irrigation water applications without severe yield reductions. The vegetative stage begins at crop emergence and ends after tasseling, which immediately precedes the beginning of the reproductive period when the silks begin to emerge. The potential number of ears/plant is established by the fifth leaf stage in corn. The potential number of kernels/ear is established during the period from about the ninth leaf stage until about one week before silking. Stresses during the 10 to 14 days after silking will reduce the potential kernels/ear to the final or actual number of kernels/ear. Therefore, in research studies designed to examine water stresses during the first one-half of the corn crop season, both ears/plant and kernels/ear might be critical factors. Additionally, there could be permanent damaging effects from the vegetative and early-reproductive period water stress that may affect grain filling (kernel weight). The objectives of this study were to examine the effects of delaying the first irrigation during the vegetative and early-reproductive periods on corn production. Pertinent factors were corn yield and yield components as affected by irrigation dates, total water use, evaporative demand, and critical levels of soil water.

PROCEDURES

The study was conducted at the KSU Northwest Research-Extension Center at Colby, Kansas USA on a productive, deep, well-drained Keith silt loam soil (Aridic Argiustolls) with funding from Pioneer HiBred, Inc. during the four-year period 2004-2007 using two corn hybrids [Pioneer 32B33 (full season,118 days to maturity) and Pioneer 33B50 (medium season, 112 days to maturity)]. An additional five years of data (1999-2003) was added to the analysis for the hybrid Pioneer 3162 (full season, 118 days to maturity). The corn was planted in late April to early May, and standard cultural practices for the region were used. Both studies utilized the same field site that had a subsurface drip irrigation (SDI) system installed in 1990 with 5-ft dripline spacing and an emitter spacing of 12 inches. The 2.5-ft spaced corn rows were planted parallel and centered on the driplines such that each corn row would be 15 inches from the nearest dripline. The nominal dripline flowrate was 0.25 gpm/100 ft, which is equivalent to an emitter discharge of 0.15 gal/h for the 12-inch emitter spacing. The 2004-2007 study had six main irrigation treatments and the two corn hybrid split-plot treatments replicated three times in a randomized complete block (RCB) design. The 1999-2003 study used the same experimental design without the split plot.

Irrigation was scheduled as needed by a climate-based water budget except for the specific treatment delays. Calculated water use was determined with a modified Penman equation with empirical crop coefficients suitable for western Kansas. The six irrigation treatments were imposed by delaying the first normal irrigation either 0, 1, 2, 3, 4, or 5 weeks. This would typically result in the first irrigation for Trt 1 being between June 5 and June 15 and the first irrigation for Trt 6 being around July 10 to July 24. The actual dates of treatment initiation are in Tables 1 and 2. The corn silking period typically occurs between July 15 and 20. In some years, excessive rainfall between two adjacent treatment initiation dates would negate the need for irrigation. In that case, the later treatments would be delayed an additional week to provide an extended data set. After the treatment initiation date occurred, SDI was scheduled to provide 0.4 inches/day until such time that the climate-based water budget fully eliminated calculated soil water deficits. It should be noted that this irrigation capacity of 0.4 inches/day is much greater than the typical irrigation capacity in this region. Additionally, the procedure of eliminating the severe irrigation deficits later in the season after the plants had been stunted may lead to excessive deep percolation. The purpose of the study was not to optimize irrigation use within the study but rather to determine what capability the corn crop had to tolerate early season water stress. Thus, the procedures were tailored to alleviate soil water deficits relatively quickly after the treatment initiation date. Soil water was measured in each plot on a weekly or biweekly basis with a neutron probe to a depth of 8 ft. in 1-ft increments. These data were used to determine crop water use and to determine critical soil water depletion levels.

Corn yield components of crop yield, plants/area, ears/plant, and kernel weight were measured by hand harvesting a representative 20 ft-row sample. The number of kernels/ear was calculated with algebraic closure using the remaining yield components.

RESULTS AND DISCUSSION

Delaying irrigation only statistically affected the yield components in three of the nine crop years and then only for the later irrigation dates (Tables 1 and 2). Delaying irrigation until July 10, 2001, July 17, 2003 and July 27, 2005 significantly reduced the number of kernels/ear and the grain yield. These 3 years had an average weather-based calculated July crop ET rate of 0.32 inches/day. This compares with an average July crop ET rate value of 0.26 inches/day for the other six years. It should be noted that the years 2000 through 2003 were extreme drought years in northwest Kansas. Delaying irrigation also significantly reduced ears/plant in 2003 and 2005. In 2003, the reduction in kernels/ear and ears/plant for Trt 6 was partially compensated for by a statistically higher kernel weight. Overall, these results suggest that corn grown on this soil type has great ability to handle vegetative and early-reproductive period water stress provided the water stress can be removed during later stages.

Table 1. Summary of yield component and irrigation data from an early season water stress study for corn hybrid Pioneer 3162, KSU-NWREC, Colby, Kansas, 1999-2003.

Year and Parameter		Trt 1	Trt 2	Trt 3	Trt 4	Trt 5	Trt 6
1999	First Irrigation Date	22-Jun	29-Jun	6-Jul	13-Jul	20-Jul	27-Jul
	Total Irrigation (in.)	11.2	11.2	11.2	10.0	10.0	7.6
	Yield (bu/a)	253 a	265 a	256 a	255 a	259 a	255 a
	Plant Pop. (p/a)	31073 a	32234 a	31944 a	31653 a	32234 a	32234 a
	Ears/Plant	0.99 a	0.99 a	0.97 a	1.00 a	0.99 a	1.01 a
	Kernels/Ear	575 a	570 a	555 a	572 a	543 a	555 a
	Kernel Wt. (g/100)	36.3 a	36.9 a	37.8 a	35.8 a	38.1 a	35.9 a
2000	First Irrigation Date	5-Jun	12-Jun	19-Jun	26-Jun	3-Jul	10-Jul
	Total Irrigation (in.)	19.7	19.7	19.7	18.9	18.9	18.9
	Yield (bu/a)	225 a	235 a	225 a	227 a	216 a	217 a
	Plant Pop. (p/a)	27878 a	28169 a	26717 a	26717 a	27007 a	27297 a
	Ears/Plant	1.02 a	1.04 a	0.99 a	1.03 a	1.02 a	1.01 a
	Kernels/Ear	544 a	553 a	568 a	544 a	548 a	529 a
	Kernel Wt. (g/100)	36.9 a	36.8 a	38.0 a	38.4 a	36.4 a	37.8 a
2001	First Irrigation Date	12-Jun	19-Jun	26-Jun	3-Jul	10-Jul	17-Jul
	Total Irrigation (in.)	19.2	19.2	19.2	19.2	19.2	19.2
	Yield (bu/a)	254 a	260 a	261 a	250 a	213 b	159 c
	Plant Pop. (p/a)	33977 a	34993 a	35138 a	35284 a	34413 a	33831 a
	Ears/Plant	0.96 a	0.98 a	0.99 a	0.99 a	0.97 a	0.99 a
	Kernels/Ear	581 a	584 a	582 a	541 a	476 b	347 c
	Kernel Wt. (g/100)	33.8 a	33.2 a	32.8 a	33.7 a	34.6 a	34.9 a
2002	First Irrigation Date	12-Jun	19-Jun	26-Jun	3-Jul	10-Jul	17-Jul
	Total Irrigation (in.)	18.5	18.0	18.0	18.0	18.0	18.0
	Yield (bu/a)	233 a	232 a	217 a	219 a	222 a	223 a
	Plant Pop. (p/a)	34558 a	34848 a	34558 a	35719 a	35719 a	34558 a
	Ears/Plant	0.98 a	0.97 a	0.98 a	0.99 a	1.00 a	0.99 a
	Kernels/Ear	454 a	443 a	407 a	435 a	391 a	422 a
	Kernel Wt. (g/100)	38.6 a	39.8 a	40.3 a	36.6 a	40.5 a	39.2 a
2003	First Irrigation Date	12-Jun	21-Jun	26-Jun	3-Jul	10-Jul	17-Jul
	Total Irrigation (in.)	18.8	18.0	18.0	17.2	17.2	17.2
	Yield (bu/a)	177 a	180 a	190 a	186 a	171 a	93 b
	Plant Pop. (p/a)	32815 a	33396 a	34267 a	33106 a	34558 a	32815 a
	Ears/Plant	0.96 a	0.92 b	0.96 a	1.00 a	0.97 a	0.82 c
	Kernels/Ear	588 a	567 a	576 a	569 a	486 b	262 c
	Kernel Wt. (g/100)	24.1 b	26.2 b	25.5 b	25.2 b	26.8 b	33.6 a

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

Table 2. Summary of yield component and irrigation data from an early season water stress study for corn hybrids Pioneer 33B50 and 32B33, KSU-NWREC, Colby, Kansas, 2004-2007.

Year and Parameter		**Trt 1**		**Trt 2**		**Trt 3**		**Trt 4**		**Trt 5**		**Trt 6**	
2004 First Irrigation	**Hybrid**	8-Jun		28-Jun		13-Jul		20-Jul		27-Jul		3-Aug	
Total Irrig. (in.)		12.8		11.6		10.8		10.8		10.8		10.8	
Yield (bu/a)	33B50	220	aA	213	aA	206	aA	233	aA	245	aA	210	aA
	32B33	226	aA	211	aA	209	aA	222	aA	229	aA	206	aA
Plant Pop. (p/a)	33B50	29040	aA	28169	aA	28169	aA	28169	aA	28750	aA	27878	aA
	32B33	28459	aA	29621	aA	29621	aA	28459	aA	29040	aA	28459	aA
Ears/Plant	33B50	0.85	aA	0.91	aA	0.89	aA	0.93	aA	0.88	aA	0.84	aA
	32B33	0.88	aA	0.80	aA	0.79	aA	0.90	aA	0.83	aA	0.83	aA
Kernels/Ear	33B50	595	aB	574	aB	589	aB	595	aA	648	aA	590	aB
	32B33	624	aA	616	aA	634	aA	600	aA	643	aA	612	aA
Kernel Wt. (g/100)	33B50	38.0	aA	36.8	aA	35.7	aA	38.2	aA	38.2	aA	38.6	aA
	32B33	36.8	aB	36.4	aA	36.2	aA	36.8	aB	37.6	aA	36.4	aB
2005 First Irrigation	**Hybrid**	21-Jun		28-Jun		6-Jul		12-Jul		19-Jul		26-Jul	
Total Irrig. (in.)		13.2		13.2		13.2		13.2		13.2		13.2	
Yield (bu/a)	33B50	254	aA	259	aA	256	aA	238	abA	227	bA	149	cA
	32B33	254	abcA	254	abcA	258	abA	264	aA	235	cA	162	dA
Plant Pop. (p/a)	33B50	28750	aA	28459	aA	28459	aA	28459	aA	29621	aA	28169	aA
	32B33	28459	aA	29040	aA	28459	aA	27848	aA	28750	aA	29621	aA
Ears/Plant	33B50	0.99	abA	1.00	aA	0.99	abA	0.98	abA	0.96	bcA	0.95	cA
	32B33	0.98	bA	0.97	bcA	1.01	aA	1.00	abA	0.96	bcdA	0.94	dA
Kernels/Ear	33B50	641	abA	653	aA	670	aA	604	bA	564	cA	422	dA
	32B33	638	bA	647	abA	644	abA	680	aA	654	abA	421	cA
Kernel Wt. (g/100)	33B50	35.4	aA	35.4	aA	34.5	aA	36.0	aA	35.9	aA	33.6	aA
	32B33	36.2	aA	35.4	aA	35.4	aA	35.5	aA	33.1	aA	35.1	aA
2006 First Irrigation	**Hybrid**	8-Jun		15-Jun		26-Jun		29-Jun		6-Jul		14-Jul	
Total Irrig. (in.)		14.0		13.6		12.8		12.8		12.4		12.4	
Yield (bu/a)	33B50	225	aA	230	aA	220	aB	220	aA	220	aB	206	aB
	32B33	229	aA	234	aA	246	aA	230	aA	241	aA	244	aA
Plant Pop. (p/a)	33B50	27588	aA	27007	aA	28169	aA	28169	aA	27588	aA	27297	aA
	32B33	28459	aA	27878	aA	28459	aA	27878	aA	28168	aA	28169	aA
Ears/Plant	33B50	0.98	aA	0.98	aA	0.99	aA	0.99	aA	0.99	aA	0.96	aA
	32B33	0.96	aA	0.98	aA	0.98	aA	0.97	aA	0.98	aA	0.97	aA
Kernels/Ear	33B50	561	aB	594	aAB	544	aB	547	aB	550	aB	519	aB
	32B33	597	aA	602	aA	618	aA	583	aA	585	aA	612	aA
Kernel Wt. (g/100)	33B50	37.8	aA	37.2	aA	36.8	aA	36.5	aA	37.4	aA	38.7	aA
	32B33	35.7	aA	36.2	aA	36.3	aA	37.1	aA	38.1	aA	37.2	aA
2007 First Irrigation	**Hybrid**	7-Jun		21-Jun		28-Jun		4-Jul		12-Jul		19-Jul	
Total Irrig. (in.)		12.1		11.3		11.3		11.3		11.3		10.9	
Yield (bu/a)	33B50	243	aA	252	aA	250	aA	245	aA	234	aA	213	aA
	32B33	259	aA	235	aA	252	aA	239	aA	255	aA	229	aA
Plant Pop. (p/a)	33B50	29040	aA	29621	aA	29331	aA	28459	aA	29040	aA	28169	aA
	32B33	29040	aA	28459	aA	28169	aA	27878	aA	28459	aA	28169	aA
Ears/Plant	33B50	0.98	aA	0.99	aA	1.00	aA	0.99	aA	0.99	aA	1.00	aA
	32B33	0.98	aA	0.95	aA	0.99	aA	0.99	aA	0.99	aA	0.97	aA
Kernels/Ear	33B50	668	aB	672	aB	693	aA	682	aA	645	aB	597	aB
	32B33	728	aA	724	aA	712	aA	712	aA	714	aA	674	aA
Kernel Wt. (g/100)	33B50	32.5	aA	32.5	aA	31.2	aA	32.4	aA	32.0	aA	32.2	aA
	32B33	31.6	aA	30.6	aA	32.3	aA	30.9	aA	32.3	aA	31.7	aA

Irrigation treatment values within the same row followed by the same lower case letters are not significantly different at P=0.05, and hybrid treatment values within the same column followed by the same upper case letters are not significantly different at P=0.05.

The hybrid selection affected yield in only one of four years, 2006 with the longer season Pioneer 32B33 providing significantly greater yields for the later irrigation initiation dates (Table 2). This is probably because of earlier pollination for the Pioneer 33B50 prior to receiving irrigation. Kernels/ear was significantly less for the shorter season Pioneer 33B50 hybrid in three of four years. Hybrid selection did not affect ears/plant in any of the 4 years. In 2004, kernel weight was significantly higher for Pioneer 33B50 for some irrigation treatments, probably because of the smaller number of kernels/ear for this hybrid in that year.

It should be noted that the results do not mean that irrigation can be delayed in the Western Great Plains until mid to late July. These plots generally started the season with reasonably full soil profiles. Most irrigators do not have irrigation systems with adequate capacity (gpm/acre) to quickly alleviate severely depleted soil water reserves. In addition, it is difficult to infiltrate large amounts of water into the soil quickly with sprinkler and surface irrigation systems without causing runoff problems. Rather, look at these study results as describing the corn plant's innate ability to tolerate vegetative-period water stress.

The tabular data do not give a mechanistic explanation of the results. Attempts were made to relate yield component data to a large number of water factors in the broad categories of water use, evaporative demand, and critical profile soil water levels. Final grain yield was largely determined by the number of sinks or kernels/area (Plants/Area population x Ears/Plant x Kernels/Ear) indicating there was little or no effect on the grain-filling stage imposed by the vegetative and early-reproductive period water stress in these two studies (Figure 1). The individual treatment values of corn grain yield and kernels/area were values compared to the irrigation treatment that had no initial delay in irrigation (Trt 1) to give relative values. In a few cases, the Trt 1 values were not the highest value and, thus, relative values could be greater than one. Deviations below the 1 to 1 unity line in Figure 1 would indicate a permanent negative effect on corn grain yield of early-season water stress because of reduced kernels/area. Deviations above the line would indicate some grain yield compensation resulting from better grain filling of the reduced kernels/area.

Relative kernels/area was found to be reasonably well related to relative July water use, the minimum available soil water in the top 4 ft of the soil profile during July and to the July 1 through July 15 water deficit (Ratio of calculated well-watered corn ETc to the sum of irrigation and precipitation). Further analysis is needed to determine an improved overall relationship involving more than a single factor, but the results from each individual factor will be discussed here.

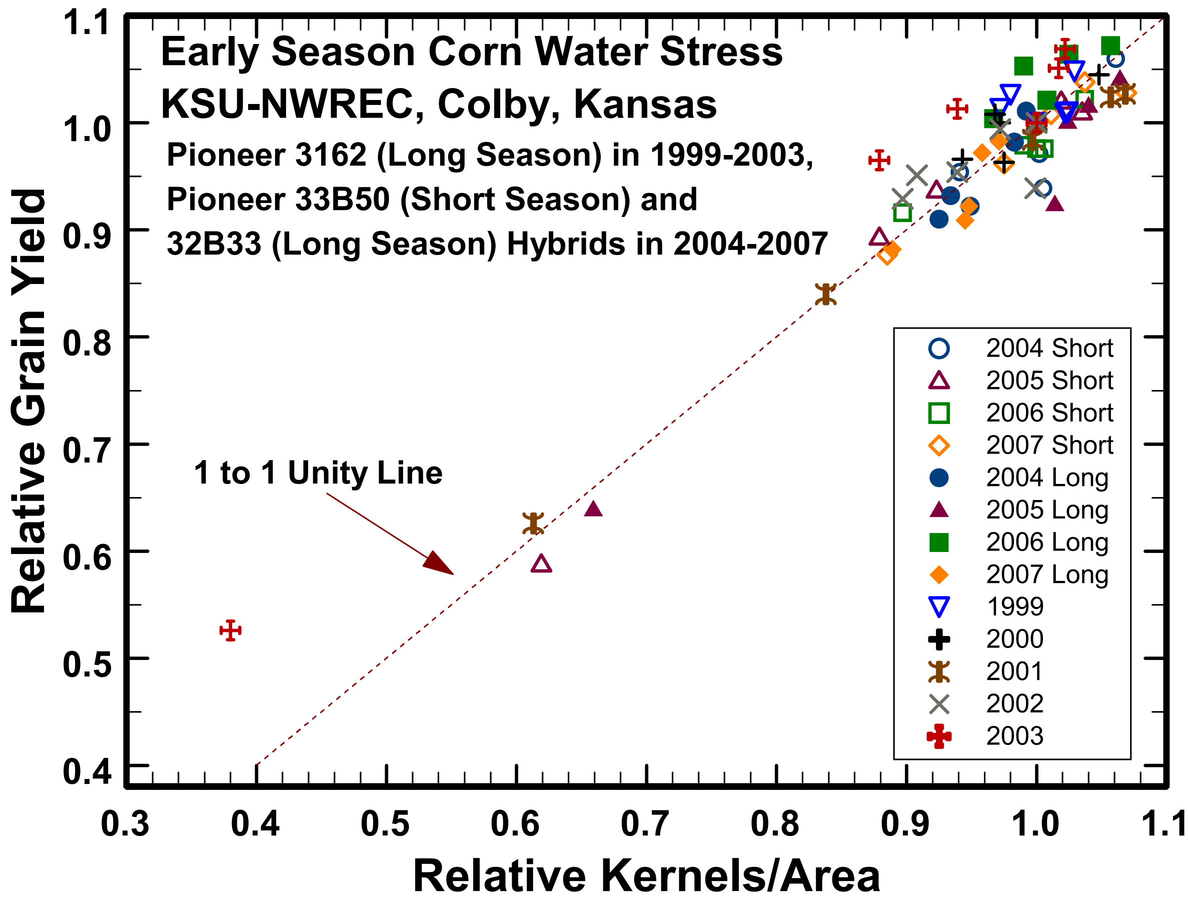

Figure 1. Relative corn grain yield as affected by relative kernels/area in an early-season corn water stress study, KSU-NWREC, Colby, Kansas, 1999-2007.

The 50% critical silking period for corn in this study ranged from approximately July 17 to July 22 during the study period (1999 to 2007). The short-season hybrid in the latter study would typically silk approximately one week earlier. A window of approximately two weeks on both sides around the silking period was used to compare the relative kernels/area to the relative July measured water use (sum of change in available soil water in July plus July irrigation and precipitation). Actual soil water measurements were taken on an approximately weekly basis except for equipment problems or when excessive precipitation delayed measurements, so it was not possible with the data set to always have exactly 31 days of water use. Dates used were those closest to July 1 through 31. There tended to be some reduction in relative kernels/area when relative July water use was less than 80% (Figure 2). Scatter at the lower end of relative July water use may be related to water-use differences occurring within the month or differences in evaporative demand between the years. This relationship may not result in a very good signal for procedures to determine irrigation need because the relative July water use cannot be determined until it is too late to handle the reduction in relative kernels/area.

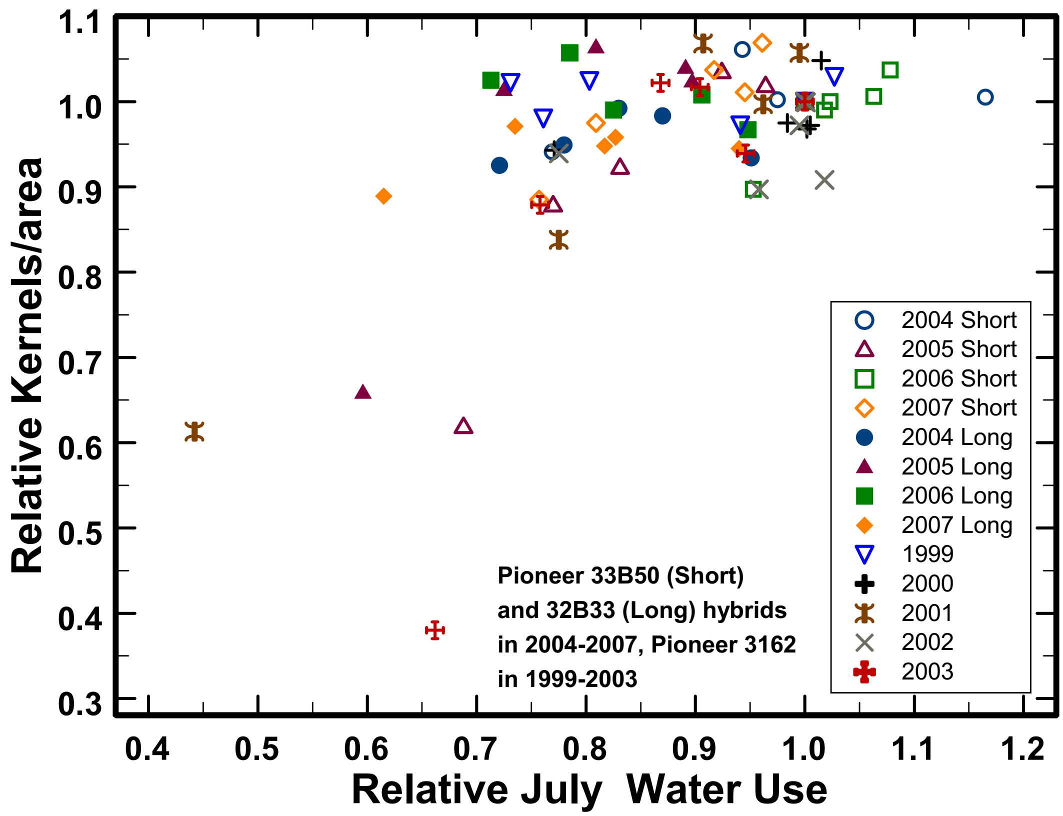

Figure 2. Relative corn grain yield as affected by relative July water use in an early-season corn water stress study, KSU-NWREC, Colby, Kansas, 1999-2007.

The relative kernels/area tended to be reduced when July minimum available soil water in the top 4 ft (JASW) was below 0.6 (fraction) in some years (Figure 3). During years of less evaporative demand, water could be extracted from the soil profile to a further reduced level without much detriment to relative kernels/area, but severe reductions occurred for similar soil water conditions in years with large July evaporative demands. The upper and lower envelope lines of Figure 3 were manually drawn to indicate the effect of evaporative demand of the given year on relative kernels/area. These envelopes would match known theories of water stress and water flow through plants. Water stress is both greater with reduced available soil water and with greater evaporative demand. The kernels/area was most sensitive to the JASW in the top 4 ft of soil as compared to both lesser and greater profile depths. This is reflecting the approximate rooting and soil water extraction depth of corn in July on this soil type. There remains considerable unexplained scatter in this graph that does not appear to be related very well to differences in evaporative demand between the years. For example, there was very little effect on relative kernels/area in 2002, although it had a moderately high evaporative demand. The relationship of relative kernels/area to a critical level of available soil water can have some merit as a signal for determining the need for irrigation because available soil water can both be measured in real time and the value can be projected a few days into the future.

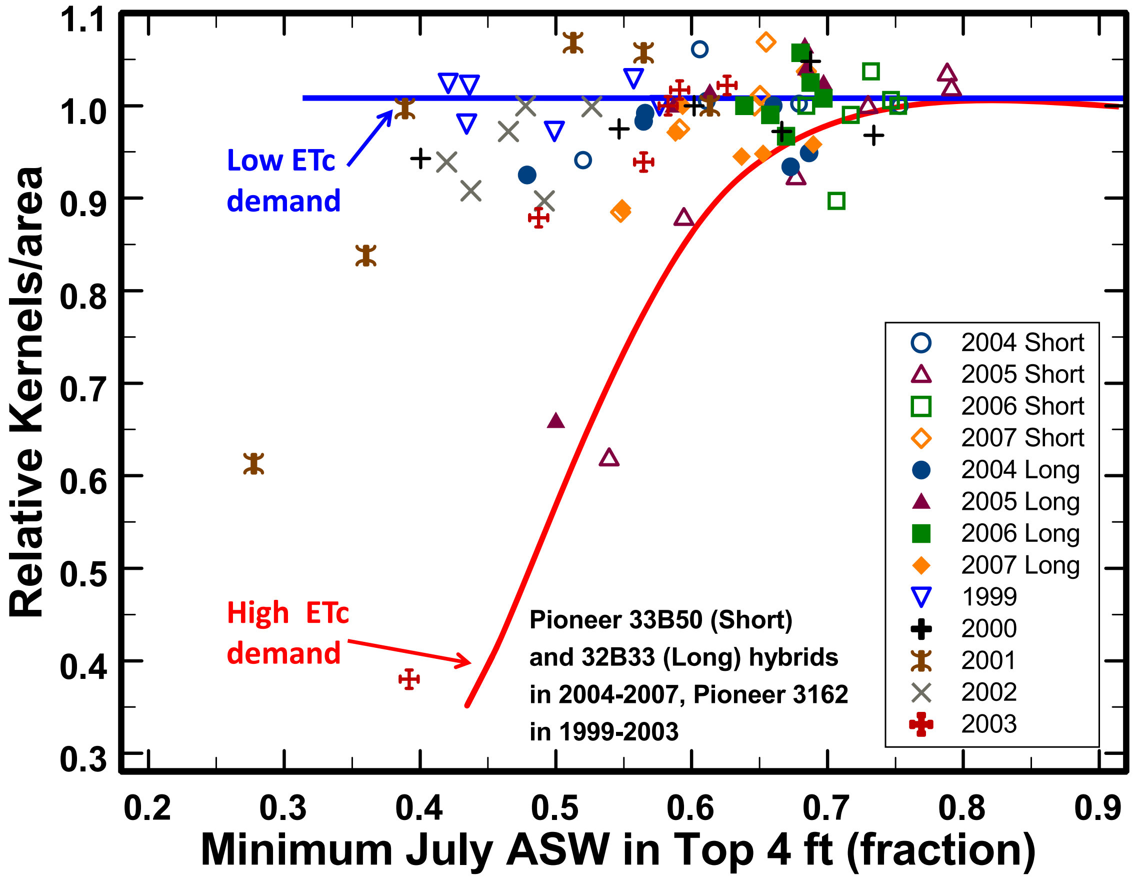

Figure 3. Relative kernels/area as affected by July minimum available soil water in the top 4 ft of soil in an early-season corn water stress study, KSU-NWREC, Colby, Kansas, 1999-2007. The upper (red) and lower (blue) lines are manually drawn to illustrate years with larger and smaller July evaporative demand.

The ratio of calculated well-watered crop ETc to the sum of irrigation and precipitation for July 1 through 15 was also related to the relative kernels/area (Figure 4). Attempts were also made in varying the timeframe of the ratio (both longer and shorter and also shifting within the month of July). It appears that some of the remaining scatter in this graph is related to timing of irrigation and precipitation near the actual point of silking. For example, the isolated point from 2002 near the vertical axis may be related to a significant precipitation event that occurred near silking, but later than July 15. Further analysis should be conducted to allow the window to actually vary around the individual silking dates of each year. This might be done by computing windows based on the number of thermal units (also known as Growing Degree Days) required for silking. This relationship might also be a good signal in determining the need for irrigation because it can be determined in near real time using the accumulated ratio to that point in time.

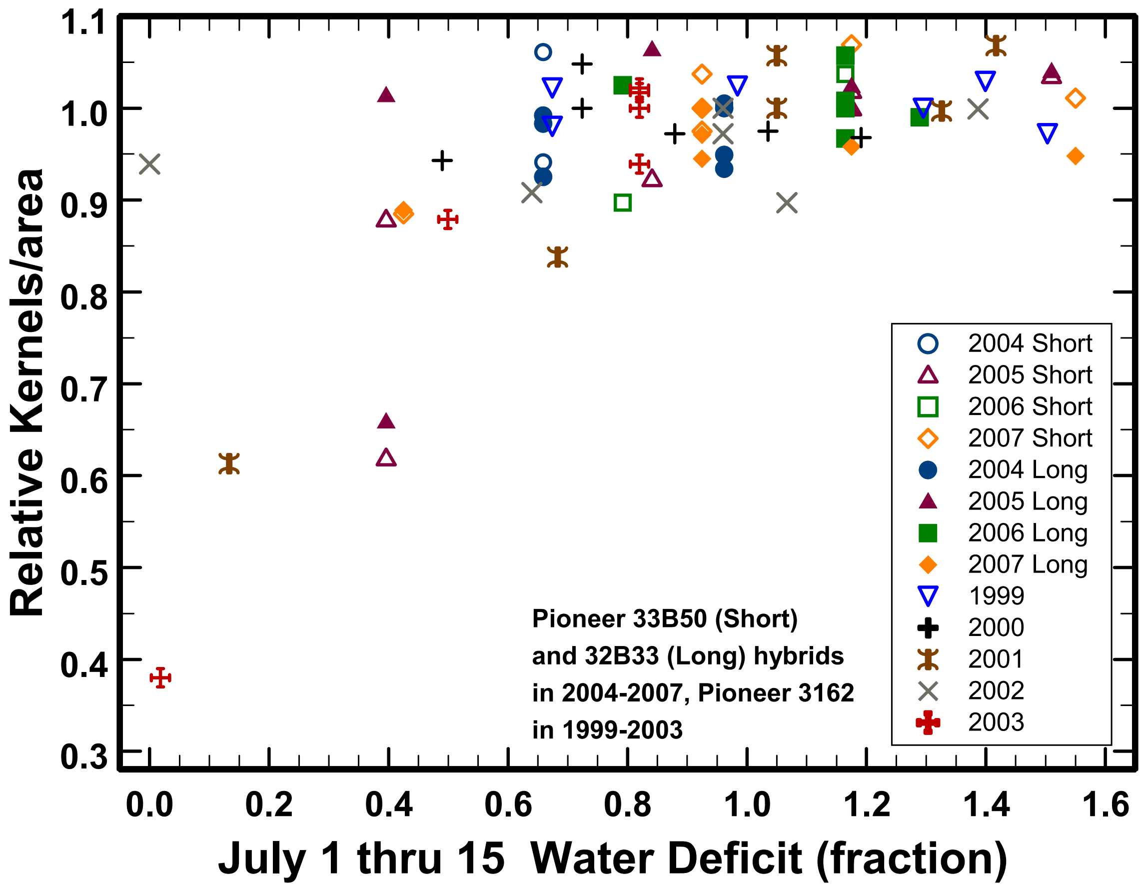

Figure 4. Relative kernels/area as affected by the July 1 through 15 water deficit (ratio of calculated well-watered crop ETc to the sum of irrigation and precipitation) in an early-season corn water stress study, KSU-NWREC, Colby, Kansas, 1999-2007.

CONCLUSIONS

The corn has greater than anticipated ability to withstand vegetative season water stress provided that the water stress can be alleviated during the early-reproductive period. In years of lower evaporative demand, corn grown on this soil type in this region can extract greater amounts of soil water without detriment. Timeliness of irrigation and/or precipitation near silking appears to be important in establishing an adequate number of kernels/area.

Further analysis should center on attempts to combine multiple factors (e. g., measured water use, available soil water, evaporative demand, and/or timing of irrigation and precipitation) with a focus on developing irrigation signals that can be used in near real-time to make early season irrigation decisions.

A sustainable alternative of exploiting Nepal's water resources to benefit the riparian countries

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Abstract. *This article suggests that inter-basin transfer of water from larger rivers by tunneling is a sustainable and ecosystem friendly method of utilizing Nepal's water resources which will benefit the riparian countries. It proposes to divert water from eastern rivers to the western by gravity, coupled with generating hydropower. It will transfer 20 km^3 water annually to the Mahakali river from the Karnali which can be supplied to most groundwater overdraft affected areas of west and south India. About 15 km^3 will be transferred from the Koshi to the Gandak and from the Gandak to the Karnali, 10% of which will be used for Nepal's Terai and the rest will be supplied to India. The proposed plan will help groundwater recharge and spring flow generation at numerous drains in the basin by three ways :1) the link canals pass over the porous zone ,2) due to the provision of storage in local reservoirs and 3) expansion of irrigated rice. It provides an alternate to large dams in Nepal, which cannot be justified in a high earthquake risk region like Nepal and having no solution to tremendous sediments in the rivers apart from the negative impacts they bring to the people and biodiversity of the affected area. Hence the method suggested in this study is a sustainable way of exploiting rivers. It is capable of preserving the river ecosystem, simultaneously opening ways towards integrated watershed management, conjunctive use of ground and surface water, and revival of traditional methods of storage in local reservoirs.*

Keywords. Ecosystem, groundwater, inter-basin transfer, local reservoirs, sediments.

1. Introduction

The conventional engineering methods applied in Nepal's irrigation and flood control in the years after 1950s are only partially successful in achieving the targeted goals. For example, the country has developed canal infrastructures to irrigate 1.121 million ha, whereas only 0.50 million ha is getting round the year irrigation (NWP, 2005). Increasing the year-round irrigated area in the southern plain of the country known as the *Terai*, is crucial for maintaining food security in the country. The fact that only 27% of lands in the *Terai* is getting year round irrigation, 38% gets irrigation during the rainy season only and the rest 35% is rain fed (WRSN, 2000) shows huge potentials for expansion of year round irrigation in the *Terai*. Until 1960s the importance of agriculture in the *Terai* was not realized in the scale of today due to which Nepal had agreed to supply unlimited volume of water to India from its Himalayan rivers through the *Koshi, Gandak* and *Mahakali* Treaties signed in 1954, 1959 and 1920 respectively. Nepal's civil society presently is dissatisfied with these water sharing treaties with India because they cannot address present requirements of the *Terai* and Nepal's large area is adversely affected from the diversion structures made by India. The recent breach of the *Koshi* embankment caused the two governments to agree to review the previous agreements and to correct the mistakes. Bangladesh from its 50 years long experience of flood control by cordon approach has felt the need of a new approach for sustainability (Islam, 2001).

The spread of groundwater pumping technology to the hands of millions of farmers during last decades and the observed weaknesses of traditional engineering concept require dramatic changes in the existing water resources planning approaches. In the same time, dams are questioned from sustainability and seismic stability considerations (WCD, 2000). Particular to the study area where the community had survived for millennia fighting floods and droughts using indigenous knowledge, the sustainability can only be achieved through integration of indigenous and modern technologies. This study attempts to provide an alternative solution by means of east west transfer of water thorough tunneling across the last hills in order to cover larger part of the *Terai*, supply water to most water deficit parts in western and southern India and to reduce floods in Bangladesh in a sustainable way. It advocates revival and promotion of traditional water harvesting in local reservoirs, recharging groundwater by expanding irrigated rice cultivation during the monsoon season and preservation of water bodies to achieve sustainability of water resources exploitation in the Ganges basin. The paper proceeds on the following order: Section 2 deals with the Nepal's renewable water resources and its utilization by Nepal and India. Section 3 describes the proposed River Linking Project in India, basically concentrating on the Himalayan component that concerns rivers flowing from Nepal. Section 4 covers in detail the proposed transfers and associated parameters. Section 5 presents points regarding sustainability of the proposed solution and Section 6 as a concluding section provides discussions and recommendations.

2. Nepal's water resources and its utilization

The annual renewable water resources of Nepal is 210 km^3 .The country's total requirements in 2000 was 14 km^3 which is projected to reach 39 km^3 in 2027.Although the 2027 projections are only 18.56 % of the generation, there is a need of serious efforts to achieve the goal due to differences in the supply and demand periods. Eighty percent of the flows occur during the monsoon season (June-Sept) whereas the river flows decline dramatically during the peak demand months (March-May) with highest evapotranspiration. The average annual flow of the nine large and medium rivers of Nepal flowing to India is 5,675 m^3/sec as shown in Table 1. Comparing with the average discharge of the *Ganges* river at the Indo-Bangladesh boarder: the *Farakka* it can be seen that Nepal's contribution to the Ganges average flow is 47% which reaches to 75% for the driest months of March to May (Mishra et al., 2007; WECS, 2002). This shows the importance of Nepal's water resources for both downstream countries. Even with great contribution to the Ganges flows, the volume of water that Nepal is getting to irrigate its *Terai* from the three diversions made under Indo-Nepal agreement is extremely low.

Nepal and India have signed four water resources treaties. The first was the *Mahakali* treaty signed in 1920 between British India and Nepal. The *Koshi* treaty was signed in 1954, the *Gandak* treaty in 1959 and the *Pancheshwor* treaty in 1996 (Parajuli et. al, 2003) which envisaged preparing the Detailed Project Report (DPR) within 6 months. However, even after 12 years of the treaty the DPR could not be prepared because Nepal's civil society still considers that the treaty is still detrimental to Nepal. Soon after the *Koshi* and the *Gandak* treaties it was realized in Nepal that both treaties were detrimental for the country. The *Gandak* treaty was most harmful because that deprived Nepal to withdraw water at the upstream affecting the water requirements of the *Gandak* Project, which meant virtual end of the future prospects for irrigation development in the *Gandak* basin within Nepalese territory. However, the treaty was revised in 1964 by which Nepal got the right to withdraw for irrigation or any purposes from the river or its tributaries. Learning lessons from the past agreements, there is a need to work seriously in order to find ways of fulfilling Nepal's requirements first while making any joint water resource development schemes with India in the future.

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Table 1: Average monthly flows of nine rivers of Nepal, m^3/sec.

River name	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Average
Mahakali	167	156	149	182	266	560	1579	1332	1489	577	227	198	658
Karnali	370	335	348	445	702	1520	3290	4370	3020	1320	632	446	1410
Babai	19	15	13	10	15	56	222	241	232	95	36	23	82
W. Rapti	28	23	18	14	15	93	298	388	355	147	57	33	123
Narayani	351	286	264	348	568	1610	4210	4970	3420	1600	790	492	1590
Bagmati	19	17	15	17	32	214	539	513	338	137	51	27	161
Kamala	7	5	4	3	8	46	130	160	102	45	17	11	45
Saptakoshi	364	315	318	424	705	1660	4110	4340	3460	4160	795	501	1550
Kankai	12	9	8	11	21	72	198	145	106	51	23	15	56

(Source: Thapa and Pradhan 1995, as cited in Mishra et al., 2007)

3. The Indian river linking project Himalayan component

India is implementing the River Linking Project (RLP) to satisfy growing water demands and to combat the severe groundwater overdraft at its western and peninsular parts. The RLP Himalayan Component intends to divert surplus water of the Himalayan rivers to the western and peninsular parts for which several large dams within Nepal and Bhutan are proposed. In this regard a 300 m rock fill dam at the *Koshi* River is being studied. Bangladesh also favors constructing dams in Nepal for flood controls as well as increasing the lean season Ganges river flows. The proposed high dams in Nepal around the fault lines are neither sustainable nor free from high earthquake risks. The ever increasing sediment loads in the rivers due to human encroachment on the hill slopes and landslides needs careful assessment and consideration before deciding on a dam construction. Most importantly the dams themselves may be the cause of bigger earthquakes due to dramatic increase in water pressure in the faults. It is really a daunting task for the planners to find sustainable solutions in a fragile geology with seismic risks which could address or satisfy these very different interests of the three countries affected by flows in Nepal's rivers.

The present version of the RLP is based on the conventional approaches adopted in industrialized countries in last two centuries. It is being criticized by the civil society in India itself. There is a growing demand to modify plans to make them environment friendly, sustainable and socially acceptable and capable to preserve the river ecosystem. Experience of the past has shown that the conventional engineering developed in the west cannot address the problems existing in the region. Developing countries do not have to repeat the mistakes that early industrialized countries have made, and instead can make fruitful use of the accumulated experience (Islam, 2006) Sustainable solution will only be possible if modern engineering concept could be integrated with old traditions of the community to behave with rivers. For example, the traditional design considers the design life of dams as a limited period of about 100 years. However, the rivers will flow for ever and traditional engineering does not have answer to the question: what to do with the dam after its design life? Particular to Nepal there is a need to consider various typical aspects like steep hill slopes and steep river beds, tremendous suspended and bed sediments carried out from the mountains and deposited at the *Terai*. Failure to consider these aspects during the design of the *Koshi* Barrage resulted to the situation of embankment breach and flooding in August 2008 affecting 3 million people which provides important lessons for future planning and shows how a technically incorrect choice was made by the designers of the *Koshi Barrage*.

The RLP is criticized by various NGOs and civil society in India for its erroneous basic premise, faulty concept, doubtful technical feasibility, doubtful financial feasibility, doubtful flood mitigation, doubtful economic feasibility, irreparable ecological damage and other non economic costs, exacerbation of conflicts. The governing concepts in the RLP planning are still the traditional 19th and 20th century methods leading to unsustainable solutions. The recently introduced concept of sustainable development requires applying ecological approach to rivers where the river itself is to be treated as an important stakeholder. Existing groundwater overdraft in western and southern India and the anticipated expansion of urbanization, increase in the living standard of population will eventually make water transfers from surplus basins to deficit basins an unavoidable option in the future. This is supported by Shah et al., 2003: "as groundwater becomes more scarce and more costly to use in relative terms, many ideas- such as trans basin movement or using surface water systems exclusively for recharge- which in past years were discarded as not feasible or unattractive can now offer new promise, provided that Asia learns intelligently from these ideas and adapts them appropriately to its unique situation".

4. Transfer by tunneling: beneficial for all countries

The concept of inter basin transfer through tunneling was forwarded in Nepal in 1970s during the reconnaissance study of the *Babai* Irrigation Project. To cope with the water shortage in the *Babai* river, a proposal to divert 35 m^3/sec of water from the nearby *Bheri* river by making a 8 km long tunnel. Soon after the *Sunkoshi- Kamala* diversion was identified to irrigate dry lands of the central *Terai.* However, both of them could not be materialized due to financial constraints. Now almost all the viable surface irrigation projects have been constructed and the inter-basin transfer is in the priority in Nepal. Adhikari et al., 2007 have suggested a gravity canal from the *Karnali* river, which is a very economic replacement to the *Bheri Babai* diversion. Considering this fact this study proposes the following three diversions as the most viable schemes from point of view of covering maximum areas of the *Terai* and transferring large volumes of water from east the west absolutely by the gravity to attain the RLP goals.

4.1 Sunkoshi – Bagmati- Kamala Diversion (Diversion 1)

The proposed diversion site is located at 2 km downstream from the *Beni Ghat*, the confluence of the *Sunkoshi* and the *Tamakoshi* rivers. At the beginning, a 18 km long tunnel as indicated by tunnel 1A in Figure 1, will deliver water to the *Bagmati* basin, By constructing another tunnel of about 8 km length, indicated as tunnel 1B in Figure 2, it is possible to further divert the flow to the *Kamala* river basin as well. The satellite image of the diversion site obtained from GoogleEarth showing the tunnel 1A alignment has been presented in Figure 2. Salient parameters of the proposed diversion work have been presented in Table 2. The catchment area of the *Sunkoshi* river at the diversion site is 11,000 km^2. The monthly flows have been estimated based on the measured discharges of the *Narayani* river due to the similarity of the conditions between the *Sunkoshi* and the *Narayani* basins. The *Saptakoshi* river flows at the *Chatara* is influenced by the significant basin area of the *Arun* river part of which contains the rain shadow areas of Tibet, due to which the specific discharge of the *Saptakoshi* is less than that of the *Narayani* and the *Karnali*. However, the *Sunkoshi* basin area at the proposed diversion site is 11,000 km^2 whereas the *Kaligandaki* river has a basin area of 11,400 km^2 at the diversion point. Hence the flows of the *Sunkoshi* are taken same as those of the *Kaligandaki* .

Table 3 shows the available and divertible monthly discharges at the diversion site and at *terai exit* **TE1**. This arrangement can divert 14 km^3 of water annually from the *Koshi* basin to the *Gandak* basin without making any negative impact to the downstream ecosystem. The available head of 200 m between the tunnel exit and the proposed link canals at the *Bagmati* can be used to generate hydropower. It is proposed to share the diverted flow half-half by Nepal and India during the dry season while major flows of the months June to December will be transferred to the *Gandak* river. During the summer period additional flow augmentation from other small rivers is also possible. Out of total 14 km^3 diverted water Nepal will consume only 2 km^3 which is just 11.60% of the diverted flow.

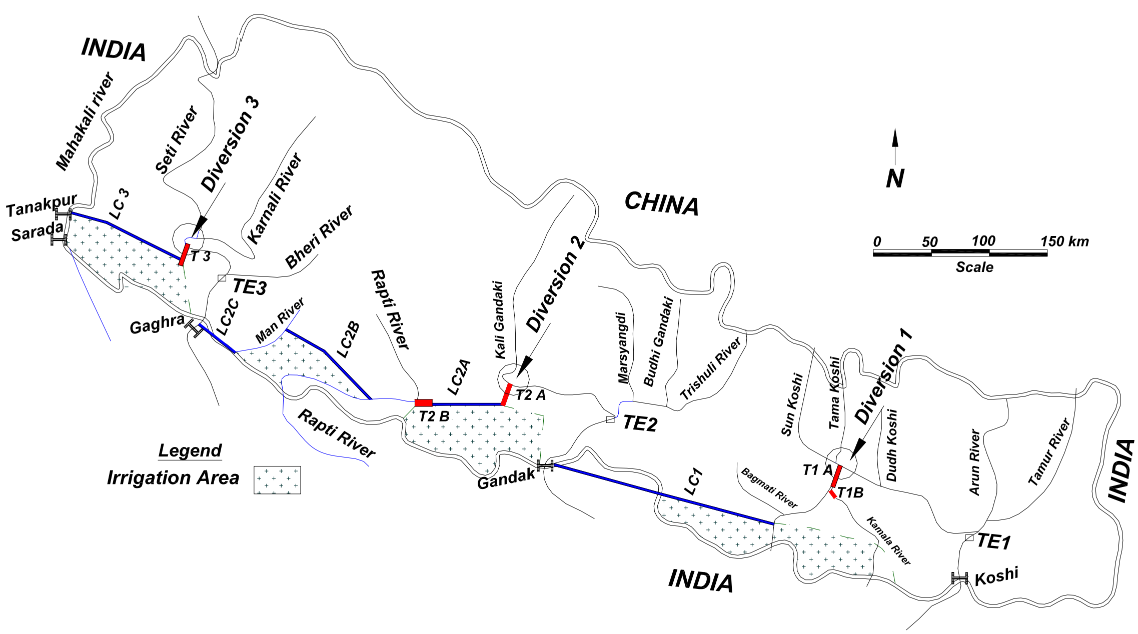

Figure 1: Map of Nepal showing major rivers draining to India from Nepal, proposed diversion tunnels and link canals, area to be irrigated and the existing barrages at the *Koshi*, *Gandak* ,*Karnali* and *Mahakali* rivers.

Table 2: Salient Parameters of the *Sunkoshi-Bagmati-Kamala* Diversion.

S.No.	Parameters	Unit	Value
1.	River bed level at diversion site	m	460
2.	Tunnel exit level at Bagmati basin	m	412
3.	Tunnel 1 A length	km	13
4.	Tunel 1 B length	km	6
5.	River level at the Bagmati barrage	m	137
6.	Bagmati- Gandak distance	km	200
7.	Narayani river level at the Gandak	m	122

(Source: Google Earth 2008)

Figure 2: GoogleEarth image of the *Sunkoshi- Bagmati-Kamala* diversion site showing the tunnel alignment.

(Source: Google Earth 2008)

Table 3: monthly discharge at the *Sunkoshi* river at the diversion site, m^3/sec

Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sunkoshi flow	129	105	97	128	208	591	1545	1824	1255	587	290	181
Divertible discharge	80	80	80	100	150	500	1000	1,500	1,000	500	250	150
D/S Flow after diversion	49	25	17	28	58	91	545	324	255	87	40	31
Saptakoshi flow(TE1)	364	315	318	424	705	1,660	4,110	4,340	3,460	1,460	795	501
Flow at the *Saptakoshi (TE1)* after diversion	284	235	238	324	555	1,160	3,110	2,840	2,460	960	545	351

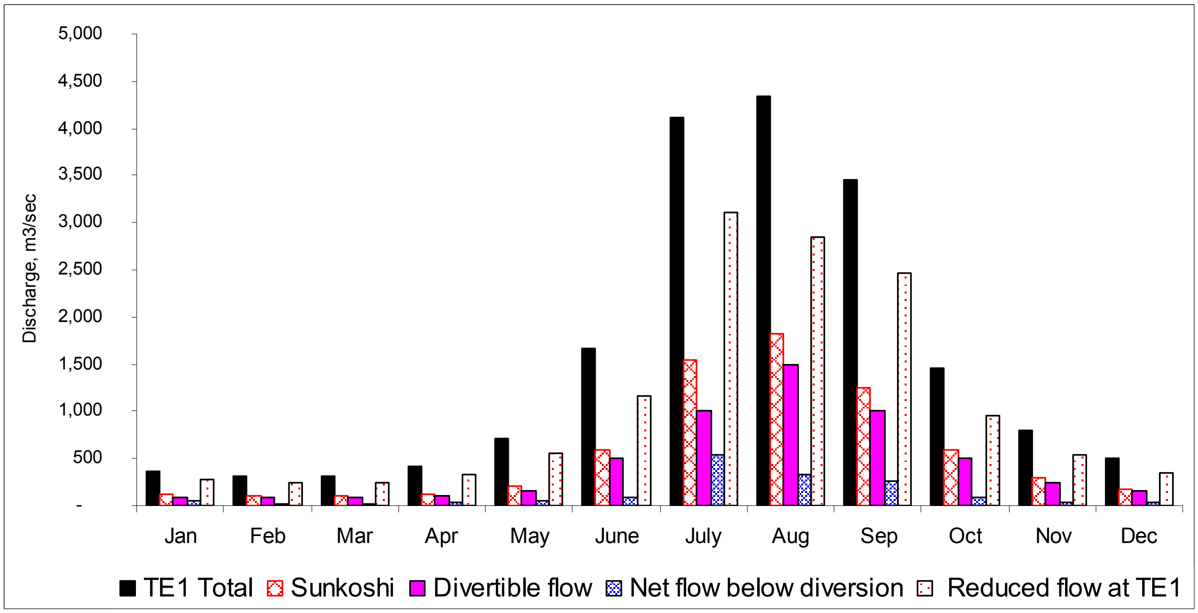

Figure 3: Monthly discharge at the TE1 (Chatara) and at the diversion 1 site before and after the project and the divertible discharge.

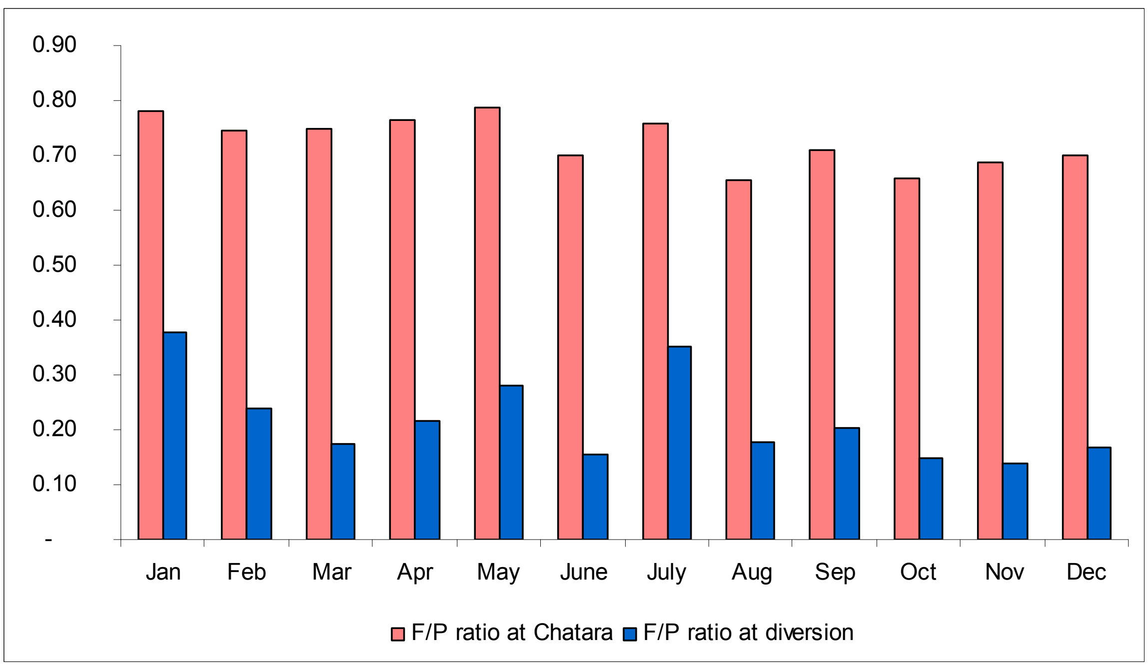

Figure 4: Future and present discharge ratios at the diversion site and at the TE1 (*Chatara)*.

Figure 3 shows the monthly distribution of the discharges available at the diversion site, divertible flow, and discharge at the Sapta Koshi. Figure 4 shows the future and present (F/P) discharge ratios at various months at the *Chatara* of the *Saptakoshi* and at the diversion site in *Sunkoshi* rivers which indicates that the dry season discharge at the *Saptakoshi* will be maintained at 70 to 80%. In the period from June to October the discharge in the *Sunkoshi* river remains very high, as can be seen from Figure 3, indicating the possibility to increase the diversion volume.

4.2 Kaligandaki Tinau-Rapti Diversion (Diversion 2)

The proposed diversion will transfer water from the *Kaligandaki* river to the *Tinau* river through a 18 km long tunnel initially, and will join the *Rapti* from Link Canal 2A and Tunnel 2B as shown in Figure 1. From the *Sikta* barrage in the *Rapti* River which is under construction now, a link canal, as indicated by Link Canal 2B in Figure 1, will supply water to the *Man River* after which Link Canal 2C will finally drop water upstream of the *Gaghra* barrage. GoogleEarth image of the diversion site with the tunnel alignment is shown in Figure 5 and the salient parameters of the diversion are presented in Table 4.

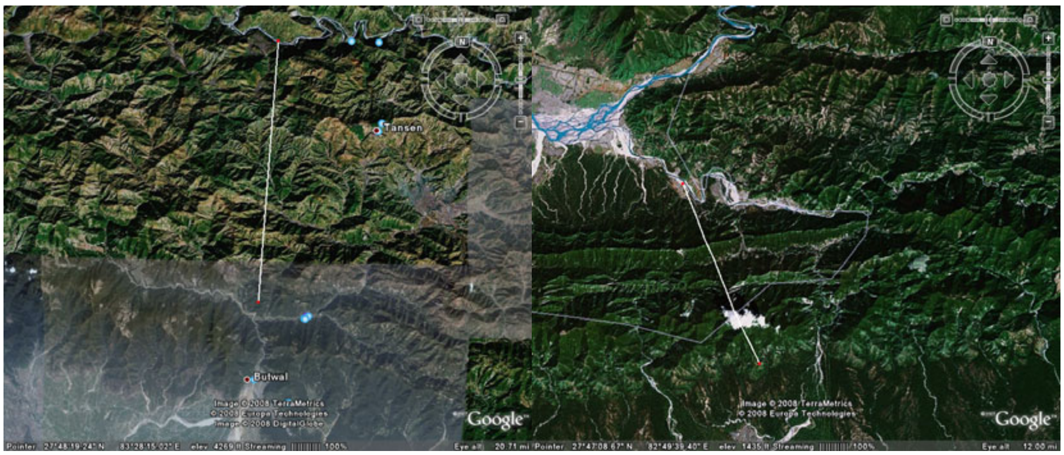

Figure 5: Satellite image of the *Kaligandaki Tinau* diversion site (left) showing the tunnel alignment and the link to the *Rapti* river (right).
(Source: Google Earth 2008)

Table 4: Salient Parameters of the Kali Gandaki-Rapti-Gaghra Diversion.

S.No.	Parameters	Unit	Value
1.	River bed level at diversion site	m	463
2.	Tunnel exit level at Tinau river	m	450
3.	Tunnel 2 A length	km	18
4.	Tunel 2 B length	km	8
5.	River level at the Rapti bridge	m	305
6.	Tinau Rapti distance	km	160
7.	Gaghra river level at the barrage	m	122

(Source: Google Earth 2008)

Table 5: monthly discharge at the Kali Gandaki river at diversion site, m^3/sec

Description	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Available flow	129	105	97	128	208	591	1,545	1,824	1,255	587	290	181
Divertible discharge	100	80	50	50	100	500	1,200	1,500	1,000	500	200	150
D/S Flow after diversion	29	25	47	78	108	91	345	324	255	87	90	31
Narayani (TE2) total flow	351	286	264	348	568	1,610	4,210	4,970	3,420	1,600	790	492
Flow at Narayani after abstraction	251	206	214	298	468	1,110	3,010	3,470	2,420	1,100	590	342

This component contains the transfer from the *Kaligandaki* to *Tinau* where after a 160 km long open channel at about 315 m elevation the flow will be transferred to the *Rapti* river through a 8 km long tunnel. The head difference between the *Tinau* and the *Rapti* may be used for hydropower generation. Monthly discharges are shown in Figure 6, while the future present discharge ratios are presented in Figure 6. Out of 14 km^3 water Nepal will be entitled to only1.5 km^3, which is 10.6% of the diverted flow.

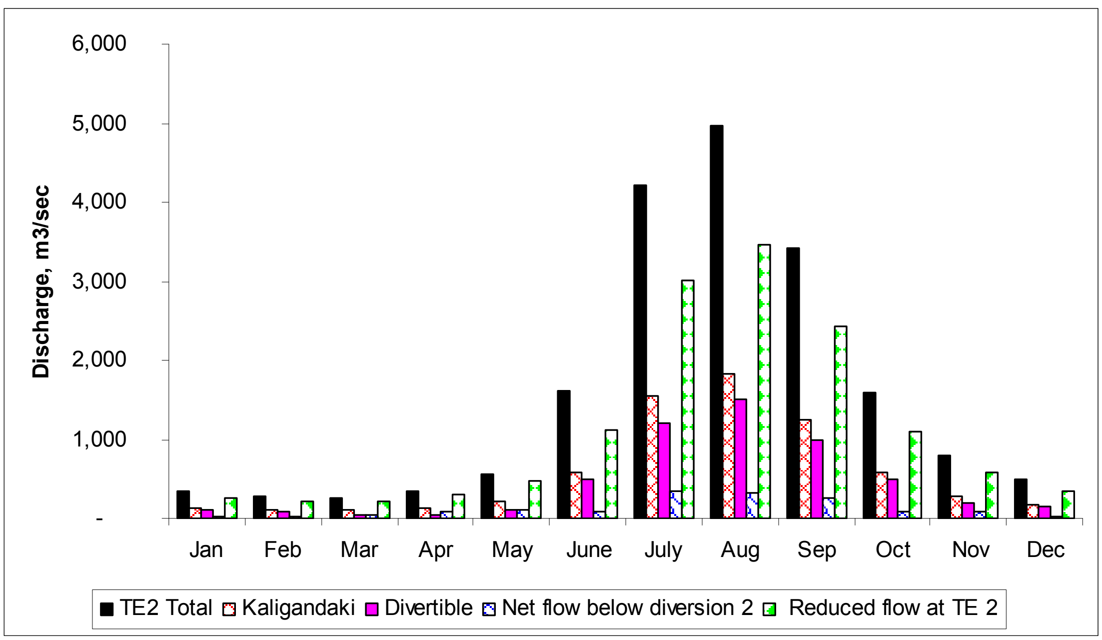

Figure 6: Monthly discharge at the TE2 and the diversion 2 before and after the project showing the divertible monthly flow.

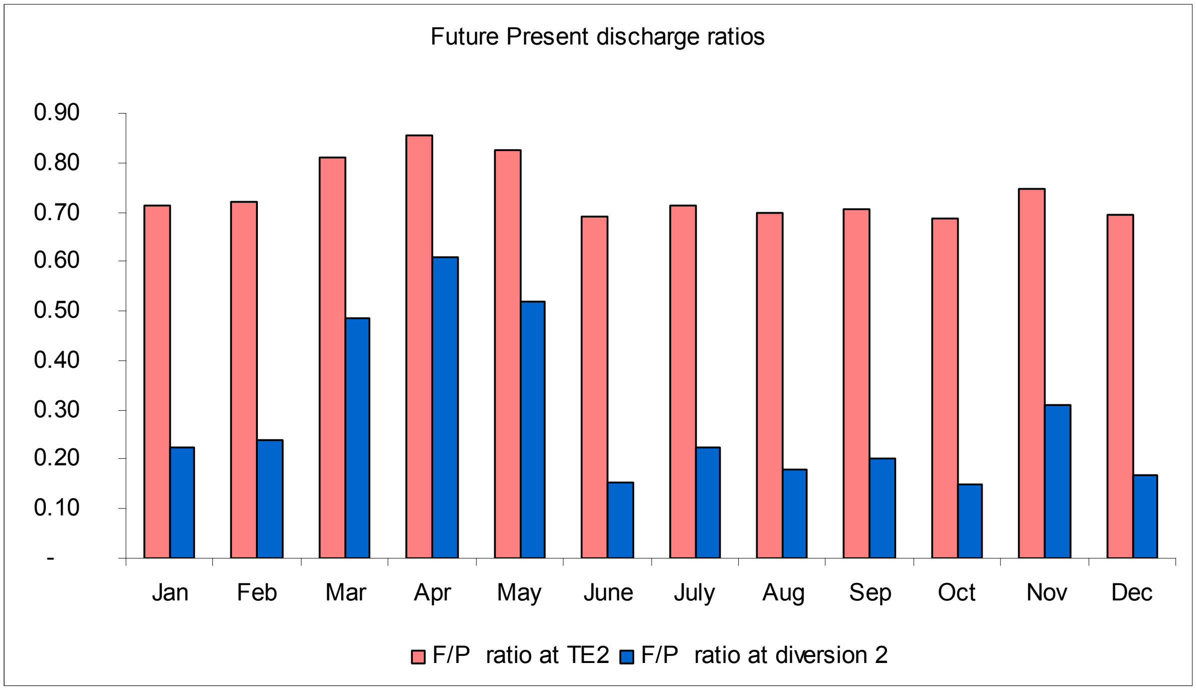

Figure 7: Future and present discharge ratios at the diversion 2 site and at the TE2 of the *Gandak* river.

4.3 Karnali Mahakali diversion (Diversion 3)

The proposed diversion site with the tunnel and link canal are shown in Figure 1 by indicating T3 and LC3 while the GoogleEarth image of the diversion site and tunnel alignment is presented in Figure 8. Relevant parameters of the proposed diversion are presented in Table 6. The proposed tunnel length is 14 km and the length of the link canal will be 110 km. It is proposed to allocate 2.1 km^3 of water for Nepal's usages out of 20 km^3 which is 10.60% of the total diverted discharge. The available and divertible monthly discharges are presented in Table 7. The future present discharge ratios at different places are shown in Figure 10 which shows that the discharge at the TE3 (*Chisapani)* will drop by about 60 per cent. Figure 9 shows monthly discharges at the diversion site and at the *Chisapani* at before and after diversion scenarios, including the divertible discharges.

Figure 8: Map of the *Karnali* diversion site showing the proposed tunnel alignment.
(Source: Google Earth 2008)

Table 6: Salient parameters of the Karnali River at the diversion site and Chisapani.

S.No.	Parameters	Unit	Value
1.	River bed level at diversion site	m	296
2.	Tunnel exit level	m	270
3.	Tunnel length	km	14
4.	Link canal length	km	110
5.	*Mahakali* river level at *Tanakpur*	m	250

(Source: Google Earth 2008)

Table 7: monthly discharge of the Karnali river at the diversion site, m^3/sec

Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Karnali at diversion site	261	236	245	314	495	1,072	2,319	3,081	2,129	931	446	314
Divertible	100	100	100	100	100	800	1,700	2,000	1,500	500	400	250
Net flow below diversion	161	136	145	214	395	272	619	1,081	629	431	46	64
Karnali Chisapani, TE3	370	335	348	445	702	1,520	3,290	4,370	3,020	1,320	632	446
Reduced flow at Chisapani, TE3	270	235	248	345	602	720	1,590	2,370	1,520	820	232	196

Figure 10 shows the discharge ratio in the TE3 at the future and present situations. In the *Koshi* and the *Gandak* the reduction is likely below 30% whereas in the case of the *Karnali* it is between 50 to 60 percent in months from June to December. In all the diversion sites at least 20 percent discharge is released for sustaining the downstream ecosystem. The farmers' systems in the *Rajapur* may be affected during the dry season from the reduced flows. Negative impacts to the farmers' systems from the proposed diversion during the dry period can be mitigated by carrying out sediment removal around the side intakes whereas during the rainy season generous amount of flow will enter the farmers' canals and these systems will be safer due to possible reduction of floods from the proposed arrangement.

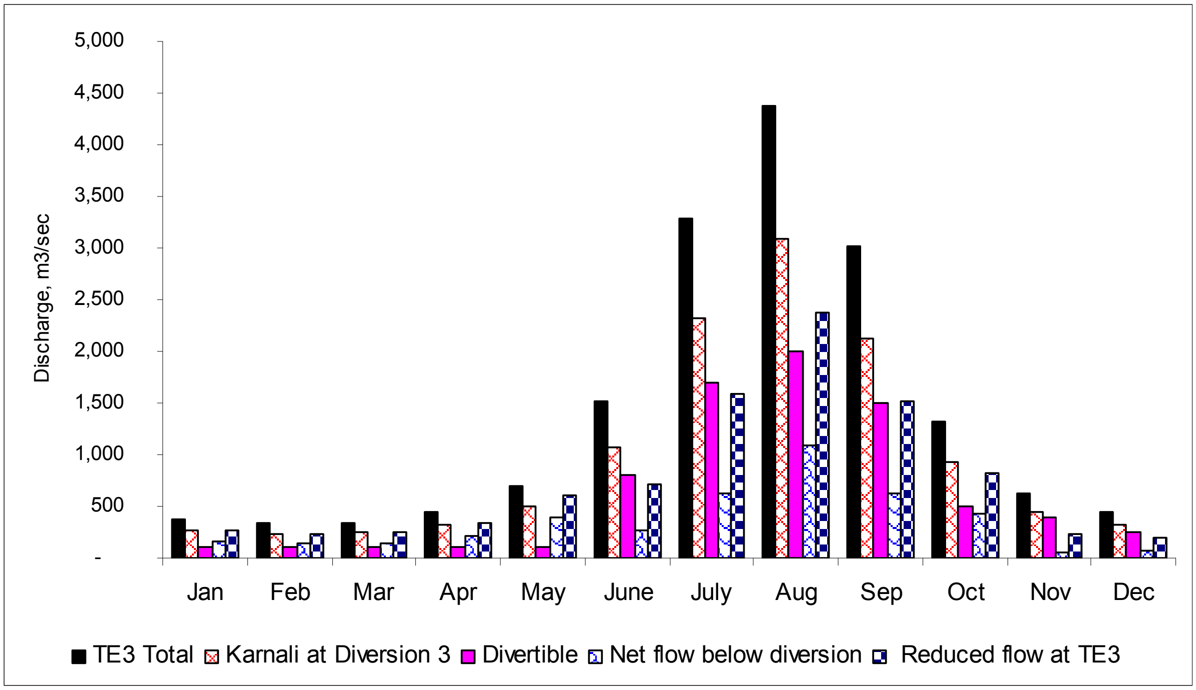

Figure 9: Monthly discharges at the diversion 3 site and at the TE3 (*Chisapani)* before and after the project showing the divertible monthly flows.

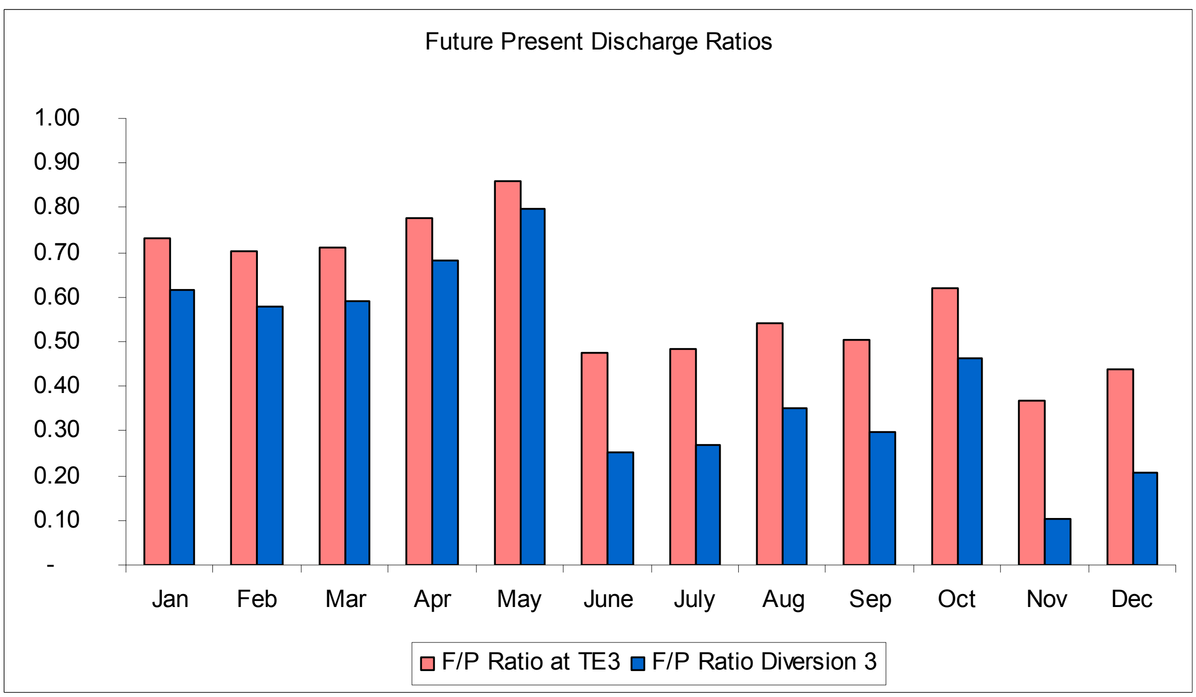

Figure 10: Future and present discharge ratios at the diversion 3 site and at the TE3 (*Chisapani)*.

5. How the proposed solution is sustainable?

The conventional water storage behind dams across the rivers is highly risky and unsustainable for Nepalese context. Dams can never be justified in a fragile and steep mountainous and a highly earthquake prone zone. Seismologists expect a major earthquake in the near future of devastating magnitude like 1834 and 1934 shakes. Sediment loads in Nepalese rivers is another serious question. It is estimated that the *Koshi* River carries about one billion cubic meter of sediment in a year. In case of damming, the sediment deposition will occur in the pond. A front of delta formed by the sediment deposition will proceed towards the dam, eventually converting the total pounding area into a sediment deposition zone in a very short time span which would be a great burden afterwards. The traditional dam design concepts and assumptions cannot seriously consider this aspect. The run off the river type diversions proposed in this study are capable to address both the above concerns simultaneously favoring hydropower generation. Another important factor unseen by the dam proponents is that the weight of the reservoir catalyzes an earthquake by creating huge pressure in faults. Increase in soil moisture in the hill slope around the reservoir may induce hill slope failures of unimaginable extent which hardly gets any consideration during the design of dams. One can just imagine the worst situation of slope failure during severe shakings. A huge landslide behind the *Vaiont* dam in northern Italy in 1963 took the lives of 2500 people when a wave of water and debris spilled over the dam and swept away a small town. This bitter experience shows that the run off the river type diversion is far appropriate than dams for fragile Himalayan conditions of Nepal. The diverted sediment free water can be stored in thousands of local traditional reservoirs or small check dams covering the total service area. This would enhance groundwater recharge and would generate perennial spring sources. Revitalized water bodies means favorable condition for preserving aquatic ecosystem. Another vital space of storing water is the groundwater aquifer. For this purpose spread of the irrigated rice cultivation plays key role. The percolation occurring during rice cultivation eventually contributes to groundwater recharge helping ground water table stabilization.

5.1 No significant negative impact on the downstream ecosystem

All the proposed diversion points are situated in a tributary of the main river comprised of several rivers. The Koshi river has seven tributaries and hence named as the *Saptakoshi* which means seven *Koshi*. Similarly the *Ganda*ki or *Narayani* river is called as *Saptagandaki*. The proposal of withdrawing about half of the flows during summer and about eighty percent flows during dry season will always maintain more than 80 percent flows in the main stream. The twenty percent discharge released for preserving fish spices in the tributary will be sufficient because there are no other utilization of river at the downstream area which is comprised of mainly hard rock outcrops without any wet lands or any type of natural habitats. Settlements in the river bank use other small sources to fulfill their requirements. The supply of water to Indian large irrigation projects located at the boarder will be maintained nearly in their present level because the *Gandak* will get diverted water from the *Sunkoshi* and the *Karnali* will get water from the *Kaligandaki*. Moreover, surplus water of other small rivers like the *Bagmati* and the *Rapti* will also be diverted to west eventually increasing the water volume in the western river during the monsoon season.

Significant expansion of irrigation in the *Terai* coupled with the seepage from the link canals passing over thick gravel deposits will enrich the groundwater aquifer. The seepage and infiltration are normally considered as losses, but for particular case of the vast Ganga plain it might be the right method of storing water in the underground reservoir to use it during the lean period. This would help generating perennial flows in numerous downstream streams .The stored groundwater can be pumped in required amount at required time. Although various sources mention that the dry season flow from Nepal's rivers contribute more than 75% of the Ganges flow at the *Farakka*, but that is not happening in a straightforward way because all the tributaries of the Ganges are captured and diverted to irrigate vast lands in Bihar and Uttar Pradesh leaving practically no flows at the downstream. Then the general question arises: from where the flow at the *Farakka* comes? The dry season flow in the *Ganges* should be the result of groundwater spring occurring in its huge plain which is one of the largest groundwater reservoirs on the earth. Keeping this huge groundwater reservoir full and saturated should be more efficient than storage in dams to benefit Bangladesh by increasing the lean season flow at the *Farakka*.

5.2 Ecosystem not affected

The proposed solution is a complete environment friendly water resource development plan. The river ecosystem will not be affected from the proposed interventions. Sufficient flow will be released downstream to sustain the ecosystem, mainly to preserve the fish spices. The river passes along the rock outcrops and hence does not contain any wetlands, or withdrawals for irrigation or other purposes. Hence the reduction of the discharge will not provide any harm to downstream population and ecosystem. Any unforeseen harms if observed during the detailed study and during the mandatory public hearing process can be mitigated. This scheme does not contain any resettlement works and thus can be taken as a very environment friendly proposition which is capable of fulfilling Nepal's requirements as well as beneficial for India and Bangladesh.

5.3 No risk of earthquake induced disaster

The proposed transfer is completely free from the earthquake induced disasters and hence deserves special attention. Conventionally conceived high dams in Nepal to store large volume of water are not appropriate solutions due to risk of failure from earthquakes. Nepal lies in highly earthquake prone zone and the fault line passes along the east west flowing rivers. Dams themselves can be the cause of earthquakes due to the increased water pressure at the fault lines. Loss of life and property from reservoir failure will be enormous. If imagine the scenario at the upstream and downstream end after the failure of the dam, one becomes compelled to think on the alternatives of such type of so called development. The proposed diversion is completely out of the risks of such type and magnitude. Canals and tunnels if cracked and leaked due to the however big earthquake, can be easily repaired without much difficulty and there is no risk of damage to life and property.

5.4 No sedimentation problem

Our proposal of transferring water will not create any sedimentation in the source river and in the canals. As there is enough discharge released during the high flow period and the diverted water will be sediment-free using a suitable deposition device, sediment transportation and deposition at the downstream will get continuity. Sediment free water carried from the link canals can be stored in tanks and the process can be continued for centuries without any silt problem. Fertile sediment which is spread over the Ganges plain by the floods is an important nutrient for keeping high fertility and yield of the basin. This aspect will not be affected from our proposal.

5.5 No need of resettlement and no loss of lands from impoundment

It will be very hard to convince Nepalese public for high dams construction submerging fertile river valleys and settlements. And only the agreement between governments will not be sufficient to launch the project. Even till now many families displaced by the *Koshi* Project in 1960s have not got the land compensation and resettlement costs. In 1996 a treaty between Nepal and India was signed fro the development of water resources in the *Mahakali* river basin which had envisioned to construct a high dam at the *Pancheshwor*. The Detailed Project Report (DPR) was said to be prepared in six months. However after even 11 years there is no sign of producing the DPR. That is why both the countries need to do intensive homework and reach mutually agreeable and transparent option of project development before making any treaty. In the 1960s Nepal's technocrats and leaders trusting the draft prepared by the Indian counterparts signed the treaty which soon after was realized to be harmful for the country. Now the situation has changed. Even inside India one state's surplus water is being a matter of selling to the deficit state, Nepal will and should not sign treaties which would be harmful to her interest.

5.6 Flood control at Bangladesh is not possible from damming Nepal Rivers

During the 1988 floods, the maximum discharge of the Brahmaputra corresponded to a 100 year return period flood, and the Ganges river reached its peak discharge, a 40 year return period flood, three days later. At the *Goalundo* stream gauging station, the maximum discharge 132,000 m^3/sec was measured. In the same flood period, the *Karnali* river recorded the peak discharge of 11,000 m^3/sec and the *Mahakali* river 4,079 m^3/sec (Nippon, 1993). The above data show that even large dams in all the larger rivers in Nepal will not be able to control floods in Bangladesh territory. Floods are mixed blessings. They spread fertile soil over the Ganges plain and make significant contribution in groundwater recharge and soil moisture retention. Hence a degree of flooding is even required at certain intervals. That is why our view is that floods should be managed but not completely controlled and stopped. Diversion and retention in traditional water bodies and groundwater recharge in an integrated way and a careful flow dispersion mechanism might be a sustainable solution to flood protection.

6. Discussion and Conclusions

Careless application of the conventional engineering developed in 19^{th} century for damming rivers and making canals is inappropriate for Nepal's context. Many unavoidable specific features should be considered before making a final decision on intervention to rivers. In South Asia where annual precipitation exceeds 1000 mm, there is a great possibility of storing rain water making small reservoirs. That will increase flow in the local streams, contribute to more groundwater recharge, in addition to providing surface irrigation. In those areas where groundwater overdraft needs to be countered by recharging of transferred water, the transfer will be unavoidable. So, firstly it is extremely important to find out the most groundwater overdraft affected areas and asses the volume of water for transfer duly considering the possible contribution by rainwater harvesting and other water management practices.

High dams in Nepal are subject to high risk of failure due to earthquake, the prevailing principles of dam design are not sound in view of long term performance and sustainability. And hence Nepal cannot accept high dams. This view is in line with the WCD studies of dams. The proposed solution is free of all shortcomings and simultaneously serves a large part of the *Terai*. It also contributes to the groundwater recharge in the *Ganga* plain which will ultimately increase lean period discharge at the *Farakka*, as desired by Bangladesh. Although this study at the first hand gives direct benefit to Nepal *Terai,* for which this is the most appropriate solution, the RLP of India which largely relies on the surplus water of rivers flowing from Nepal, should be modified to the concept suggested in this study.

The alternative to the conventional design and management of the water resources suggested by this study is a sustainable solution appropriate for geological, topographical and ecological condition of the Ganges basin. Construction of small reservoirs at the remote areas of the Himalaya may be a possibility for increasing the dry season flow to some extent. While with the proposed approach tremendous groundwater storage will be achieved at the upstream area, it also will be effective to increase the dry season flow in the Ganges, simultaneously serving the agriculture with conjunctive use of ground and surface water.

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