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IA is dedicated to promoting efficient irrigation technologies, products and services. The association serves its members and the irrigation industry by:

- Improving industry proficiency through continuing education.
- Recognizing and promoting experience and excellence with professional certification.
- Influencing water-use policy at the local, state, regional and national levels.
- Ensuring industry standards and codes reflect irrigation best practices.
- Providing forums that promote innovative solutions and efficient irrigation practices and products.

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- Define best practices for effective water management.
- Establish benchmarks and guidelines for irrigation products and applications.
- Promote efficient irrigation technology and practices.
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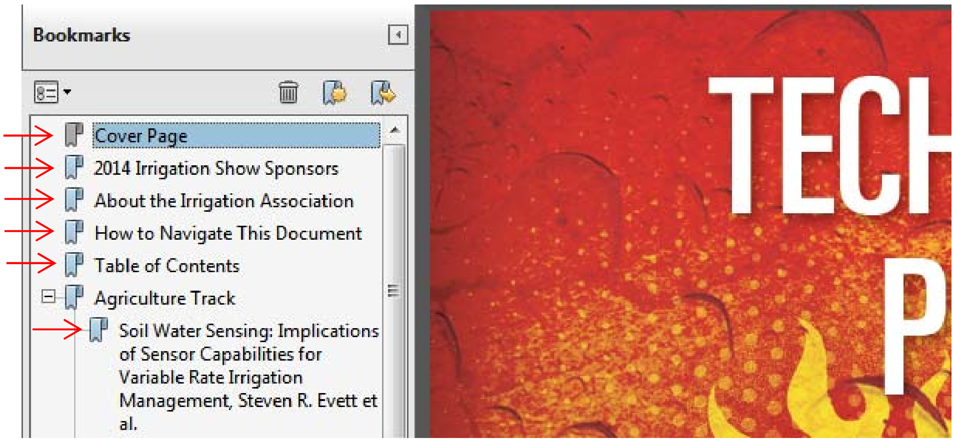

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Soil water sensing:
Implications of sensor capabilities for variable rate irrigation management

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Abstract. *Irrigation scheduling using soil water sensors aims at maintaining the soil water content in the crop root zone above a lower limit defined by the management allowed depletion (MAD) for that soil and crop, but not so wet that too much water is lost to deep percolation, evaporation and runoff or that the crop quality is impaired. To be useful for managing water to prevent over filling the soil or allowing it to dry so much that crop yield is compromised, soil water sensors must be accurate to the order of 0.02 to 0.04 inch/inch. Issues of sensor performance, numbers of sensors required for effective variable rate irrigation (VRI) management, and other factors complicating sensor application to VRI management all hamper adoption of soil water sensing systems for VRI. An alternative to soil water sensing that may be helpful is soil bulk electrical conductivity mapping, which can delineate field zones of different soil textures if salinity is not a factor. Another alternative, soil canopy temperature sensing, has been shown to accurately reflect plant water status and thus soil water status in semi-arid and arid irrigation regions; and this method is approaching commercial availability. A combination of crop canopy temperature sensing, which effectively uses the crop as many thousands of biological soil water sensors, and a few accurate soil profile water content sensors may prove to be the most practical approach to variable rate irrigation management in many regions.*

Keywords. Soil water sensor, variable rate irrigation, accuracy, management allowed depletion, bulk electrical conductivity, canopy temperature, crop water stress index

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Soil Water Criteria for Irrigation Scheduling

Soil water sensing has been used to guide irrigation management since the advent of commercially successful neutron probes in the 1960s. The neutron probe (NP) became widely used in the 1970s and has remained an important tool for consultants and some large farming operations, particularly with high value crops. More onerous regulation, including licensing, use, storage and training requirements, has increasingly limited the use of the NP. In addition, the advent of commercially available capacitance systems for soil water sensing in the early 1990s has caused some users to adopt these admittedly less accurate sensors due to the absence of regulations concerning their purchase and use. The more accurate time domain reflectometry (TDR) method also became commercially available for soil water sensing in the early 1990s, but was not widely adopted for irrigation scheduling because of its expense and complicated methods of application. In the late 1990s, the International Atomic Energy Agency (IAEA) and Food and Agriculture Organization (FAO) joint division on soil and water convened an expert panel to conduct a coordinated research project investigating whether the capacitance (frequency domain) and TDR systems would be capable of replacing the NP. The conclusion of that panel, based on five years of research on four continents, was that the capacitance sensors were not accurate enough to replace the NP, and that the conventional TDR systems, although accurate enough, were not presently able to be installed deeply enough or inexpensively enough for wide spread irrigation scheduling (Evett et al., 2008).

Irrigation scheduling using soil water sensors is an exercise in maintaining the water content of the crop root zone soil above a lower limit defined by the management allowed depletion (MAD) for that soil and crop (Fig. 1), but not so wet that too much water is lost to deep percolation, evaporation and runoff. The management allowed depletion for a corn crop on a clay loam soil is only about 0.06 inch/inch. To be useful for managing water to prevent over filling the soil or allowing it to dry so much that the crop yield is compromised more than acceptable, soil water sensors must be accurate. The accuracies needed are on the order of 0.02 to 0.04 inch/inch (Table 1), which is better than many commercial soil water sensors are able to provide. Values of field capacity and permanent wilting point for a particular field (needed for determining the available water holding capacity and MAD values) may be found from NRCS soil maps, at least to a close approximation. The values are, however, likely to change with depth in the soil and with position in the field, meaning that irrigation management should be site specific to be most effective, and to do that requires sensors be installed in the different soils of the field. NRCS soil maps are available on the Internet: http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm.

Plant root zones deepen during the growing season, often extending to five foot depth and sometimes deeper if the soil does not have a restrictive horizon and soil water content at depth is large enough to encourage root penetration. Since soil water sensors typically are sensitive only to the soil immediately around them, and since most sensors are small, it is typical that two or more sensors must be installed at different depths in order to understand how soil water content is changing in response to irrigation and crop water uptake. Depths of six and 18 inches or six and 24 inches are common. Seeing that the soil is above field capacity at 24 inches may indicate that deep percolation losses are occurring.

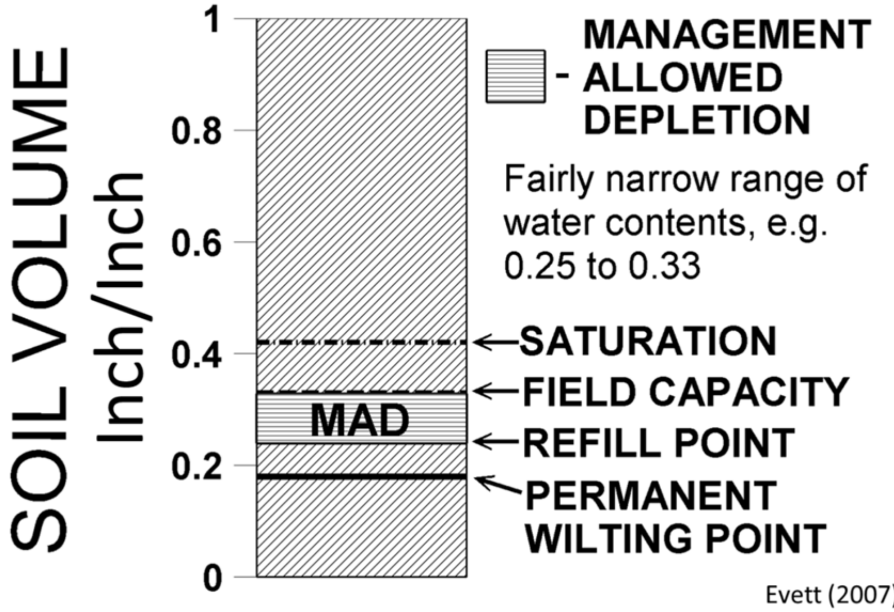


Figure 1. Sketch defining the key crop root zone water content values. In the clay loam soil depicted here, the water content at saturation is about 0.42 inch/inch and equal to the soil porosity. The soil cannot hold more water than saturation, and a saturated soil layer will drain to drier soil layers beneath until the soil reaches field capacity, about 0.33 inch/inch for this soil. If the soil dries to the permanent wilting point, about 0.18 inch/inch in this soil, the crop will be permanently damaged. The refill point is the water content below which the crop will be water stressed and yield may be reduced. It is about 0.25 inch/inch for a corn crop in this soil. The difference between the field capacity and the refill point is the management allowed depletion, about 0.08 inch/inch in this soil for a corn crop.

Table 1. Example calculation† of management allowed depletion (MAD, $m^3\ m^{-3}$) in three soils with widely different textures. The small range of MAD severely tests the abilities of most soil water sensors, particularly for the loamy sand soil.

Horizon	θ_{PWP}	θ_{FC}	θ_{AWHC}		MAD		MAD
	----------- $m^3\ m^{-3}$ ---------				fraction		$m^3\ m^{-3}$
silt loam	0.086	0.295	0.209	×	0.6	=	0.126
loamy sand	0.066	0.103	0.037	×	0.6	=	0.022
clay	0.190	0.332	0.142	×	0.6	=	0.085

† θ_{FC}, θ_{PWP}, and θ_{AWHC} are soil water contents at field capacity, at the permanent wilting point, and the plant-available water holding capacity (designated as AWHC).

Spatial Variability of Soil Properties

Center pivots are sometimes placed on sloping land that changes from one soil type to another across the area covered by the pivot. Sometimes soil type changes are unrelated to slope and aspect, for example in glacial till soils, flood plains, salt affected soils, etc. Figure 2 illustrates a situation with slope and soil type variations. There are four soil types irrigated by this pivot, the Lazbuddie clay and Loften clay (LcA and LoA) are in irrigation capability class 2 due to their small slopes and deep profiles. They represent the margins of a playa. The Pullman clay loam (PuB) under the pivot is in class 3 due to its greater slope and potential for runoff. The Pep clay loam has slopes of 3 to 5% and so is in class 4 due to very high runoff potential. Site-specific, variable rate irrigation could be used to reduce irrigation rates on the areas with high runoff potential.

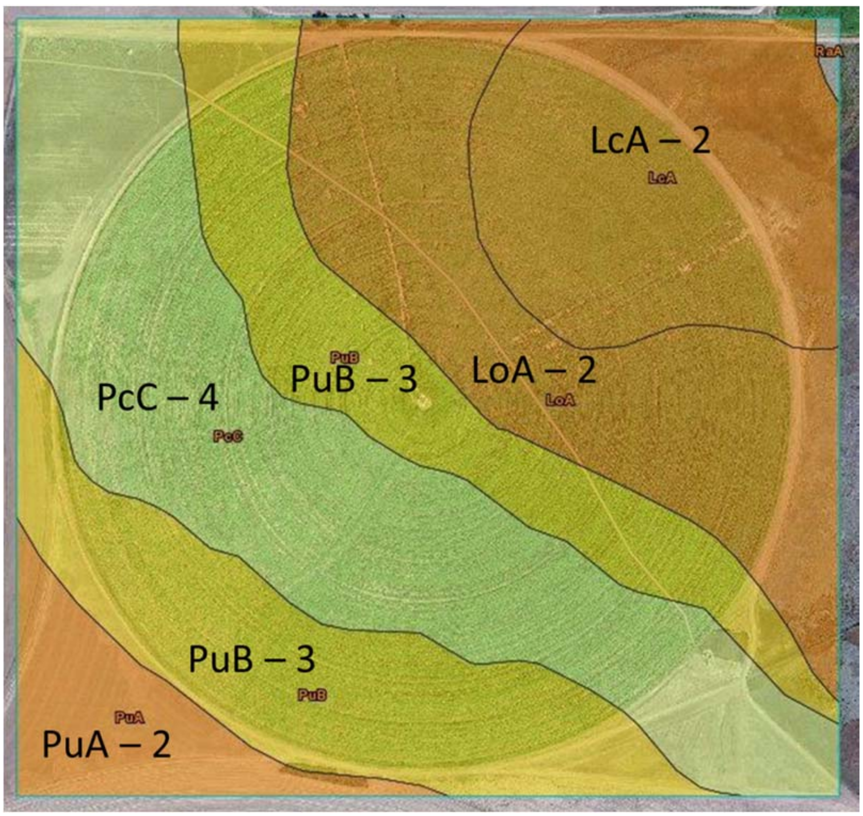


Figure 2. Soil and irrigation capability classification map from the NRCS soil survey web site for a center pivot in the Texas Panhandle. Letter codes indicate soil type; numbers indicate irrigation capability class. See Table 2 for details.

The soils illustrated in Figure 2 are all clays or clay loams, but do differ somewhat in available water holding capacity (Table 2). The most important difference between them is their slope, in particular the greater slopes of the Pep clay loam. One could lump the Lofton, Lazbuddie and Pullman soils together in terms of soil water sensing, leaving only the Pep soil to be sampled separately. However, the interpretation of soil water content data should be viewed in light of the FC and PWP values for each soil type, which means that a given water content will have different meaning in different soils. Depending on the degree of lumping, sensors in eight locations may be necessary to guarantee that soil water content variations are adequately captured.

Table 2. Summary by Map Unit of Classifications in the Area of Interest (AOI) in Figure 2.

Map unit symbol	Map unit name	Rating	AWHC* (in/in)	Acres in AOI	Percent of AOI
LcA	Lazbuddie clay, 0 to 1 percent slopes	2	0.161	40.4	17.1%
LoA	Lofton clay loam, 0 to 1 percent slopes	2	0.140	46.5	19.7%
PcC	Pep clay loam, 3 to 5 percent slopes	4	0.170	68.7	29.1%
PuA	Pullman clay loam, 0 to 1 percent slopes	2	0.165	14.3	6.1%
PuB	Pullman clay loam, 1 to 3 percent slopes	3	0.158	65.3	27.7%
RaA	Randall clay, 0 to 1 percent slopes, frequently ponded			0.5	0.2%
Totals for Area of Interest (the square, not the circle)				235.7	100.0%

***AWHC is available water holding capacity, the water that the soil holds between field capacity and permanent wilting point. In this case it is given in inch per inch for the top 40 inches of soil.**

Soil Water Sensing – Relationship to VRI

Factors that Influence Spatial Variability of Crops

Crop variations in space are influenced by other factors in addition to soil type, texture, salinity, depth and depth to restricting layers. Slope and aspect affect runoff and evaporative demand. In hilly terrain, evaporative demand is typically greater on south facing slopes than on north facing slopes. Disease and insect pressure can create field variability, as can temporary ponding due to runoff, or lack of sufficient infiltration of applied irrigation due to runoff from steeper slopes. Of course, agronomic mistakes in planting, spraying and fertilization can also create variability in the crop, which will translate into variability in crop water uptake rates and soil water content variability. Several of these factors cannot be ameliorated by irrigation, but irrigation can be varied in response. For example, irrigation of areas of a field hard hit by disease or insect pressure may no longer be economically viable, in which case a Site-Specific VRI (SSVRI) system prescription can be written to stop irrigation in those areas. Irrigation can be reduced on field areas in which slope is causing runoff problems, thus ameliorating parts of the field prone to ponding and water logging. Soil water sensors placed in these two areas (sloping and prone to water logging) will detect problems of lack of soil water on slopes and excess of soil water on areas that pond. Reducing irrigation rates on sloping areas will, however, likely lead to crop water stress there, which can only be addressed by extra irrigations on those areas. While an SSVRI system may allow this site-specific irrigation to occur, there may not be time in the irrigation schedule to allow these extra irrigations on sloped areas. Also, it should be recognized that evaporative loss is a greater fraction of smaller irrigations than of larger irrigations (Tolk et al., 2014).

Number of Measurement Locations and Depths Required

As a first approximation, the needed number of soil water measurement locations will vary according to the spatial variability of soil types and the interactions between soil type, slope and aspect. Perhaps the most tractable and easily understood approach to this problem is to begin with defining management zones. The number of management zones that can be separately delineated by a VRI irrigation system depends on whether the system's VRI capabilities are limited to sector-only variations in application rate determined by varying lateral rotation speed (Fig. 3A), or whether it can vary both lateral rotation speed and application rate in zones radially (Fig 3B). Angular size of sectors can vary, not being limited to the regular angular sizes of 18 degrees shown in Figure 3. And, radial sector sizes are not restricted to those shown in Figure 3, although radial dimensions typically are defined by the linear dimensions of banks of nozzles that can be controlled together, e.g., six nozzles per bank with nozzle spacing of 5 feet would give a 30-ft radial zone width.

If management zones can be defined in both angular (speed control) and radial (nozzle bank control) dimensions, then management zones can be more adequately tailored to field differences (soils, slopes, etc.) that impact water infiltration and runoff (Fig. 4B). If only speed control is possible such that only sector-wide zones can be defined, then management zones may not adequately respond to field soil variations, especially if the long axis of an area of variation is oriented perpendicular to the pivot lateral (Fig. 4A).

Assuming that the four management zones defined in Figure 4B are to be managed on the basis of soil water sensing, then at least one soil water sensing system is needed for each zone, for a total of four sensing systems, each composed of at least two sensors, one in the shallow root zone and one nearer the bottom of the root zone, for a total of eight sensors. This total assumes, however, that each system is capable of adequately representing the soil water content of a zone. There are two major factors affecting this assumption; the accuracy and spatial representivity of the sensor, and the field variation in microrelief, which will affect the surface and subsurface redistribution of water. Little can be done about field variation in production fields, except to recognize it where possible, but soil water sensors can be chosen that are more accurate and spatially representative.

A B

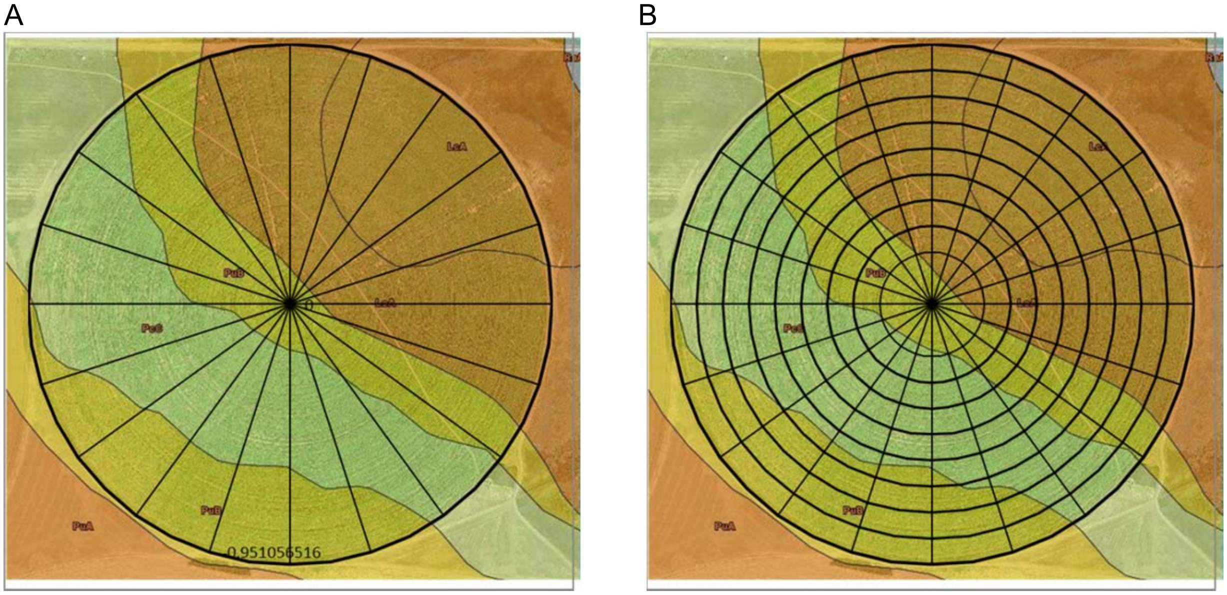
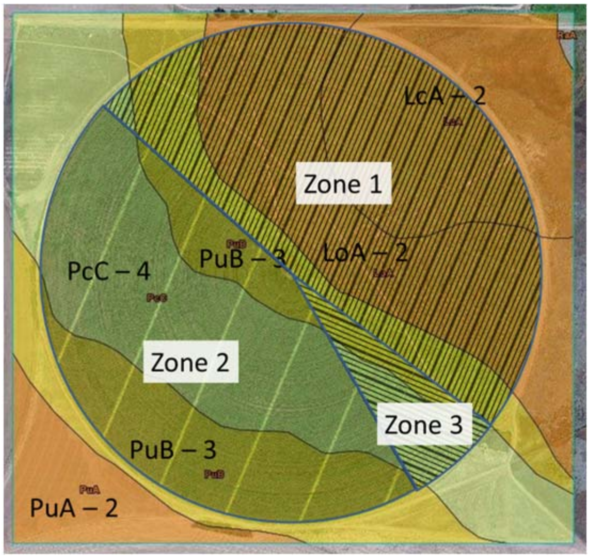


Figure 3. Examples of management zones. (A) Sector-only management zones are all that can be defined by varying lateral rotation speed alone. (B) If nozzle banks can be controlled along the length of the lateral, then radial sector dimensions can be defined as well, giving much more spatial control of irrigation application.

A



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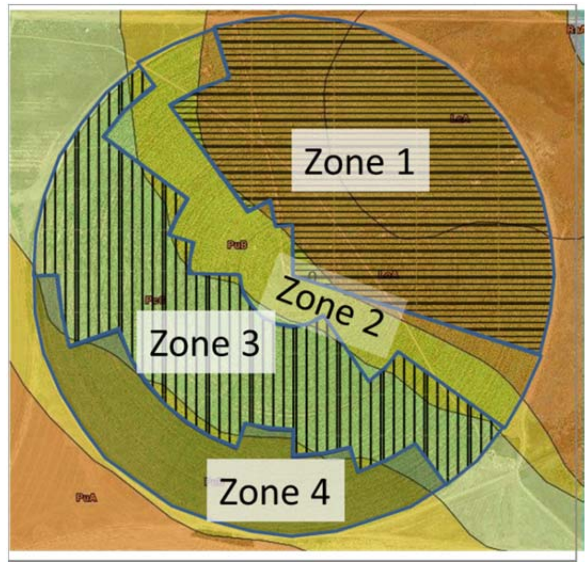

Figure 4. Examples of management zones for the soils and center pivot shown in Figure 1. (A) Sector-only management zones prescribed to cover the low lying and shallow slope soils in the NE half of the circle (Zone 1), some of the sloping soils (Zone 2), and the rest of the sloping soils and upper elevation Pullman soils (Zone 3). (B) Management zones prescribed according to both angular and radial dimensions, for the low lying and low slope Lazbuddie clay and Loften clay loam soils (Zone 1), the sloping Pullman soils (Zone 2), the sloping Pep soils (Zone 3) and the higher lying, less sloping Pullman soils (Zone 4).

Selecting Soil Water Sensors & Systems

Due to the numbers of sensors involved, labor associated with soil water sensing for VRI must be minimized. To be useful in VRI scheduling, soil water sensors must be accurate, relatively inexpensive, and require little labor. The latter criterion means that these sensor systems must be capable of being left in the field with little or no maintenance throughout the growing season, not require moving them when machine operations (mostly spraying) are needed, and be capable of wireless data transmission to either the farm office or directly to the irrigation controller.

Soil water sensors vary widely in their accuracy and spatial representivity (CPIA Proceedings: Chávez and Evett, 2012; Evett et al., 2007; Evett et al., 2012). In general, sensors can be classed as those that respond to the electromagnetic (EM) properties of soils as influenced by water content (and also by salinity and temperature), resistance blocks (e.g., gypsum blocks, granular matrix sensors and the like), tensiometers and the neutron probe. Tensiometers and the resistance blocks respond to soil water potential rather than water content, but these sensors can be useful since plants respond directly to soil water potential. Tensiometers are too difficult to maintain in the field to be useful for VRI scheduling. The several kinds of resistance blocks can, however, be easily installed and left for a season, connected to a datalogger and radio transmitter. With flexible antennae, field installations can allow tractor movement. The main disadvantage of resistance sensors is their limited range. They operate best near field capacity, but may lose contact with the soil before it dries to the management allowed depletion, a particular problem if deficit irrigation is being managed to improve water use efficiency and reduce pumping costs. A VRI scheduling system using a wireless soil water sensing system based on granular matrix resistance sensors with a "high density of nodes" is being demonstrated by Velledis et al. (2013a,b), but so far the emphasis is on developing and testing the wireless data transmission capabilities, not the aspects related to accuracy of soil water sensing and effectiveness of VRI management. Recently, an underground wireless communication system was tested with soil water sensors at the University of Nebraska (Tooker et al., 2012). The granular matrix sensors were buried at 16-inch depth to be clear of tillage operations. An antenna suspended from a center pivot lateral picked up the wireless signal as the lateral moved over the location of each sensor. This system is still in the development stage. Soil type, water content and amount of vegetation affect the wireless signal strength, and optimal radio frequency and antenna size and design are still being studied (Dong and Vuran, 2013; Dong et al., 2013).

The neutron probe is an excellent research tool, but expensive and labor intensive since it cannot be left in the field. Part of the expense is the regulatory requirement for licensing and safety training due to the radioactive source involved in this method. It is not suitable for production agriculture VRI.

Most relatively inexpensive and commonly available soil water sensors are of the EM type, of which there are two major kinds, the capacitance sensors and the travel time sensors. There are important differences between the two main kinds of EM sensors (Evett et al., 2012). The capacitance sensors radiate an EM field into the soil, thus involving the soil as part of the dielectric of a capacitor in an oscillating electric field. The frequency of oscillation decreases as water content increases, but the frequency is also affected by soil bulk electrical conductivity and bound water content. All soils are somewhat conductive, but conductivity increases with water content, temperature, content of high CEC clays and salinity. Thus the capacitance sensors are also temperature, conductivity and clay content sensors. Bound water is water that is bound by attraction to the surface charge of clay particles, and there are important amounts of bound water in high surface area clays (smectites, montmorillonites, etc.). The degree to which water is bound to clay is also temperature sensitive, which causes a secondary effect on the frequency of oscillation of capacitance sensor. Although soil-specific calibration may improve the accuracy of capacitance sensors, at least in laboratory studies, there will still be effects of varying temperature and salinity in the field.

An equally important disadvantage of the capacitance technique is related to the EM field that is radiated into the soil. This so-called fringing field does not uniformly penetrate the soil, but is instead attracted to more conductive parts of the soil. Because soil structure and water content vary a great deal on the small scale in field soils, there is a large random variation in the EM field shape and frequency response depending on the exact location of a capacitance sensor. The random response makes the capacitance sensors relatively non-representative of soil water content on the scale of plant root systems. In field studies in California and Texas of the major capacitance sensors used in access tubes, Evett et al. (2009) and Mazahrih et al. (2008) found that these sensors reported field variability of soil water content that did not in fact exist when measured directly by soil coring or by the neutron probe. The neutron probe has a much larger measurement volume and is insensitive to conductivity and temperature effects. The false variation was so large that these sensors were incapable of providing data accurate enough to schedule irrigations using the MAD paradigm.

The variability of sensed soil water content is described by the standard deviation (SD) of water content. Even in a quite uniform soil, there is a certain irreducible variability of soil water content that dictates the number of sensors or access tubes needed to determine the water content to within a given precision criterion. Based on data from Evett et al. (2009), Evett and Steiner (1994) and Mazahrih et al. (2008), Table 3 gives the number of access tubes needed in order to determine profile water content to precisions of 0.4 and 0.8 inch (1 and 2 cm in a 100 cm profile) for several different soil water sensors and for gravimetric core sampling using a push tube. Statistically speaking, only the gravimetric sampling and the neutron probe can deliver a precise profile water content with only one access tube per uniform management zone. The capacitance sensors (first four listed in Table 3) all require several access tubes to determine a mean water content with sufficient precision. In addition, the studies cited indicate that this precise water content will likely still be inaccurate. Note that in drier soils all sensing and measurement methods become more imprecise due to the increased random variation in soil water content as soils dry. As discussed previously, this random variation has larger effects on the capacitance sensors than on the neutron probe or gravimetric sampling.

Table 3. Number of access tubes (*n*) needed to find mean volumetric water content (VWC) to a precision *d* (unitless) at P=95% for a given field-measured standard deviation (*s*, -) of volumetric water content. For 40-inch deep soil profile, a VWC precision of 0.01 is equivalent to 0.4 inches of water, and a precision of 0.02 is equivalent to 0.8 inches of water.

		s	***n***	
Method	**Soil condition**	**Volumetric (unitless)**	***d* = 0.01**	***d* = 0.02**
Diviner 2000	**Wetter**	**0.0131**	**7**	**2**
	Drier	**0.0242**	**23**	**6**
EnviroSCAN	**Wetter**	**0.0152**	**9**	**2**
	Drier	**0.0266**	**27**	**7**
Delta-T PR1/6, PR2/6	**Wetter**	**0.0272**	**28**	**7**
	Drier	**0.1216**	**568**	**142**
Sentry 200AP	**Overall**	**0.0378**	**55**	**14**
Trime T3	**Wetter**	**0.0075**	**2.2**	**1**
	Drier	**0.0238**	**22**	**5**
Gravimetric by push tube	**Wetter**	**0.0045**	**1**	**1**
	Drier	**0.0070**	**2**	**1**
Neutron probe	**Wetter**	**0.0015**	**1**	**1**
	Drier	**0.0027**	**1**	**1**

In contrast with capacitance methods, the travel time sensors work by sending an electric pulse (step pulse) along an electrode that is buried in the soil and measuring the time it takes the pulse to move along the electrode. Travel times are associated nearly linearly with water content. The travel time sensors employ different physical laws than do the capacitance sensors (Evett et al., 2012) and so are relatively immune to the effects of soil electrical conductivity, temperature and salinity, unless conductivity is so large that these sensors cannot determine the travel time. Early travel time sensing systems depended on expensive, research quality pulse time domain reflectometry instruments, expensive coaxial multiplexers for connecting more than one soil probe to the instrument and a computer system to control the instrument and switching of the multiplexer(s). These systems required many cables and were not useful in production agriculture although, like the neutron probe, they became a standard for research efforts. Within the last ten years, however, the adoption of miniaturized high frequency electronic components of the type used in cell phones has allowed the creation of time domain measurement circuits that are inexpensive, low power and small enough to be contained in the plastic head of a soil water sensor. These tend to be superior to the capacitance sensors and typically report accurate water contents, soil bulk electrical conductivity (useful for monitoring salinity in soils prone to it) and temperature (useful for timing of planting operations). Three examples are the CS655 (Campbell Scientific, Inc., Logan, Utah) and the ACC-TDT and TDR-315 sensors (Acclima, Inc., Meridian, Idaho). All can be used in solar-powered field systems with wireless connectivity that can be left unattended in the field for months. Until recently, time domain sensors were only useful in the upper root zone where they could be installed easily. However, a deep profiling soil water sensor has now been patented (Evett et al., 2014) that would allow for wireless, automatic sensing of soil water content to 48 inch depth in 8-inch increments. The sensor can also sense soil bulk electrical conductivity and so is useful for salinity management as well. The tube-type sensors can be connected together to access deeper root zones (up to 96 and 144 inches). Data such as those in Table 3 have not yet been collected for this sensing system, which is not yet commercially available.

The present state of the art does not provide a complete soil water sensing solution for variable rate irrigation management. Limitations include the costs of deploying sufficient densities of sensors to detect within-field variations, sensor inaccuracy (except for the time domain sensors) and calibration effort needed, often insufficient sensor depth range and limitations of wireless communications in dense vegetation. All of these limitations are being addressed by state, federal and commercial research and development efforts.

Alternatives to Soil Water Sensing

Conductivity Mapping

The availability of soil bulk electrical conductivity (BEC) mapping using equipment pulled by tractors or other vehicles (e.g., Veris Technologies, www.veris.com; EM38, Geonics Limited, www.geonics.com; GEM-2, Geophex, www.geophex.com) has resulted in easy availability of field BEC mapping. As explained previously, soil BEC is influenced by many factors, including temperature, salt content (including fertilizers), water content, soil texture and buried metal (e.g., wiring and piping). If soil salinity is the predominant influence on BEC, it may also have an effect on yield (Fig. 5). In a given field, more clayey soils are often more conductive both because they can hold more water than sandier soils and because the clay itself is more conductive when wet than is sand at an equivalent water content. Thus soil BEC may be related to the water holding capacity of soils, and BEC maps may be correlated with soil texture, which can provide a basis for prescriptive irrigation scheduling. Grisso et al. (2009) stated that soil EC values change over time due to wetting and drying of a field, but that mapping of relative water holding capacity remained stable over time, and can be related to yield (Fig 6). They also stated that soil BEC maps more accurately identified the locations of transitions between soil types and small areas of different soil texture than did Order 2 NRCS soil surveys, which were not designed to identify areas smaller than 2.5 acres and were not as accurately georeferenced (Fig. 7).

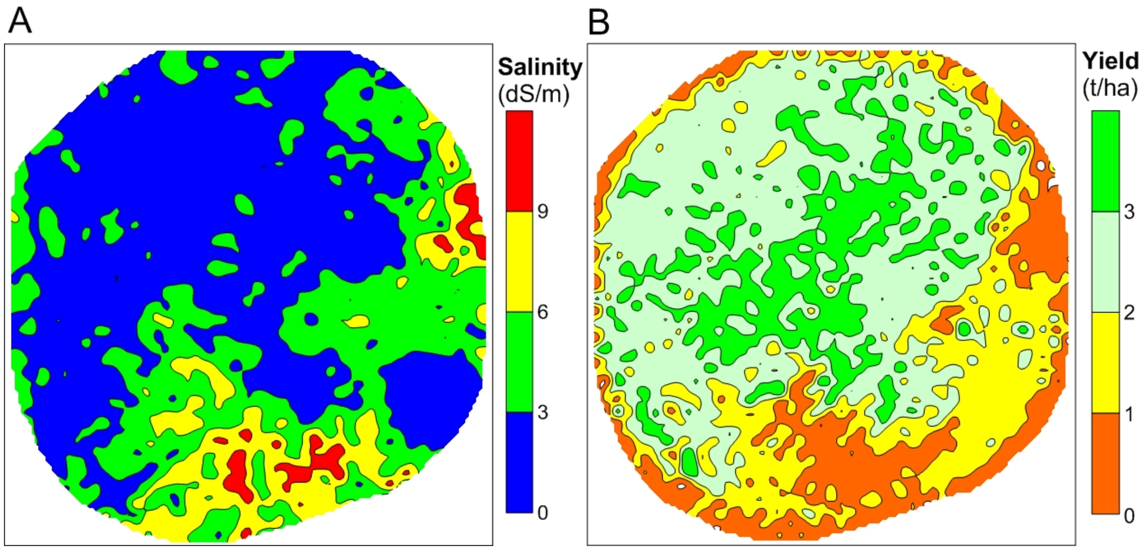

Figure 5. Georeferenced soil bulk electrical conductivity data can be transformed into maps of soil salinity using georeferenced soil salinity samples for calibration of the transform. As shown here, there can be a strong relationship between salinity and yield, especially for salt-sensitive crops such as dry beans. Illustration courtesy of Woods (2013).

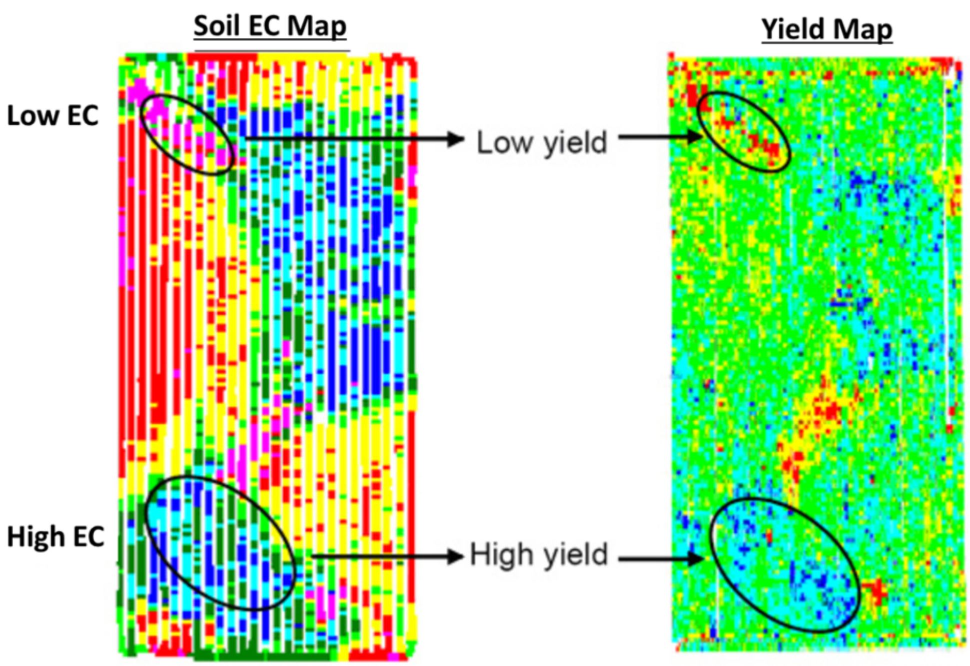

Figure 6. Example of a soil EC map that mostly represents soil texture differences. The lower EC areas were more sandy and had smaller water holding capacity, which resulted in less yield. The larger EC areas were more clayey and had larger water holding capacity, which resulted in more yield. Illustration courtesy of Grisso et al. (2011).

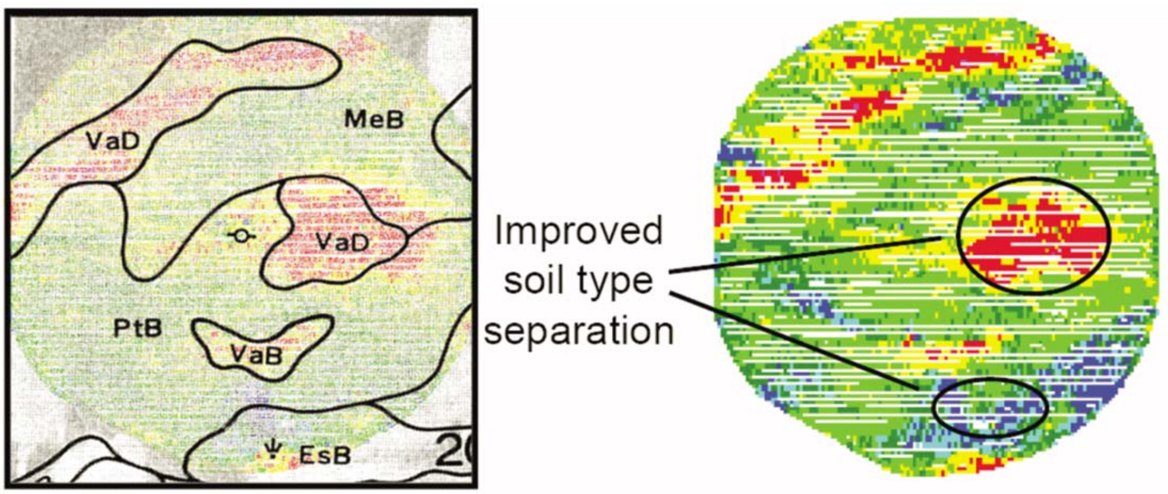

Figure 7. Example of soil EC map over which NRCS soil map boundaries have been overlaid (left), illustrating how the soil map could be corrected to more accurately represent the soil units. Illustration courtesy of Grisso et al. (2011).

Grisso et al. (2009) did, however, recommend using a soil BEC map in conjunction with an NRCS soil map because of the added information available from NRCS such as slope, crop suitability, etc. Factors such as large applications of manure or other fertilizer, variable irrigation in the past or very dry soils may result in misleading soil BEC maps. It should be remembered that soil BEC maps may indicate variations in soil water holding capacity, all other things being equal, but not necessarily crop water needs. Also, soil BEC sensing is typically done when there is no crop in the field, and it is relatively expensive, meaning that irrigation scheduling for VRI cannot be done using this technique.

Plant Water Status Mapping – Connection to ET & Soil Water Status

In arid and semi-arid climates, greater crop canopy temperatures indicated greater crop water stress (Fig. 8) because crops with sufficient soil water availability are cooled by transpiration. Crop water stress irrigation scheduling can be accomplished automatically (or manually) using crop water stress data from infrared temperature sensors mounted on moving irrigation systems (Peters and Evett, 2008). An empirical crop water stress index (eCWSI) based on georeferenced data from sensors on a center pivot lateral can be mapped to show spatial changes in crop water stress that develop over time (Fig. 9). Crop leaf temperature data from infrared thermometers (IRTs) can be combined with on-site measured weather data from inexpensive weather stations to calculate a crop water stress index that is integrated over the daylight hours to improve stability, resulting in maps of the integrated Crop Water Stress Index (iCWSI) for an entire field (O'Shaughnessy et al., 2010). The iCWSI is well correlated with plant stem water potential, which is a direct indicator of plant water stress. Automated VRI irrigation using a supervisory control and data acquisition (SCADA) system has been demonstrated to produce yields and crop water use efficiencies as good as or better than those resulting from irrigation scheduling using the best scientific irrigation scheduling method – the neutron probe used weekly in many access tubes spread over a field (Evett et al., 2006; O'Shaughnessy et al., 2012a), and has been recently patented (Evett et al., 2014). These methods are being transferred to commercial center pivot irrigation systems for eventual sale to producers. The wireless IRTs eliminate initial and maintenance costs of wiring (O'Shaughnessy et al., 2012b, 2013); and this IRT technology has been transferred to manufacturer who offers it for sale (model SapIP-IRT, Dynamax, Inc., Houston, Tex.).

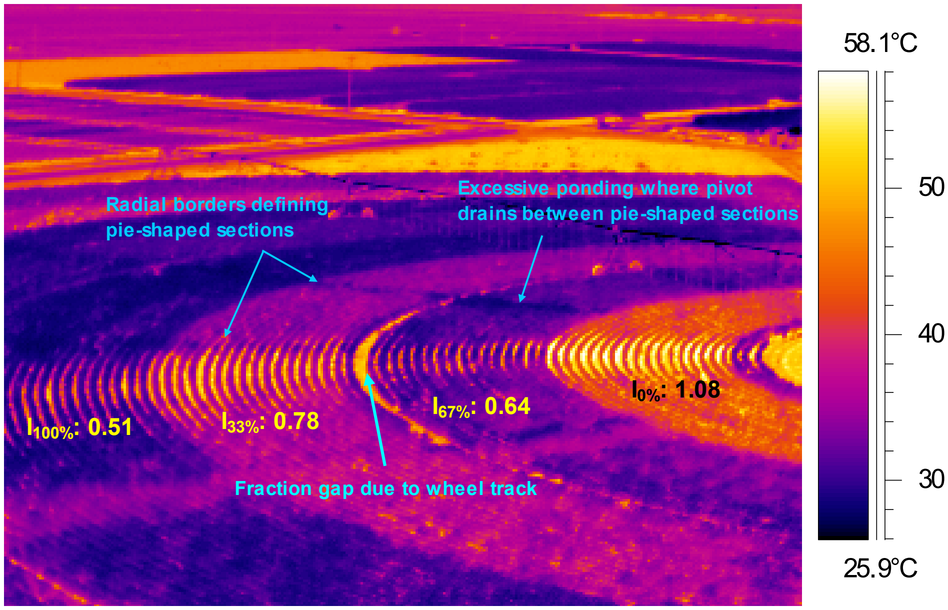

Figure 8. False color radiometric image of a center pivot irrigated field showing increasing canopy temperature as irrigation deficit increased from full irrigation ($I_{100\%}$) to 67% of full irrigation ($I_{67\%}$), to 33% of full irrigation ($I_{33\%}$) and to a non-irrigated (dryland) treatment ($I_{0\%}$). The values 0.51, 0.78, 0.64 and 1.08 are CWSI values. Also shown are cooler areas that received excess water when the pivot lateral was stopped to drain between treatments. The importance of infrared sensor aiming is also illustrated. View angles that look across rows see only plant canopy, whereas view angles that look down rows see both plant canopy and bare soil (brighter and warmer in this false color image).

Planting a crop can be seen as the installation of many thousands of sensitive biological soil water sensors per acre. Crop water stress is well correlated with leaf water potential, which in turn is correlated with soil profile water content. The cotton CWSI values illustrated in Figure 9B were well correlated with soil profile water content within the root zone (Fig. 10), at least relatively later in the irrigation season. Other research has shown that the crop temperature data can be used in energy and water balance models of crop water use (ET), which can be used to estimate changes in soil water content over time (Colaizzi et al., 2003), thus closing the circle between soil water sensing and crop water stress sensing.

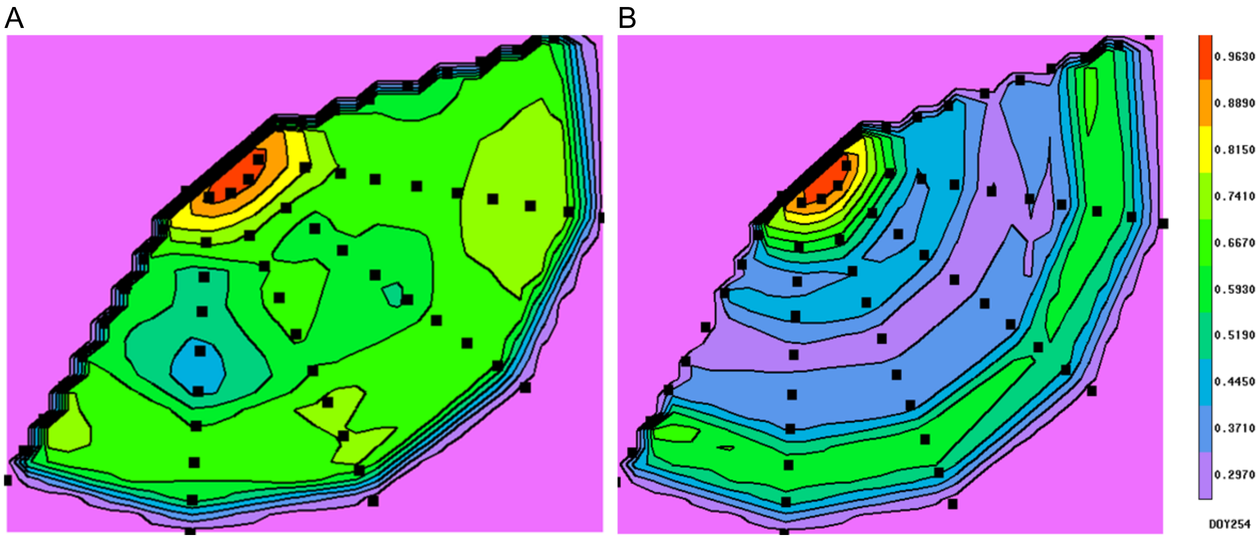

Figure 9. Empirical crop water stress index (eCWSI) calculated for a cotton field in which different deficit irrigation treatments were established. (A) Cotton early in irrigation season, DOY 204, 2007. (B) Cotton at end of irrigation season, DOY 254, 2007 (O'Shaughnessy et al., 2011). Early in the irrigation season, DOY 204, when a minimal number of differential irrigation treatments were applied, the stress index values do not vary substantially spatially. Only the unirrigated pivot center and the outer border rows showed appreciable differences. Near the end of the irrigation season, DOY 254, after imposing differential treatments for nearly 50 days, the variations in crop water stress were visible as a concentric pattern. The scale on the right varies from 0.297 to 0.963, which is the range of the data illustrated. The CWSI theoretically ranges from zero to unity,

Summary

Soil water sensing for variable rate irrigation scheduling is hampered by presently available accurate soil water sensors and wireless data transmission to the irrigation control center. Present challenges include field installation labor and timing to avoid machine operations that disturb the soil and may damage the sensors and antennas used. Depending on the spatial variation in field soil properties, installing an adequate number of sensors may be overly expensive. Wireless plant water stress sensors mounted on moving irrigation systems may be less expensive and offer proximal remote sensing that does not get in the way of field operations or require installing sensors in the soil. Nevertheless, soil water sensing will remain an important tool in irrigation scheduling, including as a check on VRI prescriptions generated using plant water stress sensors.

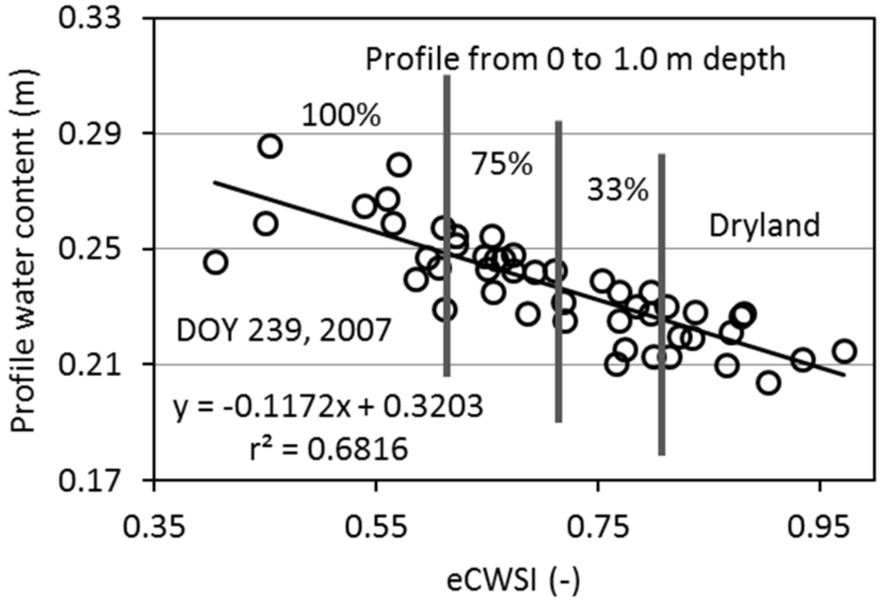

Figure 10. The soil profile water content within the crop root zone is correlated with the empirical crop water stress index (eCWSI). Different irrigation amount treatments produced groups of eCWSI values that did not overlap along the regression line, illustrating that eCWSI is a good surrogate for profile water content. Irrigation treatments were full (100%), 75% of full, 33% of full and dryland.

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Data Standards for Precision Irrigation

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Abstract. *Manufacturers over the years have provided growers with improved equipment for irrigation and advanced software programs for timing and controlling water applications. However, these software programs are proprietary and are not designed to work together. Improving interoperability among these programs would not only save time and money but would also promote the use of precision irrigation management.*

Over the past two years, a group of companies has been collaborating to develop data standards to enable interoperability of broad range of agricultural technologies and software programs. The goal of this collaboration is an industry-wide, standard format that will enable the exchange of data and allow for their use in precision irrigation management systems. The work on this goal is currently taking place in the context of AgGateway's Water Management Group and PAIL project. We will present the results of this collaborative work and the progress made during 2013 and 2014.

Keywords. Irrigation, Data Standards, Decision Support Systems, Schema, Use Case, System Integration

Introduction

Irrigated agriculture in the US accounts for 80-90% of the consumptive water use and approximately 40% of the value of value of agricultural production(USDA, 2009; Schaible and Aillery, 2012). This value, totaling nearly $118 billion, is produced on 57 million acres. Given the increasing challenges in water availability caused by climate change, and the likelihood of increased water conflicts from competing users, irrigated agriculture must increase its efficiency without sacrificing a reduction in the value it produces (Schaible and Aillery, 2012). Much of this efficiency can be derived through application of precision irrigation technologies, and on-farm management systems that facilitate sound agricultural practices. However, less than 10% of irrigated farms use any type of advanced decision support tools or technologies (USDA, 2009). Improving adoption of these technologies is critical to increasing efficiency.

SIS has been advocated for the past 3 decades as a technique that improves water management practice (Bjornlund et al. 2009; Leib et al. 2002; Montoro et al. 2011; Ortega et al. 2005; Quinones et al. 1999). Early on, it was recognized that growers required accurate and agriculturally appropriate meteorological data support to implement SIS. This need led to the development of agricultural weather networks such as the California Irrigation Management Information System (CIMIS) and the AgriMet system. CIMIS started in 1981 and grew rapidly. By 2001, CIMIS had 4700 users, thus the network served 15000 farms (Eching 2002). The first advantage of agricultural weather networks is the relative low cost (to the grower); the secondary benefit is that the data collection and assimilation can be automated.

Automated data entry into SIS systems remains an active research topic today, and technological progress in soil moisture sensing and data telemetry has made possible the development of spatially distributed networks of soil sensors that automatically upload data to SIS software (Bjornlund et al. 2009; Evans et al. 2012; Zotarelli et al. 2011). However, for all the advancement in data services, growers must still enter their own irrigation water use to the SIS software e.g. (Laboski et al. 2001) or other checkbook methods (Li et al. 2011; Lundstrom; Stegman 1983; Steele et al. 2010).

There is a variety of technologies available for precision management of irrigation (Smith et al, 2010). Remotely actuated center pivots, drip irrigation systems, soil moisture sensing, on-farm weather stations all enable precise application with precise timing. Numerous software tools exist for deciding when and how much water to apply. However, rarely do these tools interoperate effectively. Data must be moved manually from one application to another and the burden is on the grower to do the data management.

An important remaining task required for the full automation of SIS is automated data input of irrigation water use: timing, placement, and depth. Irrigation equipment suppliers have realized the importance of data automation and have introduced technological solutions e.g. Valley (2012); however these technologies may remain challenging for small farms because of their high capital costs relative to the returns they produce.

Data Standards provide a foundation for agricultural irrigation solutions. They define the structure and format of information sent and received between two or more devices. Technology has provided many tools to help growers irrigate their land more efficiently. However, these tools rarely work together well, and; growers using them must invest extra effort to bring the information together. Improving the ability to share data among these tools will reduce users' effort, increase adoption, and lead to greater water use efficiency through improved accuracy and precision of irrigation management.

In 2011, the Northwest Energy Efficiency Alliance (NEEA) convened a group of irrigation expert to discuss issues that will lead to improved energy efficiency of agricultural irrigation. One of the conclusions from that conference was that the irrigation industry needs to support more integration of agricultural technologies. To that end, a group of companies, industry representatives, academics, and interested parties are collaborating to address the integration problem. This project, called **Precision Ag Irrigation Leadership** (PAIL), has the specific goal of producing a set of data exchange standards that will enable development of more efficient and easier to use solutions for irrigation management. The PAIL project is taking place in the context of AgGateway's Precision Ag

Council and Water Management Group. AgGateway is a non-profit consortium of over two hundred companies focused on helping growers, retailers, manufacturers and supply chain partners reduce the cost and frustration of managing of complex data in today's agricultural industry.

Target Market for an Integrated Ag Irrigation Solution

The USDA Economic Research Service (ERS) categorizes farms primarily on the basis of Gross Cash Farm Income (GCFI) [1]. Previous versions only used annual sales income. ERS recently updated the typology to reflect three important trends: commodity price increases, a shift in production to larger farms, and the rapid growth of the use of production contracts among livestock producers.

For PAIL's purposes the relevant categories are derived from (Hoppe and MacDonald, 2013):

1. Small Family Farms, GFCI less than $350,000
2. Mid-size Family Farms, GFCI between $350,00 and $900,00
3. Large Scale Family Farms, GFCI greater than $1,000,000
4. Large Family Farms, GFCI of $1M - $499,999
5. Very Large Farms, GFCI of $5M or More
6. Non-Family Farms (includes Corporate Farms and Cooperatives). GFCI level is not specified. Defined as any farm where the operator and persons related to the operator do not own a majority of the business.

The previous version (2001) of the typology included large farms, with sales between $250,000 and $499,999, and very large family farms, with sales of $500,000 or more. However, farm production is shifting to much larger farms, thus the additional category of Mid-size family farms and the much higher levels of GCFI. Farms that annually generate $250,000 plus in sales represent just 10% of the nation's farms, but account for 82% of U.S. food production (CNN Money, Nov 2012).

Due to the size of investment (both time and money) to deploy an integrated solution, the *ideal* target customer for a level 2 or 3 Integrated Ag Irrigation solution is the Large Scale Family Farm or the Non-Family Farm. Mid-size Family Farms who are early adopters may also be targets, but would likely need large incentives as part of purchase. Small Family Farms are more likely to adopt the Level 1 solution, if they are to make a change.

In addition to the definitions above, the ideal target customers have one or more of the following characteristics:

1. They have a requirement or compelling need (either through natural causes or government regulations) to reduce irrigation water use.
2. They must manage multiple brands of equipment, especially center pivots.
3. They already have a level of data management on their farm and employ one or more employees who are dedicated to data management and integration.
4. Their overall attitude toward farming technology is forward thinking.
5. They are required by their local government, utility or crop insurance provider to report applied irrigation and/or chemigation.
6. They are already ready to purchase new irrigation capital equipment.

For the grower, the opportunity is to increase profitability through lower energy use and reduced costs with the availability of an integrated, easy-to-use decision support solution that uses a flexible

[1] GCFI includes the farm's sales of crops and livestock, receipts of Government payments, and other farm-related income. Gross farm sales, in contrast, exclude other farm-related income and include items than are not revenue to the farm: the value of sales accruing to share-landlords and production contractors and Government payments accruing to landlords.

approach combining optimal irrigation techniques with well-integrated soil, moisture, and weather data.

The irrigation data standards should also be seen as part of a larger set of data standard requirements. Growers are seeing an increasing need to integrate distinct sets of farm data. Merging precision farming technologies offer advantages in identifying, managing and tracking their products. However, given the lack of data standards and interoperability between manufacturers and suppliers, they also create significant challenges as dissimilar products and platforms multiply.

Allan Fetters, Director of Technology at J.R. Simplot Company and a PAIL team member, agreed with McDowell. “Growers are inundated with data. We have diagnostic and performance data coming in from each piece of equipment we use, on each and every field of the farm, let alone what and where all the crop inputs are being applied. This is compounded especially if you are running a mixed fleet of equipment,” he explained. “Each source of data received on the farm is displayed in its own configuration, on its own site, so a lot of extra time is being spent trying to analyze this data and interpret it into useful information that is going to make the farmer more productive. We need a free flow of data to enable us to farm with the best real-time data available. Ideally I would have all of my key farm data and digital decision making accessible through one common, easy to use dashboard, so I can control, manage, troubleshoot, view, and analyze my farm data.”

In short, growers do not need more data, so much as the information and insights that the data provides.

Data Standards Important for Complex Sales

Developing and marketing integrated precision agriculture solutions is not a simple matter. These solutions are not widgets that can be shelved and sold like individual sensors or sprinkler heads. In his book, “Dealing with Darwin,” business consultant and author Geoffrey Moore makes a clear distinction between making and selling “widgets” and making and selling integrated solutions. Moore calls the former “high volume” and the latter ‘complex systems.” Complex solutions require the integration of a lot of moving parts. If those parts are not under the control of a single entity, such as a company or agency, it becomes very challenging to get them to work together (e.g. vertical integration).

For precision agricultural solutions, developing and aligning to a set of data standards is a critical component of a larger system that must be configured before an integrated solution actually reaches the market. The data standards help form the underlying technology architecture that not only supports a well-integrated solution, but makes it easier to tie that solution into a grower’s existing farm management system.

Figure 2 below shows an adaptation of Geoffrey Moore’s model for complex systems (Moore, 2005), as applied to an integrated, agricultural irrigation solution. The model is organized around the grower because market success is dependent upon a relatively small set of customers making relatively large purchase commitments. Qualified customers are the scarcest resource in the system. Growers typically have the power in sales negotiations, and solutions must be customized to fit within their existing farm management processes and equipment infrastructure. No two solutions are identical. Lead times are long.

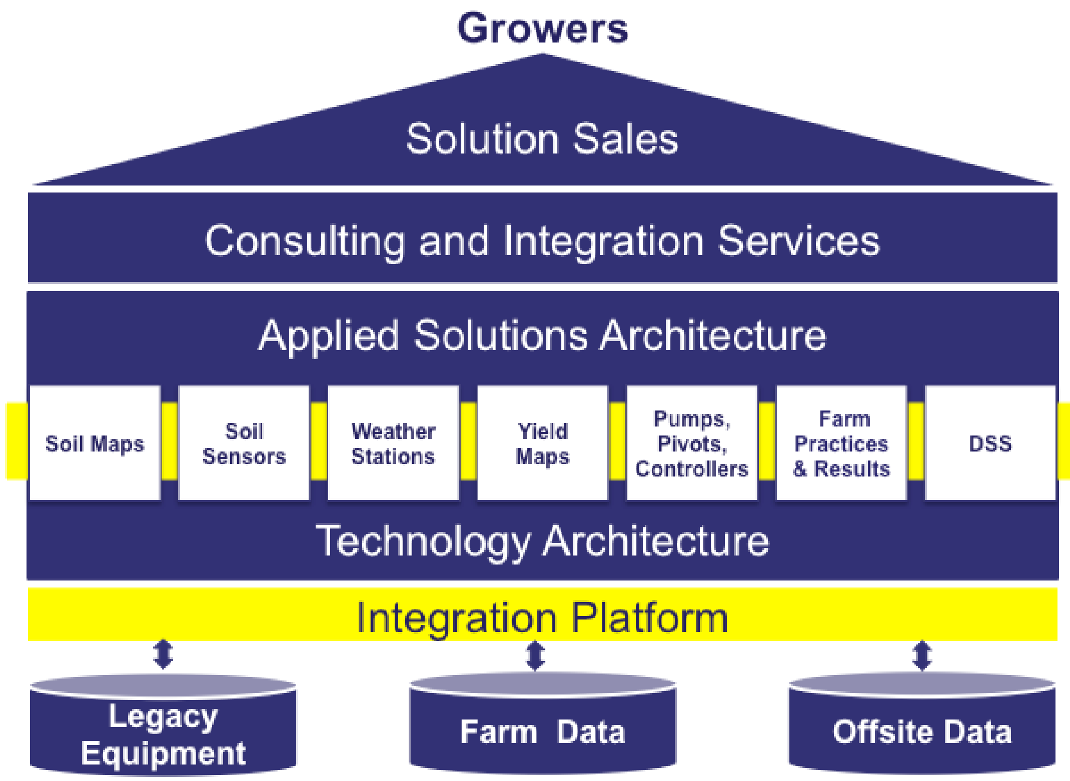

Figure 1 Complex Systems Market Model

Solution Sales can be driven from a local sales source, such as an irrigation equipment retailer, or in conjunction with a consulting service. Irrigation consultants can either work directly with growers or vendors. In some cases, they may be tied directly with a particular pivot or irrigation services provider. Their role is to bridge the specific needs and requirements of the grower and the core capabilities of the Ag Irrigation solution.

Two sub-architectures surround a set of multiple, disparate elements. These elements are modules that can be used to provide the system's ability to generate irrigation prescriptions and to monitor and report the results. Different vendors often supply them. The system is extensible: new modules can be added. And the system can integrate with other FMIS systems if necessary or desired.

The technology architecture unifies the system on the systems-facing side. It includes common facilities and protocols, such as the PAIL data standards and data transfer mechanisms. It would also include the business rules for those data standards. The technology architecture enables disparate elements to be swapped in and out to create different solution sets, without having to reconstruct everything from the ground up.

The solution architecture unifies these elements in a way that is clear and actionable by the grower. It consists of application specific templates that align the generic Ag Irrigation solution with the specific grower's needs. It embodies business and farm processes that are specific to that grower, and communicates the business results of the applied application. It is also understandable and sellable by the consultants and system integrators, as well as the solution sales force. It includes the user interface, as well as instructions and training.

The bottom layer indicates what the grower already has in place: pivots and other equipment, a local database, as well as offsite data, such as SSURGO soil maps or Agrimet weather forecasts. Above that, the Integration Platform provides a buffer that is familiar to the current generation of farm managers, has proven reliability, probable longevity, and is predictable in its interactions with the equipment and systems with which it interfaces.

No one member of the value chain can deliver all the products and services end-to-end. Typically this requires a company that has a reputation in the solution space that gives it permission to lead, bringing in value-added partners who can complete the solution model.

Value Proposition for Growers

While the overall precision irrigation solutions allow growers the potential to save energy and water costs, a common set of data standards provides a different, but compatible, value proposition. As noted above, growers are inundated with many different types of data. In summary:

- Growers spend too much precious time trying to sort through data that comes to them through different portals or websites
- Each piece of equipment not only sends its own data, but does so in a different format, through its own data portal
- User interfaces vary, and many are difficult to understand
- The issues above make it difficult to convert data to meaningful, actionable information
- Using a mixed fleet (different brands) of equipment compounds the issues above

The need for real time data to effectively manage farms is only going to grow

The output from the PAIL project will allow growers, and their irrigation consultants, use real-time data, from multiple pieces of equipment, from multiple vendors, without having to acquire, digest and translate individual data formats.

Value Proposition for Vendors

For vendor participants, the data standards work provides three main advantages:

1. **Financial Benefits**:
   Vendors save time and effort currently required to interact with multiple vendor products. They also increase the likelihood of purchase of their irrigation products and services, removing the barrier of growers having to learn multiple data systems.
2. **Technological Benefits:**
   Vendors can enable their equipment or software to interact with an irrigation application without having to rewrite specific code every time a partner's software program or application is changed.
3. **New Market Opportunities**:
   Working in partnership or in short-term alliances, vendors can create new market opportunities with data-driven products and services. A commonly used set of data standards also makes it easier to partner with other businesses, both upstream and downstream.

The following example describes an integration effort that actually occurred between two companies in 2008. Both companies invested a significant amount of time and effort. The collaboration was successful and both companies benefited from the project however, the costs were not trivial. If an API had been available both companies could have achieved the same goal with lest time investment required. This is how the API reduces costs for the grower: by reducing cost of development of new interoperability between existing systems, those savings can be passed on to the customer.

Summary: In 2009, CropMetrics and AgSense worked jointly to develop the industry's first wireless Variable Rate Irrigation solution.

Issue/Problem: CropMetrics developed a VRI speed control prescription program but did not have any way to implement or load the prescription file effectively on the center pivot. At the same time, all center pivots were limited on the number of application adjustments they could make.

Solution: Working collectively with AgSense, they developed a prescription data format to upload wirelessly to AgSense's pivot monitoring and control website via a new API protocol developed by AgSense. AgSense then controls the speed of the pivot to adjust water application based on the CropMetrics variable rate prescription file. This was the first full integration of variable rate speed control irrigation.

Collaboration: Without the close working collaboration of both companies, the success of this technology would have been delayed or halted. Working together to develop a data standard, made wireless data transfer possible with greatly improves the efficiency, effectiveness and overall simplicity of the technology today.

Business Success: The development of this VRI technology introduced new development by pivot manufacturers to improve hardware to accept similar capabilities as well as introduced business opportunity for agronomic service providers. Most importantly, this joint effort delivers a solution to improve water use efficiency and conserve our most valuable natural resource.

The PAIL Project

The fundamental goal of the Precision Agriculture Irrigation Leadership (PAIL) Project is to improve agriculture irrigation by developing a common set of data standards and formats to convert data for use in irrigation data analysis and prescription programs.

"Ultimately, the objective of this project is have a common set of data standards and protocols used across the agriculture industry," says Terry Schlitz, AgSense President and Chair of AgGateway's Water Management Council. "With those in place, industry can deliver much more efficient, easy-to-use solutions for producers, which in turn will help them use available water and energy more effectively."

Producers and manufacturers currently report that it is difficult and time-consuming to make decisions on how much water to apply when and where. That's because weather, soil moisture and other relevant data are stored in a variety of Original Equipment Manufacturer (OEM) formats and data sources.

"Growers have many more options now to irrigate their fields more effectively," said Andres Ferreyra, AgGateway Precision Agriculture Council Chair, and AgConnections research and development coordinator. "For example, they can invest in soil maps, install different types of pumps or flow meters, use soil moisture sensors, and put variable rate irrigation systems on their center pivots. There are a few software applications that tie them together. However, these tools don't actually talk to each other effectively or efficiently."

As noted, the PAIL Project is housed within AgGateway, and collaborates with other AgGateway projects, where leverage can be gained. For example, PAIL has been collaborating with AgGateway's Standardized Precision Ag Data Exchange (SPADE) Project to ensure that common terms and data formats are the same. Specific areas of collaboration include data management for location and boundary, soil testing, and crop identification. Adjacent activities to support the development and adoption of the PAIL data standards include a list of glossary definitions and helping to create the ontology for irrigation terms.

Areas that PAIL addresses include:

- Irrigation system setup, configuration, performance specification
- Irrigation system operation, control, and status
- Pumps
- Data acquisition systems (Observations. Source is on- farm)
- External Data Inputs (Offsite, weather networks, etc.)
- Data Outputs (climate data, yield analysis, water balance results, NRCS IWM reporting, etc.)

PAIL Project Deliverables include:

- Business and technical use cases, including description of processes supported by the messages that arise from PAIL
- Glossary of terms used in this project (lists and definitions)
- Ontology document for representing and uniquely identifying the different variables referenced in the project (e.g., air temperature at 2 m, pressure at the base of the irrigation system, latitude of the pivot center, etc.)
- Schema describing messages for retrieving data from the field and for sending prescriptions to the field.
- Results of testing the proposed standard
- Proposed standard(s) submitted to ASABE and/or other standards organizations for discussion / implementation use by the industry

Project Plan

The PAIL group officially began work in early 2013. The project will have two phases. The first will focus on specifying the standard. The second phase will focus on testing and implementation, expansion of the standard to include other uses of irrigation technology, and inclusion of emerging issues. Specific deliverables of the first phase are:

- Use Cases - These will describe most (or all) of the likely scenarios where systems will use the data standards. The use cases also help to define the scope of the data standard.
- Glossary - a robust dictionary of terms and definitions as they are used within the context of specifying the data standard.
- Ontology - a technical specification of each of the quantities and variable referenced in the standard. The ontology uniquely identifies each of the variables referenced in the project.
- Schema - a technical document that unambiguously specifies all of the potential information, its structure, and interrelationships. This document is the basis for creating, verifying, and using documents and messages that conform to the data standard.
- Multiple tests of the standards wherein the standard's function and completeness are verified within the context of an integrated irrigation management system
- A proposed standard submitted to the American Society of Agricultural and Biological Engineering

While no common process exists for developing data standards, PAIL has taken the approach shown in Figure 2 below. While the diagram indicates a smooth progression, work was often iterative, as team members gain new insights.

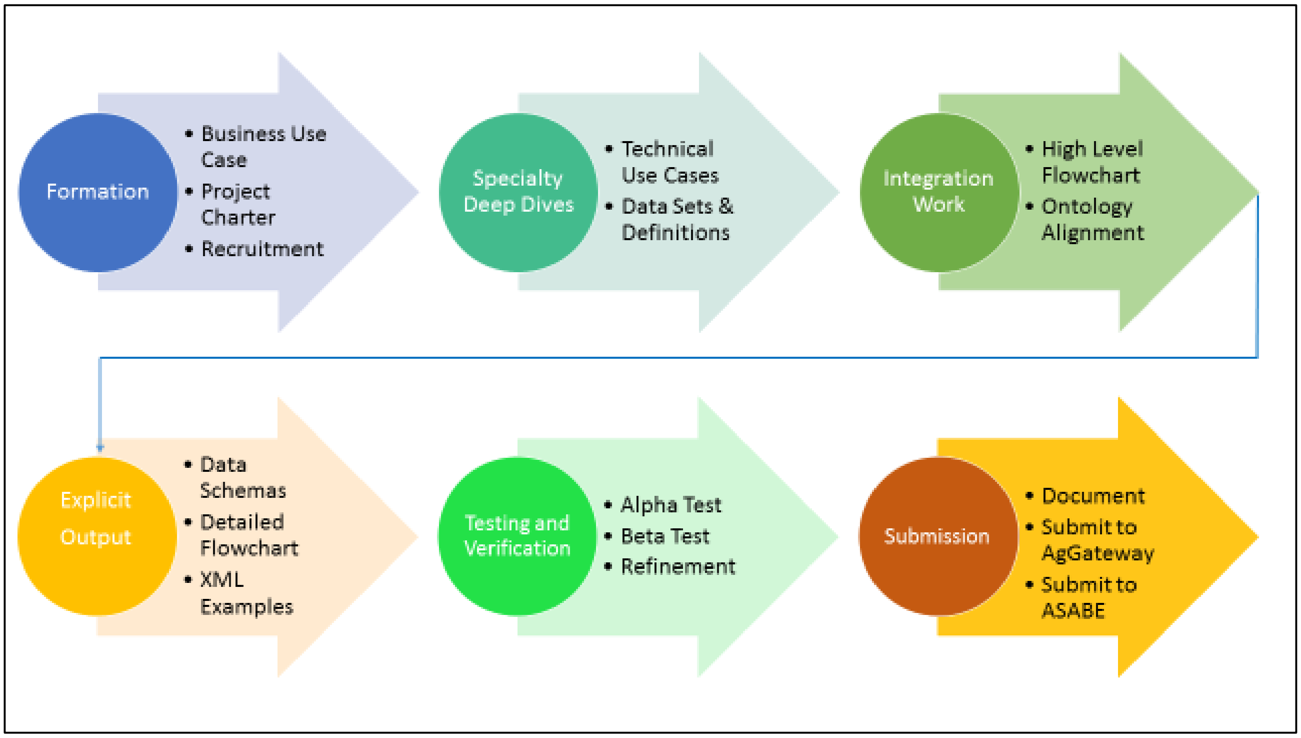

Figure 2: Data Standards Process Flow

Project Scope

A broad definition of the PAIL scope is included in the PAIL project charter. The scope of the PAIL project is shown in the following two inset boxes.

In Scope

1. Irrigation system (not restricted to pivots) setup, configuration, performance specification
    1. Location and geometry of the irrigation system
        1. Opportunity to discuss end gun, corner arm specification
    2. Flows and pressure
2. Irrigation system operation, control, and status
    1. Schedules (how much and when) and Prescriptions (where)
        1. Data representation for establishing a schedule / prescription's scope in space and time
    2. Error reporting, Alerts
    3. As-applied / resource use accounting (non-economic)
3. Pumping Plants
    1. Setup & Configuration
    2. Monitoring & Control
4. Data acquisition systems (Where source is on-farm)
    1. Setup & Configuration
    2. General environmental monitoring
    3. Soil monitoring
    4. Atmospheric monitoring
    5. Plant-based monitoring
5. External Data Inputs (weather networks, etc.)
    1. Weather Forecast, aggregated weather / climate info, weather networks
    2. Soil (SSURGO and other soil maps, EC maps, holding capacity maps)
    3. Energy
    4. DEM
    5. Historical Yield Data (Explore cooperation w SPADE)
    6. Manual Soil Sampling
    7. Crop Performance, Crop coefficients
6. Data Outputs
    1. Historical Weather summary
    2. Yield analysis
    3. Water balance (e.g., NRCS IWM reporting)

Out-of-Scope

1. Data exchange below the OSI (Open Systems Interconnection) Transport Layer, corresponding to the International Standards Organization (ISO) 7498 standard.
2. Crop simulation details
3. Biotic factor scouting details.
4. Considerations / recommendations about sampling rates.
5. Crop performance: Yield modeling
6. Human-mediated data acquisition (e.g. scouting)
    1. Stand density, quality, growth stages
    2. Abiotic stress factors, such as water and flooding
    3. Biotic stress factors, such as insects and diseases
7. Economics (energy use, energy cost, water costs, revenue forecast (estimated yield & price), estimated costs of other production practices (fertilizers, crop protection).

Technologies

The following methods and processes will be used during the development process:

- **Use Cases -** These will describe the most likely scenarios where systems will use the data standards. The use cases also help to define the overall scope of the data standard.
- **User Stories** – These are textual narratives that describe specific hypothetical cases where the data exchange standards might be used. User Stories are different from Use Cases in that they are less structured and less abstract. The stories are essentially a fictional construction where the data exchanges are explicitly described
- **Glossary** - a robust dictionary of terms and definitions as they are used within the context of specifying the data standard.
- **Business Process Model Notation** diagrams (Weidlich and Weske 2010) – This is a graphical tool for describing business processes. These are similar to flow charts or UML activity diagrams and are useful for describing where and when data exchanges occur relative to expected farming activities.
- **XML Schemas** (Fallside and Walmsley 2004) - a technical document that unambiguously specifies all of the potential information, its structure, and interrelationships. This document is the basis for creating, verifying, and using documents and messages that conform to the data standard.

Organization

The preceding scope statement includes a broad variety of information sources and types. Accordingly, the PAIL participants also represent a diverse group of technologies. Companies producing Farm Management Information Systems, Pivot Irrigation Systems, environmental monitoring equipment, soil moisture monitoring equipment, and a few large growers are participating in the PAIL project.

Table 1: PAIL Vendor Participants

AgConnections	Lindsay Corporation
Agrian	Map Shots
AgSense	Monsanto
Campbell Scientific	Observant
CropIMS	OnFarm Systems
Crop Metrics	Ranch Systems
Decagon	Simplot
FirstWater Ag	Valmont
Irrinet	Wysocki Farms
Irrometer	ZedX, Inc.
John Deere Water	

AgGateway

The irrigation data standards work is happening within the Water Management Working Group, part of AgGateway's Precision Ag Council. In November 2012 the companies that had previously been working on data standards development with NEAA agreed to move the standards development effort into the AgGateway environment. This moved allowed the PAIL group to benefit from AgGateway's anti-trust umbrella, AgGateway's existing infrastructure and standards development and maintenance services, and to benefit from the synergies that could arise from exposure to a larger group of businesses committed to data exchange standards. As a result, AgGateway's Precision Ag Council chartered the PAIL (Precision Ag Irrigation leadership) Project in early 2013.

Northwest Energy Efficiency Alliance

The Northwest Energy Efficiency Alliance (NEEA) is a non-profit organization working to increase energy efficiency to meet our future energy needs. NEEA is supported by and works in collaboration with the Bonneville Power Administration, Energy Trust of Oregon and more than 134 Northwest utilities on behalf of more than 12 million energy consumers. NEEA uses the market power of the region to accelerate the innovation and adoption of energy-efficient products, services and practices. Since 1997, NEEA and its partners have saved enough energy to power more than 600,000 homes each year.

Workgroups

Given the breadth of information covered by PAIL's scope, it is impractical to have the entire group address the entire scope simultaneously. Instead three sub groups have been formed: Inbound data sources, Field Operations, Off-site data. The scope of the different groups illustrates the collaborative development process used in PAIL. The work groups were not defined *a priori*. The groups evolved out of several of the PAIL group meetings. The different company representatives whose products interacted or performed similar functions gravitated together to focus on data exchanges that their products were likely to perform. Not only does this partitioning provide a practical decomposition of the scope, it also provides a convenient way for new participants to find the right workgroup for their participation.

Schema

The primary technical product of the PAIL group is an XML Schema that defines the structure of the information that is exchanged during the process of irrigation management. A process preceded development of the schema where the PAIL group examined tasks and problems typical of precision irrigation. Documentation of these tasks is embodied as a set of Use Cases that effectively defined the scope of the PAIL schema. Development of the Use Cases was followed by an examination of the data flows that occurred in each of the tasks.

Dataflow overview

Using Figure 2 as an overall guideline, the PAIL team developed specific flow charts to simulate the data flow in support of the grower use case, including the following steps:

1. A grower communicates a crop plan to an irrigation consultants
2. The consultant gathers and analyzes relevant data
3. The consultant communicates a recommendation
4. The grower and irrigation consultant create a work order (with an irrigation schedule and/or prescription)
5. The work order is converted to machine task (ISO 11783) language
6. A work record captures the results which can be stored at the grower's or consultant's Field Management Information System (FMIS)

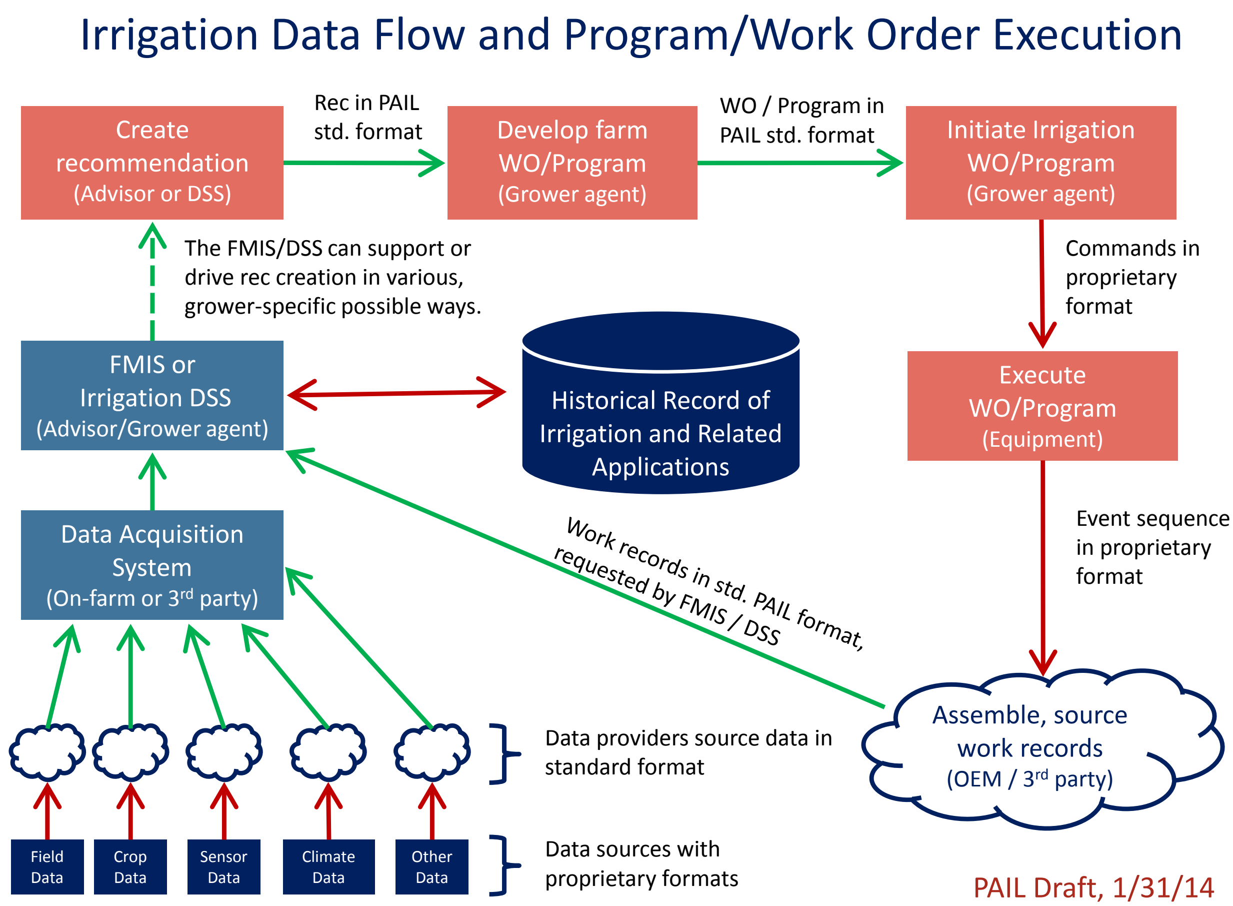

Figure 3 Overview of expected data flows occurring in precision irrigation management

BPMN Diagrams

Figure 3 and Figure 4 show the BPMN diagram that corresponds to the simulation described in the previous section (the original diagram is too large to be readable in a single figure so it has been split into two parts). These are the interactions that are expected during a typical irrigation management cycle.

Readers familiar with current irrigation management practices may find the interactions overly specified. In many operating farms the interactions are not formal in any sense and do not involve any exchange of information other than simple verbal communication. The level of specificity in the BPMN diagram is by design. The management practices being modeled here are those needed to execute precision irrigation management. This management practice is necessarily more complex, and thus more information intensive than conventional management styles. It should also be noted that the process described by the BPMN is not the only possible form that irrigation management may take. This specification is intended to represent what is considered the most likely form of the process. Extensions and modifications are still possible and the data standards will be designed to accommodate those differences.

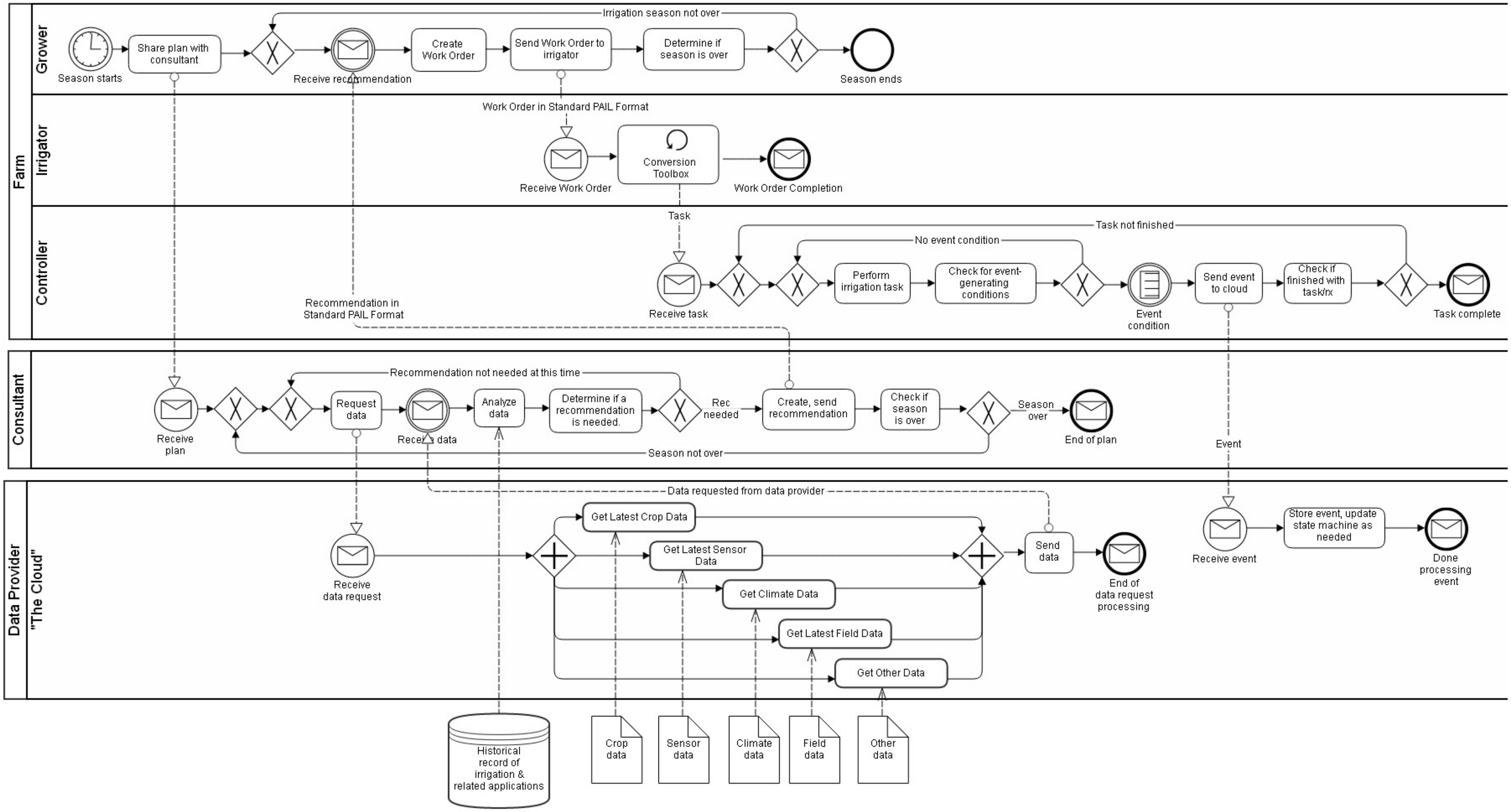

Figure 4 BPMN Diagram (part 1)

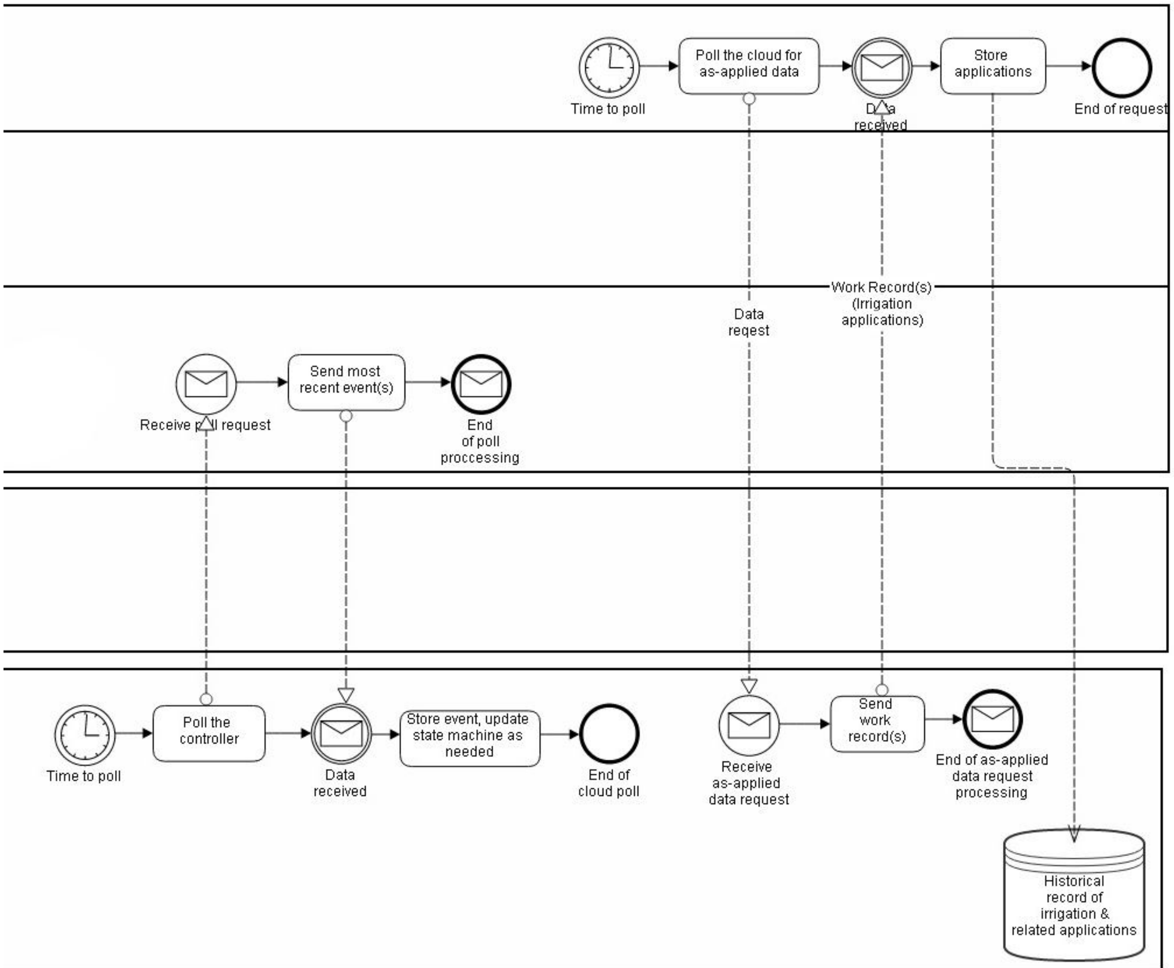

Figure 5 BPMN Diagram (part 2)

Schema Elements

PAIL XML files can contain several different types of 'document' as shown in Figure 6[2]. The documents effectively contain the information that is moving with each of the interactions shown in the BPMN diagram. The PAIL schema can be roughly divided into three parts: InBound, AsApplied, and OffSite. The three parts correspond to the three main working groups within the PAIL project. Each of these parts is described in the following sections.

[2] These diagrams were generated with Altova's Xml Spy schema development software.

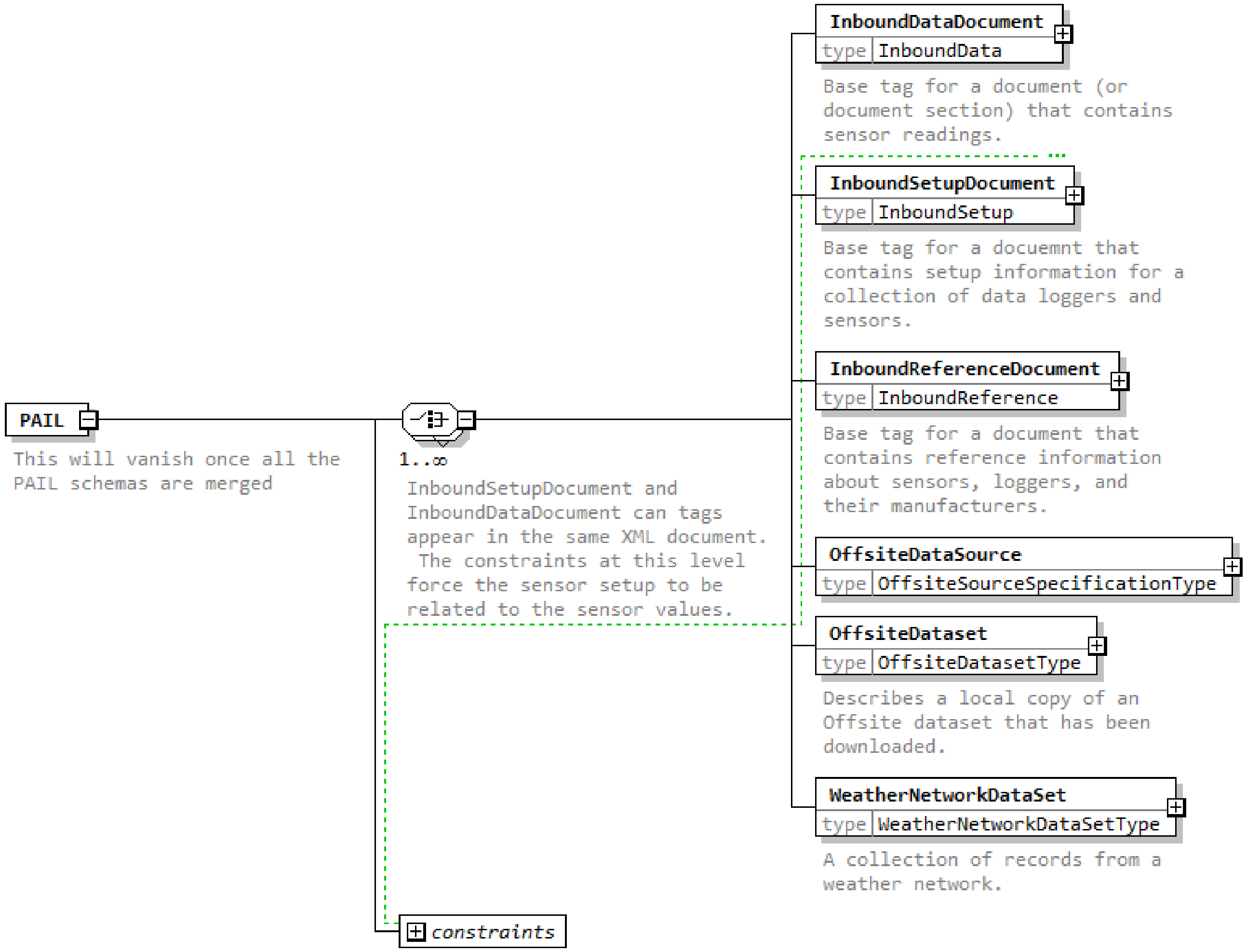

Figure 6 Schema top level elements

As Applied

This schema includes specification of irrigation work orders and elements for describing water applications that have been completed (i.e. the 'as applied' water use records). Figure 8 shows the **WorkRecordItemType** which is used to describe irrigation that has occurred or will occur. This element can also contain elements used to specify variable rate irrigation prescriptions. The AsApplied section also contains the elements that describe the physical characteristics of an irrigation system. The element that describes pivots is shown in Figure 7. The current schema development has focused on pivot systems however later development will also include drip, micro sprinkler, and other system types.

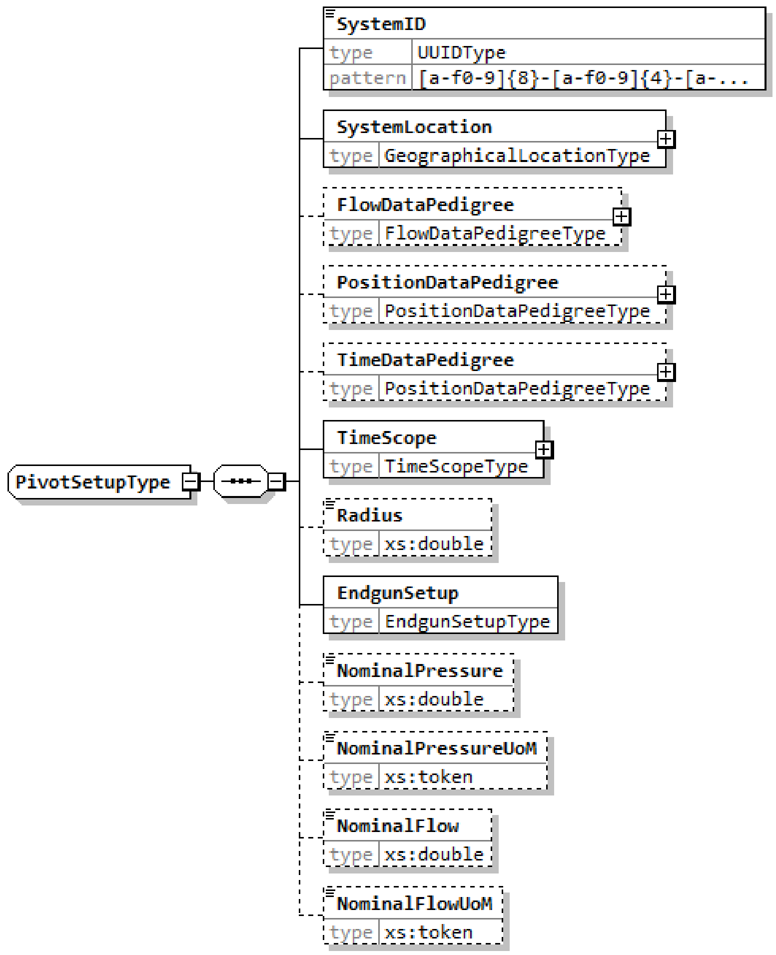

Figure 7 PivotSetupType schema element

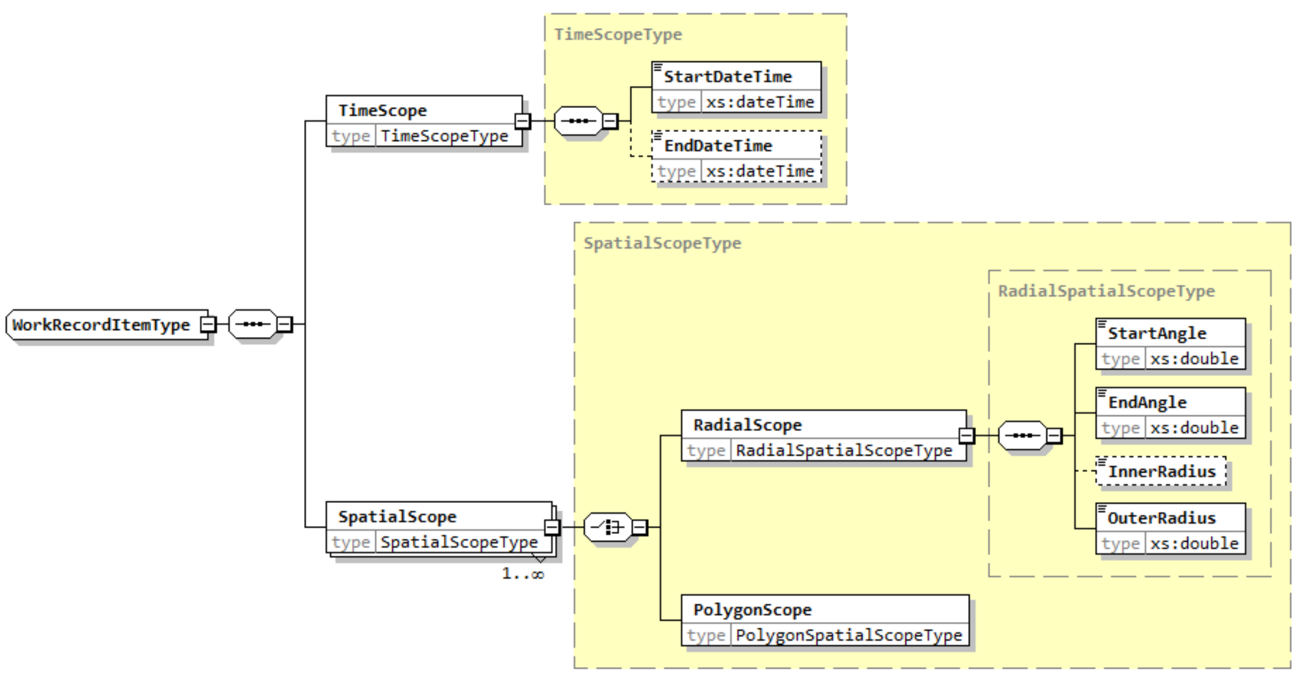

Figure 8 **WorkRecordItem** Type schema element

Inbound

This schema section describes any data collected on farm using sensing devices (e.g. a weather station). The three main document types in this section are

1. **InboundData** (Figure 9) which contains data collected by on-farm sensing devices,
2. **InboundSetup** (Figure 10) which describes the deployment of the sensors and dataloggers as well as their technical capabilities,
3. **InboundReference** (not shown) which is used to identify reference properties (e.g. unique identifiers) that are manufacturer specific.

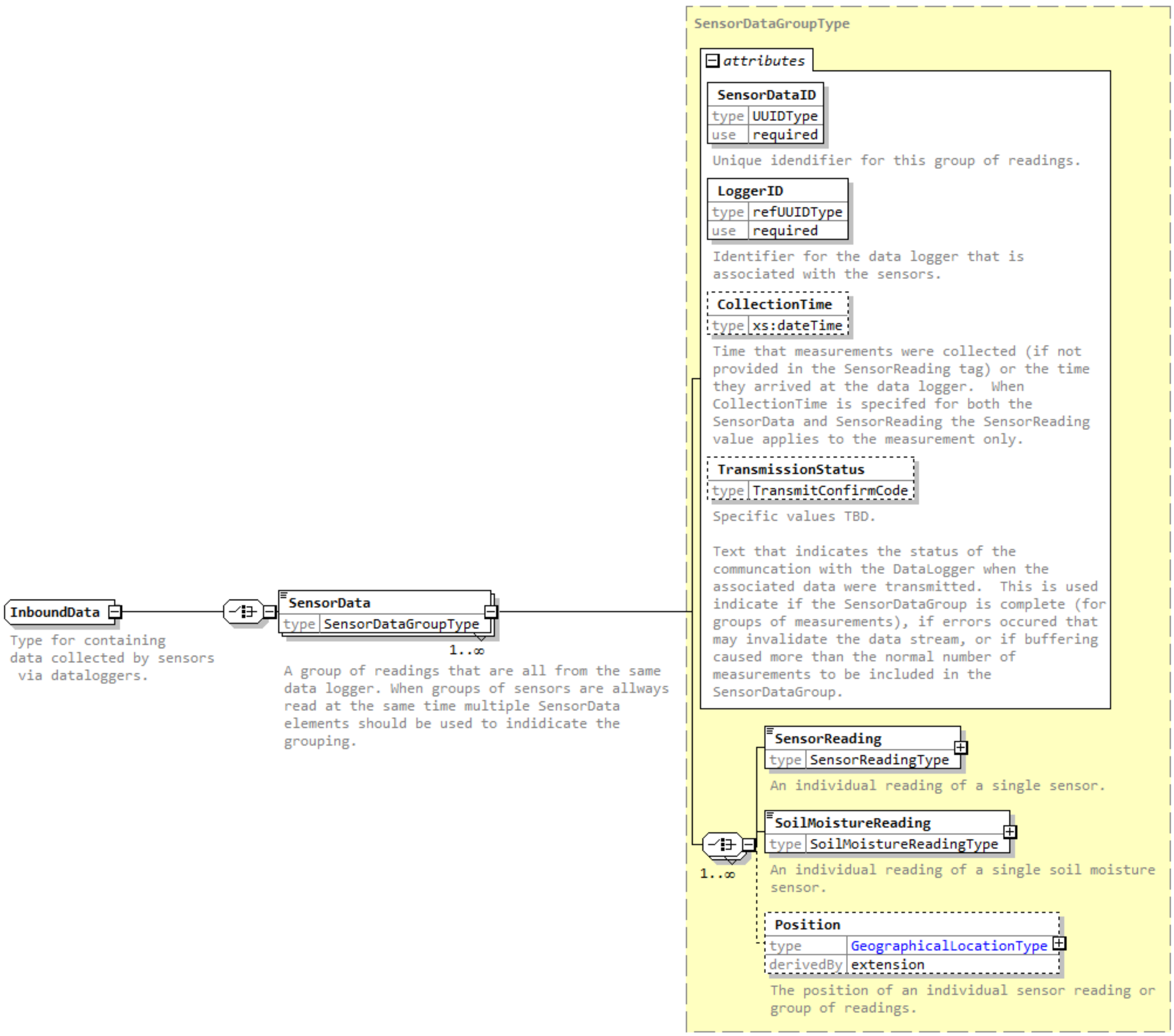

Figure 9 **InboundData** schema element

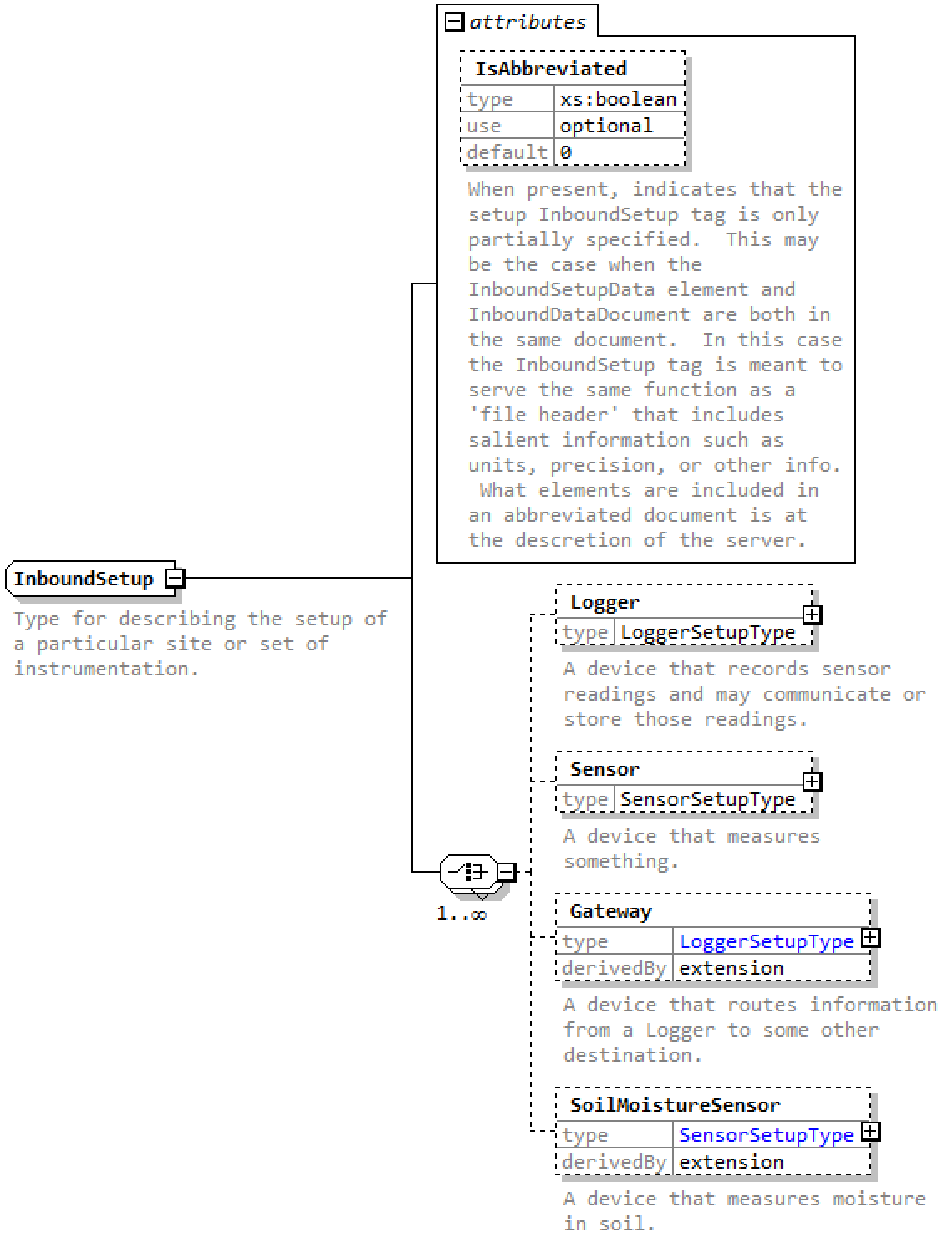

Figure 10 **InboundSetup** schema element

OffSite

This section describes information sources that are external to the farm enterprise. Typical examples are NOAA web services or similar weather data provider's data outputs. This section has documents that describe how/where to obtain data and how/where the data is stored. These two documents, called **OffsiteDataSource** and **OffsiteDataSet** respectively, do not specify the content of the information, only its attributes and means for obtaining the data. A third document type is intended specifically for containing weather data collected by agricultural weather networks. The basic structure of this element is shown in Figure 11.

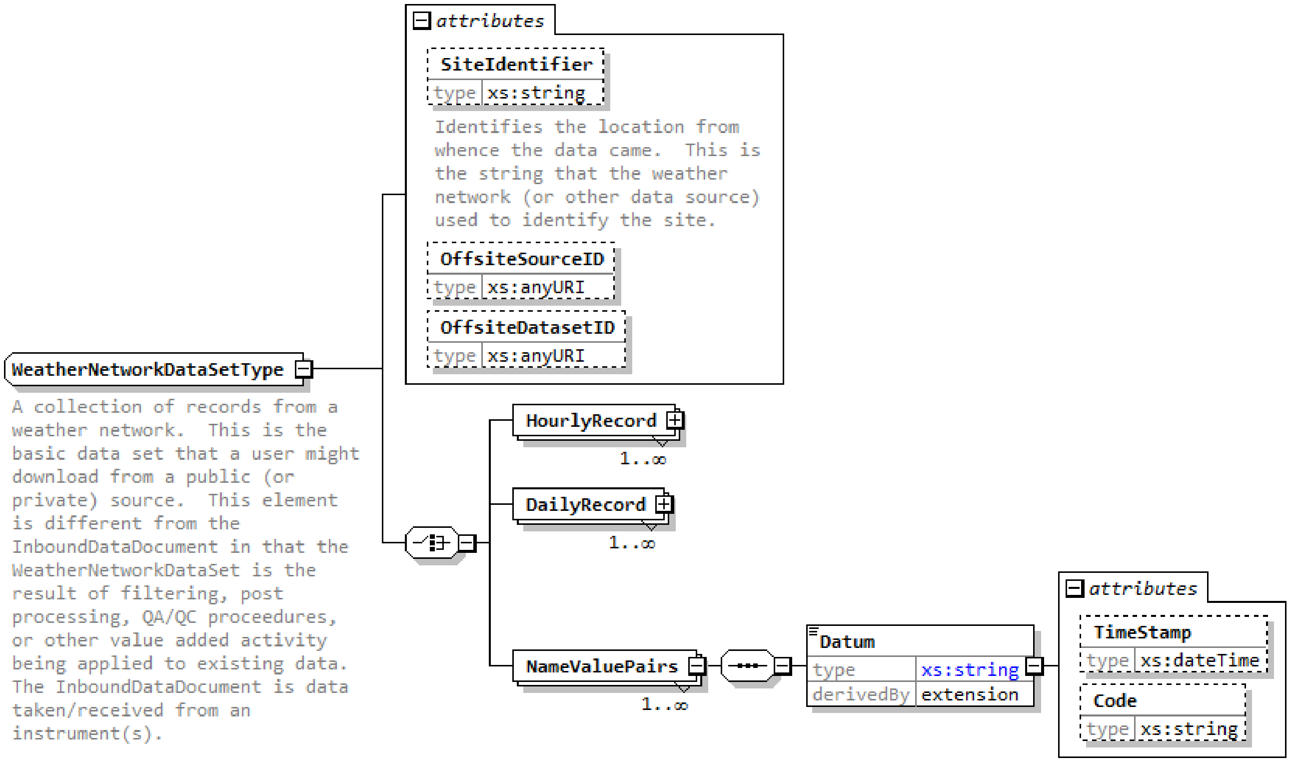

Figure 11 **WeatherNetworkDataSetType** schema element

Development Progress

The PAIL group has been actively working since 2013 and this work will continue into 2015. Preliminary results of the group's efforts are presented in the following sections.

Schema Development

Since beginning work in 2012, the PAIL team has develop a robust set of Use Cases that cover several common irrigation management operations. Schema development has been ongoing since the formation of the first use cases. Each workgroup is developing a separate schema that roughly corresponds to the technical domain of that group. The schemas will, wherever possible, uses schema elements defined by existing AgGateway schemas. Common information elements like units of measure or geographical locations will use existing well recognized schemas already in the public domain. As PAIL schema development progresses these schemas will be merged into a single cohesive document.

Simulation Testing

In order to demonstrate that the proposed schema will support irrigation decision making, a combined simulation and field test is being constructed. This test will act as a proof of concept demonstration and will exercise as much of the schema as is practical. The full details of the simulation test are beyond the scope of this paper; only an overview of the interactions will be described here.

The field trail currently consists of two sites that are generating data. OEM providers and data providers are working to transfer data produced at the test sites using documents that comply with the PAIL schema. Two samples of data produced during the field trial are shown in Figure 12 and Figure 13. Figure 12 shows an example of the work record element described in Figure 8. This document also includes the **PivotSetupType** element described in Figure 7.

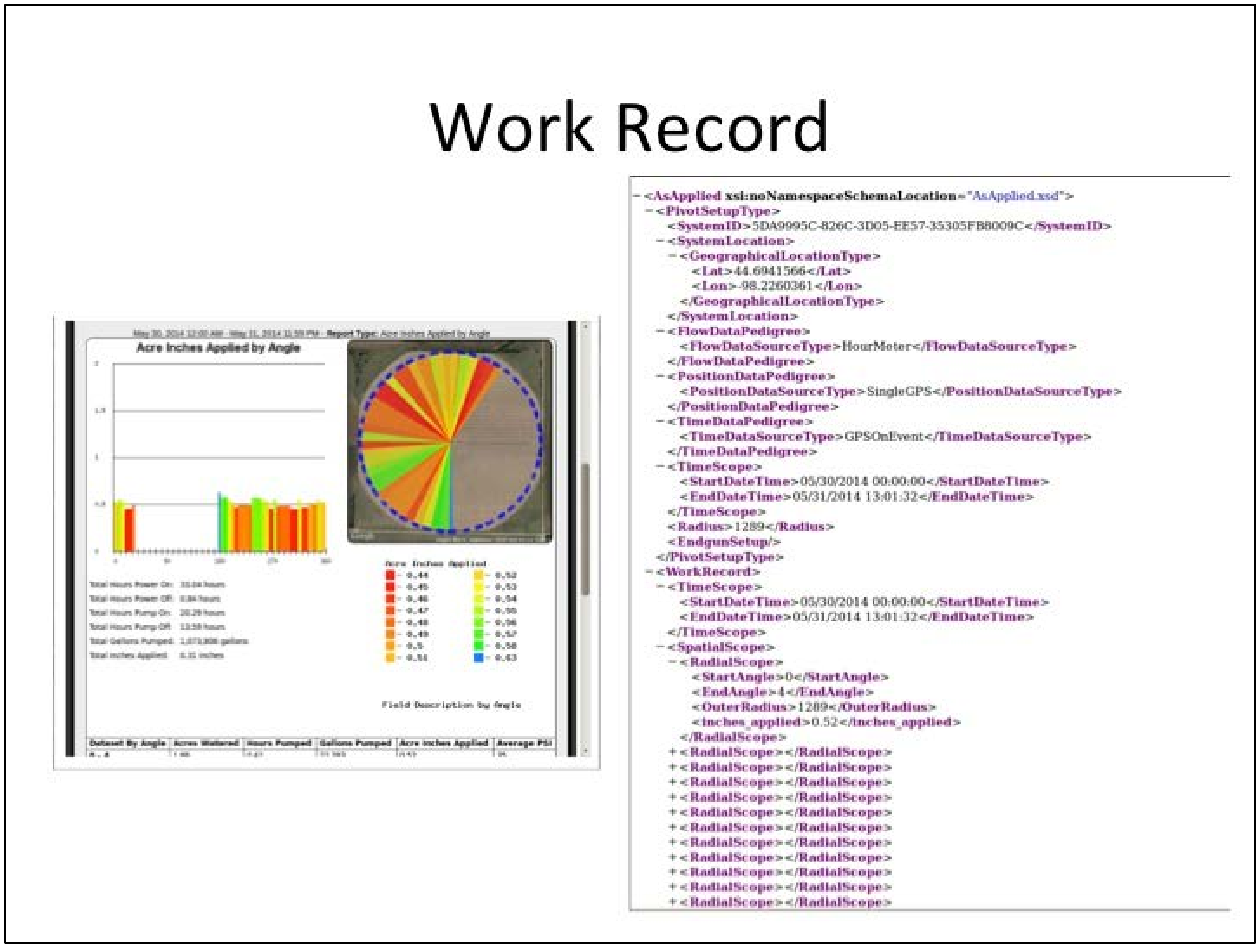

Figure 12 Example of a work record document

Figure 13 shows and example of the InBound data elements produced during the field trial. In this example soil moisture data has been converted into an **InboundData** element as specified in the PAIL schema. In this example, the **DataDocument** element contains an array of sensor readings that are intended for us in a decision support system.

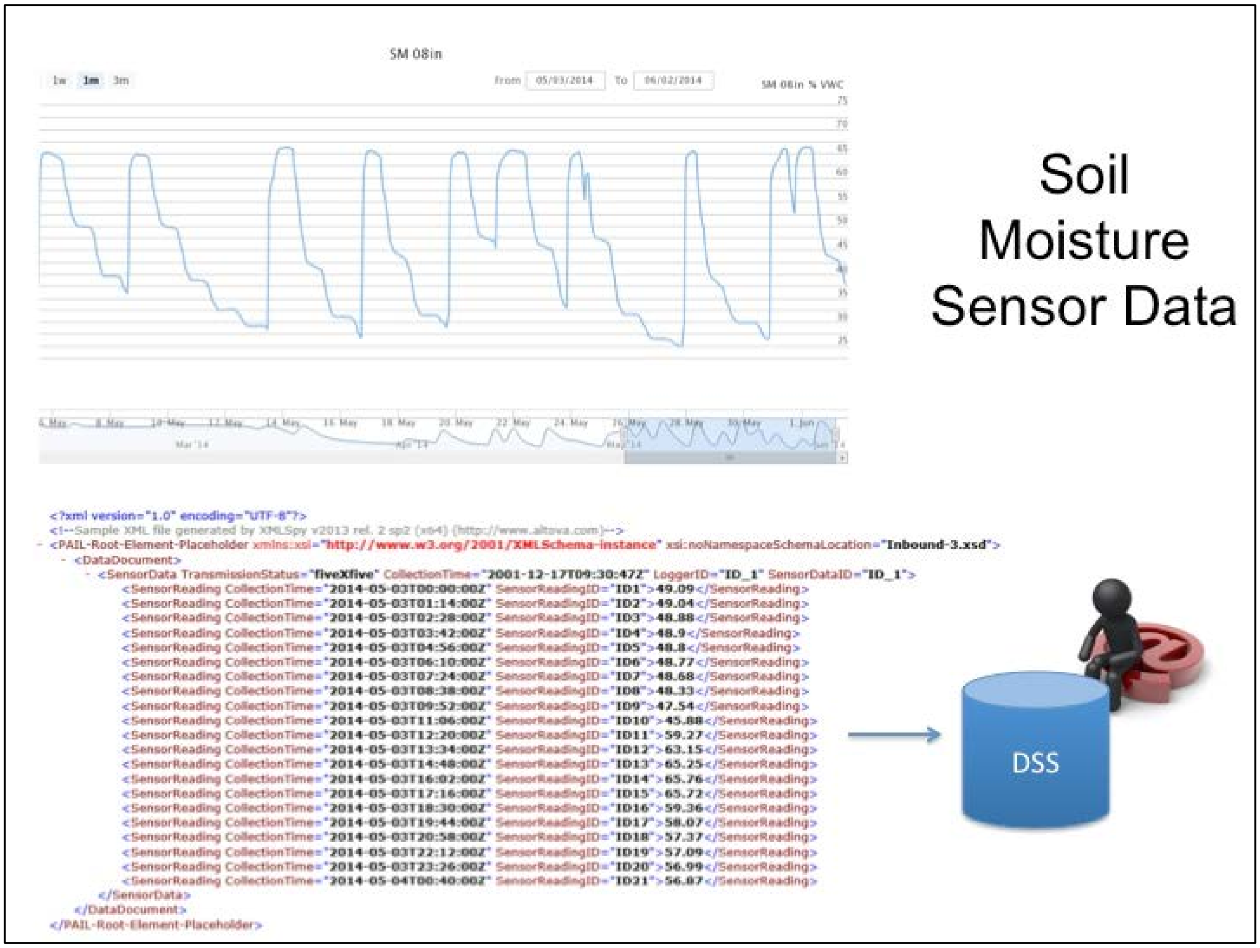

Figure 13 Example of Vendor's Soil Moisture Data Converted to PAIL XML Format

Glossary

AgGateway's SPADE group has already created a substantial glossary of precision agriculture terminology. The PAIL group is building on that glossary and adding terms as they are used in the data schema development. The glossary is being aligned with ASABE S526.3 Soil and Water Terminology standard and ISO/TC 23/SC 18/WG1 Agreed Irrigation Definitions standard.

PAIL worked with ISO and the NRCS to align irrigation terms that are primarily *agronomic* with ISO terms that are primarily *equipment-oriented*. Bridging this gap is important to align irrigation schedule and prescriptions with execution on equipment. Figure 6 below shows an example of this work. Joe Russo from ZedX, Inc. has been the lead on this part of the project.

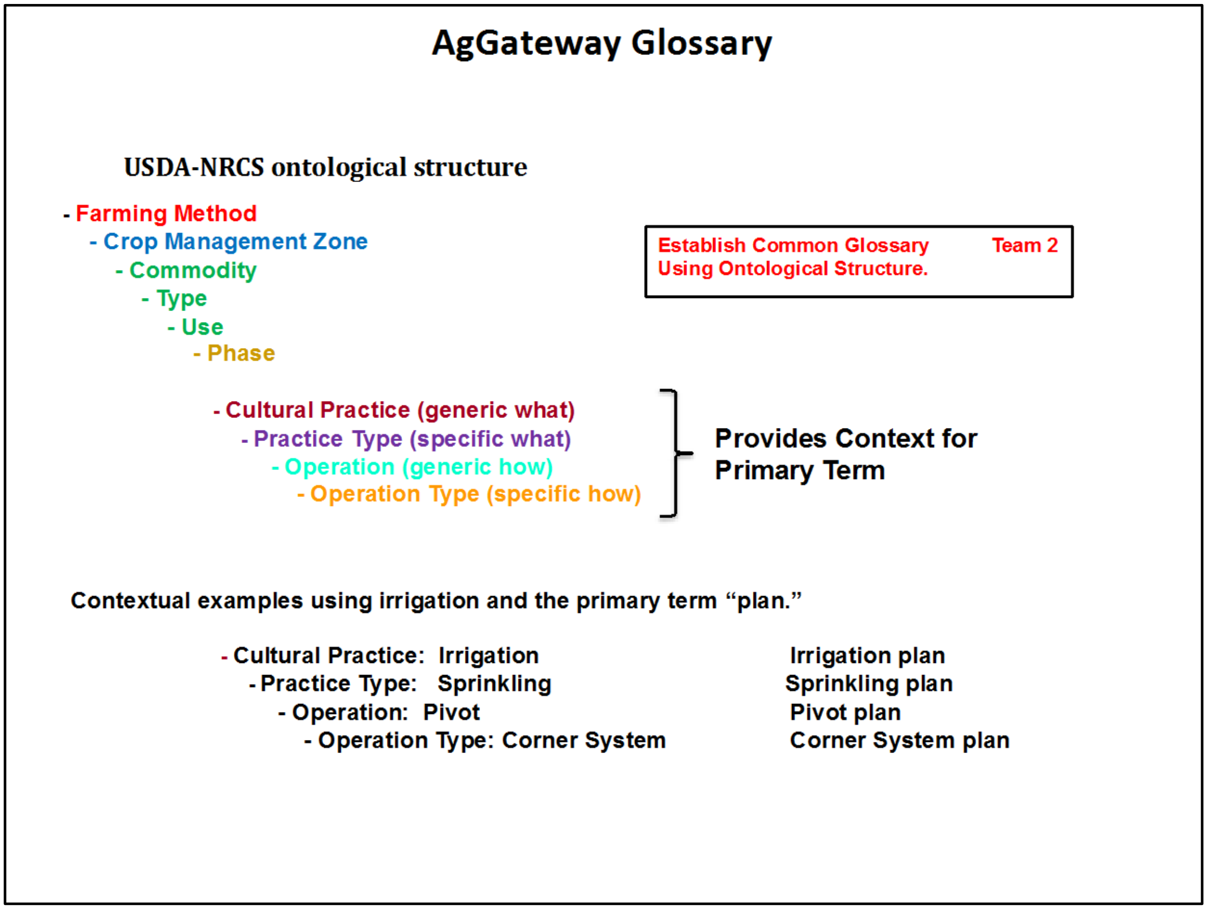

Figure 14: Providing Context and Structure for Agricultural Irrigation Terminology

Proposed ASABE Standard

A standards development project has been initiated within ASABE. This project, titled Agricultural Irrigation Data Exchange Standard (project number X632), will formalize the standards developed within the AgGateway. This project is housed under the SW-244 Irrigation Management committee. Ultimately, this standard will also become an ISO standard.

Conclusion

Precision irrigation management is an information intensive process. A variety of tools and technologies exist that enable or support irrigation. These tools rarely interoperate readily without significant effort by the irrigator. System integration is a significant factor in ease of use of advanced technologies. Adoption of new irrigation technology is limited by the effort required to use the technology. Thus, system integration is a significant factor in ease of use of advanced irrigation technologies. The Precision Ag Irrigation Leadership project is expected to have a lasting beneficial impact on the agricultural irrigation industry. PAIL will improve interoperability of irrigation technologies and, consequently, increase adoption of more efficient irrigation practices. The PAIL project is ongoing and the workgroups expect to complete their goals in 2015. Plans for the second phase, PAIL 2, are already underway. Companies, individuals, institutions, and organizations interested in participating should contact the authors for instructions on how to join AgGateway and how they can contribute to this effort. As of November 2014, membership in the PAIL project is still open to new participants; it requires membership in AgGateway, and membership in the PAIL project. Interested parties should contact AgGateway Member Services (member.services@aggateway.org) for more information.

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Evaluation of Neural Network Modeling to Calculate Well-Watered Leaf Temperature of Wine Grape

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Abstract. *Mild to moderate water stress is desirable in wine grape for controlling vine vigor and optimizing fruit yield and quality, but precision irrigation management is hindered by the lack of a reliable method to easily quantify and monitor vine water status. The crop water stress index (CWSI) that effectively monitors plant water status has not been widely adopted in wine grape because of the need to measure well-watered and non-transpiring leaf temperature under identical environmental conditions. In this study, a daily CWSI for the wine grape cultivar Syrah was calculated by estimating well-watered leaf temperature with an artificial neural network (NN) model and non-transpiring leaf temperature based on the cumulative probability of the measured difference between ambient air and deficit-irrigated grapevine leaf temperature. The reliability of this methodology was evaluated by comparing the calculated CWSI with irrigation amounts in replicated plots of vines provided with 30, 70 or 100% of their estimated evapotranspiration demand. The input variables for the NN model were 15-minute average values for air temperature, relative humidity, solar radiation and wind speed collected between 13:00 and 15:00 MDT. Model efficiency of predicted well-watered leaf temperature was 0.91 in 2013 and 0.78 in 2014. Daily CWSI consistently differentiated between deficit irrigation amounts and irrigation events. The methodology used to calculate a daily CWSI for wine grape in this study provided a real-time indicator of vine water status that could potentially be automated for use as a decision-support tool in a precision irrigation system.*

Keywords. Canopy temperature, wine grape, irrigation management, water stress.

Introduction

Irrigation is commonly used in arid region wine grape production to manage growth and induce desirable changes in berry composition for wine production (Chaves et al. 2010, Lovisolo et al. 2010). A mild to moderate water deficit in red-skinned wine grape has been found to increase water productivity and improve fruit quality (Romero et al. 2010, Shellie 2014). However, the ability to uniformly and reliably induce and maintain a desired water stress within a vineyard is hindered by the lack of a rapid method to monitor vine water status with high spatial and temporal resolution. The ability to use precision irrigation techniques in wine grape to manage the severity and duration of water deficit requires a reliable method for monitoring vine water status coupled with an irrigation system capable of applying water on-demand, in precise amounts (Jones, 2004).

Soil- and plant-based methods currently available for monitoring vine water status include measurement of soil water content and plant water potential both of which are either too laborious for automation and/or have poor spatial and temporal resolution. Traditional soil volumetric water content measurement has low spatial resolution and is not necessarily a reliable indicator of vine water status because water availability is influenced by soil attributes, such as texture and depth, which are spatially heterogeneous. Wine grapes are commonly irrigated with drip irrigation which leads to non-uniform spatial wetting of the plant root zone, exacerbating reliable determination of bulk root zone water content. A given soil volumetric water content may induce different severities of water stress in different grapevine cultivars due to differing hydraulic behaviors (Shellie and Bowen 2014) and rooting patterns. Consequently, vine response may not correspond with bulk changes in soil water content or soil water potential (Jones 2004, Ortega-Farias et al. 2012). Plant-based methods of monitoring water status integrate soil, plant and environmental factors; however, their poor temporal and spatial resolution and high labor requirement limit their potential for automation into a precision irrigation system. The poor temporal resolution of plant water potential is due to its high sensitivity to environmental conditions (Rodrigues et al. 2012, Jones 2004). Also, there is no general agreement as to which measurement of plant water potential (leaf or stem measured pre-dawn or midday) most reliably indicates vine water status (Williams and Araujo 2002, Ortega-Farias et al. 2012). However, a midday value of leaf water potential greater (less negative) than -1.0 MPa has generally been accepted to be indicative of a well-watered condition (Shellie 2006, Williams et al. 2012, Shellie and Bowen 2014).

Canopy temperature has been used successfully to monitor water status in crops other than grapevine (Raschke 1960, Jackson 1982). The difference in leaf temperature between stressed and non-water stressed plants relative to ambient air temperature has been used to develop an empirical crop water stress index (*CWSI*) (Idso et al. 1981, Jackson et al. 1981) for monitoring plant water status. The *CWSI* is defined as:

$$CWSI = \frac{(T_{canopy} - T_{nws})}{(T_{dry} - T_{nws})} \tag{1}$$

where T_{canopy} is the temperature of the crop canopy (˚C), T_{nws} is the temperature of the canopy (˚C) when the crop is non-water-stressed and T_{dry} is the temperature of the canopy (˚C) when the crop is severely water stressed under dry conditions. Temperatures T_{nws} and T_{dry} are the lower and upper baselines used to normalize the index for environmental conditions (air temperature, relative humidity, radiation, wind speed, etc.) of T_{canopy}. The *CWSI* ranges from 0 to 1 where 0 represents a well-watered condition and 1 represents a non-transpiring, water-stressed condition. Practical application of the *CWSI* has been limited by the difficulty of estimating T_{nws} and T_{dry}. Experimental determination of a crop specific constant for T_{nws} and T_{dry} relative to ambient air temperature has not been fruitful due to the poorly understood and complex influences of environmental conditions on the soil-plant-air continuum (Idso et al. 1981, Jones 1999, Jones 2004, Payero and Irmak 2006). Artificial wet and dry reference surfaces have been used successfully to estimate T_{nws} and T_{dry} under the same environmental conditions as T_{canopy}. (Jones 1999, O'Shaughnessy et al. 2011, Jones et al. 2002, Leinonen and Jones 2004, Cohen et al. 2005, Grant et al. 2007, Möller et al. 2007, Alchanatis et al. 2010); however, the required maintenance of the artificial reference conditions limits potential use for automation in a precision irrigation system.

Physical and empirical models have been developed to estimate T_{nws} and T_{dry} with varying degrees of success. A leaf energy balance (Jones, 1992; eq. 9.6) was used by Jones (1999) to model grape leaf temperature as a function of environmental conditions. Fuentes et al. (2012) found excellent agreement between artificial reference leaf surface temperatures and T_{wet} and T_{dry} calculated using the physical model of Jones (1999). Alves and Pereira 2000 developed a physical approached to estimate T_{nws} based on the Penman-Monteith equation and a saturation pressure curve approximation relating T_{nws} to wet bulb temperature. They obtained a correlation coefficient of 0.92 between calculated T_{nws} and measured canopy temperature of well-watered lettuce when model parameters were independently calibrated. Physically based models require measurement of additional plant characteristics in order to estimate model parameters needed to calculate baseline canopy temperature(s). Empirical models using multiple linear regression equations have also been used to estimate T_{nws} and T_{dry} as a function of air temperature, solar radiation, crop height, wind speed, and vapor pressure deficit, with correlation coefficients ranging from 0.69 to 0.84 between predicted and measured leaf temperature of well-watered corn and soybean (Payero and Irmak 2006). Irmak et al. (2000) determined in corn that T_{dry} was 4.6 ˚C to 5.1 ˚C above air temperature and, in several subsequent studies in crops other than corn, a value of air temperature plus 5.0 ˚C has been used to estimate T_{dry} in equation 1 (Cohen et al. 2005, Möller et al. 2007, Alchanatis et al. 2010). O'Shaughnessy et al. (2011) used maximum daily air temperature plus 5.0 ˚C for T_{dry} of soybean and cotton. Regression equations have been the most promising, practical approach used to estimate T_{nws} and T_{dry} for the *CWSI.* However, regression, by necessity, simplifies complex, unknown interactions into a priori or assumed multiple linear or nonlinear relationships (Payero and Irmak 2006).

Artificial Neural Networks (NN) have been used successfully to model complex, unknown physical relationships and predict responses in water resource applications (ASCE, 2000), such as estimating stream flow, sediment transport and evapotranspiration (Kumar et al. 2002, Bhakar et al. 2006, Trajkovic et al. 2003). A common NN architecture consists of multiple layers of simple parallel computing nodes that operate as nonlinear summing devices interconnected between layers by weighted links. Each weight is adjusted when measured data are presented to the network during training. Successful training of a NN results in a numerical model that can predict an outcome value for conditions that are similar to the training dataset. To the best of our knowledge, NN modeling has not been used to predict T_{nws} and T_{dry} for calculation of a *CWSI*. A NN is particularly well-suited for predicting T_{nws} and T_{dry} because the relationships between environmental factors, plant physical characteristics and plant response are complex, poorly understood, and difficult to represent mathematically. Also, a training database of T_{nws} and T_{dry} for NN model development can be rapidly and reliably generated.

The *CWSI* could be used for real time monitoring of water stress severity in wine grape. An increase in the surface temperature of deficit irrigated grapevine canopy has been remotely monitored using infrared thermometers (Glenn et al. 2010, Shellie and King 2013). Changes in leaf temperature have been correlated with rates of stomatal conductance and leaf or stem water potential in grapevine and responsiveness has been shown to vary by cultivar (Glenn et al. 2010). However, measurement of T_{nws} and T_{dry} under the same environmental conditions as T_{canopy} poses logistical problems in commercial vineyards where neither T_{nws} nor T_{dry} are desirable soil moisture conditions. The objective of this study was to investigate the feasibility of using a NN model to estimate leaf temperature of well-watered grapevine and to evaluate the reliability of its use in calculating a *CWSI* for wine grape under deficit irrigation. Feasibility was evaluated by comparing predicted with measured values of well-watered leaf temperatures and relating the calculated *CWSI* to irrigation amounts to wine grape that were deficit-irrigated at fractional amounts of evapotranspiration demand (ET_c).

Materials and Methods

The study was conducted during the 2013 and 2014 growing seasons in a field trial site located at the University of Idaho Parma Research and Extension Center in Parma, ID (lat: 43´78°N; long: 116´94°W; 750 m asl). The soil (sandy loam, available water-holding capacity of 0.14 cm/cm soil), climatic conditions (semi-arid, dry steppe with warmest monthly average temperature of 32°C), and irrigation water supply (well water with sand media filter) at this location were well-suited for conducting deficit irrigation field research. The wine grape cultivar Syrah was planted as un-grafted, dormant-rooted cuttings in 2007 and was well-watered using above ground drip through the 2010 growing season. Row by vine spacing (1.8 x 2.4 m), training and trellis system (double-trunked, bilateral cordon, spur-pruned annually to 16 buds/m of cordon, vertical shoot positioned on a two wire trellis with moveable wind wires), and disease and pest control were managed according to local commercial practices. Alley and vine rows were maintained free of vegetation.

The irrigation system provided for the application of four, independent irrigation treatment levels in a randomized block design with four (Syrah) replicate blocks and independent irrigation water supply to border vines located in the field trial perimeter. Each water supply manifold was equipped with a programmable solenoid, a flow meter (to measure delivered irrigation amount), a pressure regulator and a pressure gauge (to monitor delivery uniformity). Treatment plots consisted of three vine rows with six vines per row (18 vines per plot). The vines in outer plot rows were considered buffers and data were collected on interior vines in the center row of each plot. The trial was bordered by a two-vine deep perimeter. Border vines in the trial perimeter were irrigated frequently with an amount of water that met or exceeded ET_c throughout canopy and berry development. Border vines were used to measure T_{nws}. Treatment plot replicates received one of four irrigation treatments: deficit irrigation amounts supplying either 70 or 35% ET_c at a frequency of one or three times per week; however, in 2014 the 70% ET_c three irrigations per week treatment was not included in the study. The 70% ET_c amount was intended to induce a sustained, mild water deficit throughout berry development that was similar to standard local industry practice (Keller et al. 2008). Irrigation amount was calculated weekly using the 1982 Kimberly–Penman equation (Jensen et al. 1990) with alfalfa as a reference crop obtained from a weather station (http://www.usbr.gov/pn/agrimet/wxdata.html) located within 3 km of the study site and a variable crop coefficient (0.3 to 0.7) (Allen et al. 1998; Keller et al., 2008). Midday leaf water potential of border vines was monitored every 14 days in 2013 and weekly in 2014. The irrigation amount was adjusted as needed to ensure that the midday leaf water potential of well-watered vines was less negative than -1.0 MPa. Deficit irrigation treatments were initiated each year just after fruit set and were continued throughout berry development. Deficit irrigation in all plots was first initiated in the 2011 growing season.

Canopy temperature was measured with infrared temperature sensors (SI-121 Infrared Radiometer; Apogee Instruments, Logan, UT) positioned approximately 30 cm above fully expanded leaves located at the top of the vine canopy and pointed northerly at approximately 45˚ from nadir with the center of field of view aimed at the center of sunlight leaves. The measured canopy area received full sunlight exposure during midday. The temperature sensing area was approximately 20 cm in diameter. The possibility of bare soil visibility in the background was limited by leaf layers within the canopy below the measured location. Temperature sensor view was periodically checked and adjusted as necessary to ensure the field of view concentrated on sunlit leaves on the top of the canopy. Temperature sensors were installed in one well-watered and one deficit-irrigated data vine in a single replicate of each irrigation amount and irrigation frequency. In 2014 two temperature sensors were used in the well-watered border plot. Environmental parameters; wind speed (*WS*), air temperature (T_{air}), relative humidity (*RH*), and solar radiation (*SR*) were measured in the vineyard adjacent to the irrigation treatment plots. Canopy temperature and environmental parameters were sampled at 1-min intervals and 15-min averages recorded on a data logger from July 11 (berries were pea-sized) until September 22 (fruit maturity) in 2013 and from June 26 until September 25 in 2014. Environmental sensors were located in the vine row, above the grapevine canopy. Air temperature (T_{air}), *RH* and *SR* were measured 2.2 m and *WS* was measured 2.5 m above ground level. Wind speed was adjusted to a standard height of 2 m (Allen et al. 1998).

Neural network software NeuroIntellligence (Alyuda Research Inc., Cupertino, CA) was used to develop a NN model for estimating T_{canopy}. The recorded well-watered canopy temperature and environmental dataset for 2013 was filtered to include only values collected between 13:00 and 15:00 MDT based on previous experience with grapevine canopy temperature measurement (Shellie and King 2013). The filtered dataset was randomly subdivided into one of three datasets used to train, validate and test the NN model. Sixty-five percent of the filtered dataset was used for training, 16% for validation, and 16% for testing. Input parameters were linearly scaled to a range of -1 to 1 which is a normal procedure for NN modeling. The maximum and minimum values of measured parameters in the complete, filtered dataset were used for linear scaling. A multilayer perceptron feed forward NN architecture was used to estimate canopy temperature of well-watered grapevines. Hidden layer neurons used a hyperbolic tangent activation function and the single output neuron used a logistic activation function. Neural network architectures were evaluated with one and two hidden layers with up to ten neurons per hidden layer. The Conjugate-Gradient and Quasi-Newton methods (Haykin 2009) were used to train the network using the training dataset. The best NN architecture (number of hidden layer neurons, input parameters) was selected based on maximizing model efficiency (ME) (Nash and Sutcliffe 1970), while using a minimum number of neurons to reduce risk of over-training the NN to the data. Model efficiency, which is commonly used for hydrologic model evaluation (Moriasi et al. 2007), is defined as:

$$ME = 1 - \frac{\sum\left(y_i - y_{pred}\right)^2}{\sum\left(y_i - y_{ave}\right)^2} \qquad (1)$$

where y_i is the *i*th data value, y_{pred} is model predicted value for y_i and y_{ave} is the mean of the data values. Model efficiency is similar to the correlation coefficient associated with linear regression in that its value ranges from -∞ to 1. A value of 1 means the model is a perfect fit to the data. A negative *ME* value signifies that the data mean is a better prediction of data values than model output.

Results and Discussion

In 2013, April 1 through October 31 precipitation and average total direct solar radiation were nearly equal to the 19-yr site average (Table 1). The number of days that daily maximum temperature exceeded 35˚C was greater than the 19-yr site average, but was within one standard deviation of average. Cumulative growing degree days (GDD) in 2013 were 5% greater, but within one standard deviation of the site average. The grape production climate classification for the study site, based on cumulative growing degree days in the Winkler system (Winkler et al. 1974), was region III (1666-1944 GDD), which is suitable for production of the wine grape cultivar Syrah. Reference evapotranspiration (ET_r) for the study site in 2013 was more than one standard deviation greater than the 19-yr site average. April 1 through September 30 climatic conditions in 2014 were very similar to 2013 (Table 1) with the exception that GDD and days with maximum daily temperature greater than 35˚C were less. Growing season amount of water provided to well-watered vines was ~50% of ET_r. Since the crop coefficient used to calculate irrigation amount varied from 0.3 to 0.7 during the growing season, the irrigation amount supplied to well-watered vines provided 100% of ET_c. The irrigation amounts supplied to vines deficit-irrigated with 35 or 70% ET_c were ~35 and 70% of the irrigated amount of well-watered vines in both years.

The study site had a high evaporative demand with vapor pressure deficits (*VPD*) up to 6 kPa in 2013 (Fig. 1). Linear correlation between the temperature difference of well-watered leaves and ambient air (T_{nws}-T_{air}) and *VPD* were significant ($p<0.0001$) with a correlation coefficient of 0.32 (Fig. 1). The high variability of T_{nws}-T_{air} at any given value of *VPD* illustrates a strong influence of additional factors on leaf temperature that is unrelated to water deficit which makes determining plant water status difficult with only measurement of T_{nws}-T_{air} and *VPD*.

The NN model developed to predict leaf temperature provided excellent estimation of well-watered leaf temperature for the 2013 test dataset (Fig 2). Model efficiency of predicted versus measured well-watered leaf temperature was 0.89 and root mean square error of the NN model was 1.06 ˚C. The feed-forward NN model architecture selected to estimate well-watered grapevine leaf temperature (T_{nws}, Eqn. 1) used four input parameters, one hidden layer with six nodes, and one output node (4-6-1). The four inputs were the measured environmental parameters T_{air}, *SR*, *RH* and *WS*. Increasing the number of hidden nodes beyond six provided minimal decrease in NN model standard error or increase in ME. Using *VPD* rather than *RH* did not affect performance of the NN models, which was expected since *RH* and *VPD* are highly correlated for a given air temperature. The performance of the NN model using the entire filtered dataset (training, validation and test datasets combined) was similar to the performance of the test dataset (Fig. 2) indicating that the randomly selected test dataset was representative of the entire dataset. Root mean square error of the NN model for the composite dataset was 0.98 ˚C and ME was 0.91. The NN model has a slight bias to over-estimate canopy temperature < 23 ˚C and under estimate canopy temperature > 31˚C. This bias may be a result of the limited number of training dataset values for low and high canopy temperatures (Fig. 2). A larger dataset over multiple years with a greater proportion of high and low leaf temperature

Table 1. Historical, 2013, and 2014 climate data (± standard deviation) collected from Bureau of Reclamation AgriMet system [(www.usbr.gov/pn/agrimet/), latitude 43°48´00”, longitude 116° 56´00”, elevation 702 m] for Parma, Idaho weather station. Accumulated growing degree days were calculated from daily maximum and minimum temperature with no upper limit and a base temperature of 10˚C.

April 1 through October 31	2013	1994 – 2012 Average
Precipitation (mm)	101	99.6 ± 115
Daily average total direct solar radiation (MJ m^{-2})	22.3	22.1 ± 0.9
Days daily maximum temperature exceeded 35˚C	35	28 ± 12
Accumulated growing degree days (˚C)	1798	1708 ± 115
Alfalfa-based reference evapotranspiration, ET_r (mm)	1307	1212 ± 55
April 1 through September 30	2013	2014
Precipitation (mm)	81	80
Daily average total direct solar radiation (MJ m^{-2})	23.8	24.0
Days daily maximum temperature exceeded 35˚C	35	27
Accumulated growing degree days (˚C)	1752	1667
Alfalfa-based reference evapotranspiration, ET_r (mm)	1226	1230
Well-watered vines (mm)	603	614
70% ET_c with 1 irrigation/week (mm)	407	448
70% ET_c with 3 irrigations/week (mm)	413	---
30% ET_c with 1 irrigation/week (mm)	214	240
30% ET_c with 3 irrigations/week (mm)	215	244

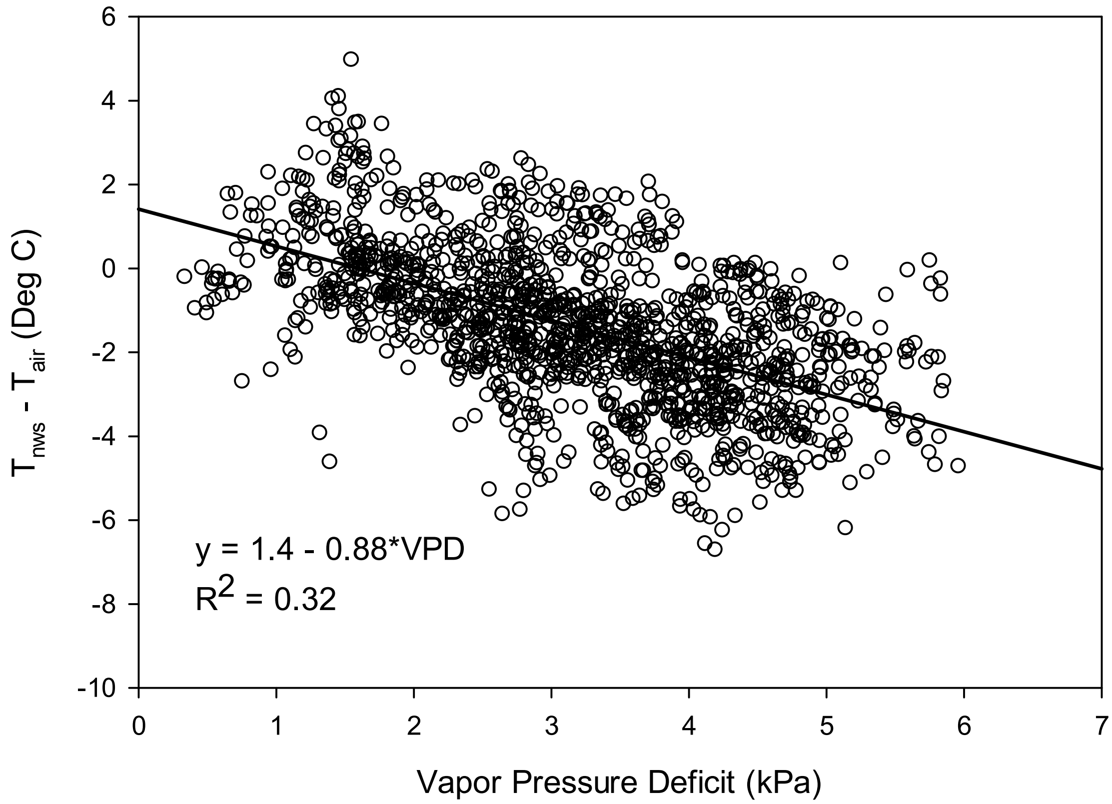

Figure 1. Influence of vapor pressure deficit on the difference in surface temperature of an exposed, well-watered leaf (T_{nws}) of the wine grape cultivar Syrah and the temperature of ambient air (T_{air}) measured between 12:00 and 16:00 MDT at 1-min intervals and recorded as 15-min average values from July 11 until September 22, 2013 at Parma, ID.

measurements would likely improve NN model performance at the upper and lower temperatures. A dataset larger than the one used in this study that is filtered to include an even occurrence of data values over a range of measured leaf temperatures during NN model development could also further minimize bias.

Prediction performance of the NN model for well-watered leaf temperature measured in 2014 was less than for 2013 but still provided a good estimate of leaf temperature (Fig. 3). Model efficiency for prediction of well-watered leaf temperature in 2014 was 0.78 with a root mean square error of 1.8 ˚C. The NN model tended to over predict leaf temperature for measured leaf temperatures < 23 ˚C in 2014. Leaf temperatures < 20 ˚C was rarely measured in 2013, which was the data set used to develop and train the NN model. Model bias can likely be reduced by using data from both years to retrain the NN model.

Cumulative probability distributions of measured temperature differences between the canopy and air of deficit-irrigated vines supplied with 35% ET_c were used to determine an appropriate value for T_{dry} (Fig. 4) needed to calculate CWSI (eqn. 1). Irrigation frequency influenced the maximum measured temperature difference between the canopy of deficit-irrigated vines and

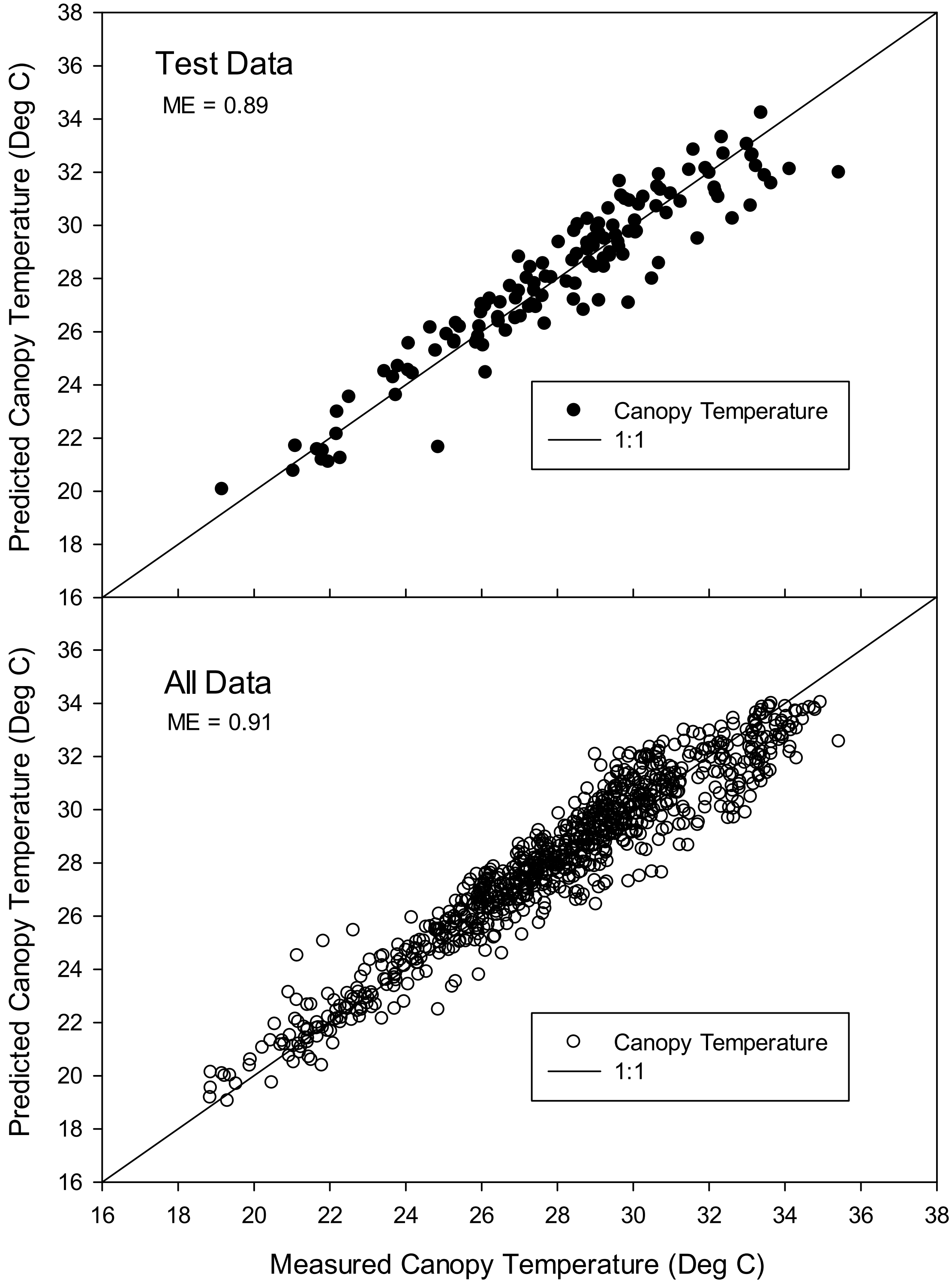

Figure 2. Performance of neural network model for predicting non-water stressed canopy temperature relative to the measured leaf temperature of well-watered Syrah grapevines recorded between 13:00 and 15:00 MDT as 15-min average values measured at 1-min intervals from July 22 until September 22, 2013 in Parma, ID.

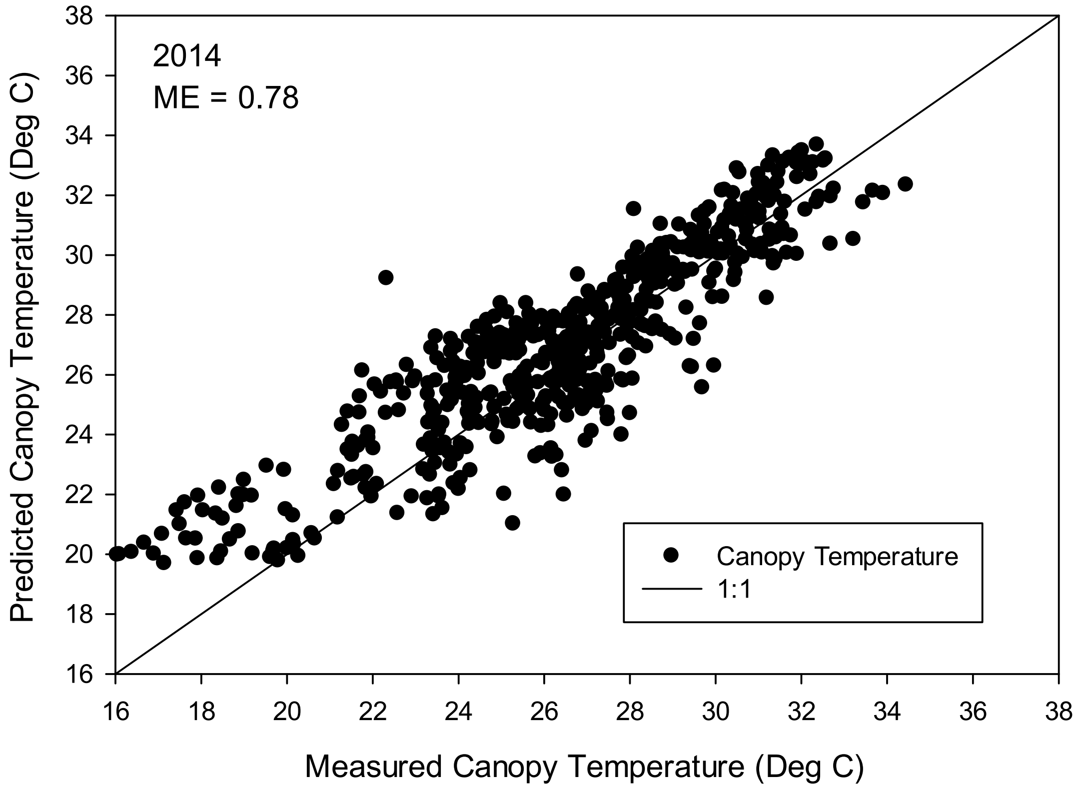

Figure 3. Performance of neural network model for predicting non-water stressed canopy temperature relative to the measured leaf temperature of well-watered Syrah grapevines recorded between 13:00 and 15:00 MDT as 15-min average values measured at 1-min intervals from July 17 until October 6, 2014 in Parma, ID.

T_{air} (Fig. 4). Vines irrigated one time per week had a slightly greater maximum temperature difference than vines irrigated three times per week. The maximum canopy to air temperature difference was 14˚C. Using the physical grape leaf model of Jones (1999), the cumulative probability distribution calculated for a non-transpiring leaf (zero transpiration) had a maximum temperature difference between canopy and ambient air of 20˚C (Fig. 4). This value appeared to be an extreme estimate of the maximum value of T_{dry} for the study conditions. We therefore estimated T_{dry} for calculation of the *CWSI* (Eqn. 1) as T_{air} + 15˚C, which will rarely be exceeded (Fig. 4). It is possible that leaf transpiration may not be zero at T_{air} + 15˚C, but the rate of transpiration is likely less than required for desirable yield and berry composition. Reference temperatures do not necessarily need to be an absolute canopy temperature limit, but serve rather as indicator temperatures to scale measured canopy temperature to the environment for calculating relative water stress (Grant et al. 2007).

A daily *CWSI* was calculated for vines deficit-irrigated at 70% or 35% ET_c using the NN estimated values for T_{nws} and T_{air} + 15˚C for T_{dry} by averaging 15-min *CWSI* values for each 15-min average value of T_{air} and T_{canopy} recorded daily between 13:00 to 15:00 MDT. The daily *CWSI* of deficit-irrigated vines in 2013 irrigated three times per week at a rate equal to 70% ET_c (Fig. 5) was consistently lower than the daily *CWSI* of vines deficit-irrigated with 35% ET_c and the daily *CWSI* consistently corresponded to irrigation events. The *CWSI* decreased following

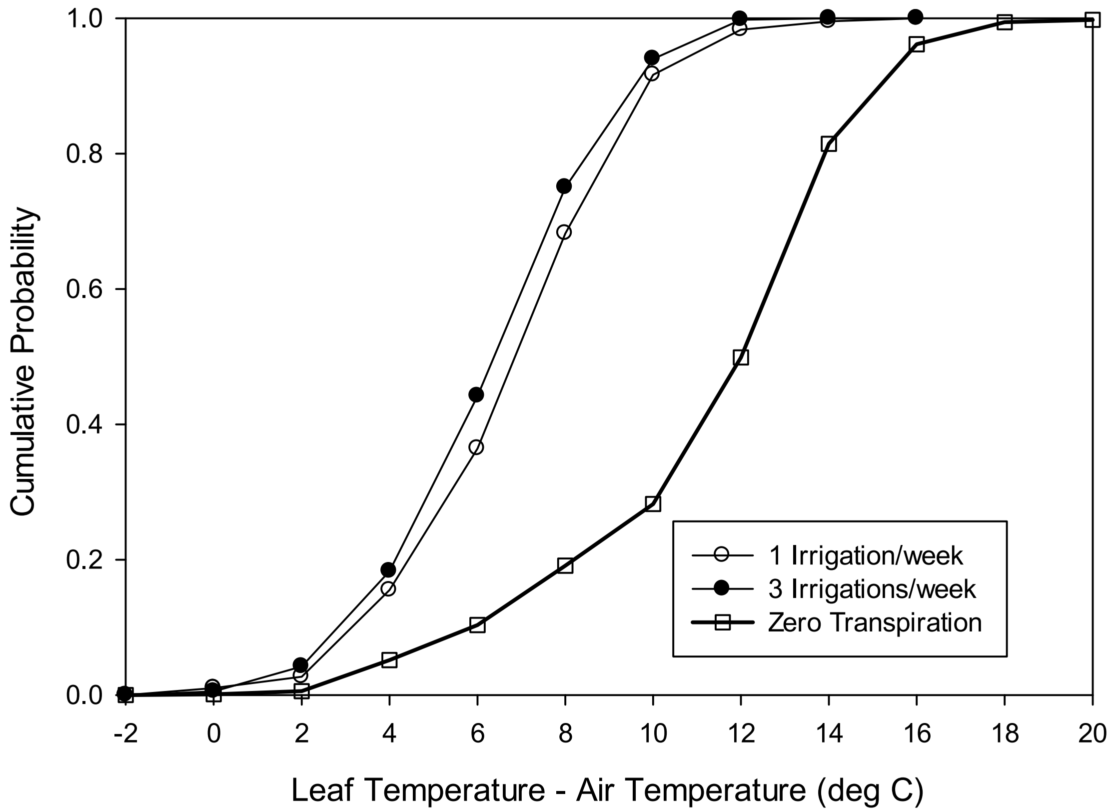

Figure 4. Cumulative probability for difference between canopy and ambient air temperature in Syrah grapevines deficit-irrigated at 35% of well-watered evapotranspiration rate (ET_c) irrigated with a frequency of once or three times per week. Temperatures were 15-min average values measured at 1-min intervals between 13:00 and 15:00 MDT from July 11 until September 22, 2013 in Parma, ID. Zero transpiration represents the estimated difference between a non-transpiring leaf and air temperature for the environmental conditions assuming isothermal radiation.

an irrigation event and gradually increased between irrigation events as soil water was withdrawn for ET_c. The same trend in daily *CWSI* between irrigations was present for vines irrigated once per week (Fig. 5). The response of CWSI to weekly irrigations was more pronounced due greater variation in soil moisture content resulting from larger irrigation amounts and greater time interval between irrigations. The response of CWSI to weekly irrigations of deficit irrigated vines in 2014 (Fig. 6) was nearly identical to 2013 indicating that application of the NN model developed using 2013 data provided an effective estimate of well-watered canopy temperature in 2014. The CWSI for vines irrigated with 70% ET_c was consistently lower than for vines irrigated with 35% ET_c. The response of CWSI of vines irrigated three times per week at the rate of 35% ET_c (Fig. 8) was very similar to 2013 (70% ET_c was not present in the study trial in 2014).

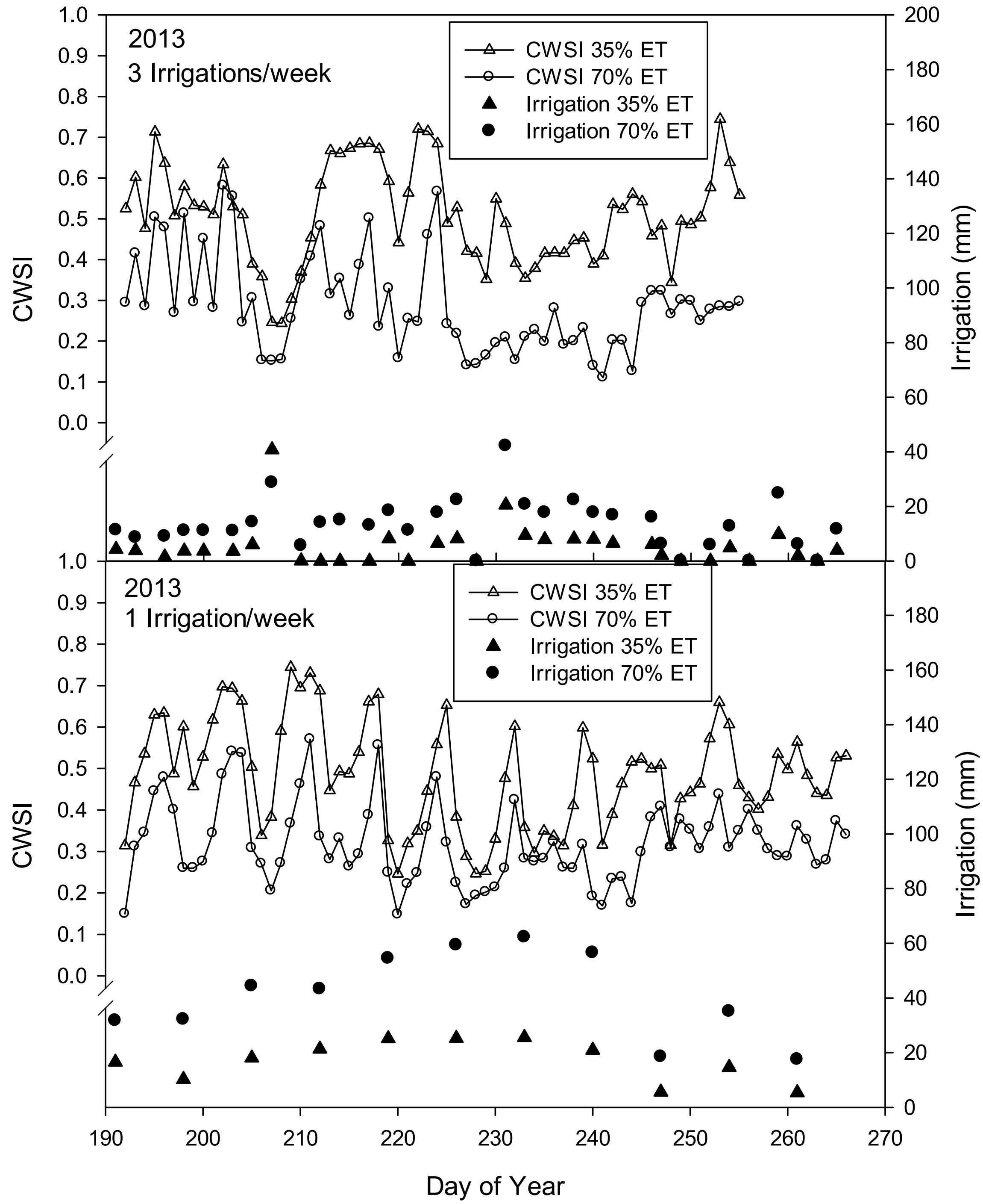

Figure 5. Irrigation amounts and calculated *CWSI* values for Syrah grapevines in treatment plots deficit-irrigated at 35 or 70% of well-watered evapotranspiration rate (ET_c) irrigated three times per week and once per week. Well-watered canopy temperature was estimated using the neural network model. Ambient air and deficit-irrigated leaf temperature were recorded as 15-min average values measured at 1-min intervals between 13:00 and 15:00 MDT from July 11 until September 15, 2013 in Parma, ID.

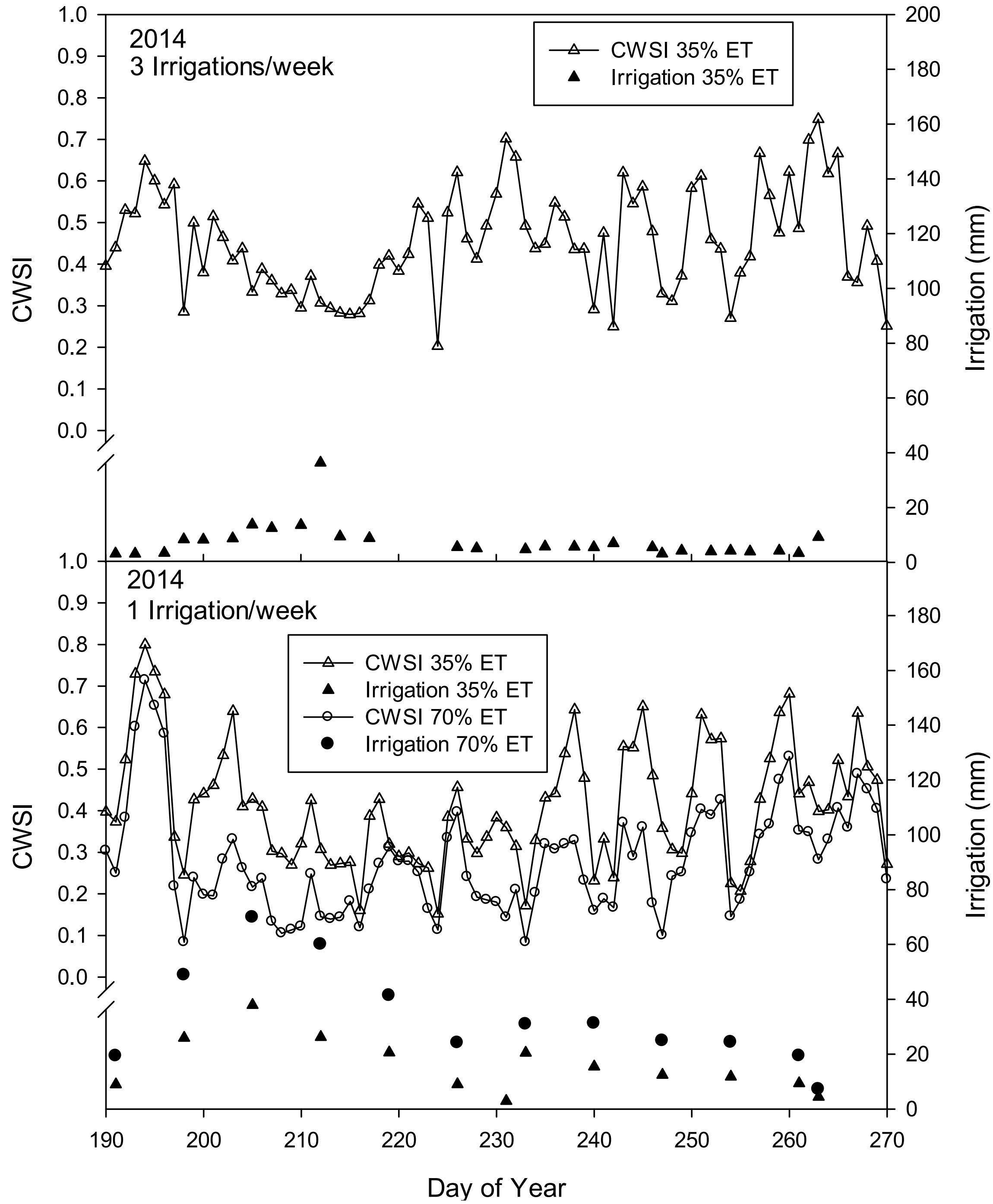

Figure 6. Irrigation amounts and calculated *CWSI* values for Syrah grapevines in treatment plots deficit-irrigated at 35 or 70% of well-watered evapotranspiration rate (ET_c) irrigated three times per week or once per week. Well-watered canopy temperature was estimated using the neural network model. Ambient air and deficit-irrigated leaf temperature were recorded as 15-min average values measured at 1-min intervals between 13:00 and 15:00 MDT from July 9 until September 27, 2014 in Parma, ID.

Averaging 15-min *CWSI* values between 13:00 to 15:00 MDT to calculate a daily *CWSI* reduced the potential influence of transient environmental conditions. Daily *CWSI* consistently corresponded with irrigation events and differentiated irrigation amounts throughout the growing seasons of 2013 and 2014. The 15-min averaging approach in this study deviates from the calculation method proposed by Idso et al. (1981) and Jackson et al. (1981), where a near instantaneous measure of canopy temperature was used to calculate the *CWSI*. A major advantage of the averaging approach used in this study is that it minimizes the influence of rapid fluctuations in leaf temperature due to variability in cloudiness or wind speed and results in a more representative value of *CWSI*. Our method of calculating T_{dry} for the *CWSI* supports the concept used by others of estimating T_{dry} as the sum of measured T_{air} and a constant (Cohen et al. 2005, Möller et al. 2007, Alchanatis et al. 2010); however estimating the constant value from the cumulative probability of measured leaf temperatures under water deficit generated an effective estimate of T_{dry} for the study conditions.

Conclusions

The feasibility of using neural network (NN) modeling to estimate the lower threshold temperature (T_{nws}) needed to calculate the traditional *CWSI* was demonstrated for wine grape. The neural network model developed for estimating T_{nws} based on 2013 measured canopy temperature of Sarah wine grape performed exceptionally well for calculating CWSI of deficit irrigated vines in 2013 and 2014. Use of NN model estimated T_{nws} for calculating *CWSI* over a 70-day period in 2013 and 2014 successfully differentiated between two levels of water stress. The maximum difference in temperature between the vine canopy and ambient air for the 35% ET_c irrigation treatments was found to be about 14˚C, much greater than 5˚C used in other studies as an estimate for non-transpiring leaf temperature (T_{dry}). Air temperature plus 15˚C used to estimate T_{dry} in calculation of *CWSI* provided an effective upper reference temperature. A 2-hour averaged *CWSI* value based on 15-minute averaged canopy temperature, T_{air}, solar radiation, relative humidity and wind speed values provided a consistent daily *CWSI* value under variable climatic conditions. Additional research should focus on evaluation of the NN modeling approach to estimate T_{nws} for other grape cultivars over multiple years and across locations to determine the range of applicability of a large database for calculation of a daily *CWSI* that could be automated to provide decision support in a precision irrigation system for wine grape.

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Using a Spatially Explicit Analysis Model to Evaluate Spatial Variation of Corn Yield

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Abstract: *Spatial irrigation of agricultural crops using site-specific variable-rate irrigation (VRI) systems is beginning to have wide-spread acceptance. However, optimizing the management of these VRI systems to conserve natural resources and increase profitability requires an understanding of the spatial crop responses. In this research, we utilize a recently developed spatially explicit analysis model to analyze spatial corn yield data. The specific objectives of this research are 1) to calculate a suite of estimates needed for the types of analyses mentioned above and to provide credible intervals around these estimates and 2) to examine whether the conclusions from this rigorous re-analysis are different from the prior analysis and if the results force any modifications to the conclusions obtained with the prior analyses. The model simultaneously accounted for spatial correlation as well as relationships within the treatments and has the ability to contribute information to nearby neighbors. The model-based yield estimates were in excellent agreement with the observed spatial corn yields and were able to more accurately estimate the high and low yields. After calculating estimates of yield, we then calculated estimates of other response variables such as rainfed yield, maximum yield, and irrigation at maximum yield. These estimated response variables were then compared with previous results from a classical statistical analysis. Our conclusions supported the original analysis in identifying significant spatial differences in crop responses across and within soil map units. The major improvement in the 2014 re-analysis is that the model explicitly considered the spatial dependence in calculation of the estimated yields and other variables and, thus, should provide improved estimates of their impact in system design and management.*

Keywords. *Varying coefficient model; Response curves; Semiparametric regression; Site-specific agriculture.*

INTRODUCTION

With the convergence of geopositioning (GPS), geospatial (GIS), and increased computing technologies in the 1980's and 1990's, much attention has been placed on precision, or site-specific, agriculture as a way to improve economics and environmental benefits of agriculture. Many crop inputs, including fertilizer, plant population, and pest control, have been examined for potential to reduce costs or increase yield, or perhaps shift the location of use from where the input is not used efficiently to other places in the field where it is. When one considers irrigation as an input to be managed concurrently with all other inputs, it becomes a logical extension to consider if spatially-varying irrigation could be a water-conserving approach. This was demonstrated to be the case based on research in South Carolina (Sadler et al., 2005), where optimal variable-rate irrigation had potential to save from 10 to 15% in three fairly dry years (1999-2001). It was also been shown in other locations and clearly, water conserving aspects of variable rate irrigation merit further examination.

One data source that has potential to inform this question was obtained in Florence, South Carolina, at a variable-rate center pivot research facility (Camp and Sadler 1998; Camp et al. 1998, Sadler et al, 2002). A 3-year corn yield experiment was conducted to examine the simultaneous effects of irrigation and N fertilization. The experiment was intended to be analyzed by both analysis of variance (ANOVA) and geostatistical analyses. The constraints on the experimental design were discussed in detail in Sadler et al. (2002). In brief, there were four irrigation treatments: 0%, 50%, 100%, and 150% of irrigation to replace evapotranspiration (ET) applied simultaneously in all irrigated plots when the mean soil water tension in the 100% plots in 4 (1999) or 6 (2000-2001) soil map units was less than or equal to -30 kPa at the 0.3-m depth. There were two N treatments: 134 kg/ha, which is the extension recommendation for rainfed corn in SC, and 225 kg/ha, for irrigated corn. Nitrogen fertilizer was a blended dry granular pre-plant application common to all plots within a year, followed by treatments applied as urea-ammonium nitrate with sulfur (UAN 24S) injected in a nominal 13-, 11-, and 16-mm irrigation in all plots during the three years. Where sufficient area existed within a map unit, one or more randomized complete blocks (RCB) of these eight treatments were imposed. Where insufficient area existed, a randomized incomplete block (RICB) was used. In total, there were 39 RCBs and 19 RICBs, for a total of 396 plots. Harvest was done with a plot combine from 2 rows 6.1 m in length near the center of the plots. Additional details can be obtained in Sadler et al. (2002).

In the initial ANOVA analysis, the irrigation main effect was, as expected, highly significant in both linear and quadratic contrasts over the irrigation ranges (0 to 150% of full irrigation). Somewhat surprisingly, however, between the two N fertilizer rates of 134 and 225 kg/ha, the main effect of N was significant in only one of three years. The test of whether the soil variation was a significant contributor to variation in yield was significant, despite the limitations of the experimental design. Interaction effects were not consistent, either in 2-way or 3-way interactions. In short, the soil variation was important, the expected irrigation effect was obtained, and the N effect was somewhat surprising. Sadler et al. (2002) further evaluated the quadratic irrigation production functions for map unit means in that experiment, and solved for maximum yield and the irrigation to obtain it. These analyses were all done with soil map units as a class variable, and did not explicitly account for spatial variation within blocks, within soil map units, or among soil map units. The only indication of spatial variation in the production functions was that block-level functions for the most common soil map unit were provided. Further, the map-unit-mean analytical expressions for yield as a function of irrigation were obtained separately for N treatments in only 2001, the year in which the N treatment was significant. These characteristics of the analyses limited interpretation of spatial variation in the production functions themselves.

A first attempt to explicitly account for spatial variation in these data was described by Sadler et al (2002b). The goal of this analysis was not to test statistical significance, but to allow generation of maps of derived characteristics, including rainfed yield, maximum yield, and irrigation water use efficiency, plus the maps of irrigation to achieve those. All derived results were obtained from averages over N treatment, on the basis that the N treatment was not significant in two of three years. This analysis involved two steps – a separate interpolation of yields from each individual treatment to estimate the yield that would have been expected for all four irrigation treatments at each of the 396 plot centers, and a quadratic regression of the four yields on seasonal irrigation rate in mm.

Sadler et al. (2003) described the marginal N response for given irrigation levels, and explained the 2-step process for all eight treatments, producing analytical expressions of irrigation production functions for both N treatments at each of the 396 plot centers. The maps of derived surfaces qualitatively showed distinct spatial patterns in the field. The primary conclusion was that spatial patterns in marginal N response were not stable across years, and further that it was surprisingly variable, ranging from negative to positive in credible areas (i.e., multiple data points in each) of the field. These results demonstrated the utility of having mathematical expressions for irrigation production functions at many areas within a field and were, at that time, to our knowledge, the only such results in existence. Spatial patterns of maximum yield, rainfed yield, irrigation water use efficiency, and with prices, results of marginal economic benefits of irrigation and N can be provided. However, the procedure suffers a number of limitations, including dependence on only spatial variation for step one and on only irrigation for step two (N is accounted for by performing regressions separately for the two N treatments). There is also no good means to provide estimates of uncertainty (variation) around the yield estimates themselves, nor of significance in the estimated yield.

Spatially Explicit Analysis

Despite the benefits of the analyses performed, these data required a spatially explicit analysis. The spatially explicit analysis was achieved using a Bayesian mixed model formulation of bivariate penalized smoothing splines (Holan et al., 2008). This model simultaneously accounted for spatial correlation as well as relationships within the treatments – in other words, considered X, Y, Irrigation, and N, all with the ability to contribute information to nearby neighbors. The outcomes of this analysis were required to include yield estimates, analytical expressions for irrigation and N production functions, and estimates of the uncertainty in yield estimates, coefficients of the analytical expressions, and in the derived variables (e.g., maximum, rainfed, and economic yield), the irrigation required to provide them, irrigation water use efficiency or water productivity. Additionally, the model provided credible intervals around the estimated variablesThis paper employs the method of Holan et al. (2008) to re-analyze the experimental data using a spatially explicit analysis. The specific objectives of this research are to 1) to estimate the suite of variables needed for the types of analyses mentioned above and to provide credible intervals around those estimated variables, and 2) to examine whether the results of this rigorous re-analysis differed from the prior analysis and whether the results force any modifications to the conclusions obtained with the prior analyses.

METHODS

The observed spatial corn yield data collected from Sadler et al. (2002) (2002 analysis) was used to estimate a suite of variables using the recently developed spatially explicit analysis model (2014 analysis). The 2014 analysis, described above inputs the spatial coordinates, imposed irrigation and nitrogen (N) treatments, and observed yield data to estimate the spatial yields. Additionally, the 2014 analysis provides credible intervals (posterior distributions) for the individual estimated yields and uses a spatially-treatment-varying coefficient model to fit the observed yield data.

For a general comparison of the performance of the 2002 and 2014 approaches, the results of both sets of yield estimates were compared to the observed yields using linear regression (SAS, Cary, NC). For a comparison of derived analysis variables (maximum, rainfed, and economic yield, the irrigation required to provide them, irrigation water use efficiency or water productivity), standard summary statistics (means, standard deviations, minimum, and maximum values) were calculated (calculations were carried out using SAS), and the differences between the estimated variables were calculated (i.e., 2002 versus 2014). The point estimates from both analyses were also compared using linear regression (i.e., perfect agreement would result in an intercept=0, slope=1, and R^2=1.0). Contour maps of the calculated variables were generated using the Surfer software (Golden Software, Inc., Golden, CO) using default interpolation parameters (point Kriging, slope=1, aniso=1.0).

RESULTS

Estimated Yield: The observed yields were fit using the spatially explicit analysis (Holan et al., 2008). The 1999-2001 estimated corn yields were calculated using the 2014 analysis (figure1). The yield estimates were then plotted against the observed yields for comparison. In 1999, the 2014 analysis estimated the yields very well in terms of R^2. The estimated yield slope was 0.82 Mg/mm (R^2=0.83, rmse=0.82, Figure 2). Additionally, the upper and lower credible intervals for the 2014 estimated yields are plotted along with the regression (Figure 2). The 1999 growing season was generally considered a drought year; it required the greatest irrigation depths and had the widest variation in corn yields. The 2002 yield estimates were also plotted for comparison (Figure 2; slope=0.72 Mg/ha, R^2=0.84, rmse=0.68). The 2014 yield estimate had a slope closer to 1.0, indicating it did a better job of estimating the high and low yields than the 2002 yield estimates.

In 2000, the estimated yield slope was 0.78 Mg/ha and had an R^2 of 0.80. The 2000 slope was lower than in 1999 and may be attributed to the lower irrigation amounts applied. Again, the 2002 estimated slope was lower than that found for the 2014 analysis. The 2001 season had the lowest irrigation applications of the 3-yr study, indicating a better weather year than either of the first two, and correspondingly lower observed variation in yield. The 2014 estimated yield slope was 0.64 Mg/ha (R^2 = 0.66, rmse=0.67) while the 2002 analysis slope was much lower, 0.39 Mg/ha (R^2=0.77, rmse=0.32). The overall estimated yield fit over the three years decreased from 1999-2001 due to the decreasing irrigation depths required and the corresponding decreased variation in corn yields. The 2001 growing season was considered a more typical rainfall year than the two earlier ones. In each year, the slopes of the two analyses were

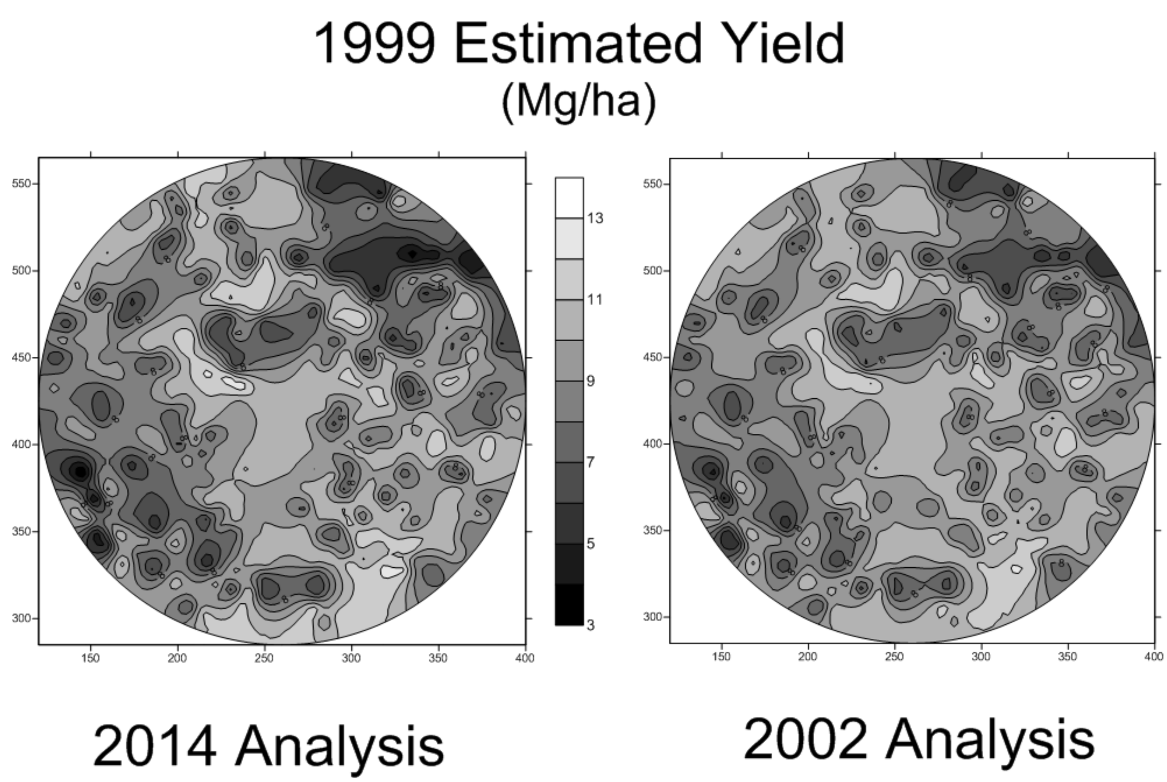

Figure 1. Estimated yield maps for the 2014 and 2002 analysis for 1999.

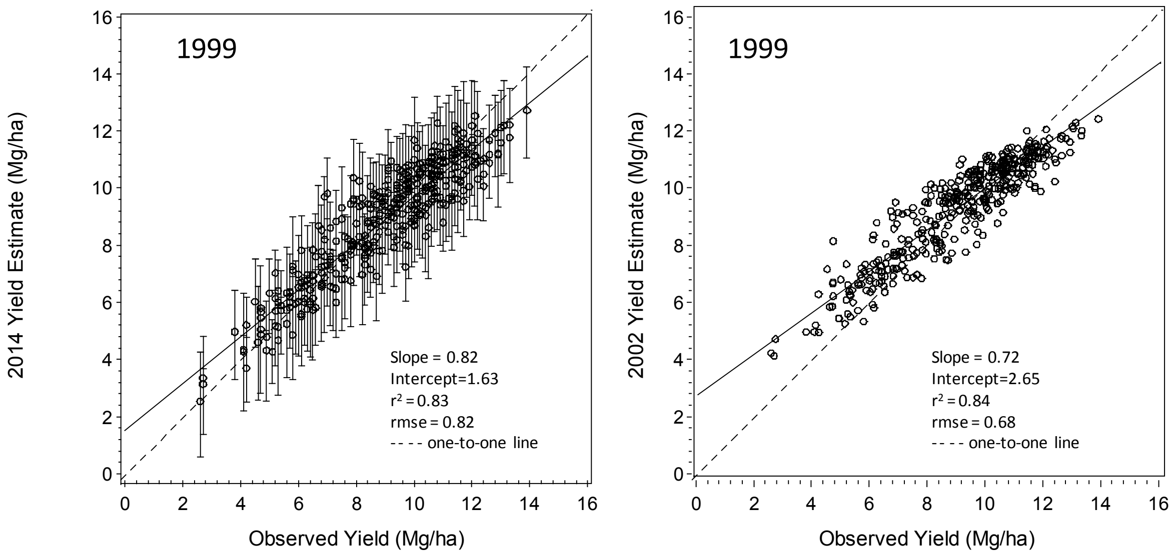

Figure 2. Regression of the 1999 estimated yields versus observed yields for the 2014 and 2002 analysis. The 2014 analysis provides the 95% credible intervals for the estimates.

significantly different. It appears that over the 3-yr study period, the 2014 analysis was able to estimate the corn yields better than the 2002 analysis. This would be a result of the two approaches: the 2002 analysis used blocks of measured yield to calculate yield response curves whereas the 2014 analysis approach estimated yield response curves using the entire sample population, taking into account the spatial dependence.

Comparison of 2014 Predicted Variables to 2002 Estimates

In our analysis, there are several quantities of interest that can all be obtained directly as output from the spatially-treatment varying coefficient model or as deterministic transformations of this output. The items of interest in this analysis are: rainfed yield (i.e., yield when irrigation equals 0), maximum yield, and irrigation that produced maximum yield. Other variables could be estimated for additional analysis but due to space constraints, only those identified above will be discussed.

Rainfed yield: The rainfed yield estimates, particularly in drought years, can provide irrigation designers a good initial estimate of the potential areas of a field where irrigation may provide the most benefit. The 1999 and 2000 corn growing seasons were generally considered drought years. In these two years and for each estimation method, estimated rainfed yields were similar (Figures 3 and 4). The 1999 mean rainfed yields for the 2014 and 2002 estimation methods were 6.75 and 6.44 Mg/ha, respectively, and for 2000 were 5.7 and 5.3 Mg/ha, respectively. In 1999, the 2014 analysis estimated rainfed yields ranging from 2.6 to 10.4 Mg/ha, and the 2002 analysis rainfed yields ranged from 3.7 to 8.2 Mg/ha. The larger ranges between the minimum and maximum rainfed yields for the two estimation methods is due to the 2002 analysis using only points that were in the same irrigation treatment which reduced the number of points used in estimating the response surface. The 2014 analysis utilized the entire data set in predicting the estimated rainfed yields and retained the influence of the extreme values. In both the 1999 and 2000 contour plots (Figures 3 and 4), there appears to be a consistent area from

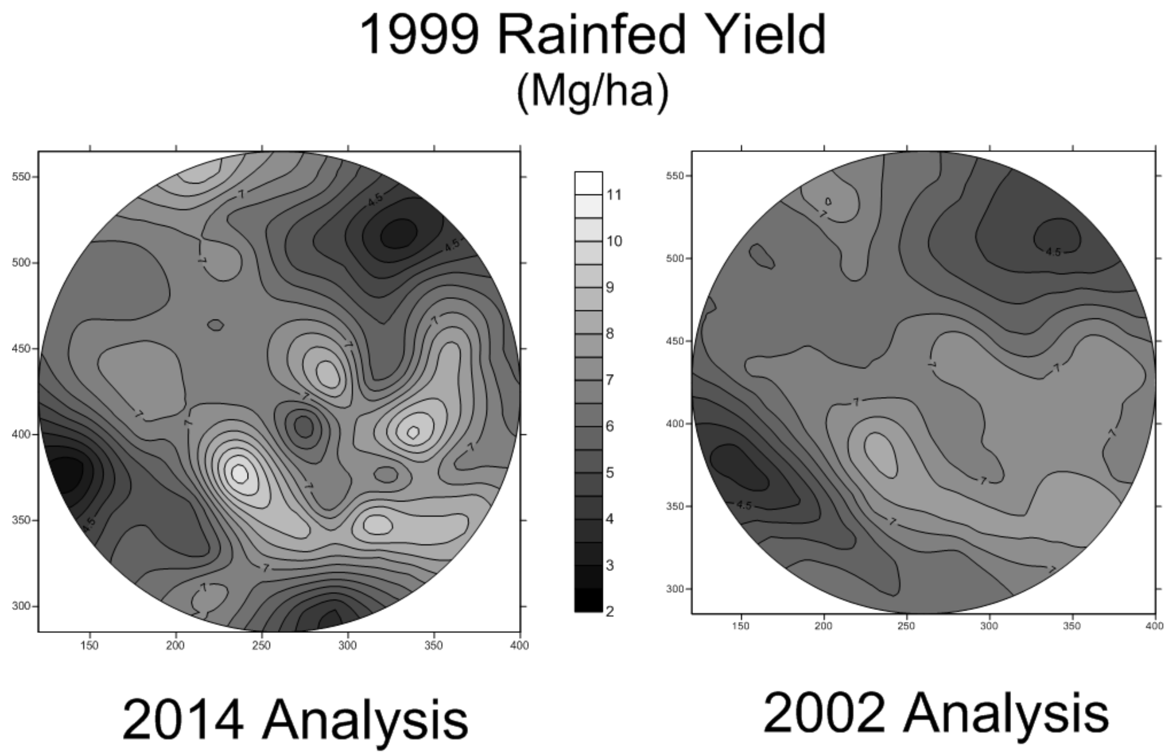

Figure 3. Rainfed estimated yield maps for the 2014 and 2002 analysis for 1999.

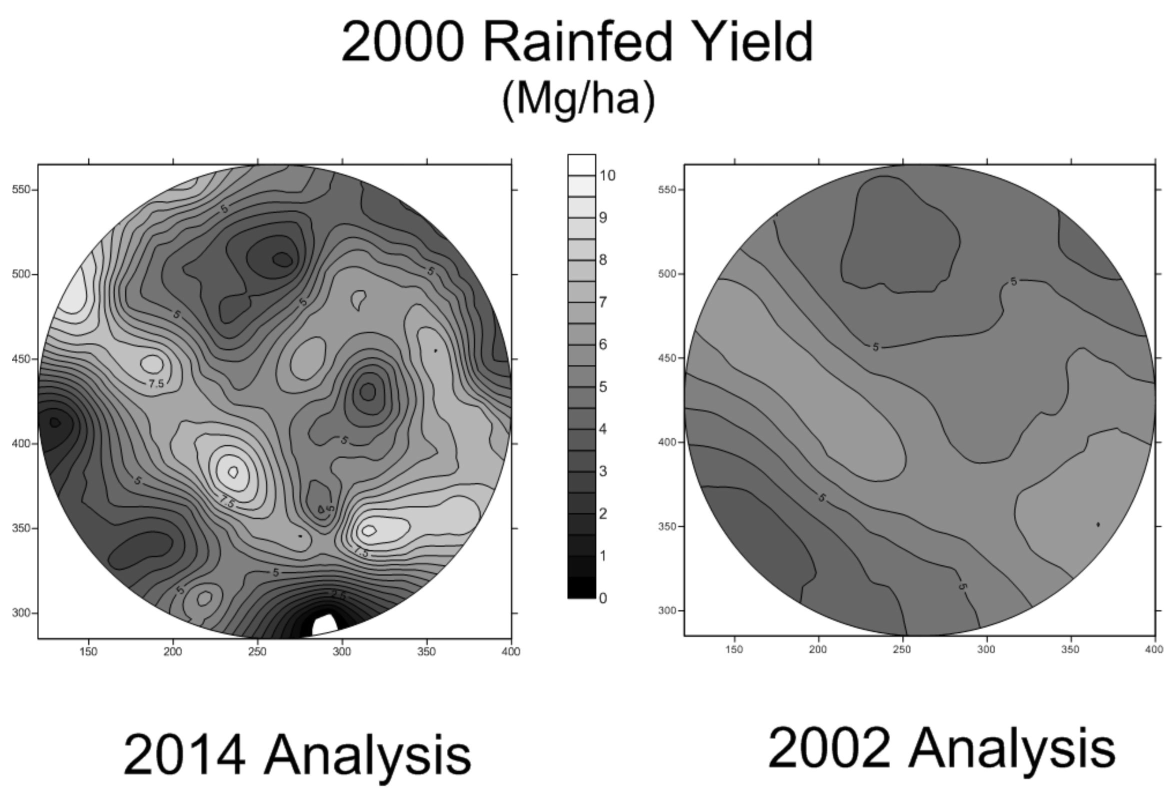

Figure 4. Rainfed estimated yield maps for the 2014 and 2002 analysis for 2000.

upper left to lower right that has relative higher rainfed yields indicating that this area would be the most productive region of the field under rainfed condition. The 2002 growing season was a more typical rainfall year and there were less defined regions within the field (data not shown).

Maximum Yield: The maximum yield estimates provide the potential spatial yields achievable under ideal conditions. The 2001 maximum calculated yields were higher than the 1999 and 2000 maximum yields (Figure 5). For the 2002 analysis, the 1999 to 2001 maximum yields ranged from 8.7 to 12.2, 8.7 to 11.6, and 10.6 to 12.8 Mg/ha, respectively with mean maximum yields 10.7, 10.4, and 11.7 Mg/ha, respectively. The 2014 analysis 1999 to 2001 maximum yields ranged from 5.8 to 12.7, 6.2 to 13.3, 9.2 to 14.4 Mg/ha, respectively, with mean maximum yields of 10.9, 10.6, and 12.0 Mg/ha, respectively.

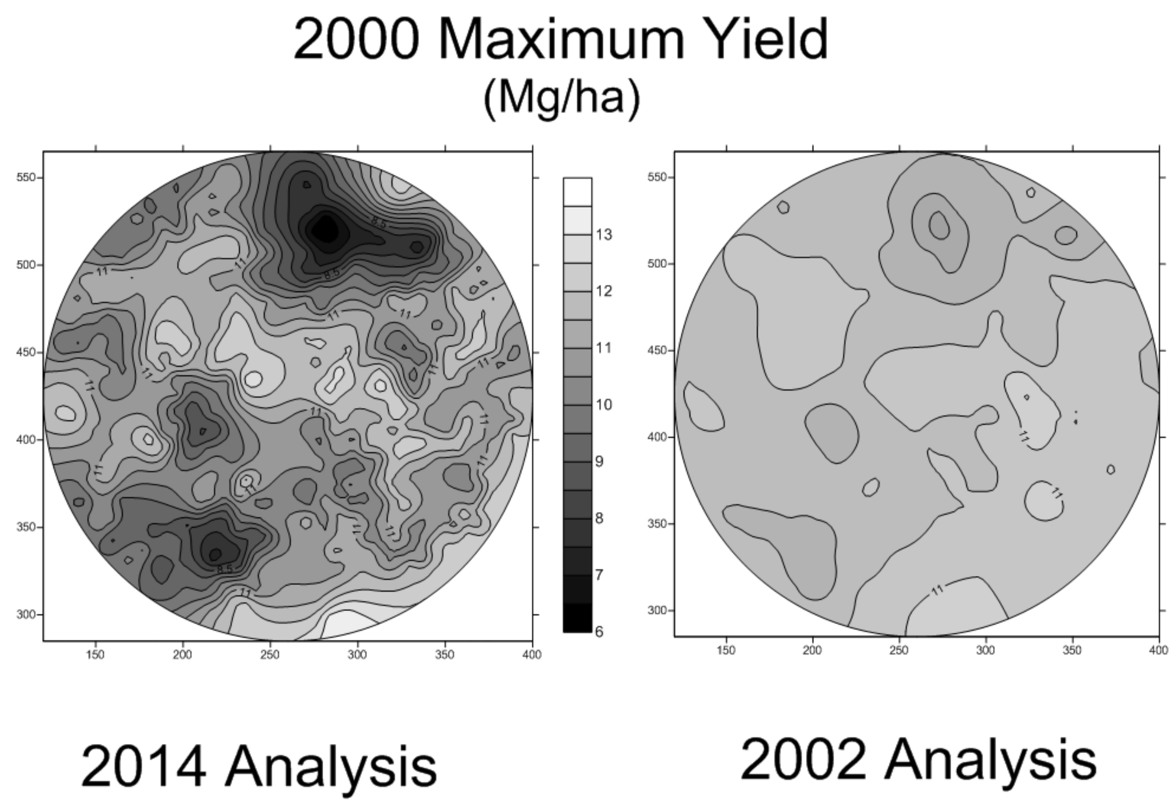

Figure 5. Maximum yield estimate yield maps for the 2014 and 2002 analysis for 2000.

Irrigation at Maximum Yield: The estimation of irrigation required for maximum yields can provide designers the appropriate design parameters for calculating maximum water application rates and irrigation system design flow rates. The irrigation depth corresponding to the calculated maximum yield using the 2014 analysis ranged from 186 mm in 2001 to 282 mm in 1999 (Figure 6) compared to the 2002 analysis which ranged from 204 in 2001 to 286 mm in 1999. The contour maps created for the irrigation depth at maximum irrigation illustrate the differences between the two estimation methods. The 2002 analysis calculated response resulted in areas of the field with little detail. The 2014 analysis utilized the entire dataset and was able to fill areas that were very flat in the 2002 analysis. In comparing the two methods using regression analysis, the slopes were 0.62, 0.39, and 0.23, for 1999-2001, respectively.

However, from 1999 to 2001, the irrigation at maximum yield regression R^2 values were 0.43, 0.19, and 0.05, respectively, indicating poor correlation between the two analyses. Clearly, the results obtained from the 2014 analysis provide more information for irrigation system design on this and other fields with similarly large variation in the soil resource.

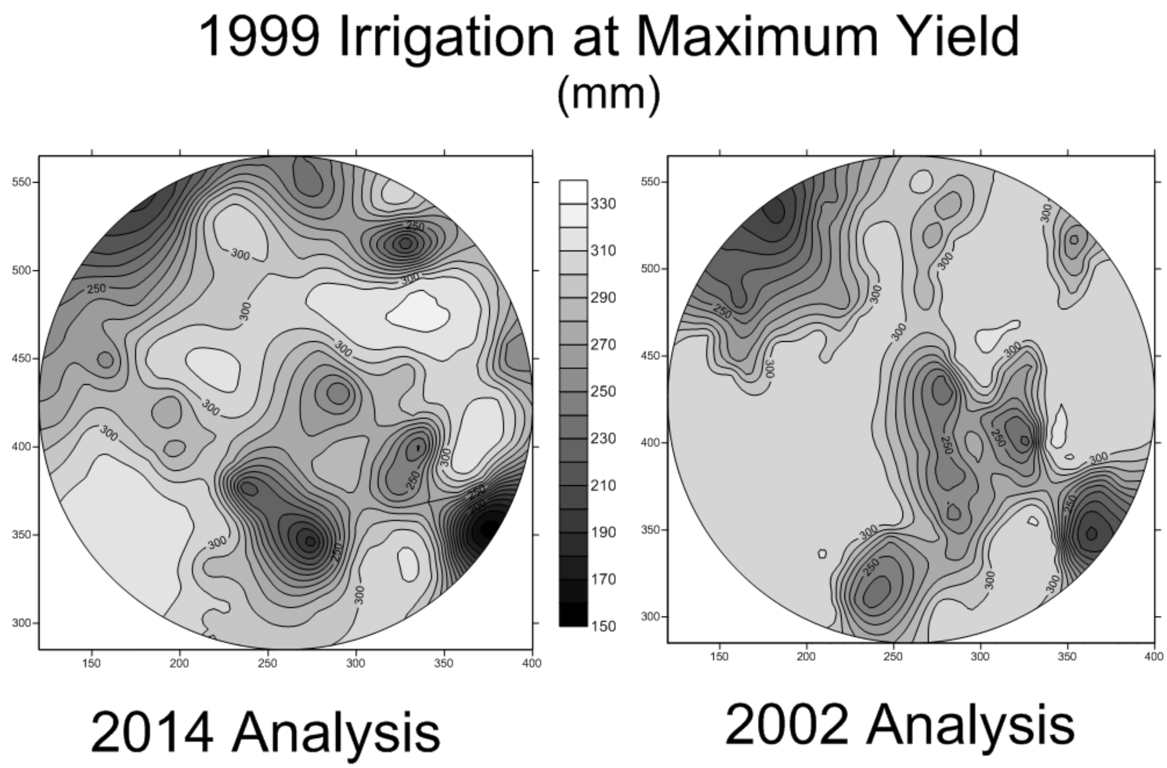

Figure 6. Irrigation at maximum yield estimate maps for the 2014 and 2002 analysis for 1999.

SUMMARY AND CONCLUSIONS

The recently developed spatially explicit analysis (2014 analysis) was used to re-analyze spatial corn yield data. The 2014 method fitted estimated yields in excellent agreement with the observed spatial corn yields. The 2014 analysis preserved more of the spatial variation in the predicted yields and response variables. Overall, the 2014 analysis predicted mean estimated yields for each response variable in relatively close agreement to the 2002 analyses and additionally provided uncertainty estimates.

Our second objective asked if the 2014 analysis would change the conclusion reached in the 2002 analysis. The 2002 analysis concluded that 1) significant differences existed in the response of corn to irrigation, both across soil map units and within soil map units; 2) differences between soil map units existed at magnitudes that would likely be important in irrigation system design and management; and 3) irrigation system managers and designers should consider the effects of unexpectedly large spatial variation in crop response.

In our re-analysis of these data, we confirm their conclusions. However, unlike the 2002 analysis, the 2014 analysis specifically accounts for spatial dependence and provides measures of uncertainty, and is therefore more rigorous and intellectually satisfactory. The 2014 analysis model coefficients are spatially varying resulting in model estimates and credible intervals obtained using all of the observations simultaneously, adding confidence to the results. In all, the 2014 analysis can provide additional insights into spatial responses of crops to irrigation and that it could be used to provide irrigation managers and designers with tools needed to make critical water management decisions.

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Application of RDI Precision Irrigation

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Abstract: *Precision irrigation via various forms of drip and mechanized irrigation addresses many of the challenges facing the pressures on water resources for agriculture. Each has some limitations such as water quality, ability to effectively irrigate irregular shaped fields, energy requirements and management expertise. This paper will provide an update of performance in commercial fields of thenon-coated, porous tube precision irrigation package developed by DuPont, Inc and Valmont Industries, Inc. referred to as RDI. The focus will be on the science behind the product and its application to particular field situations where other types of precision irrigation may be challenged to provide economical solutions. The paper will provide information on differences of a RDI design and other types of precision irrigation.*

Keywords: Precision irrigation, plant roots, sub surface irrigation, center pivot

Introduction:
Shrinking availability of resources in many parts of the world have driven advances in precision irrigation. This has led to changes in irrigation methods. Center pivots have changed from having sprinklers operating at 50psi or more on top of the pipeline to mounted on drops in the crop canopy operating at 10psi. Drip irrigation methods have adapted and one direction it has taken is subsurface irrigation. More and more the focus is on applying the water as efficiently as possible and controlling the water in the root zone. This matches up with interest in the root environment (Arkin, 1981). Precise application of water for plant production has become common. While mechanized and subsurface drip irrigation are overall doing a good job, opportunities still exist to improve the delivery of water for irrigation. As discussed during the 2013 Irrigation Association Technical Meetings (LaRue, 2013) center pivots are an economical delivery system, but may not meet farmer needs to irrigate small irregularly and oddly shaped fields. Subsurface drip irrigation can be very efficient, but has some limitations due to maintenance requirements and water quality challenges. Both types of irrigation require good management practices to work well. The RDI product was introduced to better meet the challenges of precision irrigation.

Objective:
The goal of this study is to provide an update to the science and application of using a porous, non-coated tube for precision irrigation.

Discussion:
The RDI tube is made from a DuPont porous material and converted into a tube by Valmont. The tube is designed to release water through its pores when the surface tension is broken. This can be accomplished in two ways

- When surfactants come in contact with the surface of the tube
    - These can be either natural or artificial

    - Naturally occurring surfactants are released by the plant roots
- When the water pressure in the tube exceeds the hydro head of the specific tube material. As the pressure changes the flux through the tube walls changes linearly.

The tube does not have defined emitters spaced along its length but rather due to is porosity releases water at all along the tube. Work is being done and data collected to see how this product ‘fits’ with conventional subsurface drip irrigation (NRCS, 2004)

In the spring of 2014 the limited commercial sale of the RDI product began. Other field tests were continued and maintained. The design basic design parameters are:

- The preferred operating mode is having water available twenty four hours per day, seven days per week.
    - Typical operating pressure in the tube is 2.0 psi
    - With a spacing of 30 inches between lines the daily application could be 0.30 in/day or more depending on the release of exudates
- Often however water is not available twenty four hours per day due to an electric pump being on load management or when the subsurface irrigated field is connected to a well also supplying a center pivot. In either of these cases the pressure in the tube is maintained at a higher level to ensure the adequate delivery of water to the crop. At these higher pressures the impact of surfactants (exudates from the roots) is minimized.

The following are specific examples of some field situations from the 2014 growing season.

Example #1

- Area – southwest corner of center pivot, 7.5 acres
- Soils – silt loam
- Slope – uniformly about 1.5%
- Crops – corn / soybean rotation
- Situation
    - Amount of water used and labor for furrow irrigation
    - Poor yields due to uneven distribution
    - Want simple solution
- Challenge to sub surface design
    - Operating the sub surface irrigated field with the center pivot
- Solution
    - Regulating the operating pressure at the well to the general required pressure range
    - Installation of three zones to meet uniformity requirements for the field by providing slightly different pressures

Example #2

- Area – east and west sides of a field where corner machine could not cover
    - East side – 34 acres, west side – 14 acres
- Soils – silt loam

- Slope – varies by corner
  - Northeast – uniform 0.20%
  - Southeast – rolling with up to 4% slops
  - Northwest – uniform 0.20%
  - Southwest – uniform 2.5 to 3.0%
- Crops – corn / soybean rotation
- Situation
  - West side – rarely sufficient water or time for furrow irrigation
  - East side – energy use and poor yields due to uneven water distribution using furrow irrigation
  - Due to slopes in field had to plant rows in different directions
    - Wanted to plant and manage the field in one direction
- Challenge to the sub surface irrigation design
  - Topography in parts of the field
  - High iron levels in the east well
- Solution
  - East side
    - Replace 50hp flood pump with 7.5hp pump dedicated to the RDI field
    - Break the field into three zones each operating at a slightly different pressure
    - Use of RDI 73B40 to minimize the impact of the iron levels
  - West side install a small well with 2.0hp pump dedicated to RDI
    - Break the field into two zones each operating at a slightly different pressure

Example #3
- Area – southeast corner of a center pivot – 4.5 acres
- Soils – loamy sand and fine sand
- Slope – uniform 0.20%
- Crops – corn / peanut rotation
- Situation
  - Had not been farmed in twenty years
  - Only corner farmable and not economical for a corner pivot
  - Want to generate some income
- Challenge to subsurface irrigation
  - Old building site
  - Sandy soils
- Solution
  - Installed a 2.0hp pump in the old well dedicated to RDI field
  - Installed RDI 73B40
  - Installed fertigation package to apply 28-0-0-5

Example #4
- Area – long narrow shaped field with building site – 22 acres
- Soils – split between sandy loam and silt loam

- Slope – rolling field with changes along the field of one to five feet
- Crops – corn / soybean rotation
- Situation
    - Nutrient management and cost of pre applying all of the nitrogen
    - Most years to maximize profitability need only three to six inches per acre of irrigation
    - Not economically feasible to water with center pivots or linears
- Challenge to subsurface irrigation
    - Soil changes
    - Topography
- Solution
    - Installed RDI 73B40 in three different zones for the sub surface irrigation
    - Applied 28-0-0 through the 73B40

Results:
For the payback assumed a price of $4.50 per bushel price for corn and expected yields except for Example #3 where harvest has been completed. Savings were based on actual energy costs when available and an estimate of labor.

Example #1
- Outcome
    - Labor required – none, never checked during the growing season
    - Water - significant savings over previous flooding – at least 40%
    - Energy savings – operated with the center pivot
    - Yield – four to five times yields of previous years
- Payback with savings and yield increase – four to six years

Example #2
- Outcome
    - Labor required – very little, rarely checked other than to shut off after significant rain event
    - Water - significant water savings over previous flooding – about 45 to 55%
    - Energy savings – on the east side about $1,500 for the season
    - Yield – significantly more crop harvested than had been previously
        - West side – during previous five years almost no crop had been harvested
- Payback – with savings and yield increase four to five years

Example #3
- Outcome
    - Labor required – none other than to fill fertilizer tank
    - Water savings – none as had not been irrigated
    - Energy savings – none as had not been irrigated
    - Fertigation was critical due to early season excessive rainfall
- Payback – four years

Example #4

- Outcome
  - Labor required – none other than to fill fertilizer tank
  - Water savings – none as had not been irrigated
  - Energy savings – none as had not been irrigated
  - Fertigation was critical to maintain the crop
- Payback – five to six years

Conclusion:
The application of a porous, non-coated tube for subsurface irrigation has had a few challenges that are being overcome and its significant benefits continue to drive interest in the product. In installations being specifically monitored the customer expectations are being met and in some cases significantly exceeded. The non-coated porous tube has been easy to use in irregular fields. Water quality issues have not been significant other than high iron in one well which has not impacted the flows of the porous tube. Management and maintenance requirements have been minimal and in some cases there has been none other than to turn the system off and back on after significant rain events.

Work continues to explore performance of the non-coated, porous tubes with more crops and soils. In addition work is continuing to see if and how the porous tube can be described and characterized like conventional drip with emitters or if a different way of characterizing is needed.

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Drip Irrigation Lateral and Submain Configurations for Field and Row Crops

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Abstract. Drip irrigation systems consist of lateral pipes that emit water directly to the root zones of crops, and submain pipeline networks that supply water to the laterals. Lateral and submain pipelines are available in a number of configurations that may be classified as season or permanent. Field crop (cotton, corn, alfalfa, soybeans, etc.) and row crop (fruits, vegetables, etc.) growers routinely use one or more of the following lateral and submain combinations: 1) Seasonal laterals with seasonal submains, 2) Seasonal laterals with permanent submains, 3) Permanent laterals with seasonal submains, and 4) Permanent laterals with permanent submains. Typical applications of each of these four combinations, and the relative pros and cons of each, will be reviewed. Discussion topics will include crop germination and/or transplant setting, labor, system maintenance, operational flexibility and the effect upon initial cost and yearly operating cost. Examples will show how each of these combinations are successfully deployed.

Keywords. *Subsurface Drip Irrigation (SDI), Drip Irrigation Economics, Drip Irrigation Design*

Introduction

The use of drip irrigation is growing rapidly in the United States. Drip not only increases resource-use efficiency, including water, fertilizer, labor and energy, but enhances yield and quality.

Drip irrigation has traditionally been implemented in higher value fruit, nut and vegetable crops. More recently, it has become very popular in field crop applications, including corn/soybean rotations and alfalfa, cotton and processing tomato fields. The U.S. Department of Agriculture's most recent Farm and Ranch Irrigation Survey reported 3.76 million acres of drip in the United States. Drip acreage is expected to be significantly higher in the 2013 report due in October of 2014.

One reason drip is gaining in popularity is because the systems are flexible and can accommodate diverse cropping and application demands. Drip irrigation systems consist of lateral pipes that emit water directly to the root zones of crops, and submain pipes that supply water to the laterals. For field and row crop applications, lateral and submain pipelines can be classified as seasonal or permanent and are available in a number of configurations.

Pros and Cons of Drip System Combinations

Drip irrigation systems rely on five major components:

- Drip tape is a “line source” drip irrigation lateral product that incorporates a continuously produced flowpath emission device into a thin- to medium-walled seamed or extruded tube. Toro’s Aqua-Traxx premium drip tape with the PBX advantage is an example of an extruded drip tape with rotary molded emitters using a polyethylene flowpath, while Toro’s Aqua-Traxx FC uses an elastomeric material.
- Flat emitter dripline is a “point-source” lateral product that incorporates injection molded emitters into a thin- to medium-walled extruded tube. Toro’s Neptune flat emitter dripline is an example of this type of lateral.
- Oval hose is a submain pipe made from polyethylene (PE) that is flattened to an oval shape during production to simplify transportation.
- Layflat is a submain pipe made from flexible PVC that is coiled flat.
- PVC pipe is rigid and available in various thicknesses and cut lengths.

Figure 1 illustrates three different types of drip tape and flat emitter dripline components:

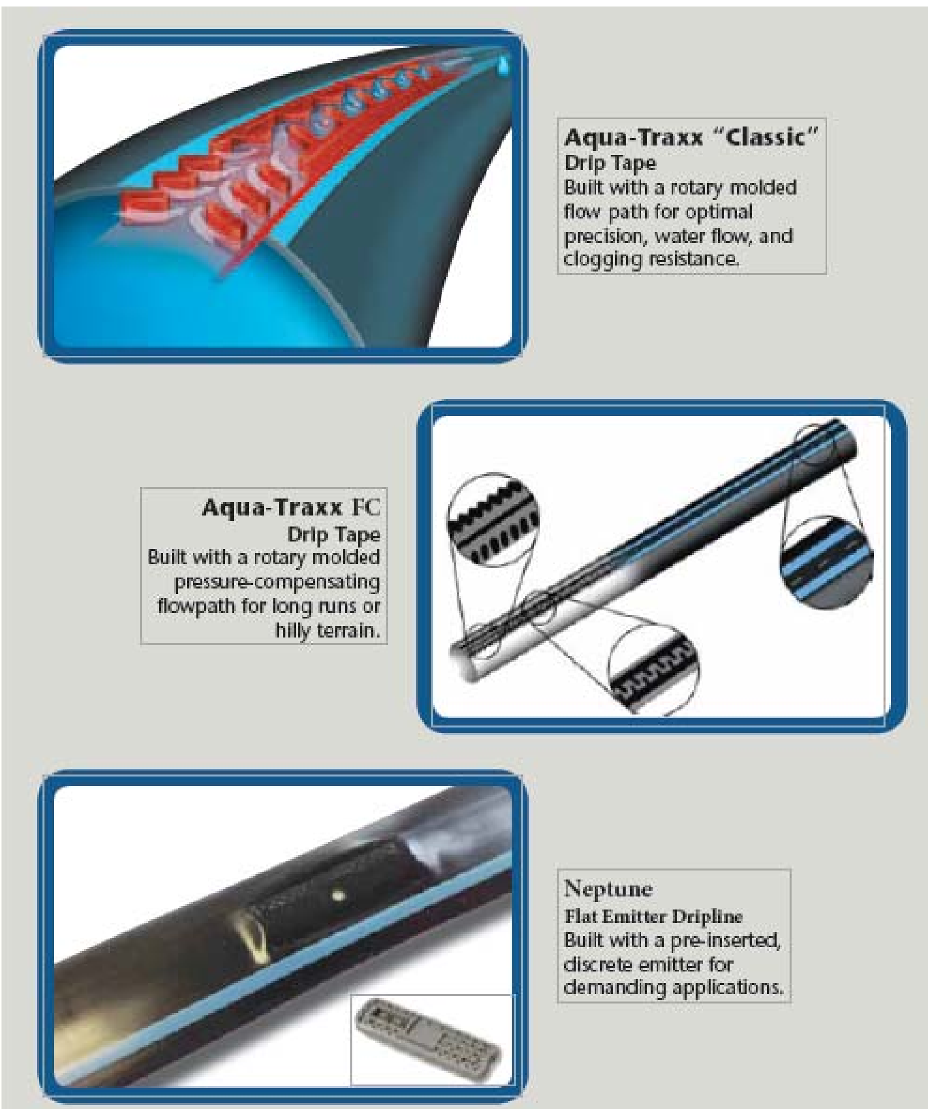

Figure 1: Examples of drip tape and flat emitter dripline options from The Toro Company.

Figure 2 shows the seasonal and permanent options of the lateral and submain components combined with one another in four quadrants, and then lists the pros and cons of each combination. In addition, application examples are provided. Factors to consider when deciding upon permanent or seasonal submains and laterals include crop germination and/or transplant setting, labor, system maintenance requirements, operational flexibility, initial cost and annual operating cost. A summary of each quadrant of the matrix follows below.

Pros and Cons of Drip Irrigation Lateral and Submain Configurations for Field and Row Crop Applications*

	Seasonal Submain (Layflat, Oval Hose)		**Permanent Submain (PVC)**		
Seasonal Lateral (Drip Tape, Flat Emitter Dripline)	Pros	Cons	Pros	Cons	**Seasonal Lateral (Drip Tape, Flat Emitter Dripline)**
	Portable with ability to follow crop	High flushing labor	Automate flushing	Winterization needed	
	Germinate crop	High moving labor	No submain moving labor	Trenching required	
	Average maintenance	Disposal costs	Germinate crop	Repairs more difficult	
	Low initial cost	Seasonal lateral replacement cost	Average maintenance	Lateral replacement more difficult	
		Periodic submain replacement cost	Multii-year PVC use	Moderate lateral costs	
				Manifolds for various crops difficult	
	Example: Onions, celery, vegies		***Example: Some vegetable growing regions***		

	Seasonal Submain (Layflat, Oval Hose)		**Permanent Submain (PVC)**		
Permanent Lateral (Drip Tape, Flat Emitter Dripline)	Pros	Cons	Pros	Cons	**Permanent Lateral (Drip Tape, Flat Emitter Dripline)**
	Multi-year lateral use	Often need supplemental moisture for germination	Automate flushing	Often need supplemental moisture for germination	
	Portable submain	Lateral repairs more difficult	No submain moving labor	Lateral and submain repairs more difficult	
	Medium initial cost	Need excellent maintenance	Multi-year lateral and submain use	Need excellent maintenance	
		High flushing labor or need flushing manifolds		Winterization needed	
				Higher initial cost	
	Example: Processing tomatoes		***Example: Corn/soybeans, alfalfa, cotton***		

* Based on information developed by Jim Klauzer, Clearwater Supply and Inge Bisconer, Toro Micro-Irrigation

Figure 2 - Pros and cons of drip irrigation lateral and submain configurations for field and row crops.

Seasonal Laterals and Seasonal Submains (upper left quadrant)

Systems with seasonal laterals and seasonal submains are popular in vegetable crops like celery or onions and fruit crops such as strawberries. They may be used to germinate the crop, are portable and have a low initial cost. Because they are expected to last only one season, they require only moderate maintenance. Drawbacks to this type of system include the labor needed to move submains and flush laterals, as well as lateral disposal and lateral replacement costs.

Permanent Laterals and Seasonal Submains (lower left quadrant)

Permanent laterals used with seasonal submains are popular in processing tomato production because the laterals can be used for multiple years, and yet the submains are portable. Drawbacks to this type of system include more difficult lateral repairs, the possible need for supplemental germination moisture, and heavier maintenance requirements since laterals are expected to last multiple seasons. Maintenance for these systems typically includes flushing manifolds and/or flushing labor, and chemical treatment. Initial system cost is higher compared to seasonal, portable laterals used on vegetable and strawberry crops since the permanent laterals need to be more robust. However, the submain costs are about the same since both are seasonal.

Permanent Laterals and Permanent Submains (lower right quadrant)

Permanent laterals with permanent submains are used for field crops, such as corn, soybeans, alfalfa and cotton. System advantages include multi-year use and amortization of both the laterals and submains. Using permanent laterals with permanent submains also allows automated flushing and eliminates submain moving costs.

The drawbacks to this type of system include more difficult lateral and submain repairs, high maintenance requirements, the possible need for supplemental moisture for germination, and the need for winterization in cold climates. The initial cost is higher because the components must be durable enough for multiple year use and the system must be trenched in.

Seasonal Laterals and Permanent Submains (upper right quadrant)

Finally, seasonal laterals are sometimes combined with permanent submains in vegetable growing regions to avoid submain moving costs. Submain repairs for these systems are more difficult, as is lateral replacement.

Conclusion

Drip irrigation offers growers a number of benefits, but choosing the right system can be complex. Growers are encouraged to consult with reputable manufacturers, qualified dealers, consultants, farm advisors, government personnel, associations and irrigation service providers for help determining the best combination of components for their specific conditions. Drip irrigation education material is available at http://driptips.toro.com.

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Water requirements of drip irrigated tomatoes in Central California

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Abstract. Accurate estimation of crop water requirements (CWR) is essential to optimize water use efficiency and develop efficient irrigation scheduling practices. This is particularly important in Central California where continuous droughts have accentuated the need to conserve water and improve on-farm water management. The most accurate method to determine CWR is with precision weighing lysimeters, which measure actual crop evapotranspiration (ET_a). Thus, the objectives of this study were to determine ET_a data, develop new crop coefficients (K_c), and evaluate the relationship between K_c and crop ground cover for processing tomatoes grown under subsurface drip irrigation. The study was conducted on a clay loam soil. Average ET_a , K_c , and ground cover data will be presented. Relationship between K_c and ground cover will also be evaluated.

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

Major changes in crop production systems have occurred over the past decade throughout California. In the Central Valley, many agricultural producers have transitioned from low-value crops grown under flood irrigation to higher value crops, such as vegetables and fruits, produced with low-volume irrigation, i.e., drip. A typical example is the conversion of flood-irrigated cotton to processing tomatoes grown with drip irrigated systems. Other growers have also opted for production of row crops under drip irrigation. These changes, partly due to farmers' desire to increase their revenues as well as constrained agricultural water supplies to satisfy urban and environmental water demands, has been accentuated in the last few years following multiple droughts and consequent reductions in surface water allocations. In some areas of the Central Valley, growers received 20% or less of their normal allocations the last few years. Under such reduction in surface water availability throughout the region and with the adoption of new cropping and irrigation practices, it is important to develop management practices that conserve water and optimize water use efficiency (WUE).

A direct factor affecting WUE is irrigation efficiency (IE). Although IE has improved with the implementation of drip irrigated systems, most agricultural producers continue to schedule irrigations based on visual observations of soil moisture conditions and plant health, as well as general knowledge of historical needs. Such practices often lead to over application of irrigation water, particularly in vegetable cropping systems. Few growers utilize estimations of crop water requirements (CWR) for scheduling irrigations, although such method has been found to increase yields and reduce total applied water (Parker et al., 1996). This is mostly attributed to the difficulty in determining daily CWR values for site specific conditions and to the paucity of data available, especially for drip irrigated systems.

Crop water requirement, also defined as crop evapotranspiration (ET_c), is commonly calculated by multiplying weather-based estimates of reference evapotranspiration (ET_o) with a crop coefficient (K_c): $ET_c = K_c * ET_o$. The ET_o represents the evaporative demand of the atmosphere and daily values can be easily obtained through the California Irrigation Management Information System (CIMIS). The K_c represents the effects of crop, management, and environmental conditions on ET_c (i.e., crop type, growth development stage, soil water content, texture, fertility, salinity, pests, diseases, as well as irrigation management - method/frequency). Published K_c data are available for major agricultural crops (Allen et al., 1998; 2007). However, these published data were developed a few decades ago for specific growing conditions and irrigation practices (i.e., flood) which are not always representative of cropping systems observed today. This is particularly true for crops grown under low-volume irrigation (i.e., drip).

To date, research on such production systems has been limited to very few vegetable crops (Ayars, 2008; Bryla et al., 2010). Therefore, there is a need to expand the development of CWR and K_c data to additional drip irrigated cropping systems important for California agriculture. The most accurate method to determine CWR is with precision weighing lysimeters, which measure actual crop evapotranspiration (ET_a). Thus, the objectives of this study were to determine ET_a data, develop new crop coefficients (K_c), and evaluate the relationship between K_c and crop ground cover for processing tomatoes grown under subsurface drip irrigation.

The study was conducted in the Central Valley of California on a claim loam soil. The site included two large weighing lysimeter facilities, each containing a 15-tonne soil tank (2 m x 2m x 2.25 m) positioned on a scale system capable of measuring small weight changes of less than 0.01 kg. The lysimeters were located in the center of two adjacent 1.7-ha (4.2 acre) fields. One lysimeter was planted with grass to measure the reference ET (ET_o). The second lysimeter, referred to as crop lysimeter, was planted with processing tomatoes grown under drip irrigation. The tomato crop was transplanted both in the crop lysimeter and in the surrounding field on 60-inch beds. The tomatoes were planted 12 inches apart along the beds and were irrigated with a sub-surface drip irrigation system installed at 12 inches. The cultural practices and fertilizer applications followed the regular site schedule.

The lysimeter was replenished each time a predetermined crop ET depth had been withdrawn from the soil tank. The surrounding field was irrigated based on the ET data obtained from the crop lysimeter. Irrigation was applied daily. The parameters measured during the growing season included: daily ET_c, K_c, and weekly ground cover which was obtained from a Tetracam infra-red camera. These data are currently being compiled and analyzed and will be presented. Relationship between K_c and ground cover will also be discussed.

Partial funding for this project was provided by the California State University Agricultural Research Initiative Program.

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Optimal practices for drip-irrigated onion differ based growers' market opportunities.

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Abstract

Past research at the Oregon State University Malheur Experiment Station, Ontario, Oregon, demonstrated the sensitivity of onion yield and grade to soil water tension. The ideal soil water tension for initiating irrigations for drip-irrigated onion was determined to be close to 20 cb (Shock et al. 2000). Premiums are paid for bulb size in the United States. In many other countries onions are grown at higher plant populations for smaller sized bulbs. A higher plant population might require a different SWT. This trial tested four SWTs with two varieties and two plant populations. At high plant populations, high yields of smaller bulbs are realized over a broader range of soil water tensions.

Materials and Methods

Onions were grown in 2013 on an Owyhee silt loam. The field was planted to wheat in 2012. In the fall of 2012, the wheat stubble was shredded and the field was irrigated. The field was then disked, moldboard plowed, and groundhogged. A soil analysis taken in the fall of 2012 showed a pH of 7.3, 1.6% organic matter, and 22 ppm of phosphorus. Based on the soil analysis, 49 lb of phosphorus/acre, 200 lbs of sulfur/acre, and 1 lb of boron/acre were broadcast before plowing. After plowing, the field was fumigated with Vapam® at 15 gal/acre and bedded at 22 inches.

Seed was planted on March 13 in double rows spaced 3 inches apart at 9 seeds/ft of single row. Each double row was planted on beds spaced 22 inches apart. Planting was done with customized John Deere Flexi Planter units equipped with disc openers. Immediately after planting, the onions received a narrow band of Lorsban® 15G at 3.7 oz/1,000 ft of row (0.82 lb ai/acre), and the soil surface was rolled. Onion emergence started on April 4.

The field had drip tape laid at 4-inch depth between two pairs of double rows during planting. The drip tape had emitters spaced 12 inches apart and a flow rate of 0.22 gal/min/100 ft (Toro Aqua-Traxx, Toro Co., El Cajon, CA). The distance between the tape and the center of each double row of onions was 11 inches.

The experimental design was a split-split plot randomized complete block with six replicates. The four irrigation treatments were the main treatments. Four treatments tested different soil water tensions for initiating irrigations: 10, 20, 30, and 50 cb. The main plots were 4 double rows wide by 54 ft long.

Two onion varieties ('Vaquero', Nunhems, Parma, ID and 'Swale', Seminis, Payette, ID) were planted as split plots within each main plot. Each variety split plot was divided into two plant population split-split plots (120,000 and 450,000 plants/acre). Variety split plots were 27 ft long and plant population split-split plots were 13 ft long.

On March 21, a mixture of humic acid (CHB Premium 6, BioGro, Mabton, WA, 5% humic acids, 6 gal/acre), phosphoric acid (NUE 0-30-0, Bio-Gro, 26 lb phosphorus/acre), and Avail® (Simplot, Caldwell, ID, 0.5% of the final volume) was sidedressed between the seed row and the drip tape at 3 inch depth.

On May 16, the population split-split plots were thinned by hand. The plots thinned to 120,000 plants/acre had onions thinned to 4.75 inches between plants in each single row. The plots thinned to 450,000 plants/acre had onions thinned to 1.4 inches between plants in each single row.

In order to monitor plant nutrient status, every 2 weeks, starting on May 22, bulbs from the border rows in each split-split plot of 10 cb treatment of Vaquero from the 450,000 plants/per acre population were removed and the roots washed in deionized water. A sample consisting of a composite of roots from all replicates was sent to Western Labs (Parma, ID) for nutrient analysis.

Soil solution analysis is an estimate of the amount of each nutrient that the soil can supply to the crop per day. Soil solution analysis uses an extraction method that simulates the extraction capacity of plant roots. Every week starting on June 24, soil samples were taken from the same split-split plots as the root issue samples and were sent to Western Labs for soil solution analysis. Each sample consisted of a composite of 7 cores to 9-inch depth from border rows in each plot.

Nutrients were applied based on root tissue analysis and soil solution analysis (Table 1). Nutrients were injected into the drip irrigation system using an Ozawa Precision Metering Pump (Ozawa R and D, Ontario, OR).

Table 1. Nutrients applied (lb/acre) through the drip tape. All nutrients were applied based on root tissue analysis, except as indicated. Malheur Experiment Station, Oregon State University, Ontario, OR, 2013.

Date	N	P	K	B	Ca	Mg	Cu
28-May	40						
10-Jun			20	0.2	3.5		
20-Jun	20		20	0.2			
3-Jul	20		20				
18-Jul		5	20			5	
25-Jul							0.1*
30-Jul							0.7*
1-Aug	20		20			5	
16-Aug		10	20				
19-Aug						5	
total	100	15	120	0.4	3.5	15	0

* based on soil solution analysis

Onions were irrigated automatically to maintain the SWT in the onion root zone below the target for each treatment (Fig. 1). Soil water tension was measured in each 450,000 plant/acre split-split plot in the Vaquero split plot in each main plot. Soil water tension in each split-split plot was measured with four granular matrix sensors (GMS, Watermark Soil Moisture Sensors Model 200SS, Irrometer Co., Riverside, CA) installed at 8-inch depth in the center of the double row. Sensors had been calibrated to SWT (Shock et al. 1998). The GMS were connected to the datalogger via multiplexers (AM 410 multiplexer, Campbell Scientific, Logan, UT). The datalogger read the sensors and recorded the SWT every hour. The datalogger made irrigation decisions every 12 hours. The irrigation decisions were based on the average SWT of the four GMS in each plot. The irrigation durations were 8 hours, 19 minutes (0.48 inches of water) for the 20-, 30-, and 50-cb treatments and 4 hours, 9 minutes (0.24 inches of water) for the 10-cb treatment. The irrigations were controlled by the datalogger using a controller (SDM CD16AC controller, Campbell Scientific, Logan, UT) connected to a solenoid valve in each main plot. The water for the drip system was supplied by a well that maintained a continuous and constant water pressure of 35 psi. The pressure in the drip lines was maintained at 10 psi by pressure regulators in each plot.

The automated irrigation system was started on July 9. Prior to July 9, irrigations were run manually based on sensor readings. Irrigations for the whole trial were terminated on September 3. Onion evapotranspiration (ET_c) was calculated with a modified Penman equation (Wright 1982) using data collected at the Malheur Experiment Station by an AgriMet weather station. Onion ET_c was estimated and recorded from crop emergence until the onions were lifted.

The onions were managed to avoid yield reductions from weeds, pests, diseases, water stress, and nutrient deficiencies. Roundup® at 1 lb ai/acre was broadcast on April 2 prior to onion emergence. On May 3, Goal Tender® at 0.06 lb ai/acre (4 oz/acre), Buctril® at 0.25 lb ai/acre (16 oz/acre), and clethodim at 0.19 lb ai/acre (12 oz/acre) were applied for weed control. On May 26, Prowl® H_2O at 0.83 lb ai/acre (2 pt/acre) was applied for weed control. On June 10, Goal Tender at 0.09 lb ai/acre (6 oz/acre), Buctril at 0.31 lb ai/acre (20 oz/acre), and clethodim at 0.25 lb ai/acre (16 oz/acre) were applied for weed control. For thrips control, the following insecticides were applied: Movento® at 5 oz/acre on May 23 and 31; Agri-Mek® at 16 oz/acre on June 14, 27, and July 4; Radiant® on July 12; and Lannate® on July 18 and 24.

The onions were lifted on September 10 to field cure. Onions from 9 ft of the middle 2 rows in each split-split plot were topped by hand, bagged, and placed in storage on September 19. The storage shed was ventilated and the temperature was slowly decreased to maintain air temperature as close to 34°F as possible. Onions were graded out of storage on November 25.

During grading all bulbs from each split-split plot were counted. Split bulbs were counted and weighed. Bulbs were then separated according to quality: bulbs without blemishes (No. 1s), double bulbs (No. 2s), bulbs infected with neck rot (*Botrytis allii*) in the neck or side, plate rot (*Fusarium oxysporum*), or black mold (*Aspergillus niger*). The No. 1 bulbs were graded according to diameter: <30 mm, 30-50 mm, 50-57 mm, 57-70 mm, 70-76 mm, 76-90 mm, 90-102 mm, 102-108 mm, >108 mm. The grade data was analyzed according to U.S. standards: small (<2¼ inches), medium (2¼-3 inches), jumbo (3-4 inches), colossal (4-4¼ inches), and supercolossal (>4¼ inches). The grade data were also analyzed according to Brazilian standards: <30 mm, 30-50 mm, 50-70 mm, 70-90 mm, >90 mm. Bulb counts per 50 lb of supercolossal onions were determined for each plot of every variety by weighing and counting all supercolossal bulbs during grading.

Treatment differences were compared using analysis of variance (ANOVA) and regression analysis. Means separation was determined using Fisher's least significant difference test at the 5% probability level, LSD (0.05).

Results

Soil water tension over time oscillated around the target for each treatment, with the amplitude of the oscillations increasing with the increase in the irrigation criteria (Fig. 1). The amount of water applied with irrigation at 20 cb paralleled crop evapotranspriation (ET_c) (Fig. 2), (Table 2). Irrigation at 10 cb exceeded ET_c. The other treatments applied less than ET_c for the season (35.3 inches).

Irrigation Treatment Effects

Averaged over varieties, irrigation criterions drier than 10 cb resulted in increasingly lower colossal yield for the 120,000 plants/acre population (Table 3). For the 450,000 plants/acre population, irrigation criterions drier than 20 cb (30 and 50 cb) resulted in increasingly lower jumbo yield. For the 450,000 plants/acre population, there was no supercolossal yield and colossal yields were very low. Averaged over varieties and populations, irrigation criterions drier than 20 cb (30 and 50 cb) resulted in increasingly lower total yield and marketable yield than the 10- or 20-cb treatments.

Averaged over populations, marketable yield for Swale was more sensitive to increasing irrigation criterion than for Vaquero. This was due mainly to a bigger decline in colossal yield with increasing irrigation criterion for Swale than for Vaquero. Regression analysis shows that, for Vaquero, marketable yield was not responsive to SWT, but colossal plus supercolossal yields declined with increasing average SWT for both plant populations (Figs. 3 and 4). For Swale, both marketable and colossal plus supercolossal yields declined with increasing average SWT for both plant populations (Figs. 5 and 6).

For the 450,000 plants/acre population, averaged over varieties, the 10-cb and 20-cb irrigation treatments resulted in higher storage rot than the drier treatments. There was no difference in storage rot between irrigation treatments for the 120,000 plants/acre population.

Plant Population Effects

Averaged over varieties and treatments, marketable yield, supercolossal yield, colossal yield, and jumbo yield were higher with the 120,000 plants/acre population (Table 3). Total yield, medium yield, small yield, total rot, and bolting were higher with the 450,000 plants/acre population.

Bulb Single Centers

There was no significant difference in bulb single centeredness between irrigation treatments. The 450,000 plants/acre population resulted in higher single centered and functionally single centered bulbs (Table 4). The 450,000 plants/acre population resulted in a higher percentage of tops down on July 25 than the 120,000 plants/acre population. The percentage of tops down on July 25 increased with the increasing SWT (dryness) of the irrigation treatments for the 450,000 plants/acre population. There was no difference in the percentage of tops down on July 25 between irrigation treatments for the 120,000 plants/acre population.

Discussion

The results of this study agree with previous research at Malheur Experiment Station. Research in 2012 showed that with plant populations up to 200,000 plants/acre (highest tested), total and marketable yield is not very sensitive to plant population, but colossal and supercolossal yield is very sensitive to plant population (Shock et al. 2013). In the current study, plant populations of 318,000 plants/acre resulted in lower marketable yield, suggesting that onion marketable yield might level off somewhere between 200,000 and 318,000 plants/acre. The 2012 research on plant population also agreed with the present trial, where higher plant populations resulted in earlier maturity.

Research in 1997 and 1998 showed that depending on the year, irrigation criterions drier than 10 or 20 cb resulted in reduced marketable yield and bulb size (Shock et al. 2000). In this study, averaged over two varieties, irrigation criterions drier than 20 cb resulted in reduced marketable yield and bulb size. However, the regression analysis showed that marketable yield was less sensitive to irrigation for Vaquero than for Swale.

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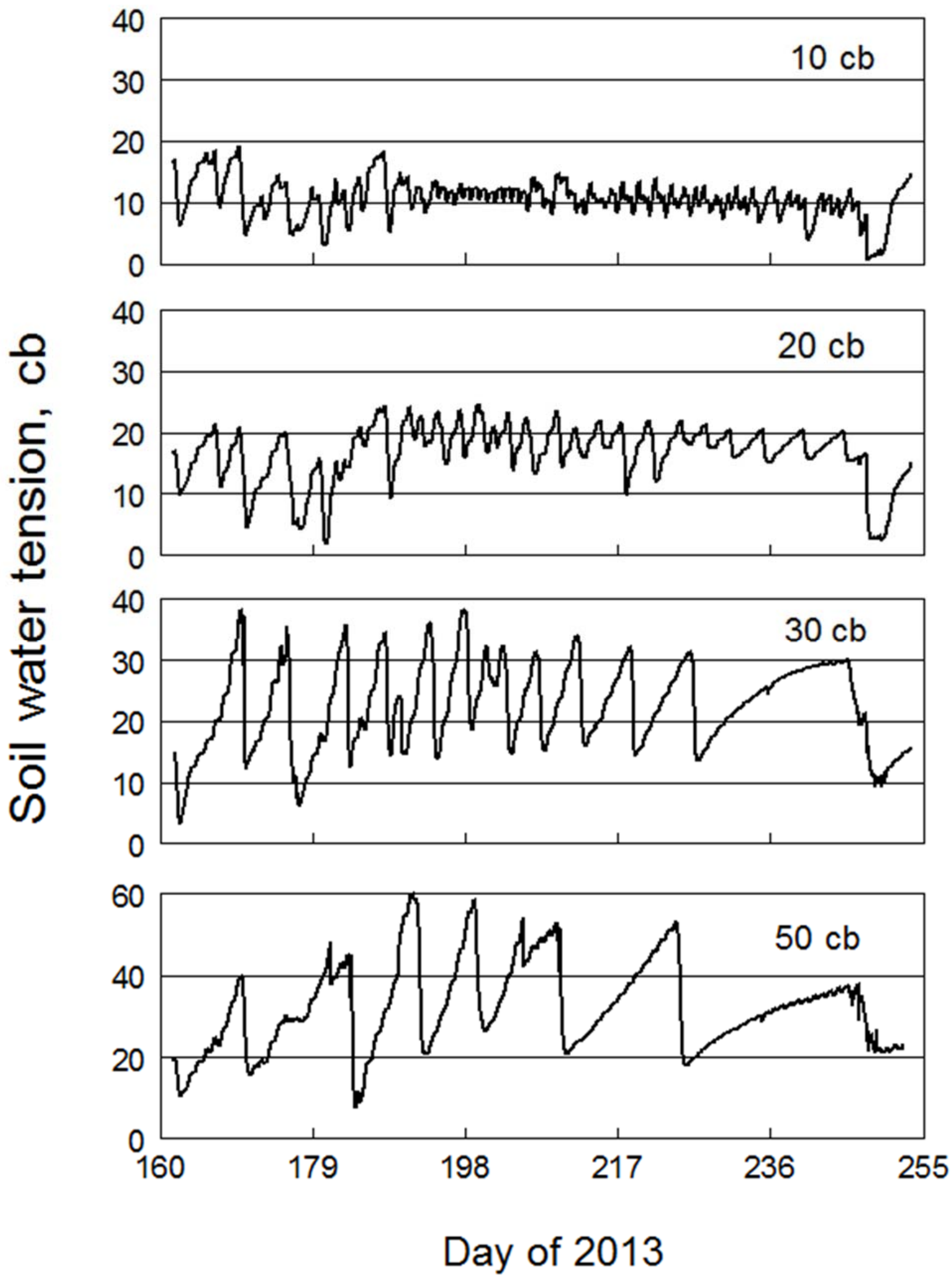

Figure 1. Soil water tension at 8-inch depth for onions irrigated at four soil water tensions. Malheur Experiment Station, Oregon State University, Ontario, OR, 2013.

Table 2. Total water applied (includes 1.5 inches of precipitation) from onion emergence to the last irrigation and average soil water tension. Evapotranspiration from emergence to lifting totaled 35.3 inches. Malheur Experiment Station, Oregon State University, Ontario, OR, 2013.

Irrigation criterion	Total water applied	Average soil water tension
	inches	cb
10 cb	45.3	13.8
20 cb	36.4	17.4
30 cb	24.5	22.9
50 cb	22.0	33.0
LSD (0.05)	6.9	3.3

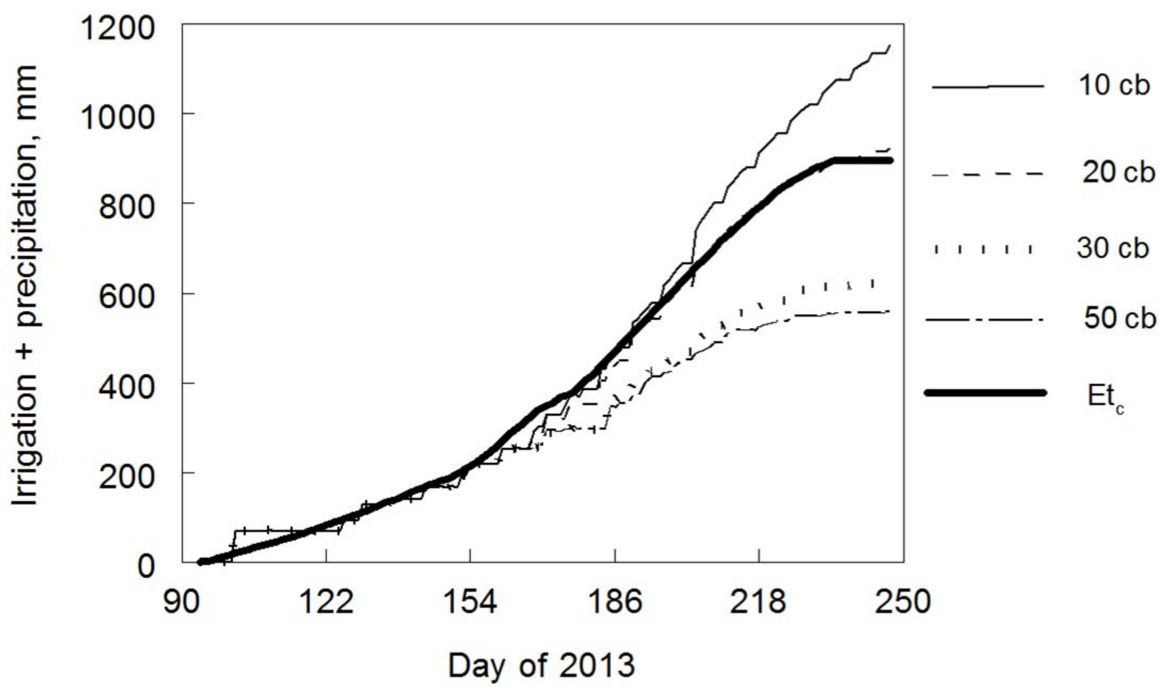

Figure 2. Water applied plus precipitation and evapotranspiration (Et_c) for onions irrigated at four soil water tensions. Malheur Experiment Station, Oregon State University, Ontario, OR, 2013.

Table 3. Onion yield and grade for two varieties under two plant populations in response to soil water tension. Malheur Experiment Station, Oregon State University, Ontario, OR, 2013. Continued on next page.

		Plant population			Marketable yield by grade								
Variety	Treatment	target	actual	Total yield	total	>4¼ in	4-4¼ in	3-4 in	2¼-3 in	Small	Bulb counts >4¼ in	Total rot	Bolting
		--- plants/acre ---		----------------------------- cwt/acre -----------------------------							#/50 lb	% by yield	%
Vaquero	10 cb	120,000	101,277	964.3	920.8	28.9	365.0	498.6	28.3	13.7	31.9	3.0	1.3
	20 cb	120,000	110,331	995.0	967.2	23.8	335.0	587.8	20.6	9.6	33.2	1.8	2.3
	30 cb	120,000	119,587	954.2	926.2	6.0	258.6	632.7	29.0	12.0	36.5	1.6	2.5
	50 cb	120,000	109,677	920.3	904.1	10.1	230.5	619.0	44.4	9.6	32.9	0.8	1.4
		average	110,218	958.4	929.6	17.2	297.3	584.5	30.6	11.2	33.6	1.8	1.9
	10 cb	450,000	343,036	1158.1	900.1	0.0	14.5	491.2	394.4	168.2		7.7	6.6
	20 cb	450,000	294,484	1196.6	922.5	0.0	23.5	616.0	283.0	154.8		10.2	9.5
	30 cb	450,000	314,494	1055.5	856.1	0.0	6.0	477.5	372.7	176.9		2.2	4.5
	50 cb	450,000	286,146	1029.0	839.5	0.0	0.0	436.8	402.7	153.5		3.7	5.0
		average	309,540	1109.8	879.5	0.0	11.0	505.4	363.2	163.3		5.9	6.4
	10 cb	average	222,157	1061.2	910.4	14.5	189.7	494.9	211.4	91.0	31.9	5.3	4.0
	20 cb		202,408	1103.5	943.1	11.0	167.3	603.0	161.9	87.8	33.2	6.3	5.9
	30 cb		217,041	1004.8	891.2	3.0	132.3	555.1	200.8	94.5	36.5	1.9	3.5
	50 cb		197,911	974.6	871.8	5.1	115.3	527.9	223.5	81.6	32.9	2.2	3.2
	average		209,879	1036.0	904.1	8.4	151.1	545.2	199.4	88.7		4.2	4.2
Swale	10 cb	120,000	103,598	1093.9	1081.6	15.1	325.2	715.4	26.0	4.9	34.7	0.7	1.7
	20 cb	120,000	127,431	990.3	963.6	7.6	159.2	762.7	34.1	11.1	35.0	1.6	2.6
	30 cb	120,000	114,301	897.3	888.0	2.9	142.1	700.7	42.3	7.0	37.9	0.3	1.6
	50 cb	120,000	103,062	789.5	784.3	0.0	45.1	681.9	57.3	5.2		0.0	1.1
		average	112,098	942.7	929.4	6.4	167.9	715.2	39.9	7.0		0.6	1.7
	10 cb	450,000	329,713	1159.8	932.1	0.0	0.0	515.5	416.6	172.6		4.2	7.8
	20 cb	450,000	331,838	1121.9	882.8	0.0	1.9	408.4	472.5	201.0		3.6	8.4
	30 cb	450,000	337,836	929.4	673.5	0.0	0.0	264.2	409.3	248.5		0.8	4.6
	50 cb	450,000	330,880	945.4	657.0	0.0	0.0	188.4	468.6	282.5		0.6	4.7
		average	332,567	1039.1	786.4	0.0	0.5	344.1	441.7	226.1		2.3	6.4
	10 cb	average	216,656	1126.8	1006.8	7.5	162.6	615.4	221.3	88.7	34.7	2.5	4.7
	20 cb		253,219	1071.3	913.8	2.9	62.4	544.7	303.9	128.0	35.0	2.8	5.7
	30 cb		226,069	913.3	780.8	1.5	71.1	482.5	225.8	127.8	37.9	0.5	3.1
	50 cb		206,615	867.4	720.7	0.0	22.6	435.2	262.9	143.8		0.3	2.7
	average		225,640	994.7	855.5	3.0	79.7	519.4	253.5	122.1		1.5	4.1

Table 3. Continued. Onion yield and grade averaged over two varieties under two plant populations in response to soil water tension. Malheur Experiment Station, Oregon State University, Ontario, OR, 2013.

		Plant population			Marketable yield by grade								
Variety	Treatment	target	actual	Total yield	total	>4¼ in	4-4¼ in	3-4 in	2¼-3 in	Small	Bulb counts >4¼ in	Total rot	Bolting
		--- plants/acre ---		------------------------------ cwt/acre ------------------------------							#/50 lb	% by yield	%
Average	10 cb	120,000	102,437	1029.1	1001.2	22.0	345.1	607.0	27.1	9.3	32.8	1.9	1.5
	20 cb	120,000	117,456	992.8	965.5	16.4	255.1	667.3	26.7	10.2	33.6	1.7	2.5
	30 cb	120,000	116,944	925.7	907.1	4.4	200.4	666.7	35.6	9.5	36.8	1.0	2.0
	50 cb	120,000	106,369	854.9	844.2	5.1	137.8	650.5	50.8	7.4	32.9	0.4	1.2
		average	110,802	950.6	929.5	12.0	234.6	647.9	35.1	9.1		1.2	1.8
	10 cb	450,000	336,375	1158.9	916.1	0.0	7.2	503.3	405.5	170.4		5.9	7.4
	20 cb	450,000	314,406	1156.7	901.3	0.0	12.0	505.3	384.0	179.5		6.7	9.1
	30 cb	450,000	326,165	992.4	764.8	0.0	3.0	370.9	391.0	212.7		1.5	4.6
	50 cb	450,000	306,480	987.2	748.2	0.0	0.0	312.6	435.6	218.0		2.2	4.6
		average	320,856	1073.8	832.6	0.0	5.6	423.0	404.0	195.1		4.1	6.4
	10 cb	average	219,406	1094.0	958.6	11.0	176.2	555.2	216.3	89.9	32.8	3.9	7.2
	20 cb		226,873	1087.4	928.5	7.0	114.9	573.8	232.9	107.9	33.6	4.6	9.0
	30 cb		221,555	959.1	836.0	2.2	101.7	518.8	213.3	111.1	36.8	1.2	4.6
	50 cb		202,074	921.0	796.2	2.5	68.9	481.5	243.2	112.7	32.9	1.3	4.8
LSD (0.05)													
Treatment			NS	82.9	93.0	NS	NS	50.7	NS	NS	NS	NS	1.1
Population			17,471	43.1	44.1	6.1	26.9	45.9	25.2	13.2	NS	1.2	0.7
Variety X Population			NS	NS	NS	NS	38.0	64.9	35.6	18.6	NS	NS	NS
Treatment X Variety			NS	NS	69.0	NS	NS	NS	NS	NS	NS	NS	NS
Treatment X Population			NS	NS	NS	NS	53.7	91.7	NS	26.3	NS	2.4	1.4
Treatment X Variety X Population			NS	NS	NS	NS	NS	NS	71	37	NS	NS	NS

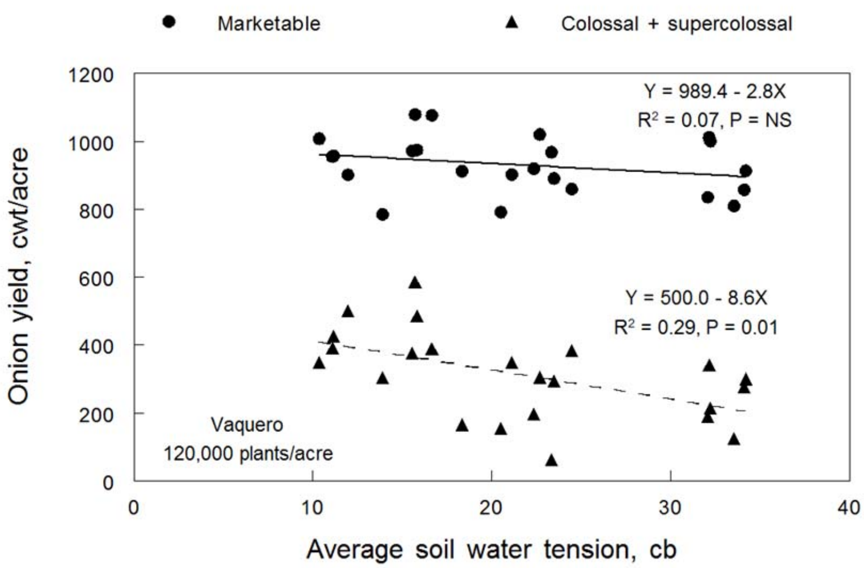

Figure 3. Marketable and colossal plus supercolossal onion yields in response to average soil water tension for Vaquero grown at 120,000 plants per acre. Malheur Experiment Station, Oregon State University, Ontario, OR.

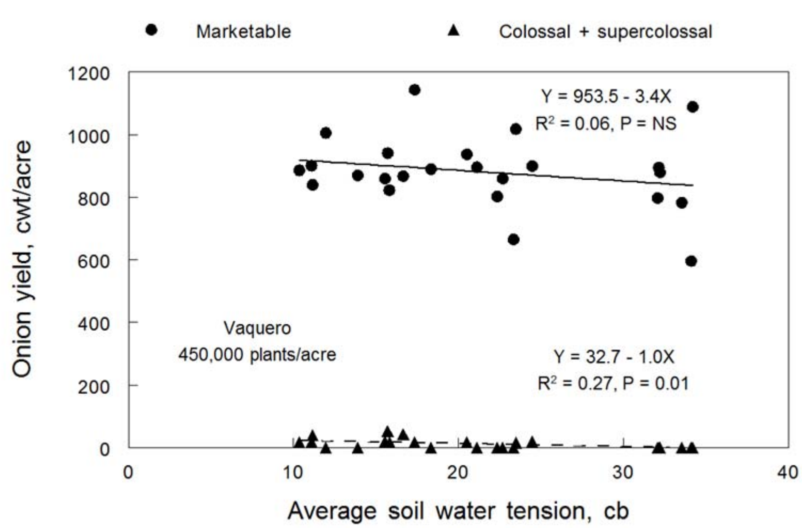

Figure 4. Marketable and colossal plus supercolossal onion yields in response to average soil water tension for Vaquero grown at 450,000 plants per acre. Malheur Experiment Station, Oregon State University, Ontario, OR.

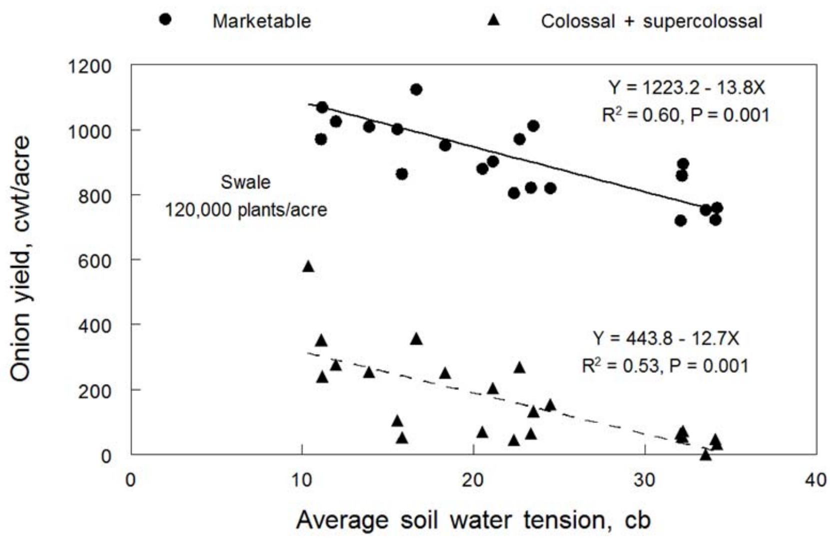

Figure 5. Marketable and colossal plus supercolossal onion yields in response to average soil water tension for Swale grown at 120,000 plants per acre. Malheur Experiment Station, Oregon State University, Ontario, OR.

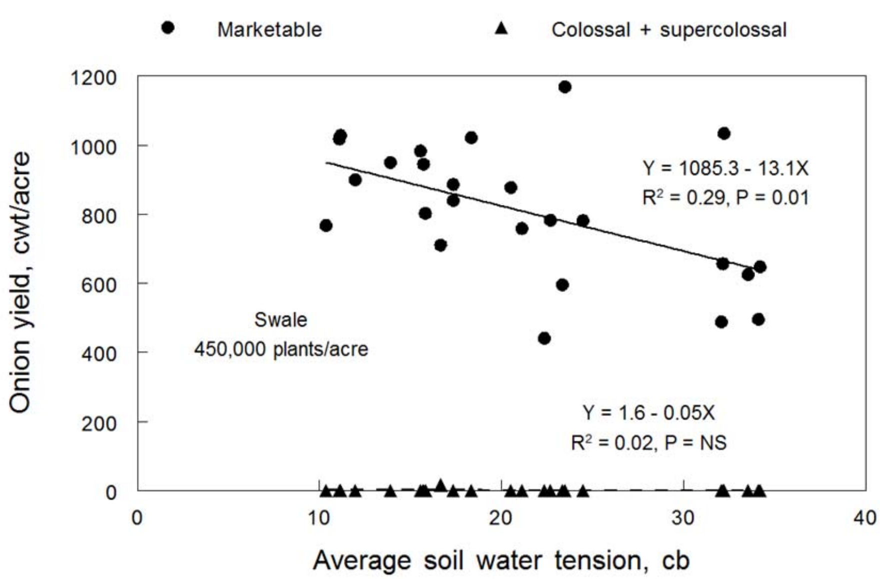

Figure 6. Marketable and colossal plus supercolossal yields in response to average soil water tension for Swale grown at 450,000 plants per acre. Malheur Experiment Station, Oregon State University, Ontario, OR.

Table 4. Onion single-center ratings and maturity for two varieties under two plant populations in response to soil water tension. Malheur Experiment Station, Oregon State University, Ontario, OR, 2013. Continued on next page.

		Plant population	Multiple center			Single center		Maturity July 25	
Variety	Treatment	target	large	medium	small	functional[a]	single	tops down	dryness
		plants/acre	%						
Vaquero	10 cb	120,000	2.2	6.5	23.2	91.2	68.0	0.0	0.0
	20 cb	120,000	3.0	6.5	20.1	90.6	70.5	0.0	0.0
	30 cb	120,000	2.8	5.8	17.7	91.4	73.7	0.0	0.0
	50 cb	120,000	3.4	5.9	15.8	90.8	75.0	0.0	0.0
	average	average	2.8	6.2	19.2	91.0	71.8	0.0	0.0
	10 cb	450,000	0.9	1.8	7.8	97.3	89.5	6.0	0.0
	20 cb	450,000	1.0	3.1	11.5	95.9	84.5	4.7	0.0
	30 cb	450,000	0.0	0.0	2.0	100.0	98.0	56.3	0.0
	50 cb	450,000	0.0	1.5	8.9	98.5	89.6	67.0	2.6
	average	average	0.5	1.6	7.5	97.9	90.4	33.5	0.7
	10 cb	average	1.5	3.9	14.7	94.6	79.9	3.8	0.0
	20 cb		1.9	4.7	15.4	93.5	78.0	2.5	0.0
	30 cb		1.4	2.9	9.9	95.7	85.8	32.1	0.0
	50 cb		1.5	3.4	12.0	95.1	83.1	37.2	1.4
	average		1.6	3.7	13.0	94.7	81.7	18.9	0.4
Swale	10 cb	120,000	2.2	6.0	20.6	91.8	71.2	0.0	0.0
	20 cb	120,000	1.1	5.8	26.4	93.1	66.7	1.4	0.0
	30 cb	120,000	4.0	7.3	20.1	88.7	68.6	0.0	0.0
	50 cb	120,000	3.7	6.5	18.5	89.8	71.3	0.0	0.0
	average	average	2.8	6.4	21.4	90.8	69.4	0.4	0.0
	10 cb	450,000	0.5	3.1	15.7	96.5	80.8	1.0	0.0
	20 cb	450,000	0.3	2.6	12.6	97.1	84.5	10.0	0.0
	30 cb	450,000	0.4	2.5	10.5	97.2	86.7	51.7	0.0
	50 cb	450,000	0.0	1.6	8.5	98.4	89.9	85.0	2.5
	average	average	0.3	2.4	11.8	97.3	85.5	36.9	0.6
	10 cb	average	1.3	4.5	18.1	94.1	76.0	0.5	0.0
	20 cb		0.7	4.1	19.0	95.3	76.3	5.7	0.0
	30 cb		2.2	4.9	15.3	92.9	77.6	25.8	0.0
	50 cb		1.9	4.0	13.5	94.1	80.6	42.5	1.3
	average		1.5	4.4	16.5	94.1	77.6	18.6	0.3

Table 4. Continued. Onion single-center ratings and maturity for two varieties under two plant populations in response to soil water tension. Malheur Experiment Station, Oregon State University, Ontario, OR, 2013.

		Plant population	Multiple center			Single center		Maturity July 25	
Variety	Treatment	target	large	medium	small	functional[a]	single	tops down	dryness
		plants/acre	%						
Average	10 cb	120,000	2.2	6.2	21.8	91.5	69.8	0.0	0.0
	20 cb	120,000	2.0	6.1	23.3	91.8	68.6	0.8	0.0
	30 cb	120,000	3.6	6.7	19.2	89.8	70.6	0.0	0.0
	50 cb	120,000	3.6	6.2	17.4	90.2	72.8	0.0	0.0
	average	average	2.8	6.3	20.4	90.8	70.4	0.2	0.0
	10 cb	450,000	0.7	2.4	11.7	96.9	85.2	3.5	0.0
	20 cb	450,000	0.6	2.9	12.0	96.5	84.5	7.4	0.0
	30 cb	450,000	0.2	1.5	7.1	98.3	91.2	53.5	0.0
	50 cb	450,000	0.0	1.6	8.7	98.5	89.8	76.8	2.5
	average	average	0.4	2.1	9.9	97.5	87.7	35.3	0.6
	10 cb	average	1.4	4.2	16.5	94.4	77.9	1.9	0.0
	20 cb		1.3	4.4	17.2	94.4	77.2	4.2	0.0
	30 cb		1.9	4.1	13.1	94.0	80.9	28.2	0.0
	50 cb		1.7	3.8	12.8	94.5	81.7	40.2	1.3
LSD (0.05)									
Treatment			NS	NS	NS	NS	NS	13.3	NS
Population			0.9	1.0	2.5	1.7	3.5	5.4	NS
Treatment X Population			NS	NS	NS	NS	NS	10.7	1.4
Treatment X Var. X Pop.			NS	NS	7.0	NS	9.9	NS	NS

[a] Single center plus small multiple center.

Crop Yield, Tube Longevity, and Economics with Shallow Subsurface Drip Irrigation (S3DI)

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Abstract. *The objectives were to determine crop yield, drip tube longevity, and economics when using S3DI with conventional, strip- and no-till regimes. Drip tubing was buried about 3-cm in 2006 and left in the field for 5 years for strip- and no-till areas and removed, stored, and reinstalled in conventional tilled. Crop rotation was cotton (Gossypium hirsutum), corn (Zea mays, 3 years), and peanut (Arachis hypogaea). There was no difference in cotton lint yield within tillage treatment. Irrigated lint yield was 2.4 times greater than non-irrigated. There was no difference in irrigated corn grain yield due to tillage practices or time (years). Irrigated corn yield was 5.8 times greater than nonirrigated yield. Irrigated peanut yield was not different across tillage treatments but was 2.6 times greater compared with non-irrigated yields. For tube longevity, conventional tilled areas had less tube repairs compared with either strip- or no-tilled regimes. Thinner wall tubing had 3.5 times more holes compared with the thicker wall tubing. The "cost to repair" versus "cost to replace" tubing indicates replacement at about 5.8 years. There was less production expenses for strip- and no- till compared with conventional tillage. Strip- and no- till practices seem to be the most economical for S3DI.*

Keywords: drip irrigation, crop yield, strip tillage, no-tillage,

Drip irrigation has been used to irrigate vegetables and high value crops for many years due to its simplicity of design (Bucks et al., 1974; Hanson et al., 1997). Drip irrigation can precisely deliver water, nutrients, and chemicals to the crop root zone. Previous research has shown that surface drip irrigation (SDI) can be installed with low initial investment and labor, used on a variety of crops, and can increase crop yield compared with nonirrigated areas (Sorensen et al., 2008; Sorensen et al., 2009). Burying the drip tubing 5-cm below the soil surface (shallow subsurface drip irrigation – S3DI) can significantly reduce rodent damage (Sorensen et al., 2007). Yield potential of irrigated crops using S3DI was over 2, 3, and 7 times greater than nonirrigated crops of peanut, cotton, and corn, respectively, depending on yearly precipitation timing and amount (Sorensen et al., 2010). The increased yield and eventual gross revenue was great enough in the installation year to cover the cost of the in-field portion of the S3DI system expenses compared with the nonirrigated revenue (Sorensen et al., 2010).

Conventional tillage consists of mixing or burying plant residue into the soil for quicker decomposition and in some cases may be critical for pest control for the upcoming crop (Boyle, 1956). Tillage not only buries plant debris but also levels the soil surface in preparation for other tillage operations and the comfort of the equipment operator. Conventional or clean tillage provides a clean, smooth, soil surface conducive for ease of operation during planting, pesticide applications, and eventual harvest. Conventional tillage may have benefits for the operator's comfort and ease of other operations but has added expense for fuel, labor, equipment, and time. Tillage also has the added problem of increased soil moisture loss that may be critical for crop emergence in drought situations.

Strip-till is a form of conservation tillage that only disturbs a small strip of soil where the crop is planted (Johnson et al., 2001) and can be an effective management tool to reduce crop production expenses. However, the acceptance of strip-till, especially in peanut, has been slow due to grower concerns of increased plant or soil-borne diseases and ultimately loss of yield. The loss of peanut yield to *Sclerotium rolfsii* (stem rot) and the recommendation to bury plant debris (which acts as a pathogen host when left on the soil surface) has become traditional with growers since the late 1950's (Boyle, 1956).

No-till is another form of soil conservation where a crop is planted in the existing debris of the previous crop. No-till as the name implies, does not have any tillage investment costs. Depending on the amount of crop debris, additional row cleaners or cutting coulters may be installed on a planter in order to sow the new crop. Both strip- and no-till operations may be less expensive as management tools but may not always be cost effective due to possible lower yields and possible cost of additional herbicides to control troublesome weeds.

Subsurface and surface drip irrigation on crop rotations in the southeast has been effective in increasing crop yield when compared with nonirrigated crop production (Sorensen et al., 2000; Sorensen et al., 2008; Sorensen et al., 2009; Sorensen et al., 2010). The use of S3DI with conservation tillage techniques on agronomic crops and rotations could be of major interest in conserving water, reducing agronomic inputs, and possibly increasing on-farm revenue that would benefit the agricultural community.

If a grower implemented a conservation tillage technique, either strip- or no-till, then S3DI could be installed and maintained for multiple years which would be economical than removing the tubing on a yearly basis as describe previously (Sorensen et al., 2010). If tubing can be left in the field for multiple years and if crop yield increased as described above, then using S3DI may be economically feasible for traditional row crops in the southeastern U.S. This type of drip irrigation system would also be of interest to growers with small, irregular shaped fields where irrigation water from small domestic deep wells may be available, such as old homesteads. However, the crop yield response to S3DI along with strip- or no-till is unknown. Additionally, the useful life of the drip tubing installed near the soil surface (S3DI) where it is vulnerable to biological and mechanical damage is unknown. Similarly, the economic cost or benefit of using a more expensive, i.e., thicker wall tubing in these tillage situations has not been determined. The objectives of this research were to determine: 1) crop yield when using S3DI in conjunction with conventional, strip and no tillage, 2) longevity of drip tubing with various wall thicknesses to biological or mechanical damage, and 3) economic viability of S3DI with conservation tillage techniques.

Land Preparation and Crop Management

This research was conducted at the USDA-ARS Multi-crop Irrigation Research Farm in Shellman, GA during the 2006 through the 2010 growing seasons on a Faceville fine sandy loam (fine, kaolinitic, thermic Typic Kandiudults) with up to 3% slope.

The field for this research was 57 m wide by 61 m long. Crop rotation was cotton, corn (three years), and peanut. The field was separated into three sub-fields/plots for the tillage treatments of conventional, strip till and no till. Each sub-plot was 16.5 m wide by 61 m long. Each sub plot was divided into smaller sub-sub plots that consisted of drip tube wall thickness. Three tube wall thicknesses were tested within each tillage system replicated three times. Tubing wall thickness variables were 0.2, 0.25 and 0.38 mm. The irrigation system, drip tube laterals, and tube thickness will be described later.

In the first year, the whole field was prepared in the fall (2005) using the following tillage operations, disk harrowed, chiseled, row bedded and cultivated following fertilizer and herbicide application. A winter cover crop of wheat (*Triticum aestivum*) was planted across the entire field. The wheat crop was killed in early spring using glyphosate herbicides at recommended rate and timing.

Conventional tillage consisted of the following practices in order after the first year described above: 1) disk harrow (fall), 2) chisel plow (fall), 3) row bedding (spring), and 4) field cultivate (spring) to incorporate fertilizer and/or pre-plant herbicides. Drip tubing was installed on the conventionally tilled area immediately following plant emergence. Following cotton and corn harvest, drip tubing in the conventional tilled area was removed from the soil, rolled, and stored on spools using experimental equipment. Following drip tube removal in the conventional plot area, all crop residues were mowed at 20 cm height with a rotary mower and plant stalks were pulled with a stalk puller (Arizona Drip Systems, Coolidge, AZ). In early spring, the conservational tillage part of the project was strip tilled (Brown Manufacturing Corp., Ozark, AL 36360) creating a 20-cm wide planting bed. Nothing was done with the no-till area prior to planting.

At the end of the project, just prior to peanut harvest, all drip tubing was removed using experimental equipment (USDA-ARS-National Peanut Research Laboratory) that lifted the tubing from the soil and laid it on the soil surface for evaluation. Following tube evaluation (described later), the drip tube laterals were rolled for disposal.

All crops were planted with the same planter in all years. The planter had attached row cleaners used for strip- and no-till type conditions (Monosem, Inc. Edwardsville, KS and Yetter Manufacturing Company, Colchester, IL). Prior to planting cotton, 22 kg N ha^{-1} of dry fertilizer was applied along with other recommended fertilizer (phosphorus, potassium, and sulfur) as determined by soil test. Cotton was planted and harvested 2006. Cotton cultivar DPL555BR was planted at a density of 106,300 seeds ha^{-1}. A total of 60 kg N ha^{-1} (yearly total 82 kg N/ha) was applied to the soil surface in three split applications using 28-0-0-5 liquid fertilizer. Nitrogen fertilizer was applied prior to either an irrigation or precipitation event. Herbicides were applied as recommended by field scouting. Cotton was picked using a 2-row spindle picker. The picker was modified to collect cotton in a large mesh bag. The sample was weighed and a small subsample (0.3 kg) was used to determine lint out-turn on a table top gin. A 0.2 kg sub-sample was collected from each ginned sample to determine lint quality. Gross revenue was determined using the average price received for lint cotton each year cotton was grown. The price used to determine gross revenue was \$1.473 kg^{-1} (7).

Corn was planted in 2007, 2008, and 2009. Corn (DeKalb 6972RR) was planted at a density of about 79,000 seeds ha^{-1}. Prior to strip tillage and planting, 22 kg N ha^{-1} of dry fertilizer and the recommended rate of other fertilizers (phosphorus, potassium, and sulfur) were applied as determined by soil test. Liquid fertilizer, 28-0-0-5, was applied on the soil surface in three split applications for a total of 225 kg N ha^{-1} (yearly total 245 kg N ha^{-1}). Fertilizer was applied prior to an irrigation or precipitation event to aid in nitrogen movement into the soil. Herbicides were applied at recommended timing and rates determine by field scouting. Corn was harvested with a 4-row combine. Each sample was discharged from the combine into a weigh buggy. After weighing, a 2-kg subsample was collected from the weigh buggy and tested for moisture and test weight. Gross revenue was determined using the average price received for corn grain across the 2008 and 2009 cropping season of \$0.181 kg^{-1} (7).

Peanut was planted in 2010. Peanut cultivar, Georgia 06G, was planted in a single row seeding pattern with a density of 20 seeds m^{-1} as recommended for reducing the risk of Tomato Spotted Wilt Virus (TSWV) (2, 3). Aldicarb (2-methyl-2-(methylthio)-O-((methylamino)carbonyl) oxime) was applied in each crop row at recommended rates. Boron was applied to foliage twice each season for a total of 0.56 kg B ha^{-1}. Fungicides, insecticides, and herbicides were applied at recommended rates and timing as determined by field scouting during the growing season for disease, insect, and weed control. Peanut maturity was determined by the hull scrape method (Williams and Drexler, 1981). Yield rows were dug with a 2-row inverter, allowed to field dry, and harvested with a two row field combine. Pod yield, farmer stock grade, and kernel size distribution were determined after being mechanically dried, weighed, and adjusted to 7% moisture (wet basis) and using screens specified in USDA grading procedures (USDA, 1993). Gross revenue was determined using the average market price for 2010 of \$0.45 kg^{-1} (http://www.nass.usda.gov/Publications/Todays_Reports/reports/pnpr4310.pdf).

Irrigation System Design and Management

Irrigation water was supplied through a series of 5 cm diameter flexible hose (Sun-Flow Layflat SFAF2-300V; Jain Irrigation, Inc. Fresno, CA) with drip tubing connected to the flexible hose using plastic barb adapters (Agricultural Products, Inc., Ontario, CA, Model 400B-06-LS). The drip tubing was 16 mm diameter with wall thickness of 0.2, 0.25 and 0.38-mm (Netafim USA, Fresno, CA). All drip tubing had the same flow rate per emitter. All drip tube laterals were spaced in alternate row middles, 1.83-m apart. Drip tubing was buried an average of 3-cm soil depth. The irrigation water was from a deep well, filtered using a manually cleaned 120 mesh (130 micron) disk filter (Netafim USA, Fresno, CA) and received no chemical amendments during any irrigation events to begin or end the season. Operating pressure was regulated at 100 kPa (Senninger Irrigation, Inc., Clermont, FL, Model PR-HF-15) at the head of the field (200 kPa at the pump) and water flow rate and total water applied (liters/min and total liters) was measured with a mechanical water meter.

Irrigation events for cotton, corn, and peanut were determined by soil moisture sensor data in association with IrrigatorPro® (Davidson et al., 1990; Davidson et al., 1991; Lamb et al., 1993). The average total water applied at each irrigation event was about 3 to 3.5-cm. Meteorological data were collected with an electronic weather station with precipitation being verified with an onsite manual gauge. A nonirrigated conventional and/or strip-tilled plot was maintained as a control.

In the conventional tillage area, drip tubing was removed following crop harvest and stored. Tubing was reinstalled following planting and crop emergence. In the conservation tilled areas, the drip tubing was left in the field throughout the entire project. Each spring, after planting, the irrigation system was activated and the laterals checked for leaks. Repairs were made by cutting out the section of thin wall tubing with the hole using scissors, then inserting thick walled tubing (1.2 mm wall thickness) inside the thin wall tubing, and clamping each end with stainless steel wire ties (Sorensen et al., 2007). The number of repairs was to be documented to identify the number of hole/repairs made during each growing season. However, various personnel were used to make repairs within and across years such that yearly repair activities were not adequately documented. The following procedure was used to document tube longevity. Prior to peanut harvest, each tillage treatment was separated into four equal lengths of 15.25 m. Each drip lateral was evaluated within these smaller field lengths to document total number of repairs and total number of existing holes. Splitting the field into four equal distances would document if the was an "edge effect" of biological damage, i.e., rodents moving in from the edge of the field and causing damage compared with rodent damage in the middle of the field (Sorensen et al., 2007).

The expense to repair drip tubing was documented in previous research (Sorensen et al., 2007) at \$0.67/repair and was used to calculate tubing repair costs in this research. We recognize that labor expense, along with repair equipment has increased in cost and may be higher than previously documented.

Treatment Expenses

Table 1 shows the expenses for various tillage operations, infield irrigation system, and tubing removal and installation. All management practices for seed rate, irrigation amount, pest control, fertility, and harvest procedures were the same across tillage and irrigation treatments. Table 1 shows expenses for conventional, strip- and no-till operations were different from each other. We see that no-till treatments had the lowest expenses attribute to tillage, followed by strip-till, with the greatest expense in the conventional tilled treatments. Conventional tilled expenses were over 16 times more expensive compared with no-till treatment. Strip-till treatment was 4 times more expensive compared with the no-till treatments.

In 2006 the initial irrigation system was installed. Material expenses needed to install the infield irrigation system was \$377 ha^{-1} for drip tubing, \$32 ha^{-1} for barbed adapters, and \$26 ha^{-1} for flexible hose for a total of \$435 ha^{-1}. The expenses for irrigation conveyance system to the field, filters, electronic controls, irrigation pump, valves, water meters, and pressure regulators were not included with the installation cost.

The cost of removing and installing the drip tubing in the conventional tilled plots was assumed to be the same across all years. There was not a cost assigned for tubing storage. There was also not a cost assigned for equipment since the equipment is experimental and has no commercial value. Tubing retrieval and installation involved the use of a tractor, specialized equipment for retrieval and installation (both experimental), and a minimum of two people. The retrieval and installation equipment was only designed to handle one drip tube lateral at a time. Commercial drip tube installers and retrievers will typically handle multiple rows decreasing time and energy across the field. For this research, the use of one row equipment was utilized, and the expenses modified to simulate multiple (3-lateral) equipment. The approximate time to install or retrieve the tubing in the spring or fall, respectively, was about 0.75 hr on the conventionally tilled treatment. The estimated time with “three lateral equipment” would be about 0.25 hr for an estimated time of 2.5 hrs ha^{-1} or a total of 5 hr ha^{-1} for both installation and retrieval per year. We used a labor expense of \$10 hr^{-1} and an estimated fuel consumption of 3.1 L hr^{-1} (fuel cost = \$1.00 L^{-1}). Total estimated expense of fuel and manpower to retrieve and install tubing was about \$66 ha^{-1} yr^{-1}.

The expense to repair drip tubing was documented in previous research (Sorensen et al., 2007). They showed an approximate cost of \$0.67 per repair. In 2006 labor expense was about \$8/hr; however, we valued labor expenses closer to \$10 which would increase the cost of tubing repair. However, calculations for tubing repairs were kept at the \$0.67 per repair.

Crop yield, tillage type, gross revenue, net revenue and interactions of tillage by yield, gross, and net revenue were analyzed by crop year using a general analysis of variance procedure (Statistix9, Tallahassee, FL). The drip tube laterals were analyzed by tube thickness for tillage, field location (edge or middle), holes and repairs, and total expense. Tukey’s mean separation range test was used to show differences between means ($P \leq 0.05$) when *ANOVA F*-test showed significance. Total net income for each tillage treatment was totaled across years and tillage treatment to identify best economic benefit.

Crop Yield Analysis

Each crop will be discussed independently. Cotton in 2006 received 394 mm of rainfall and 322 mm of irrigation (Table 3). There was no cotton lint yield difference within irrigation or by tillage treatment (Table 4). Irrigated cotton lint yield was greater than the non-irrigated cotton yield by an average 2.4 times. Within the nonirrigated regimen, the non-irrigated strip-tilled treatment had higher lint yield than the non-irrigated conventionally tilled treatments by almost double (1.8 times). These data are consistent with other research using subsurface drip irrigation (SSDI). Texas data shows that conventionally tilled cotton had the same yield as that with no-tilled (cotton planted in rye) two out of three years. The three year average showed no difference between conventional and no-till systems when irrigated using SSDI with laterals spaced 1 or 2-m distance (Sij et al., 2010).

Corn was raised in 2007 to 2009 inclusive. Rainfall data show that 2009 had double and almost triple the rainfall in 2008 or 2007, respectively. The effect of rainfall is directly shown in the nonirrigated treatments where there were no corn yield recorded for 2007 or 2008 in any tillage treatment. In 2009 within the non-irrigated regime, only the conventional tilled treatment was planted and crop yield was

1976 kg ha^{-1} which was much lower than the irrigated treatments. Within the irrigated treatments, there was no corn yield difference between tillage practices. The average corn yield across all three years was 11490 kg ha^{-1}. These data are similar to current agronomic yield values in GA that suggest conservation tillage practices (strip- or slit- tilled) are equal to or slightly better than those with conventionally tilled treatments and yield from no-tilled treatments was lower than either conventional or conservational tilled practices (Lee, 2010).

In 2010, there was no peanut yield difference due to tillage treatments. Irrigated peanut yield was 2.6 times greater than the non-irrigated peanut yield. Peanut grade values show that both the strip and no-tilled treatments had higher grade values (Total Sound Mature Kernels - TSMK) compared with the conventionally tilled treatment. These data agree with previous research which showed that peanut production with strip-tilled treatments using various crop covers did not have any clear yield advantage over conventionally tilled treatments (Grichar, 1998; Prostko, 2001; Sorensen et al., 2010), but strip-tilled treatments has been found to reduce yield losses from some diseases (Grichar, 1998; Johnson et al., 2001).

Drip Tube Longevity

The analysis of repairs and holes counted prior to peanut harvest is shown in Table 5. These probability values indicate there were different amounts of repairs when comparing tillage treatments, tubing wall thicknesses, and tillage by wall thickness interactions but with field location (edge versus middle of the field). The number of repairs within the tillage treatments show significantly less repairs in the conventionally tilled treatment compared with either strip- or no-tilled treatment. This was probably due to the time of “infield exposure” where the conventionally tilled area had the tubing removed resulting in less time available for biological or mechanical damage. Thus, tubing repair costs for the conventional tillage was a third less when compared with either strip or no-tilled practices.

The thinner wall thickness (0.20-mm) had 3.5 times more holes/repairs compared with the other thicker wall drip tubing. Consequently, the thinner wall thickness had higher associated repair costs compared with the other thicker wall tubing. Thinner wall thickness having more repairs or holes is just opposite of previous research (Sorensen et al., 2007) which showed fewer holes with thinner tubing compared with thicker tubing.

Tillage by wall thickness interaction shows that most repairs occurred with the thinner walled tubing in the strip- and no-tilled treatments and not in the conventional treatment. Again more holes or repairs in strip- or no-tilled treatments can be explained by “field exposure” but does not explain why the thicker walled tubing with the same time exposure had less damage than the thinner walled tubing. Another possible reason for more damage in the thinner walled tubing could be from mechanical mowing (commonly called “bush-hogging”) of corn and cotton stalks. During mechanical mowing events, it was notice that an “air vacuum” occurs under the equipment with the rotating blade lifting plant debris and soil from the soil surface and in some areas removing enough soil to expose the drip tubing. At this time, fast moving plant debris could pierce the thinner walled drip tubing but not the thicker walled tubing. It is unknown if this occurred, however, it was noticed by personnel, small pin-like holes in the thinner tubing following a mechanical mowing. More data would need to be collected to determine if more holes occur in tubing with mechanical mowing in which case the tubing would need to be buried deeper or the tractor operator should not have the mower deck close to the soil surface.

Table 6 shows the total number of repairs and holes per hectare counted over the 5-yr life of the project. Previous research indicated that the “break even” point for the cost to repair holes versus replacement cost of drip tubing was about 500 holes ha^{-1} (Sorensen et al., 2007). The total number of holes in the conventionally tilled treatment averaged across all wall thickness was 58 holes yr^{-1} with a projected life to replace lateral at 8.6 years. The no-till treatment averaged 98 holes yr^{-1} or about 5.1 years and strip-till treatment averaged 136 holes yr^{-1} or 3.7 years before tubing cost to repair was greater than the cost to replace. The average time for tube replacement across all tillage regimes and wall thickness was about 5.8 years. It would seem plausible that 5-yrs would be a good time to replace tubing, depending on management as noted above with mechanical mowing or other mechanical type tillage practices used in the field. With good management in keeping the tubing buried (or remove and re-install), the drip tubing could last up to 8 years before replacement is needed.

Partial Net Revenue

Since there was no difference in crop yield by year or tillage treatment, there was also no difference in gross revenue within crop specie (year) or tillage treatment. There were large differences between irrigated and non-irrigated gross revenues by year. This was especially true in corn where yields were zero in 2007 and 2008 due to drought and gross revenue in those same years was also zero.

The total gross revenue over the life of the project averaged over all the irrigated treatments was \$10313 ha^{-1}. Numerically, conventional tillage had greater gross revenue, followed by strip- till, then followed by no-till. When subtracting expenses due to irrigation, tillage, tubing repair and tubing removal and re-installation (conventional tillage only), the numerical order changed such that the no-till had higher dollar value return per area (\$9372 ha^{-1}), followed by strip-till (\$9350 ha^{-1}), then followed by conventional till (\$8897; Table 7).

The cost of tillage was significantly greater for the conventionally tilled treatments compared with strip- or no-tilled treatments. The cost of drip tube repairs was 2.5 times greater for both strip- and no- tilled treatments compared with conventionally tilled treatment. The cost of tillage may have been less for strip- and no-till treatments, but the extra cost of tubing repairs brought the total expenditure to values similar to conventional tillage. Conversely, the yearly cost of tubing removal and installation with the conventionally tilled treatments decreased the net returns below that of strip- or no-till treatments. Overall, there was less expense with strip- and no-till treatments with S3DI compared with conventionally tilled treatments and the yearly removing and reinstalling drip tubing.

As to which tillage regime is recommended for S3DI, strip- and no-till seem to be the most economical, however, the final decision should be left to the grower due to his personal preferences for tillage equipment and style of management. Each tillage type has its own unique challenges, conditions, expenses and results and must be evaluated by the grower.

Conclusions

There was no yield difference within irrigation or tillage treatment for cotton, corn, or peanut. Yield in all three crops were greater with irrigation compared with non-irrigation in all treatments tested.

There were significantly less repairs in the conventional tillage treatment than other treatments probably due to less exposure time in the field. There were more repairs in the thinner wall tubing than thicker tubing probably due to mechanical damage from mowing crop debris and operator error of lowering the “bush-hog” too close to the soil surface.

The cost of tillage was significantly greater for the conventional tillage compared with strip tillage or no tillage. The cost of tillage may have been less for strip and no tillage but the extra cost of tubing repairs brought the total expenditure to values similar to conventional tillage. The cost of yearly tubing removal and installation was greater for conventional tillage such that the partial net return to the grower was numerically less compared with strip or no tillage operation system. Overall, there was less expense with strip and no tillage with S3DI compared with conventional tillage with the yearly removing and reinstalling the same drip tubing.

Overall, the use of S3DI is recommended for strip and no till situations with cotton, corn and peanut for best yields and economic returns. The average time for tube replacement across all tillage regimes with a cotton-corn-peanut rotation would be about 6 years provided cotton and corn was raised in the first 5 years and peanut in the last year of the rotation.

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Table 1. Expenses documented or simulated for various management techniques of conventional and conservation tillage, drip irrigation installation and retrieval. Operations that were the same for all tillage treatments are not shown. In fall 2005 all plots were prepared the same with winter wheat being planted across all plots. CT= conventional tillage, ST = strip tillage, and NT = no tillage.

Treatment	**CT**	**ST**	**NT**
		$/ha	
Disk harrow[†]	20	--	--
Chisel plow	19	--	--
Row bedding	25	--	--
field cultivate	22	--	--
Strip tillage	--	28	--
Spray – spring	--	9	9
Tubing removal	33	--	--
Tubing install	33	--	--
Yearly total	152	37	9
5-year total	760	185	45

[†] Expense values determined from University of Georgia crop budgets with $10/hour labor and $1.0/L fuel costs.
www.ces.uga.edu/Agriculture/agecon/budgets/budgetsexcel.htm

Table 2. Crop, year, irrigation, rainfall, and time period of rainfall measured during the growing year for 2006 to 2010.

Crop	**Year**	**Irrigation**	**Rainfall**	**Time period**
		--------- mm	**--------**	
Cotton	2006	322	394	01May - 15 Oct
Corn	2007	480	276	15 Mar-15 Aug
Corn	2008	380	388	15 Mar-15 Aug
Corn	2009	314	766	15 Mar-15 Aug
Peanut	2010	224	451	01 May - 01 Oct

Table 3. Crop yield measured by year for irrigated and nonirrigated tillage treatments. CT= conventional till, ST = strip-till, and NT = no-till.

Treatment		**2006 Cotton**	**2007 Corn**	**2008 Corn**	**2009 Corn**	**2010 Peanut**
irrigated			**yield – kg ha^{-1}**			
	CT	1769a	11452a	11889a	10963a	3854a
	ST	1775a	11001a	12343a	11059a	3079a
	NT	1718a	11571a	12392a	10744a	3307a
nonirrigated						
	CT	515b	0	0	1976	1288
	ST	957b	0	0	--†	--

Means within column and treatment followed by the same lower-case letter are not significantly different (p=0.05).
† = Not planted

Table 4. Gross revenue received by crop and by year for irrigated and non-irrigated tillage treatments and total gross revenue for the copping system. CT= conventional till, ST = strip-till, and NT = no-till.

Treatment	Cotton	Corn	Corn	Corn	Peanut	Total
irrigated			**$ ha^{-1}**			
CT	2605a	2027a	2152a	1984a	1734	10503
ST	2615a	2048a	223a4	2002a	1386	10284
NT	2530a	1947a	224a3	1945a	1488	10153
nonirrigated						
CT	758	0	0	358	580	1696
ST	1409	0	0	--†	--	1409

Means within the same column and treatment with the same lower-case letter are not significantly different (p=0.05).
† = Not planted

Table 5. Probability values for holes and repairs by tillage (T), wall thickness (W), and field location (L) of drip tubing in the field.

Source	DF	Holes P value	Repairs P value
Tillage (T)	2	0.3863	0.0059
Wall (W)	2	0.1548	0.0000
Location (L)	3	0.9542	0.2117
T*W	4	0.2131	0.0494
T*L	6	0.1125	0.3192
W*L	6	0.7694	0.7092
T*M*L	12	0.3902	0.4982

Table 6. Number of repairs, holes, and total repairs and holes counted at the end of the project by tillage treatment and tube thickness. CT= conventional till, ST = strip-till, and NT = no-till.

Tillage treatment	Tube thickness	Repairs	Holes	Total	Average holes
	mm	------------ ha^{-1}		--------------	yr^{-1} ha^{-1}
ST	0.20	987a	239a	1226	245
NT	0.20	837ab	120a	957	191
CT	0.20	269c	150a	419	84
NT	0.25	299bc	0a	299	60
CT	0.25	240c	150a	389	78
ST	0.25	209c	329a	538	108
NT	0.38	209c	0a	209	42
ST	0.38	209c	60a	269	54
CT	0.38	0c	60a	60	12

Means in the same column followed by the same lower-case letter are not significantly different (p=0.05).

Table 7. Total gross revenue, tillage expense, irrigation expense, tubing repair expense, and partial net revenue compared with tillage treatment over the life of the project. CT= conventional till, ST = strip-till, and NT = no-till.

Tillage treatment	**Total gross revenue**	**Tillage expense**	**Irrigation expense**	**Repair expense**	**Partial Net revenue**
			$/ha		
CT	10503	760	732†	114	8897
ST	10284	185	435	314	9350
NT	10153	45	435	301	9372

† $435 initial S3DI installation plus $297 for estimated total yearly cost to install and remove tubing in conventionally tilled treatments.

Predicting emitter sensitivity to clogging: a focus on the biological component

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Abstract. *A standard test for prediction of emitter sensitivity to clogging has not been developed yet. One conventional test procedure developed by the IRSTEA, France exists but it predicts emitter sensitivity to physical clogging only. This study was carried out to contribute towards developing a modified clogging test that would consider both physical and biological processes in emitters clogging. In this regard, a microirrigation test rig was constructed containing three types of pressure compensated emitters arranged in four replications inside an environmental chamber. Two tests were conducted, one according to the IRSTEA schedule; and the other according to a modified procedure developed to introduce biological load. The modified test included recycled water and was formed on the principle that biofilms should be allowed to develop and attain maturity during the test span. The results suggest that clogging due to biofilm growth is always a quicker process than clogging by physical particles alone. Emitters were quick to show signs of clogging in the modified test, while all the emitters managed to pass the IRSTEA test. In case of biofouling, particles were found to be trapped into the slimy bacterial biofilms at the emitter's section of entry. In physical clogging, however, particles were found to be passing through the emitter's section of entry, travelling along the labyrinths and settling at the end basin. In almost all the cases, the IRSTEA recommended filtration requirements were found to be overestimating the appropriate filter sizes.*

Keywords. Emitter clogging, sensitivity test, biological clogging, biofouling, clogging test, drippers, recycled water, wastewater irrigation.

Backdrop

Performance of an unclogged emitter in a drip irrigation system is largely dependent on the design characteristics. Modern design tools have made it possible to design emitters with greater precision than ever. Once an emitter is made it needs to go through several processes of testing (Zhang et al., 2010) so as to ensure that its performance is up to the expected standard. The results from these tests and evaluations are usually posted with the product catalogue by the manufacturers, and irrigators completely rely on them. For sustainable drip practice, it is crucial that this information is obtained by following an appropriate and, where possible, a standard procedure. In the emitter manufacturing industry, there are set standards and procedures to evaluate certain features of a product. One of such tests includes assessment of an emitter's anti-clogging performance. The test methods to assess this property of newly manufactured emitters are but few. A test method is known to be in the process of development (Mecham, 2012) by the ISO through its technical working groups (SC18\TC23\WG5) since 2003 (Nájera, 2013). This work is anticipated to be divided into two parts, one concerning a short duration test method, the second on a longer term basis. This work is contributed by a French organisation, IRSTEA (formerly Cemargref) which developed the first clogging test procedure in 1972 at the Center for Irrigation Equipment in Le Tholonet (Decroix, 1990). It was mainly developed to obtain practical recommendations for the selection of suitable filter sizes. The test method being developed by the ISO is also expected to concentrate on the physical clogging only. Both the IRSTEA and the ISO propose to use an increasing load of solid particles to be mixed with water so as to test the emitter sensitivity in their tests (Zhang et al., 2010). The performance of emitters is then to be compared with the reference characteristics established under clean water condition through four or eight stages of experimentation. Every stage is categorised by a specific amount of operating and non-operating hours. The time for non-operation is provided for the particles to settle in their flow path. The IRSTEA procedure has established five levels of sensitivities (Di Maiolo, 2012) based on the emitter's ability to withstand certain level of physical load in water (four stages of increasing dirtiness). Such categorisation of anti-clogging behaviour based on physical clogging alone is a serious miscalculation of the actual fouling process, especially under reclaimed water irrigation (RWI) where biofilms play a crucial role in clogging. Results and opinions from many long standing studies (Adin and Sacks, 1991; Camp, 1998; Nakayama and Bucks, 1991) including the more recent ones (Li et al., 2013; Puig-Bargués et al., 2010; Sánchez et al., 2014; Yan et al., 2009) also justify the importance of biological growth in the clogging process. Therefore, the fact that biofouling in RWI is far complex than physical blockage must be acknowledged and incorporated in any clogging test.

Biofouling is a popular term to describe emitter clogging when biological agents of are involved in the plugging process. The biomass that blocks the flow has been studied in recent years from multidisciplinary perspectives. Endeavours are known to have been carried out to expose the very fabric of the fouling biomass under irrigation schemes with recycled water ((Capra and Scicolone, 2005; Liu and Huang, 2009)), raw wastewater (Capra and Scicolone, 2007), storm water (Kunhikrishnan et al., 2012), groundwater (Jimenez, 2006; Pavelic et al., 2007) and even with human excreted urine (Zandee, 2012). From the available literature on this topic, it is possible to have a good understanding of the process of biofouling under specific conditions. A consensus (Oliver et al., 2012) seems to have been formed in the scientific community regarding the processes that govern formation of any clogging biomass. It has been well defined that physical (suspended solids), chemical (dissolved solids) and biological (microbes) quality of recycled water are the actual determinant of clogging (Lamm and Camp, 2007). The general agreement, however, is that neither of these parameters work in isolation to form the fouling material (Li et al., 2011). In fact, a sizable biomass emerges only when all three of them, at least two, work simultaneously (Lamm and Camp, 2007). It is also agreed that the biological component of recycled water is responsible for initiating the clogging phenomenon (Ravina et al., 1997). This means that physical parameters (suspended particles & chemical precipitates) may amplify the biomass once it is formed, but its initiation is definitely of microbial origin. This process of biomass development is often described by an adhesion-detachment-regrowth (ADR) model (Nicolella et al., 1997). To be able to fit into this model, suspended particles must need a place inside emitters where they can adhere to. In RWI schemes, biological growth provides this opportunity of assembly by secreting slimy gelatinous matter (Yan et al., 2009) known as biofilms. These microbial secretions are of slimy nature and attract many flowing particles on its periphery. Once a particle is attached to the exterior of biofilms, further microbial development takes place around the newly captured particle. Once in the exterior, a particle quickly finds itself inside a three dimensional matrix of biofilms (Hermanowicz, 1999). Such propagation of biofilms causes the whole biomass to grow in volume. As the size increases, the hydraulic shear force of water also escalates until a part of the biomass is detached from the main body to travel further downstream in the system. After losing some of its parts, the biofilm biomass regrows again until a substantial biomass blocks the emitter flow. Therefore, generation of biofilm-biomass is a different process than plugging by particles alone. None of the existing anti-clogging performance evaluation procedure considers this factor in their tests. This paper reports the results of two experimental studies carried out to contribute towards developing an appropriate emitter clogging test focusing on the biological components.

Test Principle

Incorporation of biological components in the clogging test is complex. The sources of complexity originate from the variable water quality and thermal condition although they can be managed if the test is contained in a controlled environmental. The main sources of complexity, however, come from the lack of information about the stages of growth and development of biofilms. For a specific water quality, the biofilm constituents were still not quantified until in a recent study, Oliver et al. (2014a) examined the reclaimed water biofilms at different stages of irrigation using biochemical techniques. The water used was treated with dissolved air flotation and filtration method followed by a onetime chlorination targeted for 1 ppm free chlorine. In an irrigation experiment for 760 hours with pressure compensating (PC) emitters, Oliver et al. (2014a) showed how cohesive bond of a clogging biomass changes with time. In their seven-stage experiment, the biofilms were obtained by destructive sampling from a large lot of emitters and examined for exo-polymeric substances (EPS) that form the biofilm matrix. The major EPS constituents i.e., exo-polymeric protein and polysaccharides were quantified at different stages of irrigation.

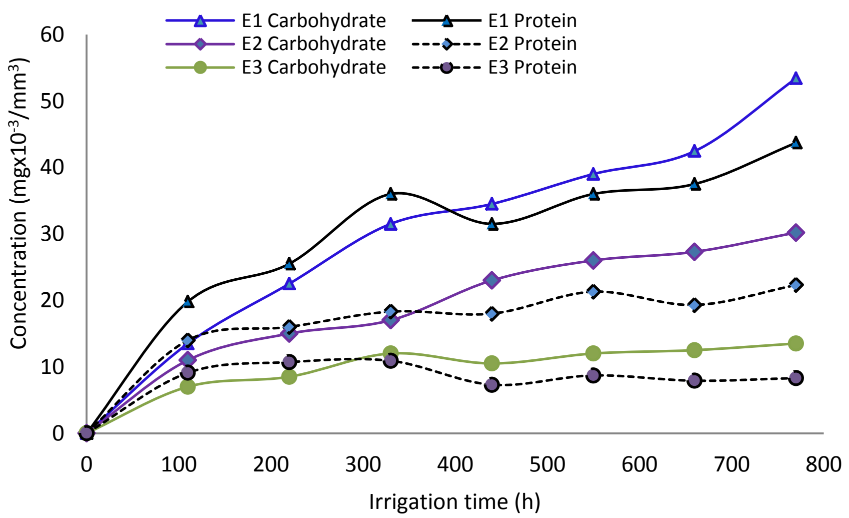


Figure 1. Changes in the exo-polymeric content of recycled water biofilms with irrigation time; after Oliver et al. (2014a)

According to Oliver et al. (2014a), the onset of the recession of protein content (Fig. 1) in the EPS is an indication that the biofilms have attained maturity. It was also shown that biofilms take at least 220 hours of irrigation time to establish themselves to maturity when a specific irrigation pattern (2 days on @8 h/day, the next 24 h off) is followed. The formulation of a new clogging test described in this paper is based on these research outcomes from Oliver et al. (2014a, and b).

The Test Rig

If the biological components are to be incorporated in the clogging test, the biofilms must be allowed to grow during the test and reach at least the early stage of maturity. Based on this principle (Oliver et al., 2014a), the new test procedure was decided to run for a period of 44 days which is fairly a long term procedure. A DI system was built for this purpose inside a closed environmental chamber where desired temperature could be achieved. All the components were compatible with the ISO standard 9261 (ISO, 2004). The feeding sub-main of the DI was connected to a pump which delivered water into the system from an attached 400 L tank. Three types of commercially available PC emitters; each with different discharge, (emitter E1 with 1.6 l/h, E2 with 2 l/h and E3 with 2.3 l/h) were used in the test. A total of 12 laterals were attached to the sub-main containing a mixture of all three emitter types in four replications (Fig. 2). There were nine emitters (30 cm spacing) in each lateral to be assessed for clogging which would yield a statistically sound data of 36 samples for each emitter type. The emitters would discharge water into the base of the chamber which ultimately drains into the water tank through a return passage (Fig. 2)

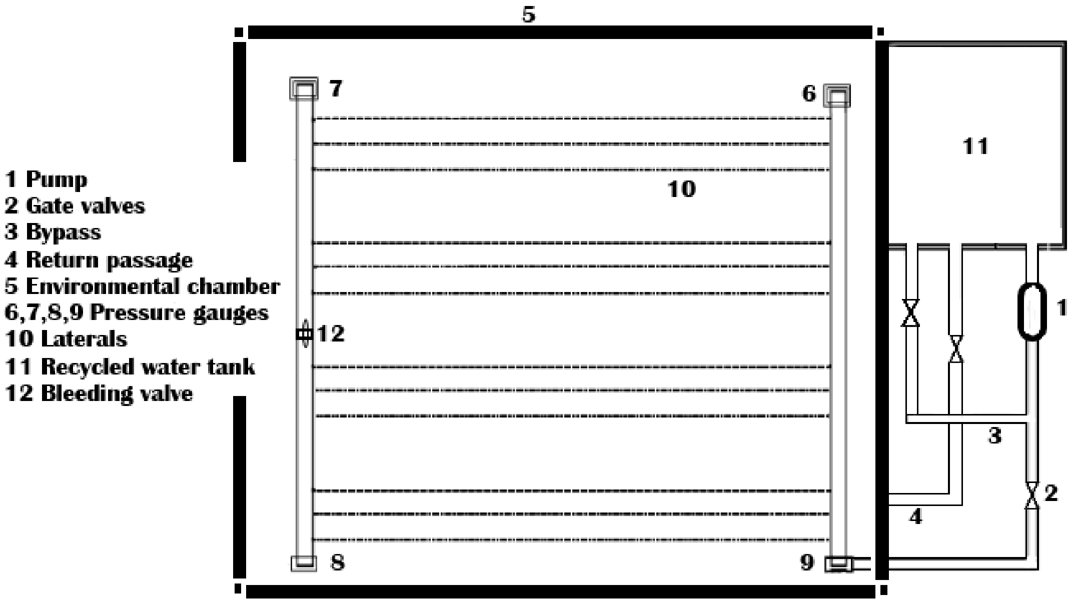


Figure 2. Experimental clogging test rig for the clogging test

Formulation of the Test

The modified test was divided into four active stages of irrigation. Each stage (11 days) was designed to provide a total of 56 hours of irrigation by following a schedule of 8 hours on and 16 hours off per day for two consecutive days; and the next day (24 hours) off. During the entire test period, this schedule would provide a total active irrigation of 224 hours (Table 1) allowing the biofilms to reach their early stage of maturity. Class A reclaimed water (heterotrophic bacterial count 0.003 to 1.22 × 10^6 CFU/100 mL) from the Bolivar wastewater treatment plant in South Australia was used for irrigation. The other water quality data can be obtained from Oliver et al. (2014a). This water comes with less than 1 ppm of suspended solid which is ideal for this kind of test. At the beginning of the first stage, 75 mg/l of suspended solids (0-25 µm size range) was added into the water and irrigation was given according to the schedule. This threshold of 75 mg/l is only valid when the above mentioned scheduled is followed together with Class A recycled water. The second stage was designed to reflect an increasing level of dirtiness in the water. Therefore, another 75 mg/l of suspended solid containing larger particles (25-50 µm) was added into the water. During each of the next two stages, the same amount of suspended loads was added containing different particle sizes.

Table 1. Modified clogging test encouraging biological growth (experiment 1)

Stages	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
Particle load, mg/l	75	75	75	75
Particle sizes, µm	0-25	25-50	50-150	150-250
Day 1	Operation*	Operation	Operation	Operation
Day 2	Operation	Operation	Operation	Operation
Day 3	*Non-OP ^*	*Non-OP*	*Non-OP*	*Non-OP*
Day 4	Operation	Operation	Operation	Operation
Day 5	Operation	Operation	Operation	Operation
Day 6	*Non-OP*	*Non-OP*	*Non-OP*	*Non-OP*
Day 7	Operation	Operation	Operation	Operation
Day 8	Operation	Operation	Operation	Operation
Day 9	*Non-OP*	*Non-OP*	*Non-OP*	*Non-OP*
Day 10	Operation	Operation	Operation	Operation
Day 11	*Non-OP*	*Non-OP*	*Non-OP*	*Non-OP*
	TEST	TEST	TEST	TEST
Irrigation time	56 hours	56 hours	56 hours	56 hours
Time of Non-OP	208 hours	208 hours	208 hours	208 hours
Total irrigation time	224 hours			
Total time of Non-OP	832 hours			
Total experimental time	1056 hours †			

Table 2. IRSTEA clogging test schedule (experiment 2)

Stages	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
Particle load, mg/l	125	125	125	125
Particle sizes, µm	0-80	80-100	100 - 200	200 – 500
Day 1	Operation*	Operation	Operation	Operation
Day 2	Operation	Operation	Operation	Operation
Day 3	Operation	Operation	Operation	Operation
Day 4	Operation	Operation	Operation	Operation
Day 5	Operation	Operation	Operation	Operation
Day 6	*Non-OP ^*	*Non-OP*	*Non-OP*	*Non-OP*
Day 7	*Non-OP*	*Non-OP*	*Non-OP*	*Non-OP*
Irrigation time	40 hours	40 hours	40 hours	40 hours
Time of Non-OP	128 hours	128 hours	128 hours	128 hours
	TEST	TEST	TEST	TEST
Total irrigation time	160 hours			
Total time of Non-OP	512 hours			
Total experimental time	672 hours ††			

* Operation means 8 hours continuous irrigation and 16 hours OFF
^ Non-OP means complete shutoff of the system for 24 hours
† Total experimental time under 28±3 °C temperature
†† Total experimental time under 23±3 °C temperature

The particle size range in the last stage was selected to be 150-250 µm according to the results of Oliver et al. (2014b) who showed that the interior of the initial biofilm biomass is exclusively built by particles less than 30 µm in size with a standard deviation of 15 µm.

Some larger particles (>150 µm) were discovered at the periphery of biofilms but was not significant in amount. Similar results were also reported by Niu et al. (2013) who found that smaller particles (31-38 µm) actually forms the interior of the clogging biomass. Therefore, the test procedure was designed to provide an opportunity for circumferential establishment of the larger particles (up to 250 µm) while encouraging the central existence of the smaller particles (0-50 µm) in the biomass. All the particles were soil mineral aggregates dried in the oven at 105 ^{O}C for 24 hours and screen to their sizes before being added into the test water.

Experiment 1 – Modified Test

The schedule for the modified test is described in Table 1. At the beginning of each stage the suspended solid was thoroughly mixed with the reclaimed water and the mixing continued while the system was under operation. Inside the test chamber, a temperature of 28±3 ^{O}C was set and maintained throughout the experiment. Selection of this thermal regime was done according to the results of a series of experiments conducted by the authors (Oliver et al. 2014a and b) under varying soil thermal conditions. The PC emitters were found to be showing their worst performances at the range of 24-31 ^{O}C. In the clogging test, the hypothetical target was to expose the test samples to the worst possible condition that an emitter faces in the field. This test was, therefore, run at a temperature of 28±3 ^{O}C to achieve the worst clogging scenario. The authors can be contacted for additional unpublished data on this topic. A throttle was added at the end-of-line sub-main to achieve a minimum velocity (ranges from 30-50 cm/s) in the laterals so as to prevent settlement of particles near the dead end.

Experiment 2 – IRSTEA Test

In order to compare the results of the modified test, the IRSTEA clogging test (Di Maiolo, 2012) was also conducted under the same arrangement shown in Fig. 2 and with the similar set of emitters. However, for the IRSTEA clogging test (Table 2), the thermal regime was maintained at 23±3 ^{O}C. It involved standard clean water as specified by the ISO 9261 with less than 2 mg/l of total suspended matters. The minimum velocity maintained in the laterals was 50 cm/s because of the higher suspended load.

Both the tests were conducted under a pressure of 100 kPa and the pressure variation was contained within 1% of the design pressure. The base of the environmental chamber was regularly cleaned so that particles do not settle on it and thoroughly mixes with the running water in the tank. At the end of each experiment, the throttle was used for gravitational drainage of the laterals. Emitter flow rates were measured every day during the first stage and once at the end of each subsequent stage for a period of 5 minutes using graduated plastic cylinders according to ISO (2004). The degree of clogging due to physical/biophysical substances was then assessed by comparing the emitter flow at any stage with the reference discharge of that particular emitter type. The reference characteristics were established according to the ISO 9261 procedural clause of 9.1, 9.2 and 9.8 (ISO, 2004).

Evaluation of the Result

Reduction of emitter flow (q_{fr}) at any stage was used as the prime measure to assess the effect of clogging. It was calculated as

$$q_{fr} = 100 \times (1 - q_r) \quad (1)$$

Here, q_r is the relative discharge of an emitter. It is defined as the ratio of average emitter flow at any time (q_a) to the emitter's reference flow rate (q_d):

$$q_r = \frac{q_a}{qd} \qquad (2)$$

The average flow rate (q_a) for a particular emitter type was obtained by averaging the individual flow rates (q_i) of emitters from each lateral.

$$q_a = \frac{1}{n} \sum_{i=1}^{i=n} q_i \qquad (3)$$

Equation 3 was also used to calculate the average of the lower quarter flow rates ($q_{1/4}$) from each lateral. Interpretation of the results from IRSTEA test was carried out following the existing recommendations (Decroix, 1990) presented in Table 3.

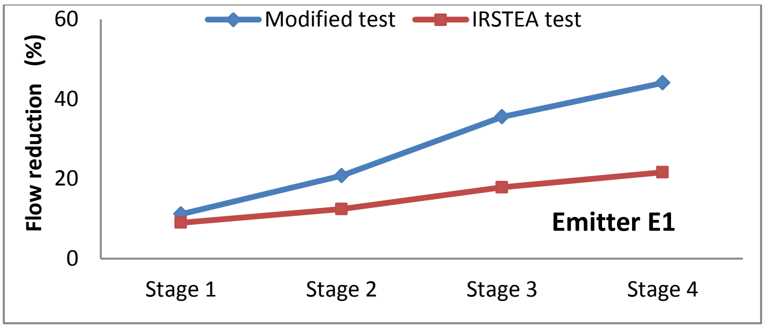
Table 3. Interpretation of results from the clogging test of IRSTEA

Test Results	Sensitivity Level	Recommended Filtration Size
sample did not pass the 1st stage	Ultra-Sensitive	Below 80 µm
sample did not pass the 2nd stage	Very Sensitive	80 µm
sample did not pass the 3rd stage	Sensitive	100 µm
sample did not pass the 4th stage	Little Sensitive	125 µm
sample passed all the stages	Very Little Sensitive	150 µm

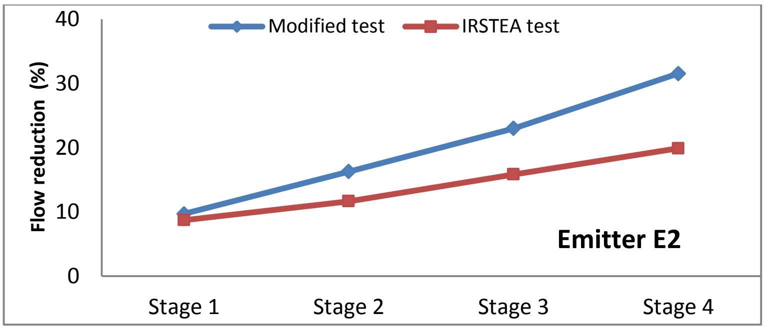
Results and Discussion

The results of both the modified and the IRSTEA test procedure came into having considerable contrast among them. Emitters (E1) with low flow rate (1.6 l/h) were the quickest to accumulate considerable clogging biomass which resulted in significant reduction of flow. IRSTEA suggests that any reduction of 30% or more at any stage is a sign of sensitivity to clogging. As can be seen from Fig. 3a, emitter E1 experienced a 22% reduction of flow and therefore passing the fourth stage of the IRSTEA test. The last concentration of suspended load that emitter E1 withstood was 500 mg/l containing 0-500 µm particle sizes. According to Table 3, this emitter would be marked as “very little sensitive to clogging” and 150 µm filter size would be recommended. However, the results from experiment 1 show that 150 µm filter size could be insufficient for E1 if reclaimed water is used. In the modified test, emitter E1 did not pass (Fig. 3a) the third stage (0-150 µm) although the concentration of suspended solid was much lower (225 mg/l) compared to the same stage of the IRSTEA test. This means biomass accumulation was much quicker in the modified test although the dose of suspended solid was only 75 mg/l/stage compared to 125 mg/l/stage of the IRSTEA test. According to Table 1, our interpretation is that a 100 µm filter size would be more appropriate for this type of emitter and this size will be able to address the effect of biological intervention in the fouling process.

On the other hand, emitter E2 (2 l/h) passed all the stages of IRSTEA test (20% reduction of flow) but failed to pass the last stage of the modified test. It’s flow rate diminished by almost 32% by the end of 224 hours of irrigation. According to Table 1, a filtration size of 125 µm seems more appropriate for this type of emitter compared to 150 µm as recommended (Table 3) by the IRSTEA. Fig. 3 also shows that initial cogging was almost similar in both the tests for all emitter types (≈10% reduction of flow). Nonetheless, as irrigation time progressed, the difference between the two tests became evident, especially after stage two. In general, emitters in the modified test involving reclaimed water experienced more flow reduction than those in the conventional IRSTEA test with clean water. This means that clogging is more acute if biological intervention occurs. A possible reason is that



a)



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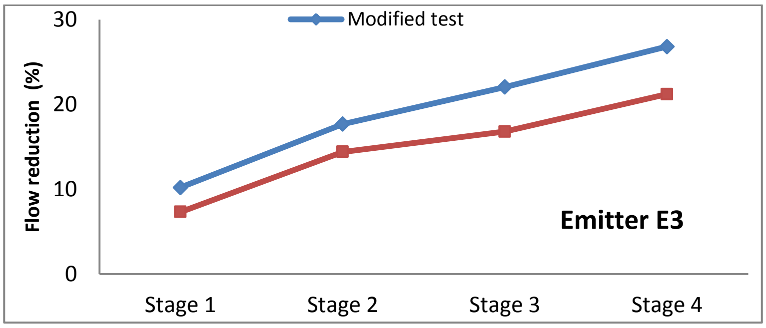


c)

Figure 3. Reduction of emitter flow rates with the progression of irrigation stages in two different clogging tests for *a)* emitter E1; *b)* emitter E2, and c) emitter E3

Emitter E1 (1.6 l/h) and E2 (2 l/h) were comparatively smaller emitter sizes and both of them failed to pass the modified test although they were successful in the IRSTEA test (Table 4). The other specimen tested in this study was emitter E3 which had slightly larger flow rate (2.3 l/h) than E1 and E2. Interestingly, E3 managed to pass both the tests and the reduction of flow was limited to 30% in all cases.

Table 4. Flow rate of emitters at different stages of the clogging tests

Procedure followed		Stage 1		Stage 2		Stage 3		Stage 4	
		q_a (l/h)	q_r	q_a (l/h)	q_r	q_a (l/h)	q_r	q_a (l/h)	q_r
Modified Test	Emitter E1	1.42	0.89	1.27	0.79	***1.03***	***0.64***	0.90	0.56
	Emitter E2	1.81	0.90	1.67	0.84	1.54	0.77	***1.37***	***0.68***
	Emitter E3	2.07	0.90	1.89	0.82	1.79	0.78	1.68	0.73
IRSTEA Test	Emitter E1	1.46	0.91	1.40	0.88	1.31	0.82	1.25	0.78
	Emitter E2	1.83	0.91	1.77	0.88	1.68	0.84	1.60	0.80
	Emitter E3	2.13	0.93	1.97	0.86	1.91	0.83	1.81	0.79

Note: values in bold and italics are the points of failure i.e., $q_r < 0.7$

The relative discharge for E3 in the final stage stood out to be 73% in the modified test and 79% for IRSTEA test (Table 4). Although the performance was similar, the test without reclaimed water (IRSTEA) showed low biomass accumulation than the one with it (modified test). In all the cases where emitters could not pass the modified test, the IRSTEA recommended filtration size was found to be greater than what was obtained through the modified test. This means an emitter branded as ‘not sensitive’ by the existing test procedure may actually be sensitive to clogging if used in conjunction with poor quality water. It is understood from the available documents that the ISO is going to recommend a new flow reduction threshold to assess an emitter’s sensitivity to clogging. The new standard will take 25% flow reduction as a sign of sensitivity to clogging. If this value is applied to Table 4, emitter E2 and E3 along with emitter E1 will fail to pass the modified test. Emitter E1 will nonetheless fail at stage three and the remaining emitters will fail at stage four. However, all of them will be passing the IRSTEA test indicating that the sensitivity of emitters is being underestimated in the existing procedure. In almost all the cases, the IRSTEA clogging test seems to be overestimating (Table 4) the appropriate filter size.

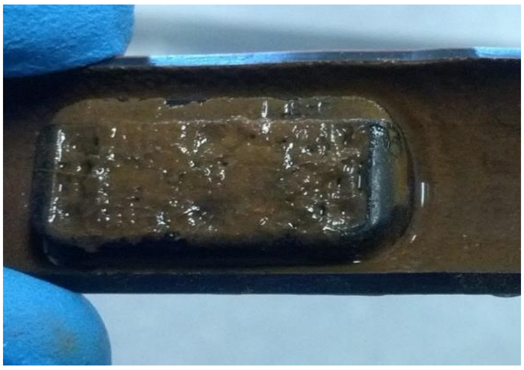
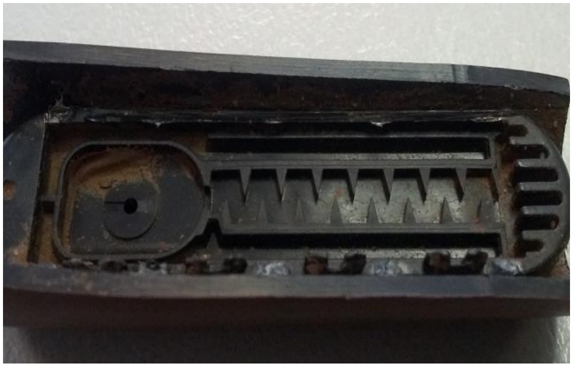
a)  *b)* 

Figure 4. *a)* biomass development and average particle size trapped in E1 during the modified test b) accumulation of physical clogging material in emitter E2 during IRSTEA test

In the modified test samples, the slimy fouling biomass was found to be sprawling over the section of entry (Fig. 4a) and obstructing the flow. However, in the IRSTEA test, the physical clogging materials were found to have passed through the section of entry; travelling along the labyrinths and settling at the edge of the detention basin (Fig. 4b). No slimy material was observed in the IRSTEA test samples. This fundamental difference between the biofouling process and the physical clogging must be acknowledged in any clogging test. The overall experience from this study suggests that incorporation of biological component in the clogging test can help obtain more accurate information about the filtration requirement in drip irrigation. This study was, therefore, carried out to contribute towards developing a universal clogging test in the near future.

Conclusion

Testing emitters for their sensitivity to clogging is very important because users rely on these test results to decide which emitter is best for their condition. This paper presents the results obtained from two experimental clogging tests. One test was carried out according to the existing procedure of IRSTEA which predicts emitter sensitivity to physical clogging only. The other clogging test was carried out according to the procedure proposed by the authors from their previous studies where recycled water is used to encourage biological growth. It was found that the filtration size obtained through the clogging test of IRSTEA may not be appropriate if recycled water is used. The dose of suspended solid added into the water during the four-stage experiments was much lower (75 mg/l) in the modified test but quite high (125 mg/l) in the IRSTEA test procedure. Nevertheless, emitters in the modified test showed signs of clogging much earlier than those in the IRSTEA module. Three types of PC emitters having different discharges (1.6 l/h, 2 l/h, 2.3 l/h) were tested. Interestingly, all the emitters managed to pass the existing IRSTEA test but at least two of them failed to pass the modified test. This suggests that if biological growth is not encouraged in the clogging test, emitter sensitivity cannot be predicted property. The modified test is based on the idea that biofilms are able to establish and attain early maturity during 220 hours of irrigation time if a particular schedule is followed. Since biofilm growth largely depends on the water quality, this study recommends that some benchmark experiments must be carried out to establish the quantitative relationship between water quality and biofilm growth. Only then, a comprehensive clogging test can be developed for prediction of emitter sensitivity to all sorts of clogging agents.

Acknowledgement

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Improved Irrigation Efficiency as a Tool for Climate Change Adaptation in Arid Environments

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Abstract. *Potential changes in irrigation efficiency were investigated to assess their impact on agricultural and urban water demand in the Rio Grande basin in Jujuy province, Argentina, over the 50-year period from 2010 to 2060 within the context of three climate change scenarios derived from the Fourth Assessment of the Intergovernmental Panel on Climate Change and applied to two Global Circulation Models. The basin is an arid region that suffers from water scarcity, seasonal shortages and competition among water users, including urban, agriculture, food processing, and hydropower. The case-study evaluated feasible improvements in the efficiency of irrigation water systems to determine whether water savings from such improvements would be sufficient to off-set anticipated growth in water demand. This study is an attempt to contribute to the broader assessment of applying the principles of 'climate-smart agriculture' to arid, water scarce environments, and correlates the improvement in water efficiency to two other objectives: achieving equal or greater agricultural yields of current crops; and mitigating the ecological damage caused by traditional, extensive agricultural regimes . This paper focuses on two potential irrigation interventions providing irrigation efficiency greater or equal to 60% and the baseline ('no-intervention') option using reference transpiration derived from CROPWAT calculations based on five decadal climate projections for sugar cane and tobacco and suggests that improved irrigation efficiency is a critical intervention for climate change adaptation. Irrigation efficiency is one of the major component tools of 'climate-smart agriculture'*

Keywords. Climate-smart Agriculture, Food Security, Global Circulation Models, Irrigation Efficiency, Water Scarcity

Introduction

Water scarcity

Those most in need of poverty and undernourishment reductions live in the most water-scarce environments. Currently, about 700 million people in 43 countries suffer from water scarcity. A region is experiencing water stress when annual water supplies drop below 1,700m^3/capita. When annual supplies drop below 1,000m^3/capita the population faces water scarcity, and when annual water supplies drop below 500m^3/capita the population faces absolute scarcity (UN, 2005). "By 2025, 1.8 billion people will be living in countries or regions with absolute water scarcity, and two-thirds of the world's population could be living under water-stressed conditions" (FAO, 2007). Food insecurity increases as populations transition from water-stressed conditions to water-scarce conditions (Bellarby, Foereid, Hastings, & Smith, 2008; DuBois, Chen, Kanamaru, & Seeberg-Elverfeldt, 2012; Murphy & Boyle, 2012). Almost half the world's population will be living in areas of high water stress by 2030. In addition, water scarcity in some arid and semi-arid places will displace between 24 million and 700 million people (FAO, 2007).

Greenhouse gas emissions

Agriculture accounts for more than one-third of all greenhouse gas emissions and consumes 36% of all arable land (Rockstrom, Gordon, Folke, Falkenmark, & Engwall, 1999), and agricultural irrigation consumes 70% of the world's available water (Agricultural Water Conservation Clearinghouse, 2009). Climate scientists posit that the planetary threshold for the percentage of global land cover converted to cropland is 11.7% (Rockstrom, et al., 2009) and, that if traditional extensive farming techniques continue to expand, the percentage of global arable land under agriculture will grow to an unsustainable 60% by 2050 (Rockstrom, et al., 2009). Reducing the need for additional land conversion to agriculture represents nearly as much GHG emissions as those directly generated from agricultural activities (Branca, McCarthy, Lipper, & Jolejole, 2011). The problem addressed in this research is how agricultural production can be improved intensively in arid regions (on currently cultivated land) within the context of projected climate change impacts over the next five decades while also providing available water for urban consumption.

Arid warm-dry regions have average (mean) carbon sequestration values of approximately 1.14 tons of CO_2 equivalent/hectare/year (European Commission, 2011). Carbon sequestration for "set-side" land,i.e., land that is not transformed to agricultural production from a natural state, in warm-dry areas has an average (mean) of 3.93 tons of CO_2 equivalent/hectare/year (European Commission, 2011). They key metric for reducing greenhouse gas emissions is the extent to which agricultural yields are increased on extant agricultural land. According to the United Nations Framework Convention on Climate Change (UNFCCC) "emissions from the conversion of grassland to cropland were 29.3 Mt CO_2 and removals from the conversion of cropland to grassland were -31 MT CO_2. Thus, a net contribution from total land conversion between cropland and grassland was a slight sink of -2.5 Mt CO_2" (European Commission, 2011).

Climate-smart agriculture

The methodology to: mitigate the environmental damage that is caused by traditional agricultural regimes; adapt to changing environmental conditions; and improve agricultural production and profitability for the grower, is referred to as "climate-smart agriculture" (CSA). Improved irrigation efficiency and intensive agricultural production are key tools of CSA and make up the scope of this research. Other tools that complement improvements in irrigation efficiency and intensive agriculture include: conservation tillage; integrated pest and nutrient management; utilization of green (rain) water; water harvesting; runoff capture; improved drainage; terracing; and the utility of hybrid cultivars.

Research questions

The research questions for this study are:

- What will be the urban and agricultural water demand by 2060 in an arid region in response to a range of downscaled climate scenarios derived from the Intergovernmental Panel on Climate Change (IPCC)?
- What will be the theoretical implications of different degrees of irrigation efficiency on urban and agricultural water availability over the same period?
- What are the potential reductions in greenhouse gas emissions as a result of improved irrigation efficiency?

Materials and methods

This study does not empirically measure outcomes of interventions on agricultural farmland. Rather, this research models a baseline agricultural regime and then calculates the potential change in yields, environmental indicators and overall water availability as a function of changes in irrigation efficiency.

Climate modeling methodology

The framework for this research design is scenario planning. Climate scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) describe future developments. Scenario planning for this research is based on IPCC Climate scenarios, which emanate from the Fourth Assessment of the IPCC, for three storylines or socio-economic scenarios—A2, A1B, B1 (IPCC, 2008). These three storylines represent worst, moderate, and best case projections, respectively. The A2 scenario projects an increase of 3.4^0C best estimate for the period 2090-2099; A1B—2.8^0C; and the B1 scenario—1.8^0C. (IPCC, 2008). These scenarios were downscaled by use of the online climate projection tool known as Climate Wizard to project changes in temperature and rainfall for the period under investigation. Downscaling climate data is a method for generating locally relevant data by utilizing Global Circulation Models (GCMs) that provide estimates for climate change in a given spatial and temporal setting. Two GCMs are integrated in the research: the Commonwealth Scientific and Industrial Research Organization (CSIRO) MK3 model and the UK Met Office (UKMO) Hadley CM3.1 model. The CSIRO model is utilized by the World Bank for 'dry' scenarios. The CSIRO Mk3 GCM has a spatial resolution of 1.25o latitude by 1.875o longitude with 38 layers in the vertical extending to over 39 kilometers making it reliably representative over the study area (Science and Technology Facilities Council: Natural Environment Research Council, 2011. The UKMO model has been frequently used for climate projections in Argentina.

Computations for this research were carried out in twelve successive steps in the following manner:

1. Identification of the "combined basin of the Rio Grande and the upper Rio San Francisco" (Wyatt, et al., 2012) of Jujuy Province and estimation of the stream flow of the basin using data provided by the Hydro-BID watershed modeling tool in the IDB and RTI study (Wyatt, et al., 2012).

2. Selection of the agricultural sample for the study. This research does not use a randomly selection sample but, instead includes 100% of all the sugarcane and tobacco fields in Jujuy Province, Argentina: 14,238 Hectare (ha) tobacco, and 19,122 ha sugarcane (equivalent to 35,597 and 48,030 acres, respectively).

3. Integration of reliable data for baseline precipitation and temperature for the period 1974-2010 from the local Jujuy Province El Perico airport station as reported by the Argentine National Weather Data service.

4. Identification of the current and estimated growth in population of San Salvador de Jujuy and per capita water supply. San Salvador is the capital city of Jujuy Province and has a current population of 265,249, the water supply is 74,400 m^3/day corresponding to a daily per capita supply of 273 liters. Population growth is about 1.5 percent/year and increases in rural water consumption is estimated at 2.5 percent/year (FAO, 2008; Wyatt, et al., 2012)

5. Downscaling of the three socio-economic scenarios based on two GCMs: the Commonwealth Scientific and Industrial Research Organization (CSIRO) MK3 model; and the UK Met Office (UKMO) Hadley CM3.1 model. for the Jujuy Province utilizing climate wizard.com. The climate scenarios are based on IPCC's Fourth Assessment: A2, A1B, B1 (IPCC, 2008).

6. Projection of temperature and precipitation changes for the decades 2010-2060 based on the three climate scenarios for each GCM.

7. Conversion of precipitation (P) to "effective precipitation" (Pe) using the calculations provided by the Food and Agriculture Organization of the United Nations (FAO). Pe= (0.8P)-25 if P>75 mm/month; Pe-(0.6P)-10 if P<75 mm/month. (FAO, 2008)

8. Calculation of Etr for each decade from CROPWATER 8.0, a software program, and verfied as locally reasonable. Kc factors were derived from multiple professional agricultural sources including the FAO (FAO, 2010).

9. Calculation of "Irrigation Need" $IN=(ETr-P_e)*(K_c)*(A_i/E_o)$ where, IN=Irrigation need; ETr=Reference ET (mm/month); Pe=Effective precipitation (mm/month); Kc=Crop coefficient (percent/month); Ai=Area irrigated; and Eo=Overall efficiency of the irrigation system, which is calculated by multiplying the efficiencies of water

conveyance (Ec) and water application (Ea). The water conveyance system is a control variable

10. Recalculate IN by inputting three variations of Eo (37%, 60%, 90%). 37% represents no-intervention which is characterized by unscheduled, furrow irrigation; 60% represents solid-set sprinklers; and, 90% represents a drip irrigation system.

11. Summarize and analyze water availability for irrigation and urban use for socio-economic scenarios.

12. Provide estimate for 'set-aside' land. Set aside land is the aggregate change in greenhouse gas emissions for every unit reduction in land not required for agricultural production. This method follows the formula that says that for every unit reduction in agricultural land (due to increased yield, or, 'intensive agriculture') for each season, the aggregate mean change in greenhouse gas emissions will be 3.93 tons of CO_2 equivalent/ha (t CO_2-eq/ha).

Study area: Jujuy Province Rio Grande river basin

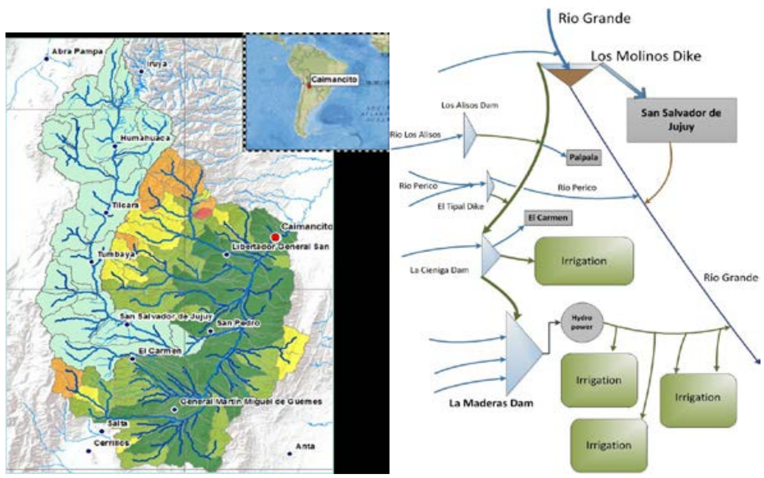

Figure 1 Jujuy watershed and Schematic Rio San Francisco river basin

This research study area is the Jujuy Province in northwest Argentina which is one of the most remote and least developed provinces in the country. The water basin under study is an arid region that suffers from water scarcity, seasonal shortages and competition among water users, including urban, agriculture, food processing, and hydropower. The two predominant crops in the province are tobacco and sugar cane. This is a predominantly agricultural region that was first selected as a test site to assess the negative consequences of climate change on water resources for the five decadal periods, 2010-2060 by the Inter-American Development Bank (IDB) and RTI International in (Wyatt, et al., 2012) .
Water diverted for irrigation is stored in four downstream dams with total capacity of 341 million cubic meters (Mm^3). Local data reports that sugar cane consumes about 77 Mm^3/year; tobacco consumes about 48Mm^3/year. Observations from the field indicate that sugarcane consumes about 103 Mm3/year and tobacco about 77 Mm^3 (Wyatt, et al., 2012).
Water demand for irrigation varies monthly. Baseline data indicate that there is surplus of water from January-April and a deficit from May-December. Industrial, urban and hydropower consumption is constant throughout the year.

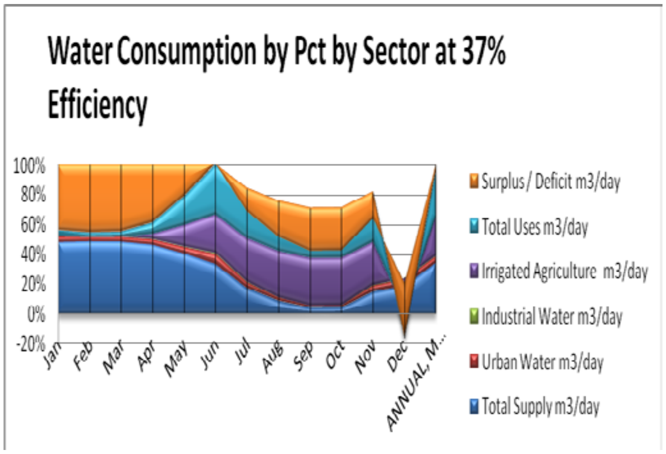

Figure 2 Water consumption by sector

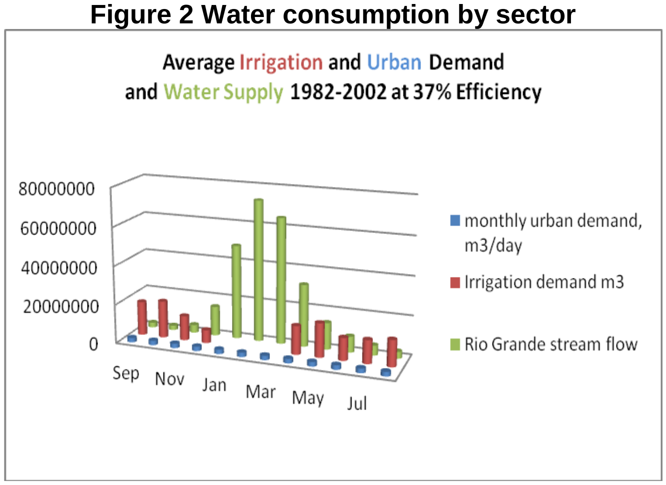

Figure 3 Average irrigation and urban demand 1982-2002

Agricultural production

Tobacco and sugarcane are the dominant crops in the Jujuy Province. Together they make up about 99% of all agricultural production.

Table 1 Irrigated agriculture in Jujuy province (Wyatt A. , 2013)

Irrigation Area (Ha)				
PLACE	Tobacco	Sugar Cane	Other	Total
	Ha	Ha	Ha	Ha
Carmen (10)	12392.80	1646.30	150.00	14189.10
Palpalá (9)	1058.50	183.00	200.00	1441.50
San Antonio (11)	539.10	0.00	65.00	604.10
Dr. M. Belgrano (8)	182.00	0.00	45.00	227.00
San Pedro (12)	66.00	17382.50	25.00	17473.50
Total	**14238.40**	**19211.80**	**485.00**	**33935.20**
%	**0.42**	**0.57**	**0.01**	**1.00**

Records of production of tobacco and sugar cane have been kept since the 1980's in Jujuy province but production over that period has been relatively stagnant (Province of Jujuy, 2010) as the figures below illustrate.

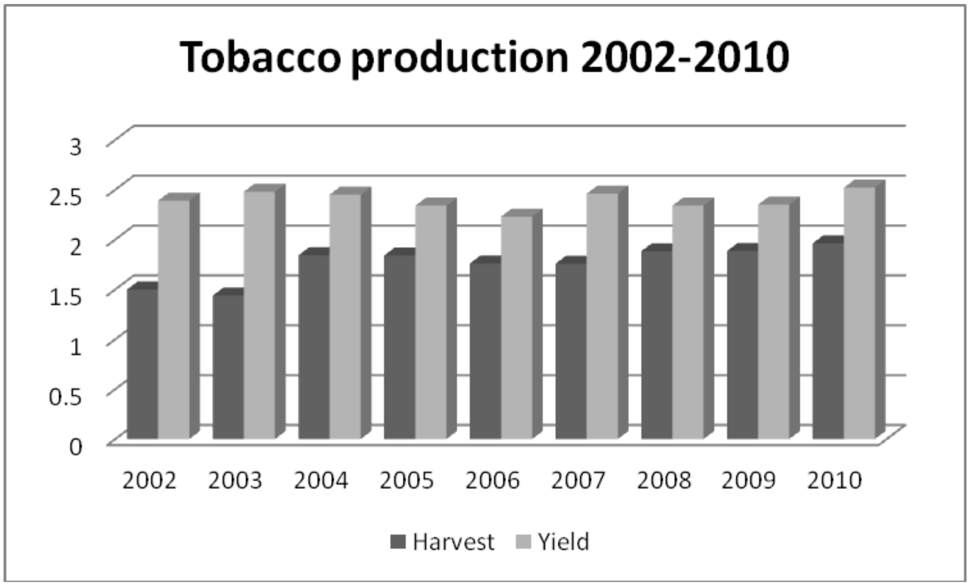

Figure 4 Tobacco production in Jujuy 2002-2010 (Province of Jujuy, 2010)

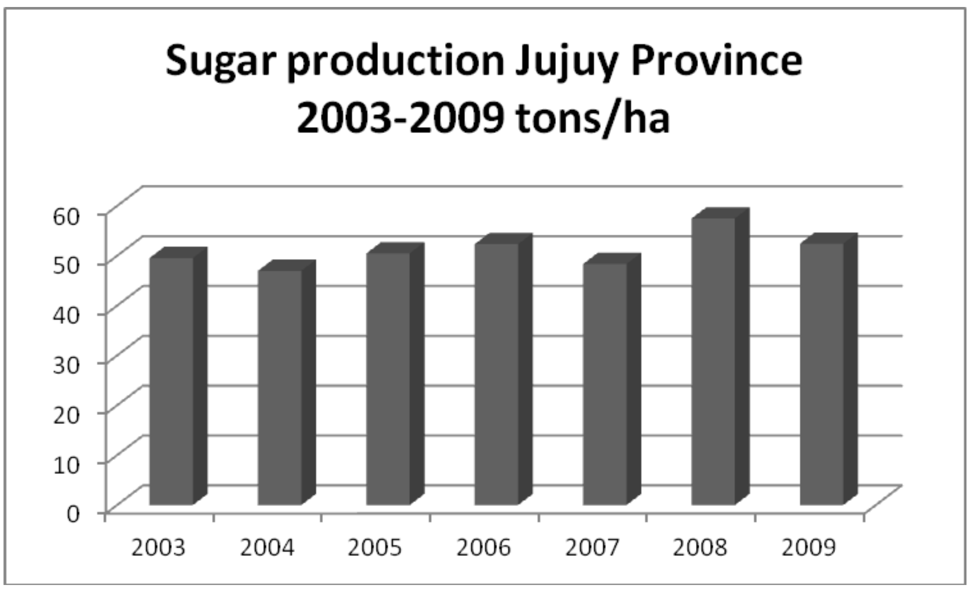

Figure 5 Sugarcane production in Jujuy 2003-2009 (Province of Jujuy, 2010)

Potential yields

By utilizing crop coefficient data over the growing season, regardless of irrigation regime, it is possible to achieve improved production. The basic proposition is that delivering irrigation applications at varying degrees over the growing season will improve production. The general schematic illustrating this procedure follows.

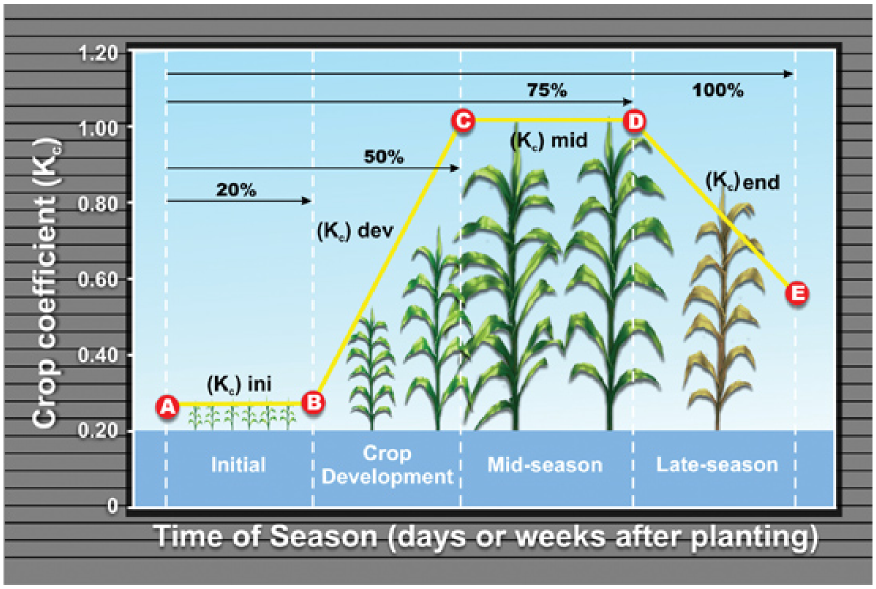

Figure 6 Crop coefficient schematic (Irmak, 2009)

Conducting an empirical evaluation of all the salient variables necessary to achieve optimal agricultural production is beyond the scope of this research but it is necessary to briefly explain that scheduled irrigation regimes provide yield benefits.

For sugarcane the critical inputs for optimal production include: land preparation; planting patterns; spacing; proper seeding rates; weed control; applications of pre-emergence and post-emergence herbicides; proper selection, installation and maintenance of the irrigation system; crop irrigation scheduling; seasonal fertigation; 'hilling-up' soil; detrashing; propping; and harvesting properly (Barak, 2012). Under these conditions yields can reach between 140-160 tons/ha or about 2.5 times the current yield in Jujuy (Barak, 2012).

For tobacco, yields for the past decade have consistently been between 2-2.5 tons/ha. Irrigation in tobacco is complex because tobacco is susceptible to over watering and its water content requires attention throughout the growing season. Nonetheless, drip irrigated tobacco regularly achieves yields between 3 and 3.5 tons/ha (Duncan & Warner, 2003)

Baseline Data

Baseline data for the research area were derived by consultants on the ground who discovered disparities between reported water usage and actual consumption. (Wyatt A. , 2013).

- Baseline data for irrigated agriculture is 37% efficient.
- Baseline ETr was reported to be 433.67 mm/year.
- Crop coefficients (Kc) for sugar cane were reported to be calculated at 1.15 for every month; Kc for tobacco at 0.95 for every month. Further investigation in the field revealed that no consideration of Kc values have been implemented.
- Sugar cane: ETr 433.57 mm; No data for precipitation; Total irrigation volume is 77,179,469 m^3/year. Further investigation in the field revealed that sugar cane water consumption was approximately 103 Mm^3/year.

- Tobacco: ETr 433.67 mm; Total irrigation volume is 47,252,053 m^3/year. Further investigation in the field revealed that sugar cane water consumption was approximately 77 Mm^3/year.
- Urban demand in San Salvador de Jujuy is provided by water treatment plants and is 26,438,410 m^3/year (72,434 m^3/day); population is 265,249. Average is 273 liters/capita/day but water only provided approximately10 hours per day.

	Sugar Cane	Tobacco
Area (ha)	19,212	14,238
Crop Coefficient (Kc/month)	1.15	0.95
Precipitation	NA	NA
Total irrigation volume (Mm^3/year)	77	47
Observed irrigation volume (Mm^3/year)	103	77
Application efficiency (E_a)	0.37	0.37
Irrigation modality	Furrow	Furrow
Average yield (ton/ha) (USDA estimate Sugar: (Rojas, 2004) USDA estimate Tobacco (Hager, 2000)	55	2

Figure 7 crop data

Hydrologic model

The Hydrologic Model for this research is illustrated below. The model utilizes the three scenarios of the IPCC Fourth Climate Assessment This research downscales the model using the UKMO-Had CM3 and CSIRO Mk3.0 GCMs. This model derives Temperature and Precipitation data to determine ETc, modifies the delivery systems based on irrigation efficiency and then assesses the availability of adequate water for irrigation and for urban use.

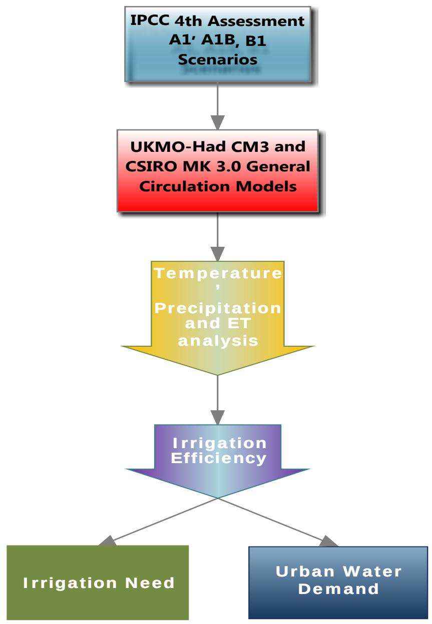

Figure 8 Hydrologic model

Scenario model

The graphic summary of the trend lines for the three scenarios for precipitation and temperature changes for each GCM in the study period, 2010-2060, is illustrated below. Significant to note is that the trend lines for changes in temperature are significant and positive, the trend lines for precipitation changes are positive and insignificant.

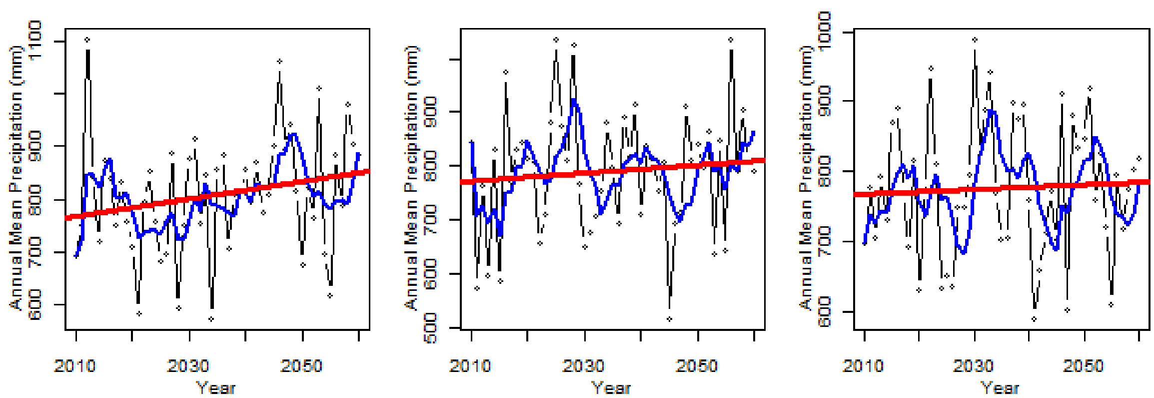

Figure 9 High (A2), Medium (A1B) and Low (B2) Precipitation changes, 2010-2060 CSIRO GCM

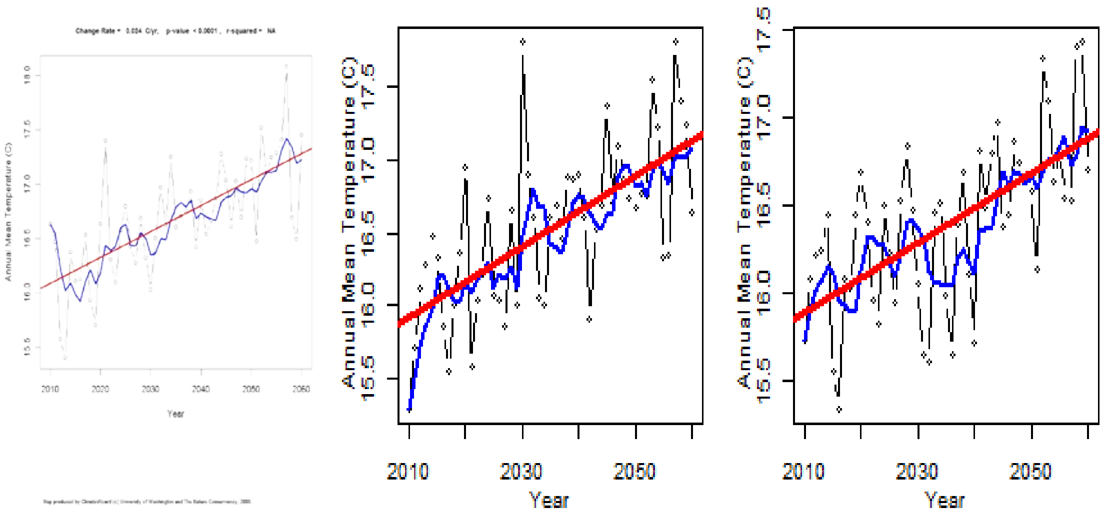

Figure 10 High (A2), Medium (A1B) and Low (B2) Temperature changes, 2010-2060 CSIRO GCM

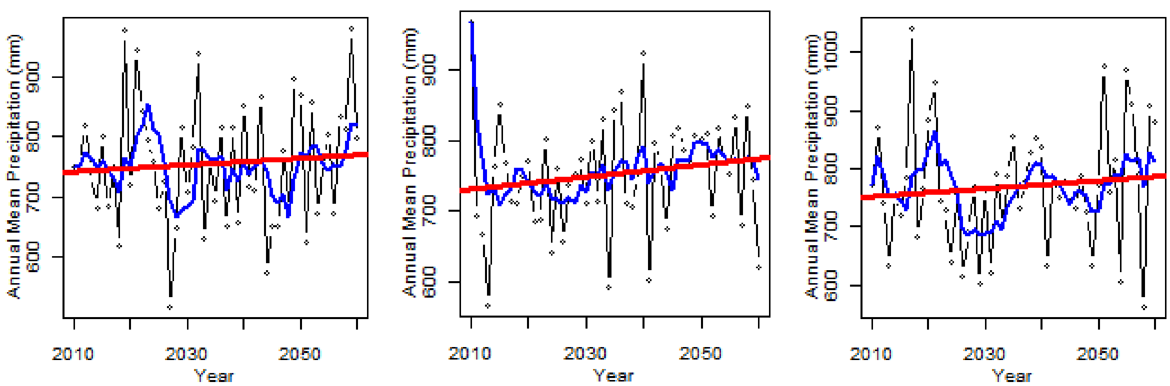

Figure 11 High (A2), Medium (A1B) and Low (B2) Precipitation changes, 2010-2060 UKMO GCM

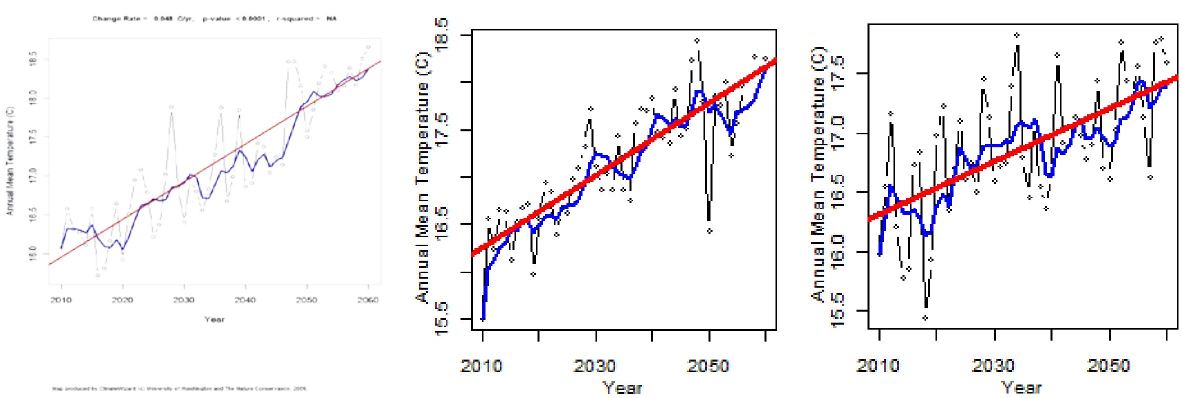

Figure 12 High (A2), Medium (A1B) and Low (B2) Temperature changes, 2010-2060 UKMO GCM

Table 2 Irrigation data

	Approximate Attainable Efficiencies	Value in study
Surface Irrigation		
Furrow	60-75%	37%
Sprinkler Irrigation		
Center Pivot or Linear Move	75-90%	
Solid Set	70-80%	60%
Trickle Irrigation		
Point Source Emitters	75-90%	90%
*Sub-surface Drip	90-95%	

Adapted from Solomon (Solomon, 1998).

Results: 2060 Ensemble

The results of the data analysis are illustrated below. Ensemble data refers to a "group of parallel model simulations used for climate projections. Variations of the results across the ensemble member provide an estimate of uncertainty" (IPCC, 2007). This research uses the 50th percentile which represents the median uncertainty values. The three scenarios produce different temperature and precipitation predictive values which are used as variables to produce different reference transpiration rates and effective precipitation rates, respectively.

The Irrigation Need is calculated according to the three degrees of irrigation efficiency: 37%, 60%, and 90%. The Irrigation Need formula determine the amount of irrigation water demanded by the crop.

All projections are based on 2060 scenarios.

GCM	CSIRO Mk3.0 2060 projection						UKMO-Had CM3 2060 projection					
Scenario	A2		A1B		B1		A2		A1B		B1	
Ensemble T (C) P (mm/year)	T	P	T	P	T	P	T	P	T	P	T	P
	16.7	809	16.5	791	16.4	777	16.9	756	17.2	753	17.1	769
Mean T; Pe	16.7	420	16.5	408	16.4	397	16.9	383	17.2	380	17.1	392

(mm/year)												

ETo (mm/year)-(Pe)	867	877	894	902	916	910

37; 60; 90 E_0 Sugar (m^3/ha)	5390	2100	1406	5452	2134	1422	5557	2176	1450	5608	2194	1486	5694	2228	1486	5656	2214	1476
Mm^3 19212 ha sugar	103	40	27	105	41	27	107	42	28	108	42	29	113	43	29	109	41	28

37; 60; 90 E_0 Tobacco (m^3/ha)	5398	2080	1404	5462	2104	1386	5557	2146	1430	5608	2164	1444	5694	2198	1466	5656	2184	1456
Mm^3 14238 tobacco	77	30	20	78	30	20	79	31	20	80	31	21	81	31	21	81	31	21

Figure 13 Ensemble data for 2060

Total available water (Mm^3/year) 2060	341
Total Urban demand (Mm^3/year) 2060	124

There are 341 Mm^3 water available in the basin. Anticipated population growth for the Jujuy province in 1.5% and increased water consumption is estimated at 2.5%. The projection for urban water use by the year 2060 is approximately 124 Mm^3/year, or about a 100% increase over current demands (Wyatt A. , 2013). The urban water supply efficiency is estimated at 70%, primarily because of leaking water mains (Wyatt A. , 2013).

Discussion

The three scenarios in each of the two GCMs projected mild changes in T and more significant changes in Pe.

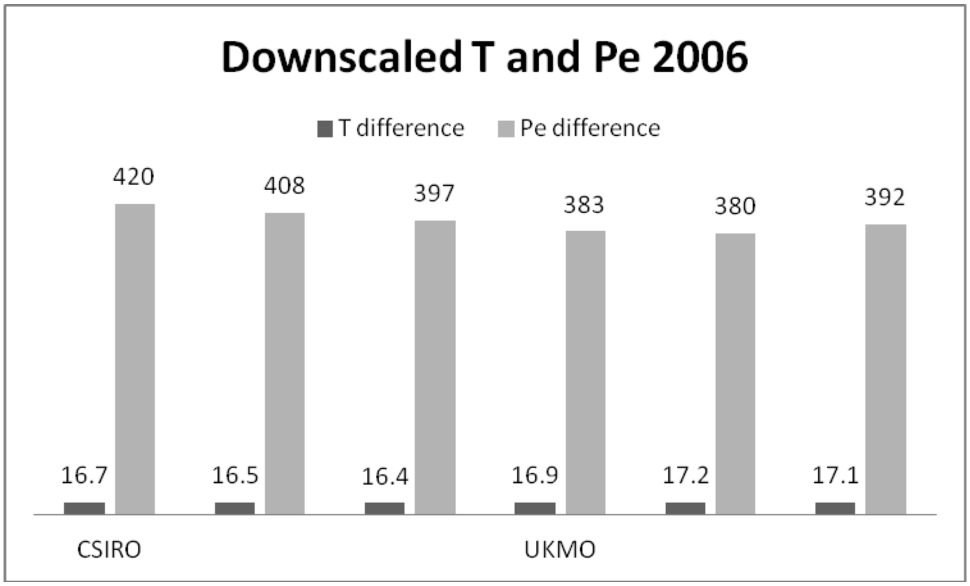

Figure 14 Downscaled T and Pe projections 2060

The range of Pe is 383-420 which correlates to a total water demand range of 171 Mm^3-318 Mm^3. The following figure illustrates that, regardless of GMC and regardless of scenario, the most significant change in availability of water is the efficiency of the irrigation system.

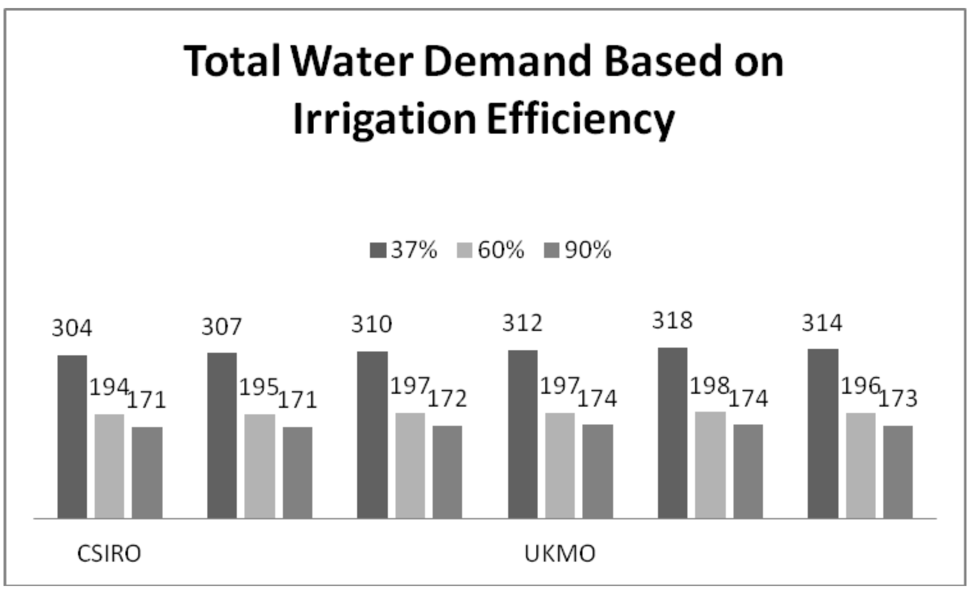

Figure 15 Total water demand based on irrigation efficiency

The research questions under consideration for this paper were:

- What will be the urban and agricultural water demand by 2060 in an arid region in response to a range of downscaled climate scenarios derived from the Intergovernmental Panel on Climate Change (IPCC)?

The changes to water demand based on the three scenarios of the two GCMs are negative and insignificant. .

- What will be the theoretical implications of different degrees of irrigation efficiency on urban and agricultural water availability over the same period?

The changes to available water in all scenario based on changes to the efficiency of the irrigation systems are positive and significant.

- What are the potential reductions in greenhouse gas emissions as a result of improved irrigation efficiency?

The potential savings in greenhouse gas emissions are significant and positive. With the adoption of any scheduled irrigation system, particularly at the 60% or 90% levels of efficiency, it is likely that for each year a savings of 3.93 t CO_2-eq/ha.

Conclusion

The total available water for Jujuy is 341 Mm^3/year. At current rates of consumption at 37% efficiency of the irrigation system, and 70% efficiency of the urban system, the total consumption is approximately 304 Mm^3/year. This represents consumption of 88% of available water. The infrastructure of the Jujuy water system is in disrepair and it is reasonable to expect that leaks, which currently amount to 30% loss in the system, will increase in number and severity. The current level of inefficiency is not sustainable.

Critical for solving improved agricultural production, mitigation of environmental damage that traditional agriculture causes, and for mitigating the encroaching problem of water scarcity, is the consideration of implementing regimes of improved irrigation efficiency.

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Efficacy of Boom Systems in Limiting Runoff on Center Pivots

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Abstract. Center pivot and linear move irrigation systems' design and operation are primarily limited by soil infiltration rates. Boom systems have been suggested to improve infiltration and decrease runoff by reducing the instantaneous water application rate of center pivots and linear move systems. In this research project, we compared runoff from plots irrigated with typical in-line sprinklers on a linear move irrigation system with those irrigated with off-set boom systems. In-line drops consistently generated greater runoff than 'the boom systems in all of the irrigation events. Differences in runoff between the drop types were significantly different for the second, third, fourth and fifth irrigation events. The runoff differences from in-line drops ranged from 3% to 24% greater than the boom systems. Runoff as a percentage of irrigation water applied increased with each irrigation event on both drop types.

Keywords. Center Pivot, Irrigation, Sprinklers, Offset, Boomback, Application Rate

Introduction

The use of mechanized sprinkler irrigation systems, particularly center pivots and linear move systems (or linears) have rapidly increased in the United States. Several surface irrigated areas are being gradually converted to sprinkler irrigation, especially center pivots. In 2007, center pivot and linear move irrigation systems accounted for 25 million acres (10.5 million ha) or 46% of the total area (56.8 million acres) irrigated in the United States (USDA, 2010). The growth in mechanized sprinkler irrigation systems, particularly center pivots in the recent years may be due to the automation built into them that allows for irrigation of many types of crops with minimal labor input, large area coverage, ability to operate on relatively rough topography, and finally, these systems can be highly efficient and uniform when they are designed and managed properly (Wilmes et al., 1993; Kincaid, 2005). However, the efficiency and uniformity of these systems can be considerably reduced by potential runoff as a result of the high application rates that are inherent with moving sprinkler systems (Kincaid et al., 1969; Thooyamani et al., 1987; Kincaid, 2005; Luz, 2011). Water application rates in moving sprinkler irrigation systems are generally much higher than those of stationary sprinkler systems. This is because moving systems must apply water over a given point in the field in a limited amount of time. When the application rate exceeds both the soil infiltration rate and the soil surface storage, water will flow on the soil surface producing runoff (Mielke et al., 1992; Luz and Heermann, 2004).

Potential runoff continues to be the major problem associated with moving sprinkler systems (Kincaid, 2005). Surface runoff is particularly more severe in center pivots or linears operated at low pressures (Wilmes et al., 1993; Thooyamani et al., 1986). The problem worsens at the outer end of the lateral for center pivots where the application rate is much higher than the other points closer to the pivot center (Allen, 1990; Kincaid et al., 1997; Bjorneberg, 2003; Bjorneberg et al., 2003; Smith and North, 2009).

Potential runoff can be reduced by increasing the lateral speed on the center pivot or the linear move systems, thereby reducing the irrigation depth applied during each irrigation 'run'. This however can be detrimental for plants needing deeper depths of irrigation. The major challenge in the design and operation of center pivots and linears then becomes designing systems that apply sufficient water to meets plants' water requirements with no or minimal surface runoff. The design should therefore be able to limit water application rates to values that are less than the sum of the soil's infiltration rate and the surface storage capacity at all times and along all points on the laterals (Allen, 1990). The infiltration rate varies with the soil type and the soil moisture conditions. Surface storage temporarily allows the water to pond until it infiltrates completely. Soil surface storage capacity is the ability of a soil to hold a particular depth of water ponding on its surface depressions without letting it flow. Soil surface storage capacity depends on the field slope, soil surface conditions and the type of crop grown on that field. Runoff can be prevented or reduced by increasing the amount of soil surface storage (Neibling et al., 2009).

Another way of trying to reduce runoff potential is by reducing the water application rate while maintaining an irrigation depth appropriate for the needs of the plants. Booms (offset-booms, or boombacks) are one way of decreasing the water application rate. In boom systems, the sprinkler heads are offset 10-20 ft (3 to 6 meters) from the irrigation tower's frame (Figure 1). Booms lower water application rate by applying water to a larger area (that is, by increasing the sprinkler wetted area) thereby allowing the soil to absorb the water at a slower rate, thus allowing larger application depths. This allows for less frequent irrigations and thus reducing surface evaporation and also reduces diseases in some crops (Kincaid et al., 2000). Less frequent irrigations of more water per pass also result in deeper root zones, less wear-and-tear on the pivot's motors and gear boxes, and power savings. Booms on alternate sides of the center pivot or linear move system can reduce the application rate of low-pressure spray sprinklers (King and Kincaid, 1997). The objective of this work was to compare runoff from booms with typical in-line drops that have the sprinkler heads in-line and directly underneath the irrigation tower's frame.

Materials and Methods

The research was conducted at the Washington State University (WSU) Irrigated Agriculture Research and Extension Center (IAREC) located near Prosser, Washington (latitude 46° 15' N, longitude 119° 44' W), USA.

A linear move irrigation system, Valley 8000 Series model, 148 m long was used for this experiment. Originally the system had all of its drops directly underneath the tower frame. The system was modified to include alternating booms in two groups as shown in Figure 2. The drops for the booms were moved 15 ft (4.6 m) from the irrigation tower's frame using light-weight galvanized steel tubing (BoomBacks made by IACO, Vancouver, WA). All the drops across the linear move system (both in-line and booms) were located approximately 9 ft (3 m) apart along the tower frame and 5 ft (1.5 m) above the soil surface. The sprinkler type used on both booms and in-line drops included a Nelson S3000 spinner with a yellow plate (Nelson Irrigation Corporation, Walla Walla, Washington, USA), a sprinkler nozzle diameter of 11/64ths (4.37 mm; Nelson nozzle size # 22) and a Nelson 15 psi (103-kPa) pressure regulator to give an application rate of 3.2 gpm (12.2 L min^{-1}). A pond nearby the experimental field was the source of water. The pond received surface water diverted from the Yakima River.

Figure 1. A part of the linear move system fitted with booms for the sprinkler runoff tests in 2013.

The experimental field was formerly a wheat field. After the wheat was mowed, the field was plowed with a disk plow. The runoff area plots were prepared manually using a shovel and a rake towards the end of the month of September 2013. The field contains Warden silt loam soil with average sand, silt and clay of 21, 68 and 11% respectively and with a slope of about 0.5%. Twelve runoff plots were installed in a three row by four column arrangement as shown in Figure 2. Average distance between the plots in a column ranged between 16 and 25 ft (5 to 7.5 m). There were two plot locations under regular drops and two locations under booms in each row. The plot locations were such that when the linear move system was directly over the plots, each plot was mid-way between two adjacent drops on the irrigation tower frame. Before the runoff plots were demarcated by metal frames, the areas where the plots were to be located underwent some preparations. First, the locations were raked back and forth to remove wheat straw that was covering the field surface after the field was plowed. The areas were then dug up with a shovel; the soil was dug up and turned over. This was to help loosen up the subsoil and to also break up clods of the earth. The plot areas were then raked back and forth again to further remove any straw that might have been remaining on the surface and to also make sure that all the plots were at the same slope and soil surface condition. This helped to minimize the variability between the plots' infiltration and soil surface storage components of the infiltration-storage-runoff process. All irrigation applications for this experiment were on relatively smooth and bare soil conditions.

Metal steel frames of area 12 ft^2 (1.12 m^2) were used to capture a representative sample field runoff and to prevent plot run-on from the surrounding areas. The metal frames were 1/8 inch (3 mm) thick and 8 in (20.2 cm) wide. The frames were oriented vertically and their bottom edges driven into the ground to a depth of about 3.5 in (9.5 cm). A PVC pipe, 2 inches (5.1 cm) in diameter and 5 inches (12 cm) long was fitted through a hole on the down slope outlet end of the frame (Figure 3). The cracks were sealed by using duck tape to widen the pipe just so that it had a pressure fit. The PVC pipe routed the runoff into a clear plastic bag tightly tied on to the PVC pipe. A hole was dug into the soil near the outlet of the plot for the bag to sit when collecting runoff from the plot. The volume of the runoff that collected in the bag was measured using a graduated cylinder, and the depth of runoff and percent runoff (that is, depth of runoff / depth of irrigation applied × 100) was determined for each plot.

Five irrigations were applied to the runoff plots with irrigation intervals varying between 1 to 4 days during the month of October. The dates that the experiment was run and the application depths are recorded in Table 1. The one day irrigation interval didn't let the soil profile drain sufficiently before irrigations. The application depths were hence progressively decreased as the experiment progressed to prevent excessive runoff. Application depths for particular irrigation events were chosen to ensure that measurable runoff occurred on the plots for each irrigation event. Rainfall was minimal during the experimental period; less than 0.04 inches (1 mm) of rainfall was received on 10/8/2013. Each runoff plot had two catch cans placed on the ground near the plot that were used to measure the volume of water applied (Figure 3).

A block design with two blocks, two treatments and three replications per treatment was used for this experiment and solved using Minitab 16.2.3 GLM procedure (Minitab, 2012). Tukey's Studentized range test was used for treatment mean comparisons of runoff and runoff percentage at a 0.05 probability level.

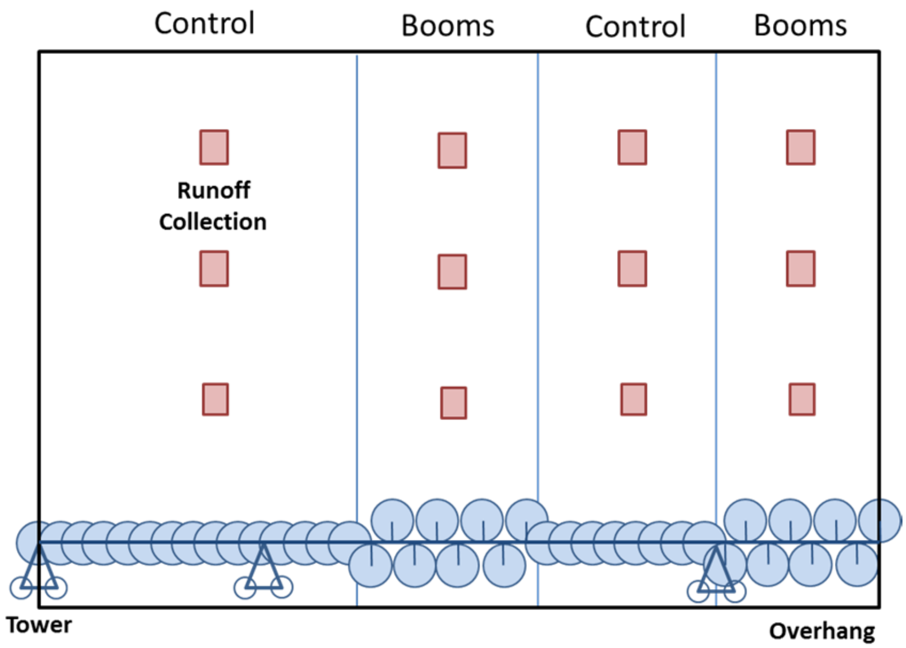

Figure 2. Runoff plot layout for field studies in 2013.

Figure 3. Runoff plot components.

Results and Discussion

Runoff from irrigation events was determined during the month of October of 2013. The irrigation events, including dates, application depths and runoff are summarized in Table 1. Runoff from the in-line drops ranged between 11.2% and 60.1% of the irrigation depth applied during the period of testing (Figure 4). The booms generated runoff ranging between 6.9% and 39.5% of the irrigation depth applied. In-line (control) drops generated greater runoff than the booms in all the irrigation events; the runoff differences between in-line drops and the booms ranged from 3% to 24% of the irrigation depth applied.

The differences in runoff from in-line drops and booms were significant for 2nd, 3rd, 4th and 5th irrigation events. On a field level, this reduction in runoff through using booms will minimize crop water stress by allowing more water to infiltrate into the soil and be used by the crop. This will boost crop yields and also improve the efficiency of the irrigation system. Also, with less runoff and more infiltration, pumping costs are reduced since less passes of the center pivot or linear move system will be required to sufficiently irrigate the crop during the growing season. A boost in crop yields increases farm revenue while reduction in pumping costs reduces crop production costs. Increase farm revenue and savings in water and pumping costs due to booms may be more than enough to compensate for the increased equipment costs due purchase, installation and management of booms.

Table 1. Date, wind speed, and average irrigation and runoff for each irrigation event and for each drop type.

Irrigation		Wind	Application	Runoff (in)		ANOVA	Difference in
Event	**Date**	**speed (mph)**	**depth (in)**	**Control**	**Booms**	**probability**	**runoff** (%)**
1	10/2/2013	3.13	1.25	0.13 a*	0.09 a	0.28	3.0
2	10/9/2013	2.71	0.70	0.26 a	0.20 b	0.03	7.9
3	10/14/2013	3.60	0.61	0.25 a	0.16 b	0.00	14.6
4	10/16/2013	3.13	0.40	0.25 a	0.16 b	0.02	22.4
5	10/18/2013	3.20	0.41	0.24 a	0.14 b	0.02	24.2
Total			**3.37**	**1.14 a**	**0.76 b**	**0.003**	

***** Values in rows with the same letters are not significantly different at a significance level of 5%.
** Difference in runoff between in-line drops and booms expressed as a percentage of irrigation applied per irrigation event.

The runoff trends (Figure 4) for both the in-line drops and the booms show similarity in runoff patterns as affected by the antecedent soil moisture content, time between irrigation events and soil surface sealing. The soil surface layer in both treatments was equally dried by evaporation and infiltration differences may have been largely influenced by soil surface sealing which was as a result of droplet impact on to the bare soil. This could explain the increasing percent runoff in both treatments as the number of irrigations increased (Figure 4). Runoff percentages generally increased with increased number of irrigations in both treatments. However, the increase was steeper with in-line drops than with booms. This suggests that boom systems may preserve the soil structure and reduce soil compaction. Booms thus may be a way of minimizing the increase of runoff that might occur throughout the season for in-row crops like potatoes.

Four out of the five irrigation events produced significantly different runoff percentages between the regular drops and the booms. The first irrigation event produced the least runoff for both regular drops and the booms due to minimal surface sealing as the plots had just been established and also because the runoff plots' soil moisture content was lowest prior to the first irrigation event. As the initial soil water content increases, infiltration decreases. The application intervals for this experiment ranged between 1 to 4 days. Not allowing the soil profile to sufficiently drain before an irrigation event further increases the occurrence of runoff.

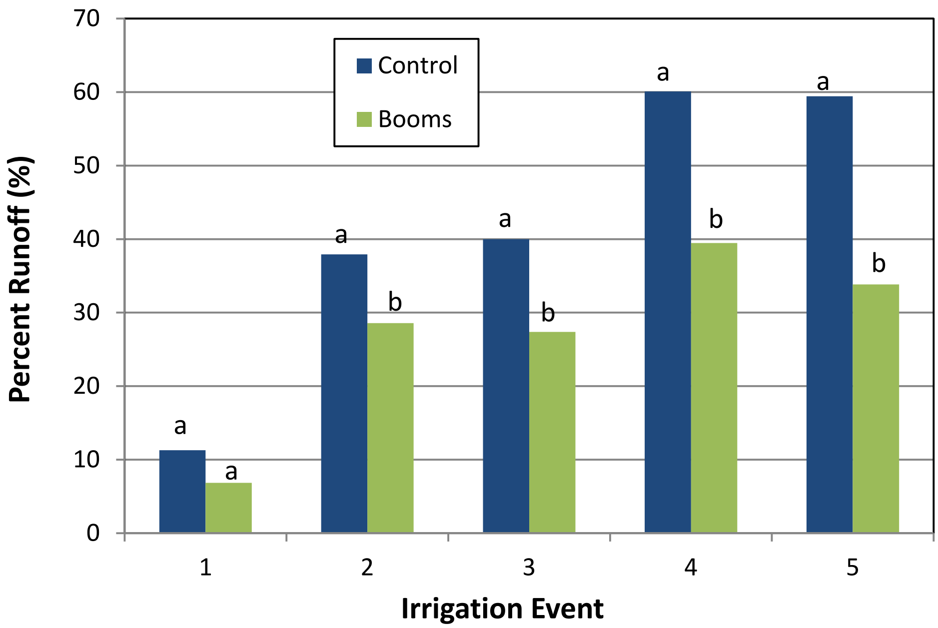

Figure 4. Runoff percentage (that is, measured runoff expressed as a percentage of measured applied water) for the runoff tests for each irrigation event. Treatments with the same letter for a particular irrigation event are not significantly at a significance level of 5%.

Conclusions

This study compared runoff from in-line drops with boom systems. The highest runoff occurred with in-line drops in all the irrigation events. In-line drops produced between 3% to 24% more runoff than the booms. This study shows how the use of boom systems is an effective way of lowering the water application rate through increasing the wetted sprinkler area thus minimizing soil compaction and encouraging infiltration of water into the soil. It appears that the more difficult it is to get water into the soil, the greater the benefit is from using booms.

Runoff from a particular area in a field depends on the slope, the initial soil water content and the roughness of the soil surface. In the application of mechanized sprinkler systems, care must be taken to match water application rates to infiltration rates of the soil under sprinkler conditions, and to the soil surface conditions in order to minimize runoff. Minimizing runoff will result in water savings, savings in pumping costs and minimize crop water stress.

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Simplified Irrigation Scheduling on your Phone or Web Browser

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Abstract. *When good irrigation scheduling is practiced everybody wins. However data-based irrigation scheduling is still not commonly practiced because it is often expensive, complicated, and time consuming. To be useful, irrigation scheduling tools must be very simple, intuitive, robust, and not ask growers for information that they don't know. Irrigation Scheduler Mobile is a free online irrigation scheduling tool for doing simplified check-book style irrigation scheduling. It works on any smart phone platform including iPhone, Android, or MS Windows Phone, or Blackberry. There is also a downloadable Android version with an iPhone version in development. However, because it operates as a web page it also works perfectly well on any desktop web browser. It is fully integrated with most of the agricultural weather networks in the west. Daily crop water use (ET) estimates and rainfall data are automatically filled in. It is free, and to date over 2000 fields have been set up on it. It works for turf as well as most agricultural crops. This paper describes this tool and its operation as well as how to adapt it to other areas of the U.S. or world.*

Keywords. Irrigation scheduling, evapotranspiration, crop coefficients, mobile app

Introduction

Irrigation scheduling is finding the answers to two basic questions: “When do I turn the water on?” and, “How long do I leave it on?” Improved irrigation scheduling has tremendous public and private benefits. Including the following:

Benefits to the grower:

- Improved yields,
- Improved quality,
- Lower pumping energy costs,
- Lower irrigation-related labor costs, and
- Decreased loss of expensive fertilizers to runoff or leaching.

Benefits to the environment:

- Less movement of fertilizers and pesticides with the water off of farms fields into streams, water-bodies, and groundwater (non-point source pollution), and

- More water remains available in groundwater and in streams for alternative uses including fish and wildlife habitat.

Benefits for energy supply/conservation:

- Decreased irrigation energy pumping costs (typical values are 10-20% savings), and
- Water remains in rivers to drive power-generation turbines at multiple dam sites.

There are many irrigation scheduling tools available including paper-and-pencil versions (e.g. Wright, 2002), spread sheet versions (e.g. Clark et al., 2001), compiled program versions (e.g. Rogers et al., 2009), and online versions (e.g. Hillyer and English, 2011). However these tools are not widely used and most of them are not readily adaptable to other states or countries. The most common reason cited for not using these tools is that they are difficult to learn, time consuming to use, and that the grower does not feel that it is worth this time and effort required. Agricultural producers are also rarely in the office and don't get many chances for, and tend to not enjoy doing "desk-work." A simple and user-friendly irrigation scheduling tool that is accessible from a smart phone is needed to increase the adoption of data-based irrigation scheduling.

Irrigation Scheduler Mobile is a soil water balance model that meets these requirements. It is a free irrigation scheduling tool developed by Washington State University that is designed for use on a smart phone or on a desktop web browser for doing simplified check-book style irrigation scheduling. In addition it has the following features:

- It is simple to set up and intuitive to use.
- There are help menus on each page.
- It uses tables of default crop and soil parameters to simplify setup
- It automatically pulls daily crop water use (evapotranspiration, or ET) estimates from a chosen weather station in a fairly expansive number of agricultural weather networks.
- It readily displays useful charts and tables for visual evaluation of soil water status and model inputs.
- It is flexible enough to allow modifications by educated users for improved accuracy.
- The model can be corrected using soil water measurements or estimates.
- It includes a one-week forecast of crop water use and soil water status for irrigation decision planning.
- It works with cutting dates to model forage regrowth.
- Growers can interact with it in terms of hours of irrigation run time or in inches of water applied. Simple calculators are included to help calculate irrigation application rate if required.
- A correction for the smaller active soil volume due to un-irrigated inter-rows is included.
- Soil water can be displayed as a percent of the total available water (100% = full, 0% = empty), or as volumetric soil water content (water's percentage of the total soil volume) for better comparison with soil moisture sensors.
- It can send push notifications to growers in the form of an email or as a text message.
- When adding a new field you can copy settings from an existing field.
- Since it is designed as a web application, it can be run on any mobile phone platform with internet access, or directly from a full sized computer web browser.

- There is a full-size computer web browser interface from http://weather.wsu.edu.
- You can download all of the data to a comma-separated variable (csv) file for more detailed analysis.
- It can do use reporting of the number of days each field was viewed and or edited by month. This was requested for cost-share documentation.
- It is possible to set up different crop defaults for different climatological regions (groups of weather stations).

Background Information and Model Assumptions

Soil serves as a reservoir to store water and nutrients for the plant. Knowing when to irrigate and how much water to apply requires knowledge of three things:

1. How much water can the soil hold?
2. How much water is the plant using?
3. At what point (soil water content) will the plant begin to experience water stress?

Let's discuss each of these separately.

How Much Water Can the Soil Hold?

Water is held in the empty spaces between soil particles. When these empty spaces are completely filled, the soil is said to be saturated (Figure 1). Excess water will drain out over time until a point where the soil can hold a certain amount of water indefinitely against the downward pull of gravity. This soil water content is the soil's *full* point called ***field capacity (FC)*** and in this application is measured in inches of water per foot of soil depth. The excess water that drains will move down to lower soil layers. Applying more water than a soil can retain in the plant's managed root zone results in water loss to ***deep percolation (DP)*** or "deep water loss". Water loss to deep percolation wastes water, pumping energy, and vital plant nutrients that are held in the soil water solution.

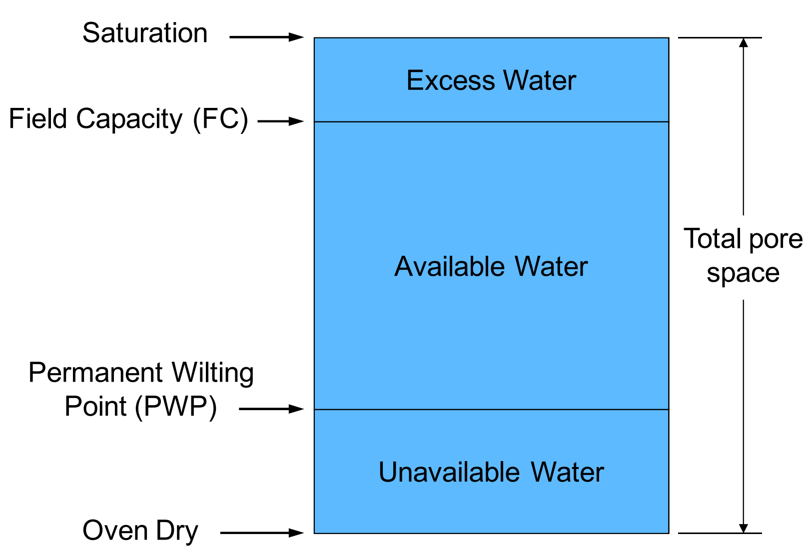


Figure 1. The various components of the soil water content.

As a plant's roots remove water from the soil, the soil dries out to the point where the suction or pull of the soil on the water is greater than the plant's ability to absorb water. At this point the plant will wilt and die. Although there is water left in the soil, from the plant's perspective the soil is *empty.* This soil water content is referred to as the ***permanent wilting point (PWP)*** and is also measured in inches of water per foot of soil depth. The difference between field capacity and permanent wilting point is known as the ***available water-holding capacity (AWC)*** again given in inches of water per foot of soil depth.

$$AWC = FC - PWP$$

Different soils have different available water-holding capacities. For example, sand cannot hold as much water as a silt soil. The default values of FC, PWP, and AWC that are used in this model for different soil textures are given in Appendix A.

A plant's rooting depth is also an important consideration. A plant with deeper roots has access to much more soil and consequently has a larger reservoir of soil water to draw upon compared to plants with shallower roots. The FC, PWP, and AWC are multiplied by the rooting depth to get the *amounts* of water held at those points in inches. Rooting zone depths change over time as the plant and its roots grow. Root growth in Irrigation Scheduler Mobile is assumed to increase linearly from a beginning depth at the planting or emergence date and is assumed to reach their maximum depth at the same time the crop canopy reaches full cover or covers (shades) 70-80% of the field area (Figure 2). After this time the root depth is assumed to remain constant until the end of the growing season.

Default values for the parameters that define the changing root zone depth for the various crops are given in Appendix B.

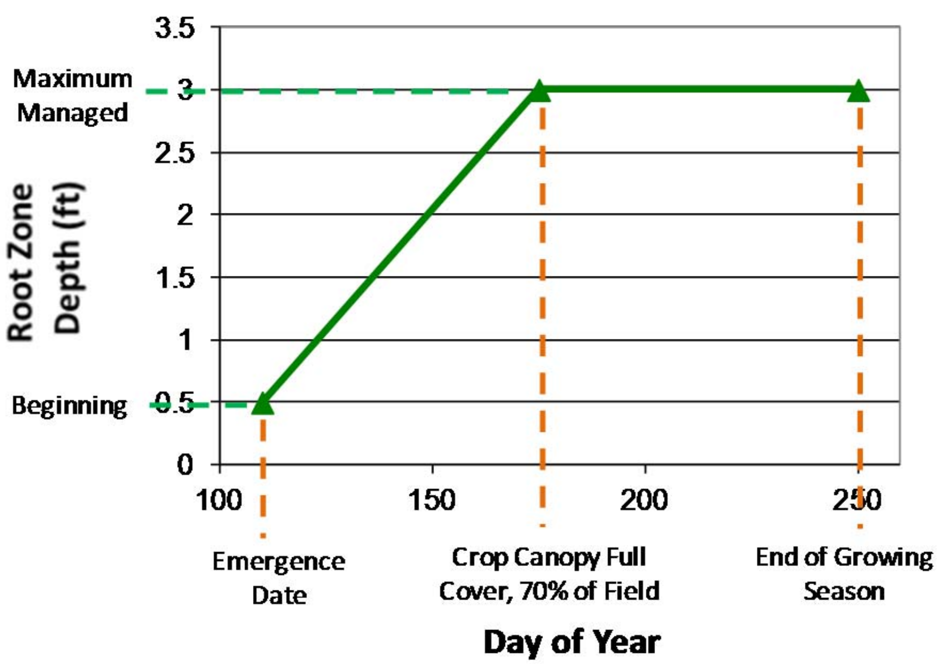


Figure 2. Parameters that define the changing root zone depth. Defaults values for these parameters are set based on the crop chosen, but can be modified in "Advanced Field Settings."

How Much Water is the Plant Using?

The amount of water required to grow a crop consists of the water lost to evaporation from a wet soil surface and leaves, and transpiration of water by the plant. Together these are called ***evapotranspiration (ET)*** and are also referred to as crop water use. ET is measured in inches of water used per day. The crop evapotranspiration (ET_c) is calculated as:

$$ET_c = K_c \times ET_r$$

where ET_r is the estimated evapotranspiration of a reference surface of full grown alfalfa that is calculated from measured weather data. The weather data used to calculate ET_r include solar radiation, air temperatures, humidity, and wind speed data. Irrigation Scheduler Mobile uses alfalfa reference ET_r as calculated by the ASCE standardized Penman-Monteith Equation (ASCE – EWRI, 2005). K_c is a crop coefficient specific to a crop and that crop's growth stage over the season. Crop coefficients Irrigation Scheduler Mobile are mean crop coefficients and defined as in the FAO-56 publication (Allen et al., 1998; Figure 3). Default dates and crop coefficient values for different crop s are given in Appendix B.

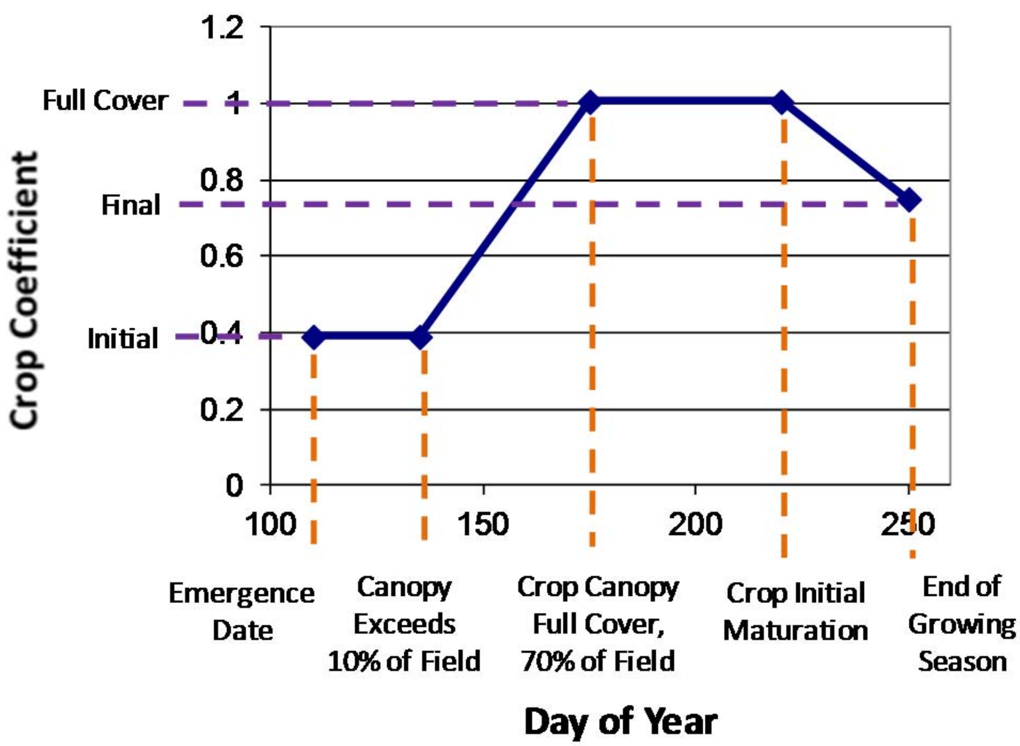


Figure 3. Parameters that define the crop coefficient curve.

At What Point Will the Plant Experience Water Stress?

As water is removed from the soil through ET there is a point below which the plant experiences increasing water stress. This point is known in this model as the first stress point or more generally as the ***management allowable depletion (MAD)***. To manage the soil water for maximum crop growth, depletion below this point is undesirable. As the soil water content decreases below MAD the stomata in the plant leaves will begin to close, the leaves will often curl or droop, and the plant will use less water and the growth will decrease. *The model estimates this decrease in water use according to Figure 4*. Daily crop water use is proportionately decreased as the % of available water decreases below MAD towards the PWP. This follows the water stress coefficient (Ks) concept as described by Allen et. al. (1998). Irrigation scheduling for maximum crop growth requires maintaining the soil water content between field capacity and the MAD.

Different plants are more resistant to water stress than others and therefore the MAD for each crop may be different. The default MAD values for the various crops are given in Appendix B.

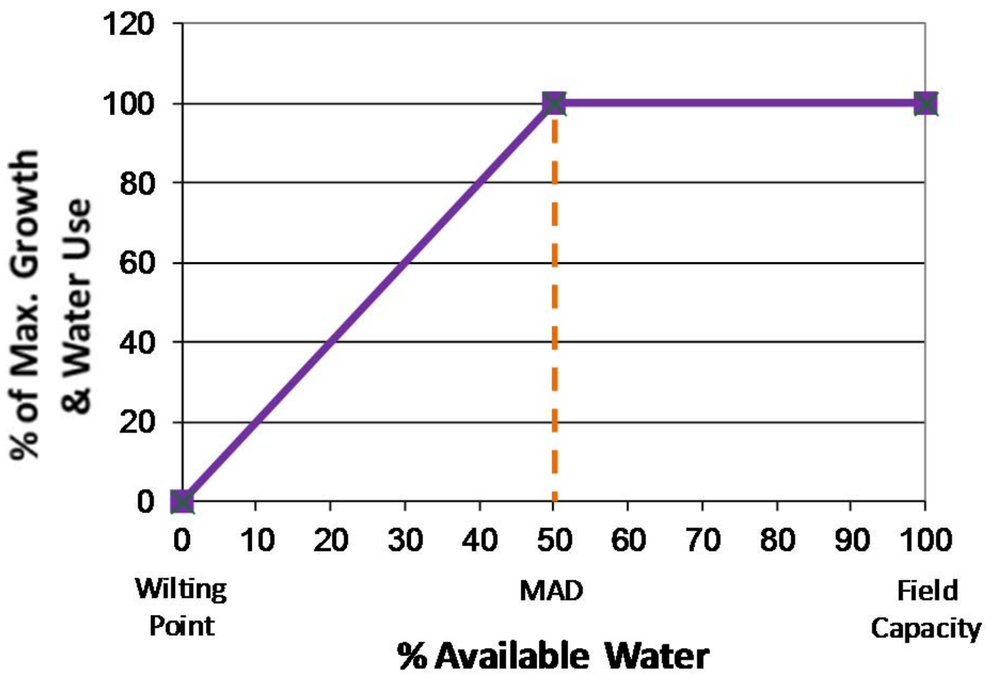


Figure 4. Water use is proportionately decreased as the % of available water goes below the MAD. Yield is also assumed to decrease in the same pattern. Defaults values for MAD is set based on the crop chosen, but can be modified in "Advanced Field Settings."

Other Model Assumptions

The following additional assumptions are made by this soil water balance model in order to simplify the model and to avoid requiring information from the grower that he/she does not know.

- All rainfall or water entered as an irrigation amount infiltrates into the soil.
- Water in the plant's root zone is equally available to the plant regardless of depth.
- The season begins with a full soil profile (at field capacity). This beginning soil water content can be modified by using the "Reset/ Correct Soil Water Availability" option on the first day in the Daily Budget Table. Plant roots grow into soil that is at field capacity.
- Water moves quickly into the soil and excess water is lost quickly to deep percolation (within the daily time step, or 24 hrs).
- All rainfall goes towards satisfying the calculated atmospheric ET demand.

Using the Model / Page Descriptions

7-Day Daily Budget Table

The Daily Budget Table screen (Figure 5) shows the most relevant values from a daily soil water budget and allows the user to edit the inputs for each day using the “Edit” link.

The data in each column is described below:

Water Use (in/day): This is the daily crop water use (evapotranspiration or ETc) estimated from measured weather parameters from the selected weather station, and the entered crop coefficients. This model uses alfalfa reference evapotranspiration calculated using the standardized ASCE Penman-Monteith method. The model gets the weather data from the weather network when the model is first opened, if it has been greater than two hours since the data was pulled, or after a change is made in Field Settings. Because of this, if the weather network managers make corrections to the historical data for that weather station, these changes are reflected in the model.

Rain& Irrig. (in): This is the sum of the measured rainfall at the weather station for that day and/or and the irrigation amount. Irrigation events must be entered using the Edit link. This is net irrigation, not gross. Some applied irrigation water is lost to evaporation. Therefore gross irrigation amounts must be discounted for irrigation efficiency. Typical irrigation efficiency values are: drip-95%, center pivot-85%, wheel/hand lines/lawn sprinklers-70%, big guns-60%. For example a gross depth of 1 inch of water is applied by a center pivot, enter 0.85 here (1 inch x 85%/100). If you use measured application depths, don’t correct for efficiency. *For surface irrigation, a reasonable assumption is that you completely refill the soil to field capacity, or replace the soil water deficit.*

Soil Water (%): This is the calculated daily soil water content expressed as a percent of the available soil water. 100% is equivalent to field capacity, and 0% is equivalent to wilting point. Entering a measured or estimated soil moisture value here (using the Edit link) will correct the model to the entered value from that day forward. Volumetric soil water content for comparison with soil moisture sensor readings is available in the expanded information (click the date; Figure 9).

Water Deficit (in): The soil water deficit in the root zone. This is the amount of "space" in the soil, or the depth of irrigation water that can be applied before the soil is full again (reaches field capacity).

Edit Data: Use this link at each line to add irrigation amounts or correct the model for measured soil water contents (Figure 7).

Some descriptions of how the page operates:

Line Colors: When the calculated soil water content is well above the MAD point and the plant growth should be at maximum, then the row is highlighted green (Figure 5). When the soil water content gets close to the MAD line (only 15% of the readily available water remaining) then the row turns yellow. And when the soil water content goes below the MAD line the row is highlighted red as a warning of crop water stress.

The Most Important Number: The most important value for irrigation scheduling is *this morning's soil water deficit*. This is the amount of water that I need to apply today to completely refill my soil profile. If I apply more water than this, some will be lost to deep percolation because the soil can't hold it all. It is highlighted in **red** (can be seen in Figure 9).

Navigation: You can navigate to other dates in the growing season using the buttons at the bottom of the table. The date button in the middle is used to go to the week starting with the chosen date (Figure 6). Note that you cannot navigate outside of the growing season as defined by the crop's planting date and end-of-season or harvest date as defined in Field Settings. The |<< and >>| buttons takes you to the beginning of the growing season and to today (or to the growing season) respectively. The <<< and >>> buttons navigation you forward or backwards respectively in time by one week.

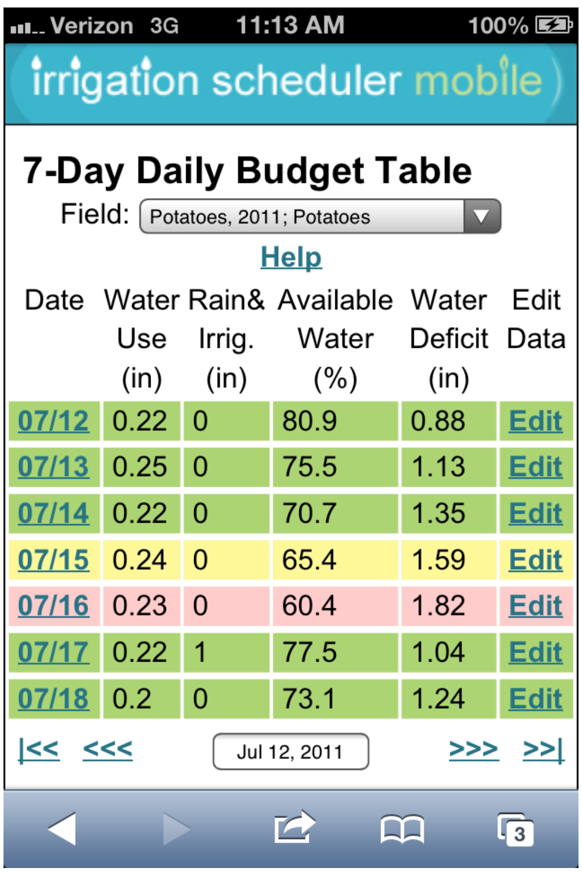


Figure 5. Daily Budget Table screen

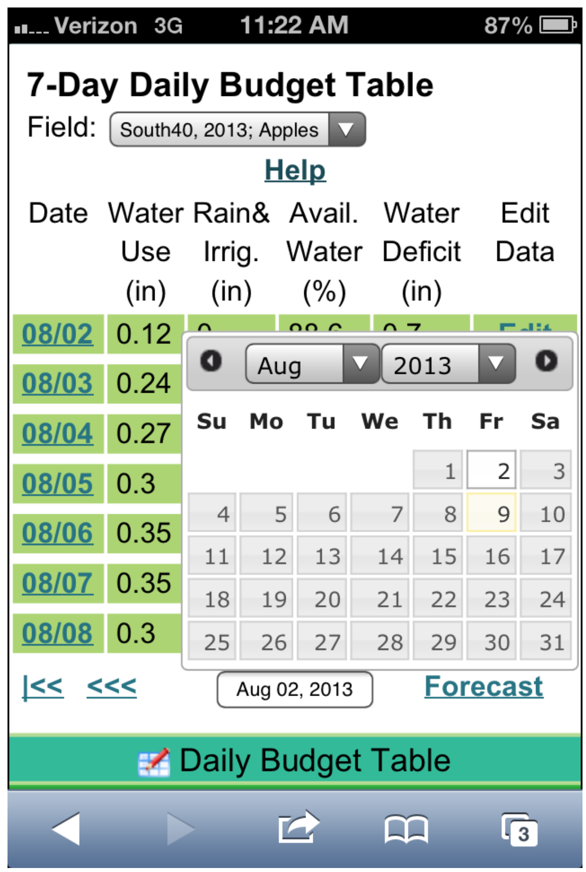


Figure 6. Choose first date of week to view.

Forecast: The last day on the Budget Table represents very early this morning. A seven-day forecast is available. This forecast is based on the projected maximum and minimum temperatures from the National Weather Service (NWS) for those days at the latitude and longitude of the chosen weather station. The Hargreaves equation is used with these temperature data to estimate grass reference ETo which is then multiplied by 1.2 for alfalfa reference ETr which is used in the model. If the model is viewed late in the day, the 7th forecasted day is from the NWS. However before 6 PM the 6th forecasted day is repeated for the 7th forecasted day. Irrigations can be entered in the future to do planning. These irrigation events will remain as time passes from the future to the past. Historical ET information always overwrites forecasted values. Forecast values are pulled when the field is first viewed, once every two hours, or after a change is made in Field Settings.

Edit Data: Clicking the Edit link on that day expands the screen to accept inputs for that day as shown in Figure 7. From here you can add or edit irrigation amounts, or reset or correct the soil water availability to make it better match reality based on observations or soil moisture measurements. Click Cancel closes the table up again. You must click Save for these changes to be applied.

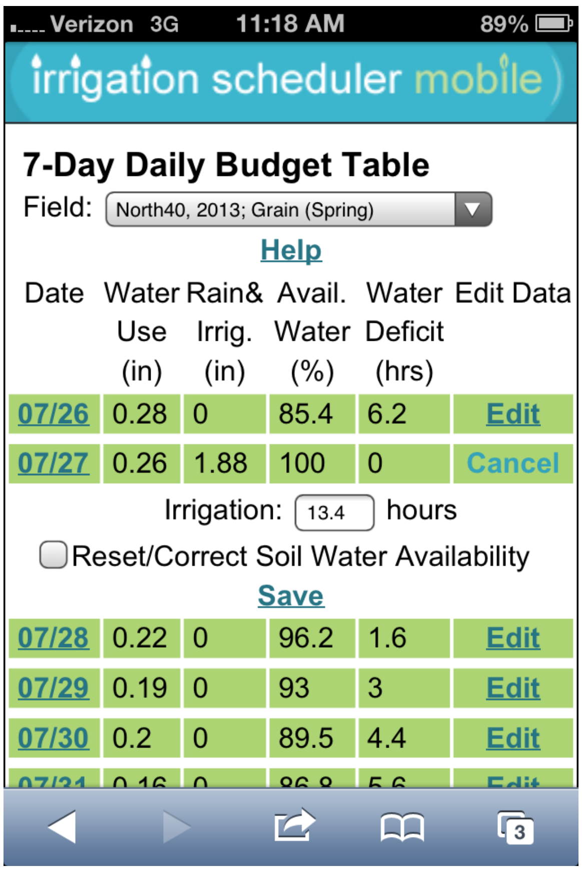


Figure 7. Edit button expands table for inputs.

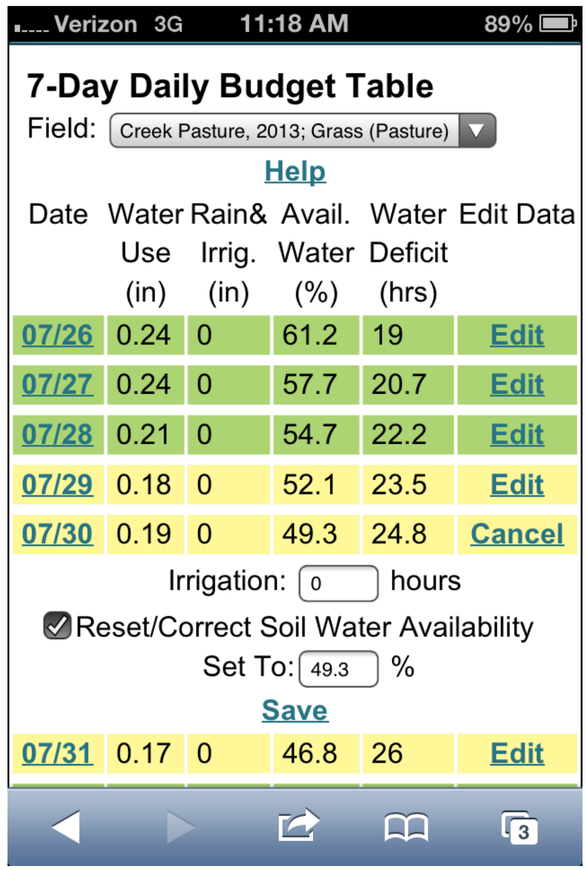


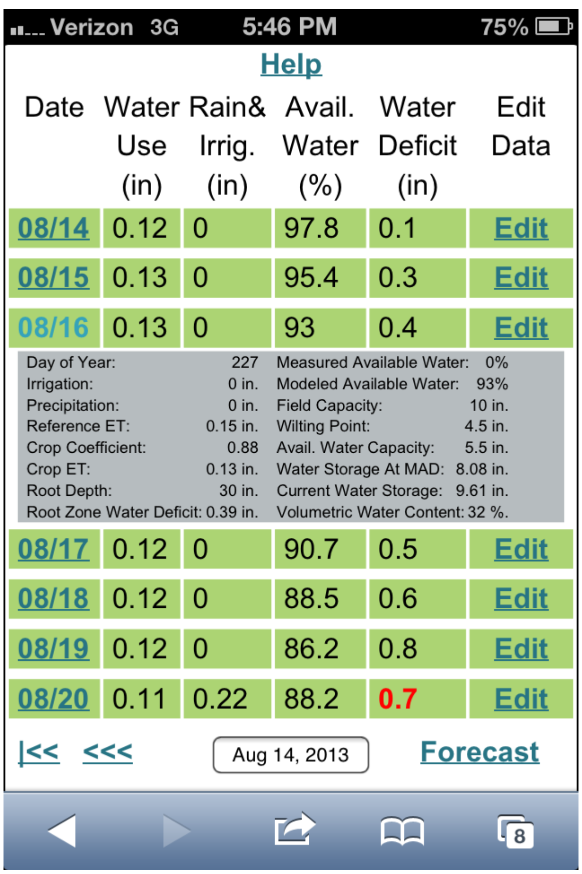
Figure 8. Reset/Corrective Soil Water Availability

Irrigation: Enter the net amount of irrigation applied to the field on this date. If you chose to use hours instead of inches in Field Settings then you can enter this value in hours of irrigation run time. Some applied irrigation water is lost to evaporation. Therefore *gross irrigation amounts must be discounted to account for irrigation inefficiency*. This is done by multiplying by the irrigation efficiency as a decimal (% / 100). Typical irrigation efficiency values are: drip-95%, center pivot-85%, wheel/hand lines/lawn sprinklers-70%, big guns-60%. For example, a gross depth of 1 inch of water is applied by a center pivot, enter 0.85 here (1 inch x 85%/100). If you use measured application depths, don't correct for efficiency. For surface irrigation, either use a very large number (like 3-4 inches at each irrigation) or a reasonable assumption is that you completely refill the soil to field capacity to 100% Available Water, or completely replace the soil water deficit.

Reset/Correct Soil Water Availability: Check this box to overwrite the calculated percent of available soil water with an entered number (Figure 7). You might want to do this to correct the model to make it better match observations or a soil moisture measurement. The model will use your entered value as the new value and will calculate the estimated soil water content from that point on. Unchecking this box will make model return to the calculated value.

Correcting Rainfall (in): Measured rainfall is automatically included from the weather station. If you measured rainfall at your field and it differs significantly from the existing value, you can correct it by adding *the difference* as an irrigation. If you measured less rainfall than the weather station reported, you can subtract the difference by adding this difference as a *negative* irrigation value. It makes the soil water chart look funny to plot that negative value, but the math works correctly.

Additional Details: Additional details of the daily soil water budget are available by clicking on the date (Figure 9). This will expand the table to show these details. The table can be returned to normal again by clicking the date again.



Date	Water Use (in)	Rain& Irrig. (in)	Avail. Water (%)	Water Deficit (in)	Edit Data
08/14	0.12	0	97.8	0.1	Edit
08/15	0.13	0	95.4	0.3	Edit
08/16	0.13	0	93	0.4	Edit

Day of Year:	227	Measured Available Water:	0%
Irrigation:	0 in.	Modeled Available Water:	93%
Precipitation:	0 in.	Field Capacity:	10 in.
Reference ET:	0.15 in.	Wilting Point:	4.5 in.
Crop Coefficient:	0.88	Avail. Water Capacity:	5.5 in.
Crop ET:	0.13 in.	Water Storage At MAD:	8.08 in.
Root Depth:	30 in.	Current Water Storage:	9.61 in.
Root Zone Water Deficit:	0.39 in.	Volumetric Water Content:	32 %.

Date	Water Use (in)	Rain& Irrig. (in)	Avail. Water (%)	Water Deficit (in)	Edit Data
08/17	0.12	0	90.7	0.5	Edit
08/18	0.12	0	88.5	0.6	Edit
08/19	0.12	0	86.2	0.8	Edit
08/20	0.11	0.22	88.2	0.7	Edit

Figure 9. Clicking on the date expands the table to show additional details for that date.

Soil Water Chart

The soil water chart (Figure 10) shows the estimated soil water content (blue line) over time in relation to the field capacity (light green line), management allowable depletion (MAD; red line), and the wilting point (**black line**). All of these may change over time as the soil volume available to the plant increases with the growing plant roots (i.e. the upwards slopes in the first part of the season).

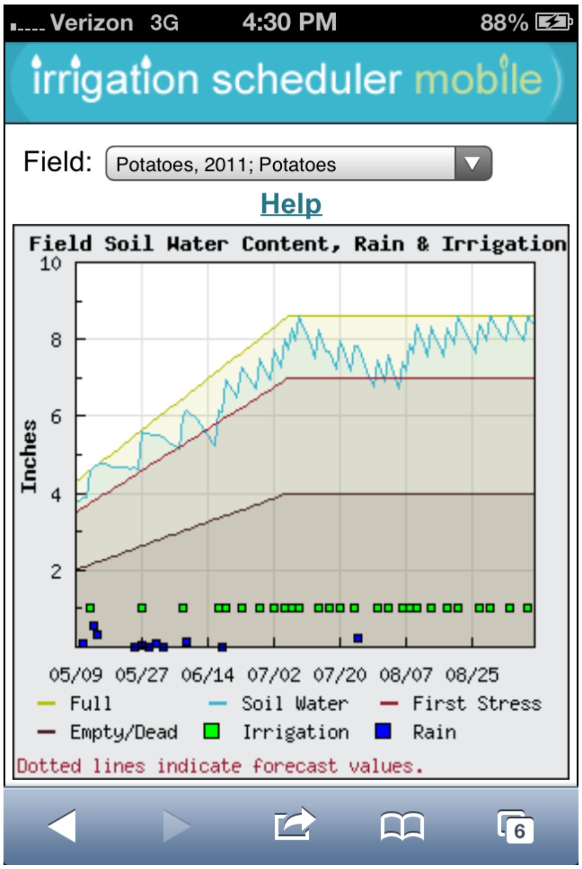


Figure 10. Soil Water Chart

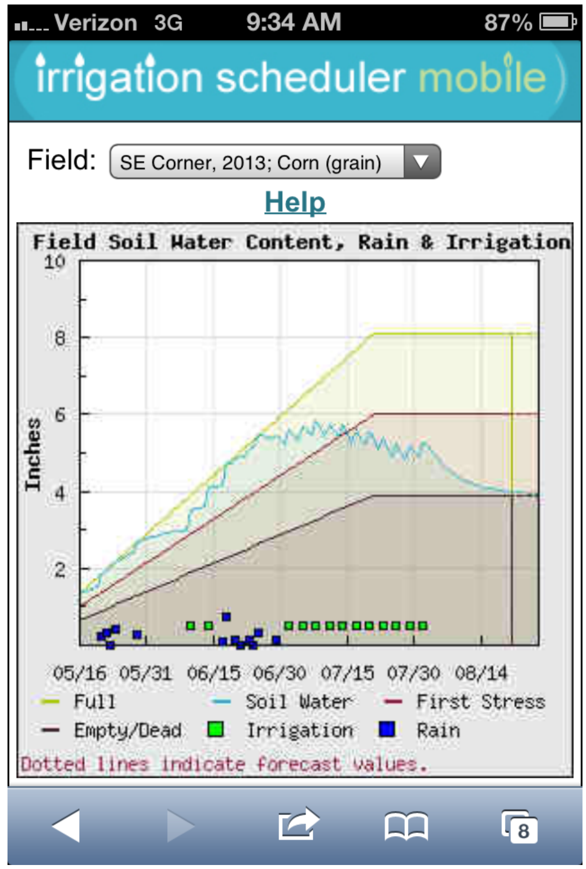


Figure 11. Shows how water stress (below the MAD line) causes daily water use to decrease.

Enter irrigation events (green points), or correct the estimated % available water content based on soil moisture measurements or estimates in the “Daily Budget Table” to make the soil water content better represent your field conditions. Rainfall amounts are pulled from the weather station (blue points). If you find that this model is consistently off, try editing the dates and crop coefficients in “Field Settings”.

Figure 11 is an example of a field where the irrigation system cannot keep up with crop water use demands and also shows how the model will modify daily crop water use numbers using the assumptions illustrated by Figure 5. As the soil dries below the First Stress (MAD) point, the *rate* of drop in the soil water content decreases over time as the plant shuts down.

For maximum crop growth and production keep the soil water content (blue line) between the Full point, or field capacity; top green line) and the and the First Stress (MAD, middle red line).

More Charts

Clicking the "More Charts" button will give you access to the additional charts shown in Figure 12 that help you understand and evaluate your field and your soil water balance model. Clicking "Less Charts" hides these charts again.

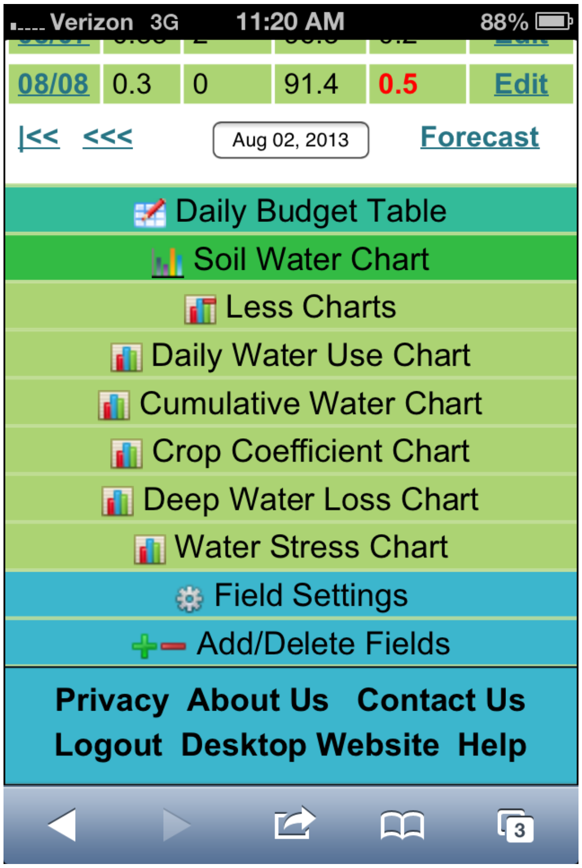


Figure 12. Clicking More Charts

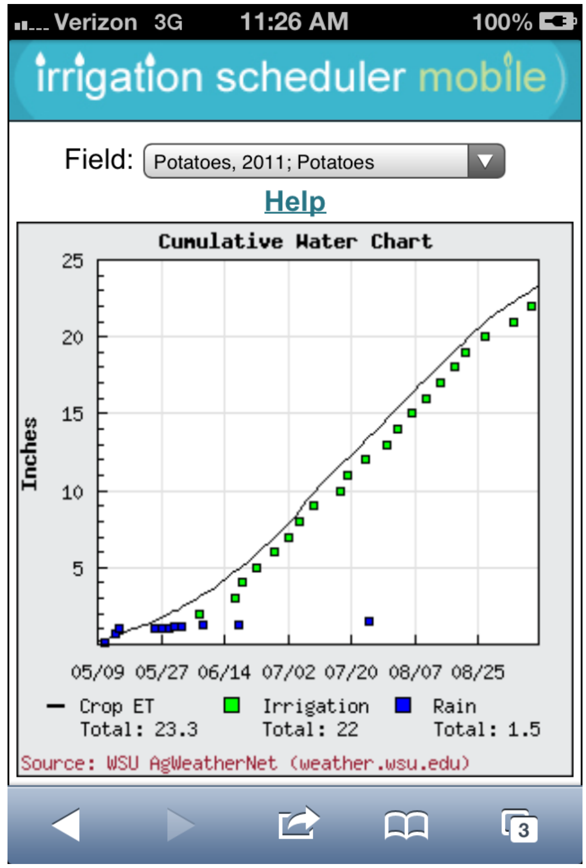


Figure 13. Cumulative Water Chart

Cumulative Water Chart

Figure 13 shows the cumulative crop evapotranspiration (ETc, or crop water use), irrigation, and rainfall over the specified growing season. The season totals are given in the chart legend.

Crop Coefficient Chart

Crop coefficients (Kc) are multiplied by the daily reference alfalfa evapotranspiration (ETr) rate that is calculated from the measured weather parameters from your chosen weather station. The Crop Coefficient Chart (Figure 14) shows the crop coefficient curve used for this field over the growing season. Also shown is the root zone depth over time. The values that define these curves can be viewed and edited on the "Advanced Field Settings" page

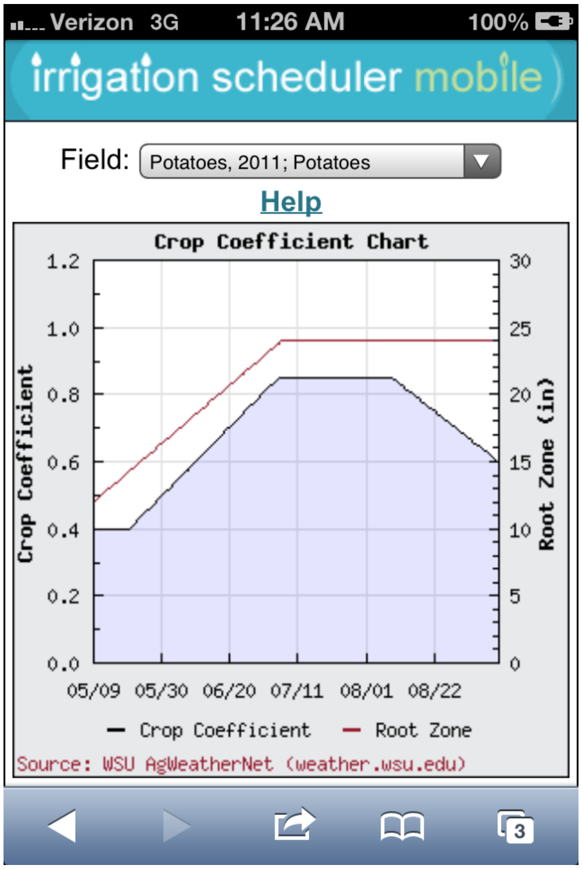


Figure 14. Crop Coefficient and Root Depth Chart.

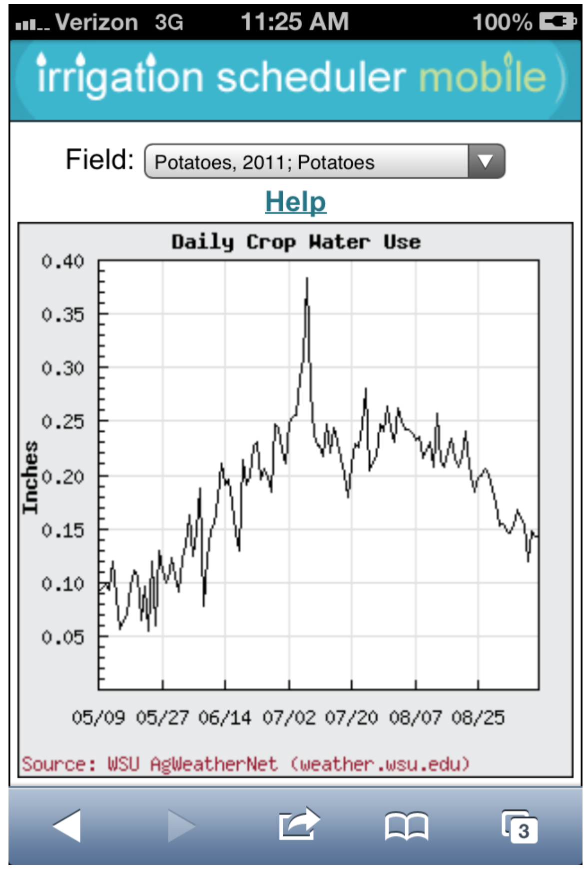


Figure 15. Daily Crop Water Use Chart

Daily Water Use Chart

The Daily Water Use Chart (Figure 15) shows the daily crop water use (evapotranspiration, or ETc) over the specified growing season. This is calculated as ETc = ETr x Kc where ETr is alfalfa reference evapotranspiration and Kc is the crop coefficient for that day. These values are affected by the weather (hot, dry, sunny, and windy days cause the plants to use more water), the crop coefficients, and the water stress status of the plant (below MAD, the crop water use is proportionately decreased as described in the user's manual).

Deep Water Loss Chart

When more water is applied than can be held in the root zone (soil water content exceeds field capacity), then this water moves down past the bottom of the root zone and is lost to deep percolation. The deep water loss chart (Figure 16) shows the cumulative water losses to deep percolation.

Water Stress Chart

This model uses a very simplified method of yield loss estimation. When the soil water content goes below the red MAD line as in Figure 11 it is assumed that there is yield loss that is equivalent to the amount of decreased water use similar to Figure 5. In other words:

$$\frac{Y}{Y_m} = \frac{ET}{ET_m}$$

Or solved for yield,

$$Y = Y_m \times \frac{ET}{ET_m}$$

where Y is the actual crop yield, Y_m is the maximum obtainable crop yield, ET is the actual crop water use, and ET_m is the maximum possible crop water use. The right-hand portion of this equation can be simplified as a crop water stress coefficient (K_s) that behaves as shown in Figure 8 as:

$$K_s = \frac{ET}{ET_m}$$

The % yield reduction on any particular day is therefore (1-Ks) × 100%. This is what is charted (Figure 17).

The season-long total estimated yield loss due to water stress as shown on this chart is therefore calculated using the season-long mean K_s (K_{sm}) as:

$$(1 - K_{sm}) \times 100\%$$

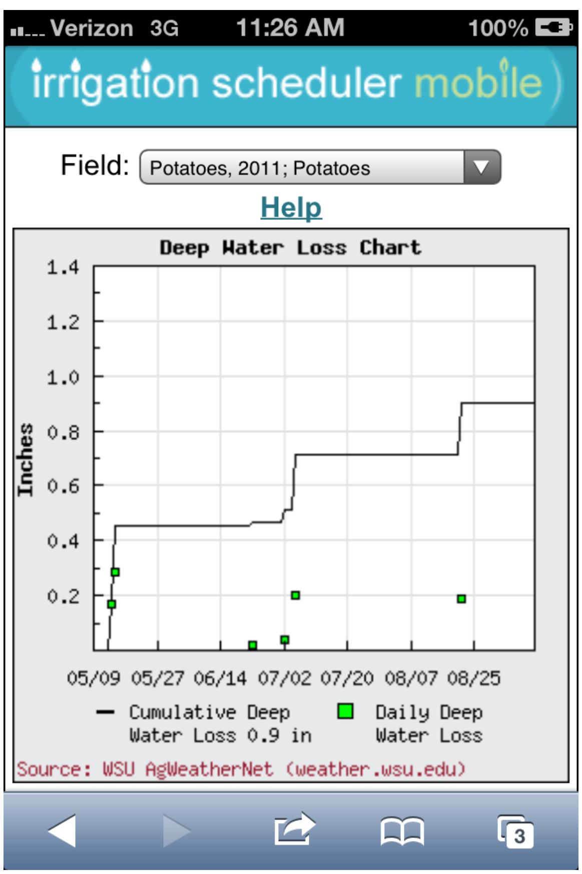


Figure 16. Cumulative Deep Water Loss

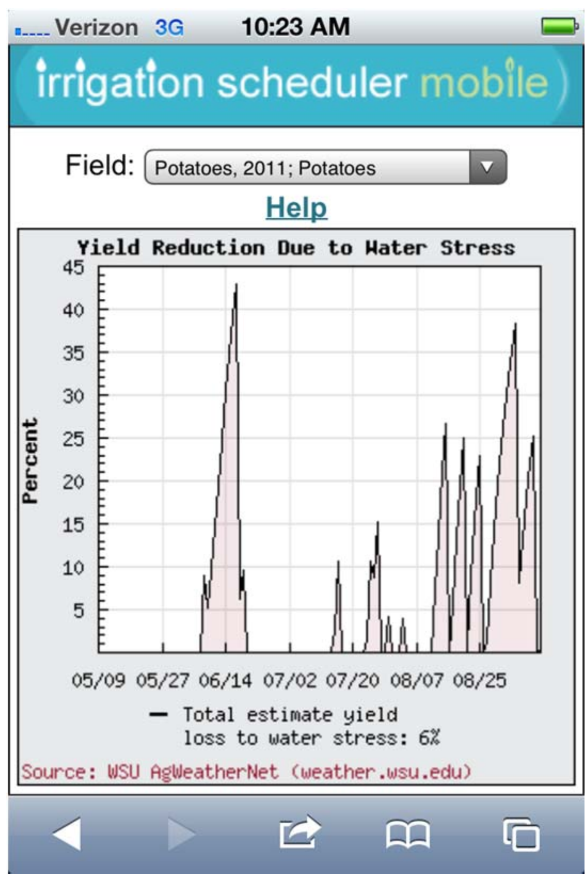


Figure 17. Corresponding Water Stress Chart

Field Settings

Field Settings allows users to select model interaction options and to change the field defaults that were chosen based on the crop and soil type chosen during field setup. Default values for each crop and soil are in Appendix A & B. Entering alternate values here overwrites these defaults. *The "Update Field" button must be clicked for any changes to be applied.*

Additional information about each option follows:

Show Forecast Values: If checked, the model will get a seven day forecast of the maximum and minimum temperatures from the National Weather Service based on the location of the chosen weather station. The Hargreaves equation is then used to estimate grass reference evapotranspiration (ETo) and multiplied by 1.2 to estimate alfalfa reference evapotranspiration (ETr). Forecasts are refreshed every 2 hours. (See Figure 18)

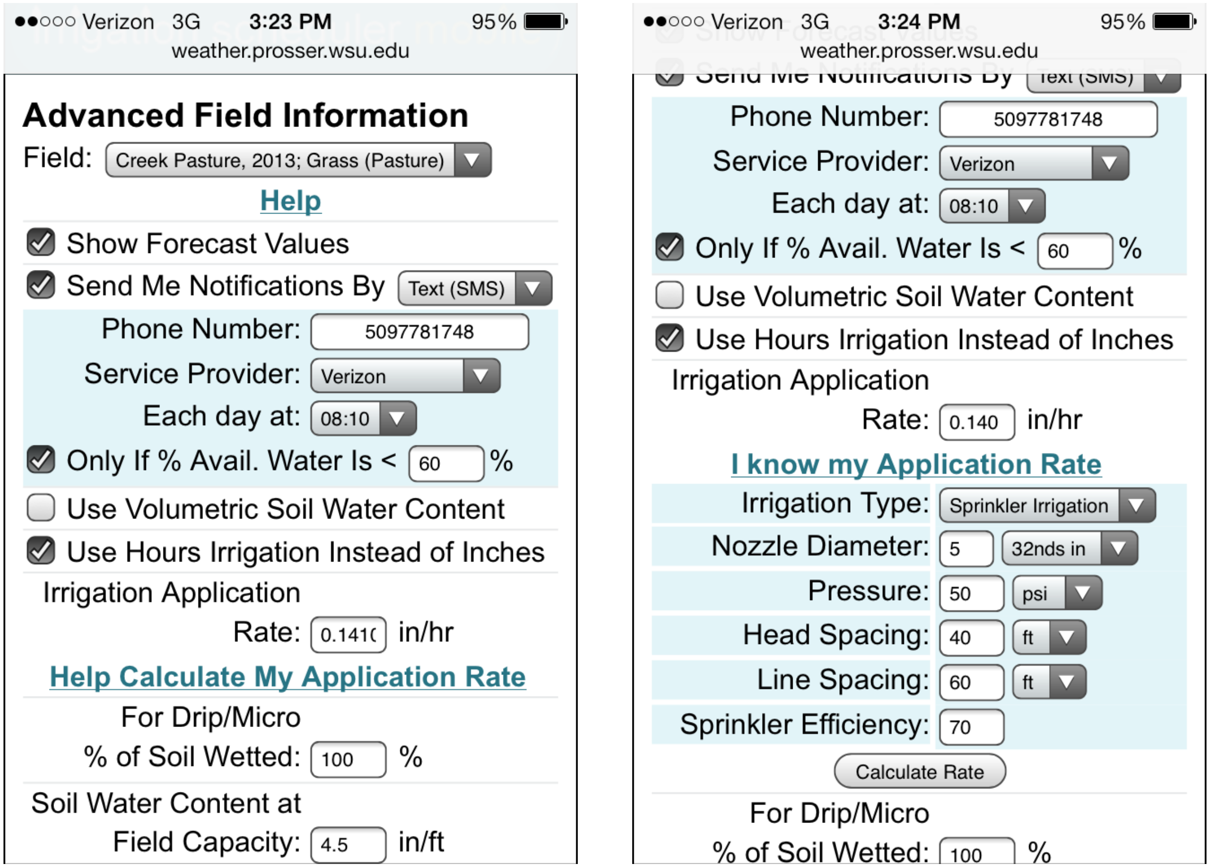
Send Me Notifications: Check this box to get email or text message notifications sent to you on the status of your field. If you choose to be notified by email you will be asked for your email address. If you choose to be notified by text (SMS) message you will be asked for your mobile phone number and your service provider. You can also choose what time of day the notification will be sent. You can also elect to only be notified when your percent of available soil water has been depleted to less than an entered threshold value. (See Figure 12)

Use Hours Instead of Inches: Many irrigators think in terms of hours of irrigation run time instead of inches of water applied. Applied irrigation can be entered in hours, and the soil water deficit can be displayed in hours instead of inches. If you prefer to use hours an irrigation application rate in inches per hour must be provided. Calculators are available on this page to "Help Calculate My Application Rate" for drip, sprinkle, and general irrigation systems using a variety of different units. Reasonable assumptions of irrigation application efficiency are provided for each system. (See Figure 18)

Use Volumetric Soil Water Content: Most soil moisture sensors display volumetric soil water content (volume of water/volume of soil) instead of the percent of available water (which is easier to understand). If you would prefer to see and enter volumetric soil water content in the Daily Budget Table then check this box.

For Drip/Micro, % of Soil Wetted: In many perennial cropping systems under drip or micro irrigation, the entire soil volume is not used. For example a drip irrigation system in a wine grape vineyard may wet a 4 ft width of soil in an 8 ft row spacing. In this case only 50% of the soil is used to store water since the inter-rows remain dry. The soil's water holding capacity can be reduced by multiplying by this percentage to reflect this.

Soil Water Content at Field Capacity: This is the maximum amount of water that the soil can hold long term against gravity. After a soil is at the field capacity (Full point) adding more water will result in the water moving down through the soil profile and possibly past the bottom of the root zone (tracked on the "Deep Water Loss Chart"). Field Capacity is measured in inches of water per foot of soil depth.



Figures 17-18. Advanced Field Information Setup Screen

Soil Available Water Holding Capacity (AWC): This is field capacity minus wilting point, or the amount of water the soil can hold between full and empty. AWC times the soil depth gives the available water supply. The Empty/Dead (permanent wilting point) is calculated using this number and field capacity. Soil Available Water Holding Capacity is measured in inches of water per foot of soil depth.

Management Allowable Deficit (%): Abbreviated MAD, this is the percent depletion of the total available water below which the plant begins to experience water stress. *100% minus MAD is the First Water Stress point* as a percent of the available water holding capacity. As the soil dries down below this point the plant will experience increasing amounts of water stress until the plant will die when it reaches the Empty/Dead (permanent wilting) point. Daily crop water use estimates are proportionately decreased from the full value to zero as the soil water content decrease from MAD to the soil's permanent wilting point.

Planting/Emergence Date: Date the plant that the crop emerges and/or the plant starts using water. This is the start date for the soil water budget model. (See Figure 19.)

Crop Canopy Cover Exceeds 10% of Field: The date that crop water use starts increasing. (See Figure 19.)

Crop Canopy Exceeds 70% of Field (Full Cover) Date: The date that the crop canopy exceeds 70% - 80% of the field area or shades 70% - 80% of the ground area. At this point the crop coefficient reaches a maximum and stays at this maximum until the Initial Maturation Date (below). (See Figure 19.)

Crop Initial Maturation Date: After this date the crop begins to dry up, senesce or otherwise shut down and water use begins to decrease. (See Figure 19.)

End of Growing Season Date: Water use stops on this date. Often this coincides with harvest, or the first killing frost. This is the last date of the model. (See Figure 19.)

Root Depth on Start Date: The effects of a growing root depth is included in the soil water budget model. This is the root depth in inches on the starting or plant emergence date. (See Figure 19.)

Maximum Managed Root Zone Depth: This is the maximum root depth reached in the season. It is assumed that the plant root reaches this depth on the Crop Canopy Full Cover Date. (See Figure 19.)

Initial Crop Coefficient: The crop coefficient (Kc) from emergence to the 10% Cover date. (See Figure 19.) This Kc is based on alfalfa reference ETr.

Full Cover Crop Coefficient: The crop coefficient (Kc) at full cover. This is the peak, or maximum crop coefficient. (See Figure 19.) This Kc is based on alfalfa reference ETr.

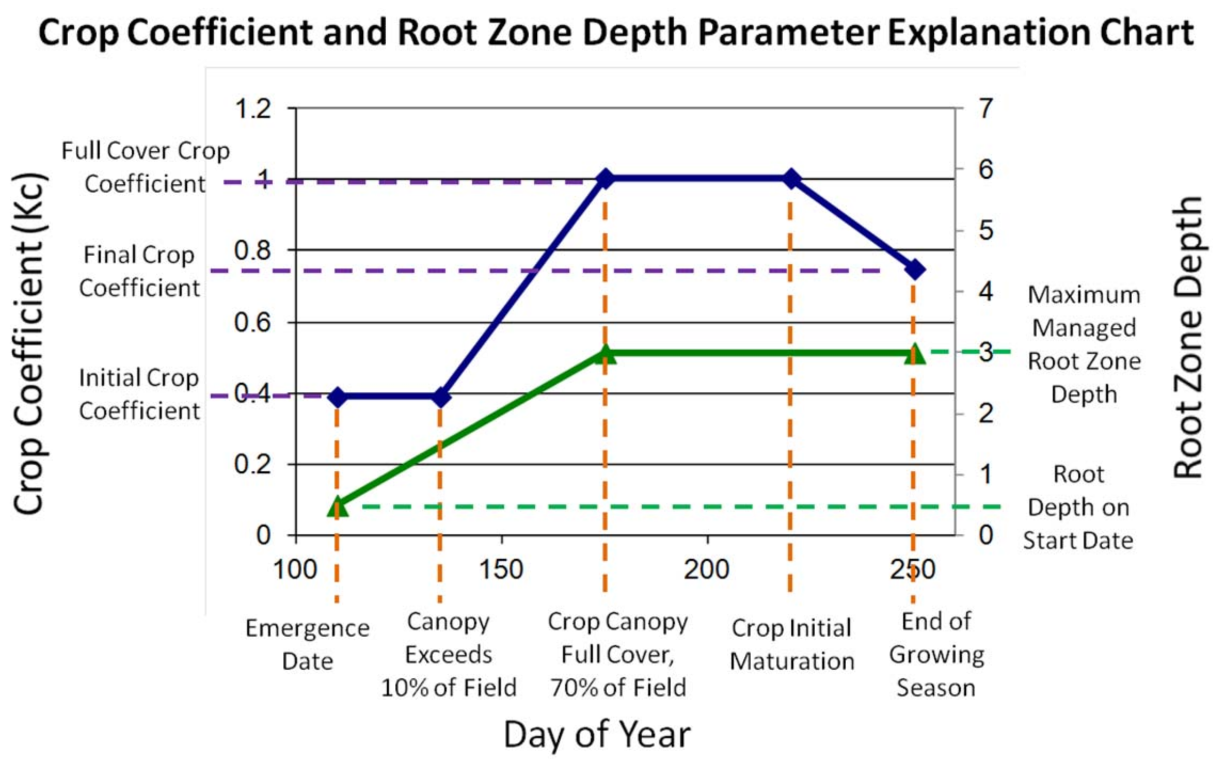


Figure 19. How crop coefficients and root growth are defined by the parameters in Field Settings.

Final Crop Coefficient: Crop coefficient (Kc) at the end of the season. (See Figure 19.) This Kc is based on alfalfa reference ETr.

Post Cutting Kc Flat Days: After cutting a forage, this is the number of days before regrowth starts.

Post Cutting Kc Recovery Days: After cutting a forage this is the number of days after regrowth starts for the forage to regrow to full cover again.

Add/Delete Fields

Selecting this menu brings up the screen in Figure 20. You can add a new field, or completely delete an existing field from this menu.

Add New Field: Use this to add a new field.

Delete Selected Field: Permanently removes the currently selected field and all of its settings and associated data.

Add Field Options:

Field Name: Use this to name the field.

Field Year: This is the growing year. If a previous year is selected, then that previous year's weather data will be used in the water budget. Use the current year for ongoing or current irrigation scheduling.

Network: Pick the agricultural weather network from your state that has the station that best represents your location. A list of agricultural weather networks whose data can be accessed by this irrigation scheduling tool are given in Table 1.

Table 1. Irrigation Scheduler Mobile currently can work with data from the following networks.

Network	States Served	Managed By	Website
AgWeatherNet	Washington	Washington State University	http://weather.wsu.edu/
CoAgMet	Colorado	Colorado State University	http://www.coagmet.colostate.edu/
AZMET	Arizona	University of Arizona	http://ag.arizona.edu/azmet/
NDAWN	North Dakota	North Dakota State University	http://ndawn.ndsu.nodak.edu/
ADAWN	South Dakota	South Dakota State University	http://climate.sdstate.edu/climate_site/ag_data.htm
CIMIS	California	California Dept. Water Resources	http://wwwcimis.water.ca.gov/cimis/welcome.jsp
AgriMet	WA, OR, ID, NV, MT	US Bureau of Reclamation, Pacific Northwest Region	http://www.usbr.gov/pn/agrimet/
AgriMet	MT	US Bureau of Reclamation, Great Plains Region	http://www.usbr.gov/gp/agrimet/

Weather Station: This tool automatically pulls the calculated daily reference evapotranspiration (ET) rates and measured precipitation from this station. Choose a station that best represents the weather conditions at your field.

Field Crop: Based on the selected crop, default growing season dates, crop coefficients, management allowable deficit (MAD) rates, and rooting depths are chosen. These crop parameters can be later edited in "Field Settings".

Field Soil: Based on the soil texture chosen, default field capacity, wilting point, and water holding capacity values are chosen. These soil parameters can be later edited in "Field Settings".

Forage Cuttings

Harvested forages such as alfalfa, grass hay, and sometimes mint can have multiple cuttings per season. After a forage crop is cut the crop coefficients are greatly decreased since the height and leaf area of the forage has been removed. The model knows which crops are forages and has default lag and recovery periods for these crops where the crop coefficients are temporarily reduced following a cutting (Appendix B). For these crops there will be an additional check box titled "Apply Forage Cutting Today" in the "Edit" expansion menu on the "Daily Budget Table". Checking this box on the day that the forage was cut will alter the crop coefficients during the recovery phase of the forage (Figure 20). It will also put a mark on the Soil Water Chart to indicate the forage cutting (Figure 21).

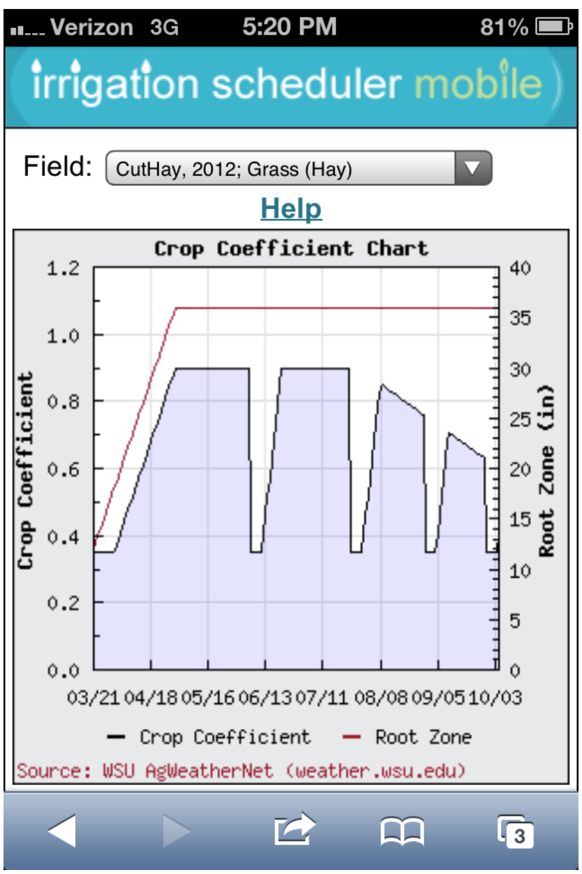


Figure 20. Crop Coefficient Chart showing cuttings.

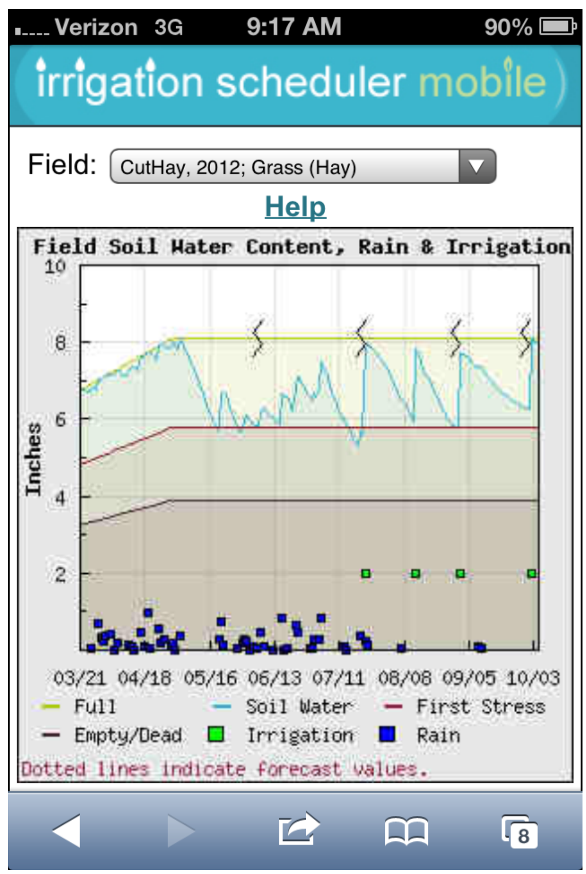


Figure 21. Cutting dates on the Soil Water Chart.

Full Size Screen Version

There is a version of this model that is set up for use on full-size computer screens at http://weather.wsu.edu (Figure 22). The operation of this is essentially identical to the mobile version, except that the charts are larger. Making changes to fields in this version will apply the changes to the mobile version and vise-versa.

Field Activity Reports: One feature that is available on the full size version that is not available on the mobile version is the option to show a report of your interaction with the Irrigation Scheduler. This was requested as a way to show certain agencies that you have been actively using the model for irrigation scheduling so that they will feel that incentives for irrigation scheduling are well spent.

The model counts the number of days that you view or edit that field in a month (Figure 23). Views or Edits are counted whether you use the full-page or small screen (mobile) version. Loading any page for the field is counted as a view. Making an edit in the Daily Budget Table (such as adding an irrigation event), or in the Field Settings is counted as an edit.

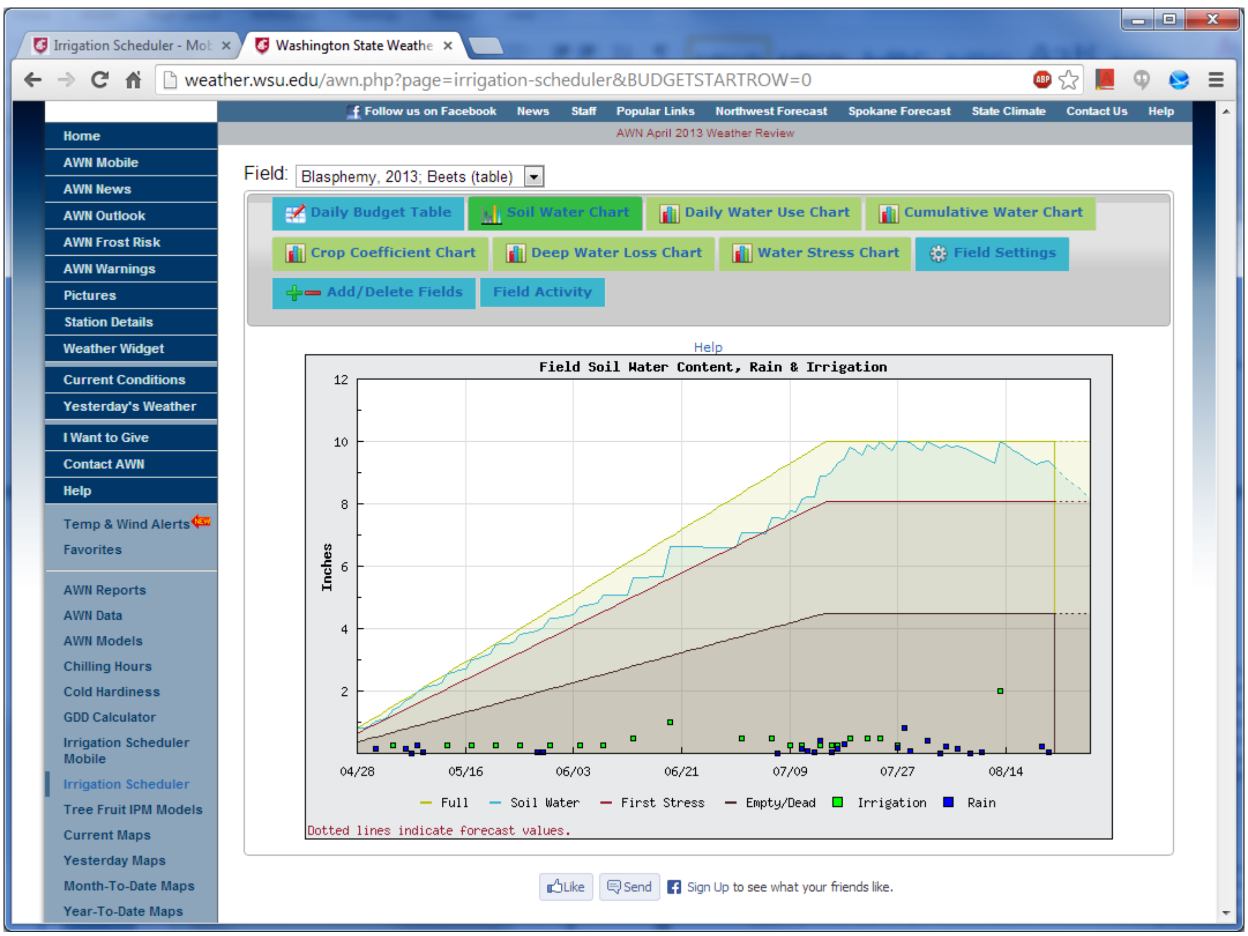


Figure 22. Full Screen version.

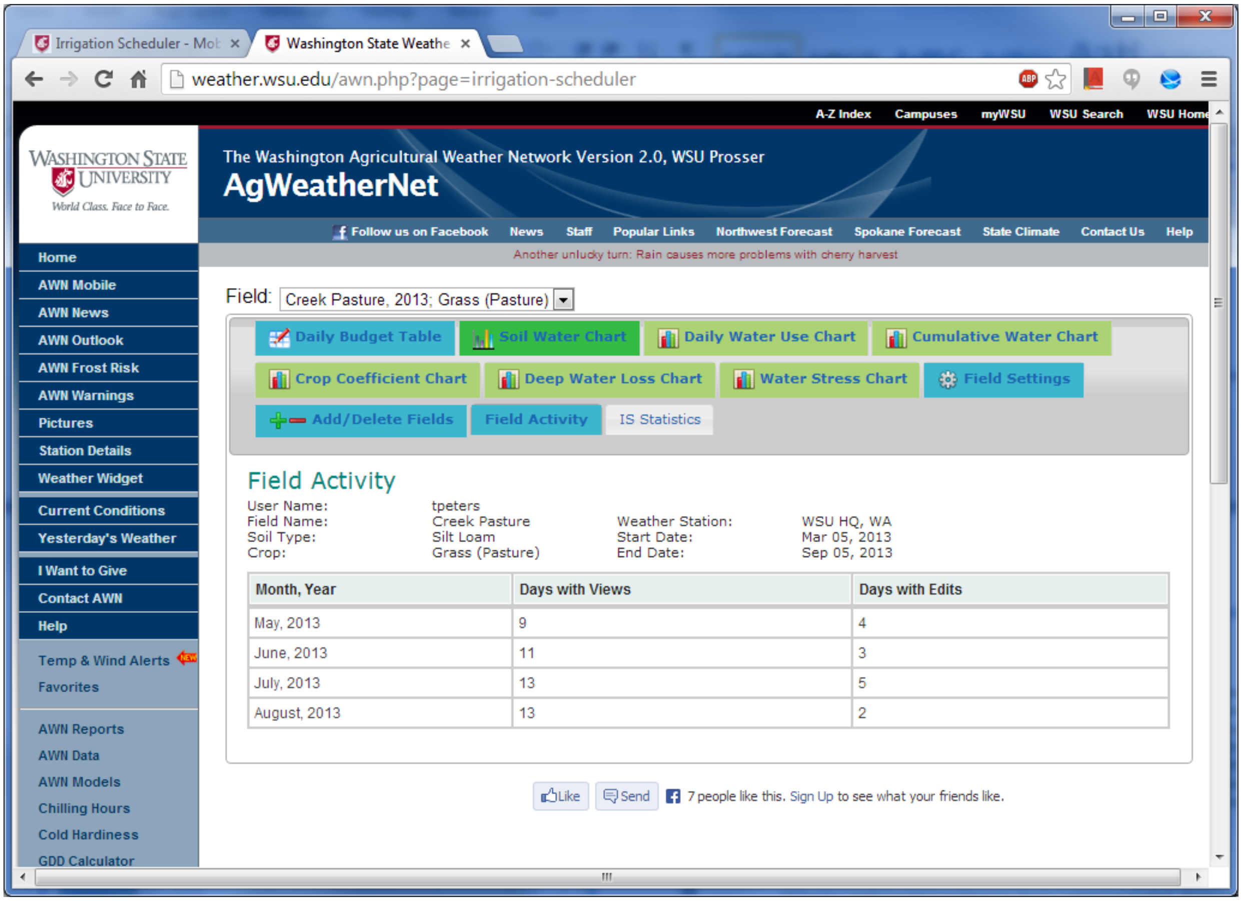


Figure 23. Field Activity report that is available from the full-screen version.

Suggestions for Different Irrigation/Cropping Systems

Rill or Furrow Irrigation: With surface irrigation methods it is difficult to know exactly how much water infiltrated into the soil. A good assumption is that at each irrigation event you completely refill the soil water deficit to field capacity in the entire root zone. Simulate this by entering a large number at each irrigation event (like 3-4 inches), entering a number equivalent to the soil water deficit, or resetting the Percent Available Water number to 100% at each irrigation event.

The model is useful with surface irrigation in that it will indicate when the soil is getting dry again and when to irrigate. To be the most efficient with your water resources, wait to irrigate when the soil water content is near the First Stress (MAD) line. Often growers learn they can wait a little longer than they thought before irrigating again and they end up saving an irrigation or two over the season.

Moving Irrigation Sets: With many irrigation systems it takes many days to irrigate an entire field. This brings up the question, “Which date should I put the irrigation on?” Simply choose one part of the field and throughout the whole season enter the irrigation on the date that that part of the field receives irrigation water. Be aware that the soil water content in the other parts of the field will either be slightly ahead or behind the model. It might be easier if you choose a location that is easier to remember when it was irrigated, such as the first set. If correlating/correcting with soil moisture measurements, be sure to choose the part of the field where the measurements are being taken.

Use with Soil Water Content Sensors: Updating the model with periodic soil moisture measurements will greatly improve the accuracy of the soil moisture estimate. These can be used to fine-tune the model as well. For example, if you find that the soil moisture measurement is consistently higher than that estimated, then the model is over-estimating crop water use and the crop coefficients should be adjusted down for that time period. Be aware that soil moisture measurements are quite variable and may be high one time then low the next. Use seasonal trends and your good judgment to adjust the model.

Most soil water content sensors provide in the number as a volumetric soil water content (% water of total soil volume) this number is available by clicking the date in the Daily Budget table for expanded information (Figure 9).

Use with Soil Water Tension Sensors: Tensiometers and Granular Matrix (Watermark) sensors don't measure soil water content and therefore it is very difficult (although not impossible) to compare the measurements directly with the model. However, these sensors should indicate that the soil is drier (greater soil water tension) as the soil water content approaches and goes below the MAD line. For additional help see the publication "Practical Use of Soil Moisture Sensors for Irrigation Scheduling" by Troy Peters.

The Effects of Irrigation Frequency. With center pivots and some solid-set irrigation systems water is applied much more frequently than other irrigation systems such as surface (rill) or hand-lines and wheel-lines. High frequency irrigations mean that the soil surface and plant leaves are wet a greater percentage of the time and therefore a greater amount of water is lost to evaporation. In other words, the crop uses/needs more water. Because of this, you might need to adjust the crop coefficients *up* 5-10% in Field Settings to compensate for this.

Deliberate Water Stress: With some crops, such as wine grapes, it is desirable to deliberately cause water stress to get the desired crop quality results. Recall that the plant will see approximately linearly increasing water stress from barely any at the red, First Stress (MAD) line to the black, Empty/Dead (Permanent Wilting Point) line (see Figure 8). Deliberately causing stress is done by purposefully allowing the soil water to dry down below the First Stress line (Figure 24).

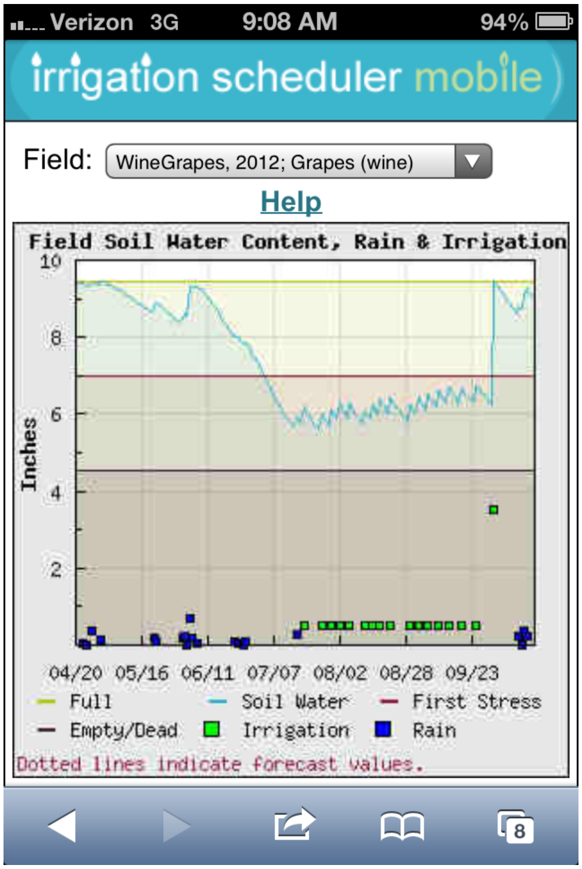


Figure 24. Water stressing wine grapes. Irrigation after harvest was done to restore the health of the vines.

Technical Details on Adapting the Model to Your Area

This model was set up to be used outside of just Washington State. It was written in PHP and MySQL, both of which are free, open-source applications that run on a web server. The code is freely available under an open source, GPL license if someone wants to set it up to run on a different server (available at http://irrigation.wsu.edu/Content/ism.zip). It is OK with the developers if this is re-branded as long as the developers are acknowledged and it is freely available to users.

Other Weather Networks: It can easily accept rainfall and weather data for evapotranspiration calculations from any weather network whose data can be accessed over the internet. It currently works with data from eight different weather networks (Table 1). A map of the current weather networks is shown in Figure 25. Additional states or networks can be fairly easily added if there is an automated way to get access to up-to-date historical weather data. Please contact us and we would be happy to help add your network.

Alternative Crops and Crop Defaults: Unfortunately crop coefficients are not always accurately transferrable from one climatological region to another. Also the growth season dates used as defaults in the model obviously vary with different climates. To account for this Irrigation Scheduler Mobile can accept different default crop coefficients and season growth dates that are attached to user-defined groups of weather stations. For example, the model is now set up so that when a grower chooses a weather station in Western Washington (the evergreen side) it will use different crop coefficients that if a weather station in Eastern Washington (the ever-brown side) is chosen. Because of this different states can also have their own set of default crops, crop coefficients, and growth season dates. Please contact Troy Peters (troy_peters@wsu.edu) for more information on how to get these made specific to your state or area.

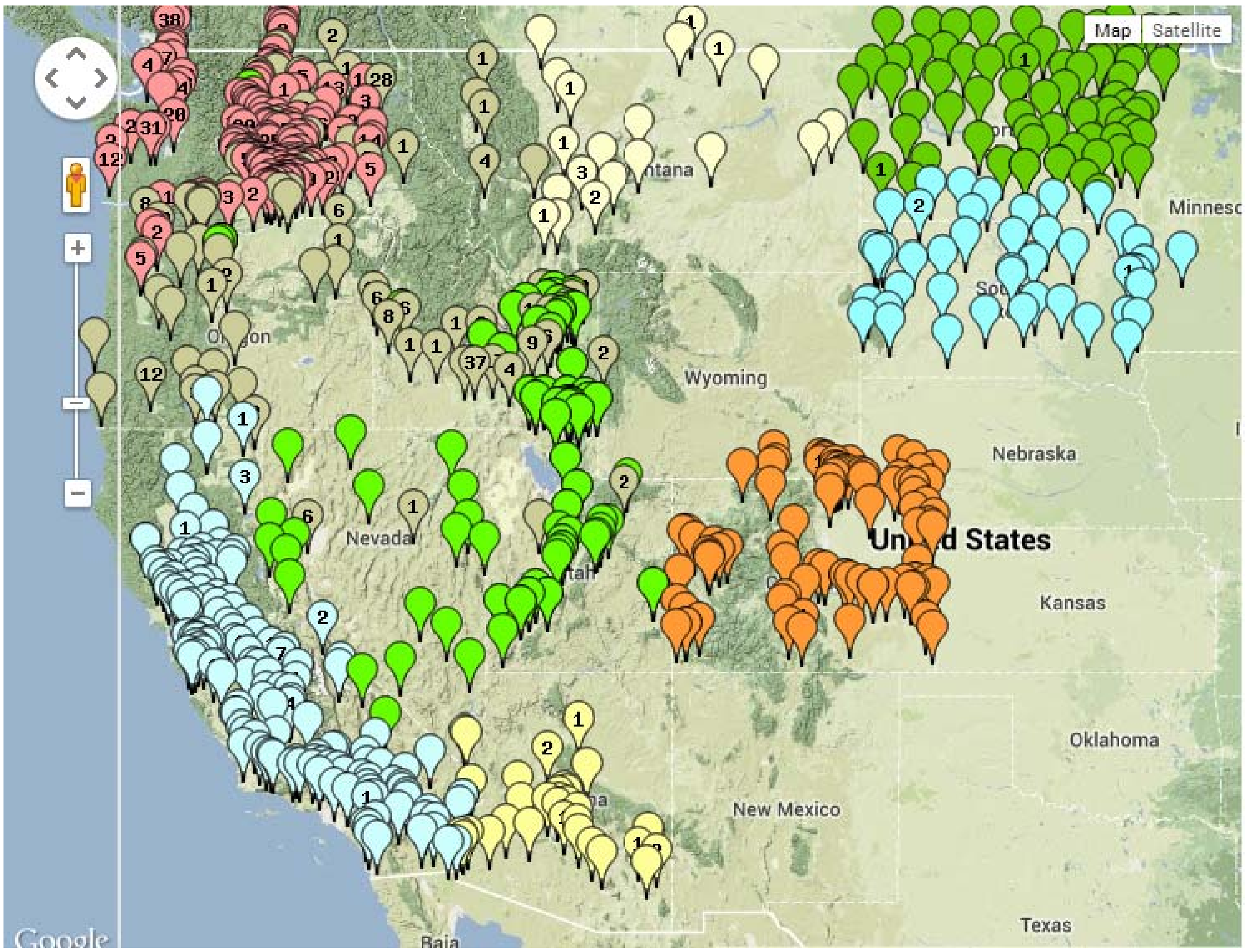


Figure 25. Map of the weather stations and networks that Irrigation Scheduler Mobile can currently work with. Not shown is that it also works in Alberta, Canada.

Conclusion

A simplified method and user friendly method of doing irrigation scheduling on your phone or desktop web browser was developed. It runs like an app on any web browser, but there is an Android version available the runs like a direct download. An downloadable iPhone version is under development. It was designed to be simple and user friendly and to automate as much of the set-up process as possible. It is being used throughout the Western United States.

Acknowledgements

Sean Hill was the primary developer of Irrigation Scheduler Mobile. He is a very bright, capable developer who conceived many of the concepts used in this program. He deserves the lion's share of the credit for making this happen. He is a web developer for AgWeatherNet. Funding for Sean's time was graciously provided by the director of AgWeatherNet; Gerrit Hoogenboom. Additional funding for prior development by Cynthia Tiawana was provided by the USDA Water Quality Research Initiative. The American Society of Agricultural and Biological Engineers (ASABE) providing funding to turn this into the downloadable Android app. Thank you!

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Appendix 1: Defaults by Soil Texture. All units are in inches of water per foot of soil depth. More accurate estimates for your particular soil are available from the NRCS Web Soil Survey (http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm)

	Soil Water Content (in/ft)		
Soil Texture	Field Capacity	Wilting Point	AWC
Coarse Sand	1.2	0.6	0.7
Fine Sand	1.5	0.7	0.8
Loamy Sand	2.2	1.2	1.0
Sandy Loam	2.7	1.3	1.4
Fine Sandy Loam	3.4	1.6	1.8
Sandy Clay Loam	4.0	2.0	2.0
Loam	4.0	1.8	2.2
Silt Loam	4.3	2.0	2.3
Silty Clay Loam	4.6	2.8	1.8
Clay Loam	4.8	3.0	1.8
Silty Clay	4.8	3.2	1.6
Clay	4.8	3.4	1.4
Peat Mucks	5.0	2.6	2.4

Appendix 2: Crop Defaults Used in the Model.

Crop Name	Crop Development Dates for Crop Coefficient Curve (DOY)					Crop Coefficients			Root Depths (ft)		MAD %
	Planting/ Emergence	> 10% of Field	Full Cover/ > 70%	Initial Maturation	End of Season	Initial	Full Cover	Final	Starting	Max.	
Alfalfa *	91	100	122	139	278	0.33	1.07	0.95	4.0	5.0	55
Apples	100	112	149	240	290	0.39	1.05	0.50	3.5	3.5	50
Apricots	100	112	149	220	278	0.39	1.10	0.50	3.5	3.5	50
Asparagus	120	130	214	260	278	0.36	1.00	0.87	3.5	5.0	55
Beans (dry)	146	156	191	211	242	0.25	0.95	0.30	0.4	2.5	50
Beans (green)	146	150	180	200	211	0.25	0.95	0.80	0.4	2.5	40
Beets (table)	117	135	195	239	276	0.40	0.88	0.79	0.2	2.5	35
Blackberries	90	95	145	190	280	0.25	1.05	0.70	3.5	4.0	50
Blueberries	85	90	111	195	225	0.25	1.03	0.90	3.0	4.0	50
Bluegrass Seed	72	80	126	155	192	0.25	0.95	0.25	1.0	2.5	50
Broccoli	91	119	160	218	243	0.50	0.87	0.80	0.2	2.0	35
Brussel Sprouts	91	119	160	218	243	0.58	0.88	0.79	0.2	2.0	35
Cabbage	91	92	160	185	243	0.25	1.00	0.25	0.5	2.0	40
Canola	76	83	122	164	183	0.20	1.05	0.30	0.5	4.0	55
Cantaloupe	136	153	195	229	243	0.42	0.71	0.50	0.5	3.0	50
Carrots	91	119	160	220	243	0.70	0.85	0.75	0.2	2.0	35
Cauliflower	91	119	160	218	243	0.58	0.87	0.79	0.2	2.0	35
Celery	127	140	186	220	253	0.65	0.80	0.80	0.2	1.5	40
Cheatgrass	60	62	83	104	130	0.25	0.80	0.25	0.5	2.5	65
Cherries	110	112	141	220	278	0.39	1.12	0.50	3.5	3.5	50
Clover *	91	95	117	244	278	0.33	0.92	0.75	2.0	2.5	45
Corn (grain)	129	151	201	236	259	0.25	1.00	0.75	0.4	3.5	50
Corn (sweet)	130	152	203	230	240	0.25	1.00	0.86	0.4	2.5	40
Cranberries	105	106	121	277	278	0.33	0.75	0.42	0.2	0.3	40
Cucumbers	136	140	174	240	278	0.50	0.70	0.70	0.5	2.5	40
Garlic	91	119	160	218	243	0.58	0.83	0.57	0.5	1.5	30

Appendix 2: Crop Defaults Used in the Model, Continued.

Crop Name	Crop Development Dates for Crop Coefficient Curve (DOY)					Crop Coefficients			Root Depths (ft)		MAD %
	Planting/ Emergence	> 10% of Field	Full Cover/ > 70%	Initial Maturation	End of Season	Initial	Full Cover	Final	Starting	Max.	
Grain (Spring)	92	100	160	195	213	0.25	1.05	0.70	0.3	3.5	50
Grain (Winter)	66	85	128	184	196	0.25	1.05	0.90	1.0	3.5	50
Grapes (juice)	110	114	180	277	278	0.25	0.90	0.75	3.0	3.0	40
Grapes (wine)	110	135	210	277	278	0.15	0.70	0.70	3.0	5.0	65
Grass (Hay) **	80	90	120	209	278	0.50	0.90	0.72	1.0	3.0	55
Grass (Pasture)	80	87	118	244	278	0.25	0.65	0.50	2.0	3.0	55
Grass (Tall Pasture)	80	87	118	244	278	0.25	0.80	0.50	2.0	3.0	55
Grass (Turf)	72	80	108	244	278	0.80	0.80	0.80	1.0	1.5	50
Hops	110	158	230	250	274	0.25	1.05	0.20	3.0	4.0	50
Lentils	105	115	155	182	215	0.25	1.02	0.30	0.5	2.5	50
Lettuce	95	96	110	123	125	0.58	0.83	0.79	0.2	1.5	25
Melons	136	140	174	240	278	0.25	0.80	0.60	0.5	2.5	40
Mustard	76	83	122	164	183	0.25	0.85	0.30	0.5	2.0	55
Onions (dry)	90	122	162	212	239	0.50	1.07	0.50	0.2	1.5	35
Onions (green)	74	99	129	139	144	0.50	1.00	1.00	0.5	1.5	35
Peaches	110	112	145	220	278	0.39	1.12	0.50	3.5	3.5	50
Pears	110	112	149	226	278	0.39	1.15	0.50	3.5	3.5	50
Peas	90	97	163	174	198	0.30	1.00	0.50	0.5	2.5	40
Peppermint *	86	93	156	270	278	0.25	0.98	0.85	1.5	2.0	40
Peppers	136	153	195	232	243	0.50	0.85	0.71	0.5	2.0	35
Plums	110	112	149	239	278	0.20	1.05	0.50	3.5	3.5	50
Potatoes	127	140	186	220	253	0.40	0.85	0.60	1.0	2.0	35
Pumpkin	136	161	212	250	278	0.42	0.83	0.67	0.5	3.0	45
Radishes	95	96	110	123	125	0.53	0.72	0.67	0.5	1.0	40
Raspberries	90	95	144	227	278	0.20	1.08	0.70	3.5	4.0	50

Appendix 2: Crop Defaults Used in the Model, Continued.

	Crop Development Dates for Crop Coefficient Curve (DOY)					Crop Coefficients			Root Depths (ft)		
Crop Name	Planting/ Emergence	> 10% of Field	Full Cover/ > 70%	Initial Maturation	End of Season	Initial	Full Cover	Final	Starting	Max.	MAD %
Safflower	90	98	143	193	220	0.20	1.08	0.25	0.5	5.0	55
Sorghum	130	150	185	230	260	0.25	0.90	0.85	0.5	2.0	55
Soybeans	121	140	175	235	260	0.36	0.96	0.30	0.5	3.0	55
Spearmint *	110	124	165	212	243	0.25	1.03	0.80	1.5	2.0	40
Spinach	88	120	168	206	215	0.55	0.80	0.75	0.5	1.5	25
Squash	136	161	212	250	278	0.40	0.80	0.60	0.5	3.5	50
Strawberries	80	93	164	207	278	0.33	0.70	0.55	1.0	1.5	30
Sugar beets	117	135	195	239	276	0.25	1.05	0.70	0.5	4.5	50
Sunflowers	105	130	165	210	234	0.25	0.92	0.29	0.5	4.5	65
Tomatoes	136	153	195	229	243	0.50	0.95	0.70	0.5	3.0	40
Tubers	80	93	164	207	278	0.42	0.92	0.79	0.5	3.5	40
Watermelon	105	130	165	210	234	0.33	0.85	0.85	0.5	3.5	50

* Default post-cutting lag and recovery time periods are 7 and 14 days respectively.

** Default post-cutting lag and recovery time periods are 5 and 10 days respectively.

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Using Soil Water and Canopy Temperature to Improve Irrigation Scheduling for Corn

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Abstract.

With declining well capacities in the Central High Plains resulting from withdrawals exceeding recharge in the Ogallala aquifer, producers will need to adopt advanced irrigation scheduling to maintain productivity with limited water. A study was conducted to assess the effect of irrigation scheduling approaches based on plant water stress sensing, soil water sensing, and climate (ET), or a combination of these methods on corn growth, yield, and water productivity of two hybrids (conventional and drought tolerant), seasonal crop water use, and total irrigation applications. The study involved five irrigation scheduling treatments applying 80% of full irrigation and a control (full irrigation) treatment and two corn hybrids arranged in a split-plot design. Results indicate there were no significant differences in yield among irrigation scheduling methods (p-value=0.38). However, there were significant differences in yield between conventional and drought tolerant corn hybrids (p-value=0.003), on average there was a 20% yield advantage for the conventional hybrid. There were no-significant interactions between irrigation scheduling and corn hybrid (p-value=0.48). Treatment T2 based on crop water stress sensing using the Time Temperature Threshold used 11% more water compared to the standard irrigation scheduling method based on neutron probe monitoring (T1) but resulted in the highest yield for the drought tolerant corn (189 bu/ac). Treatment 3 that triggered irrigation based on soil water sensors resulted in 22% more water applied compared to the standard method, but also resulted in the highest yield (219 bu/ac) for the conventional corn hybrid. Yields appear to have been affected by hail damage that occurred earlier in the season (at growth stage V14) resulting in reduced canopy cover as quantified through leaf area index measurements. Residual soil water effects from a previous study also influenced yields, with treatments located in high water level areas producing higher yields compared to those in low water level locations. Preliminary data indicates that soil-based, plant-based, and/or climate based irrigation scheduling can result in improved crop water productivity particularly under non-ideal growing environments where external abiotic and biotic factors could influence in-season crop water use. Matching irrigation applications with crop use under non-ideal environments could help producers to maintain profitability and conserve water. Integrating soil and plant water status monitoring with the scientifically robust ET-based scheduling could encourage more producers to adopt irrigation scheduling through visual illustrations of root water uptake.

Key words. Irrigation scheduling, soil water, canopy temperature

Introduction

Restrictions in water supplies whether physical (diminished well capacity) or legal (Local Enhanced Management Areas, LEMA), will force many producers to face the prospect of adopting some degree of deficit irrigation. To cope with limited water supplies, producers will have to adjust their irrigation management by adopting strategies such as: reducing irrigated acreage, deficit irrigation of a portion or all acreage, growing crops with different or lower water requirements at different times of the season (e.g., corn and soybean), minimizing water stress during critical reproductive growth stages, crop rotations, reduced tillage and residue management, drought tolerant hybrids, and advanced irrigation scheduling practices. Although it would take an integrated approach to cope with limited water supplies, this study focused on irrigation scheduling approaches involving a 20% reduction in available water as proposed under one LEMA currently operating in Northwest Kansas. Klocke et al. (2011) reported that a 20% reduction in irrigation water applied did not result in significant differences in corn yield. However, it should be noted that curves of yield responses to water are substantially influenced by variations in climate, soil, and other environmental conditions. In addition to pre-season decision making related to allocation of limited water resources to land and crop enterprises, producers have to make tactical in-season water management decisions mainly involving irrigation scheduling. In this study we evaluated water technologies that could improve reliability of irrigation scheduling for corn as the dominant irrigated crop in Kansas.

Traditionally, irrigation scheduling has been based on the producer's perceptions of plant water needs or calendar date irrespective of variation in weather conditions, or fixed crop rotations. Jensen et al. (1970) noted that farmers are reluctant to deviate from traditionally accepted scheduling methods regardless of relative merits of alternative scheduling methods until they are shown that improvements in scheduling results in greater net returns. However, as well capacities dwindle irrigators will need to adopt irrigation scheduling to maintain productivity. Howell and Evett (2005) defined irrigation scheduling as the process of making decisions on the irrigation amount and timing subject to the irrigation water supply constraints and in concert with labor and cultural crop practices with the goal to maximize profits per unit of inputs. Lamm (2014) coined a new definition for irrigation scheduling as being the process of delaying any unnecessary irrigation with the hope that the irrigation season will end before the next irrigation is needed. These definitions highlight the challenges associated with maximizing profitability when irrigating with limited water supplies.

Irrigation scheduling is accomplished using different approaches including: 1) evapotranspiration (ET) also known as ET-based scheduling, 2) measuring a soil water status property using sensors (e.g., dielectric permittivity), and 3) measuring a plant water status property (e.g., canopy temperature) using sensors. The latter is typically used to indicate need for irrigation while 1 and 2 can be used to determine need and amount of irrigation water required. Unfortunately, none of the measurement based methods or soil water balance based irrigation scheduling tools are perfect or without bias. Howell et al. (2012) noted that relying on only one measurement technology can result in mis-diagnosing of abiotic (e.g., soil water stress, wind damage) and biotic stress (e.g., crop damage due to pests, diseases) effects on irrigation scheduling decisions, and recommended using one or more irrigation scheduling methods as a check to avoid over or under irrigation. For example, the ET-based approach works well for near ideal crop conditions, but combining it with soil water sensing and thermometry can help detect abiotic and biotic stresses that could improve reliability of irrigation scheduling decisions. In this study we used the time domain reflectometer based senor to measure soil water content and individually calibrated infrared thermometers to measure canopy temperature.

There are also various types of soil water sensors with varying levels of accuracy. Chavez and Evett (2012) provided a description of various sensor technologies and comparison of various sensors. Their results indicated that the CS655 soil water sensor was one of only two sensors at the time of testing that proved to be accurate compared to gravimetric sampling and TDR measurements. For this study we used the CS655 for continuous monitoring of soil water. In addition to volumetric water content, the CS655 also provides bulk electroconductivity and soil temperature that could be useful for salinity management and planting decisions respectively. They noted that poor installation could affect measured data and that performance of the sensor could be improved by developing linear calibration equations for specific soil types. The CS655 sensor works on a similar principle as a TDR in that the travel time of a reflected electronic pulse is measured using electronics embedded in the sensor head. Unlike the TDR, the CS655 does not capture the wave form of the reflected electronic pulse. Instead, it sends out an electronic pulse along two electrodes that is reflected from the end of the rod. When the sensor head detects the reflected pulse, it sends another pulse and records the frequency of the pulses which it reports as period or inverse of frequency (µs). The period is affected by soil dielectric permittivity which is also influenced by soil water content. The manufacturer provides a calibration equation in the datalogger that relates the period to soil water content (Campbell, 2011). For optimum plant growth, it is desired that soil water is monitored to ensure it is maintained above 50% of plant available water.

There are also various types of infrared thermometers which Mahan and Yeater (2008) classified as industrial quality (e.g., S-111 [Apogee Instrument Inc., Logan, UT] and Exergen model IRt/c.2 type K 27C [Exergen, Watertown, MA]) and consumer quality (e.g., Zytemp model TN901 IRt [Zytemp HsinChu, Taiwan, ROC]). The advantage of the later is low cost and compatibility with wireless configurations. They recommended that for applications where canopy temperature must be precisely and accurately known, currently industrial quality IRts (e.g., from Apogee instruments) would be the best choice. For large scale agricultural applications, inclusion of consumer quality IRts into a wireless network could be advantageous. In this study we used the industrial quality S-111 IRt (Apogee Instrument Inc., Logan, UT). The S-111 measures both surface temperature (canopy temperature) and the sensor body temperature. Calibration equations in the data logger are then used to calculate the correct surface temperature. Plant canopy temperature has long been shown as a useful measure of plant water stress (Idso et al., 1981; Jackson, 1982). Examples of irrigation scheduling studies in which canopy temperature has been used include (Nielsen and Gardner, 1987; Steele et al., 1994; Evett et al., 2002; Lamm and Aiken, 2008; O'Shaughnessy et al., 2011; Schneekloth and Schlegel, 2012). Different indices are used to schedule irrigation based on canopy temperature including the of the crop water stress index (CWSI) and the time temperature threshold (TTT) among others. Maes and Steppes (2012) provided a review of various water stress indices. In this study we used the TTT index and the empirical CWSI to monitor water stress.

The TTT index was developed from observations that plant enzymes are most productive under a very narrow range of temperatures called the thermal kinetic window (Burke, 1993). In the TTT approach, the accumulated time that canopy temperature exceeds the threshold temperature is used as criteria for triggering irrigation. For example, the threshold temperature for corn in the South and Central High Plains was determined by Evett (2002) as 82^{o}C and threshold time was 240 minutes, implying that if corn canopy temperature exceeded 28^{o}C for more than 4 hours irrigation would be triggered. The TTT method is advantageous over the CWSI approach since it does not require determination of lower and upper baselines required to evaluate CWSI (Colaizzi et al. 2012). O'Shaughnessy and Evett (2011) reported that the TTT algorithm appeared to be more responsive to a wide range of meteorological conditions since it was a time-integrating method compared to indices based on measurement's made only once a day. The major advantage of the CWSI over the TTT is that it includes other environmental factors which could affect canopy temperature such as wind speed, solar radiation and vapor pressure deficit.

The ET-based approach was used as the main scheduling method while plant canopy temperature and soil water monitoring were used as a check for reliability or trigger of the need for irrigation. The purpose of this study was to assess the effect of irrigation scheduling methods based on canopy temperature, soil water content, and climate (ET), or a combination of these methods on reducing seasonal water applications while maintaining corn yield and productivity. The specific objectives were to: 1) evaluate the effect of irrigation scheduling method on growth, yield, and water productivity of two corn hybrids, 2) determine total irrigation water applied by each scheduling method, and 3) assess soil water response to the irrigation scheduling methods.

Materials and Methods

Experimental site characteristics

The study was conducted at the Kansas State University Southwest Research and Extension Center Finnup farm (38^{o}01'20.87''N, 100^{o}49"26.95W, elevation of 2910 feet above mean sea level) near Garden City, Kansas. The climate of the area is semi-arid. Summers are hot and generally less humid while winters can vary between warm and very cold. The soil at the study site is a deep well drained Ulysses silt loam (fine ‐ silty, mixed, mesic Aridic Haplustoll) with a slope of 0 to 1%. The soils have an average available water capacity (available water between field capacity and permanent wilting point) of 0.19 to 0.24 in/in. Bulk density ranges between 0.045 and 0.052 lb/in^{3} (or 1.24 and 1.46 g/cm^{3}) while organic matter in the top foot ranges between 1.1 to 1.6% and decreases with increasing depth. A four span (140 feet span width) lateral move sprinkler irrigation system (model 8000, Valmont Corp., Valley, NE) modified as described in Klocke et al. (2003) to apply irrigation water in any desired treatment combination was used. The system has valves to control banks of 9 nozzles along the lateral. Each bank of nine nozzles represented a management zone or experimental plot. The plot sizes were 45 feet wide by 92 feet long.

Irrigation Water Management Treatments

The experimental design was a split-plot randomized complete block design with four replications. Each span represented a replication with six randomized treatments. Irrigation scheduling was the main factor with five levels replenishing 80%ET based soil water, and canopy temperature monitoring and a control treatment replenishing 100%ET intended to quantify the impact on yield of a 20% reduction in irrigation water applied.

Irrigation scheduling treatments were to irrigate by replenishing 80% ET since the last irrigation when: 1) available soil water (ASW) in the top 4 feet of the root zone falls below 60% based on weekly soil water measurements made using a neutron probe (T1), 2) canopy temperature time-temperature-threshold (TTT) exceeds 82^{o}F for more than 240 minutes on a given day (T2), 3) ASW in the top 4 feet of the root zone falls below 60% based on soil water sensor measurements; note: although similar to treatment 1, the goal was to use a soil water sensing technology different from a neutron probe to arrive at an irrigation decision (T3), 4) either CWSI exceeds 0.3 or 60% ASW thresholds are exceeded (T4), 5) both soil water and CWSI thresholds as in T4 have been exceeded (T5), and 6) control treatment replenishing 100% ET or full irrigation (T6). Treatment 1 was used as the scientific standard reference irrigation scheduling method. All irrigation events were designed to provide a net irrigation of 1 inch to minimize evaporation losses which can be significant for small applications under advective environments in the Central Plains. The amount applied during each event was confirmed through a catch can test (data not shown). Irrigation requirements in excess of the 1 inch were transferred to the next irrigation event. Weekly soil water depletions were confirmed using neutron probe measurement. Daily crop water use (ETc) was estimated using alfalfa modified Penman equation (Lamm et al., 1994). Meteorological data for computing ET was obtained from a Kansas Mesonet weather network (http://mesonet.k-state.edu/) located approximately 2.8 miles southeast of the study site.

Soil and Plant Water Status Sensing

Soil water and canopy temperature sensors were installed to serve as checks on the adequacy of the ET-based irrigation schedules and also to indicate need for irrigation. Soil water sensors (CS655; Campbell Scientific Inc., Logan UT, USA) were installed in treatments 3, 4, and 5 in the drought tolerant hybrid. Each set of soil water sensors comprised of three sensors placed at depths of 1, 2, and 3 feet. Data was collected hourly and averaged over 24 hours. Accuracy of the soil water sensors was checked against a field calibrated neutron probe (Campbell Pacific Nuclear, Model 503DR, CPN International Inc., CA, USA) readings in each treatment. Soil water sensors have the advantage of providing soil water data with high temporal resolution and are more adaptable by the farmers compared to the neutron probe although the latter is more accurate.

Infrared radiometers (SI-111: 22^{o} half angle field of view, spectral range 8 to 14 µm, Apogee Instruments Inc., Logan UT, USA) were installed within 3 experimental plots for monitoring canopy temperature in drought tolerant corn hybrids. A total of 12 infrared radiometers were required in treatments 2, 4, and 5 by four replications. The sensors were positioned approximately 3 feet above the crop canopy at a 45^{o} from the horizontal view angle. A VP-3 relative humidity, air temperature, and vapor Pressure sensor with radiation shield (VP-3; Decagon Devices, Inc. Pullman, WA) was installed in the field to monitor the microclimate (relative humidity, temperature and vapor pressure) within the experimental plots during the study. All sensors were connected to a CR1000 data logger (Campbell Scientific Inc., Logan UT, USA) and all cables were put in PVC conduits to prevent rodent damage. Data was manually downloaded at least twice a week and analyzed for possible irrigation triggers before irrigation decisions were made. A program was written in CR Basic and passed to the CR1000 dataloggers to output alarms when TTT and CWSI thresholds were exceeded. The TTT approach was implemented as described in (Colaizzi et al. 2012). The empirical CWSI was estimated using baselines derived for corn in the Central High Plains by Nielsen and Gardner (1987).

Agronomic Management

The experimental field was maintained in a no-till cropping system for over ten years and the previous crop prior to 2014 was corn. Two Monsanto corn cultivars: 1) with transgenic drought tolerant trait [Genuity® DroughtGard, 62-27 DGVT2PRO], and 2) conventional locally adapted hybrid without transgenic DT trait [DeKalb DKC 62-98 VT2PRO] were planted. The hybrids had a relative maturity of 112 days. The planting was done using a no-till planter. Planting depth was 2 inches and seeding rate was 31,500 seeds/acre applied uniformly across all treatments. The no-till planter was equipped with a single coulter preceding a double disc furrow opener, and two rubber-tire closing wheels. The crop row direction was north -south. Fertilizer applications, weed control, and no-till planting are summarized in Table 1 and were applied uniformly to all the treatments following Kansas State University Best Management Practices recommendations. Starter fertilizer was directly delivered to the seed furrow while the side dress was applied in a stream directly behind a coulter in every other pair of corn rows.

Table 1. Agronomic Data

Parameter	2014
Variety	1. DroughtGard, 6227DGVT2PRO 2. DeKalb DKC 62-98 VT2PRO
Population	31,500 seeds/acre
Fertilizer Application	
Starter (10-34-0)	N: 10 (5/05)[1] and P_2O_5:35 (5/05)
Side dress (32-0-0)	N: 272 (6/12)
Herbicide	Rate (Date)
Pre-plant	
Atrazine	1.5 lbs/ac (04/21)
S-Metolachlor	32 oz/ac (04/21)
dicamba	6 oz/ac (04/21)
Isoxaflutole	0.75 oz/ac (04/21)
Fluroxypyr	13 oz/ac (04/21)
Glyphosate	32 oz/ac (04/21)
Post-emergence	Rate (Date)
Glyphosate	36 oz/ac (06/13)
Fluroxypyr	16 oz/ac (06/13)
Pendamethalin	32 oz/ac (06/13)
Atrazine	0.5 lbs/ac (06/13)

[1]Numbers in parentheses are dates of application

Crop Measurements and Water Use Calculations

Corn growth stages were recorded through weekly visits to the experimental plots. Dates of growth stages such as emergence, tasseling, and physiological maturity were recorded. LAI was measured on July 28, 2014 using the non-destructive AccuPAR model LP-80 ceptometer (Decagon Devices, Inc., Pullman, WA). The LP-80 ceptometer uses above canopy radiation measurements, and canopy intercepted PAR (photosynthetically active radiation) to calculate LAI. In this study, an external PAR sensor was mounted on a 6 feet long PVC pipe with a diameter of 1 inch to allow simultaneous measurement of below and above canopy PAR measurements. Grain yield was hand harvested on October 6th, 2014 by taking two 10 feet representative rows. The grain yield data were standardized to 15.5% moisture content to allow for comparison. Measured yield was then used to calculate water productivity, and irrigation water use efficiency as expressed in equations 1 and 2:

$$CWP = \frac{Y}{ET_c} \tag{1}$$

$$IWUE = \frac{Y_i - Y_r}{I} \tag{2}$$

where CWP is the crop water productivity (bu/ac-in) which is a measure of the amount of marketable product per unit volume of water input, *Y* is grain yield (bu/ac), *Yi* is economic yield of irrigated crop, *Yr* is rainfed yield, and *ETc* is actual seasonal crop evapotranspiration (in).

Estimation of Seasonal Evapotranspiration from Soil Water Balance

Soil water was measured weekly to a depth of 8 feet at intervals of 1 foot using the neutron attenuation technique (Evett, 2008). The neutron probe access tube was placed between two plants in a representative row of each hybrid. Seasonal ETc was estimated from the soil water balance equation (3):

$$ET_c = P + I - R - D \pm \Delta SWS \tag{3}$$

where ETc is crop evapotranspiration (in), P is precipitation during the growing period (in), I is applied irrigation (in), R is runoff (in), D is percolation below the root zone; drainage beyond 8 feet was considered as percolation, ΔSWS is the change in soil profile water between the beginning and end of the sampling period (in). *P* was measured using several rain gauges located adjacent to the experimental plots, *I* was estimated as previously described, *R* was observed to be negligible while ΔSWS was estimated from neutron probe readings. ETc between the first neutron probe measurements and emergence was estimated using the WAVE (Water and Agrochemicals in the soil, crop and Vadose Environment) vadose model (Vanclooster et al., 1995; Kisekka et al., 2014). By providing WAVE inputs of planting date, weather data, crop coefficient, estimated LAI and rooting depth, soil water content at emergence was simulated. The difference between soil profile water content at emergence and first neutron probe reading was used to estimate ETc between emergence and first soil water readings. The advantage of WAVE in simulating soil water dynamics is its physical basis; WAVE solves the Richards equations which allows for water movement up or down the soil profile based on hydraulic head differences within the root zone.

Statistical Analysis

Data was statistically analyzed using Proc Mixed procedures in SAS version 10 (SAS Institute Inc., Cary, NC, USA). Where the Irrigation scheduling method was the main factor and corn hybrid was the subplot factor.

Preliminary results

Weather

Rainfall during the 2014 growing season from May 1st to September 30 exceeded normal rainfall (1981-2010) by 6.8 inches. Figure 1 shows daily rainfall totals and cumulative amounts with 2014 growing season rainfall totaling 17.05 inches. About 56% of this coming in the month of June which corresponded to corn vegetative growth stages of V5 to V16. A large rainfall event of 2.7 inches occurred on June 24th in less than 24 hours which could have resulted in runoff. However, the offseason was very dry with only 1.22 inches between January 1 and April 30. Average seasonal maximum temperature was slightly above normal (86.1 versus 85.5°F), while average growing season minimum temperature was also slightly above normal (57.9 versus 57.4°F) as shown in Figure 2. Solar radiation on average was higher during the vegetative growth stages and gradually decreased during reproductive growth stages (Figure 2). Vapor pressure deficit did not show any particular trends during the growing season with a few spikes in June and late July. There were more days of high wind speeds from emergence to late vegetative growth stages than there were during reproductive growth stages, mitigating excessive evaporative demands during the critical growth periods (Figure 2).

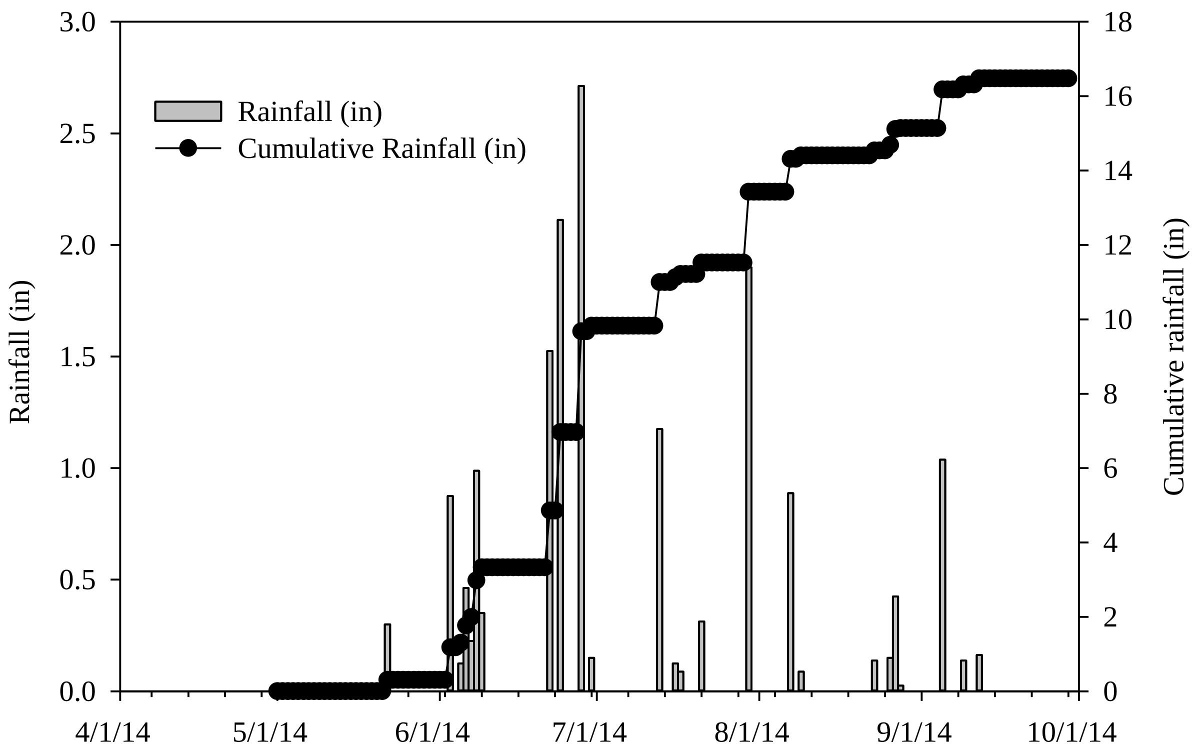

Figure 1. Daily and cumulative rainfall measured at the study site during the 2014 corn growing season.

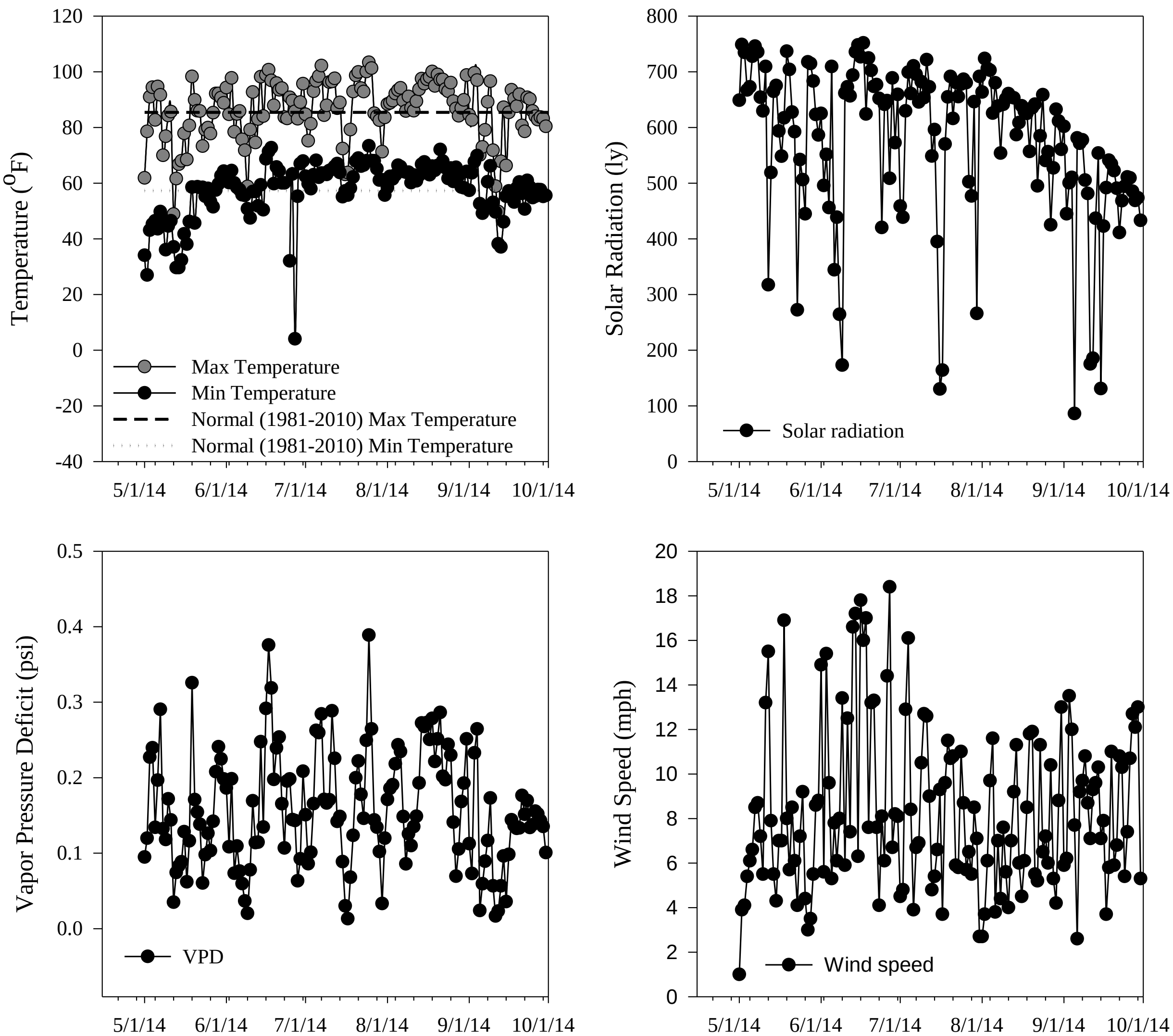

Figure 2. Temperature, solar radiation, vapor pressure deficit (calculated), and wind speed for 2014 growing season measured at the Kansas State University Mesonet located 2.9 miles southeast of the study site in Garden City Kansas.

Biophysical Measurements

Growth stages were recorded weekly as well as soil water content with the neutron probe. Major growth stages and dates of occurrence are summarized in Table 1. Both the drought tolerant corn hybrid and the conventional corn hybrid reached major growth stages approximately at the same time. However, tassel was reached sooner (3 days earlier) for the fully irrigated treatment compared to the five deficit irrigation scheduling treatments, probably due to external environmental stress. LAI measurements made on July 28 2014 (a week after tassel) indicated that the conventional corn hybrid had higher LAI compared to the drought tolerant corn hybrid particularly for the deficit irrigated treatments 1 to 5 as shown in Figure 3. The observed lower values of below canopy photosynthetically active radiation (data not shown) or PAR (μmol photons $m^{-2}s^{-1}$) suggested reduced leaf growth for the drought tolerant hybrid. Nemali et al (2014) studied physiological responses of a transgenic/biotechnologically derived drought tolerant corn hybrid to different levels of water stress and observed that the hybrid expressing the bacterial cold shock protein B (CspB) for drought tolerance exhibited increased ear growth, decreased leaf area index, and decreased leaf dry weight and sap flow rate during silking under water stress conditions, but no differences were observed under well watered conditions. The lower values of LAI observed in this study compared to values in other studies as high as 5 or larger could be attributed to hail damage that occurred on June 24, and difference planting density among other factors.

Table 2. Growth stages for two corn hybrids and five deficit irrigation scheduling treatments (1 to 5) and a full irrigation treatment (6)

Growth Stage	Date
Planting	05/05/2014
Emergence	05/21/2014
Tassel	07/21/2014 (07/18/2014)*
Black layer	10/01/2014
Harvest	10/06/2014

*Tassel date for treatment 6

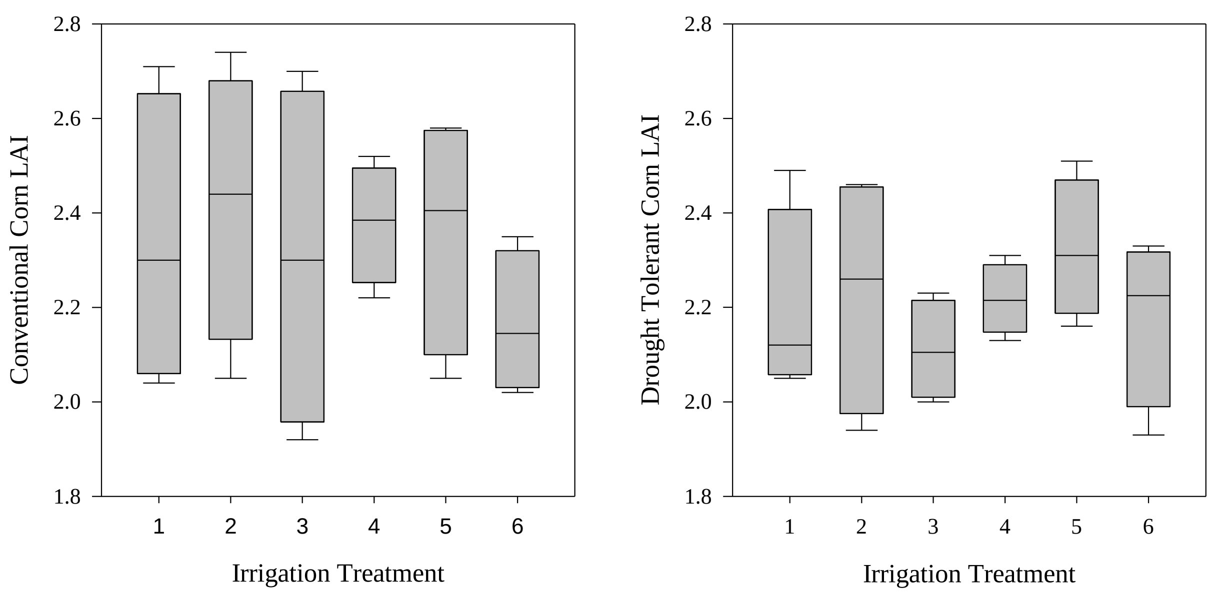

Figure 3. Measured leaf area index (LAI) on July 28, 2014 for Conventional and Drought Tolerant and corn hybrids for all irrigation treatments.

Yield Responses

Average treatment yields and seasonal crop evapotranspiration for the two corn hybrids are summarized in Table 3. Yields did not differ significantly (p-value=0.38) across the five irrigation scheduling treatments. There was also no significant difference between the 100%ET treatment (T6) and the 80%ET treatments T1 to T5. The yield of the fully irrigated treatment (T6) was lower than that for treatments 1, 3, and 5 for the conventional corn hybrid and less than treatments 1 through 5 for the drought tolerant hybrid. This could probably be attributed to the hail storm that occurred early in the season (June 24, 2014) that effected canopy cover as shown by the low LAI, particularly for the conventional hybrid (Figure 3). Treatment 2 based on canopy temperature and the time temperature threshold produced approximately 2% more yield compared to treatment 1 for the conventional hybrid and 4% higher yield for the drought tolerant hybrid. Treatment 3 based on calibrated CS655 soil water sensors produced 5% higher yield than T1 for the conventional hybrid and 1% higher yield for the drought tolerant hybrid. Treatment 4 that triggered irrigation events based either soil water or plant stress thresholds being exceeded produced yields that were 12% lower for the conventional hybrid and 3% higher for the drought tolerant hybrid compared to treatment1. Yields for treatment 5 that triggered irrigation only if both soil water and plant water stress (CWSI=0.3) thresholds were exceeded produced yields that were lower than those for treatment 1, 9% for conventional hybrid and 4% for the drought tolerant hybrid.

However, there were significant differences between drought tolerant and conventional corn hybrids (p-value=0.003). There was no-significant interaction between irrigation scheduling and corn hybrid (p-value=0.45). With the exception of treatment 4, the conventional hybrid out yielded the drought tolerant hybrid on average 20%. Again these observations could be attributed to reduced canopy cover from hail damage, particularly in the drought tolerant hybrid, which also unfortunately lead to increased weed pressure in these plots due to more direct solar radiation reaching the ground surface. From Table 3, it appears seasonal ETc did not differ substantially between the two hybrids despite the fact that the drought tolerant hybrid had less canopy which could have contributed to reduced water use. This could probably be attributed to an increase in soil evaporation as transpiration reduced.

Table 3. Yield response to irrigation scheduling method and corn hybrid during the 2014 growing at Garden City Kansas.

Treatments	Yield (bu/ac)		Yield (bu/ac)		Seasonal ETc (in)	
	Conventional	Std.[1]	Drought Tolerant	Std.	Conventional	Drought Tolerant
T1	206	32	181	18	22 (2)[2]	21 (2)
T2	209	13	189	13	25 (1)	26 (1)
T3	219	23	179	23	25 (2)	24 (2)
T4	182	26	186	17	24 (1)	24 (0)
T5	192	12	173	22	23 (1)	23 (2)
T6	189	8	173	32	25 (1)	25 (1)

[1]Standard Deviation

[2]Numbers in parentheses are standard deviations

Irrigation and Water Use

The number of irrigation events, irrigation frequency and total irrigation is summarized in Table 4. The fully irrigated treatment (T6) received 42%, 33%, 25%, 17% and 25% more water compared to treatments T1 through T5, which were designed to replenish only 80% of full irrigation. As explained earlier, despite the large amount of irrigation applied to treatment 6, its yields were lower than all other treatments with the exception of treatment 4. All treatments received 2 inches of pre-irrigation prior to emergence to allow for germination and plant establishment since only 1.25 inches of rainfall had been received since January 01, prior to planting on May 05. Of all the treatments, the standard irrigation scheduling method based on monitoring soil water using the neutron probe and a threshold of 60% plant available water required the least amount of water. Treatment 2 based on the TTT required 11% more water, while treatments 4 and 5 required 33% and 11% more water compared to treatment 1 respectively. Treatment 3 based on using a calibrated CS655 soil water sensor required 22% more water compared to treatment 1, this treatment also resulted in the highest yield for the conventional corn hybrid.

Average crop water productivity (CWP) and irrigation water use efficiency (IWUE) are summarized in Table 5. The conventional corn hybrid had higher crop water productivity compared to the drought tolerant hybrid. All deficit irrigation scheduling treatments had higher crop water productivity compared to the fully irrigated treatment since the high ET (25 inches) for treatment 6 was not proportionally related to yield as would be expected under conditions with no external abiotic stresses. Treatment 3 based on calibrated soil water sensor had the highest water productivity. Overall the CWP did not vary substantially among irrigation scheduling methods.

Irrigation Water Use Efficiency (IWUE) was higher for conventional versus drought tolerant corn. The fully irrigated treatment resulted in the lowest IWUE again probably due to external abiotic stresses since not all water applied was beneficially used to produce economic yield. Some water could have been used in producing non-economic yield like weeds. The reference irrigation scheduling treatment T1 had the highest IWUE followed by treatment T2 based on canopy temperature. These results highlight the need for integrated monitoring of the soil water, and plant stress (both abiotic and biotic) when growing crops under non ideal environments. For example, the fully irrigated treatment designed to replace 100 % ET did not account for reduced water use resulting from canopy damage caused by hail and ended up applying more than 4 inches of water than would be required given the reduced yield potential. This suggests that irrigation water management without feedback from monitoring could result in reduced profitability. Unfortunately in the Central Plains, in addition to water stress there are many other external factors that lower yield potential (e.g., hail, temperatures, pests and diseases).

Table 4. Irrigation applications, frequency and total irrigation applied to five deficit irrigation scheduling treatments (80% of full irrigation) and control (full irrigation)

Treatment	Number of Irrigation Events	Irrigation Frequency (days)	Pre-irrigation[1] (in)	In-season Irrigation[2] (in)	Total Irrigation (in)
T1	7	6.7	2	7	9
T2	8	6.0	2	8	10
T3	9	5.4	2	9	11
T4	10	5.6	2	10	12
T5	8	6.0	2	8	10
T6 (Full)	12	4.5	2	12	14

[1]Irrigation applied before crop emergence

[2]Irrigation applied between emergence and harvest

Table 5. Crop Water Productivity and Irrigation Water Use Efficiency for 5 deficit irrigation scheduling methods and a control (full irrigation)

Treatments	CWP (bu/ac-in)		IWUE (bu/ac-in)	
	Conventional	Drought Tolerant	Conventional	Drought Tolerant
T1	12.4 (2.1)	10.6 (1.1)	29.5 (4.5)	25.8 (2.6)
T2	12.9 (0.9)	10.7 (0.8)	26.2 (1.6)	23.7 (2.6)
T3	13.0 (1.7)	10.7 (1.3)	24.3 (2.6)	19.9 (1.7)

T4	11.3 (1.2)	10.7 (1.4)	18.2 (2.6)	18.6 (1.7)
T5	12.0 (0.7)	10.7 (1.0)	24.0 (1.5)	21.7 (2.7)
T6 (Full)	11.1 (0.3)	9.7 (2.4)	15.8 (0.7)	14.4 (2.7)

[1]Standard Deviation

[2]Numbers in parentheses are standard deviations

Soil Water Analysis

The first neutron probe soil water content measurement was made on July 10, 2014, due to practical issues such as wet field conditions that prohibited installation of the neutron probe access tubes earlier in the season. Soil water measurements were taken at different depth in increments of 1 foot down to 8 feet. The soil water data indicates that residual soil water effects from a prior study had significant effect on soil profile water content as shown in Figures 4 and 5. Prior to July 10, all treatments were managed the same, receiving only two pre-irrigations to support germination and plant establishment. Treatments 1, 2, and 3 were in the high water plots in the previous study while treatments 4, 5 and 6 were in the locations of low irrigation levels. Soil water measurements in the top 4 feet on DOY191, corresponding to July 10, indicated that soil water content was less than 50% depleted (based on 0.33 =0% depleted and 0.15=100% depleted) in treatments 1 to 3 while treatments 4 and 5 were between 50 to 75% depleted. Treatment 6 was very dry ranging from approximately 70% to 100% in the top 4 feet. Since the study was conducted under no-till system, the high water plots from the previous study also tended to have high crop residue cover.

The neutron probe readings were taken approximately 11 days before tassel which is a sensitive stage to water stress. These data could also explain the differences in yields between treatment sets 1 to 3 and 4 to 6. It appears the full irrigation treatment was not able to restore soil water content in the top 4 feet to less than 50% depleted by tassel (DOY 202 or July 21). This could also explain why this treatment tasseled earlier than other treatments. These results underscore the need to have sufficient soil profile water at planting, since the irrigation system might not catch up with plant water use during the season.

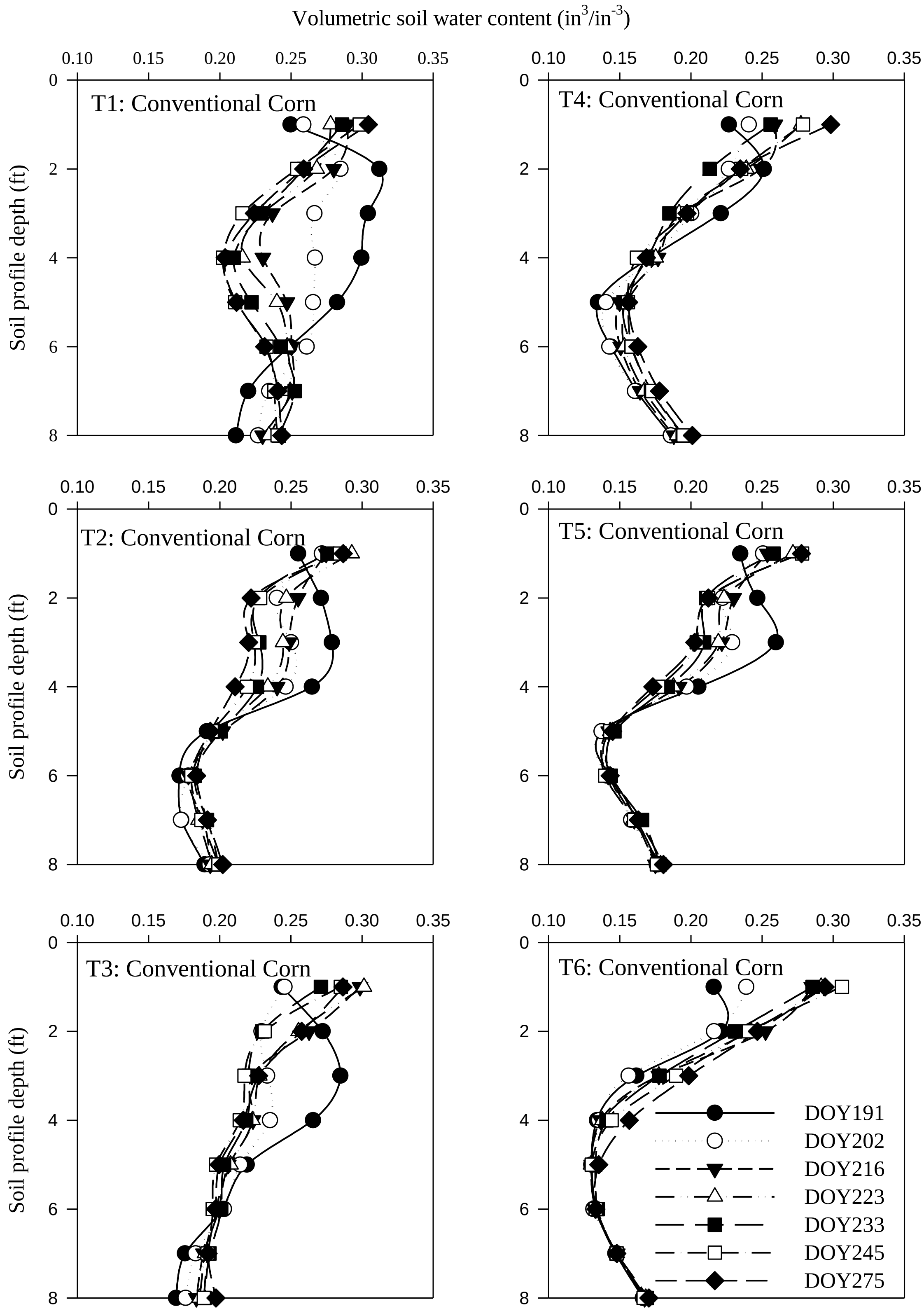

Figure 4. Soil profile water content taken at different depth using a neutron during the 2014 growing season in the conventional corn plots at Garden City Kansas.

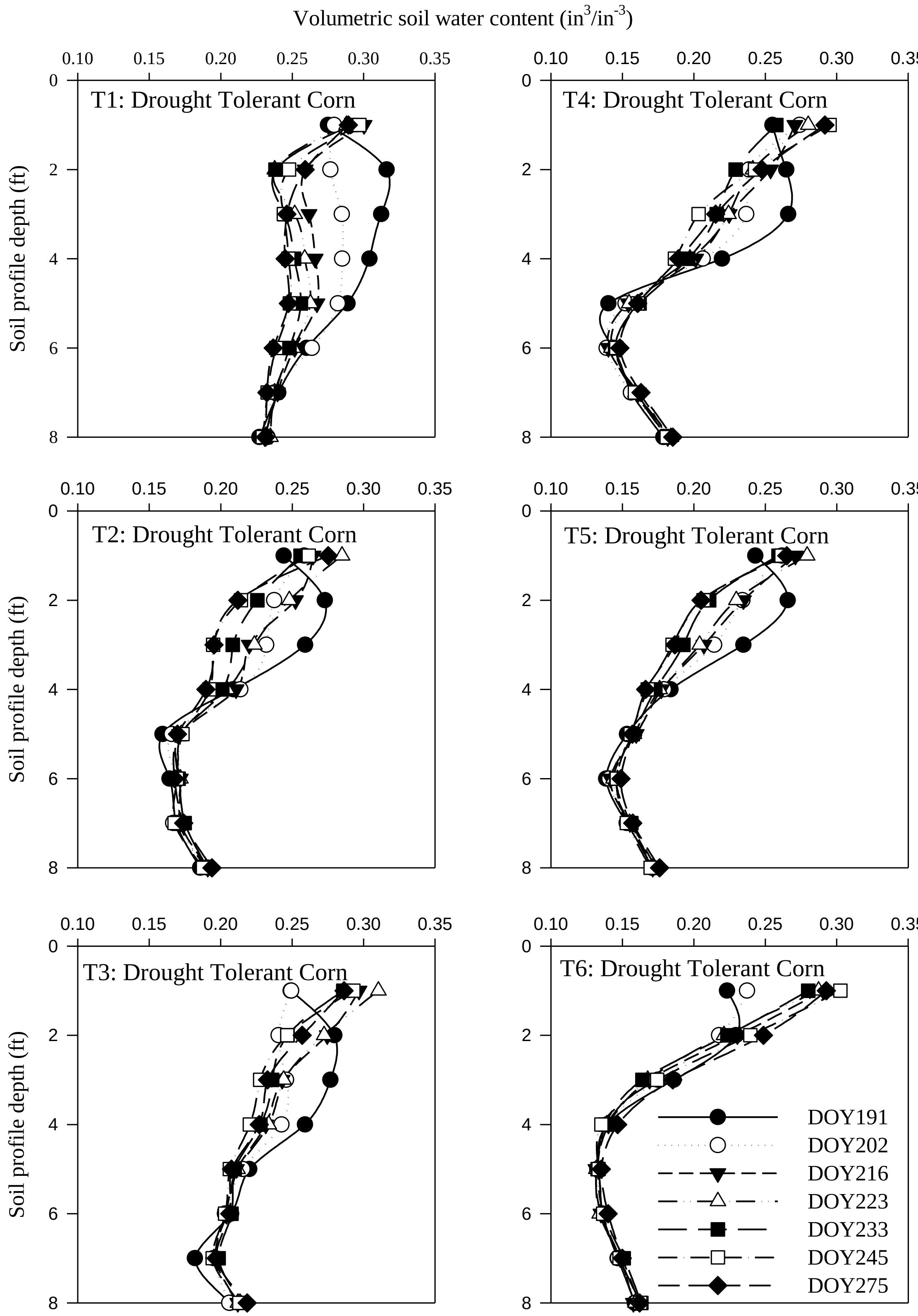

Figure 5. Soil profile water content taken at different depth using a neutron during the 2014 growing season in the drought tolerant corn plots at Garden City Kansas.

Soil water measurements from the CS655 soil water sensors were calibrated using neutron probe measurements. Prior to calibration, the sensor was over estimating soil water under wet conditions. However, after calibration using a simple linear regression (Y=0.1991X+0.2081, R^2=0.89), the sensors were able to accurately measure soil water. The soil water sensors were to track wetting (from irrigation or rainfall) and drying cycles as shown in Figure 6 and root water uptake during the day and near zero transpiration during the night as shown in Figure 7. These figures indicate that in addition to bulk soil electroconductivity and soil temperature data these types of multi parameter sensors provide, they could also be used to determine rooting depth; which could be useful in characterizing soil water extraction patterns of different hybrids. This data on root zone water use may increase the confidence of users of ET-based scheduling.

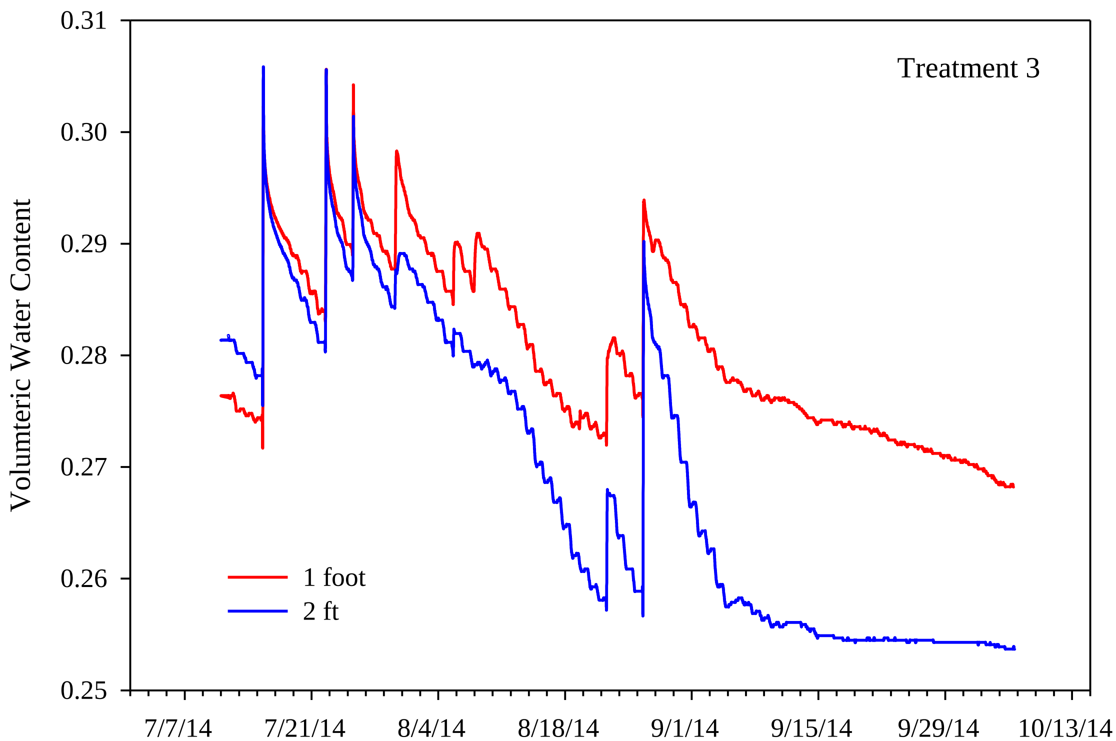

Figure 6. Soil water measurements at two different depths over time made by the CS655 soil water during the 2014 corn growing season Garden City Kansas.

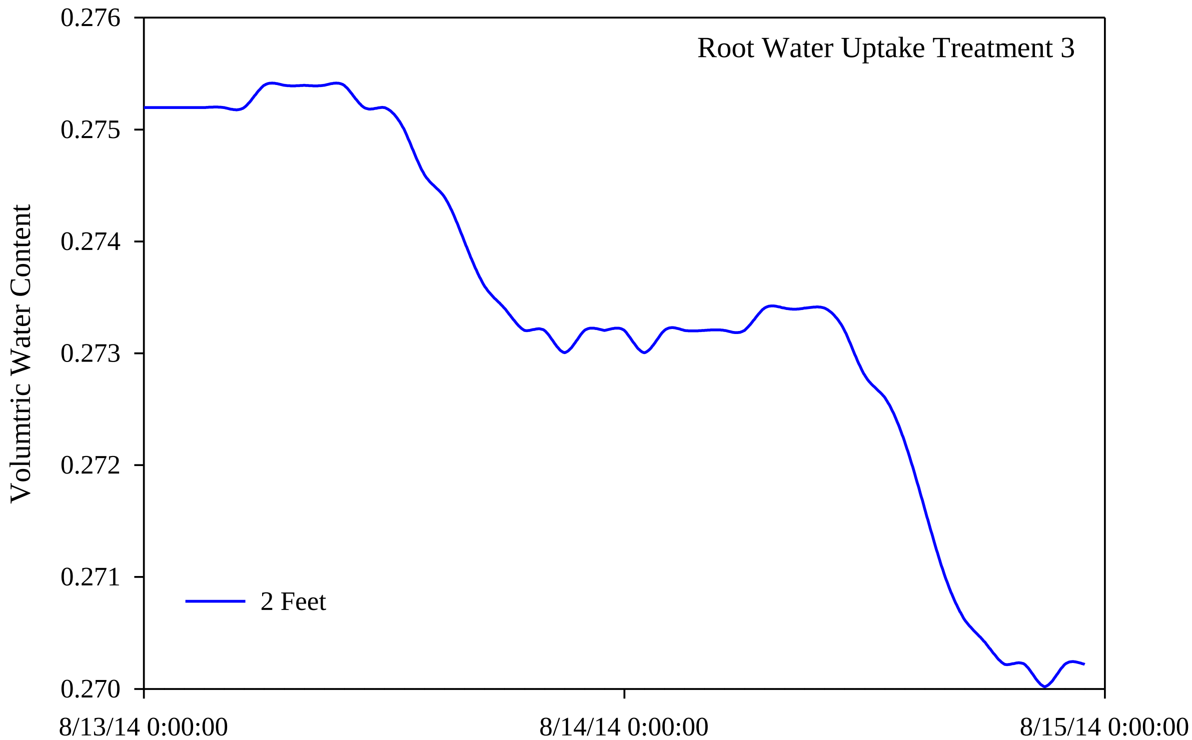

Figure 7. Illustration of root water uptake during the day and close to zero uptake during the night.

Conclusion

As well capacities continue to decline, producers will need to adopt advanced irrigation scheduling to maintain productivity with limited water supplies. Five irrigation scheduling approaches based on plant water stress sensing, soil water sensing, and climate (ET), or a combination of these methods were assessed. Preliminary data indicates that all irrigation scheduling methods could be effectively used to manage irrigation water. However, combining more than one irrigation scheduling method might increase reliability and adequacy of irrigation scheduling. Locally adapted conventional hybrids out yielded the drought tolerant hybrid in this study, although hail damage that occurred earlier in the season could have confounded the results. The study also underscored the potential impact of low soil water at planting on corn yield. Continuous soil water sensing using a calibrated CS655 sensor provided useful insights into root water update at night and during daylight hours. Integrating soil and plant water status monitoring with the scientifically robust ET-based scheduling could result in more reliable irrigation scheduling decisions, especially under nonideal growing conditions where external abiotic and biotic factors influence crop water use. Integrated irrigation scheduling technologies could also encourage more producers to adopt the practice thereby optimizing profitability while conserving water.

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Comparing Water Use Efficiency in South Texas Furrow and Drip Irrigated Watermelon

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Abstract. Crop production in the Lower Rio Grande Valley (LRGV) of South Texas is at continual risk due to drought conditions. Irrigation sources stem from the Rio Grande, and when water resources are limiting, water conserving methods are needed. The purpose of this project was to evaluate drip irrigation with plastic mulch as a water conservation strategy to drip without plastic and furrow irrigated watermelon. Crop water requirements were estimated using a weather station, Penman-Montieith evapotranspiration (ET) equation, and FAO crop coefficients. Drip irrigation was employed by a water balance approach, replacing ET water loss within the drip irrigated plots versus irrigating to soil saturation point in furrow irrigated plots. Harvested watermelon were measured for total soluble solids (TSS), size and weight to determine yield and quality. In the drip with plastic treated plots, the highest average yield and best overall irrigation use efficiency compared to the other systems was observed.

Introduction

The LRGV of South Texas faces ongoing drought conditions and water supply shortages which negatively impact the regional water users. Most of the water resources stem from the Amistad-Falcon reservoir system which is operated by Mexico and the United States by the International Boundry & Water Commission. Currently Mexico is failing to meet treaty commitments which oblige it to contribute a certain volume of water inflow from the Rio Conchos into the Rio Grande which upstreams into reservoirs such as the Asmistad-Falcon (RGRWA, 2014). As the LRGV remains to deal with such impact of current water deficits, irrigation districts have already announced to agricultural producers that water distributions may become postponed or suspended. When the LRGV districts are no longer able to pump water, metropolises will be affected as well.

LRGV crop production is at continual risk due to drought conditions. As water resources are limiting in the LRGV, the need to change to a more water conserving method to irrigate crops. Growers often apply an excess amount of water using traditional furrow (flood) irrigation. Majority of farmers in the LRGV use furrow irrigation because of how irrigation is distributed; water is pumped through gravity-flow canals and underground pipelines (Fipps & Pope, 1998) distributing a large amount of water in a short period of time. The water must be ordered, so short frequent irrigations would be costly. One of the limiting factors in using the drip system is that a cistern or small reservoir is needed where land is taken out of production to store water in order to irrigate frequently. Growers are hesitant to change because water is cheap in South Texas. However, research suggests that using a water-balance approach for irrigation scheduling may improve yield and quality as well as decrease the amount of water applied by only ordering need specific irrigation.

Objectives

The purpose of this project is to develop an irrigation strategy to manage limiting water resources by using a water-balance approach. Drip irrigation was evaluated as a water conservation strategy to conventional furrow irrigation for watermelon. The waterbalance approach was also tested with furrow irrigation, since it is the conventional method in South Texas. Water use efficiency (WUE) and Irrigation Use Efficiency (IUE) was also determined for treatments.

Determining Irrigation Scheduling

In order to estimate the crop water requirements for watermelon, a weather station, the Penman Montieth evapotranspiration (ET) equation, and FAO coefficients were used to determine waterbalance calculations.

Water balance

Influenced by South Texas' high temperatures, the primary source of water, rainfall supply, is insufficient and consequently the region's drought conditions become poorer. Irrigation is fundamentally the alteration of the environment's water balance. Water is added to satisfy the needs of crop growth. Rainfall, evaporation, surface water, and water stored in soil all make up and modify the waterbalance. A water balance is the relationship between the amount of water stored and water lost (Teare & Peet, 1982). According to (Teare & Peet, 1982), the irrigation scheduling program using meteorological data to compute water use and maintain a water balance is conveyed as

$$D_{pi} = D_{pi}\text{-}1 + K_{ci} \text{ x } E_{tpi} + E_{tri} - (R_i - Ro_i) + W_{di} \qquad [1]$$

Where D_{pi} is depletion on day I, K_{ci} represents crop coefficient (role of crop stage), E_{tpi} is the reference evapotranspiration,E_{tri} is the added soil evaporation after irrigation or rain, R_i is the the sum of effective rainfall and net irrigation on day i, Ro_i is the surface runoff, W_{di} is the drainage underneath root zone or groundwater ascending flow (Teare & Peet, 1982).

FAO Penman Montieth ET equation

The FAO Penman Montieth ET equation is known as (Allen, Pereira, Raes, & Smith, 2004):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad [2]$$

Where FAO coefficients, ET_o represents reference evapotranspiration [mm day $^{-1}$], R_n is net radiation at the crop surface [MJ $m^{-2}day^{-1}$], G is soil heat flux density [MJ m^{-2} day^{-1}], T is mean daily air temperature at 2 m height [°C], u_2 is wind speed at 2 m height [m s^{-1}], e_s is saturation vapour pressure [kPa], e_a is actual vapour pressure [kPa], $e_s - e_a$ represents saturation vapour pressure deficit [kPa], Δ is slope vapour pressure curve [kPa $°C^{-1}$], and ϒ denotes psychrometric constant [kPa $°C^{-1}$]. Evapotranspiration of different crops at different periods of the year and in different regions can be compared with the Penman Monteith equation.

Soil Water Content & Water Storage Capacity

Other values needed to determine when and amount to irrigate are the field's capacity, plant available water, and the permanent wilting point (Enciso, Porter, & Evett, 2012). The following values were obtained to determine the soil's field capacity and available water content from the USDA-NRCS National Engineering Handbook Irrigation Guide (Table 1). Water storage capacity of soil values are shown in (Table 2). It is important to note that root depths can be affected by soil and other conditions (Enciso, Porter, & Evett, 2012).

Table 1. Soil water parameters for Hidalgo Sandy Clay Loam

Soil Texture	Field Capacity (in/ft)	Field Capacity	Plant Available Water (in/ft)	Available Water Content	Permanent Wilting Point (in/ft)	Wilting Point
Sandy Clay Loam	4	0.33	1.8	0.15	2.4	0.20

Table 2. Allowable soil water depletions (MAD, %) and root depths (m) for watermelon

Crop	Allowable depletion (%)	Root depth (m)
Watermelons	40-45	79.25 - 91.44

Determining Water Use Efficiency and Irrigation Use Efficiency

Water Use Efficiency (WUE) is the proficiency with which water is able to produce yield. WUE is yield divided by irrigation applied + rainfall, WUE = (kg/ha·mm) (Sadras & Angus, 2006). Irrigation Use Efficiency (IUE) is the yield divided by the irrigation applied, IUE = (kg/irrigation applied). WUE and IUE are crucial in determining how well an irrigation treatment would be able to sustain a crop when water availability is limited.

Materials and Methods

This study was conducted during the spring watermelon growing season of 2014 at the Texas A&M AgriLife Research Center located in Weslaco, Texas (longitude 26˝ 9' N, latitude 97˝ 57' W). The soil at the research site was Hidalgo sandy clay loam (fine-loamy, mixed, hyperthermic Typic Calciustolls). This region has a semiarid climate and the average annual rainfall is 56 cm. Watermelon seedless variety SS 7191 (Abbott and Cobb®) was seeded in a greenhouse on February 10, 2014, then transplanted to field on March 17, 2014. Watermelon was planted in a 3:1 ratio (the 1 being the pollinizer) with the pollinator POL-4370 from the same company spaced 0.9 m apart in 2 m wide raised beds.

This study was conducted as a split-plot design with three treatments: Furrow, Drip with Plastic mulch (Drip-Plastic), and drip on bare ground (Drip-Bare). There were four replications per treatment. The Rio Grande was the source of irrigation water, which was filtered at both locations for the drip irrigation systems. The drip tubes with different emitter spacing had nominal discharge ratings of 0.245 GPH per emitter with 30 cm emitter spacing for the Weslaco site (Netafim USA, Fresno, Cal.).

Irrigation scheduling was targeting using a balance sheet approach at the Weslaco site. Withdrawals includes calculated crop evapotranspiration (ETc) based on Pennman–Monteith reference evapotranspiration and the crop coefficient curves for each irrigation treatment, adjusted by a stress coefficient based on the depletion level and daily ETc rate (Allen et al., 1998). Plots were irrigated approximately twice per week depending on rainfall inputs. An automatic weather station (model ET106, Campbell Scientific, Logan, UT) at the site was used to measure rainfall (TE525 tipping bucket rain gauge), maximum and minimum temperature and relative humidity (CS500 temperature and relative humidity sensor), total solar radiation (LI200X pyranometer), and average wind speed (034A wind set) which was recorded hourly using a CR10X data logger. In field soil moisture sensors (Watermark Soil Moisture Sensors, Irrometer, Co., Riverside, CA) were placed at 15 cm below the soil surface to monitor irrigation near root zone. One water mark sensor was installed per treatment in each of the replications. In field soil moisture sensors, Watermark® Soil Sensors and Decagon® 5TE and 5TM sensors, were installed. Dataloggers and handheld meters were used to obtain soil moisture readings from sensors. Watermark® Sensors were placed at 15 cm below soil surface to monitor irrigation near root zone. Decagon sensors were installed at 15, 30, and 46 cm below soil surface. Sensors were not used as an irrigation scheduling technique; they were used as a reference tool to see if patterns between sensors and water balance could be seen.

The amount of water applied to each plot through irrigation was measured with water meters connected to the irrigation system. One flow meter was installed per treatment and replication for the drip irrigation system, and one flow meter was used for all the furrow irrigated plots. Approximately the same amount of water was applied to the different drip irrigation treatments during each irrigation event. Since evapotranspiration cannot be calculated with plastic mulch covering plot topsoil, water soil sensors were used. Drip-Plastic was irrigated when sensors reached the level at which Drip-Bare needed to be irrigated. With Drip-Plastic, time in between irrigations was a lot longer than Drip-Bare because moisture was retained longer. Waterbalance calculations indicated that a total of 39.62 cm of water were evapotranspirated as shown in (Figure 1). In attempt to replace ET, Irrigation applied + Rainfall were approximately 41 cm for Furrow, 28.45 cm for Drip-Plastic, and 25.40 cm for Drip-Bare.

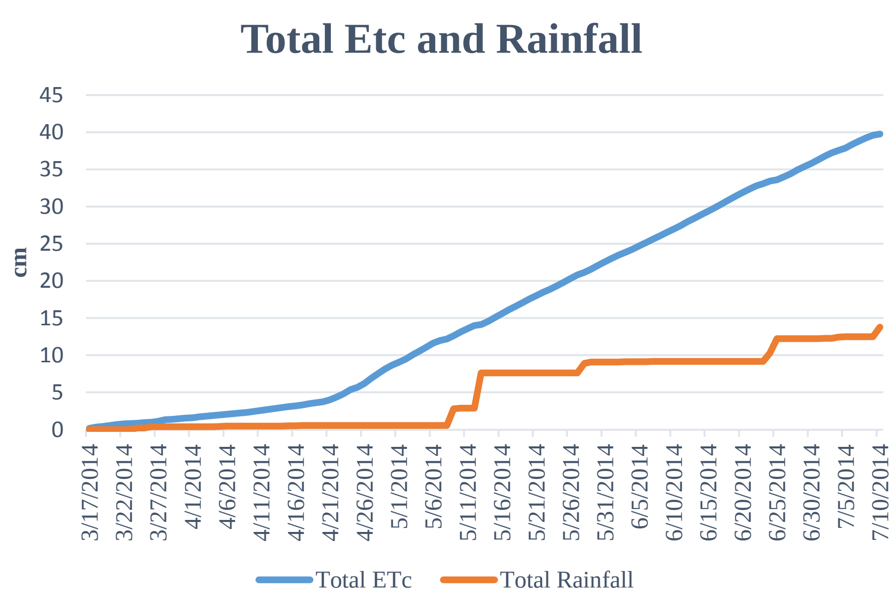


Figure 1. Total Etc and Rainfall

Crop water used was estimated using the crop coefficients for watermelon (0.7 for initial, 1.05 for mid, and 0.8 for end) as suggested by Allen et al., 1998. Curves were adjusted to local conditions regarding the duration of the various growth phases based on previous visual observation of the crop. The lengths for the four growth stages were adjusted according to visual observations. The length of each stage was 20 days for initial, 30 days for development, 100 days for mid and 10 days for the end stage. Watermelons were harvested on June 23 and July 9, 2014. The watermelons were harvested and the number of fruits and weight per fruit were recorded in each plot. After harvesting, the length, diameter, rind thickness and total soluble solids (TSS) (brix %) were measured in each fruit. Data were analyzed with a general linear model (GLM) procedure using SAS (Cary, NC). Duncan's multiple range test (P = 0.05) was used to for mean comparisons.

Results

The watermelon yields were marginally higher for the drip irrigation than Furrow (Table 3). Numerically, the yield for the Drip-Plastic was slightly higher (70,096 kg/ha) than the Drip-Bare (65,871 kg/ha). Furrow resulted in the lowest yield (64,960 kg/ha). Analysis of variance indicated that the mean yield for treatments were not statistically different (F=0.31, DF=2, P=0.742) (Figure 2).

Table 3. Watermelon yield and average fruit weight

Irrigation Treatment	Yield (kg/ha)	Average fruit weight (kg)
1. Furrow	64960	6.9 a
2. Drip-plastic	70096	7.4 a
3. Drip-bare	65871	8.0 a

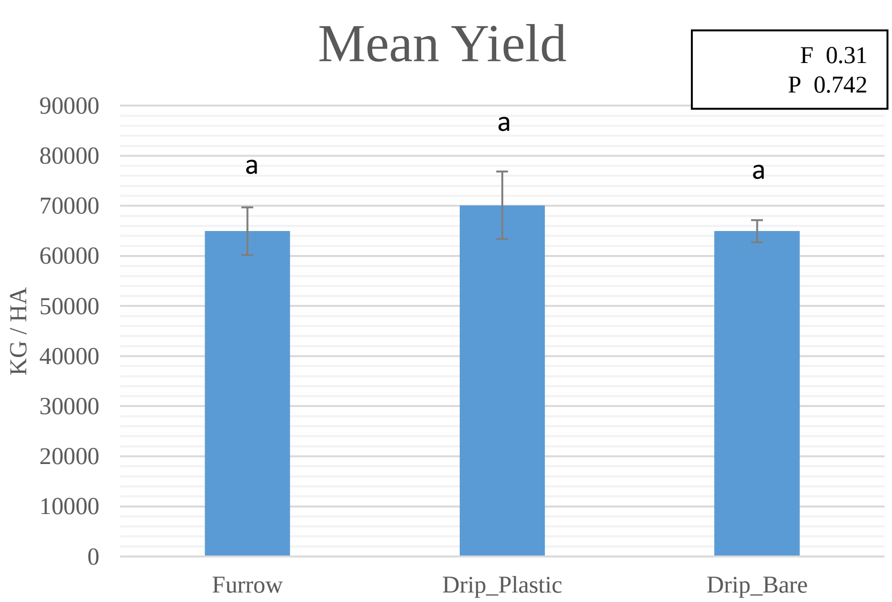


Figure 2. Mean Yield for Irrigation Treatments

Watermelon characteristics for treatments can be seen in (Table 4). Analysis of variance indicated that the TSS were higher for the drip irrigation treatments (Figure 3) compared to the furrow irrigation treatment ($F=7.88$, $DF=2$, $p=0.001$). The length of the watermelons (Figure 4) were faintly higher for the drip irrigation system but were not statistically different ($F=1.61$, $DF=2$, $p=0.21$). The watermelon diameter (Figure 5) for Drip-Plastic was rather higher, but was not statistically different from the other treatments ($F=2.43$, $DF=2$, $p=0.09$). Rind thickness was also evaluated and analysis of variance indicated similar for all irrigation the treatments ($F=0.35$, $DF=2$, $p=0.71$) (Figure 6).

Table 4. Watermelon characteristics for the Furrow, Drip-Plastic and Drip-Bare.

Treatment	TSS (brix %)	Length (cm)	Diameter (cm)	Rind Thickness (cm)
Furrow	11.13	29.22	23.63	1.83
Drip-Plastic	11.91	29.78	24.52	1.83
Drip-Bare	11.86	30.43	24.47	1.76

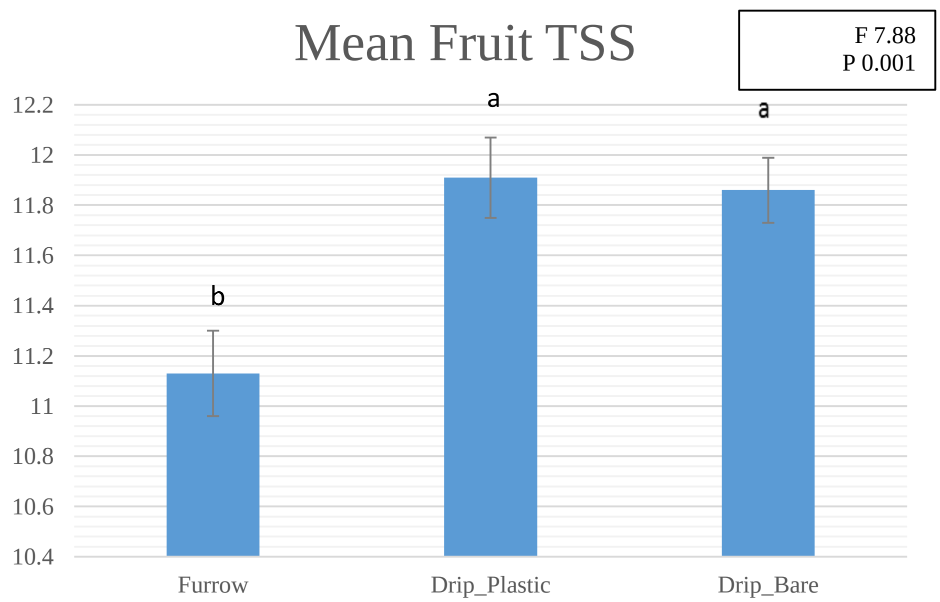


Figure 3. Mean Fruit Total Soluble Solids (Brix%) for irrigation treatments

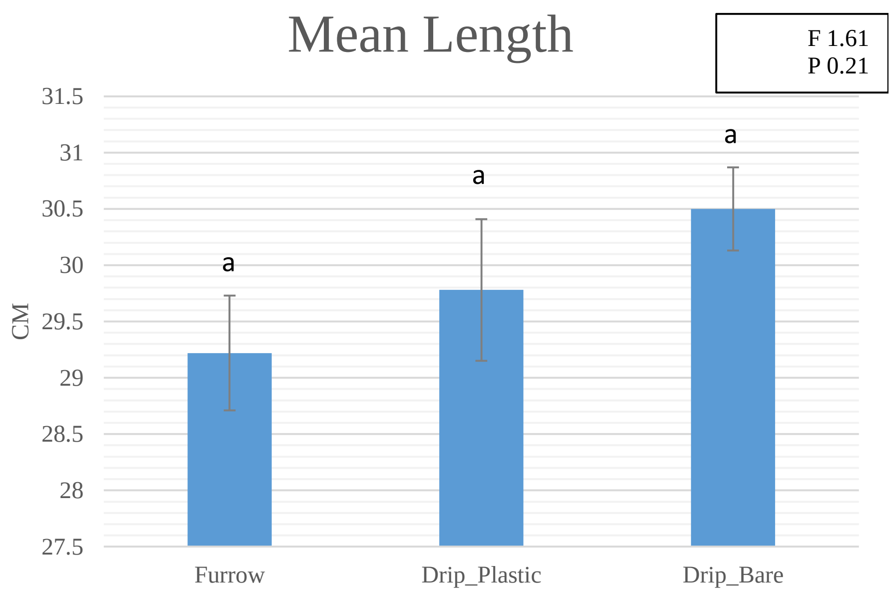


Figure 4. Mean Fruit Length

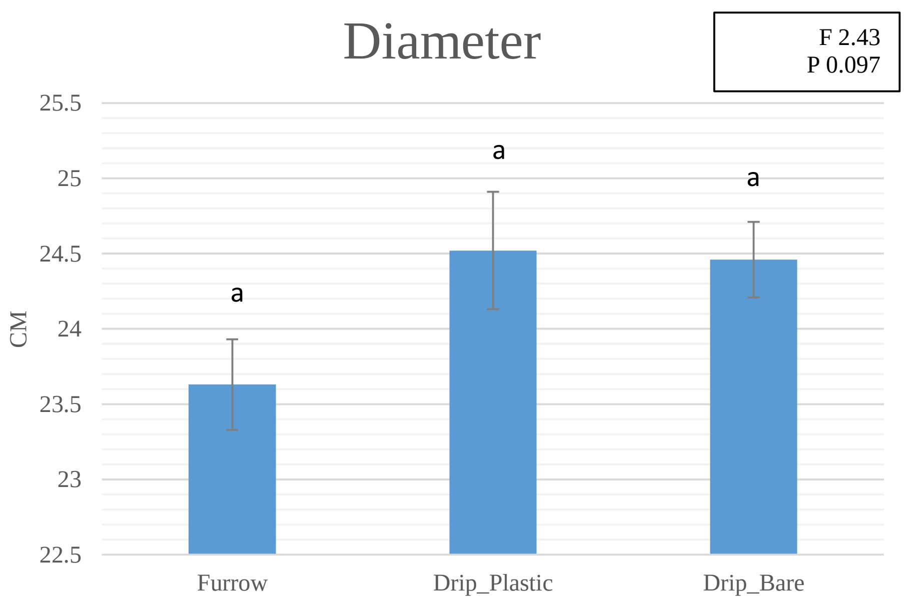


Figure 5. Mean Fruit Diameter

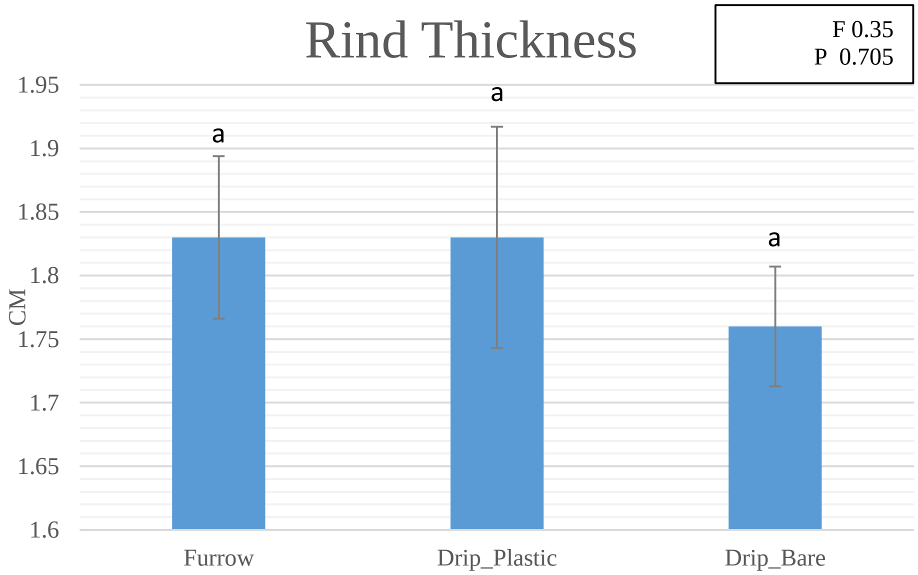


Figure 6. Rind Thickness for each Treatment

Approximately the same number of irrigation events were applied with both drip and furrow irrigation systems (Table 5). The drip irrigation systems applied less than half of the water (Figure 7) than that of the furrow irrigation system and almost double the irrigation efficiency of the furrow. It is important to notice that the length of the furrow rows in this experiment were short rows (roughly 100 m). In normal field conditions with longer furrows, it is impossible to apply small irrigation depths such as the ones applied with this experiment. Generally, commercial farms apply 10 cm or more per irrigation. Less number of irrigations applied could positively impact watermelon yields. Table 5 shows the number of irrigations, irrigation applied watermelon ET and irrigation use efficiency for Furrow, Drip-Plastic and Drip-Bare during the 2014 spring growing season.

Table 5. Calculation of ET, Water Use Efficiency (WUE) and Irrigation Use Efficiency (IUE)

System	Irrigation (cm)	Rainfall (cm)	Irrigations	ET (cm)	WUE (kg/cm)	IUE (kg/cm)
Furrow	27.43	13.71	11	39.62	1579	2368
Drip-Plastic	11.68	13.71	12	39.62	2469	4774
Drip-Bare	14.73	13.71	13	39.62	2284	4410

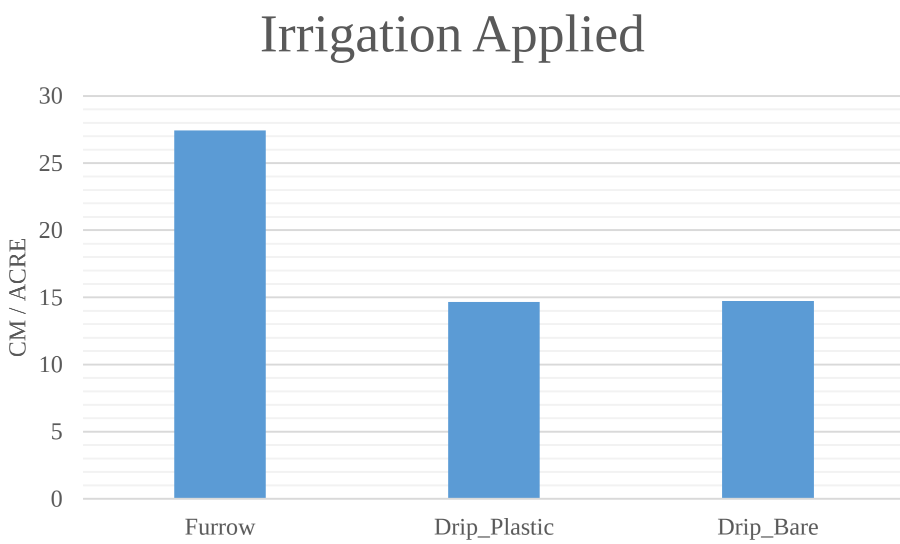
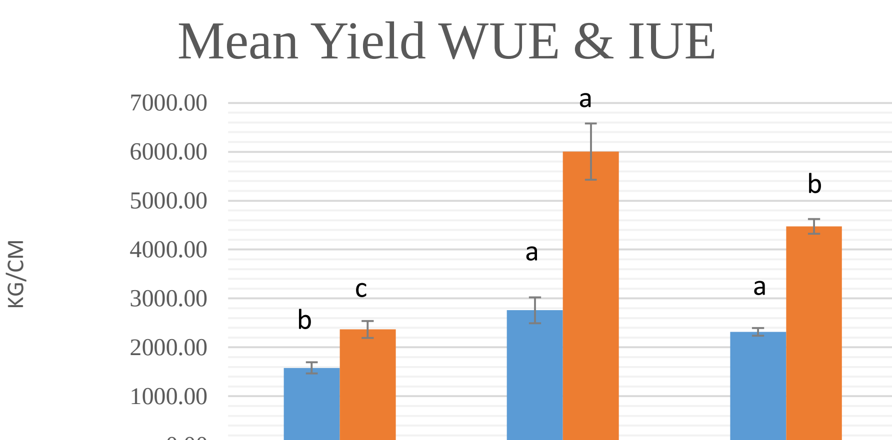


Figure 7. Irrigation Application for Irrigation Treatments



	Furrow	Drip_Plastic	Drip_Bare
WUE (kg/cm irrig)	1579.00	2760.00	2316.00
IUE (kg/cm irrig)	2368.21	6001.00	4471.00

Figure 8. Mean Yield Water Use Efficiency (WUE) & Irrigation Use Efficiency (IUE)

Analysis of variance showed that the total yield WUE of watermelon varied significantly ($F= 11.90$, $DF = 2$, $p= 0.003$). Analysis of variance for total yield IUE varied suggestively ($F= 25.90$, $DF = 2$, $p= 0.002$) (Figure 8).

Conclusions

Furrow and drip irrigated watermelon were compared for crop production WUE and IUE. The overall performance of the three irrigation methods showed little differences in the watermelon yield. Smallest yield occurred for Furrow irrigated plots, with yield about 0.95 times less than drip treatments. Overall total yield WUE for Furrow was 43% less than Drip-Plastic and 32% less thanDrip-Bare; IUE 39% lower than Drip-Plastic and 48% lower than Drip-Bare. Plots with drip irrigation applied 53% less water than furrow irrigated plots. IUE for Drip-Plastic was 1.34 times higher than Furrow; for Drip-Bare ground it was 26% lower than Furrow; WUE was 1.74 times higher for Drip-Plastic and WUE for Drip-Bare was 17% higher than Furrow.

In regards to watermelon quality indicators, percent soluble solids (TSS) measured statistically different for drip and furrow treatments. Sweeter watermelons came from drip treated plots which resulted in TSS 1.07 times higher than furrow treated watermelon. Other quality parameters measured were watermelon length, diameter, and rind thickness; results measured to be statistically similar for all treatments.
The differences in water applied demonstrated that drip irrigation could be used to reduce water usage, water runoff, and deep percolation compared to furrow irrigation. The overall results of this project show that when water availability is limited, drip irrigation will sustain production while upholding that same quality watermelon, to the point of producing higher mean yield per unit of irrigation water applied (IUE). The results also indicate that the water balance approach may be used for furrow irrigation, decreasing the amount of irrigation events.

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Irrigation Association 2014 Irrigation Show & Education Conference Technical Sessions

How Can Agricultural Producers Organize to Stretch Limited Aquifer Supplies to Sustain Themselves and Their Rural Communities?

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ABSTRACT

Most are aware that the Ogallala Aquifer is being seriously depleted as irrigated agriculture continues to be an important economic driver in those areas relying on this vast store of underground water. Some groups of farmers and ranchers, often part of groundwater management districts (GWMDs), are beginning to develop rules to control their own use of the aquifer in hopes of stretching out the resource. Presumably, such rules being proactively developed by a group of irrigators is preferable to a state mandate that may be inevitable otherwise. The author is facilitating the organization of such a group on the northeastern plains of Colorado. Here she shares some of the sociological and technological questions that are arising during the beginning stages of the conversation.

FACED WITH A CHALLENGE? ORGANIZE!

When agricultural producers are motivated, much can happen in just a few short months. This paper outlines the challenge and the response to that challenge that has been launched by a small group of committed groundwater users in northeast Colorado.

The Water Preservation Partnership of the Northern High Plains of Colorado was organized in September, 2013 and is made up of one representative from each of eight GWMDs. In addition to being located geographically in the Northern High Plains basin of the Ogallala aquifer, these districts are also geographically part of the Republican River Basin, though they use very little surface water in their operations.

A significant player in bringing these GWMDs together is the Republican River Water Conservation District (RRWCD), formed in 2004 by legislative statute to assist Colorado in achieving compliance with the interstate compact with Kansas and Nebraska over the sharing of waters from the Republican River. Those programs required a great deal of sacrifice from ag producers from the districts, including the voluntary permanent dry up of some irrigated ag lands and the building of a pipeline to transport groundwater to the river in an effort to meet compact requirements. Even a well-loved plains reservoir had to be drained as part of the efforts Colorado has had to carry out to attain compact compliance. These programs have been financed from an annual fee paid by all the well owners based on irrigated acreage and from commercial wells and municipal wells based on the annual amount of water pumped.

RRWCD has the responsibility of making sure Colorado complies with the interstate compact, but does not have authority to enact rules to reduce pumping otherwise. Now that the issue of compliance is mostly settled, several individuals on the board of the RRWCD along with community leaders and other ag producers, believe it is time to turn their attention to ways to arrest the ongoing depletion of the aquifer. Most are aware that current pumping rates cannot be sustained, and that at risk are the livelihoods not only of ag producers, but also the viability of the many small ag-based communities in which they live. Most of the economic strength of the region comes from irrigated ag production. A statewide water supply study published in 2010 shows that the region represents 16% of Colorado's irrigated acres.

Membership in the Water Preservation partnership, in addition to one member from each GWMD, includes one representative from the RRWCD and one representative from a group formed earlier during the compliance issues called Colorado Agricultural Preservation Association. The group of ten has met regularly since its formation, with attendance at meetings of other agricultural and community leaders including some of the GWMD managers and elected officials. The author of this paper, policy and collaboration specialist with the Colorado Water Institute at Colorado State University facilitates meetings.

Exemplary of the energy and focus of the group, they adopted at their very first meeting this very clear mission: To preserve, for as long as possible, the underground water resources we all rely on." They immediately focused on a study that shows that they are pumping 400,000 acre feet each year more than is being recharged.

Dialogue about various water conservation methods that could be employed, such as eliminating end guns from center pivot sprinklers quickly turned to the reality that voluntary water conservation methods alone will not reduce the pumping enough to turn things around. The group narrowed in on the belief that they need a policy or policies ag producers can all agree to that requires a reduction in pumping. Pumping less water could have a significant impact on everyone's pocketbook, but most want to preserve the farm and ranch life they now enjoy, and pass it along to future generations. Currently many young people from the area have come back to the farm and are working alongside their parents in their operations.

WHAT POLICY? HOW CAN WE GAIN COMPLIANCE WITH IT?

To help them design these policies the Water Preservation Partnership applied for and was recently awarded a grant from the Colorado Water Conservation Board. Professors of the Department of Ag and Resource Economics (DARE) at Colorado State University will analyze the likely economic effects of various potential policies and conduct a survey of producers to see which policy or policies they are most likely to agree to. The grant will also pay for facilitation of the many public meetings that will be required for the Water Preservation Partnership to educate irrigators and help them understand the necessity of this policy for reduced pumping.

In this case, it seems that the issue isn't so much an issue of what's technologically possible, but the sociological and economic issues. To illustrate the complexity, here are three difference approaches that have been discussed by the group for reducing pumping:

Approach: Education

Teach about the underlying problem and about the need for irrigation efficiencies to make better use of the water currently being applied, and then hope for the best. Issues with this approach include:

- Teaching farmers how to more efficiently use their water doesn't necessarily lead to their using less water. It could just as easily lead to using the same amount of water but getting a better yield, albeit with less input costs.
- Those who are convinced by education to use less water are at a disadvantage to those who do not choose to use less water; they might do it out of the goodness of their heart, but to no avail if everyone doesn't cut back.

<u>Approach: Maximum Inches per Irrigated Acre</u>
Adopt a hard line cap—such as 18 inches maximum per irrigated acre.
Background:

- As far back as 1937, the state of Colorado has given permits to high capacity wells, authorizing them to be pumped, and typically allowing up to 30 acre inches per acre (2.5 acre feet/acre.) This comes out to 400 acre feet applied annually to 160 acres or less.
- Some permits in the basin are for greater acreages (Expanded Acres Permit.) These permits allow the same amount of water to be pumped annually as the average of the last 10 years, which has implication of less water per acre.
- Some permits are "change of use" permits, filed for after the final permit was approved. Change of Use Permits are given when a well that has been approved for irrigation is changed to provide water for another use e.g. municipal, commercial use to sell water to another company, sell water to be used for drilling oil or gas wells, etc. The Change of Use permits are only allowed the average of the annual withdrawal over the last 10 years.
- Some permits are "under-appropriated permits." At the time the permit was granted, a calculation was made to figure out how much groundwater was available at the time. If there was not enough for the typical 30 inches/acre, the state issued an "under or short-appropriated" permit.
- Each GWMD is allowed by Colorado statute to make rules pertinent to those who irrigate within that district's boundaries. Some GWMDs are more restrictive on how much water can be pumped from a commercial well than what the state allows. For example, the State allows 80 acre feet to be pumped from a commercial well annually while the Plains GWMD and the East Cheyenne GWMD allow 5 acre-feet annual appropriation. Central Yuma GWMD allows 25 acre-feet pumped from commercial wells per year.
- The amount of water actually being pumped is verified by a power conversion coefficient (PCC) method whereby every two years during the peak of the season, each well using a PCC is certified by an independent well tester~~-~~. This test tells the well owner how many gallons per minute the well is pumping and how many kilowatt hours it takes to pump one acre-foot of water. At the end of each year the well owner has to turn in an Annual Water Use Report to the state. The state verifies the number acre feet that were pumped based on the PCC and the Annual Water Use Report.

- Another way of verifying the amount of water being used is to install totalizing flow meters (TFM), which also have to be verified as to their accuracy. Approximately 50% of the growers in the Basin have installed totalizing flow meters. The TFM must be installed at the well prior to where the pipe goes underground to the pivot(s). In 2012, when it was really dry, many growers used 100% or more of the allotment that their permit allowed.

Issues:

- In the Plains GWMD and some portions of Frenchman and Central Yuma districts, the aquifer does not produce enough water to irrigate up to 18 inches per acre, so they would have to set a more stringent number for it to equate real conservation in this area.
- The Sandhills GWMD has mostly sugar-sand for soil—so 18 inches won't supply them enough to raise a good crop. Irrigation in the sandier soils recharges the aquifer faster than others so how do you balance against that?
- If you go to a hard cap of 18 inches, you may not be effecting either the "change of use" or "under-appropriated" permits. The 18 inch approach only hits the regular final permit irrigators, which would be the majorityof the wells in the area.

Potential solution:

- Choose a basic hard line cap and then customize it for each well, factoring in consumptive use, soil type (for recharge calculation) and crop grown. This would be quite labor intensive, however. You could use a model, but models aren't trusted in the basin so that would be a hard sell. Soil textures can change within a 120 acre circle adding to the difficulty of using this potential solution.

Potential variation on hard line cap:

- Base it on 80% of your historic use.
    - Some wells would be shut off because 80% of their historic use wouldn't be enough to operate
    - This approach would discriminate against those who have already cut back on the amount of water they are using because their historic average will be lowered by those lower use years. (Example: Farmer A who has used 23 inches the past 20 years vs. Farmer B who used 23 inches the first 10 years but only 19 inches the past 10 years.) This could be considered a penalty to growers who have already tried to conserve water.

<u>Approach: Fee Based System</u>

Adopt a fee based system—to incentivize reduced pumping. The permutations could be simple or complex.

Flat fee: irrigator is charged a flat fee for up to 18". The fee for the additional inches pumped would be increased in increasing increments.

Incremental or tiered fee: Irrigator is charged increasingly more per acre-foot the closer he/she gets to the maximum allowed by state permit.

Issues:

- GWMDs currently do not have authority to collect fees.
- The state statute under which the RRWCD was formed seems to indicate that the RRWCD could not collect fees unrelated to compact compliance. The RRWCD cannot collect a fee that appears to be a penalty for pumping water i.e. a well that pumps 375 acre-feet of water gets charged a water use fee that is considerably more than a well that pumps 120 acre-feet.
- Fee collection would entail administrative costs, the extent of which is sometimes underestimated by farmers. Whoever collects the fee could add in coverage for the administration of the fee. If the RRWCD or the GWMDs collect the fees, additional help would have to be hired.
- If the state statute could be changed, and RRWCD could collect the fee, all the GWMDs could more easily all be put in the same boat. If all the GWMD boards are not on the same page on this, and each district does things differently, it will be a problem.
- The Northern Plains Groundwater Conservation District in Texas did something similar to this. Under their system, you can bank your allowed number of inches, such that you can save any not used in one year for subsequent years. On the other hand, if you use more than the allowed number of inches, you pay a fine. However, at this time, banking is not allowed in Colorado except on permits for expanded acres and on change of use final permits.
- Those using a similar system in Colorado's Rio Grande Basin say that "pay for what you pump" works well there except that it squeezes the small guy out because the big guys can pay, and they buy out the small guys. Also, they says it is expensive to administer, as reflected in the fact that they have 3-4 full time employees that continuously work year round on the administration of the water use fees.

Potential Approach:

- Develop a fee based plan under the assumption that the RRWCD would collect it. Work with RRWCD counsel to determine what in the statute would have to change for RRWCD to be able to collect the fee. Perhaps the statute could be changed so that the RRWCD could take on this water conservation/preservation role in addition to the compact compliance role. In regard to where that would leave East Cheyenne GWMD, which is not within the RRWCD boundary along with the southern part of the Plains GWMD, perhaps this would be a good time to bring them into the RRWCD. (There is some discussion of the State planning on changing the boundary of the Republican River drainage to include all of the Plains GWMD and the northeastern part of the East Cheyenne GWMD – but this area would not be subject to the water use fees that are paid by the well owners in the current boundaries of the RRWCD. There are also some wells south of Akron that are in the RRWCD but not in a GWMD.
- If the statute were changed and the RRWCD could assess the conservation fee they could handle it by expanding the current $14.50/acre/year.

- Fees collected could go into a conservation bank. Every GWMD could apply for funds from this bank if they could prove the amount of water their district is conserving. Funds granted could be used to refund some of the fees collected. Could divide the funds granted among those conserving the most, for instance.
- The current RRWCD fee for compact compliance is levied through the various counties' treasurers' offices as part of their property tax bills. That gives the RRWCD great strength in getting the money because folks cannot pay only part of their property tax bill. It required a state statute for RRWCD to be allowed to assess irrigators through the counties in this way. GWMDs also assess a special assessment on the county tax roll for the amount of appropriation of each final permit in their district up to $.15/acre foot of appropriation. Some GWMDS also have a mil-levy which has to be approved by the well owners in that GWMD.

CLOSING

GWMDs in other areas dependent on the Ogallala Aquifer, including some from Kansas, Nebraska, and Texas, have been working on the same issue. The Water Preservation Partnership will be learning from their experiences as well.

Whether or not the Water Preservation Partnership will be successful in reducing the draw on the aquifer is yet to be seen. They have already been successful grasping the problem, organizing a grassroots effort, and plowing into it head first.

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RESIDUAL SOIL WATER IN WESTERN KANSAS AFTER CORN HARVEST

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INTRODUCTION

Water shortage is the primary factor limiting crop production in the USA's west-central Great Plains, and agricultural sustainability depends on efficient use of water resources. Precipitation is limited and sporadic with mean annual precipitation ranging from 16 to 20 inches across the region, which is only 60-80% of the seasonal water use for corn. Yields of dryland crops are limited and variable and some producers have used irrigation to mitigate these effects. Continued declines within the Ogallala Aquifer will result in a further shift from fully irrigated to deficit or limited irrigation or even dryland production in some areas. As this occurs, producers will desire to maintain crop production levels as great as possible while balancing crop production risks imposed by constraints on water available for production. Efficient utilization of plant available soil water (PASW) reserves is important for both dryland and irrigated summer crop production systems.

In western Kansas, dryland grain sorghum yield was linearly related to PASW at emergence and sorghum yields increased 501 lbs/acre for each additional inch of PASW (Stone and Schlegel, 2006). When the experimental effects of tillage were considered, grain sorghum yield response to water supply (PASW at planting plus cropping season precipitation) was greater with no-tillage than with conventional tillage (417 vs. 292 lbs/acre-inch). With conventional tillage at Bushland, Texas, grain sorghum yield increased 385 lbs/acre-inch of PASW at planting (Jones and Hauser, 1974). Evaporative demands increase from north to south (i.e., decreasing latitude) in the Great Plains and this can reduce overall yield response to water (Musick et al., 1994; Nielsen et al., 2002). Precipitation increases from west to east in the Great Plains and in Kansas the average increase is approximately 1 inch for each 18 miles (Flora, 1948). Research is needed to characterize the amounts of PASW available to producers in the spring before planting of summer crops. The research results can be used to develop better cropping recommendations for producers based on their geographical location within western Kansas when used with information about their anticipated summer precipitation.

Preseason irrigation (also referred to as preplant, dormant-season, off-season, or winter irrigation) is a common practice in central and southern sections of the western Great Plains on the deep soils with large water-holding capacity that are prevalent. The residual soil water left in irrigated corn fields has a strong effect on the amount of preseason irrigation and precipitation that can be stored during the dormant period (Lamm and Rogers, 1985). Although preseason irrigation is common, research has shown it is often an inefficient water management practice (Stone et al., 1987; Lamm and Rogers 1985; Musick and Lamm, 1990). Measured water losses from marginal preseason irrigation capacities during the 30-45 day period prior to planting in a Texas study were extremely high, ranging from 45 to 70% (Bordovsky and Porter, 2003). While several reasons are given by producers for the use of preseason irrigation, Musick et al. (1971) stated its primary purpose is to replenish soil water stored in the plant root zone.

From an analysis of soil water data from producer fields with silt loam soils near Colby, Kansas, Rogers and Lamm (1994) concluded that irrigation above the amount required to bring soil water to 50% PASW water would have a high probability of being lost or wasted. They found in a three-year study (1989-1991) of 82 different fields that on average producers were leaving residual PASW in the top 5 ft of the soil profile at 70% of field capacity. Since that time, groundwater levels have continued to decline and more irrigation systems have marginal capacity. Research is needed to both assess the current amounts of residual PASW producers are leaving in the field after irrigated corn harvest and how much PASW is replenished during the period before spring planting of the next corn crop.

The primary objectives of this project were to characterize the fall residual profile PASW after irrigated corn production and the PASW in dryland wheat stubble following the winter period and prior to dryland summer crop production in producer fields in three distinct regions of western Kansas [southwest (SW), west central (WC) and northwest (NW)]. Secondary objectives were to characterize aspects of the overwinter precipitation storage for the two crop residues (i.e., irrigated corn and dryland wheat). This paper will focus only on the irrigated corn fields.

PROCEDURES

A three year study (Fall 2010 through Fall 2012) was conducted on the deep silt loam soils in western Kansas. Fifteen fields from each of the three regions (SW, WC and NW) were sought for each crop residue type (dryland wheat and irrigated corn) for sampling of PASW. In general five fields of each residue type were selected in each county (Figure 1). In a few cases, additional fields (generally 1 or 2) were selected when it was deemed useful in gaining a better geographical distribution. Another selection criterion for the irrigated corn fields was irrigation system capacity. Attempts were made to find one or two fields in each county with capacities equivalent to less than 400, 400 to 600, and over 600 gpm for a 125 acre field.

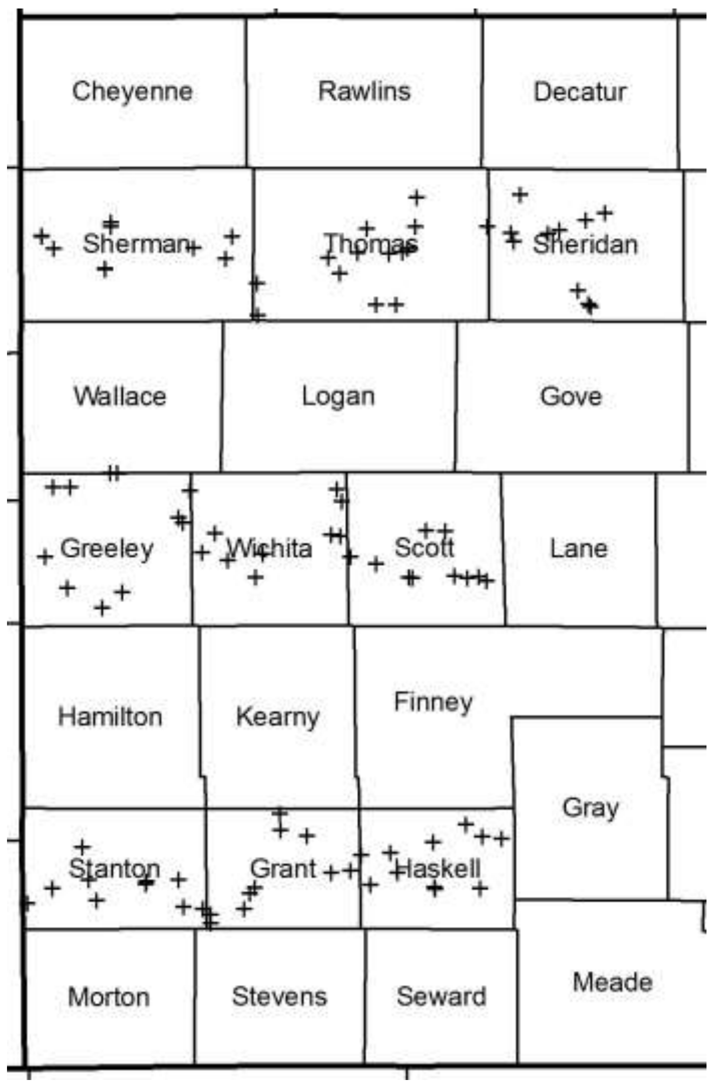

Figure 1. Geographical distribution of soil water measurements in producer fields in western Kansas, 2010. Each symbol represents a GPS-referenced producer field.

Although a broad geographical representation was a primary desire (Figure 1), an attempt was made to select producers using good management practices and for which realistic weather conditions could be obtained from public sources. Fields in NW Kansas were selected in Sheridan, Thomas and Sherman counties (east to west counties). Fields in WC Kansas were selected in Scott, Wichita and Greeley counties (east to west counties). There was increased difficulty finding producers with continuous (year-after-year) irrigated corn fields in WC Kansas, particularly in Wichita and Greeley Counties. The Ogallala aquifer in this region of Kansas is more marginal and severely depleted, so producers appear to be using more crop rotation to utilize residual soil water better, thus conserving more aquifer water for future years. Fields in SW Kansas were selected in Haskell, Grant and Stanton counties (east to west counties). There were 96 total fields in 2010 fall sampling and 91 fields in 2011.

The GPS-referenced neutron access tubes (3 per field) were installed in an equilateral triangular-shaped pattern (50-foot sides). Initial volumetric soil water content was determined in these fields after installation of tubes and again in late spring prior to summer crop initiation in one-foot increments to a depth of 8 feet. Published soil type and soil characteristics were used to estimate PASW within the profile. The data from the three sampling points was examined for uniformity between readings and to remove any anomalies. A few tubes were lost due to damage by producer field operations between the fall and spring measurement periods. Less than 1% of the data was lost due to measurement anomalies or damaged tubes. As time progressed into the third year, fewer fields were available for fall sampling due to extreme drought in western Kansas because producers had changed plans mid-summer often relegating their crop for ensilage production and replanting to winter wheat.

In 2012, corn grain yields were obtained from 26 irrigated fields by hand harvesting a representative sample in the vicinity of the soil water sampling tubes (within 50 ft.) to observe how fall PASW was correlated with yield.

RESULTS AND DISCUSSION

The analysis is still ongoing and some of the more complex interrelationships of producer practices with residual soil water have not been quantified or evaluated yet. Although it should be noted that the results may vary widely from what may be occurring on your or other fields located within these counties, the soil water results may still be indicative of some of the irrigation capacities and practices, climatic, soil, and cropping conditions of these three distinct regions of western Kansas.

Weather Conditions

Weather conditions in nearly all of western Kansas were excessively dry from early August 2010 through mid-April of 2011. The western portion of WC and NW Kansas began to get more normal precipitation in late April 2011 and ended the cropping season with normal amounts of precipitation or greater. However, SW Kansas remained under severe drought conditions through the summer and much of the fall. For example, Grant County received less than 30% of normal annual precipitation for the period September 1, 2010 through September 1, 2011. In SW Kansas, dryland summer crops resulted in almost total failure and even many of the irrigated crops were severely stressed. The western edge of WC Kansas (Greeley County) and for nearly all of NW Kansas experienced near-to above-normal precipitation for most of the summer period. A particularly wet weather multi-day period in early October 2011 that tracked across some counties in WC Kansas and the eastern half of NW Kansas with those areas receiving between 2 and 4 inches of precipitation. Because of the multi-day nature of this precipitation, much of the water infiltrated into the soil profile. Exceptional drought conditions were generally the case for all of western Kansas in 2012.

Soil Water as Affected by Location

It should be noted that in many cases in SW Kansas, some fall dormant season irrigation (both 2010 and 2011) had been practiced prior to the soil water measurements to facilitate easier strip tillage operations. However, these dormant season irrigation amounts were relatively small, just being used to facilitate easier tillage.

Fall 2010 results

The average PASW in irrigated corn fields for the three regions only varied about 1 inch (range of 9.99 in NW to 10.90 inches/8 ft in SW) and with an average value of 10.30 inches/8ft would approximate a profile at 60% of field capacity, which would suggest overall adequate irrigation management (Table 1). However, there was a large amount of field to field variation. The maximum PASW for the irrigated corn fields averaged nearly 16.4 inches/8ft which would be very wet unless there was considerable late season precipitation or fall dormant season irrigation. At the other end of the spectrum, the minimum average PASW was approximately 4.3 inches, which would be only about 25% of field capacity.

Fall 2011 results

In fall of 2011, because of the continuing drought in SW Kansas, it was anticipated that producer fields would be much drier than in 2010 (Tables 2 and 1, respectively). However, overall the irrigated corn fields were wetter (approximately 11% wetter) in 2011, with only SW Kansas having slightly drier irrigated fields in fall 2011 (approximately 7% drier). The wetter summer period in portions of WC Kansas (Greeley County) and NW Kansas no doubt had some effects on the amounts of residual PASW.

Fall 2012 results

The drought continued in western Kansas in 2012 and actually was more severe in NW and WC Kansas than in the southwest though it was only marginally better. It should be noted that SW Kansas was still experiencing precipitation shortfalls that had been very severe in 2011. On average, NW Kansas irrigated corn fields were the driest with a range of 5.95 to 16.86 inches/8 ft and an average of 10.16 inches/8 ft which would approximate a profile at 60% of field capacity, similar to 2010 values (Table 3). The average irrigated corn field PASW in SW Kansas was 12.12 inches/8 ft or approximately 70% of field capacity. These difference may reflect the increased severity of the drought in NW Kansas or some early fall rains that occurred near harvest in SW Kansas

Discussion of Annual Differences in Corn Residual PASW

Although record or near-record drought conditions existed in southwest Kansas for the entire period from the middle of the summer of 2010 through the fall of 2011, there were only minimal differences in fall irrigated corn PASW for the 31 fields that were available for PASW measurements in both years (Figure 2). Part of the rationale might be that drought conditions were similar between the two years. However, the irrigated corn residual soil water is still relatively high on the average for SW Kansas (approximately 60% of field capacity). So, the presence of severe drought may not be a good indicator of the amounts of residual soil water left after irrigated corn harvest. Sometimes, crop damage is caused by system capacity (gpm/acre) at the critical stages, rather than what irrigation amounts can be applied during the total season. Insect damage such as spider mites is exacerbated by high canopy temperatures and drought. Producers recognizing the drought and crop damage may continue to irrigate hoping to mitigate further crop damage and this sometimes increases profile PASW as the damaged crop is no longer transpiring typical amounts of water. One caveat, in some cases the PASW results are probably reflecting the effects of some fall dormant season irrigation that occurred before the PASW sampling. However, in most cases the fall irrigation amounts were not large.

There were a total of 21 irrigated corn fields in the region that were available for fall soil water sampling in all three years. Generally, there was considerable similarity in the fall PASW for a particular field (Figure 3.) with an overall difference for the 21 fields averaging 3.1 inches. The similarity suggests that fall PASW for irrigated corn is much stronger related to the irrigation management conducted on a particular field than it is to weather conditions. That management may either be reflecting the preference of the irrigator or the irrigation system capacity or a combination of both aspects.

Effect of Regional Characteristics on Corn Residual PASW

Although intuition might suggest that less saturated thickness of the Ogallala and more marginal irrigation system capacities (gpm/acre) would result in less residual PASW in the irrigated corn fields of WC Kansas, there was no strong evidence of that in the results averaged over 2010 through 2012 (Figure 4.). This might be because producers with lower capacity irrigation systems have adjusted to their limitation by using longer pumping periods. Their goal by pumping later into the crop season would be to minimize crop yield loss, but sometimes those later irrigation events also increase residual PASW.

Table 1. Plant available soil water (inches/8ft) in producer fields in western Kansas in fall 2010 (October through December).

Residue Type	County and number of fields	Average	Maximum	Minimum	CV*
Northwest Kansas, Sheridan, Thomas and Sherman Counties					
Irrigated Corn	Sheridan (5)	10.50	11.10	8.57	0.06
	Thomas (7)	10.79	15.55	6.76	0.22
	Sherman (5)	8.35	11.64	6.56	0.24
	All 3 Ctys (17)	9.99	15.55	6.56	0.24
West Central Kansas, Scott, Wichita and Greeley Counties					
Irrigated Corn	Scott (5)	11.98	16.57	8.20	0.27
	Wichita (5)	9.31	11.78	6.54	0.20
	Greeley (5)	8.78	10.63	3.96	0.32
	All 3 Ctys (15)	10.02	16.57	3.96	0.29
Southwest Kansas, Haskell, Grant and Stanton Counties					
Irrigated Corn	Haskell (6)	9.82	17.06	2.37	0.61
	Grant (5)	9.06	13.86	6.28	0.37
	Stanton (5)	13.83	16.71	11.50	0.14
	All 3 Ctys (16)	10.84	17.06	2.37	0.41

** Coefficient of variation is defined as the standard deviation of PASW divided by the mean PASW.*

Table 2. Plant available soil water (inches/8ft) in producer fields in western Kansas in fall 2011 (September through December).

Residue Type	County and number of fields	Average	Maximum	Minimum	CV*
Northwest Kansas, Sheridan, Thomas and Sherman Counties					
Irrigated Corn	Sheridan (6)	13.77	15.60	10.45	0.14
	Thomas (5)	13.07	16.86	8.94	0.22
	Sherman (5)	8.31	11.69	5.95	0.28
	All 3 Ctys (15)	11.85	16.86	5.95	0.28
West Central Kansas, Scott, Wichita and Greeley Counties					
Irrigated Corn	Scott (5)	13.00	17.85	9.75	0.23
	Wichita (5)	12.59	14.21	10.74	0.11
	Greeley (5)	11.73	12.25	10.98	0.04
	All 3 Ctys (15)	12.46	17.85	9.75	0.16
Southwest Kansas, Haskell, Grant and Stanton Counties					
Irrigated Corn	Haskell (5)	10.40	15.58	2.94	0.59
	Grant (5)	8.76	16.49	3.13	0.66
	Stanton (5)	11.11	14.30	8.65	0.20
	All 3 Ctys (15)	10.15	16.49	2.94	0.46

** Coefficient of variation is defined as the standard deviation of PASW divided by the mean PASW.*

Table 3. Plant available soil water (inches/8ft) in producer fields in western Kansas in fall 2012 (October 19 through 26).

Residue Type	County and number of fields	Average	Maximum	Minimum	CV*
Northwest Kansas, Sheridan, Thomas and Sherman Counties					
Irrigated Corn	Sheridan (6)	11.06	16.46	7.37	0.33
	Thomas (6)	10.29	16.56	7.18	0.33
	Sherman (3	8.11	11.97	4.40	0.47
	All 3 Ctys (15)	10.16	16.56	4.40	0.34
West Central Kansas, Scott, Wichita and Greeley Counties					
Irrigated Corn	Scott (3)	12.55	16.06	10.02	0.25
	Wichita (3)	10.19	10.84	9.50	0.07
	Greeley (3)	7.92	10.86	5.94	0.33
	All 3 Ctys (9)	10.22	16.06	5.94	0.28
Southwest Kansas, Haskell, Grant and Stanton Counties					
Irrigated Corn	Haskell (4)	12.32	19.45	5.11	0.54
	Grant (3)	13.06	19.10	5.14	0.55
	Stanton (2)	10.33	12.44	8.22	0.29
	All 3 Ctys (9)	12.12	19.45	5.11	0.46

** Coefficient of variation is defined as the standard deviation of PASW divided by the mean PASW.*

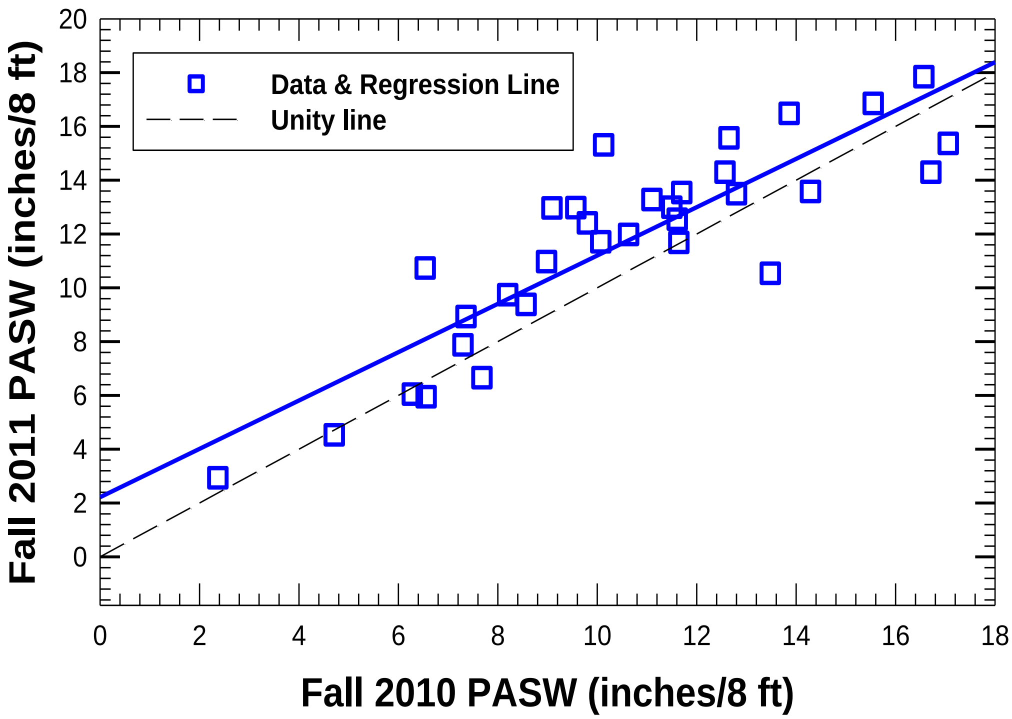

Figure 2. Similarity of plant available soil water (PASW) in the 8 ft soil profile in irrigated corn fields after harvest for the fall periods in 2010 and 2011 in western Kansas producer fields. These data represent 31 fields that producers made available for PASW measurements in both years.

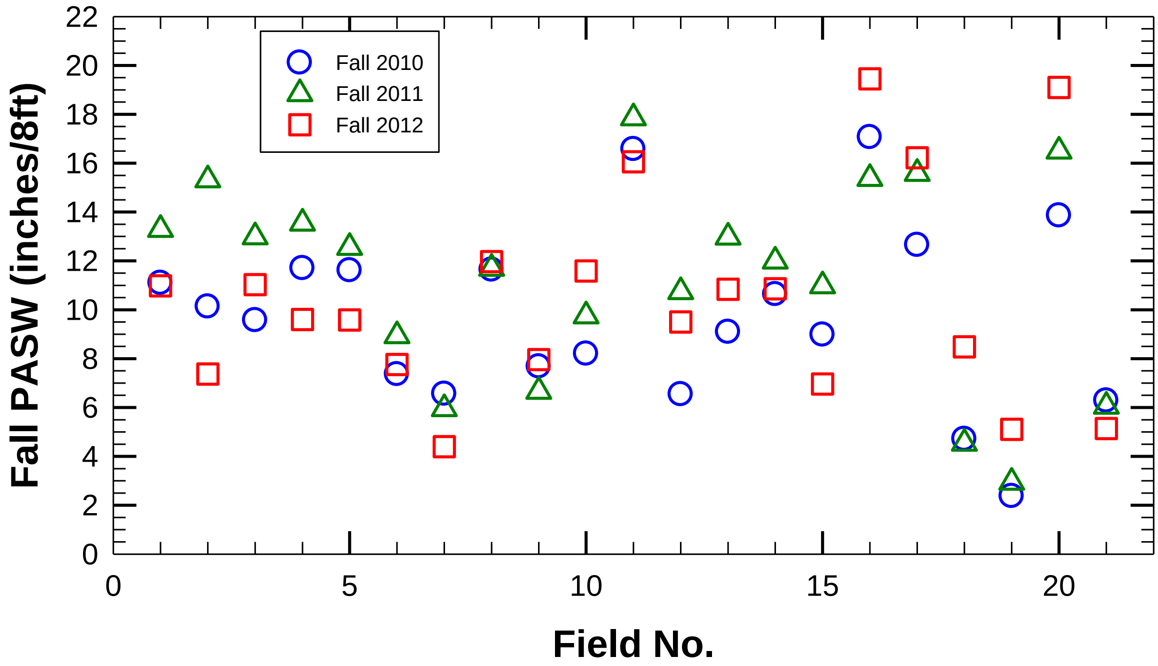

Figure 3. Similarity of plant available soil water (PASW) in the 8 ft soil profile in irrigated corn fields after harvest for all three fall periods 2010 through 2012 in western Kansas producer fields. These data represent 21 fields that producers made available for PASW measurements in all three years.

Effect of System Capacity on Fall PASW in Irrigated Corn Fields

There were only small differences in PASW (less than 1 inch) as affected by low (less than 400 gpm/125 acres), medium (400 to 600 gpm/125 acres) or high (greater than 600 gpm/125 acres) irrigation system capacity (data not shown) in 2011. Further analysis of the effect of capacity on fall PASW will be done by incorporating more precise information about system capacity and also from information to be provided by the producers about actual aspects of their irrigation cropping season and irrigation schedule.

Corn Grain Yield as affected by Fall PASW

Corn yields were related yields were related to fall PASW (Figure 5.), increasing sharply up until approximately a PASW of 8 inches/8 ft. (45% of Field Capacity) and then plateauing at approximately 10 inches/8 ft. (60% of Field Capacity). This suggests that many of the irrigators have determined from experience that they cannot severely deplete soil water reserves without encountering corn grain yield reductions.

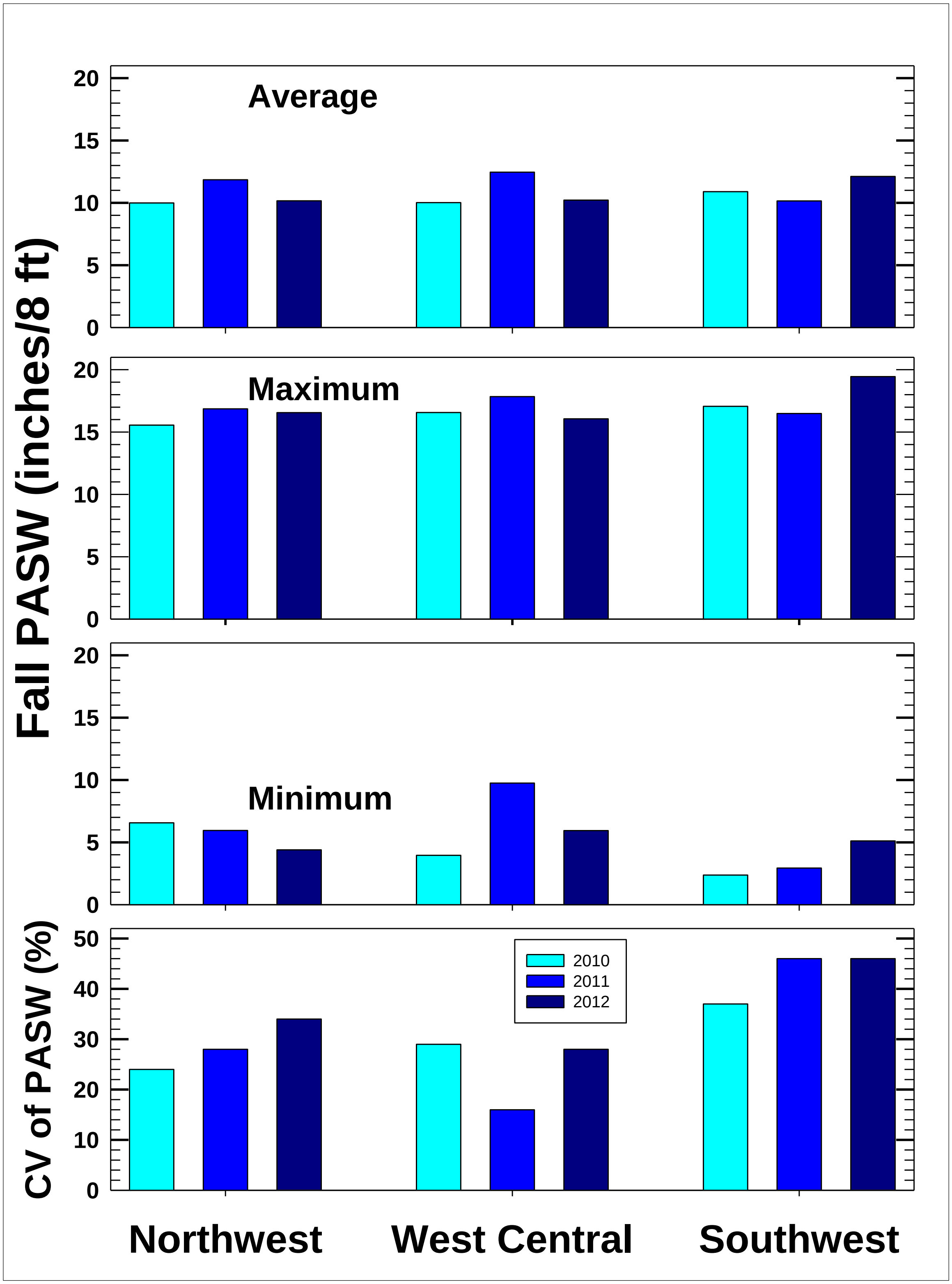

Figure 4. Effect of western Kansas region on average, maximum and minimum measured plant available soil water (PASW) in the 8 ft soil profile in irrigated corn fields after harvest for the fall periods in 2010 and 2011.

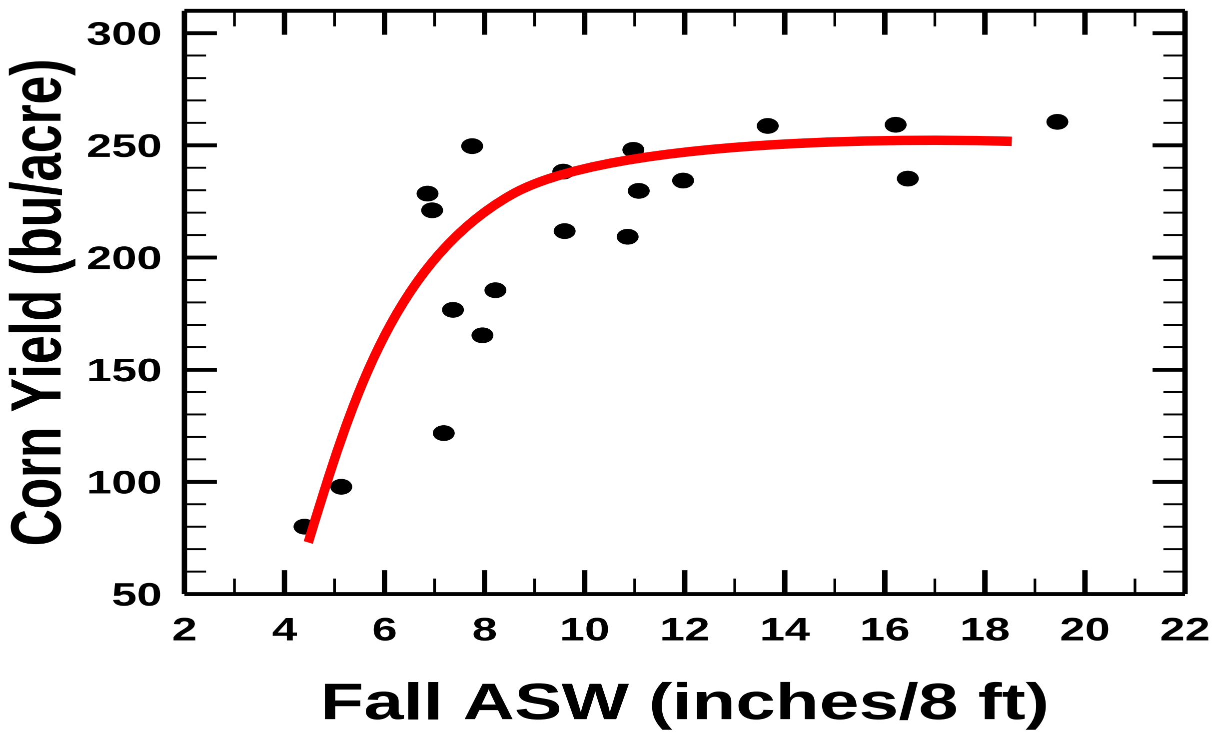

Figure 5. Corn yield as related to fall 2012 PASW in western Kansas irrigated fields.

SUMMARY

These results suggest a few very important aspects for irrigated crop production in western Kansas:

1. Irrigation not only increases the water available for crop production, but also reduces the variability in ASW in the field.
2. Average PASW may not be indicative of an individual field, so it is wise to check your each field after harvest.
3. Each year is different, so irrigating to average conditions is very risky and may be less profitable.
4. Science-based irrigation scheduling can help to better manage your water resources in-season and between seasons. Cost-sharing programs may be available to help individuals implement science-based irrigation scheduling.

ACKNOWLEDGEMENTS

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CASE STUDY

AGRICULTURAL/URBAN/ENVIRONMENTAL WATER SHARING IN THE WESTERN UNITED STATES: CAN ENGINEERS ENGAGE SOCIAL SCIENCE FOR SUCCESSFUL SOLUTIONS?†

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ABSTRACT

Throughout the world, demand exceeds supply when it comes to water for agriculture, urban needs and a healthy environment. In the western United States water is being permanently transferred from agriculture, putting food security and the viability of rural communities at risk. The authors of this paper are separately and jointly involved in projects and studies to determine how water might be shared between agricultural, urban, and environmental sectors in ways that effectively stretch supplies, with benefits to all.

Engineering solutions will be necessary. But legal and institutional changes and alternative approaches to achieve economic and other social benefits, must be addressed as well. Stakeholders from all sectors must be fully engaged at all levels.

The authors present a water-sharing model under development in the South Platte River Basin of Colorado in the western United States. They discuss the convening in 2010 of western United States water leaders from agricultural, urban, and environmental sectors to develop recommendations for western governors for overcoming obstacles to multi-sector water sharing. The authors draw from examples provided by international academics and practitioners to show that our greatest challenge in this water balance puzzle is not technological but sociological. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS: Multi-sector water sharing; stakeholder collaboration; social and economic factors in water management

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RÉSUMÉ

Partout dans le monde, la demande est de plus en plus perçue comme supérieure à l'offre quand on examine le besoin d'eau douce pour l'agriculture, pour les besoins urbains et pour maintenir un environnement sain. Cela n'est nulle part plus évident que dans l'ouest des États-Unis, où la tendance est à définitivement réallouer l'eau pour l'agriculture, au risque de mettre en péril la sécurité alimentaire et la viabilité des communautés rurales. Les auteurs de cet article sont séparément ou conjointement impliqués dans des projets et des études visant à déterminer comment l'eau peut être partagée entre l'agriculture, la ville, et l'environnement de manière à étirer efficacement les allocations, au bénéfice de tous.

Des solutions d'ingénierie telles que l'emploi d'outils de mesure de haute technologie, des techniques d'irrigation à haut rendement et l'adoption de régimes de gestion innovants seront nécessaires. Mais les changements juridiques et institutionnels, les approches alternatives pour atteindre des bénéfices économiques et autres avantages sociaux, et la gestion du paradoxe des droits d'eau privés vs eau pour le bien public doivent être considérés pour que ces solutions techniques soient acceptées. Les intervenants de tous les secteurs doivent être pleinement impliqués à tous les niveaux.

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† Agricole / urbain / urbain / environnemental: le partage des eaux dans l'ouest des États-Unis: les ingénieurs peuvent-ils s'engager dans les sciences sociales pour trouver des solutions efficaces.

Les auteurs présentent un modèle de partage de l'eau en cours de développement dans le sud du bassin de la Platte River (Colorado) pour montrer comment les ingénieurs tentent d'intégrer les considérations en sciences sociales dans leur formulation technologique pour atteindre le succès.

Ils discutent de la convocation en 2010 des dirigeants des états de l'ouest des USA des secteurs, rural, urbain et environnemental pour élaborer des recommandations pour les gouverneurs de l'ouest sur la façon dont les obstacles au partage de l'eau multisectorielle pourraient être surmontés. Les agriculteurs, les urbains et les écologistes envisagent-ils de nouvelles façons d'aborder la collaboration de leurs réalités pour répondre aux besoins multiples? Vont-ils risquer une perte afin d'augmenter les chances de gain global?

Les auteurs s'appuient sur des exemples fournis par des universitaires et des praticiens internationaux pour montrer que notre plus grand défi dans le puzzle de l'équilibre de l'eau n'est pas technologique, mais sociologique.

MOTS CLÉS: multiple usages de l'eau; collaboration entre les acteurs; facteurs sociaux et économiques de la gestion de l'eau

INTRODUCTION

The Special Session of the 21st International Congress on Irrigation and Drainage was titled 'Modernization of Agricultural Water Management Schemes.' The organizers asked for papers to address strategies by which irrigation institutions could 'link their central task of providing irrigation services' to the necessity of integrating the demands for water for agricultural production with the demands of other users, including urban and environmental. They sought strategies being used whereby delivery systems and on-farm management systems are being managed in ways that incorporate 'informed decisions on the use and reuse of agricultural water.' In addition to papers considering such technological aspects as modernizing infrastructure and automation of irrigation systems for better operation, the session organizers asked for papers considering such aspects as institutional modalities; financial, legal and policy implications; and environmental issues.

The authors of this paper attempt to combine their engineering and social science experiences and perspectives to address many of these issues in one paper. To accomplish their intent, their paper consists of three distinct sections. First is a review of international perspectives on the need to better incorporate the social sciences with technological sciences and to meaningfully involve diverse stakeholders in order to optimize use of water to meet growing global needs. Second is a description of a water-sharing model under development in the South Platte River Basin of Colorado in the western United States to show how engineers are attempting to incorporate social science considerations into their technological formula to achieve success. Third, they will discuss the 2010 convening of western US water leaders from agricultural, urban, and environmental sectors in an attempt to override polarized interests and remove obstacles to multi-sector water sharing.

INTERNATIONAL PERSPECTIVES

Juan Carlos Alurralde—Bolivia

In 1998, the Bolivian government proposed legislation that allowed for the privatization of water and provided a private, foreign-owned company with a concession to sell water. Social groups mobilized in protest, paralyzing the country, destabilizing the government and causing a political crisis. Bolivia's 'Water War' hit the front pages of newspapers worldwide. The government was forced to break the contract with the private company and set up a special council to draft a water management law based on public input (International Development Research Centre, 2006).

Bolivian water engineer Juan Carlos Alurralde became actively involved in the council. He proposed a research project to use a water simulation model developed by the Danish Hydraulic Institute to build a computerized replica of Bolivian water systems, to simulate how effective various approaches to allocating water rights would be—information critical to developing a new water law. The model would be fed with existing cartographical information and data on water, precipitation, and climate, while GIS and lot-by-lot fieldwork and surveys would be used to map water rights. The International Development Research Centre provided US$270 000 to support the research project, which ran from 2002 to 2005 (International Development Research Centre, 2006).

Alurralde was convinced that dialogue based on solid research could help point to a fair and efficient model for water management that everyone could accept. But if social groups did not trust the research, there was a risk that they would reject the findings. So, the researchers decided to include social groups that had protested against the water law in the research process—by inviting them to participate in the research design, asking them to help gather data, and regularly communicating and explaining their findings. In effect, the researchers would be using both technical and social science in their approach. Members of irrigators' groups and farmers were among those participating in the research. Ultimately it was found that the government's privatization approach would lead to more inefficient use of water and cause larger differences in water availability between communities, actually resulting in water deficits in many cases. Subsequently, the government of Bolivia enacted a water rights law that gained widespread acceptance—a successful example of combining high-tech science with grassroots dialogue.

Dipak Gyawali—Mexico City World Water Forum

Dipak Gyawali, an engineer/political economist from Nepal, spoke at the 2006 World Water Forum in Mexico City about a European Commission study investigating 67 research projects relative to the EU's Integrated Water Resource Management Goals. Gyawali said that all 67 research projects—mostly hard technology research—could be boiled down to three major findings. The first finding was that 'research must constructively engage stakeholders in all phases—from design to interpretation.' (Gyawali, 2006). He said we must constructively engage all stakeholders by incorporating what each brings to the table, not just tolerating them.

The second finding was that 'researchers must find better ways to communicate the results of their research to those who are in positions to make policy.' Gyawali said researchers have to figure out appropriate ways to communicate research, including the need to understand and deal with distinct mindsets stakeholders use to filter data. The third finding was that 'the most critical need for research is not for more technical solutions, but for socio-political solutions to water problems.' Gyawali proposes that we need research integrating water law, economics, human mindsets and behaviour, and that we should conduct such research as confidently as we address hydrology and hydraulics.

In his book *Water, Technology and Society*, Gyawali (2003) argues that we need to move from a technocratic approach to take full account of the social and political context of our water challenges. He shows that both analytical comprehension and effective policy action require a holistic conceptualization of the interface between water, technology, and social context.

Colorado Trout Unlimited—Jeopardized Stream Segments Research

At a meeting of water leaders in Colorado, Melinda Kassen, a water attorney then representing Trout Unlimited, a major US environmental organization, encountered resistance to proposed research. The research would map stream segments in the state in order to identify which were optimal to preserve or restore. Knowing that economic resources prevent restoration or preservation of all the state's jeopardized streams, the organization favoured identifying which should receive prime attention—to gain the most benefit at the least cost. Resistance to the research was not based on scientific concerns, but sociological ones. Water leaders from other sectors pointed out that identifying stream segments in jeopardy would be very sensitive politically because of private property issues.

This interchange brings up important questions of how scientists can move forward with research to determine best use of water resources given a highly politicized and polarized milieu. Should it be up to environmental organizations to conduct such research or should all sectors unite to explore these issues, recognizing that saving some water for the fish is important to all of us, whether it is because we want the fun of catching the fish, we want to keep fishermen coming to the state for the tourism economy, or because we think healthy fish is an indicator of a healthy environment we all require to thrive? In leaving such research to environmental groups to perform and fund, are we setting up an 'us versus them' scenario? How do we move beyond polarized positions to confront uncomfortable water allocation conflicts?

Klamath Basin, Oregon, United States

Stephen Snyder (2003), a New Mexico attorney and mediator, participated in a study conducted by the Natural Resources Law Centre at the University of Colorado in which he investigated what could be learned from those involved in trying to mediate water use conflicts between fishermen, farmers, and loggers in the Klamath Basin of Oregon. Scientific facts have a role in resolving such conflicts, Snyder (2003) concedes, but like Gyawali and Alurralde, he points out that research must involve all the stakeholders if the findings are to be accepted. 'If the negotiations involve contentious technical and scientific issues, a joint fact-finding process should be established for investigating these issues.' In joint fact finding an investigation of an issue is performed by a neutral expert or panel of experts chosen by a group of stakeholders. Snyder (2003) says that joint fact finding can lead to shareholders actually 'participating in an interactive dialogue with the neutral experts so as to enhance their understanding of the complexities involved in addressing problems to which there are no clear answers.' He finds that participants in joint fact finding 'often find themselves revising their original assumptions and preconceived notions about what must be done to resolve the problem. They find they are able to favourably consider negotiating proposals they would never have entertained had there been no joint fact-finding process,' (Snyder, 2003).

Snyder (2003) quotes one of the participants involved in the Klamath Basin mediation: 'Policy differences, not scientific disputes, are what are at stake in a water allocation negotiation, and no scientific panel can make credible judgments about policy issues. In a negotiation, all stakeholders must be involved both in formulating the questions asked and directing the investigation of independent experts.' He says

'Many debates over science are in fact debates over values. Pretending that uncertainty does not exist, or that there are scientific answers to questions that are in reality questions of values does nothing to further resolution of difficult issues.'

Patrick Field, William Ruckelshaus, Peter Senge

Patrick Field from the MIT-Harvard Consensus Building Institute refers to the need for 'process technology' to resolve conflict over natural resources such as water. He suggests that process technology must catch up with hard technology. We know how to engineer technological processes to solve our water problems, he says, but we need to concentrate more on the process for engaging stakeholders if we are going to be successful in solving water conflict (Snyder, 2003).

William Ruckelshaus, the first director of the US Environmental Protection Agency (EPA), says adaptive management is just as applicable to social experiments as biological ones. We don't have to get it right the first time, he says. We can learn from our mistakes and keep on experimenting. He warns that we have to break through the shallow façade of rhetoric and reach to the heart of the issue. 'Only when people are united despite their differences by hard-earned trust, does the astounding political power of collaboration become effective, (Snyder, 2003).

Peter Senge is well known in the United States for his work on a conflict resolution approach known as Appreciative Inquiry. He has lectured extensively throughout the world, translating the abstract ideas of systems theory into tools for better understanding of economic and organizational change. Applying Senge's thinking to the issue of water allocation challenges brings up the question of whether we require a paradigm shift in the way we approach such challenges. Senge says, 'we are stuck in patterns where solutions are arrived at through the process of downloading, or taking an existing framework and applying it to the situation at hand, (Senge, 2005). He talks about a perspective on leadership and social change based on slowing down to ponder a problem so that we can 'illuminate the blind spot.' He suggests we need to create a deep awareness of the problem as a whole, not just its parts. In the arena of water allocation, that could be interpreted as our needing to look not only at the technological fixes, but the economic, legal, sociological, environmental and even spiritual aspects. He challenges us to retreat and reflect, to go to an 'inner place of stillness, then listen and make sense of it, (Senge, 2005).

SOUTH PLATTE RIVER BASIN WATER-SHARING MODEL

Engineers and water scientists are working with economists, water attorneys, and social scientists to develop a model for water sharing in the South Platte River Basin of Colorado in the western United States (Figure 1), with the intent that the model can be used in other places where agriculture is under pressure to give up water for urban and environmental needs.

A Colorado study researching water supply availability and needs for each of Colorado's river basins, projects that water supply in the South Platte Basin will be significantly short of demand by 2030.To meet a forecasted 65% population growth, an additional 500 million m^3 (400 000 acre feet) of water will be needed. The prevalent presumption is that the additional 500 million m^3 will likely come from transfers of water from irrigated agriculture to municipal and industrial uses (Colorado Water Conservation Board, Camp Dresser & McKee, 2004).

This population growth and water demand dynamic is playing out throughout Colorado and elsewhere in the western United States in the form of municipal acquisition of whole farms—along with the water—through outright willing-seller, willing-buyer purchases. The transferable portion of the water right is often 100% removed from the farm and the use of the water is most often changed to municipal use. The farm is dried up into perpetuity. This process of permanent dry up is often referred to as 'buy and dry.'

Concerned about the negative effects of buy and dry on agriculture, rural communities, and even the environment, the state of Colorado has funded research into alternatives to permanent transfer of water from agriculture. These methods allow farmers to share water to which they have rights in ways that prevent permanent sale of the water. Such methods include interruptible water supply agreements, rotational fallowing, water banking and reduced consumptive use through changed irrigation and farming practices.

Given western water law, transferable water from agriculture is typically limited to the portion of the water a

Figure 1. South Platte River Basin, Colorado, Western United States. This figure is available in colour online at wileyonlinelibrary.com/journal/ird

farmer's crop historically consumes via evapotranspiration, not the full amount the farmer has rights to divert. This portion used directly by the crop is referred to as 'consumptive use' (CU) and does not include 'return flows'—water diverted that must return to the system for use by others. For example, after diversion into an earthen canal, the diverted flow immediately begins to diminish because of conveyance losses, the most notable of which is seepage. Seepage can be quite significant especially over the full length of the canal and is likely the single highest source of loss in earthen canals. Most seepage returns to the river as subsurface flows. Farmers desiring to 'conserve' water by reducing such seepage are typically not allowed to do so because that would affect supplies anticipated by downstream users. Most definitely, a farmer is not allowed to conserve that water and put it to additional use, for instance for expanding crop acreage. Farmers are not allowed to transfer such return flow water for use by others such as municipalities.

However, consumptive use water, that portion of the diverted water that is fully consumed by the crop, can theoretically be transferred for other uses, such as municipal or environmental. Once an estimated or a fully decreed consumptive use is known for a given water right, it opens up the potential to consider options for how the CU might be utilized or allocated differently in the future. The consumptive use could be allocated to a new use priority or some balance between old and new priorities. The consumptive use can now be viewed more rationally as an on-farm CU water budget with potential alternative uses. A new use of the CU might be to portion off some of this 'set aside' CU to a municipal or environmental water user for suitable monetary consideration.

The model described here is being developed to assist farmers in evaluating alternative irrigation or cropping practices to determine if they would want to consider changed practices in the future in return for an additional revenue stream to maintain or improve profitability of the overall farm operation. One such changed practice is that of rotational fallowing, a situation whereby a farmer chooses to allow some segment of his or her farm to lay fallow for a period of time so that the consumptive use water formerly used becomes available for temporary transfer for some other use, such as municipal. Lease of the water from the fallowed ground can be thought of as an additional crop-water.

A successful run of the optimization model indicates the projected net return associated with the crops to be grown, along with crop yields, the practices to be adopted, and the anticipated unit prices. This modelled net return can then be contrasted with the historic net return from the farming operation. The model utilizes farmer-user inputs for the simulated farming operation to mathematically optimize future farming operations against a quantified or presumed consumptive use water budget for the farm. The farm simulation input is easy to use by simple point and click entry of boundaries over the top of aerial imagery to outline the farm itself and existing or proposed fields, then inputs such as planned 'willing to grow' crops and practices are added. When finished, the farmer has a precise computer-generated map of the farm that becomes the basis for planning and running scenarios.

A future low-risk revenue stream may be brought into the farm's revenue forecast by virtue of the lease of a proportional amount of water to a municipal, industrial, or environmental user. Optimization algorithms are used to evaluate a farmer-considered package of changed practices which may include deficit irrigation, new crops, dryland crops, permanent or rotational fallowing of fields, and crop rotations. Some farmers will also consider upgraded irrigation systems as an aspect of implementing these practices. The farmer-driven optimization may include any or all of these changed practices as well as continued full irrigation of crops. To evaluate and compare multiple practices as a cohesive package and in the context of the option to lease water is new.

The simulation and optimization model output assists in comparing historic practices and net returns with future practices and net returns which would include a revenue stream associated with a lease or sale of a proportion of the farmer's CU water. The actual comparison between alternatives is accomplished by evaluating the change in net returns between historic practices and modelled future practices. The model utilizes crop water production functions, some of which are very newly researched and reported, to forecast crop yields based on changed irrigation practices.

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

The model allows for iteration with new cropping and management regimes, where field-based water and crop data can be fed instantly into computers and stored in databases. Annual water supply forecasts can be coupled with cropping plans, all to help farmers decide how best to use their water and to allow cities and industrial users easy entry to a water market where farmers can sell the use of a cubic metre (acre-foot) of water almost as easily as they can sell a tonne (bushel) of corn.

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

Some farmers will not consider using this technology because their operations are profitable and sustainable in today's agricultural economy. Others are farming in a marginal financial sense. An operational change using these technologies might help increase profits, allow for, or support irrigation system improvements, and otherwise help those farmers stay in business and continue providing significant regional economic benefits. The fact that new measuring systems—computer-controlled irrigation gates, networks of stream gauges, soil moisture sensors, and remote data-gathering devices—have become affordable enough to allow farmers and irrigation companies to use them, greatly increases feasibility for farmers to utilize this model.

Figure 2 shows the geographic information system (GIS) style field data entry screen. The farmer does not need to know GIS program or input features in order to input field data into the system. Data entry is facilitated by using intuitive point and click tools. Field boundaries can be input, colour coded, named, and resultant acreage returned.

Figure 3 shows the reported results of the optimization run and indicates the projected net return given the farmer inputs.

Technology, however, is not the only issue with reallocating water to protect farms and streams. In Colorado and other western states, water laws make water marketing and leasing, as well as pure conservation, difficult. These laws also sharply limit the ability to move water from one

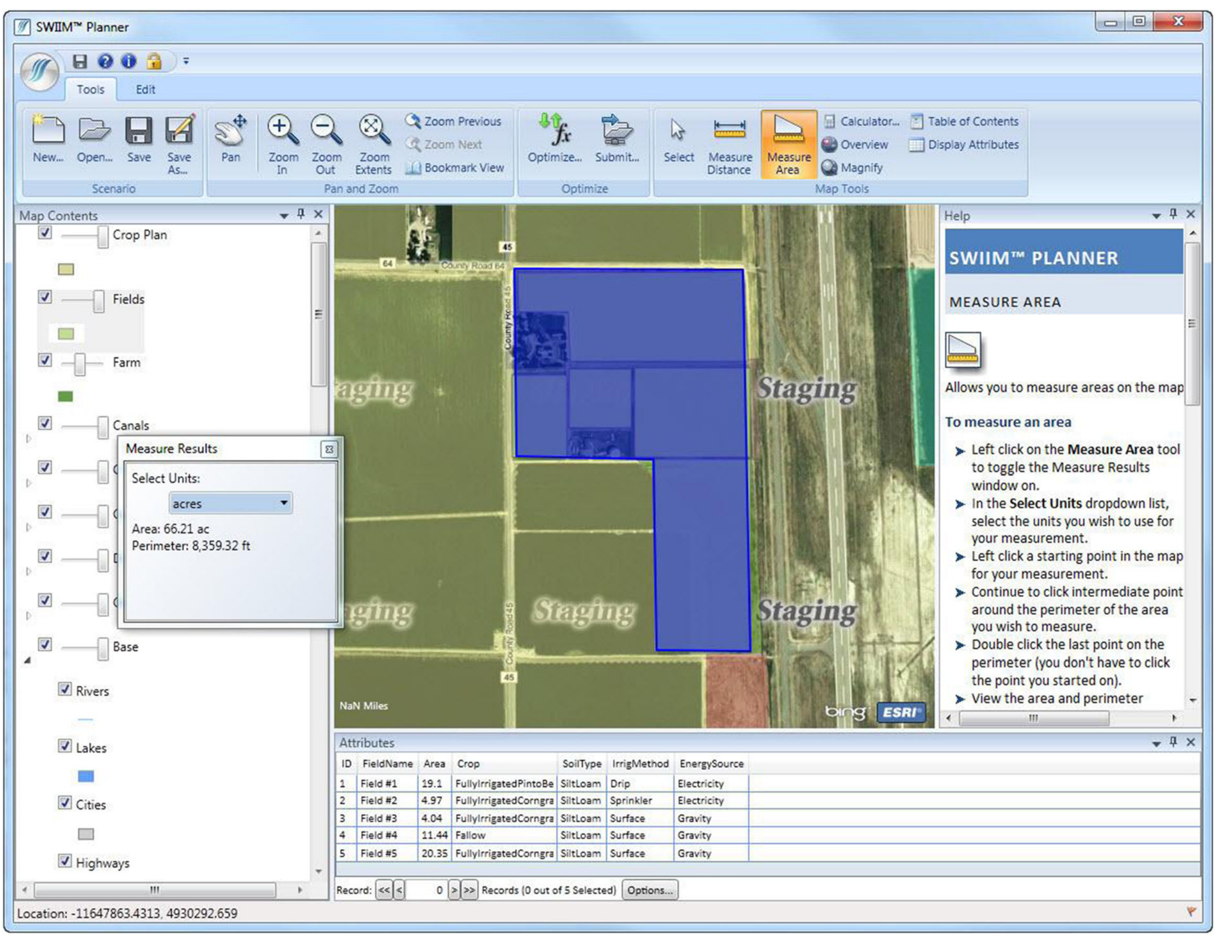

Figure 2. Geographic information system (GIS) style field data entry screen. This figure is available in colour online at wileyonlinelibrary.com/journal/ird

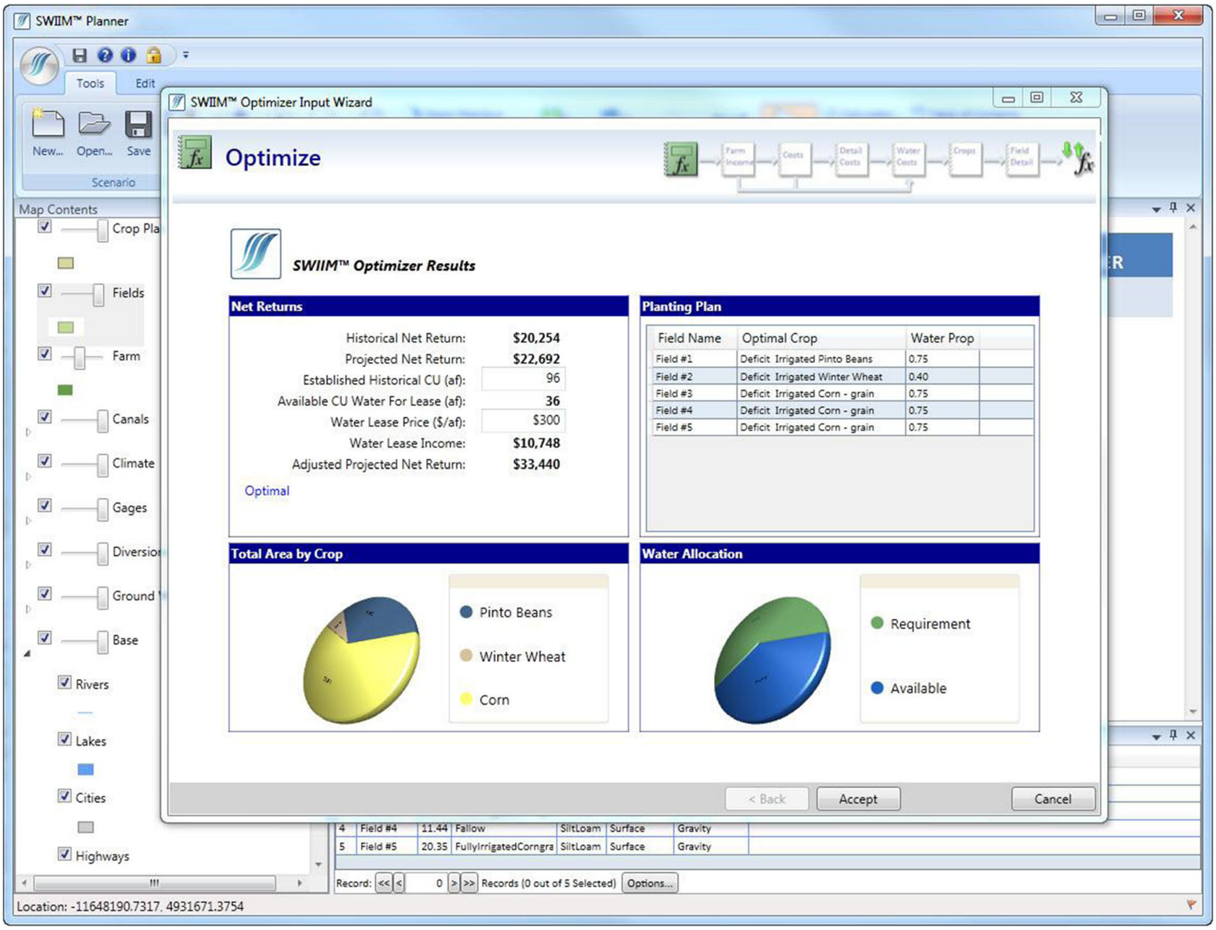

Figure 3. Reported results of the optimization run showing the projected net return given the farmer inputs

use to another quickly. Both usually require expensive engineering studies and years in special water courts, proving that the changes—from farm use to municipal or industrial use—are not harming someone else's water rights.

It is critical, therefore, to combine precise measurement with in-depth, computerized record keeping, powerful databases, and easily accessible water models whose accuracy and data can be verified by regulators and those who want to buy or lease water. The model under development will minimize the amount of time farmers and cities must spend in court to transact sales and leases while creating an efficient system to manage these transactions in the long term. Primary issues and pitfalls to implementing the process and strategies in this model are framed by questions like these:

- can municipal interests view a long-term lease as a viable part of their water portfolio and their projected safe yield at a future date?
- can farmers accept the perceived dramatic changes to their farming operations?
- can the science underpin the strategy sufficiently to satisfy change case objectors and the Colorado Water Court?
- can water be physically transferred based on existing water diversion and delivery infrastructure or is new infrastructure required in some cases?
- do existing state of Colorado statutes support the type of water transfer that is described?

CONVENING OF WESTERN US WATER LEADERS TO CONSIDER OBSTACLES TO MULTI-SECTOR WATER-SHARING STRATEGIES

In 2010, the Colorado Water Institute at Colorado State University convened representatives from the Nature Conservancy, Family Farm Alliance, Western Urban Water Coalition and two dozen other influential groups to determine if long-held adversarial positions could be set aside and new alliances built in order to remove obstacles to creative water-sharing strategies for mutual benefit. Their work resulted in a report, *Agricultural/Urban/Environmental Water Sharing: Innovative Strategies for the Colorado River Basin and the West*, which was recently presented to the Western States Water Council, the water policy arm of the Western Governors' Association.

The report was a response to a 2008 challenge by the western governors: 'States, working with interested stakeholders, should identify innovative ways to allow water transfers from agricultural to urban uses while avoiding or mitigating damages to agricultural economies and environmental values.' (Smith & Pritchett, 2010). Strategies detailed in the report include:

- farmers and cities in Arizona trading use of surface water and groundwater to the advantage of both;
- ranchers in Oregon paid by environmentalists to forego a third cutting of hay to leave water in the stream for late summer fish flows;
- a ditch company in New Mexico willing to sell shares of water to New Mexico Audubon for bird habitat on the same terms offered to a farmer to grow green chiles;
- a California flood control and water supply project creatively managed to meet multiple goals of restoring groundwater, maintaining instream flows for wild salmon and steelhead, and providing water for cities and farms;
- seven ditch companies cooperating in Colorado in a 'Super Ditch' scheme to pool part of their water through rotational fallowing, for lease to cities, while maintaining agricultural ownership of the water rights.

'While these strategies sound like good common sense, they all face sizable obstacles,' said Reagan Waskom, director of the Colorado Water Institute. If we want to share water for the benefit of all, we need a lot more flexibility, all members of the group agreed.

The group's recommendations to the western governors, developed to provide that flexibility, include:

- design robust processes that give environmental, urban, and agricultural stakeholders opportunities to plan together early on, instead of one-sided 'decide, announce, defend' processes that frequently result in opposition and polarization;
- foster a flexible, river basin-based approach that can lead to cross-jurisdictional sharing of infrastructure, cooperatively timed water deliveries, and strategies to facilitate real-time, on-the-ground, state-of-the-art water management for optimal benefit of cities, farms, and the environment; break down legal, institutional, and other obstacles to water-sharing strategies by developing criteria and thresholds that protect agriculture, the environment and any third parties to water-sharing transactions. And experiment with creative approaches such as 'water resource-sharing zones' that could be set up for trading of water, financial resources, and even locally grown food while encouraging interaction between agricultural, environmental, and urban neighbours;
- expedite the permitting process when programs or projects have broad support of agricultural, urban, and environmental sectors. A governor-championed federal/state pilot review process should be established where a state liaison and a federal designate are appointed to co-facilitate concurrent agency review and permitting without repetitive, costly information exchanges. Permitting is important to protect environmental, economic, and social values, the group agreed, but cumbersome permitting processes often lasting years need an overhaul (Smith & Pritchett, 2010).

Members of the group are promoting their recommendations and instigating dialogue throughout their constituencies.

CONCLUSIONS

Whether in the South Platte Basin of Colorado or elsewhere in the western United States, whether in Bolivia, Nepal, or Mexico City, water supply challenges are expected to increase. How scientists and engineers choose to tackle those challenges will determine whether water conflict is resolved or exacerbated. Technology is an important part of the solution, but drawing on the fields of economics, law, sociology, and other social sciences will be critical going forward. Engaging stakeholders in research and giving them a voice in the development of water policy will greatly increase the chances of success at solving very difficult water challenges. Whether humankind has the capacity to understand the necessity of setting aside personal gain for the benefit of all is yet to be seen, but our survival as a species may very well depend on it.

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Evaluating Net Groundwater Use from Remotely Sensed Evapotranspiration and Water Delivery Information

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Abstract. A detailed, comprehensive, and accurate identification of groundwater aquifer properties will likely never be fully achieved because of the high degree of variability and costs that testing involves. Furthermore, accurate estimates of boundary conditions are essential for groundwater modeling so that investigations of improved management scenarios can be conducted. The lack of key input values at the ground surface boundary limits the ability to accurately assess aquifer dynamics. Of major importance is actual evapotranspiration (water consumption or the loss of water to the atmosphere through transpiration and evaporation). The Irrigation Training and Research Center (ITRC) modified remotely sensed satellite imagery for spatial computation of actual evapotranspiration at high resolution, and integrated it into groundwater models. This paper focuses on an additional tool to assist in the calibration of groundwater models, which results in the NET contribution to or extraction from groundwater (NTFGW). By comparing surface water deliveries, precipitation, runoff, and evapotranspiration, the NTFGW can be computed spatially throughout a region. This provides a critical set of known information, in addition to historic groundwater elevation data, that can be used in model calibration.

Keywords. *Evapotranspiration, groundwater use, remote sensing, irrigation methods*

Introduction

Groundwater is vital for irrigation throughout the western U.S. Long-term, sustainable groundwater management is critical for many areas that rely on groundwater. Continuous, long-term groundwater overdraft will eventually result in a loss of crop production due to poor water quality in the lower portions of the aquifer, or the cost to pump the groundwater water will become prohibitive for agriculture. Additionally, land subsidence is a major concern in many areas. As lands subside, road, canals, buildings, pipelines and other infrastructure are damaged.

Despite attempts over the past century to counter aquifer overdraft with surface water supplies and infrastructure, long-term groundwater overdraft still exists throughout the Central Valley of California and has been well documented.

Groundwater evaluations have generally been conducted at local levels. These evaluations can be large-scale and commonly involve some type of groundwater modeling. The modeler may conduct some field evaluations to estimate some of the parameters in the aquifer(s), but these can have limited validity since these parameters can vary significantly throughout the aquifer (vertically and horizontally). Many inputs to these models are often unknown or if estimates are available they may have significant uncertainty.

Modelers believe that absolute pumping values are important to understanding how water is transported vertically through the aquifers. Additionally, these values are used to calibrate the aquifer properties. However, in most case groundwater pumping volumes are not collected; even if they are, the destinations of the pumped water are difficult to determine. If evapotranspiration by the plants is known accurately, the pumped and surface water applied (including rainfall) in excess of evapotranspiration must be partitioned into deep percolation and surface runoff (i.e., tailwater).

The following brief list of major input information is <u>traditionally</u> required for accurate groundwater modeling:

A) Surface inflows and outflows at least regionally but field/parcel level is preferred
B) Precipitation
C) Canal, drain, and stream seepage, by location
D) Plant consumptive use (evapotranspiration (ET))
E) Groundwater pumping
F) Estimated destinations of applied water
    a. Deep percolation
    b. Surface runoff
G) Key aquifer properties
    a. Transmissivity
    b. Hydraulic conductivities (vertical and horizontal)
    c. Specific yield and specific storage
    d. Physical properties such as depth and water levels at boundaries
    e. A number of other factors

The previous list is not meant to be comprehensive but will be discussed in generalities. A major point to be made is that even if A)-C) are relatively well known, most of the other important inputs are not known. Therefore, the modeling efforts generally use historical groundwater levels as the basis for calibration of the other parameters. There are a number of methods for this calibration (forward modeling, inverse modeling, etc.), but significant uncertainty remains since ET, pumping, and destinations of applied water are needed to calibrate aquifer properties. However, ET, pumping, and destinations of applied water are unknown and therefore the models must also calibrate for these values. This circular calibration can lead to significant errors in parameter calibration results.

The procedure described in this paper is intended to assist modeling efforts by providing key information to improve the calibration. This is accomplished by first providing high-resolution, actual evapotranspiration throughout the study area and timeframe. The method uses the ITRC-modified METRIC (Mapping EvapoTranspiration at High Resolution with Internal Calibration) procedure, which provides actual ET at a 30 meter resolution without the need for accurate crop type, irrigation method, and irrigation scheduling accounting.

In addition to actual ET, a procedure will be outlined that allows for the estimation of the net contribution to or extraction from the groundwater (Net to and from Groundwater (NTFGW)) spatially throughout the study area. This estimate is made with a fraction of the input data listed above and specifically without the need to know groundwater pumping or aquifer parameters.

The procedures discussed will only focus on what is occurring within fields and natural vegetation areas in the study area. Considerations of canal, drain, and river/stream/creek seepage are not included. However, in the future it is anticipated that this information will be integrated into the procedure.

Procedure

The procedure outlined here will focus on the computation of NTFGW. The ITRC-modified METRIC procedure for computing actual evapotranspiration will only be discussed briefly. Much of the background on this procedure has been published previously (Allen et al. 2007; Howes et al. 2012a; Howes et al. 2012b).

The basic procedure for evaluating the spatial distribution of NTFGW is a local root zone water balance with surface area boundaries of each ET image pixel (horizontally) and the bottom of the root zone to the ground surface (vertically). **Figure 1** shows a simple schematic of the individual components for estimating the NTFGW, assuming that the soil moisture is the same at the beginning and end of each time step. It is reasonable to assume that in most cases the soil moisture in the root zone will be similar at the start and end of the time step if the time step is one year or greater. Because of potentially large changes in root zone soil moisture with smaller time steps, the soil moisture depletion at the beginning of each time step should be examined as will be discussed.

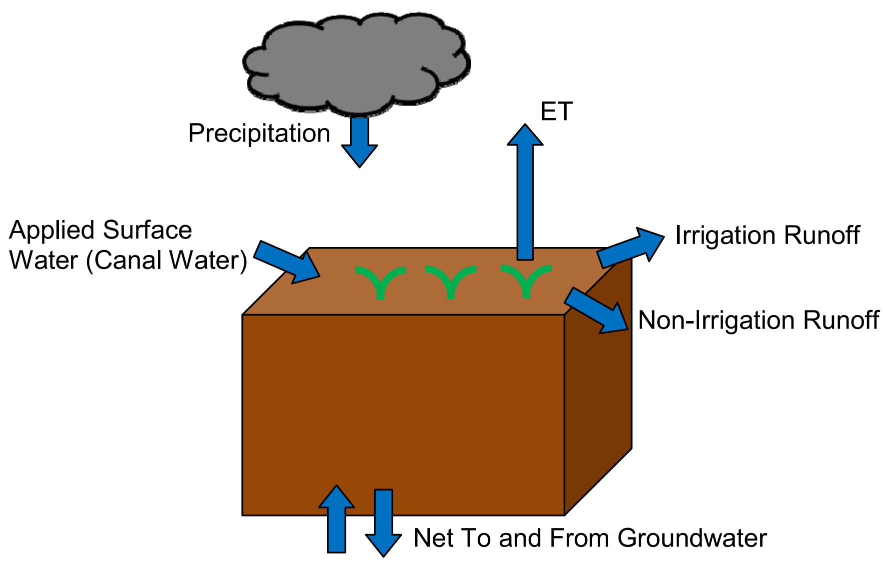

Figure 1. Schematic showing the components for computing the net to and from groundwater assuming the soil moisture is the same at the beginning and end of the time step.

The main components of NTFGW shown in **Figure 1** include:
1. Applied surface water (canal water)
2. Precipitation
3. Evapotranspiration (ET)
4. Irrigation Runoff
5. Non-Irrigation Runoff (precipitation runoff)

The *NTFGW* can be computed using the following equation:

$$NTFGW = Applied\ Surface\ Water + Precipitation - ET - Irrigation\ Runoff - Non\_Irrigation\ Runoff \quad (1)$$

When NTFGW is positive, there is a net contribution to the groundwater. If the NTFGW from equation 1 is negative, this indicates that surface water and precipitation were not sufficient to meet ET and runoff, so groundwater was assumed to make up the deficit.

On a monthly time step, this equation must include the soil moisture depletion (SMD) at the beginning of the month. In order to determine SMD, the soil type and general crop type are needed to determine the soils available water holding capacity in the crops root zone. The initial SMD is estimated based on prior months' (November and December) precipitation amounts. The evaluation of monthly NTFGW requires several checks on Equation 1:

- If Eq. 1NTFGW is positive and is greater than the SMD, the end of the month SMD is assumed to be filled and any additional NTFGW must deep percolate below the root zone (Net to Groundwater).
- If Eq. 1 NTFGW is positive and is less than the SMD, the SMD at the end of the month is equal to the SMD at the beginning plus the Eq 1. NTFGW (no Net to Groundwater).
- If Eq. 1 NTFGW is negative and is less than the water remaining in the soil root zone at the end of the month, SMD at the end of the month is decreased by NTFGW (no Net from Groundwater).
- If Eq. 1 NTFGW is negative and is greater than the water remaining in the soil root zone at the end of the month, the SMD at the end of the month is decreased to the allowable depletion and the remaining NTFGW must be pumped from the groundwater (Net from Groundwater).

The sections below discuss how each parameter of *NTFGW* was computed, beginning with the total area boundaries.

Parcels/Field Boundaries

Approximately 600,000 acres of total land area near Merced, CA was examined. A groundwater model is currently being developed by RMC Water and Environment on behalf of the Merced Area Groundwater Pool Interests (MAGPI) for this area. MAGPI is a group of agencies and stakeholders in the Merced Area that rely on the groundwater aquifer. The work presented here is in support of that effort.

Some of the input information for NTFGW determination is computed spatially over an area in raster format (actual ET and precipitation). However, applied surface water is measured at a point (district delivery to a farm that may contain multiple fields). It is unknown how that water is applied over those fields, only that it is delivered. In order to convert delivery point information along canals and pipelines to spatial data showing that volume of water applied over an area it is necessary to attribute the applied water to those fields that obtain that surface water delivery. For this project, parcel maps were used to link the surface deliveries to the farm area.

A GIS file containing individual parcel locations in Merced County was obtained from the Merced County website. **Figure 2** shows all the parcels located in eastern Merced County and within the MAGPI project boundary. **Figure 3** shows an example of an aerial image with individual parcels located just west of Merced.

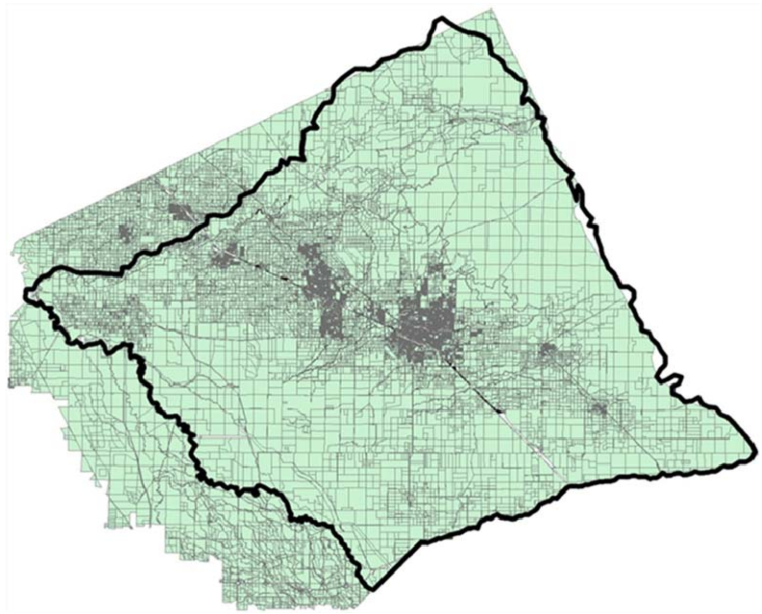

Figure 2. Individual parcels located within the project boundary

Figure 3. Aerial image shows individual parcels (outlined with black borders) west of Merced

<u>Applied Surface Water</u>

Surface water delivery events obtained from Merced Irrigation District (MID) from 1992 through 2013 were used to determine the applied water (in acre-feet) for individual water user accounts. Most of the areas outside of MID do not obtain surface water. In cases where surface water was delivered to outside-of-MID regions, this information was incorporated into the parcel map. The account numbers for individual surface water users in MID were compared to the known county assessor's parcel numbers (APNs). The location of each APN was compared to the Merced County parcel GIS file to determine the approximate location of the applied water.

With the approximate known acreage of each parcel, the volume of applied water by parcel was converted to applied inches of water on a monthly basis. Because it is not known how the surface water is applied within the parcel, the applied inches of water was assumed to be uniformly applied across the entire parcel (or multiple parcels if that was the case). A small amount of account numbers did not have an associated parcel number. If the applied water in these cases was less than 3 acre-feet, the applied water for that account was ignored. For larger volumes, the general area of the delivery was determined based on the account number and the water was applied to a parcel of similar area that had no surface water assigned to it.

This process is likely the most difficult and problematic. Assessor parcel boundaries change regularly, as do APNs. It is difficult for another agency to update these numbers regularly. In some cases APNs may not be associated with surface deliveries. While high resolution outputs are desired, a more reasonable approach in some cases may be to assign the water deliveries from multiple farms to larger areas and spread the water deliveries over those large areas. The result will show more variability at smaller resolution, which will be smoothed out at the larger scale.

Averaging Applied Water

While it was possible to attribute the vast majority of applied water to parcels, it became apparent that the surface delivery records did not contain all of the fields on which water was used. Some parcels showed unreasonably high applied water values, with surrounding parcels receiving none. It is not uncommon for water from a single delivery point to be moved one-half to a full mile away through the farm's distribution system. Since farmland is purchased and leased over the years it would be unlikely that those new fields would be included in the delivery records. To smooth the applied water data over a more reasonable area, the applied surface water by parcel was averaged over a one mile by one mile grid from the Merced County township and sections provided by the Public Land Survey System (PLSS).

The applied water was averaged over the mile sub-section in order to eliminate field outliers in such cases where small (consisting of only a few acres) irrigated fields appeared to be applying an unrealistic amount of water in a single month. The field outliers were a result of missing parcel numbers for individual accounts that clearly have multiple parcels associated with that account.

An example of the applied water by parcel can be seen in the left image of **Figure 4**. The applied surface water averaged over the one mile grid sections for the same area can be seen in the right image of **Figure 4**.

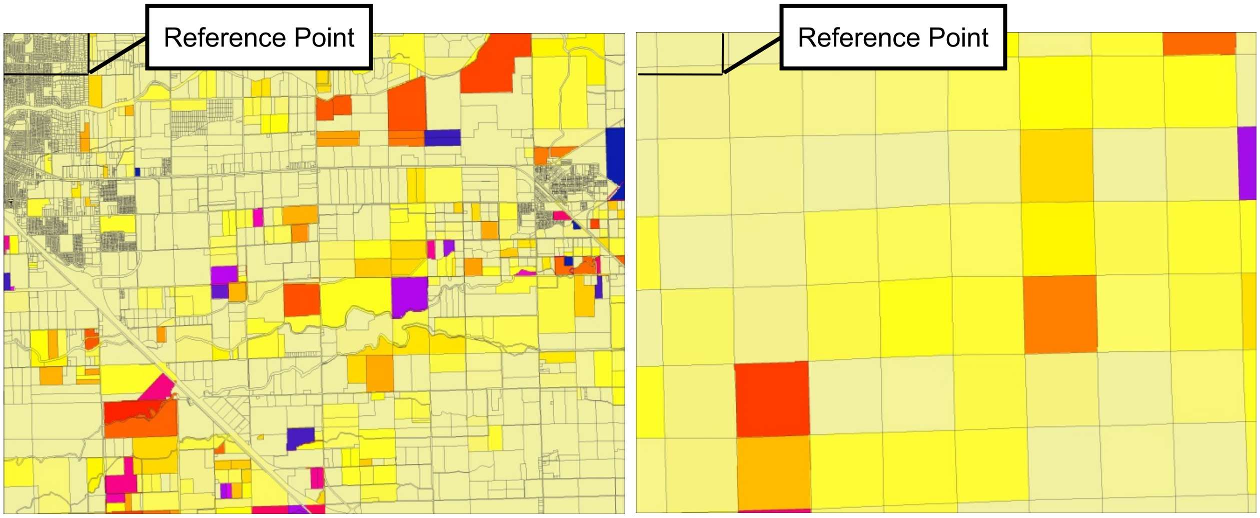

Figure 4. Example of applied water by parcel (left image) compared to applied water over one mile sections (right image) for July 2002. The darker the color, the higher the applied surface water.

Precipitation

Spatially distributed precipitation maps were downloaded from the PRISM Climate Group of Oregon State University. The raster files displayed monthly precipitation data in millimeters for the entire United States on a 4 km by 4 km resolution.

A sub-set of the original monthly precipitation raster was extracted to be just larger than the project area of interest. The precipitation values of the sub-set precipitation raster were converted from millimeters to inches of precipitation. **Figure 5** shows an example of a precipitation raster from PRISM for December 2002. The darker colors indicate a higher monthly total of precipitation.

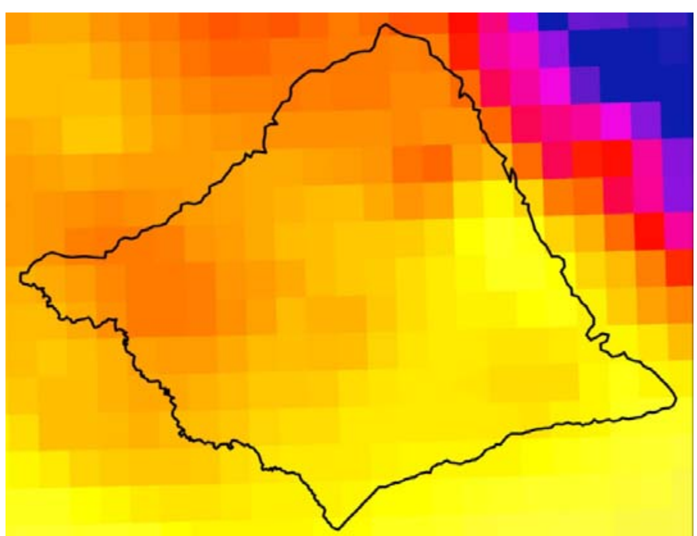

Figure 5. Example of monthly precipitation raster available from PRISM Climate Group for December 2002. The darker colors indicate a higher monthly total of precipitation.

Irrigation Runoff

Irrigation runoff was based on land use and irrigation type. Land use type for each individual parcel was determined using the land use map created from the DWR land use survey as well as the NASS CropScape procedure. Certain crops and land use types were associated with having no irrigation runoff (refer to **Table 1**). In this area, tailwater runoff is not common. There are many orchards or vineyards in the region that either use basin or drip/microspray irrigation systems, because drip/microspray has no runoff. The basins used in this region are generally closed and therefore produce no irrigation runoff.

Table 1. Land use types associated with no irrigation runoff

Orchards/Vineyards	Urban	Other
Cherries	Developed – Open Space	Forest
Peaches	Developed – Low Intensity	Shrubland
Apples	Developed – Medium Intensity	Barren
Grapes	Developed – High Intensity	Non-Agriculture
Other Tree Crops		Deciduous Forest
Citrus		Evergreen Forest
Pecans		Mixed Forest
Almonds		Grassland
Walnuts		Herbaceous
Pears		Fallow/Idle Cropland
Pistachios		Woody Wetlands
Prunes		Herbaceous Wetlands
Oranges		
Pomegranates		

In addition to the land use classifications in **Table 1**, other areas using certain irrigation types were assumed to have no runoff. The irrigation method for each individual parcel was determined from the DWR land use survey conducted in 2002 for Merced County. The following irrigation methods were assumed to have no irrigation runoff:

- Surface drip irrigation
- Buried drip irrigation (sub-surface drip irrigation)
- Microsprayer irrigation
- Center pivot sprinkler irrigation
- Linear mover sprinkler irrigation
- Non-irrigated fields

Surface irrigation methods for field crops were assumed to have some but minimal tailwater runoff leaving the farm unit or general vicinity of the applied water. It was unknown exactly how much tailwater was leaving; however, the authors have significant experience in the region and they assumed that the tailwater was approximately 5% of the monthly ET for these crop/irrigation types.

The tailwater estimate of 5% of average monthly ET is based on the following reasons:

1. There is not an extensive drainage system throughout the MAGPI boundary to collect tailwater runoff.
2. Most farmers tend not to have any tailwater runoff in their irrigation practices.
3. Some fields throughout the MAGPI boundary utilize tailwater recovery systems.

Figure 6 shows an example of the estimated irrigation runoff for each individual parcel in July of 2013. The tan color indicates approximately zero irrigation runoff while the dark colored areas (blue being the darkest) indicate a higher amount of irrigation runoff (up to approximately 0.6 inches for this example). While the color coding seems dramatic, in actuality is there is minimal tailwater leaving the region.

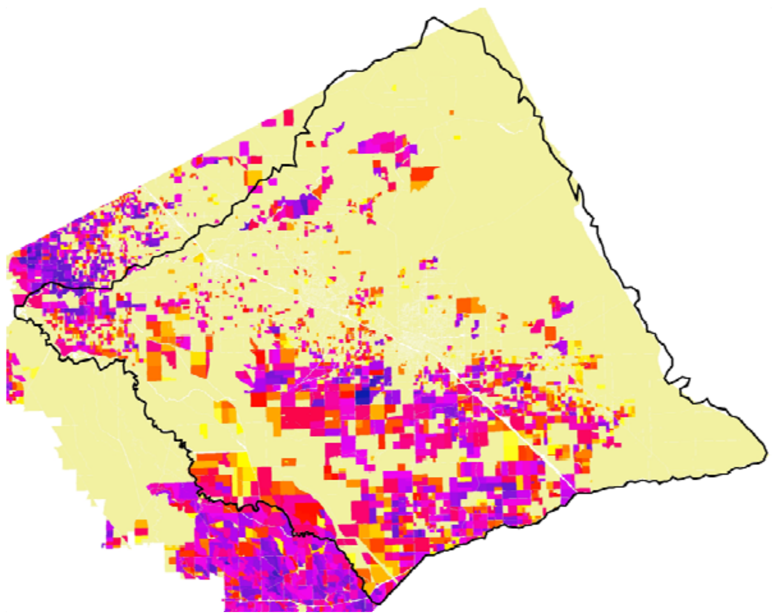

Figure 6. Example of estimate irrigation runoff for individual parcels in July 2013. The darker the color, the higher the irrigation runoff (up to approximately 0.6 inches of irrigation runoff for this example).

Non-Irrigation Runoff

The following procedure was used to estimate the non-irrigation runoff for individual parcels in the agricultural areas within the MAGPI boundary. Precipitation runoff in the urban areas was not considered for this study. The focus of the study was agricultural and natural vegetation areas.

Soil Type Characterization for Individual Parcels
Soil characteristics for Merced County were obtained from the National Resources Conservation Service (NRCS). The information provided by the county was assigned generic soil class types and soil group classifications as follows:

- Sand – Soil Group A
- Sandy Loam – Soil Group B
- Loam – Soil Group B
- Silt Loam – Soil Group C
- Clay Loam – Soil Group C
- Clay – Soil Group D

The soil types were reclassified for each individual parcel based on the majority of soil types located within each parcel. Each parcel was then assigned a uniform soil type. While it is known that soils are not uniform in fields, it is likely that the major soil type will have the most influence on precipitation runoff. Since the fields are very flat in the majority of farmed parcels it is unlikely that there is significant runoff except in very wet years. **Figure 7** shows the uniform soil types reclassified for each parcel to be used for the non-irrigation runoff estimates.

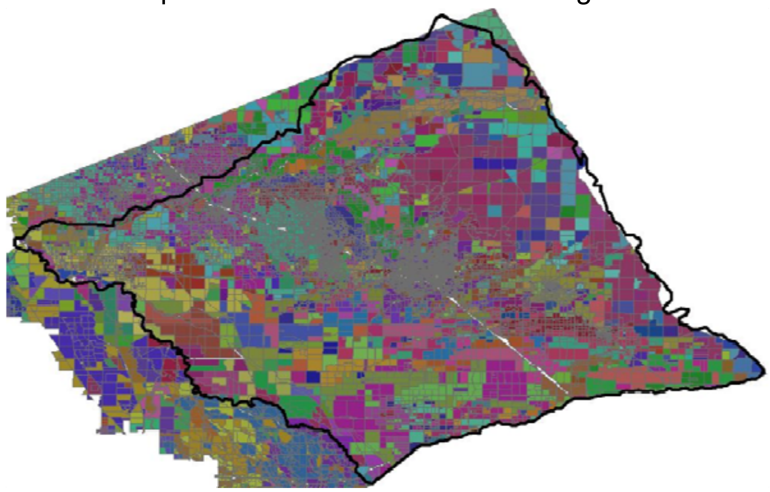

Figure 7. Reclassified soil type by parcel

NRCS (SCS) Rainfall Runoff Procedure for Non-Irrigation Runoff

The NRCS (SCS) curve number approach was used to estimate precipitation runoff on a monthly basis from agricultural fields inside the area of interest. Runoff due to precipitation can be estimated using the following equations:

$$P_e = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

$$S = \frac{1000}{CN} - 10$$

Where: P_e = direct runoff, inches
P = precipitation, inches
S = potential maximum retention
CN = runoff curve number

The precipitation input in the SCS runoff equation was based on daily precipitation totals from the two CIMIS weather stations. Since PRISM data is only provided monthly, estimating runoff on a daily basis with uniform precipitation is more accurate than trying to estimate it based on monthly spatially provided PRISM precipitation. The curve number for each parcel was determined based on:

1. Assigned land use description (agricultural crop, fallow land, etc.)
2. Hydrological soil group

Table 2 shows the assigned SCS curve numbers used in the estimation of non-irrigation runoff of individual parcels. Runoff from urban areas was not considered in the estimates.

Table 2. Assigned SCS curve numbers for different land use and soil group descriptions

Land Use Description**	Soil Group	Curve Number
All agricultural crops – for cultivated agricultural land, row crops, straight rows, in good condition	A	67
	B	78
	C	85
	D	89
Fallow/idle cropland – for non-cultivated agricultural land, pasture or range, no mechanical treatment, in fair condition	A	49
	B	69
	C	79
	D	84
Grassland herbaceous – for non-cultivated agricultural land, forested, grass, in fair condition	A	44
	B	65
	C	76
	D	82
Shrubland – for non-cultivated land, forested, brush, in poor condition	A	48
	B	67
	C	77
	D	83

** Based on SCS Curve Number Descriptions

For small precipitation events, the SCS runoff equation would produce a runoff value greater than the amount of daily precipitation. This is due to the empirical characteristics for which the SCS runoff equation was produced. Therefore, two quality control checks were performed on the calculated non-irrigation runoff estimates:

1. If the result of $\left[Precipitation - 0.2 \times \left(\frac{1000}{Curve\ No.} - 10\right)\right]$ is negative, then there is no runoff due to precipitation.
2. The amount of computed $Runoff$ must be $\leq Precipitation$.

The daily runoff estimates were summarized into monthly runoff totals for each model year.

Soil Moisture Depletion

The soil's available water holding capacity (AWHC) in the crop root zone is needed to evaluate soil moisture depletion. The NRCS soils map for Merced County provides estimates of AWHC by soil type throughout the area of interest. The AWHC is provided as inches of water held at field capacity per inch of soil (inches/inch) for each soil horizon. A weighted average over the potential root zone was used to determine the root zone AWHC.

Root zones were assumed to be 5 feet for orchards, alfalfa, and vineyards, 3 feet for field crops, and 1.5 feet for natural vegetation. If an orchard or vineyard was irrigated using drip or microspray, the assumed wetted area was 60% of the total area, which reduces the AWHC by 40% for these irrigation methods. There was not a significant amount of buried row crop drip in the region during the analysis period.

The initial soil moisture depletions were estimated based on monthly rainfall in November and December prior to the year being analyzed. ET demand is low during these months and significant precipitation generally occurs in the area between November and February. If there was heavy rainfall during this period the SMD was assumed to be small. If there was little precipitation in the prior month the SMD was assumed to be large (approximately 50%-60% of the root zone AWHC). With average precipitation the SMD was assumed to be 20%-30% of the root zone AWHC.

The soil moisture depletion at the beginning of each month was applied to the procedure for estimating NTFGW as described.

Net To and From Groundwater Results

The monthly NTFGW estimates (in inches) were created for 2002 and 2010. **Figure 8** shows examples of January, July, and October results for 2002, which was an average to slightly dry year. In January when ET demand is low, precipitation above ET and runoff tends to contribute to the groundwater. However, in the summer and early fall when ET demand is still relatively high and precipitation is low, the contribution to the groundwater depends on applied surface water. The area within the purple boundaries in the images indicates the parcels within Merced ID boundaries. The district provides surface water to its customers, so the NTFGW is more positive (indicating more contribution to the groundwater) than areas receiving no surface water outside of the boundaries. The areas in white indicate likely but unknown surface water deliveries. Work is underway to determine the amount of surface water being delivered to white regions within the boundary.

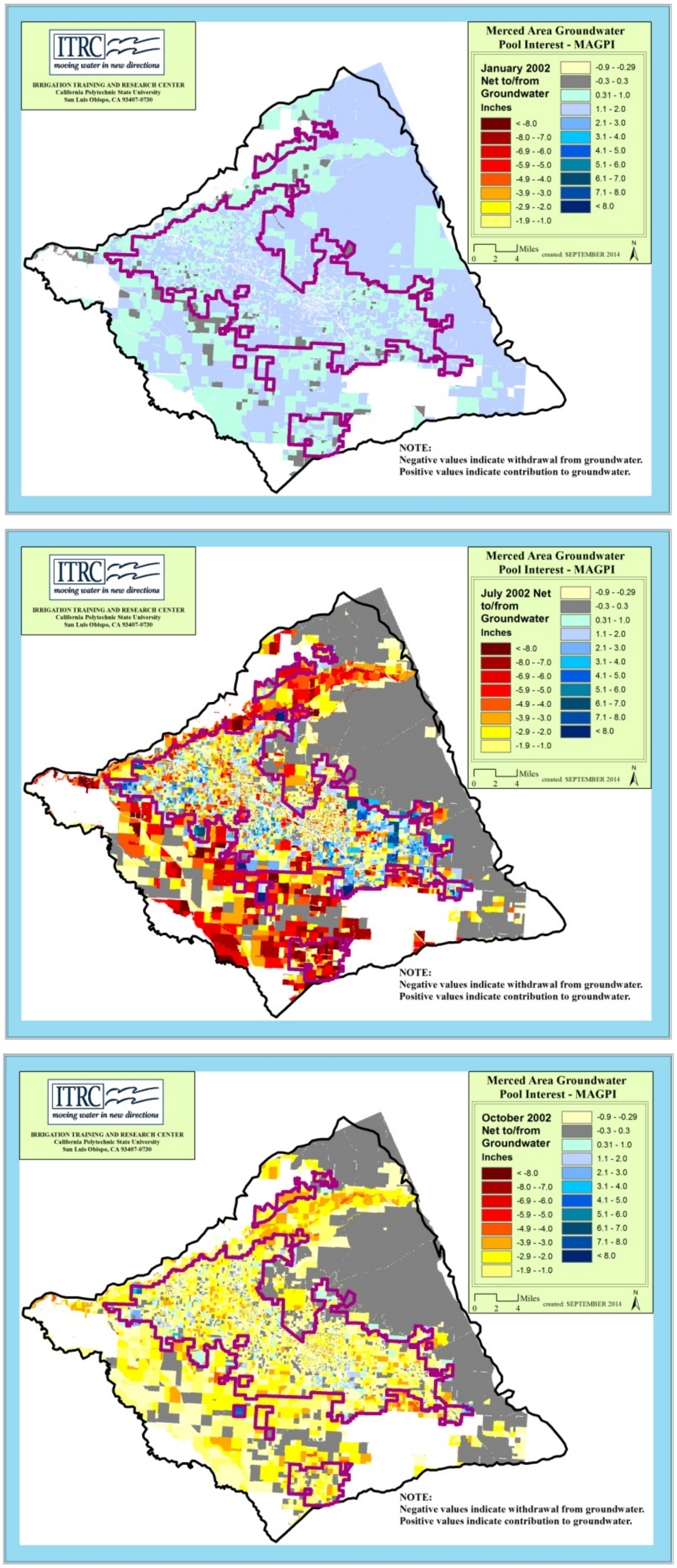

Figure 8. January, July, and October images of NTFGW. Note: these spatial images are still in draft and results in several areas in the northeast are incorrect as of October 2014 (date of paper submission).

Figure 9 shows the annual NTFGW for 2002 and 2010 for the study area. In contrast to the 2002 average precipitation year, 2010 was a wet year. Overall there is a substantially higher net to groundwater in natural vegetation areas to the east and within the district in 2010 compared to 2002. Growers within the district have groundwater wells to supplement surface water supplies. In some cases growers within the district will only use groundwater if they have converted to drip/microspray. This is not universal but the higher net from groundwater (brown regions) within MID boundaries (green lines in Figure 10) could be contributed to this. The major cities in the region also rely solely on groundwater. This study did not look at consumption other than from ET in any areas, so other uses of water in the cities are not included in **Figures 8 and 9**.

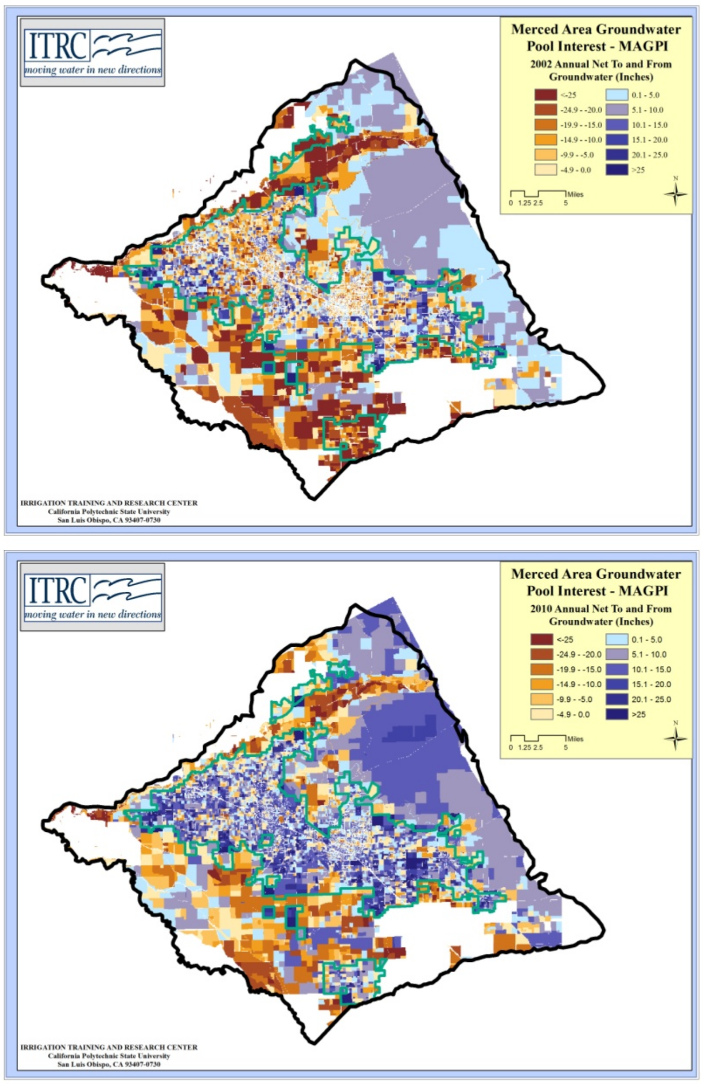

Figure 9. 2002 (Average) and 2010 (Wet) annual NTFGW. Note: these spatial images are still in draft and results in several areas in the northeast are not correct.

While the spatial output can be at any resolution, in most cases the accuracy at resolutions of less than a 1-mile grid would be misleading. Not knowing exactly where the surface water is applied is a major constraint. This is also true of traditional groundwater modeling; however, for most groundwater evaluations a 1-mile grid provides a good idea of where groundwater is being recharged and consumed.

Conclusion

Spatial data on actual ET and Net To and From Groundwater is being integrated into a groundwater model to improve the calibration of critical aquifer parameters. The actual ET will be integrated directly into the model grid to replace the traditional “maximum” potential ET or estimated ET from traditional methods. The ITRC-modified METRIC ET outputs account for alternative cropping management, decreased vigor, bare spots, and plant stress and other factors that will impact water consumption. Additionally, knowledge of crop types, crop development, and crop age is not needed to compute actual ET at high resolution.

NTFGW provides water managers and policy makers with critical groundwater use information. It provides an excellent look into what is going on within a basin without the uncertainty in aquifer parameters. The net volume of groundwater recharge and use can be examined between different months and different year types within subareas or the entire basin. The spatial presentation of the data allows managers to assess problem areas and take corrective action. Additionally, the spatially varied Net To and From Groundwater provides a set of data, on a monthly basis, to which modelers can calibrate in addition to groundwater elevation data that may be available once or twice a year.

Over the next several months the full process for integrating this information into the modeling effort should be established.

Acknowledgements

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Surface irrigation systems with water reuse deliver *E. coli*

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Abstract

The US Food and Drug Administration proposed in 2013 to adopt the EPA's primary contact recreational water standard (235 colony-forming units (CFU) *E. coli*/100ml and 126 CFU *E. coli*/100ml on a 5-sample geometric rolling mean) for as the water quality standard for vegetable crop production. In the Treasure Valley of Oregon and Idaho, surface irrigation water delivery systems maximize scarce water by reusing runoff water from other growers. Agricultural drain water is mixed with relatively clean project water to provide ample supply to all growers. Agricultural drain water in runoff reuse systems enhances the amount of water available but results in *E. coli* contaminated water.

Introduction

In 2011 Congress, through the Food Safety Modernization Act, assigned the Food and Drug Administration (FDA) the task of creating food safety standards for fresh produce. FDA's proposed rule for fresh produce was published at the beginning of 2013 and comments were due by 15 November 2013. FDA's proposed rule would require weekly testing of surface irrigation water by growers. The proposed standard is identical to the EPAs primary contact recreational water standards. If the water exceeds 235 colony-forming units (CFU) of *E. coli* in any one sample or 126 CFU in the average of any five consecutive samples, growers would have to cease using that water in any way that directly contacts the surface of fresh produce. Onion growers would have no option but to cease irrigation. Fruit producers would be unable to use that water for cooling sprays. If adopted, these rules could provide a strong disincentive to local growers.

Throughout the Intermountain West, many irrigation water delivery systems rely on the reuse of water to provide a scarce resource to multiple users. In these systems, return flows of on-farm runoff water are added to source water to be delivered onward to downstream farms. Even where source water would meet EPA's stringent primary contact recreational water standards, as it does in many of the impounded waters of the Intermountain West, only the first users of this water would be able to meet the FDA's proposed agricultural water standards. On-farm runoff waters carry substantial bacterial loads contributed by livestock and wildlife including small mammals and birds. These runoff waters can be intermixed with source water to provide sufficient quantities for delivery to downstream users. With successive on-farm uses, bacterial loads in surface irrigation water tend to increase. Bacterial loads in agricultural drain waters typically far exceed the FDA's proposed agricultural water standards for much of the irrigation season.

Different irrigation systems in the region differ in their exposure to this potential regulatory risk. In the Treasure Valley of Oregon and Idaho runoff reuse has been the primary water conservation method throughout the history of the system. Without the reuse of runoff, it would not be possible to supply water to all the current acreage. In particular, furrow irrigation dominates the landscape. Furrow irrigation uses water intensively and returns much of that water as runoff.

Although irrigation in the region shares a similar technological history, many Magic Valley Idaho and Eastern Idaho growers converted to large scale sprinkler systems beginning around the 1950s. In these systems there is limited runoff. The irrigation delivery systems no longer depend on returned runoff water; however, the potential for *E. coli* contamination still exists in the long stretches of unfenced open canals that cross rangelands and natural habitat have the potential to contaminate water supplies with *E. coli*.

Four U.S. Bureau of Reclamation (USBR) projects within Idaho and Malheur County, Oregon generate irrigated crop farm gate value of $1.933 billion and provide water to support a livestock industry worth $1.337 billion. The USBR Owyhee Project generates yearly irrigated crop farm gate value of $135 million and provides water for an $81 million livestock industry (USBR, 2009). The two divisions of the USBR Boise Project generate yearly irrigated crop farm gate value of $581 million and provide water for a $600 million livestock industry (USBR, 2012). The USBR Minidoka Project generates yearly irrigated crop farm gate value of $642 million and provides water for a $342 million livestock industry (USBR, 2010a). The USBR Palisades Project in the Upper Snake River Valley provides “supplemental water for about 650,000 acres of irrigated lands in the valley. Principal crops are grain, alfalfa, pasture, dry beans, potatoes, sugar beets, other vegetables, and seeds” totaling $575 million. The project supports a $314 million livestock industry (USBR, 2010b).

Historical water quality

To discover the extent to which delivered surface water fails to meet the proposed standard we analyzed the historical water testing results. This analysis was limited to the available data. Although many growers test water for *E. coli*, the risks of regulation and litigation make growers leery of contributing these data toward a public record. Since on-farm data are not accessible, the analysis of historical *E. coli* loads in surface irrigation water relied on test results in the public domain. The water testing sites, in roughly descending order of availability, consisted of streams, reservoirs, ponds and wetlands, agricultural drains, and canals. We relied on these indirect measures to show the pattern of microbiological loads in water that is delivered to growers.

The analysis show that although source waters in the region carry low *E. coli* loads that would nearly always meet the standards of the proposed rule, agricultural drains and streams with high runoff returns carry high loads of *E. coli*. Most have historically exceeded, often frequently, the 235 CFU single-sample standard of the proposed rule.

The Food Producers of Idaho commissioned an historical water quality database comprising 33,901 surface water *E. coli* samples from Idaho and Malheur County, Oregon covering twenty-one years (1993-2013). These historical samples are either in the public domain or have been contributed to our database by irrigation districts and watershed councils. Analysis of this database shows definitively that the conservation practice of returning runoff flows to be combined with source water that meets the EPA primary contact recreational water standard causes the combined water to consequently to fail to meet the *E. coli* water quality standards of Section 112.44(c), barring dilution by an overwhelming quantity of source water. This effect can be shown in irrigation systems within the U.S. Department of the Interior Bureau of Reclamation (USBR) Owyhee Project in Malheur County, Oregon and, and Boise Project Payette Division, Boise Project Arrowrock Division (USBR 2009, 2012). Agricultural drains that fail to meet the *E. coli* water quality standards of Section 112.44(c) and small streams that receive runoff return flows, consequently failing to meet the *E. coli* water quality standards of Section 112.44(c) can moreover be found throughout the USBR Minidoka Project and USBR Palisades Project (USBR 2010a, 2010b).

Example of the Treasure Valley:

As an example of the water bodies in the Treasure Valley, irrigation systems mix clean water with runoff water. Runoff water in the Owyhee River basin typically has around 570 CFU /100 ml. Runoff water in the Malheur River basin typically has around 1,000 CFU /100 ml. Some water *E. coli* levels are very high.

Historical Surface Water Quality:
Treasure Valley, Oregon - Idaho

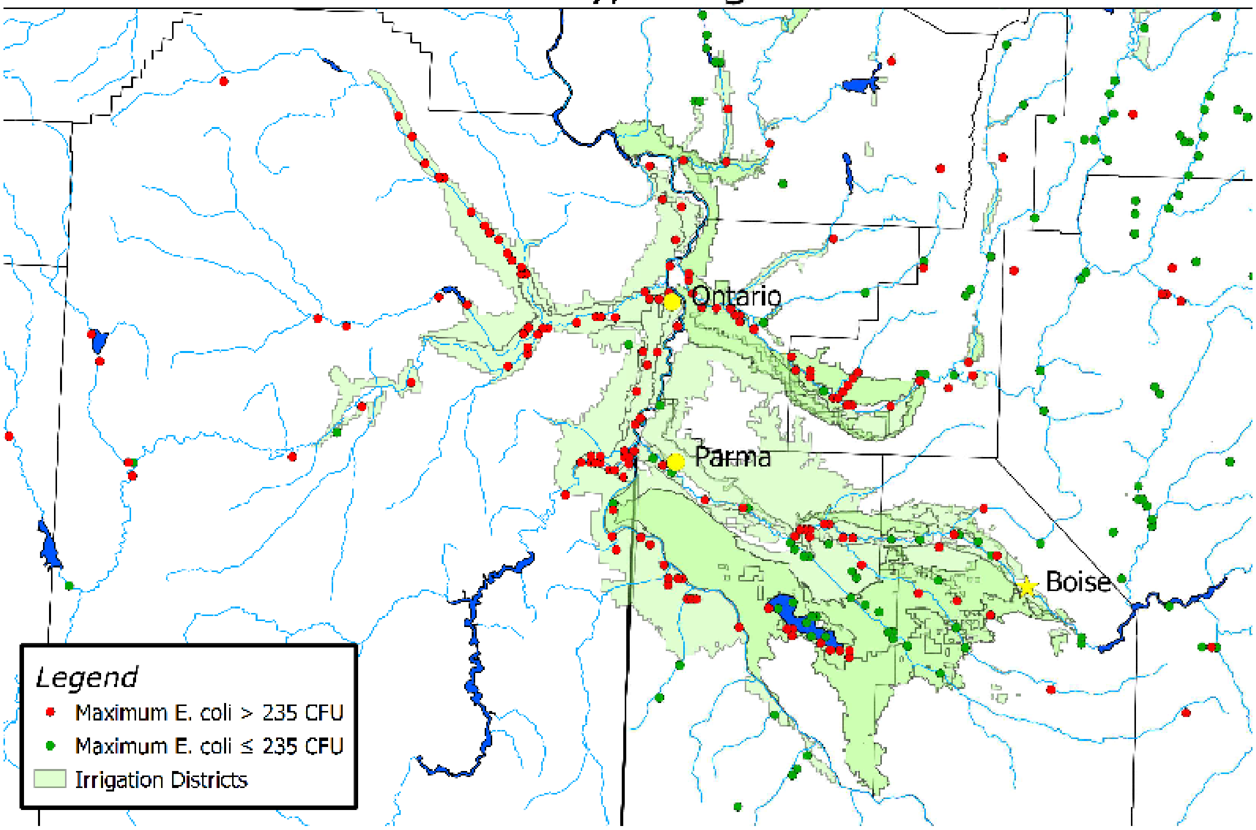

Figure 1. The Treasure Valley of Oregon and Idaho straddles the Snake River. Irrigation water is delivered predominately by gravity fed ditches. The ditches both deliver water to farms and collect runoff from adjoining irrigated land uphill from the ditch. Irrigation water often exceeds 235 CFU of *E. coli*.

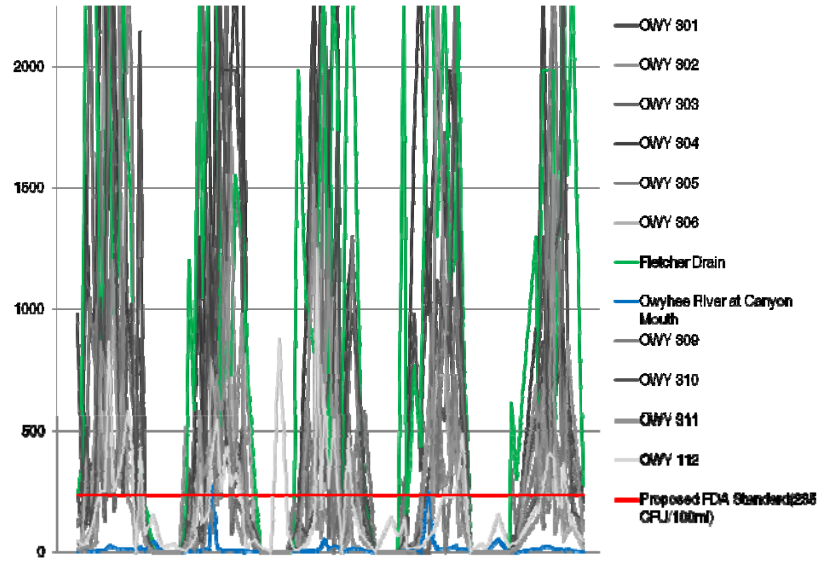

Figure 2. Variations in the *E. coli* levels are very large in the drains and other sampling sites in the Owyhee Basin.

We conclude that growers receiving water with a significant proportion of returned runoff cannot rely on receiving surface irrigation water that would meet the proposed rule throughout any irrigation season.

There are many ongoing efforts to improve irrigation systems in the Owyhee and Malheur River Basins. It might eventually be possible to redesign irrigation water delivery systems to deliver clean water to each farm.

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DEFICIT IRRIGATION OF GRAIN AND OILSEED CROPS

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INTRODUCTION

Deficit irrigation is an alternative to full irrigation where water is applied to crops in amounts that are anticipated to support transpiration at less than the maximum potential level. Under such circumstances, one might expect crop growth and yield to be less than that achieved under full irrigation. However, profitable production of certain crops can be achieved using deficit irrigation with considerable savings in water used or when the water supply is constrained. Deficit irrigation of field crops has been discussed in several research papers and reviews (English and Nuss, 1982; Musick and Walker, 1987; English et al., 1990; Musick, 1994; Fereres and Soriano, 2007; and Geerts and Raes, 2009).

Since the goal of most irrigation strategies is to optimize net economic returns under the constraints imposed by available resources, it might be wise when examining the deficit irrigation toolbox to allow some variance from the strictest definition of the term. For example, in some cases, net economic returns may be optimized by growing less land area with a less deficit irrigation strategy. For the purposes of this discussion, the topic of interest is coping with a deficient or marginal irrigation water supply that might have spatial and/or temporal aspects that must be considered. So, as the discussion moves forward, it will become evident that in some cases producers are truly applying less than the full irrigation amount to a parcel of land and in other cases the producer is trying to avoid deficit irrigation. Of course, in many cases the strategy may be a combination of mitigation and partial avoidance of deficit irrigation.

Although there are a number of ways to organize a deficit irrigation toolbox, here we will assume it is organized into these three sections:

- Agronomic management
- Irrigation management and macromanagement
- Irrigation system and land allocation management

As is the case with all good mechanics, producers facing deficit irrigation must be able to choose and utilize the best tools for the task immediately at hand and recognize when one or more additional tools are needed as the project progresses. Additionally, some of these deficit irrigation tools have temporal aspects, that is, they may be only available as adjustments for the dormant-season, in-season, or the long-term. The overall purpose of this paper is to illustrate the concepts of the tools in the tool box and not to exhaustively demonstrate how to use them. As some of the tools interact with each other, it may be useful to peruse the entire toolbox.

AGRONOMIC MANAGEMENT

A number of tools to mitigate and/or avoid deficit irrigation reside within the agronomic management section of the toolbox (Table 1). A few blank rows are provided to list additional tools that might be in your toolbox.

Table 1. Primary agronomic management tools to address deficit irrigation for grain and oilseed crops and their temporal availability.

Deficit Irrigation Management Tool	Temporal Availability		
	Dormant Season	In-Season	Long Term
Crop Selection	Yes	No	Yes
Crop Hybrid or Variety	Yes	No	Yes
Crop Rotations and Cropping Systems	Yes	No	Yes
Tillage and Residue Management	Yes	Sometimes	Yes
Nutrient Management	Yes	Yes	Yes
Plant Density and/or Row Spacing	Yes	No	Yes
Weed and Pest Management	Sometimes	Yes	Yes

Crop Selection

Crop selection has long been a tool to cope with deficit irrigation and/or a deficient irrigation water supply. Some crops are more sensitive to water stress than others and this may be particularly the situation for their economic yield (i.e., often the grain or oilseed yield rather than the biomass yield). However, one is well advised to consider the water sensitivity paradox; a water sensitive crop may have greater water productivity than a less water sensitive crop.

Deficit or limited irrigation presents a challenge for irrigators growing corn. Corn is sensitive to water stress at all stages of growth and grain yields are usually linearly related to water use from the dry matter threshold (the amount of water use where grain yield begins to accumulate) through the point of maximum yield. Deficit or limited irrigation of corn is difficult to implement successfully without reducing grain yields (Stewart et al. 1977; Musick and Dusek, 1980; Eck, 1986; Howell et al., 1989; Lamm et al., 1993; and Howell, et al., 1995). However, some strategies are more successful than others at maintaining corn yields under limited irrigation. Fully irrigated corn was found to be most profitable and having lowest risk of nine different water allocation schemes in Kansas (Lamm et al., 1993), but some other scenarios were profitable with some acceptance of risk. Grain sorghum is relatively tolerant of water stress and can be a good choice for deficit irrigation (Schneider and Howell, 1999; Schneider and Howell, 1995; Stewart et al., 1983), but is also less responsive to irrigation. Irrigated wheat can also be a good choice for deficit irrigation in the southern Great Plains (Schneider and Howell, 1997; Musick et al., 1994), but in some areas of northern Kansas, the response of wheat to irrigation has been minimal. One of the primary advantages of wheat in coping with deficit irrigation or an insufficient water supply in the US Great Plains is that the wheat growing season has less overall evaporative demand and that the season is temporally displaced from the other principal irrigated crops. Soybean is somewhat similar to corn in sensitivity to water stress, but typically requires a slightly smaller total amount of irrigation (Lamm et al., 2007). Sunflower has a considerably shorter growing period than corn and soybeans and requires less total irrigation, although all three crops' peak evapotranspiration rates are similar (Lamm et al., 2007). Summer crop yields were simulated for 42 years of actual weather data (1972-2013) from Colby, Kansas using 1 inch sprinkler irrigation events with an application efficiency of 95%. Irrigations were scheduled as needed according to the weather-based water budget but were limited to various irrigation capacities (Figure 1).

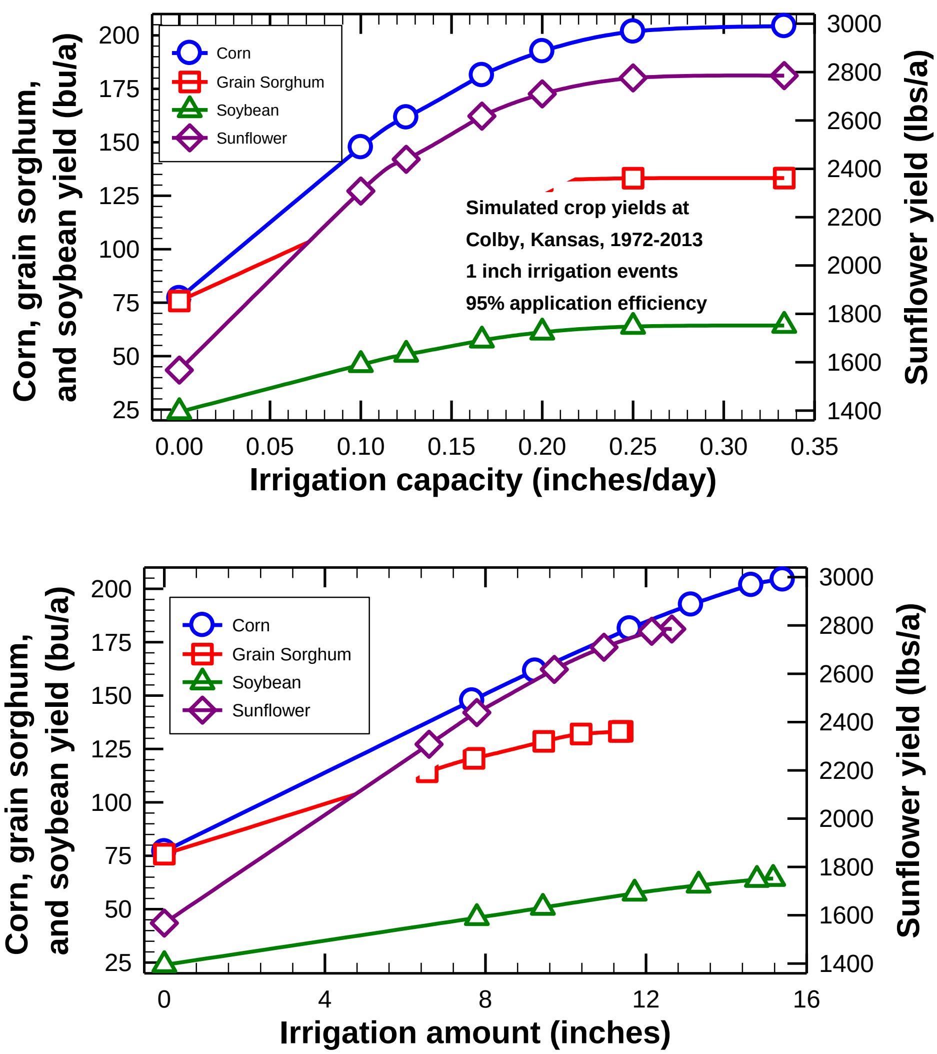

Figure 1. Simulated crop yields for corn, grain sorghum , soybean and sunflower as affected by irrigation capacity (top panel) and their corresponding response to total irrigation amount (bottom panel) at Colby, Kansas for 42 years (1972-2013) at an application efficiency of 95%. Note: These are average yield responses. Yield responses for individual years would vary considerably from those shown .

The graphs indicate that corn benefits from greater irrigation capacities and irrigation amounts, whereas grain sorghum yield plateaus at a lesser irrigation capacity and irrigation amount. Ultimately, crop selection depends on production costs and crop revenues. Irrigated land area devoted to grain sorghum in Kansas is actually decreasing and much of this is probably closely tied to economics. In a cropping simulation, similar to the one above, conducted for the period 1972-2005, it was concluded that dryland grain sorghum production was more profitable than any of irrigated grain sorghum scenarios (Lamm and Stone, 2005). However, sometimes irrigation capacity is shared across multiple crops to reduce the amount of risk. For example, maybe a portion of the land is grown in stress-tolerant grain sorghum to effectively increase the irrigation capacity for another portion of the land area growing water-sensitive corn. Of course, the economics of irrigated crop production vary greatly from year to year. Producers may wish to compare crop production as affected by the projected water supply using the Crop Water Allocator software developed by faculty at K-State (Klocke et al. 2006).

Irrigation water requirements of the various crops also vary temporally. Wheat was already mentioned as a possible crop that could allow shifting of irrigation water when the principal limitation is irrigation capacity. Similarly, a summer crop's peak water needs vary between months (Figure 2). Some producers may plant portions of their fields to sunflowers and only irrigate them when irrigation needs of other crops are declining.

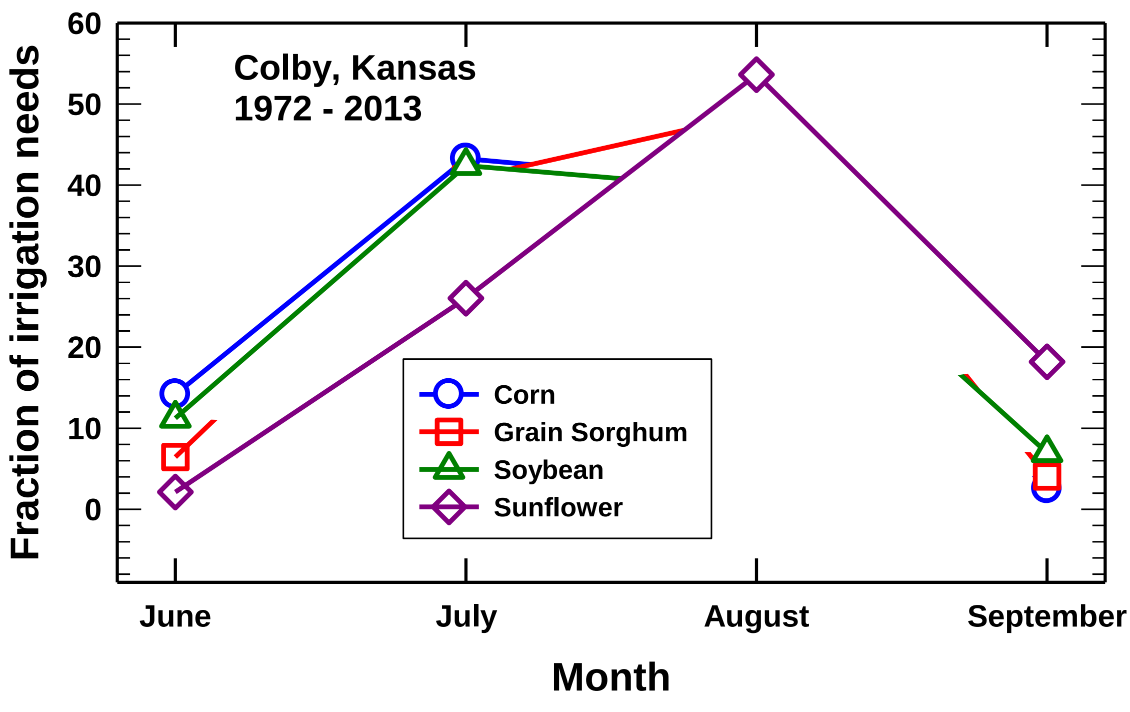

Figure 2. Average fraction of irrigation needs by month for corn, grain sorhum, soybean and sunflower at Colby, Kansas, 1972-2013.

Crop Hybrid or Variety

Some crop hybrids and varieties are more sensitive than others to water stress. Although it remains to be seen whether newer drought tolerant hybrids and varieties will actually result in decreased irrigation needs, it does appear that crop yield is better protected from water stress (e.g., kernel set on corn has improved over the years). Hybrid selection can result in greatly different yields even under the same full irrigation level. Maximum corn yield averaged 75 bu/acre greater (29% greater) than the minimum corn yield in crop performance tests conducted from 1996 through 2010 at the KSU Northwest Research-Extension Center at Colby, Kansas (Figure 3). Producers are advised to choose hybrids and varieties carefully so they can maximize their "crop per drop".

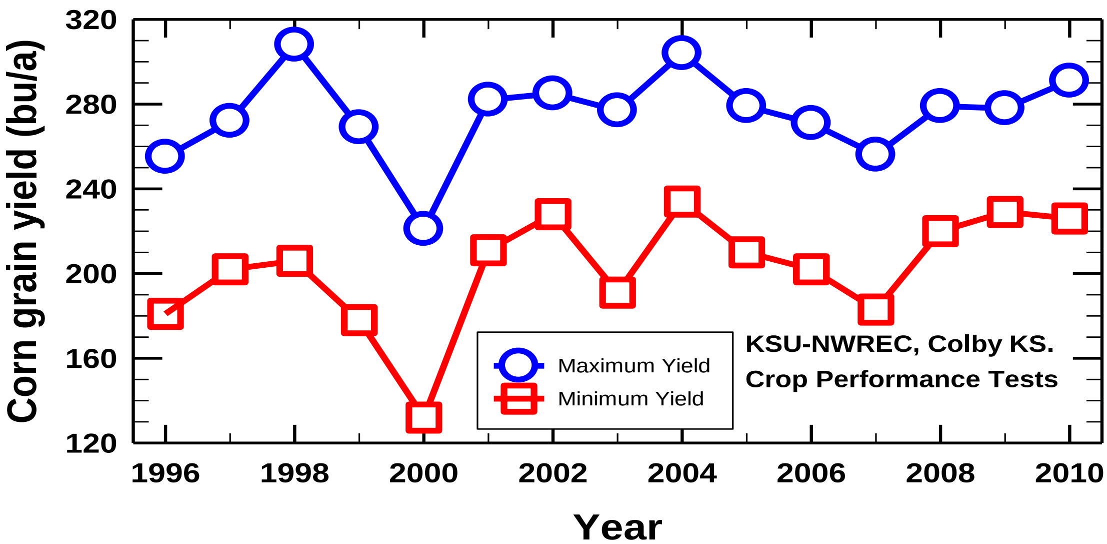

Figure 3. Variation in corn hybrid yields in KSU-NWREC performance tests during the period 1996 through 2010.

Crop Rotations and Cropping Systems

Previous crops leave behind residual soil assets, such as soil water, nutrients and increased organic matter, which can be used to offset application of these inputs and their associated costs in the coming year. For example, irrigated corn requires ample supplies of water and nutrients late in the cropping season to ensure optimum yields, so producers often choose sunflower as a rotational crop after corn in order to utilize the residual soil water and nutrients. In addition to the economic benefit, producers obtain environmental benefits of reduced usage of scarce water resources and reduced potential of nutrient leaching. Anecdotally, it has been observed that continuous corn is less common in west central Kansas than in northwest and southwest Kansas where the Ogallala saturated thickness is greater. Crop rotations also tend to reduce pest problems and to some extent weed pressures often associated with monocultures. Producers should consider crop rotation as a valuable tool to help manage a deficient or declining water supply.

Tillage and Residue Management

Residue management techniques such as no tillage or conservation tillage have long been accepted to be very effective tools for dryland water conservation in the Great Plains (Greb 1979). However, Klocke (2004) posited that residue management can be even more important in reducing soil water evaporation under irrigation. Reporting on an earlier two year study from Nebraska, soil water evaporation savings under a corn canopy with straw covering the soil averaged 0.2, 2.6 and 3.8 inches for dryland, limited irrigation, and full irrigation, respectively. In a later three year study in Kansas, Klocke et al. (2009) reported evaporative ratios (E/ETc) within a corn canopy averaging 0.30, 0.15 and 0.17 for bare soil, corn stover and wheat residue, respectively.

Strip tillage and no tillage had numerically greater corn grain yields (approximately 8% and 6% greater) than conventional tillage in all four years of a study conducted at the KSU Northwest Research-Extension Center, Colby Kansas (Lamm et al., 2009). The benefits of using strip tillage or no tillage increased as irrigation capacity became more deficit (Figure 4). Both strip tillage and no tillage should be considered as improved alternatives to conventional tillage, particularly when irrigation capacity is limited.

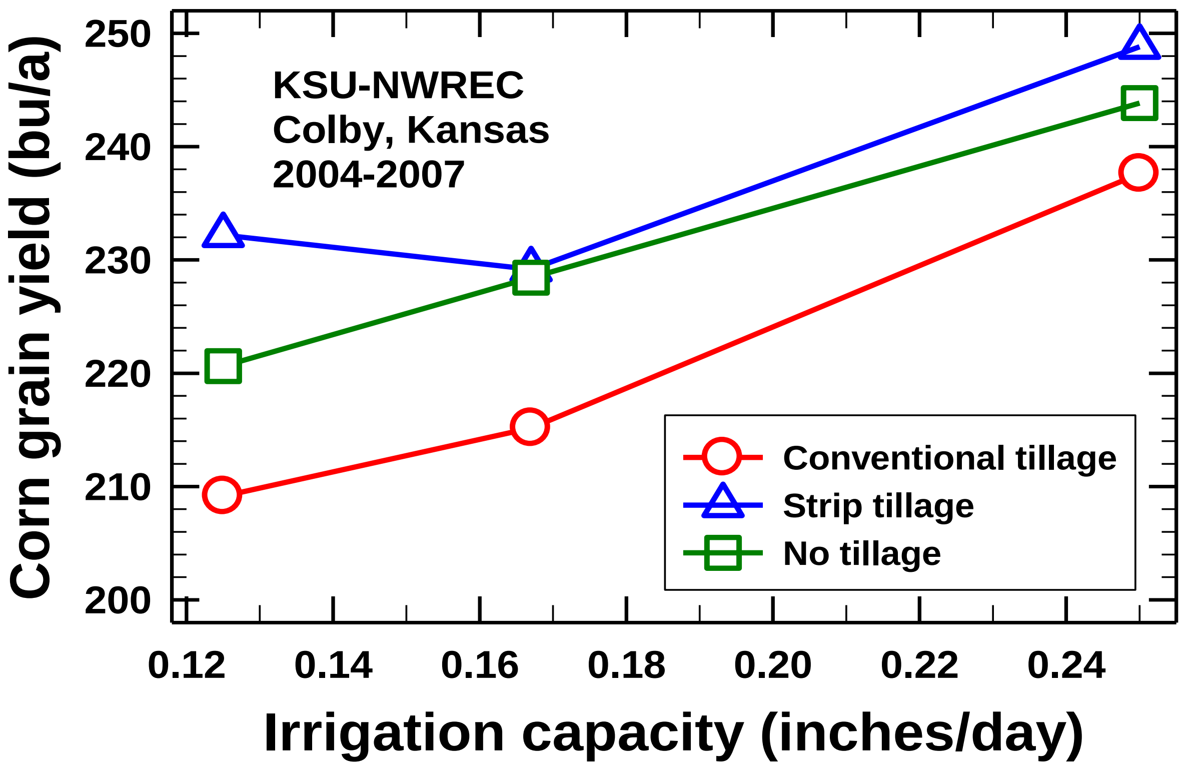

Figure 4. Corn grain yield as affected by tillage management and irrigation capacity in a four year study at Colby, Kansas.

Nutrient Management

Nutrient management can play an important role in increasing the effective use of irrigation and has been the subject of several review articles (Hatfield et al., 2001; Raven et al., 2004; Waraicha et al.,2011). Proper nutrient management increases plant growth and yield response allowing the crop to optimize use of available water supplies. Appropriate nitrogen fertilization nearly doubled corn yields without much increase in water use (Figure 5) in a two year study of subsurface drip-irrigated corn in western Kansas (Lamm et al., 2001).

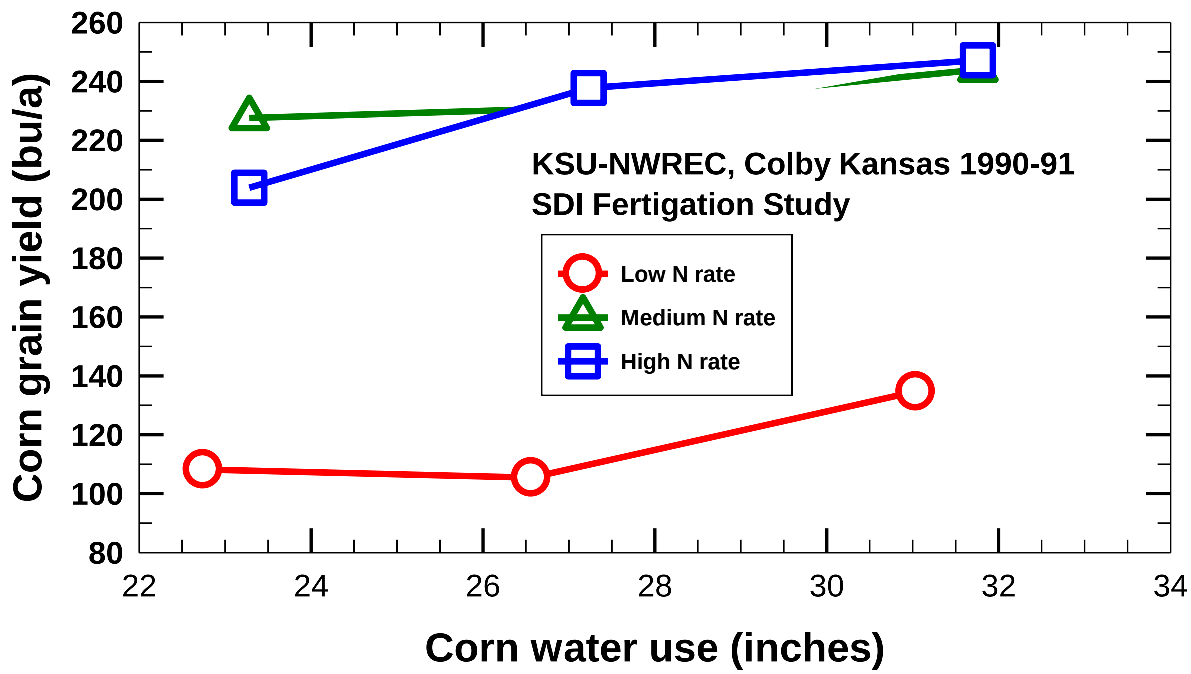

Figure 5. Corn yield as affected by nitrogen fertigation level and irrigation level in a subsurface drip irrigation study, Colby, Kansas, 1990-1991.

Plant Density and/or Row Spacing

Plant density or plant population can have an effect on water use and water use efficiency. When irrigation is severely deficit, it may be wise to reduce corn plant density to increase the probability of successful pollination and subsequent growth. As an example, Roozeboom et al. (2007) recommended corn plant densities for western Kansas of 14,000 to 20,000, 24,000 to 28,000, and 28,000 to 34,000 for dryland, limited irrigation, and full irrigation scenarios, respectively. After the corn crop reaches a leaf area index (LAI) of approximately 2.7, all of the incoming energy is captured (Rogers, 2007) and additional increases in LAI do not result in increased water use. As LAI for irrigated corn often reaches 5 or greater in the central Great Plains, plant density has to be greatly reduced to actually reduce corn water use. A key factor in managing corn plant density is assuring that pollination and kernel set are achieved. Establishing greater kernels/area often requires increased plant density. Medium to higher plant densities (30,000 to 33,000 plants/acre) generally resulted in greater corn yields (Figure 6) in a four year sprinkler-irrigated study in western Kansas (Lamm et al., 2009).

Adjustments to row spacing and planting geometry may be effective in reducing soil water evaporation losses in some cases for corn and grain sorghum in the central Great Plains. However, results to date suggest these adjustments are most likely to be advantageous only at the lower end of the range of crop yields (Olson and Roozeboom, 2012).

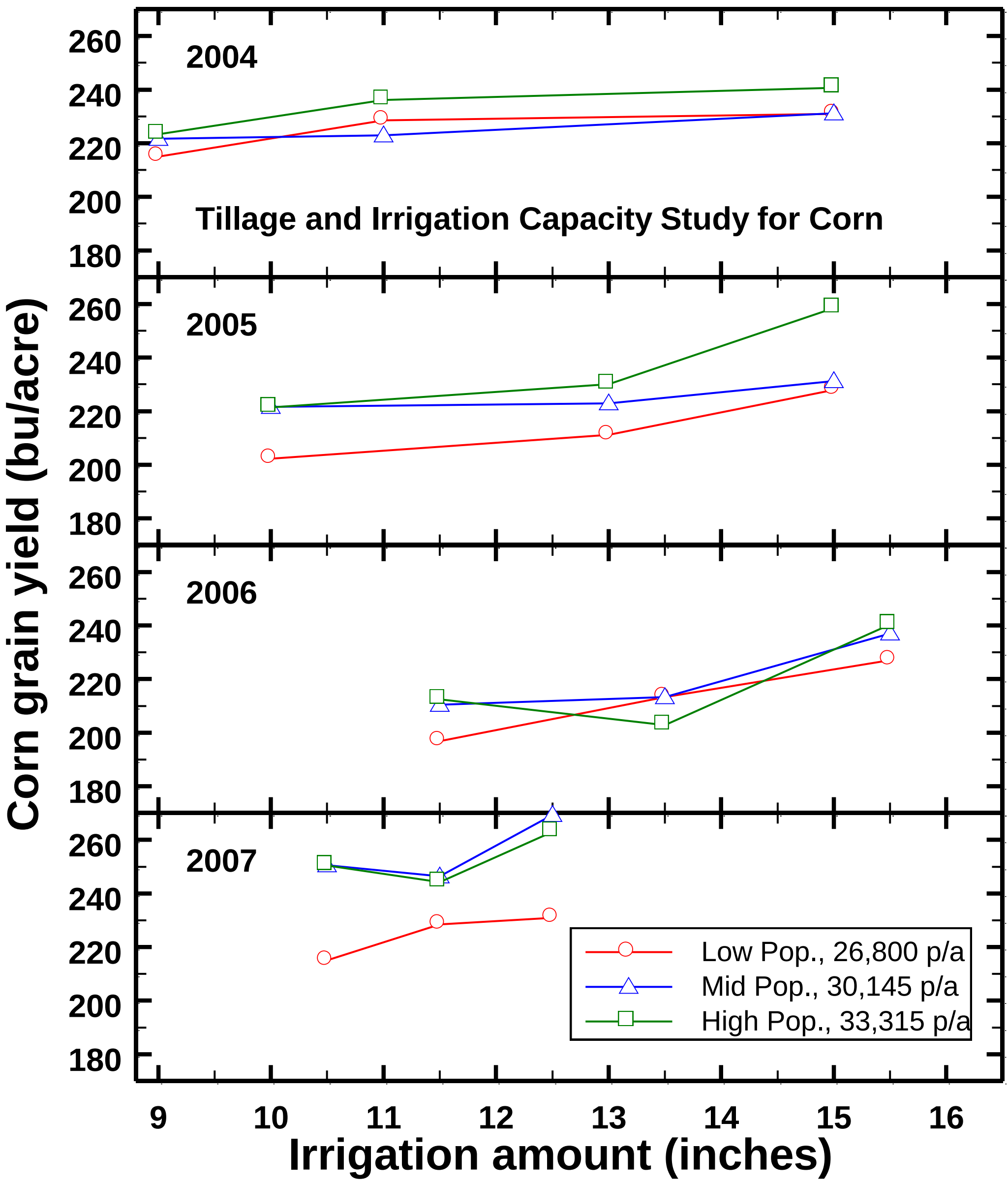

Figure 6. Corn grain yield as affected by irrigation amount and plant population, 2004-2007, KSU Northwest Research-Extension Center, Colby Kansas.

Weed and Pest Management

Weed and pest management is important in coping with deficit irrigation. Weeds may directly compete for water and nutrients and insect pests may interfere with plant growth and limit the crop's economic yield (i.e., usually the grain or oilseed). Some pests thrive under deficit irrigation conditions. For example, spider mites increase under the hotter and drier conditions associated with corn water stress. Spider mite damage that has occurred to corn's photosynthetic ability cannot be reversed even by substantial precipitation, although a reduction in the number of mites may occur. Producers coping with deficit irrigation should actively and consistently observe their crop fields managing weed and insect pests as they arise.

IRRIGATION MANAGEMENT AND MACROMANAGEMENT

A number of tools to mitigate and/or avoid deficit irrigation reside within the irrigation management and macromanagement section of the toolbox (Table 2). A few blank rows are provided to list additional tools that might be in your toolbox.

Table 2. Primary irrigation management and macromanagement tools to address deficit irrigation for grain and oilseed crops and their temporal availability.

Deficit Irrigation Management Tool	**Temporal Availability**		
	Dormant Season	**In-Season**	**Long Term**
Irrigation Scheduling	No	Yes	Yes
Timing of Irrigation	No	Yes	Yes
Initiation of the Irrigation Season	No	Yes	Yes
Termination of the Irrigation Season	No	Yes	Yes
Dormant Season Irrigation	Yes	No	Yes

Irrigation Scheduling

The most common definition of irrigation scheduling is simply the determination of when and how much water to apply. It is not uncommon to hear a central Great Plains producer indicate that they could not possibly consider irrigation scheduling because they always are in a deficit irrigation condition from the beginning to the end of the cropping season. Although this may seem intuitively correct, there are actually many years when the irrigation capacity even for marginal systems would not have to be fully utilized. Often early in the season, a deficit irrigation capacity may exceed the crop evapotranspiration rate. Simulated irrigation schedules for corn indicate that 80% or more of the maximum observed irrigation requirement is only required in 50 and 60% of the years for severely deficit irrigation capacities of 1 inch/8 days and 1 inch/10 days, respectively (Figure 7). Additionally, producers using irrigation scheduling can make better decisions about how to handle a triage situation (i.e., abandoning a portion of the field to better protect another portion).

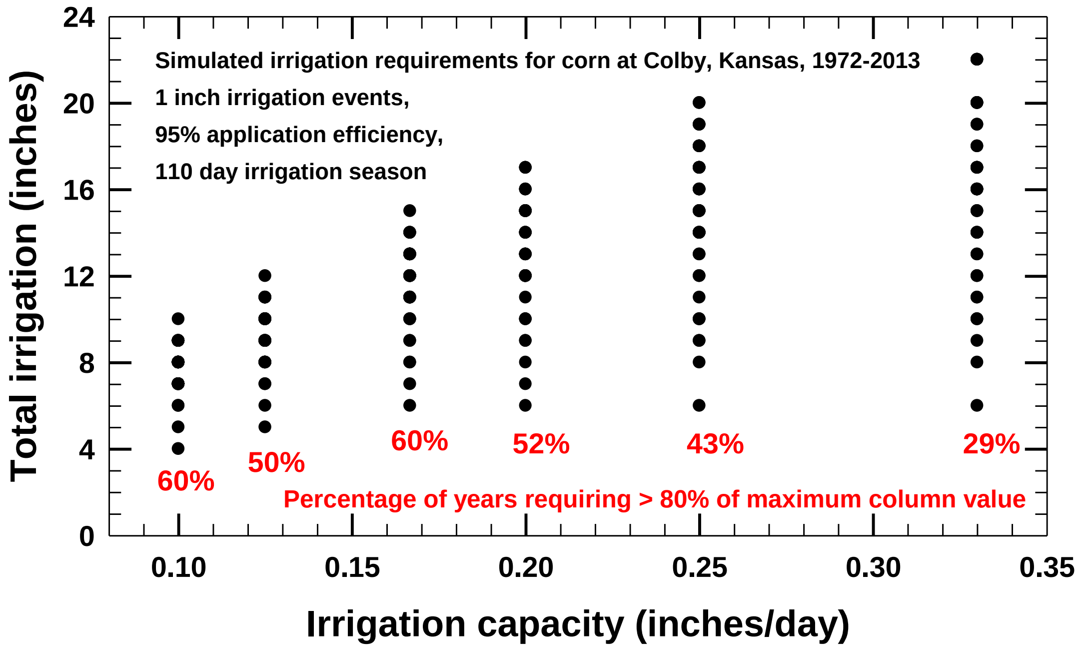

Figure 7. Simulated corn irrigation requirements for Colby, Kansas, 1972-2013 as possible with various irrigation capacities. Each indicated capacity has the 42 years shown, with some years lying on top of each other. The percentage of years requiring 80% or more of the maximum possible irrigation is shown below each capacity. As irrigation capacity increases, the percentage of years requiring 80% or more of the maximum irrigation tends to decrease.

Timing of Irrigation

Timing irrigation to the critical growth stages is a deficit irrigation strategy that can be effective in some situations. This technique may be most applicable when deficit irrigation is limited by total amount of irrigation. Examples of such scenarios would be an institutional constraint (e.g., 12 inches/year to a parcel of land) or when surface water availability constrains the application window (e.g., canal or reservoir releases). Timing of irrigation is less applicable for irrigation systems with marginal irrigation capacity and when stretched water resources limit adjustments to the irrigation event cycle. Since center pivot sprinklers irrigating from marginal groundwater wells are common in the central Great Plains landscape, timing of irrigation is a less applicable tool for many producers.

Initiation of the Irrigation Season

The determination of when to initiate the irrigation season is an irrigation macromanagement decision that can greatly affect the total irrigation amount. Ideally, the producer would delay irrigation as long as possible with the hope that timely precipitation would augment the crop water needs. A recent summary by Lamm and Aboukheira (2009) suggests that corn probably has more inherent ability to handle early season water stress than is practical to manage with the typical irrigation capacities that occur in the central Great Plains. Producers should use a good method of day-to-day irrigation scheduling during the pre-anthesis period. To a large extent, the information being used to make day-to-day irrigation scheduling decisions during the pre-anthesis period can also be used in making the macromanagement decision about when to start the irrigation season. This is because, even though the corn has considerable innate ability to tolerate early season water stress, most irrigation systems in the central Great Plains do not have the capacity (e.g., gpm/acre) or practical capability (e.g., run-off or deep percolation concerns) to replenish severely depleted soil water reserves as the season progresses to periods of greater irrigation needs (i.e., greater ETc and less precipitation). However, there is some flexibility in timing of irrigation events within the vegetative growth period. In years of lower evaporative demand, corn grown on this soil type (i.e., deep silt loam) in this region can extract greater amounts of soil water without detriment. Timeliness of irrigation and/or precipitation near anthesis appeared to be very important in establishing an adequate number of kernels/area which in this study was greatly correlated with final yield. Although, timing of irrigation is difficult with typical systems in the central Great Plains, the results suggest that monitoring soil water reserves and evaluating early season evaporative demand may allow for delays in initiating the irrigation season in some years.

Termination of the Irrigation Season

Irrigators in the central Great Plains sometimes terminate the corn irrigation season on a traditional date such as August 31 or Labor Day (First Monday in September) based on long term experience. However, there can be a large variation on when the irrigation season can be safely terminated (Table 3). A more scientific approach might be that season termination may be determined by comparing the anticipated soil water balance at crop maturity to the management allowable depletion (MAD) of the soil water within the root zone. Some publications say the MAD at crop maturity can be as high as 0.8 (Doorenbos and Kassam, 1979). Extension publications from the Central Great Plains often suggest limiting the MAD at season's end to 0.6 in the top 4 ft. of the soil profile (Rogers and Sothers, 1996). These values may need to be re-evaluated and perhaps further adjusted downward (smaller MAD value) based on a report by Lamm and Aboukheira (2009). They concluded that producers growing corn on deep silt loam soils in the central Great Plains should attempt to limit the management allowable depletion of available soil water in the top 8 ft. of the soil profile to 45%.

Table 3. Anthesis and physiological maturity dates and estimated irrigation season termination dates* to achieve specified percentage of maximum corn grain yield from studies examining post-anthesis corn water stress, KSU Northwest Research-Extension Center, Colby, Kansas, 1993-2008. Note: This table was created to show the fallacy of using a specific date to terminate the irrigation season. Note: Because there was not an unlimited number of irrigation termination dates, sometimes the date required for a specified percentage of maximum grain yield was the same as the date for the next higher percentage. After Lamm and Aboukheira (2009).

	Date of Anthesis	**Date of Maturity**	**Irrigation Season Termination Date For**		
			80% Max Yield	**90% Max Yield**	**MaxYield**
Average	**19-Jul**	**27-Sep**	**2-Aug**	**13-Aug**	**28-Aug**
Standard Dev.	**3 days**	**6 days**	**13 days**	**19 days**	**13 days**
Earliest	**12-Jul**	**14-Sep**	**17-Jul**	**17-Jul**	**12-Aug**
Latest	**24-Jul**	**10-Oct**	**14-Sep**	**21-Sep**	**21-Sep**

* *Estimated dates are based on the individual irrigation treatment dates from each of the different studies when the specified percentage of yield was exceeded.*

Dormant Season Irrigation.

Dormant season irrigation for crops such as corn has been advocated for the semi-arid Great Plains since the early 20th century, and the practice has been debated for nearly as long. Knorr (1914) found that at Scottsbluff, Nebraska, fall irrigation normally increased corn yields. Farrell and Aune (1917) found opposite results at Belle Fourche, South Dakota. Knapp (1919) recommended winter irrigation for most of western Kansas with the exception of sandy soils. The advantages of preseason irrigation (Musick and Lamm 1990) are: 1) provide water for seed germination; 2) delay the initiation of seasonal irrigation; 3) improve tillage and cultural practices associated with crop establishment; and 4) more fully utilize marginal irrigation systems on additional land area. The disadvantages are that it may: 1) increase production costs; 2) increase irrigation requirements; 3) lower overall irrigation efficiencies; and 4) lower soil temperatures. Lamm and Rogers (1985) developed an empirical model to aid in decisions concerning fall preseason irrigation for corn production in western Kansas. Available soil water at spring planting was functionally related to overwinter precipitation and initial available soil water in the fall. They concluded in most years, fall preseason irrigation for corn is not needed to recharge the soil profile in northwest Kansas, unless residual soil water remaining after corn harvest is excessively low. A recent survey of sprinkler irrigated corn fields in western Kansas has irrigated that on average, producers are leaving residual available soil water in the 8 ft. profile at approximately 60% of field capacity (Lamm et al., 2012). However, there was large variation between producers (Figure 8) emphasizing the need for each producer to evaluate their own field.

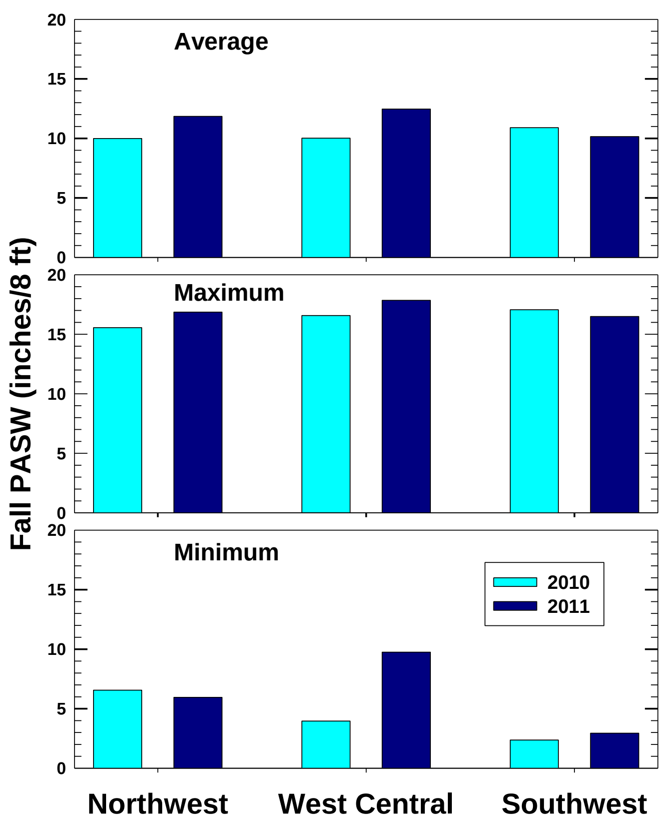

Figure 8. Effect of western Kansas region on average, maximum and minimum measured plant available soil water (PASW) in the 8 ft. soil profile in irrigated corn fields after harvest for the fall periods in 2010 and 2011.

In a recent field study (2006 to 2009) at the KSU Southwest Research Extension Center site near Tribune, Kansas, Schlegel et al. (2012) found preseason irrigation to be profitable for corn production with irrigation capacities ranging from 0.1 to 0.2 inches/day. Preseason irrigation increased grain yields an average of 16 bu/acre. The crop water productivity was not significantly affected by well capacity or preseason irrigation.

IRRIGATION SYSTEM AND LAND ALLOCATION MANAGEMENT

A number of tools to mitigate and/or avoid deficit irrigation reside within the irrigation system and land allocation management section of the toolbox (Table 4). A few blank rows are provided to list additional tools that might be in your toolbox.

Table 4. Primary irrigation system and land allocation management tools to address deficit irrigation for grain and oilseed crops and their temporal availability.

Deficit Irrigation Management Tool	Temporal Availability		
	Dormant Season	In-Season	Long Term
Irrigation System Selection	Yes	No	Yes
Managing Water Losses	Yes	Yes	Yes
Fine Tuning the Irrigation System	Yes	Yes	Yes
Land/Water Allocation	Yes	Possibly	Yes

Irrigation System Selection

No irrigation system can save water without good management imparted by the producer. However, some irrigation systems are easier to manage than others. Additionally, some systems although perhaps more complicated in design and number of components may inherently result in better water management. This concept can perhaps be considered as "purchasing improved management capabilities upfront". It has been said that one of the principal reasons that pressurized irrigation systems such as center pivot sprinklers (CP) and subsurface drip irrigation (SDI) are considered easier to manage than surface irrigation is because they remove the surface water transport phenomenon from the management. Many producers in the central Great Plains have converted from surface irrigation to center pivot sprinklers and a few are using SDI, all with a goal of better utilizing a limited and declining water resource. There is some evidence from the Great Plains that SDI may be able to stabilize yields at a greater level under deficit irrigation than CP assuming both are managed well (Lamm et al., 2010).

Managing Water Losses

Under deficit irrigation nearly all water losses result in yield reduction. It is common for the slope of the water production function for corn under deficit irrigation to be 12 to 15 bushels/inch and values of nearly 20 bushels/inch have been reported. Howell and Evett (2005) characterized the *"Big Three"* irrigation water losses as deep percolation, evaporation losses from soil, air, or plant, and irrigation runoff. An excellent tabular discussion of the management of these losses with irrigation systems, tillage management, and irrigation scheduling is provided by Howell and Evett (2005).

Fine Tuning the Irrigation System

There are some irrigation system adjustments that can be considered "fine tuning" the system but are never-the-less important to deficit irrigation management. This listing will not be exhaustive but may spur producers to look for that hidden extra capacity. Here are some system-related practical ways irrigators might use to effectively increase irrigation capacities for crop production (Lamm and Stone, 2005):

- Remove end guns or extra overhangs to reduce center pivot system irrigated area
- Clean groundwater well to see if irrigation capacity has declined due to encrustation
- Determine if pump in well is really appropriate for the irrigation system design and operating pressure.
- Replace, rework or repair worn pump

Land/Water Allocation

As it was stated in the second paragraph of this paper, deficit irrigation may be avoided by more closely matching the irrigated land area to the available water source. As economically painful as this may seem, this has always been the design criteria for irrigation systems in arid regions. Our semi-arid and more humid regions have just been able to successfully gamble with this criterion. Utilizing this management strategy might be economically painful because:

- it will likely reduce income in years with ample rainfall
- it may negatively affect land values if land is then considered non-irrigated
- it could reduce economic activity in the community as less inputs are bought and less outputs are sold.

However, if water resources and pumping rates continue to decline, the drought persists, and/or climate change imposes drier and warmer conditions, reducing the irrigated land area to avoid deficit irrigation may be the wisest decision. The previously discussed KSU-NWREC simulation modeling will be used to explore this topic further.

Corn yields were simulated for 42 years of weather data from Colby, KS. (1972-2013). Well-watered corn ETc ranged from 17.6 to 27.1 inches with average of 23.1 inches for these 42 years of record. In-season precipitation ranged from 3.1 to 21.2 inches with average of 11.8 inches. Full irrigation ranged from 6 to 22 inches with average of 15.7 inches. The marginal water productivity, WP (slope) was 17 bu/acre-in, which might result in an economic benefit of 65 to $85/acre-in. The yield threshold was 10.9 inches of ETc. Yields were simulated for irrigation capacities of full irrigation, 1 inch every 4, 6, 8 or 10 days and also for dryland conditions. As irrigation capacity decreases (Figure 9 and Table 5), corn yields decrease from the fully irrigated yields for some years and the variability in yields also increases. Typically, crop yields increase with increasing ETc, although this response is not a direct cause and effect. Rather in many cases, increased ETc is also reflecting better growing conditions (e.g., increased sunlight, warmer temperatures). As irrigation capacity decreases, the positive aspects of greater ETc on yield begins to disappear and the slope is relatively flat for an irrigation capacity of 1 inch/10 days (Figure 9). Under dryland conditions, corn yields typically decreased over the entire range of increasing ETc experienced at Colby, Kansas during this 42 year period.

Through reductions in irrigated land area, a producer could regain irrigation capacity, increase crop yield, and reduce their own risk. The short term marginal benefits to the individual producer should increase due to less input costs being associated with the non-irrigated acres. The Crop Water Allocator software (Klocke et al., 2006, accessible at http://www.bae.ksu.edu/mobileirrigationlab) may be a useful planning tool to producers in determining the optimum cropping scenario.

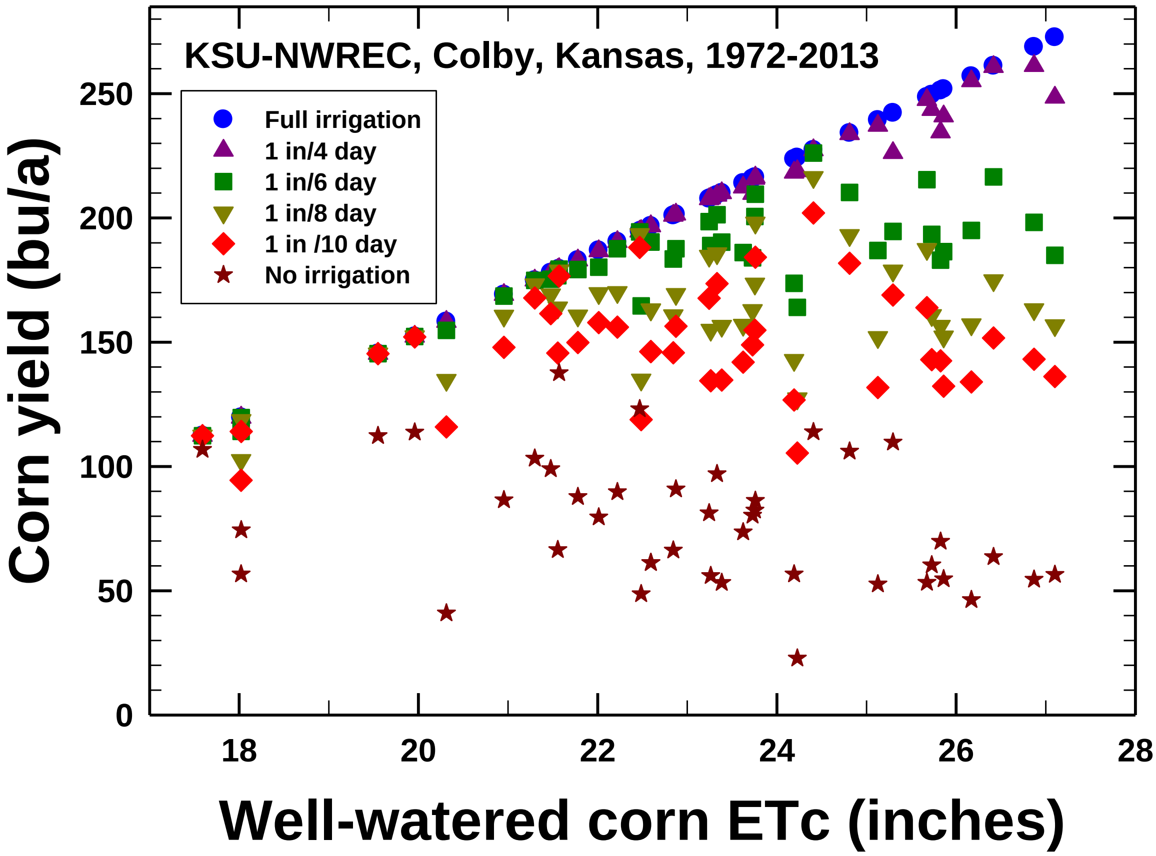

Figure 9. Simulated corn yields as a function of the calculated well-watered corn evapotranspiration for the 42 year period, 1972-2013, Colby, Kansas as affected by irrigation capacity.

Table 5. Effect of irrigation capacity on simulated corn yields for the 42-year period, 1972-2013, Colby, Kansas.

Irrigation capacity	Maximum yield	Mean Yield	Minimum Yield	Yield variation from full irrigation for maximum yield at maximum well-watered ETc
Full	273	204	112	-
1 inch/4 day	261	202	112	-4.4%
1 inch/6 day	226	181	112	-17.2%
1 inch/8 day	216	162	103	-20.9%
1 inch/10 day	202	148	94	-26.0%
Dryland	138	77	23	-49.5%

SUMMARY

As water supplies for irrigation become less available due to either hydrological or institutional constraints, irrigation producers and water managers face more uncertainty in production and increase economic risk. Increased uncertainty and risk can be mitigated through use of improved management practices or management tools. These tools can only be used effectively if producers know and understand which tool is appropriate to their situation.

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SDI FOR CORN PRODUCTION - A BRIEF REVIEW OF 25 YEARS OF KSU RESEARCH

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INTRODUCTION AND BRIEF HISTORY

Subsurface drip irrigation (SDI) technologies have been a part of irrigated agriculture since the 1960s, but have advanced at a more rapid pace during the last 25 years (Camp et al., 2000). In the summer of 1988, K-State Research and Extension issued an in-house request for proposals for new directions in research activity. A proposal entitled Sustaining Irrigated Agriculture in Kansas with Drip Irrigation was submitted by irrigation engineers Freddie Lamm, Harry Manges, and Dan Rogers and agricultural economist Mark Nelson. This project led by principal investigator Freddie Lamm, KSU Northwest Research-Extension Center (NWREC), Colby, was funded for the total sum of $89,260. This project financed the initial development of the NWREC SDI system that was expressly designed for research. In March of 1989, the first driplines were installed on a 3 acre study site which has 23 separately controlled plots. This site has been in continuous use in SDI corn production since that time, being initially used for a 3-year study of SDI water requirements for corn. In addition, it is considered to be a benchmark area that is also being monitored annually for system performance to determine SDI longevity. Currently, the NWREC SDI research site is comprised of 19 acres and 201 different research plots and is one of the largest facilities devoted expressly to small-plot row crop research in the world. Additional history is provided by Lamm et al., 2011.

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

CONSERVING WATER AND/OR INCREASING CROP WATER PRODUCTIVITY WITH SDI SYSTEMS

WATER CONSERVATION CONCEPTS WITH SDI

When properly managed, there is no need for any type of irrigation system to waste water. Using a similar train of thought, no irrigation system can save water. Only a human action or decision can actually save water. Howell and Evett (2005) correctly point out that difficulties can arise if incompatible temporal and spatial scales are used in statements about effective water use. For example, water savings from a reduction in deep percolation may be inconsequential if the temporal scale is large enough to allow return to the aquifer. Similarly, reduction of runoff is not a water savings on a large spatial scale when the runoff can be reused at a downstream location in the basin. The debate over the proper use of water conservation terms has and will continue to be the topic of many publications and presentations. Rather than go into this debate any further, discussion here will be limited to improvements in water usage at the farm level that can be obtained on a real-time basis. This temporal and spatial scale is highly relevant to the farmer in an economic sense, but is also relevant to society through stabilization of farm income and through its multiplying effect in the overall economy. Whether the water is actually conserved or extended to another beneficial use will not be the topic of this discussion.

Subsurface drip irrigation (SDI) applies water below the soil surface to the crop root zone through small emission points (emitters) that are in a series of plastic lines typically spaced between alternate pairs of crop rows (Figure 1). This method of irrigation can be used for small, frequent, just-in-time irrigation applications directly to crop root system.

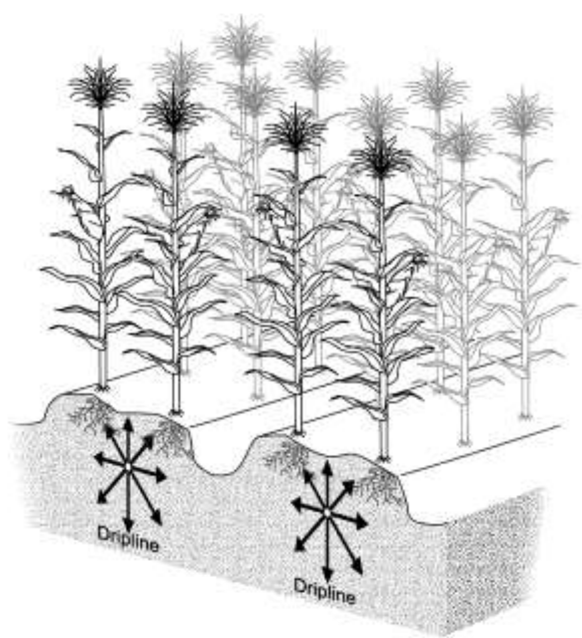

Figure 1. Alternate row/bed 5 ft SDI dripline spacing for corn rows spaced at 2.5 ft. Each plant row is approximately 1.25 ft from the nearest dripline and has equal opportunity to the applied water.

The primary ways that SDI can potentially increase crop water productivity and/or save water are:

- Reduction and/or elimination of deep drainage, irrigation runoff, and water evaporation
- Improved infiltration, storage, and use of precipitation
- Improved in-field uniformity and targeting of water within plant root zone
- Improved crop health, growth, yield, and quality.

GENERAL EFFECT OF IRRIGATION LEVEL ON CORN YIELDS AND WATER PRODUCTIVITY

The results from four SDI studies on corn water use were summarized by Lamm, 2005. Relative corn yield reached a plateau region at about 80% of full irrigation and continued to remain at that level to about 130% of full irrigation (Figure 2). Yield variation as calculated from the regression equation for this plateau region is less than 5% and would not be considered significantly different. The similarity of results for all four studies is encouraging because the later studies included the effect of the four extreme drought years of 2000 through 2003. An examination of water productivity (WP) for the same four studies indicates that water productivity plateaus for levels of irrigation ranging from 61% to 109% of full irrigation with less than 5% variation in WP (Figure 3). The greatest WP occurs at an irrigation level of approximately 82% of full irrigation. This value agrees with results summarized by Howell, (2001) for multiple types of irrigation systems.

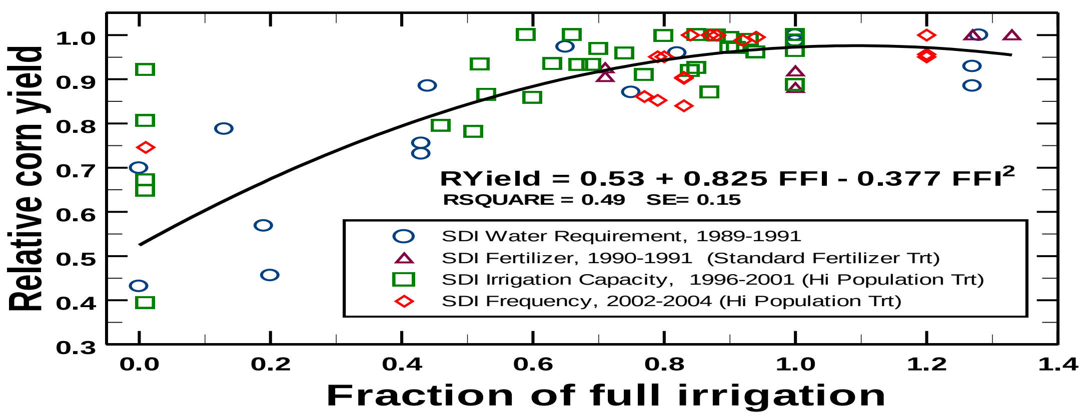

Figure 2. Relative corn grain yield for a given SDI research study and year as related to the fraction of full irrigation, KSU Northwest Research-Extension Center, Colby, Kansas.

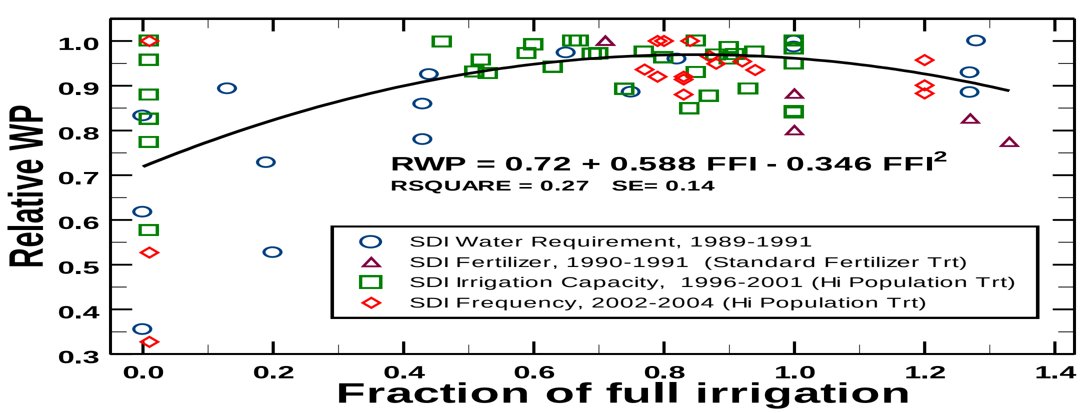

Figure 3. Relative water use productivity (WP) of corn for a given SDI research study and year as related to the fraction of full irrigation, Colby, Kansas.

The greatest WP (82% of full irrigation) also occurred in the plateau region of greatest corn yield (80 to 130% of full irrigation). This suggests that both water- and economically-efficient production can be obtained with SDI levels of approximately 80% of full irrigation across a wide range of weather conditions on the soils in this region. Some of the stability in corn yield and water productivity across this range of irrigation levels may be explained by how deep percolation is managed and by how soil water is "mined" with SDI on this soil type and in this climatic region. These aspects are discussed in the next two sections.

MINIMIZATION OF DEEP PERCOLATION WITH SDI

Deep percolation can occur with SDI if design and management considerations such as soil characteristics, dripline spacing, dripline depth, and irrigation levels are not taken into account in operational strategies (Darusman et al., 1997 a and b; and Lamm and Trooien, 2003). However, with proper management deep percolation can be minimized with SDI. Appreciable reductions in deep percolation (7% of full irrigation amount) were obtained by Lamm et al., (1995) when the corn irrigation level was reduced to approximately 74% of full irrigation with SDI without affecting actual corn water use (Figure 4). That is, corn water needs were more closely matched with smaller and timelier irrigation events.

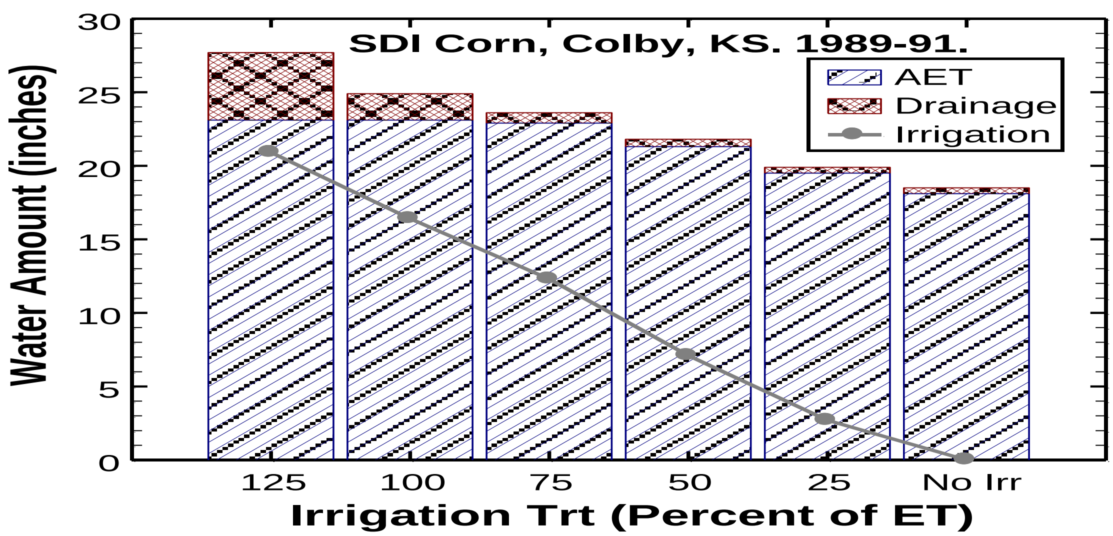

Figure 4. Calculated evapotranspiration (AET) and seasonal drainage as related to irrigation treatment in a SDI water requirement study, Colby, Kansas, 1989-1991.

"MINING" OF SOIL WATER WITH SDI

In a study from 1997 through 2000, corn was grown with SDI under 6 different irrigation capacities (0, 0.10, 0.13, 0.17, 0.20 or 0.25 inches/day) and 4 different plant populations (33100 29,900, 26800, or 23700 plants/acre). The study (Lamm and Trooien, 2001) indicated even small amounts of daily SDI can benefit corn production. Daily in-season application amounts of 0.10 inches/day resulted in corn yields of 253, 263, 236, and 201 bu/acre for the largest plant population in 1997, 1998, 1999, and 2000, respectively. Even in the extreme drought year of 2000, the 0.10 inches/day capacity resulted in corn yields twice that of the non-irrigated treatment and 78% of the maximum yield (Figure 5).

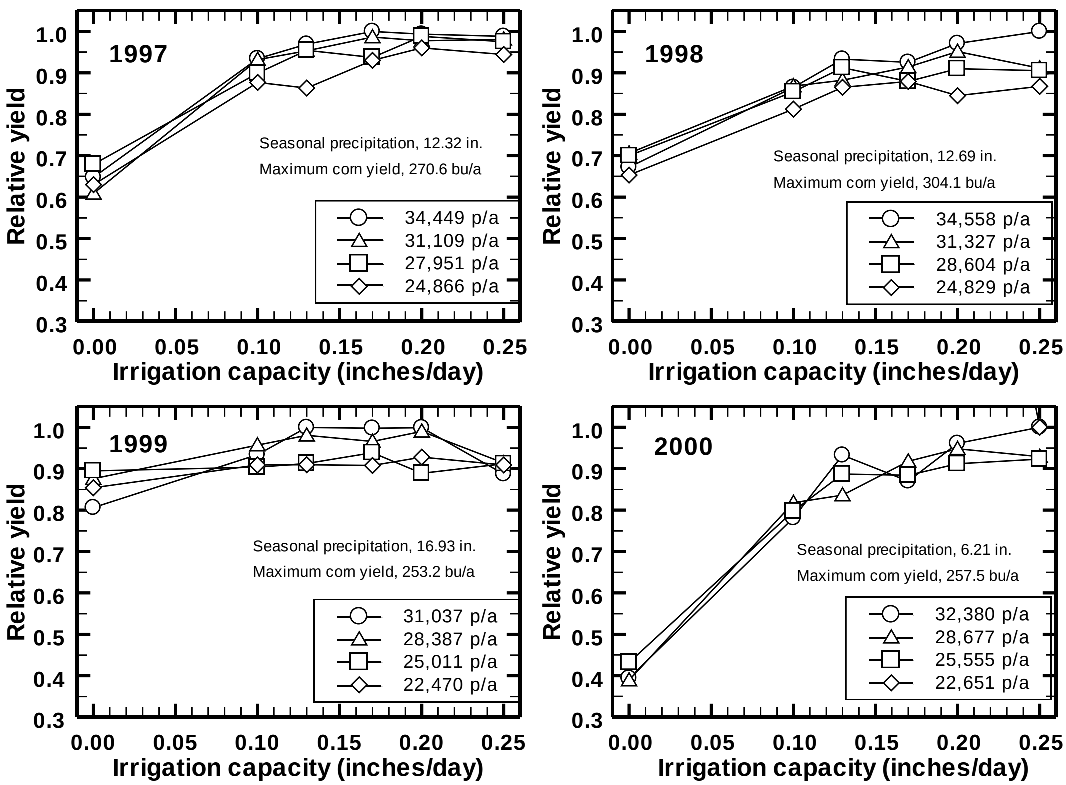

Figure 5. Relative corn grain yield as affected by daily SDI capacity and plant population. Note: Each annual panel indicates seasonal precipitation and maximum corn grain yield.

Examination of soil water profiles under these SDI capacities shows some distinctive grouping of adequately and inadequately irrigated treatments (Figure6). A possible rationale to explain the grouping is that the upper three treatments may group together because the range of 0.17 to 0.25 inches/day is sufficient to provide a large enough portion of the daily soil water needs. Even in the drier years, there are a few opportunities to shut off irrigation for the 0.20 - 0.25 inches/day treatments. This would allow these treatments to be closer to the effective value of 0.17 inches/day, which is a capacity sufficient to reach the yield plateaus shown in Figure 5. The 0.25 inches/day irrigation capacity is approximately the long term full irrigation requirement for northwest Kansas for corn using other irrigation methods. The higher efficiency, daily irrigation may allow the SDI to be more effective than other irrigation methods.

The lower three treatment may group together for almost the opposite reason. Available soil water reserves become depleted to a large extent and the corn crop begins to shut-down plant processes that use water. This shut-down tends to reduce grain yields depending on the severity and length of the water stress period. The fact that the 0.10 and 0.13 inches/day treatments obtain respectable corn yield increases over the nonirrigated control may be a good indication of how well this balancing of water use/water conservation is being handled by the daily infusion of at least some irrigation water. The grouping of the upper three treatments suggests that an irrigation capacity of 0.17 inches/day might be an adequate irrigation capacity if the producer has the desire to allocate water to an optimum land area. It should be noted that this limited irrigation capacity would not be sufficient on coarser-textured sandy soils which have limited water holding capacity.

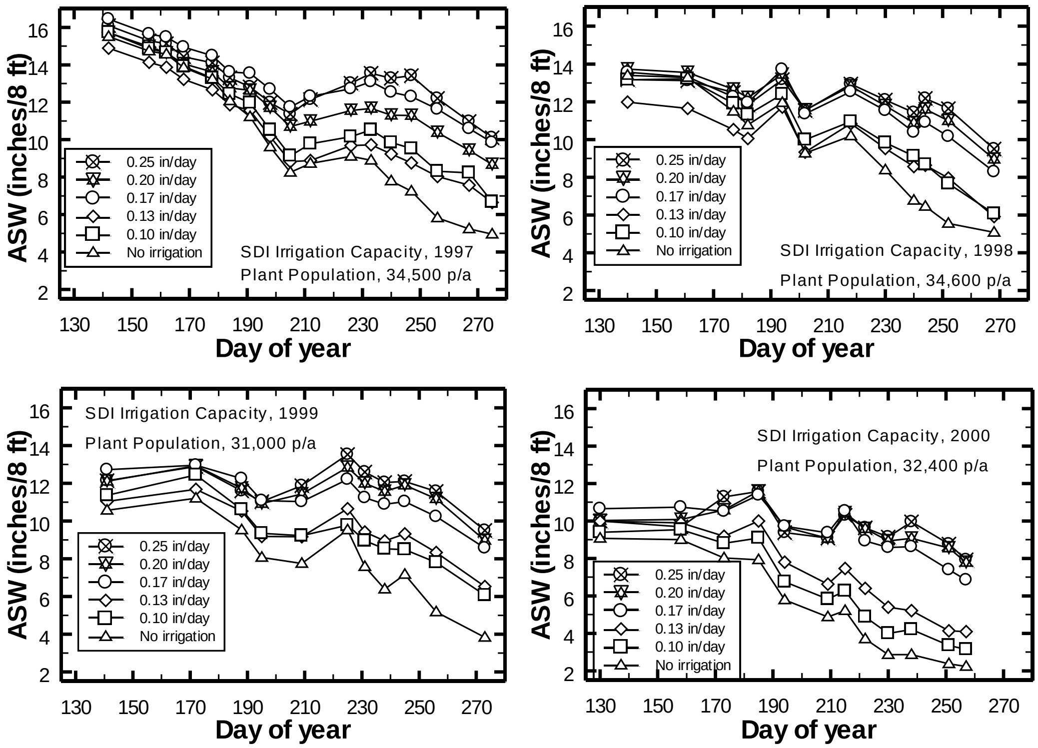

Figure 6. Progression of the available soil water in an 8 ft. profile as affected by daily SDI capacity for the highest plant population treatment.

Does SDI really increase crop per drop?

There is growing evidence from our K-State studies (Figure 7) and others in the Great Plains that SDI can stabilize yields at a greater level than alternative irrigation systems when deficit irrigated (Lamm et al., 2012).

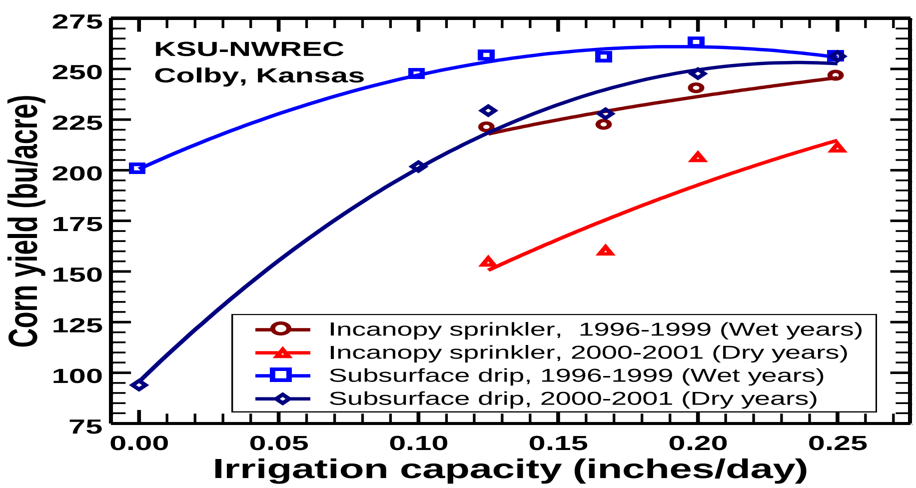

Figure 7. Corn yields for SDI and incanopy sprinkler irrigation in wet years and dry years at Colby, Kansas. Note: Results are from different but similar studies, so these are not statistical differences.

Although we believe this is true for most crop years, we have found that SDI sometimes experiences some reduction in kernel set in extremely dry years (Lamm, 2004). Research is continuing to examine this issue in search of a solution.

PROTECTING WATER QUALITY WITH SDI SYSTEMS

Properly designed SDI systems have a high degree of uniformity and can apply small frequent irrigation applications, and provide an excellent opportunity to better manage nitrogen fertilization with these systems. Injecting small amounts of nitrogen solution into the irrigation water can spoon-feed the crop just-in-time (i.e., nearer the point of actual crop need), while minimizing the pool of nitrogen in the soil that could be available for percolation into the groundwater.

COMPARISON OF PRE-PLANT BROADCAST APPLIED NITROGEN AND SDI FERTIGATION

In an early study at Colby, 1990-1991, results indicated that nitrogen applied with SDI redistributed differently in the soil profile than surface-applied preplant N (Lamm et al., 2001). Although corn yields were similar between the two fertilization methods, there was greater residual soil-N for the SDI fertigation (Figure 8).

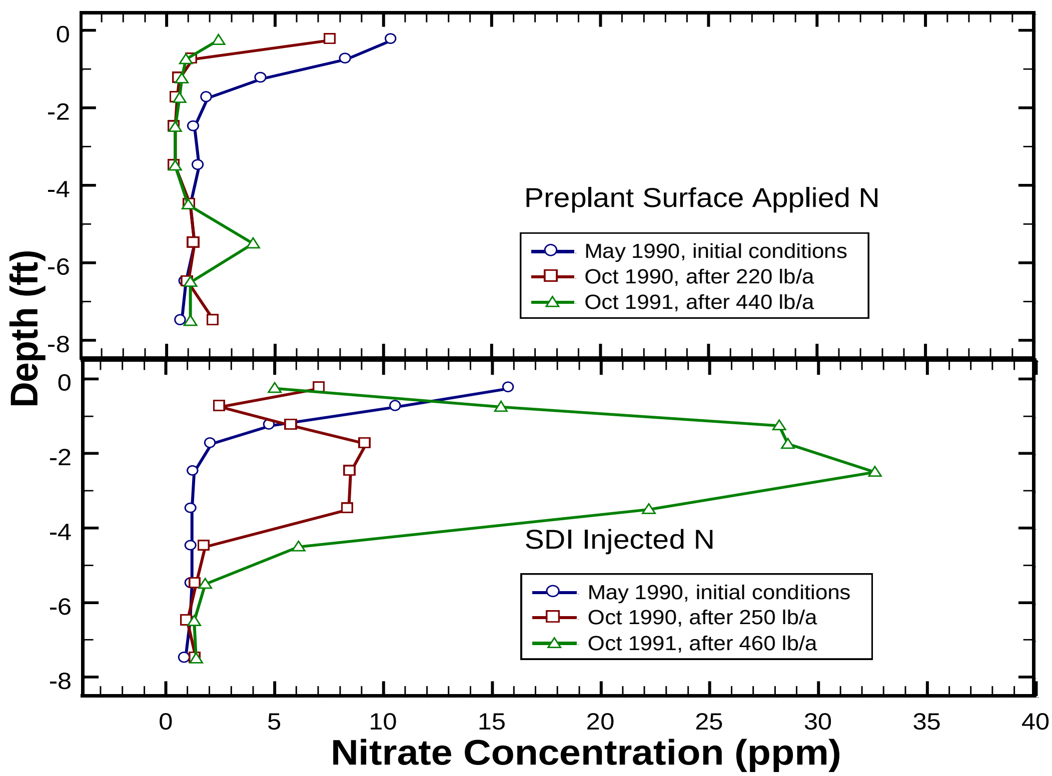

Figure 8. Nitrate concentrations in the soil profile for preplant surface-applied and SDI injected nitrogen treatments, KSU Northwest Research-Extension Center, Colby, Kansas, 1990-91. Data is for selected nitrogen fertilizer rate treatments with full irrigation (100% of AET).

The additional in-season fertigation allowed for healthier and more vigorous plants that were better able to utilize soil water. The results suggest that a large portion of the applied N could be delayed until weekly injections begin with the first irrigation provided there is sufficient residual soil N available for early growth. In both years, nearly all of the residual nitrate nitrogen measured after corn harvest was located in the upper 12 inches of the soil profile for the preplant surface-applied nitrogen treatments, regardless of irrigation level. In contrast, nitrate concentrations increased with increasing levels of nitrogen injected with SDI and migrated deeper in the soil profile with increased irrigation (Figure 8). This lead to a study to determine if SDI fertigation N needs could be lowered and still retain excellent yields.

DEVELOPMENT OF BEST MANAGEMENT PRACTICE FOR SDI N FERTIGATION OF CORN

A follow-up four year study was conducted at the KSU Northwest Research-Extension Center at Colby, Kansas on a deep Keith silt loam soil to develop a Best Management Practice (BMP) for nitrogen fertigation for corn using SDI (Lamm et al., 2004). Residual ammonium- and nitrate-nitrogen levels in the soil profile, corn yields, apparent nitrogen uptake (ANU) and water productivity (WP) were utilized as criteria for evaluating six different nitrogen fertigation rates, 0, 80, 120, 160, 200, and 240 lbs N/a. The final BMP was a nitrogen fertigation level of 160 lbs N/a with other non-fertigation applications bringing the total applied nitrogen to approximately 190 lbs N/a (Lamm et. al., 2004). The BMP also states that irrigation is to be scheduled and limited to replace approximately 75% of ET. Corn yield, ANU, and WP all plateaued at the same level of total applied nitrogen which corresponded to the 160 lbs N/a nitrogen fertigation rate (Figure 9). Average yields for the 160 lbs N/a nitrogen fertigation rate was 213 bu/a. Corn yield to ANU ratio for the 160 lbs N/a nitrogen fertigation rate was high at 53:1 (lbs corn grain/lbs N whole plant uptake). The results emphasize that high-yielding corn production also can be environmentally sound and efficient in nutrient and water use.

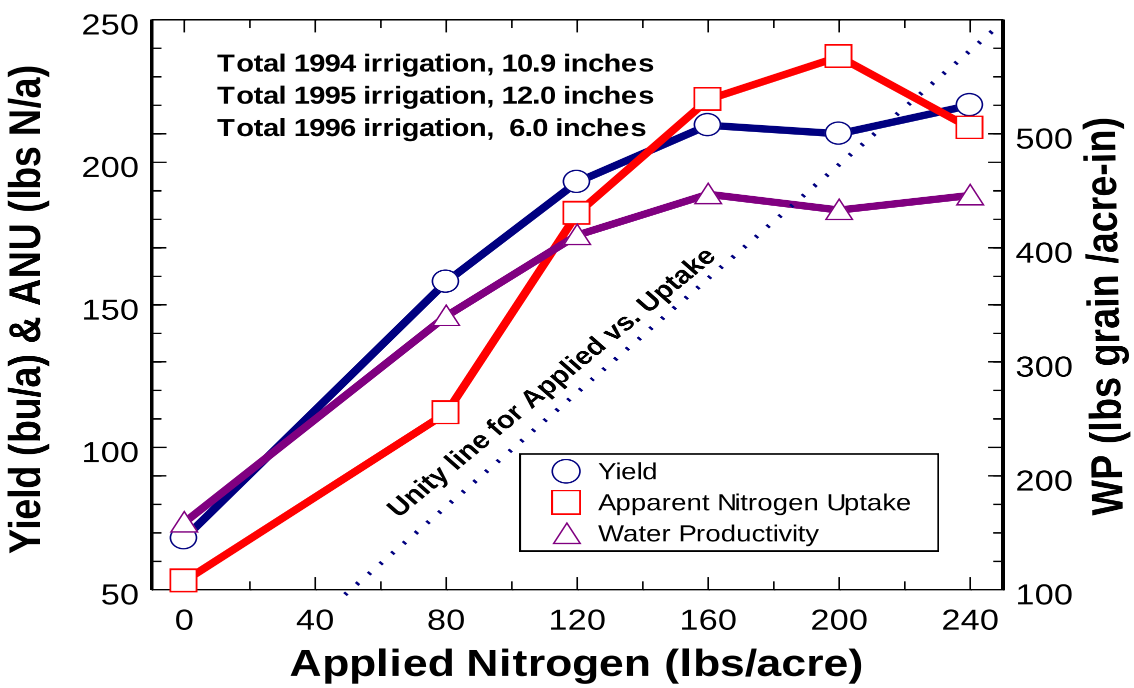

Figure 9. Average (1994-96) corn yield, apparent nitrogen uptake in the above-ground biomass, and water productivity as related to the total applied nitrogen (preseason amount, starter fertilizer, fertigation, and the naturally occurring N in the irrigation water). Total applied nitrogen exceeded fertigation applied nitrogen by 30 lb/acre.

After 4 years of continuous application of the fertigation treatments (Figure 10), nitrate-N levels in the soil were increasing and moving downward when the fertigation rate exceeded 160 lb N/a (i.e., equivalent to 190 lbs N/a total applications from all sources).

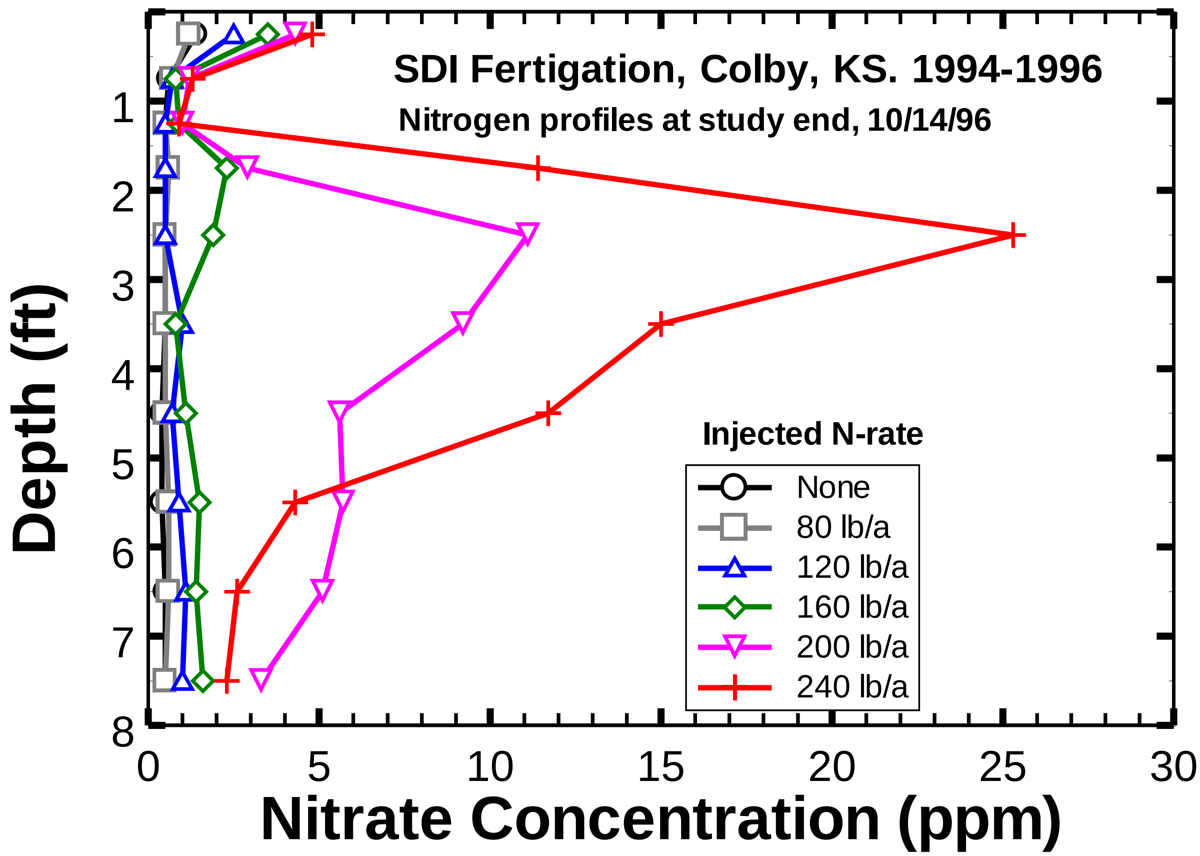

Figure 10. Nitrate concentrations within the 8 ft soil profile as affected by SDI fertigation N rate after four years of continuous application, KSU Northwest Research-Extension Center, Colby Kansas.

TIMING OF NITROGEN FERTIGATION AS AFFECTED BY IRRIGATION CAPACITY

A study was conducted at the KSU Northwest Research-Extension Center at Colby, Kansas in 2010 and 2012 to examine subsurface drip irrigation (SDI) capacity and nitrogen fertigation timing on corn production (Lamm and Schlegel, 2013). Targeted SDI N fertigation events at 3 specific early season growth stages (V5, V9 or VT) were compared under 2 levels of irrigation (0.25 inches/day or 0.25 inches/2 days). Treatment effects were evaluated in terms of corn yield components, crop water use, and crop water productivity. Overall, corn grain yields, kernels/area, kernel mass, and water productivity generally were numerically greater when nitrogen fertigation timing was earlier in the crop growth and development (Table 1). The greatest corn grain yield and greatest water productivity was obtained in 2010 by the fully irrigated treatment receiving supplement nitrogen fertigation at the V6 growth stage. The lack of supplemental nitrogen fertigation greatly reduced grain yields and water productivity in both years. Conjunctive management of both irrigation and inseason N fertigation are important for corn production with SDI.

Table 1. Corn yield component, biomass and water use results from a subsurface drip irrigated corn study as affected by irrigation capacity and nitrogen fertigation timing, KSU Northwest Research-Extension Center, Colby Kansas, 2010 and 2012.

Irrigation capacity	N-Fertigation timing	Yield, bu/a	Kernels/area, Million Kernel/acre	Kernel mass, mg	Biomass, lb/a	Water use, in	WP, lb/a-in
Crop year, 2010							
0.25 in/d	None	155.0	14.11	279	14219	23.08	376
	V6	277.0	18.71	376	22003	23.62	657
	V9	237.0	17.82	336	19143	23.33	569
	VT	239.2	17.60	345	19365	23.66	566
Mean 0.25 in/d	V6 thru V9	251.1	18.04	353	20170	23.54	597
0.25 in/2 d	V6	241.4	19.00	323	16493	21.97	615
	V9	238.2	18.68	324	18869	21.72	614
	VT	239.5	17.55	347	17070	21.52	624
Mean 0.25 in/2 d	V6 thru V9	239.7	18.41	331	17477	21.73	617
Crop year, 2012							
0.25 in/d	None	185.0	14.78	318	12150	29.13	358
	V6	246.5	17.69	354	20152	28.33	499
	V9	235.6	17.14	349	17826	27.86	477
	VT	248.1	17.92	352	20551	26.09	536
Mean 0.25 in/d	V6 thru V9	243.4	17.58	351	19510	27.43	504
0.25 in/2 d	V6	218.8	15.74	353	18431	19.29	644
	V9	220.9	16.05	349	17635	22.27	554
	VT	224.2	16.08	354	15058	20.99	609
Mean 0.25 in/2 d	V6 thru V9	221.3	15.96	352	17041	20.85	602
Mean, both years							
0.25 in/d	None	170.0	14.44	299	13184	26.11	367
	V6	261.7	18.20	365	21077	25.98	578
	V9	236.3	17.48	343	18485	25.59	523
	VT	243.7	17.76	348	19958	24.87	551
Mean 0.25 in/d	V6 thru V9	247.2	17.81	352	19840	25.48	551
0.25 in/2 d	V6	230.1	17.37	338	17462	20.63	629
	V9	229.5	17.37	337	18252	22.00	584
	VT	231.8	16.81	351	16064	21.25	616
Mean 0.25 in/2 d	V6 thru V9	230.5	17.18	342	17259	21.29	610

ACHIEVING THE GOALS OF CONJUNCTIVE MANAGEMENT OF WATER AND NUTRIENTS WITH SDI

When water and nutrients are highly managed for greatest effectiveness, there can be less margin of error. It is important that producers are diligent in observing the corn growth and development and in monitoring the SDI system. A couple of example cases will illustrate the need for this diligence.

Under drought conditions preplant surface-applied N can become positionally unavailable to the crop because of dry surface layers and no root exploration (Figure 11). One should immediately apply N through the SDI system to remedy this nitrogen deficiency when it is observed. The preplant nitrogen, although unavailable under these conditions, can be recovered and utilized later in the season or by future crops once the drought ends.

Water application with deeper SDI systems is largely unobserved. A problem as simple as a broken solenoid wire on a zone water valve can prevent irrigation (Figure 12). Producers should verify through flowrate and pressure that the applied irrigation is reaching the target. Soil water or plant water stress sensors can also be used to augment these observations.

Figure 11. SDI corn field experiencing N stress due to dry surface soil conditions despite having abundant nitrogen reserves in the soil surface layers.

Figure 12. A broken solenoid wire on a zone valve might go unobserved if producers do not monitor there system flowrate and pressure.

CONCLUSIONS

Research progress has been steady since 1989. Much of K-State's SDI research is summarized at the website, SDI in the Great Plains at http://www.ksre.ksu.edu/sdi/. Irrigators are watching the results of K-State closely. Some irrigators have begun to experiment with the technology and most appear happy with the results they are obtaining. SDI can be a viable irrigation system option for corn production, enhancing the opportunities for wise use of limited water resources and also in protecting water quality.

ACKNOWLEDGEMENTS

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SUCCESSFUL SDI - ADDRESSING THE ESSENTIAL ISSUES

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INTRODUCTION

Overall, SDI systems have been successful in the Great Plains region despite minor technical difficulties during the adoption process. In a 2005 survey of SDI users, nearly 80% of Kansas producers indicated they were at least satisfied with the performance of their SDI system, and less than 4% indicated they were unsatisfied (Alam & Rogers, 2005). However, even satisfied users indicated a need for additional SDI management information. The most noted concern was rodent damage and subsequent repairs. A few systems had failed or been abandoned after limited use due to inadequate design, inadequate management, or a combination of both.

Design and management are closely linked in a successful SDI system. Research studies and on-farm producers consistently indicate that SDI systems result in high-yielding crops and water-conserving production practices only when the systems are properly designed, installed, operated and maintained. A system that is improperly designed and installed is difficult to operate and maintain and most likely will not achieve high irrigation water application uniformity and efficiency goals. Proper design and installation alone do not ensure high SDI efficiency and long system life, though. A successful SDI system also must be operated according to design specifications while utilizing appropriate irrigation water management techniques. SDI systems also are well-suited to automation and other advanced irrigation scheduling and management techniques. Additionally, proper maintenance is crucial for the continued life of an SDI system. This paper will review the basics of successful SDI systems.

WATER QUALITY ANALYSIS, THE STARTING POINT FOR ALL SUCCESSFUL SDI SYSTEMS

Because most SDI systems are planned for multiple-year use, water quality is an extremely important consideration. Clogging prevention is crucial to SDI system longevity and requires understanding of the potential hazards associated with a particular water source. Replacement of clogged driplines can be expensive, difficult, and time-consuming. Although nearly all water is potentially usable for SDI, the added cost of complex water filtration and chemical treatment of marginal-quality water might further reduce the feasibility of SDI use on lesser-value crops. Therefore, no SDI system should be designed and installed without first assessing the quality of the proposed irrigation water supply. In some cases, poor water quality can also cause crop growth and/or long-term soil problems. However, with proper treatment and management, many waters high in minerals, nutrient enrichment, or salinity can be used successfully in SDI systems. A good water quality test (Table 1) provides information to growers and designers in the early stages of the planning process so that suitable water treatment, management, maintenance plans, and system components can be selected. Although a good water quality test may cost a few hundred dollars, the absence of it may result in an unwise investment in an SDI system that is difficult and expensive to manage and maintain. Tests 1 through 7 are usually provided in a standard irrigation water quality test package, whereas Tests 8 through 11 are generally offered as individual tests. The test for the presence of oil may be helpful in oil-producing areas or if a groundwater well with oil lubrication has experienced surging, allowing existing drip oil in the water column to mix with the pumped water.

Table 1. Recommended water quality tests to be completed before designing and installing an SDI system including threshold hazard levels (after Bucks et al., 1979; Nakayama and Bucks, 1991; and Rogers et al., 2003a).

1. **Electrical Conductivity (EC_b),** a measure of total salinity or total dissolved solids, measured in dS/m or mmhos/cm as the bulk EC of the irrigation water.	Ideal <0.75 dS/m
2. **pH,** a measure of acidity, where a value of 1 is very acid, 14 is very alkali, and 7 is neutral.	Ideal <7
3. **Cations** include Calcium (Ca^{2+}), Magnesium (Mg^{2+}), and Sodium (Na^{+}), measured in measured in meq/L, (milliequivalent/liter).	Ideal <2meq/L
4. **Anions** include Chloride (Cl^{-}), Sulfate ($SO4^{4-}$), Carbonate ($CO3^{2-}$), and Bicarbonate ($HCO3^{-}$), measured in meq/L.	Ideal <2meq/L
5. **Sodium Absorption Ratio (SAR),** a measure of the potential for sodium in the water to develop sodium sodicity, deterioration in soil permeability and toxicity to crops. SAR is sometimes reported as Adjusted (Adj) SAR. The Adj. SAR value better accounts for the effect on the $HCO3^{-}$ concentration and salinity in the water and the subsequent potential damage to the soil because of sodium.	Ideal <3.0
6. **Nitrate nitrogen (NO3 - N),** measured in mg/L (milligram/liter).	Ideal <5 mg/L
7. **Iron (Fe), Manganese (Mn), and Hydrogen Sulfide (H_2S),** measured in mg/L.	Ideal Fe<0.2 mg/L Ideal Mn<0.1 mg/L Ideal H_2S<0.2 mg/L
8. **Total suspended solids,** a measure of particles in suspension in mg/L.	Ideal <50 mg/L
9. **Bacterial population,** a measure or count of bacterial presence in # / ml, (number per milliliter)	Ideal <10,000/ml
10. **Boron*** measured in mg/L.	Ideal <0.7 mg/L
11. **Presence of oil****	-

* *The boron test would be for crop toxicity concern.*

** *Oil in the water would present a concern of excessive filter clogging. It may not be a test option at some labs and could be considered an optional analysis.*

Additional information on assessing water quality and developing water treatment plans are available from a number of sources (Rogers et al., 2003a; Burt and Styles, 2007a; Schwankl, et al., 2008).

FUNDAMENTAL SDI DESIGN CHARACTERISTICS

Fundamental SDI design characteristics need to be addressed early in the design process, namely dripline selection and dripline installation aspects. Interactions exist between these two and with other design aspects occur later in the design process. A complete discussion of these characteristics is beyond the scope of this paper, so the reader is referred to Lamm and Camp (2007) for further discussion. However, some brief discussion is necessary since the characteristics are so fundamental to SDI design.

Dripline Selection

The selection of a dripline involves consideration of dripline diameter and wall thickness, emitter type, discharge rate and emitter spacing.

Dripline inside diameter

Larger diameter driplines allow long lengths of run and large zone sizes without sacrificing water distribution uniformity. Although larger diameter driplines cost more per unit length, their selection may result in a less expensive SDI system because of reduction of trenching and system controls. Dripline diameters up to 1.375 inches are now available and often used in large fields to decrease the number of required zones and field obstructions posed by additional valve boxes. Each SDI system design is different, however, and the grower should not automatically choose the larger dripline diameter. Larger driplines require longer fill and drain times which can adversely affect water and chemical application uniformity and redistribution within the soil.

Dripline wall thickness

The wall thickness of SDI driplines is often greater than surface drip irrigation (DI) because of the additional risk of dripline damage during installation and because the SDI system is intended to have an extended, multiple-year life. Thin-walled, collapsible polyethylene (PE) driplines with wall thicknesses of 12 to15 mil are used primarily for SDI installations in the Great Plains. In situations where soil compaction or soil overburden may cause dripline deformation, thick-walled PE tubing (hard hose) can be selected, although it is considerably more expensive. Thicker-walled products allow greater maximum dripline pressures that can be used to open partly-collapsed driplines caused by soil compaction or overburden, or to increase flow of chemically treated water through partly-clogged emitters. In addition, anecdotal reports highlight less insect damage to hard hose driplines.

Emitter type

Subsurface drip irrigation emitters are fully contained within the dripline to avoid significant protrusions that may become damaged during the SDI system installation process. These internal emitters are typically formed using one of three different methods: 1) long, tortuous passageway is formed through an indention process within the seam of the dripline as it is formed; 2) integral short tortuous path emitter is fusion-welded to the internal wall of the PE tubing; and 3) continuous narrow strip containing the turbulent emitter passageway is fusion-welded to the internal dripline wall. Integral short path emitters sometimes have a smaller manufacturer's coefficient of variation

(CV) than those of the other processes, but all processes provide acceptable CV values with the modern manufacturing processes currently available. All three of these emitter types are used in SDI systems within the Great Plains region.

Emitter types are also classified by their emitter exponent (i.e., typically referred to as X, the exponent on the pressure term in the emitter discharge equation). An exponent less than 0.5 allows an emitter to be classified as partially pressure compensating, whereas a value of zero represents full pressure compensation (PC). An emitter with an exponent greater than 0.5 is classified as non-pressure compensating. Many current SDI driplines have emitter exponents with values close to 0.5 and, traditionally, PC emitters were considered too expensive for SDI installations on lesser-value crops. However, manufacturers continue to evolve product lines and processes, and some driplines with PC emitter characteristics are becoming more economically competitive.

Emitter discharge rate

Wide ranges of emitter discharge rates are available from the various dripline manufacturers. The evapotranspiration (ETc) needs of the crop have little direct influence on the choice of emitter discharge rate because most emitter discharge rates at typical emitter and dripline spacings provide SDI system application rates in excess of peak ETc. Some designers prefer emitters with greater discharge rates because they are less subject to clogging and allow more flexibility in scheduling irrigation. However, when emitters with greater discharge are chosen, the length of run may need to be reduced to maintain good uniformity and to allow for adequate flushing within the maximum allowable operating pressure. In addition, the zone size may need to be reduced to keep the total SDI system flowrate within the constraints of the water supply system. The choice of emitter discharge rate must also account for the soil hydraulic properties in order to avoid backpressure on the emitters and surfacing of water, although this problem is not common on SDI systems in the Great Plains.

Physical limitations exist to further reducing emitter discharge rate because smaller passageways are more easily clogged. The nominal dripline flowrate can be reduced with smaller emitter discharge rates or by increasing the emitter spacing. Limitations also exist to increasing the emitter spacing that are related to adequately supplying the crop’s water needs. Using a smaller emitter discharge rate in combination with a greater emitter spacing is often economically attractive (reduced design and installation costs) on deeper, medium-textured soils for crops with extensive root systems.

Emitter spacing

Emitter spacings ranging from 4 to 30 inches are readily available from the manufacturers, and other spacings can be made to meet a specific application. Increasing the emitter spacing can be used as a techniques to allow larger emitter passageways less subject to clogging, to allow for economical use of emitters that are more expensive to manufacture, or to allow for longer length of run or increased zone size by decreasing the dripline nominal flowrate per unit length. The rationale for increased emitter spacing must be weighed against the need to maintain adequate water distribution within the root zone. An excellent conceptual discussion of the need to consider the extent of crop rooting in irrigation design is presented by Seginer (1979). Although the effective uniformity of microirrigation experienced by the crop is high, the actual detailed uniformity within the soil may be quite low. Emitter spacing ranging from 1 to 4 ft had little effect on corn production and soil water redistribution in a three-year study at the KSU Northwest Research-Extension Center at Colby, Kansas (Arbat et al., 2010). It should be noted that using the widest possible emitter spacing consistent with good water redistribution can cause significant problems when emitters become clogged or under drought conditions. As a result, some plants will be inadequately watered. Generally, emitter spacing of 1 to 2 ft are used for SDI systems in the Great Plains.

Dripline installation aspects

Some dripline installation aspects require basic decisions about dripline spacing, dripline depth, and zone size (length and width). As noted earlier in the paper, these installation aspects may interact with the selection of the dripline.

Dripline spacing

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

Dripline spacing in the Great Plains region is typically one dripline per row/bed or an alternate row/bed middle pattern (Figure 1) with one dripline per bed or between two rows. The soil and crop rooting characteristics affect the required lateral spacing, but general agreement exists that the alternate row/bed dripline spacing (about 5 ft) is adequate for most of the deeper-rooted agronomic crops on medium- to heavy-textured soils. Closer dripline spacing may be used for high-valued crops on sandy soils, for small seeded crops where germination is problematic, and in arid areas to ensure adequate salinity management and consistent crop yield and quality.

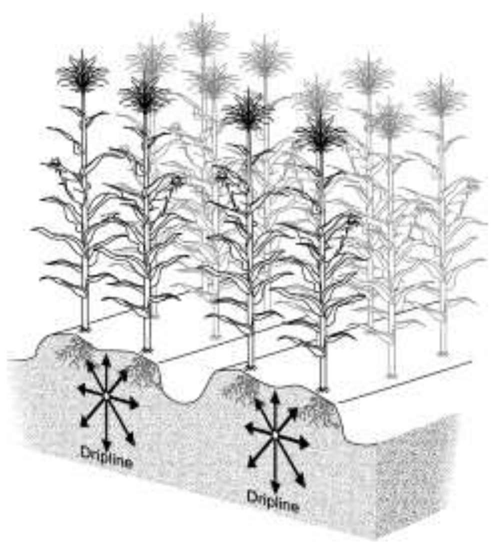

Figure 1. Alternate row/bed 5 ft SDI dripline spacing for corn rows spaced at 2.5 ft. Each plant row is approximately 1.25 ft. from the nearest dripline and has equal opportunity to the applied water.

Dripline depth

The choice of an appropriate dripline depth is influenced by crop, soil, and climate characteristics, anticipated cultural practices, grower experiences and preferences, the water source, and prevalence of pests. In an extensive review of SDI, Camp (1998) reported that the placement depth of driplines ranged from less than an inch to as much as 28 inches. In most cases, dripline depth was probably optimized for the local site by using knowledge and experiences about the crop for the soils of the region. For example, driplines for alfalfa are sometimes installed at deeper depths so that irrigation can continue during harvest. When irrigation is often required for seed germination and seedling establishment, shallower dripline depths are often used. Deeply placed driplines may require an excessive amount of irrigation for germination and can result in excessive leaching and off-site environmental effects.

Soil hydraulic properties and the emitter flowrate affect the amount of upward and downward water movement in the soil and thus are factors in the choice of dripline depth. When surface wetting by the SDI system is not needed for germination or for salinity management, deeper systems can reduce soil water evaporation and weed growth. Deeper dripline placement minimizes soil water evaporation losses, but this must be balanced with the potential for increased percolation losses while considering the crop root-zone depth and rooting intensity. Soil layering or changes in texture and density within the soil profile affect the choice of dripline depth. Driplines should be installed within a coarse-textured surface soil overlaying fine-textured subsoil so that there is greater lateral movement perpendicular to the driplines. Conversely, when a fine-textured soil overlays a coarse-textured subsoil, the dripline should be installed within the fine-textured soil to prevent excessive deep percolation losses. An excellent discussion of how soil texture and density affect soil water redistribution is provided by Gardner (1979).

For lesser-valued commodity crops (fiber, grains, forages, and oilseeds), SDI systems are usually set up exclusively for multiple-year use with driplines installed in the 12 to 18 inch depth range. Most of these crops have extensive root systems that function properly at these greater depths. Corn, soybean, sunflower, and grain sorghum yields were not affected greatly by dripline depths ranging from 8 to 24 inches on a deep Keith silt loam soil at Colby, Kansas (Lamm and Trooien, 2005; Lamm et al., 2010). Their results suggest that, in regions that typically receive precipitation during the growing season, dripline depth will not be the overriding factor in crop development and soil water redistribution. The dripline should be deep enough that the anticipated cultural practices can be accommodated without untimely delays, soil compaction, or damaging the SDI system. Pests such as rodents and insects are often more troublesome at the shallow dripline depths.

Zone size (length and width) considerations

The overall field size that can be subsurface drip irrigated is limited by the available water supply and SDI system flowrate. However, the ability to economically adjust the size of the irrigated field to the available water supply is a distinct advantage of SDI systems as compared to center pivot sprinklers. If sufficient water supply is available to adequately irrigate the crop for the overall field size, then system flowrate, field shape, and topography, along with the dripline hydraulic characteristics (i.e., emitter discharge characteristics and dripline diameter) are used to determine the number of zones and the zone dimensions. Minimizing the number of necessary zones and using longer driplines typically results in a more economical system to install and operate, which is of great importance to those growers using SDI on lesser-valued crops.

Systems are sometimes designed so that irrigation zones can be sub-divided into flush zones. Flushing, discussed in detail later, is an important maintenance requirement for SDI systems.

The combination of the emitter discharge, emitter spacing, and dripline spacing determine the flowrate per unit area. The flowrate per unit area in combination with the water supply flowrate (i.e., system or well flowrate) in turn determines the zone size. The system flowrate can be used to determine the total number of acres that can be reliably irrigated.

The irrigation capacity (IC) of an irrigation system is the depth of water that the system could apply to the entire field in one day. As a rule of thumb, a net IC of about 0.25 inches per day is sufficient to meet corn water needs for the deep silt loam soils of western Kansas. Irrigation capacity can also be reported in gpm/acre, so an IC of 0.25 in/day is equivalent to 4.7 gpm/acre. Typical surface-irrigated (flood) systems need 8 to 10 gpm/acre, while center pivot systems might need 5.2 to 5.6 gpm/acre range to have the same net IC and SDI systems would need around 5.0 gpm/ac to match a net IC of 4.7 gpm/acre. There is some evidence to suggest that SDI systems may allow more effective utilization of precipitation and some systems have been installed with gross IC as low as 3.4 gpm/acre. This allows the available water supply to be stretched over more land area but does leave the SDI system's crop vulnerable to crop water stress during drought years.

The design process may require several iterations to select the correct emitter discharge, emitter spacing, dripline spacing (usually fixed at twice the row spacing) with zone size, field size and system flowrate given the producers desired level of irrigation system reliability.

SDI COMPONENTS FOR EFFICIENT WATER DISTRIBUTION AND SYSTEM LONGEVITY

SDI system design must consider individual management restraints and goals, as well as account for specific field and soil characteristics, water quality, well capabilities, desired crops, production systems, and producer goals. However, certain basic features should be universal throughout all SDI systems (Figure 2). The long-term efficient operation and maintenance of the system is seriously undermined if any of the minimum components are omitted during the design process. Minimum SDI system components should not be sacrificed as design and installation cost-cutting measures. If minimum SDI components cannot be included as part of the system, an alternative type of irrigation system or a dryland production system should be considered.

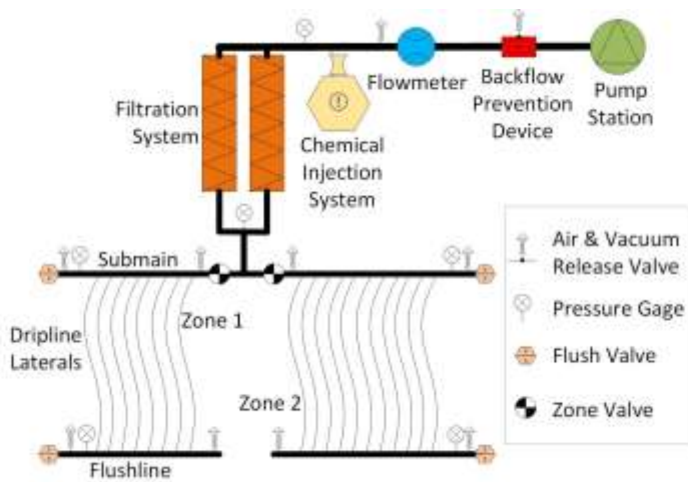

Figure 2. Minimum required components of an SDI system. Components are not to scale. After Rogers, 2003b.

Water distribution components of an SDI system include the pumping station, the main, submains and dripline laterals. Sizing requirements for the mains and submains are somewhat similar to underground service pipe to center pivot sprinklers or main pipelines for surface-irrigated gravity systems and are determined by the flowrate and acceptable friction loss within the pipe. In general, the flowrate and friction loss determine the dripline size (diameter) for a given dripline lateral length and land slope. An SDI system consisting of only the distribution components has no method to monitor system performance or conduct system maintenance, and the system would not have any protection from clogging. Clogging of dripline emitters is the primary reason for SDI system failure. In addition to basic water distribution components, other components allow the producers to monitor SDI system performance, allow flushing, and protect or maintain performance by injection of chemical treatments. The injection equipment can also be used to provide additional nutrients or chemicals for crop production. A backflow prevention device is required to protect the source water from accidental contamination if backflow should occur.

The actual characteristics and field layout of an SDI system vary from site to site, but irrigators often add additional capabilities to their systems. For example, the SDI system in Figure 3 shows additional valves that allow the irrigation zone to be split into two flushing zones. When the well or pump does not have the capacity to provide additional flow and pressure to meet the flushing requirements for the irrigation zone, splitting the zone into two parts may be an important design feature.

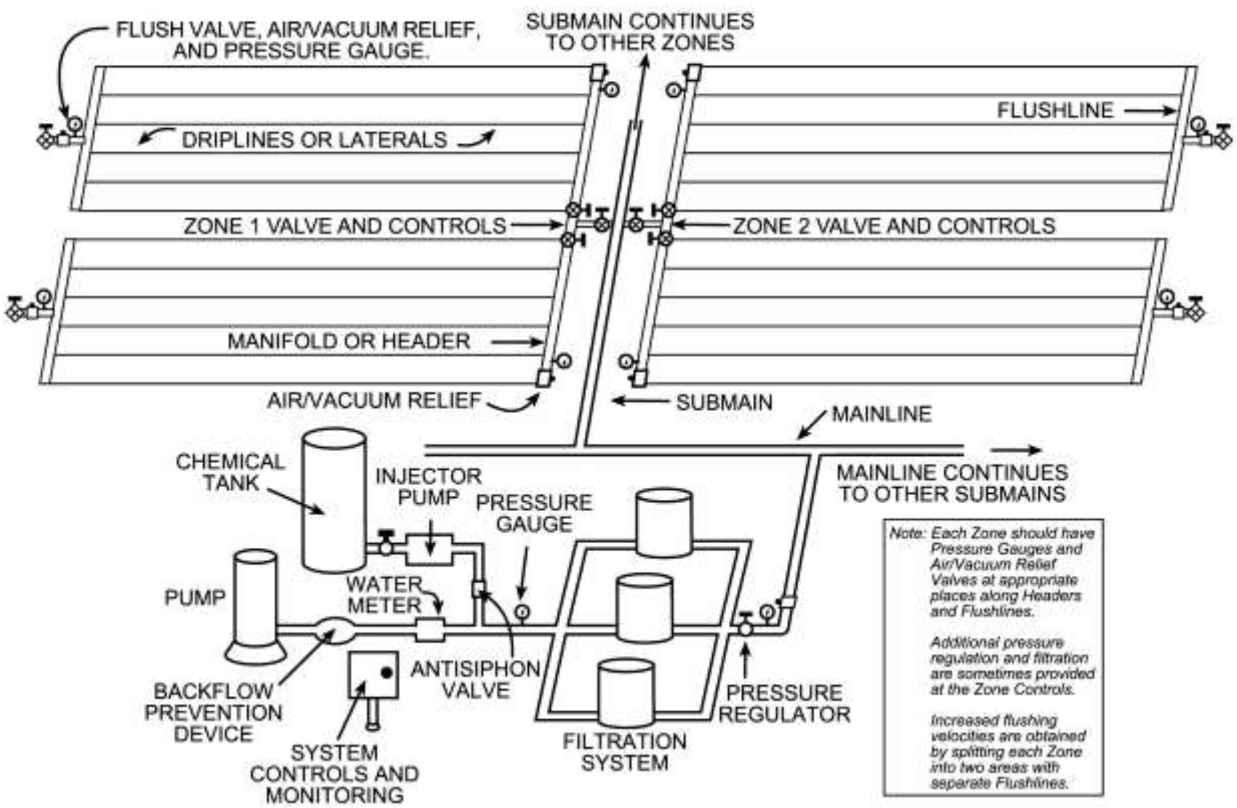

Figure 3. Schematic of a complete SDI system. After Lamm and Camp (2007).

Filtration system

The heart of the protection system for the dripline emitters is the filtration system. Many types of filtration systems (Figure 4) are commercially available and the selected type depends on the quality characteristics of the irrigation water and the clogging hazards.

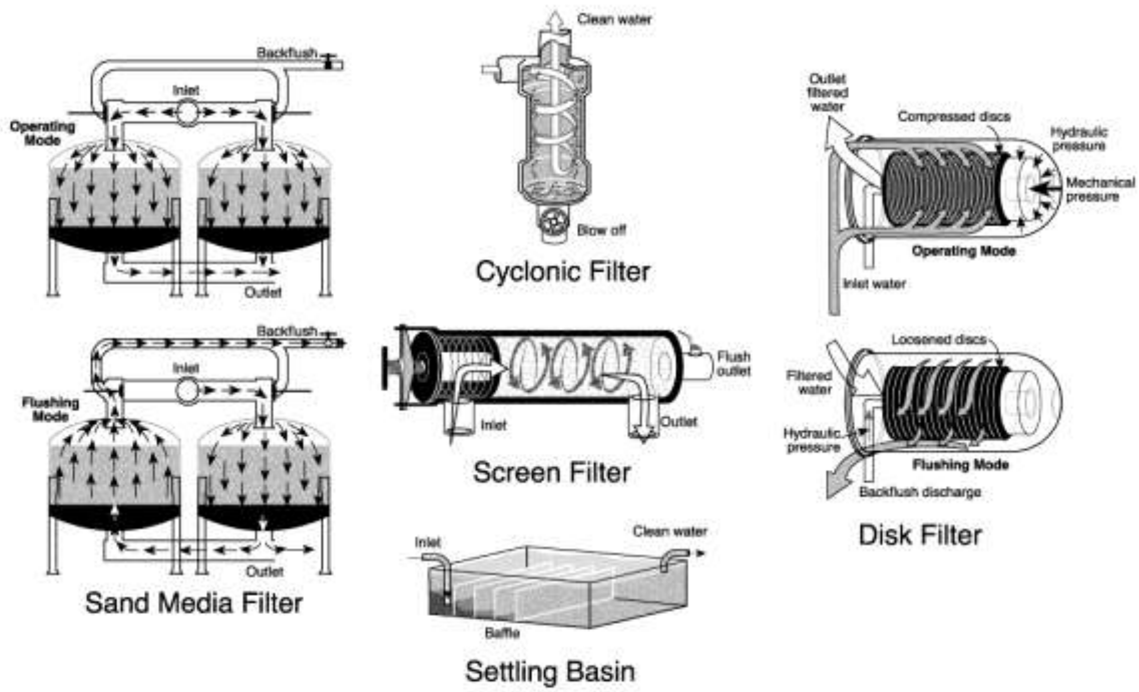

Figure 4. Schematic description of various filtration systems and components. (Courtesy of Kansas State University).

Screen filters are the simplest type of filtration and provide a single plane of filtration. They are most often used in situations where the water source is relatively clean. Sand media filtration systems, which consist of two or more large pressure tanks with specially graded filtration sand, provide three-dimensional filtration and are well-suited for surface water sources. Surface water supplies may require settling basins and/or several layers of bar screen barriers at the intake site to remove large debris and organic matter. Another common type of filtration system is the disc filter which also provides three-dimensional filtration. In some cases, the filtration system may be a combination of filtration components. For example, a well that produces a large amount of sand in the pumped water may require a cyclonic sand separator in advance of the main filter.

Clogging hazards are classified as physical, biological or chemical. Sand particles in the water represent a physical clogging hazard, whereas biological hazards are living organisms, or life by-products, that clog emitters. Water sources that have high iron content are also vulnerable to biological clogging hazards, such as an iron bacteria flare-up within the groundwater well. Control of bacterial growth generally requires water treatment in addition to filtration. Chemical clogging hazards relate to the chemical composition or quality of the irrigation water. As water flows from a well to the distribution system, chemical reactions occur due to changes in temperature, pressure, air exposure, or the introduction of other materials into the water stream. These chemical reactions may form precipitates that result in emitter clogging.

Producers should always follow the filter manufacturer's guidelines for sizing and when they should be flushed. Automatic flushing is available for many filtration systems and the flushing cycle may be specified by the pressure differential across the filter and/or a set interval of time.

Flushlines

Filter systems are generally sized to remove particles that are approximately 1/10 the diameter of the smallest emitter passageway. However, small particles still pass through the filter and into the driplines, and over time, they may clump together. Also, biological or chemical processes produce materials that need to be removed in order to prevent emitter clogging or a build-up of material at the outlet or distal end of the system. A good design should allow flushing of all pipeline and system components. Opening the flushline valves allows water to rapidly pass through the driplines, carrying away any accumulated particles. The American Society of Agricultural and Biological Engineers (ASABE) recommends a minimum flushing velocity of 1 ft/s for microirrigation lateral maintenance (ASAE EP-405, 2008). This flushing velocity requirement needs to be carefully considered at the design stage and may dictate larger sizes for submains and flushlines to assure that maximum operating pressures for the driplines are not exceeded (Lamm and Camp, 2007).

The frequency of flushing is largely determined by the quality of the irrigation water and, to a degree, the level of filtration. Evaluation of the amount of debris caught in a mesh cloth during a flushing event is an indicator of the required frequency of flushing. When only a small amount of debris is found, the flushing interval may be increased. Heavy accumulations of debris, however, mean more frequent flushing is needed.

Chemical injection system

In addition to SDI system protection, the chemical injection system may also be used to inject nutrients or chemicals into the water to enhance plant growth or yield. A variety of injectors can be used, but the choice of unit depends on the desired injection accuracy for the chemical, the rate of injection, and the chemical being injected. When a wide variety of chemicals are likely to be injected, then more than one type of injection system may be required. Also, state and federal laws govern the type of injectors, appropriate chemicals, application amounts, and required safety equipment that may be used in SDI systems, as illustrated by Figure 5.

Many different chemicals can be injected, including chlorine, acid, dripline cleaners, fertilizers, and some pesticides. Producers should avoid injecting any chemical into their SDI system without knowledge of the chemical compatibility with irrigation water. For example, various phosphorus fertilizers are incompatible with many water sources and may only be injected using additional precautions and management techniques. All applicable laws and labels should be followed when applying chemicals.

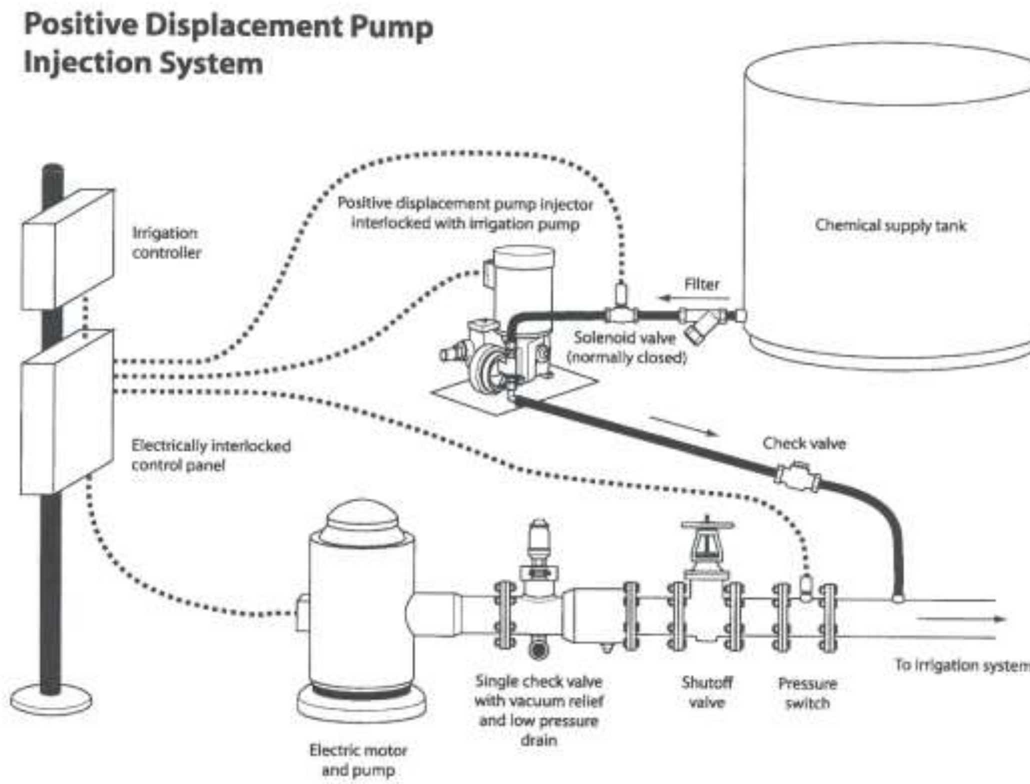

Figure 5. Layout of a chemical injection system with safety interlocks and backflow prevention devices (Courtesy of L.J. Schwankl, Univ. of California-Davis).

The injection systems in Figures 2 and 3 have a single injection point located upstream of the main filter, but some agrochemicals may require an injection point downstream from the filter to prevent filter damage. Care needs to be exercised in the location of the injection port to prevent system problems such as corrosion within the filters or chemical precipitation beyond the filter resulting in emitter clogging.

Chlorine is commonly used to disinfect the injection system and minimize the risk of clogging from biological organisms. Acid injection can also reduce the pH chemical characteristic of the irrigation water. For example, water with a high pH clogs easily because minerals drop out of solution in the dripline after the water passes through the filter. A small amount of acid added to the water reduces the pH to minimize the potential for chemical precipitates.

MONITORING THE SDI SYSTEM

In SDI systems, all water application is underground. Because surface wetting seldom occurs in properly installed and operated systems, no visual cues of system operation are available to the manager. Therefore, the flow meter and pressure gauges must be used to provide operational feedback cues. The pressure gauges along the submain of each zone measure the inlet pressure to driplines. Decreasing flowrates and/or increasing pressure may indicate clogging, and increasing flowrates with decreasing pressure may indicate a major line leak. The inlet pressure gauges, along with those at the distal ends of the dripline laterals at the flushline valve, help establish the baseline performance characteristics of the system. Good quality pressure gauges should be used at each of these measurement locations and the gauges should be periodically replaced or inspected for accuracy. The flowrate and pressure measurements should be recorded and retained for the life of the system. A time series of flowrate and pressure measurements can be used as a diagnostic tool to discover operational problems and determine appropriate remediation techniques (Figure 6).

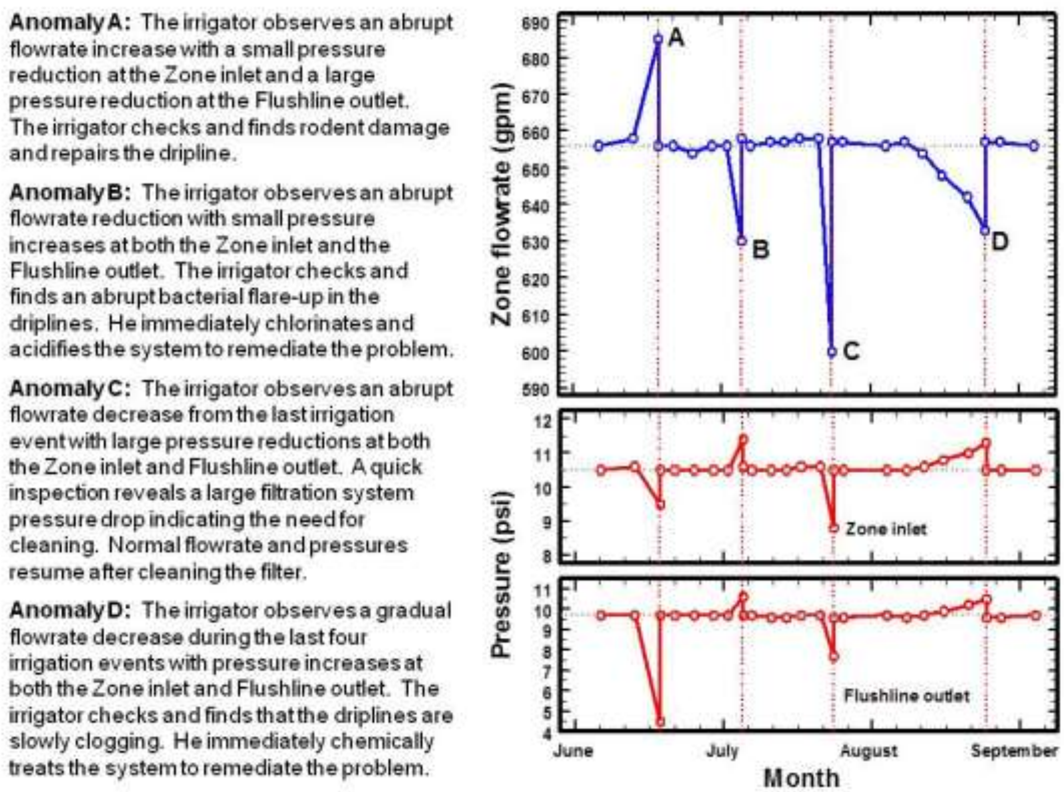

Figure 6. Hypothetical example of how pressure and flowrate measurement records could be used to discover and remediate operational problems. After Lamm and Camp (2007).

RODENT MANAGEMENT

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

Cultural practices such as tillage and crop residue removal from around SDI control heads and above-ground system apparatus seem to decrease the occurrence of rodent problems. Some growers have used deep subsoiling and/or poison bait around the SDI system field perimeters as a means of reducing rodent subsurface entry into the field. Isolated patches of residue within a barren surrounding landscape provide an “oasis” effect conducive to rodent establishment. After the smaller rodents become established, other burrowing predators such as badgers can move into the field, further exacerbating the damage. Caustic, odoriferous, pungent, and unpalatable chemical materials have been applied through SDI systems in attempts to reduce rodent damage, but the success of these trials has been varied. Anecdotal reports have indicated reduction in rodents by installing owl houses on high poles around the edges of the fields (Burt and Styles, 2007b). Periodic wetting of the soil during the dormant period has been suggested as a possible means of reducing rodent damage. Deeper SDI depths (18 inches or greater) may avoid some rodent damage (Van der Gulik, 1999) since many of the burrowing mammals of concern in the United States have a typical depth range of activity that is less than 18 inches (Cline et al., 1982).

PRODUCER RESPONSIBILITIES

As with nearly all investments, the decision of whether an SDI investment is sound lies with the investor. Wise decisions generally require a thorough understanding of the fundamentals of the particular opportunity and/or the recommendations from a trusted and proven expert. While the microirrigation (drip) industry dates back nearly 50 years and SDI application in Kansas has been researched since 1989, the network of industry support is still evolving in portions of the Great Plains region. Individuals considering SDI should spend time to determine if SDI is a viable systems option for their situation. They might ask themselves:

What things should I consider before purchasing an SDI system?

1. Educate yourself before contacting a service provider or salesperson by
    a. Seeking out university and other educational resources. A good place to start is the K-State SDI website at www.ksre.ksu.edu/sdi
    Read the literature or websites of microirrigation companies as well.
    b. Review SDI minimum design components as recommended by K-State. http://www.ksre.ksu.edu/sdi/Reports/2003/mf2576.pdf
    c. Visit other producer sites that have installed and are using SDI. Most current producers are willing to show their SDI systems to others.
2. Interview at least two companies.
    a. Ask them for references, credentials (training and experience) and completed sites (including the names of contacts or references).
    b. Ask questions about design and operation details. Pay particular attention if the minimum SDI system components are not met. If not, ask why. System longevity is a critical factor for economical use of SDI.
    c. Ask companies to clearly define their role and responsibility in designing, installing, and servicing the system. Determine what guarantees are provided.
3. Obtain an independent review of the design by an individual that is not associated with the sale. This adds cost but is relatively minor in comparison to the total cost of a large SDI system.

CONCLUSION

SDI can be a viable irrigation system option, but many issues should be carefully considered by producers before any financial investment is made.

OTHER AVAILABLE INFORMATION

Additional SDI-related bulletins and irrigation-related websites are listed below:

MF-2361 *Filtration and Maintenance Considerations for Subsurface Drip Irrigation (SDI) Systems*
http://www.ksre.ksu.edu/sdi/Reports/2003/mf2361.pdf

MF-2576 *Subsurface Drip Irrigation (SDI) Components: Minimum Requirements*
http://www.ksre.ksu.edu/sdi/Reports/2003/mf2576.pdf

MF-2578 *Design Considerations for Subsurface Drip Irrigation*
http://www.ksre.ksu.edu/sdi/Reports/2003/mf2578.pdf

MF-2590 *Management Consideration for Operating a Subsurface Drip Irrigation System*
http://www.ksre.ksu.edu/sdi/Reports/2003/MF2590.pdf

MF-2575 *Water Quality Assessment Guidelines for Subsurface Drip Irrigation*
http://www.ksre.ksu.edu/sdi/Reports/2003/mf2575.pdf

MF 2589 *Shock Chlorination Treatment for Irrigation Wells*
http://www.ksre.ksu.edu/sdi/Reports/2003/mf2589.pdf

Subsurface Drip Irrigation website: www.ksre.ksu.edu/sdi

General Irrigation website: www.ksre.ksu.edu/irrigate

Mobile Irrigation Lab website: www.mobileirrigationlab.com

ACKNOWLEDGEMENTS

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Arbat, G., F. R. Lamm, and A. A. Abou Kheira. 2010. Subsurface drip irrigation emitter spacing effects on soil water redistribution, corn yield and water productivity. Applied Engr. in Agric. 26(3):391-399. Also available at http://www.ksre.ksu.edu/sdi/Reports/2010/ESpace10.pdf

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Urban Runoff Harvesting - A Local Water Resource for Onsite Landscape Irrigation

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Keywords: Drip Irrigation Systems, Conservation, Rainwater, Runoff, Sprinklers, Stormwater, Sustainability, Turf-Landscape, Water Provider

Abstract

This urban runoff harvesting pilot project would demonstrate how to harvest local water from an underground storm drain running under (or adjacent to) a community park, and use this non-potable water for irrigating a community park, replacing municipal potable water. By tapping into an existing storm drain line, the project would be designed to divert stormwater and dry weather flows from the storm drain into an adjacent storage tank. From the tank, urban runoff would be treated and delivered to the park's existing irrigation system.

Second, the stormwater harvesting and irrigation use pilot project would demonstrate water efficiency and savings over spray irrigation by installing a sub-surface irrigation system under a small test turf patch.

This green infrastructure project harvests a local water resource, augments local water supplies, supplants potable water for non-potable purposes, reduces polluted urban runoff discharge to the receiving water body, and helps protect the reliability of a municipality's water supply.

Background

City of Santa Monica Approach to Watershed Management

Since the mid-1990s, the City of Santa Monica has shifted its watershed management program away from treat and release solutions for stormwater and toward sustainable, onsite harvesting and use of this local water resource in lieu of potable water. Such a strategy is called Low Impact Development (LID) and Green Infrastructure (GI). The former strategy focuses on a variety of earthworks and proprietary solutions, both passive and active, including stormwater storage and onsite direct use. The latter strategy focuses only on earthworks systems, as per the U.S. EPA, directing precipitation from impermeable surfaces into permeable surfaces or high efficiency bio-filtration (and release) systems. These are indirect, passive systems that put water into the ground for groundwater recharge, if an aquifer is accessible and easily rechargeable in a short time frame, into surface waters, or into plants via root uptake.

Active systems include storage tanks from smaller, simple and inexpensive gravity-flow rain barrels, to large cisterns with stored water pumped under pressure. Passive systems include infiltration pits and trenches (sub-surface); surface depressions; rain gardens; permeable paving products; and green streets.

The city's watershed management approach integrates land use with the flow of local water, whether it is precipitation or surface runoff. One management objective is at the micro-watershed level, e.g. the individual parcel, in which water use on property occurs.

Precipitation Harvesting

A sustainable watershed management approach views precipitation as a valuable resource with multiple benefits. Whether rain is harvested from common elevated surfaces, e.g. roofs, from ground-level, e.g. parking lots, alleys, and transportation grids, or from below grade, e.g. channels and storm drain lines, this water resource is locally accessible with proper treatment for most end uses. (Many different definitions exist for rainwater and stormwater. For the purpose of this article, stormwater is used as the general term; rainwater is often used for rain that lands on a roof and is harvested.) Precipitation, when harvested close to where it lands or flows, has numerous benefits.

Primary Benefits

These benefits are non-potable and potable water supply augmentation and receiving water quality improvement:

- Onsite rain harvesting retains the maximum rainfall amount possible on an annual and sustainable basis. This strategy produces the least amount of stormwater runoff entering the public right-of-way, e.g. the municipal storm sewer system;
- Onsite rain harvesting delivers effectively a water supply to an end use at an acceptable water quality and minimal energy cost; and
- Onsite rain harvesting is the least polluted water resource and cheapest to treat compared to stormwater flowing in the public right-of-way. By keeping rainwater onsite, less pollution enters surface water bodies, where water quality violations can occur.

Secondary Benefits

Keeping precipitation onsite through various harvesting strategies, whether in storage tanks (active) or through permeable surfaces (passive), eliminates stormwater runoff and has these additional benefits:

- Reduces peak flows, flooding and erosion;
- Reduces combined sanitary sewer overflows;
- Reduces the urban heat island by converting impermeable, heat-absorbing and dry surfaces (driveways, parking lots) to permeable, heat-reflecting, moister surfaces;
- Promotes a water self-sufficiency goal;
- Increases property value due to sustainable water earthworks and storage systems;
- Reduces potable water demand; and
- Keeps more water in watersheds for wildlife and human enjoyment, and reduces environmental consequences when overexploited. For many areas, potable water is removed from local watersheds and pumped to distant water users.

The structural device, installed during construction or as a retrofit, that harvests rain for indirect and direct landscape purposes is called a Best Management Practice or BMP.

Harvesting BMPs – Types and Selection

Landscape Applications

Direct/Active Systems

Low volume irrigation is most practical when using rainwater for landscape irrigation, especially with climate-appropriate plants (not with non-native, high water demand plants). Once established, such plants survive on locally available precipitation. It can often be applied by gravity alone or used in combination with pumping (e.g. under additional pressure) systems. Spray irrigation is also an option; however, spray uses more water and could exhaust quickly one's rainwater supply. Spray for a small area would be effective, especially in climates with year-round rain.

A direct system involves a number of components to harvest rain from roofs and at-grade surfaces: impermeable harvesting surface; conveyance system from surface to storage tank; pre-treatment device; storage tank; final treatment; and conveyance to end use. Final treatment can include various filters to remove small particles, remove impurities, and disinfection, depending upon the water quality required for a particular end use, usually non-potable. It is important to note that final water quality must be of a high level to meet irrigation system warranties. If the quality is low and causes damage to irrigation components, warranties may be voided.

The marketplace is replete with companies that specialize in rainwater harvesting systems. The American Rainwater Catchment Systems Association, ARCSA, is the national organization focusing on these systems. Its website (www.arcsa.org) and membership contain helpful information. Generally, proprietary systems serve this market. They range from simple to complex, depending upon the water quality of the stormwater, which depends upon the harvesting surface. A roof is generally cleaner than a parking lot or road. (Roofs with accessible recreational areas are known to contain a variety of pollutants, as are commercial and industrial roofs, where repair work can leave building materials exposed to rain and runoff.)

Indirect/Passive Systems

Various types of earthworks (landscapes) are used to harvest and retain runoff from roofs, parking surfaces and roadways for passive infiltration. Examples include: bio-filters, (bio-)swales, rain gardens, and green strips and streets. While these terms differ, generally, these are vegetated or landscaped surfaces placed in the path of runoff or where harvesting surfaces direct the runoff. One can build mounds around fruit trees to retain runoff onsite to build a sub-surface water reservoir used during the dry season. Where soils have good infiltration rates and groundwater is relatively shallow, earthwork retention features, e.g. settling ponds, for large runoff volumes can recharge groundwater for future extraction.

The most common passive BMP is the infiltration pit, over 90% of all BMPs. Residential properties have the most open space for this type of BMP, as well as surface depressions and vegetative or bio-swales. As California and the western U.S. experience drought, infiltrating BMPs are giving way to storage and direct use BMPs to water one's landscape, and vegetable and fruit gardens, and for indoor uses where potable water is unnecessary. Generally, a property owner prefers to put the BMP out of sight since space is often a premium in the city. Surface BMPs can take up space desired for landscapes, and outdoor equipment and activities.

Besides the infiltration pit, surface depressions, rain gardens (though it only rains a dozen or two times over a few months), and swales work for limited mitigation volume.

The infiltration pit is a sub-surface, carved out chamber filled with a material that allows water to be stored, yet is structurally sound. In the past, rock was used; however, about 40% of storage volume is lost using rock. To compensate for this loss, one has to make the pit 2.5 times larger. Other products made from plastic and concrete provide 95+% void space yet are structurally strong, and do not require additional excavation, e.g. cost.

Components of a Typical Rain Harvesting System - direct use

Five steps for a rain harvesting system

As the rain harvesting industry continues to grow, it is important to understand that an effective rain harvesting system with minimal annual maintenance is essential as this industry continues to make positive strides and to ensure you have a properly functioning system over time. No matter the size of the system, five essential design steps will ensure an effective and sustainable harvesting system. A typical direct-use harvesting system has the following components:

- Collection system includes impermeable surfaces upon which rain lands, and conveyance conduit to move the rainwater to a storage tank;
- Pre-treatment (screening-separation) device;
- Storage tank (cistern);
- Polishing treatment system for end-uses, where necessary; and
- Distribution plumbing system to final end-uses, whether outdoor or indoor applications, and overflow.

<u>Step One: Collection Surface</u>

A collection system harvests rain that falls on impermeable surfaces and transports it to a storage tank. For a roof surface, generally, gutters and downspouts direct rain to a tank. For a surface parking area, generally, rain would sheet flow to a centralized location, such as a catch basin, trench drain or hard-paved swale, and then continue to a storage tank. For a large project involving harvesting from a stormwater surface channel or drain pipe, collection would involve diverting stormwater flow out of a channel or pipe, and into a storage tank.

<u>Step Two: Pre-treatment</u>

Before it enters a storage tank, rain that lands on a roof, parking lot, road or any other impermeable surface and flows, or stormwater that flows through a storm drain system, must be adequately pre-treated to remove debris, sediment, and free oil and grease. Pre-treatment devices can be self-cleaning, which requires minimal maintenance and provides highly oxygenated water. The correct pre-treatment device will significantly reduce the need to clean the storage tank. The type and size of this device depend upon the volume to be collected, which relates to the harvesting area or upstream drainage area, rainfall intensity, and expected pollutants on the harvesting surface, e.g. trash, sediments, or oil and grease. For a single- or multi-family property, generally these small devices are called first flush or debris excluder; they are appropriate for small volumes, e.g. small surface areas. For larger commercial, industrial, institutional and government projects, the device needs to be bigger to accommodate the higher volume and be effective. Generally, this category or type of pre-treatment is called screening-separation or a vortex (spinning motion) device.

<u>Step Three: Storage Tank</u>

The tank design should reduce any turbulence caused as the harvested water enters the tank, which causes re-suspension of bottom sediments. This re-suspension reduces water quality of any water pumped out to end uses.

Most rain storage tanks grow a bio-film that serves as an internal ecosystem, which often assists in treating the storage tank water. Disturbing (via turbulence) this bio-film by simply "dumping" the water into the tank from the top will not allow for this micro-ecosystem to flourish. Using the proper components and design will allow the water to gently enter the tank from the bottom and help distribute oxygen throughout the tank, which reduces anaerobic issues.

A storage tank must have a properly sized and directed overflow, either to the landscape or storm drain system. An overflow is as simple as allowing the water to exit the top of the tank once it becomes full; however, some designs call for using a skimming overflow that removes floating matter such as pollen from the tank more effectively. The overflow, as well as the influent port, should have protection to keep fauna, e.g. mosquitoes to rodents, from entering the tank.

Step Four: Final treatment (optional)

Before final end use, the stored water may need to go through a final treatment system to meet local water-quality standards for each end use. The highest quality stored water is extracted from just below the surface in the storage tank or just above the bottom. Generally, final treatment should include 1-50 micron filters (depending whether UV disinfection is included), activated carbon filter and disinfection (which may or may not be required for toilet-urinal flushing or spray irrigation). Finer filtering to meet irrigation system requirements may be necessary to avoid clogging valves and emitters, and potentially invalidating equipment warranties.

One's system may or may not have a day tank so that only water being used daily is treated. This strategy avoids treating all storage tank water whether it is used or not, and reduces treatment costs. Alternately, on-demand treatment is possible without a day tank.
Check with your local authority having jurisdiction on any required, specific water quality standards.

Step Five, Distribution

After leaving the storage tank, water is pumped to an end use. If one's system will not have enough rain for the annual demand, the system should have a back-up municipal water supply. The connection can be a 3-way valve (located between storage tank/final treatment and end use), or a direct feed into the day tank (or storage tank if no day tank) with an air gap. Many municipalities require a back-flow prevention device (RPZ) on the back-up supply to prevent reverse flow and possible contamination of the municipal supply. Your local authority having jurisdiction can provide specific backflow and cross-connection requirements.

City and Private Projects

Putting the direct application strategy together with the five installation steps, the city and private developers have implemented a number of projects.

Main Library

The city's main library has a 200,000 gallon cistern under the building and underground parking structure. Rain landing on the roof, decks and parking lot is pre-treated to remove debris, trash, and larger sediment and then directed to the cistern. In the cistern, fine sediment settles out. The stored and treated water is used for sub-surface drip irrigation.

Multi-family and Single-family Projects

The city completed in 2012 multi-family residential building that includes a 13,000 gallon cistern. Rain from the roof is pre-filtered, stored and used for sub-surface drip irrigation project. For these two city projects, since the rainwater is delivered sub-surface, no disinfection is required.

Private property owners have also installed cisterns (500-5,000 gallons) to collect roof and driveway runoff for storage and sub-surface irrigation use. Sub-surface irrigation with non-turf, climate-appropriate landscaping is an efficient way to use rain for landscape irrigation, to extend harvested rain for use during dry periods and avoid the use of municipal potable water.

Future Projects

The city has embarked on a stormwater harvesting strategy to tap into storm drain lines running adjacent to or under city parks. City parks and open spaces offer opportunities to replace potable water for irrigation with non-potable stormwater where a storm drain line is close by in which to tap for a water resource. The city is currently in the design phase for one park to harvest stormwater, and any dry weather runoff, from the storm drain running along a parallel residential street. A local water district grant is helping to financially support this budgeted project. Harvested and treated water will be used for athletic field irrigation.

Another park project is in design phase, though not budgeted, to tap into a storm drain line running under the park to do the same harvest, treat and deliver to turf irrigation. This project has a U.S. Environmental Protection Agency Green Infrastructure Design grant to develop a design plan for such a solution.

Conclusion

Summary

- The use of rain and stormwater for non-potable irrigation applications offers a significant opportunity in water management to maximize local water resources to supplement or displace potable, leaving more freshwater in our surface and underground supplies;
- Treatment systems are readily available and offer safe ways to utilize rainwater and stormwater, and protect health;
- Existing, safe and reliable plumbing design and standards exist;
- Permitting procedures exist;
- No technical, treatment or health and safety obstacles exist. There is only a lack of political will or the fear to try something ‘unconventional,’ though tested and proven to work.

Going Forward

Using these steps as guidelines will ensure your stormwater system is of the highest quality and will require minimal maintenance regardless of the size of the system. Because rain harvesting design and installation involve several disciplines, it is recommended that one consult qualified professionals in this water-harvesting field.

Treated rainwater and stormwater from a properly designed, installed and maintained harvesting system can be used for all traditional water uses. Rain harvesting should be part of any effective and sustainable local approach to water management. The key is to build on the existing positive record, and ensure rainwater and stormwater utilization become commonplace, e.g. part of new construction and major re-development, as well as retrofit construction, and available at a reasonable cost and least regulatory impact to anyone who is willing to invest in a system.

Appropriately treated rain and stormwater, which matches one’s end use from a properly designed, installed and maintained harvesting system, can be used for all traditional water uses, both non-potable and potable.

The city’s sustainable watershed management approach promotes practical solutions which integrate land type, local water availability, building construction, landscapes and climate. This approach encourages living within the means of locally available natural resources. It fosters landscape designs with appropriate irrigation systems to match local water supply with climate-appropriate species.

Rainwater Harvesting for Irrigation

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Abstract. *Many are looking for an affordable alternative water source for landscape irrigation. For the average landscape, the most cost effective option is a rainwater collection system. Water use greatly increases during the irrigation season. Water utilities must have supply, treatment capability, and infrastructure to supply this increase in water use. As large urban areas grow in population and development, the cost of supply, treatment and infrastructure increases therefore the water cost to customers increase.*
For every square foot of imperious surface, a one inch rainfall will collect 0.623 gallons of water. So a 2,000 square foot building can collect 1200 gallons every one inch rain. A 10,000 square foot office building or parking lot can collect 6,000 gallons from every one inch rain. Rainwater in the most areas is salt free and slightly acidic. Plants benefit from slightly acid water.

Rainwater Harvesting for Irrigation
Capturing rainwater in above ground or below ground cisterns is an ancient practice many homeowners, businesses and municipalities are adopting to use for irrigation, topping ponds and pools, greenhouse water, livestock, wildlife, firefighting and potable water. Some cities and states are encouraging rainwater capture particularly for summer irrigation when water use increases anywhere from 25 to 60%. This increase is attributed to irrigation. As population growth and development continues to strain water resources, landscape water conservation is not just an issue but a necessity. Future landscapes must conserve water to be sustainable. In urban areas, harvesting rainwater for irrigation will take the strain off municipal water supplies, delay building expensive new water treatment plants, and reduce flooding, erosion and stormwater contamination. In rural areas, rainwater harvesting is an optional supply for potable water when no other source is available and as a water supply for firefighting, livestock and wildlife.

Large-scale rainwater harvesting is an option for landscapes in parks, schools, commercial sites, parking lots, apartment complexes and greenhouse operations. Smaller rainwater harvesting systems are an option to supply irrigation water in residential landscapes.

A rainwater harvesting system consists of a method to collect, divert, store, filter and distribute water into the landscape. Systems are designed to collect the amount of water required landscape irrigation minus rainfall or if not enough collection surface is available to supplement with municipal water or groundwater. Of course using an efficient irrigation method and resource efficient plants will greatly reduce the amount of irrigation required.

Roof and other hard impervious surfaces are the best collection sites although collecting runoff from landscaped areas is another option particularly on a slope. Gutter and downspouts or a roof valley can direct rainwater into a rain barrel or a large tank/cistern. Drip irrigation tubing can deliver the water into the landscape. One inch of rain will provide 0.6 gallons per 1 square foot of roof. So an average 2,000 square foot home can collect 1,200 gallons during a 1 inch rain event. Where the average rainfall is 36 inches a year, a 2,000 square house will collect 43,000 gallons, more than enough for irrigation for a small landscape using water conserving plants and turf.

A rain catchment system cost as little as $0.50 a gallon for a do-it-yourself rain barrel to as much as $10.00 a gallon for a large underground cistern.

Calculate Supply **(Amount of Rainwater Collected off all or part of Roof)**

Supply In gallons	=	Rainfall In inches	X	0.623	X	Catchment Square feet	X	Runoff Coefficient

Calculate Demand **(Water Required for Irrigation)**

Demand In gallons	=	Evapotranspiration	X	Plant Coefficient	X	0.623	X	Irrigated Area Square feet

Every site generates unique supply and demand. For some sites, rainwater harvesting systems will provide enough water to meet irrigation demands, while for others, harvesting will only partially satisfy demand. Remember that supply fluctuates from year to year, depending on the weather (when and how much it rains). Demand can increase/decrease with plant water requirement, warmer-than-normal weather, as the landscape ages, irrigation issues, mulch layer maintained and with establishment of new plantings in the landscape.

Rainfall Harvesting Supply Worksheet						
	A	B	C	D	E	F
Follow the lettered instructions for each month	Enter the rainfall amount in inches for each month	Multiply “A” by 0.623 to convert inches to gallons per square foot	Enter the square footage of the catchment surface	Multiply “B” by “C” to yield the gross gallons of rainfall per month.	Enter the runoff coefficient for your catchment surface	Multiply “D” by “E” to obtain the total monthly yield of harvested water in gallons
January	0.53	0.33	1625	536	0.9	**483**
February	0.58	0.36	1625	585	0.9	**526**
March	0.42	0.26	1625	425	0.9	**383**

April	0.73	0.45	1625	793	0.9	**665**
May	1.79	1.11	1625	1812	0.9	**1631**
June	1.71	1.06	1625	1731	0.9	**1558**
July	1.89	1.13	1625	1842	0.9	**1658**
August	1.77	1.10	1625	1725	0.9	**1553**
September	2.31	1.39	1625	2259	0.9	**2033**
October	1.77	1.10	1625	1725	0.9	**1553**
November	0.65	0.39	1625	633	0.9	**570**
December	0.65	0.39	1625	633	0.9	**570**
Annual	14.80					**12518**

Plant water requirement is based on evapotranspiration and plant coefficient.

Rainfall Harvesting Demand Worksheet						
	A	**B**	**C**	**D**	**E**	**F**
Follow the lettered instructions for each month	Enter the ET amount in inches for each month	Enter the appropriate plant water use coefficient	Multiply “A” by “B” to obtain plant water needs in inches	Multiply “C” by 0.623 to convert inches to gallons per square foot	Enter the total square footage of landscaping	Multiply “E” by “D” to obtain total landscaping water demand in gallons
January	1.30	0.75	0.96	0.61	1200	729
February	1.70	0.75	1.27	0.76	1200	918
March	4.20	0.75	3.15	1.89	1200	2268

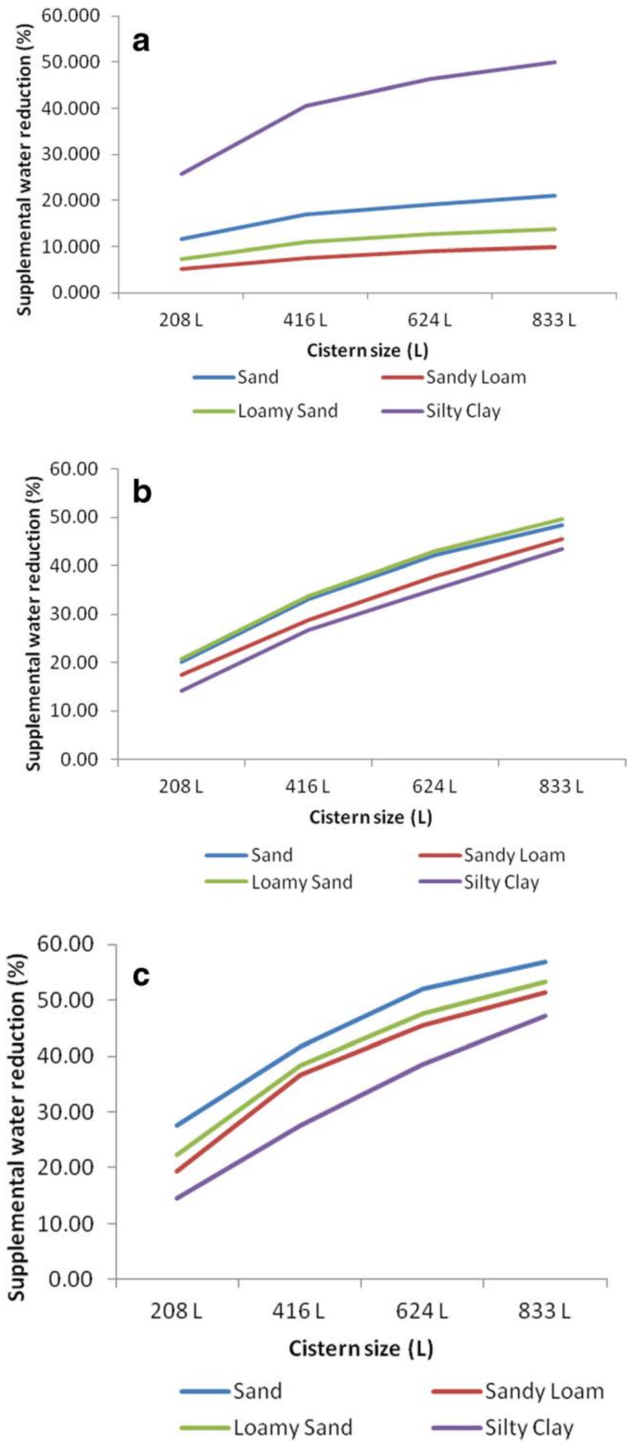
April	5.60	0.75	4.2	2.52	1200	3024
May	8.60	0.75	6.45	3.87	1200	4644
June	9.23	0.75	6.92	4.15	1200	4984
July	9.10	0.75	6.82	4.09	1200	4914
August	8.35	0.75	6.26	3.75	1200	4509
September	7.60	0.75	5.70	3.42	1200	4104
October	5.20	0.75	3.90	2.34	1200	2808
November	2.00	0.75	1.50	0.90	1200	1080
December	1.10	0.75	0.82	0.49	1200	594
Annual	64.98					25488

Plant Coefficients

Plant Water Use Coefficients	
Plant Type	Percentage
Low Water Use (Blue Grama, Buffalo, Zoysia, Desert Willow)	0.20
Medium Water Use (Bermudagrass, Spiraea)	0.50
High Water Use (St. Augustine, Fescue, Magnolia)	0.75

The plant water use coefficient represents the water requirements of a particular plant relative to rates of reference evapotranspiration (Et_o). Thus, a low-water-use plant requires only 20 percent to ET_o, but a high-water-use plant requires 75 percent of ET_o. New plantings of all types require more water. Supplemental water must be supplied when a plant's water use requirement (demand) exceeds the amount of water available from precipitation (supply).[2]

Research show rainwater harvesting is a feasible source for irrigation water.



Supplemental water reduction percentage for different cistern sizes, different irrigation scheduling methods **A** time-based; **B** soil moisture-based, and **C** ET-based as compared to NO RWH system for each irrigation scheduling method[3]

Connection to Irrigation

For a new irrigation system, the main line water source is the water from the cistern. For existing irrigation systems, disconnect the main line from the potable water source and connect the main line to the cistern.

Filtration

Clean water is essential for irrigation efficiency. Rainwater requires filtration before storage and distribution to remove any particles and debris. Debris off a roof will accumulate in the cistern, damage pump and clog nozzles. Debris of roof include roofing material, leaves, catkins and other flowers and fruit/nuts off trees and bird and animal droppings.

Keep gutters free of leaves and other debris. Clean gutters at least twice a year. Once in the fall after all the leaves have finished falling and again in spring after all the flowers fall. Or add gutter device to exclude debris.

Filter stormwater before entering the cistern and again before the water enters pump and irrigation system. For a small system use a first flush diverter. Larger systems, there are many types of filters for large systems. Consult with a Rainwater Harvesting Professional about the many selections, sizing the filter and maintenance. Filter water going into pump and irrigation system using an drip irrigation filter.

Pump

The pump size is determined by knowing the pressure required to run the irrigation system properly. Too high or too low a pressure will create unsatisfactory irrigation.

The "head" required of the pump is determined by calculating the total dynamic head of the system.

Equation 1. Total Dynamic Head (TDH)

$TDH = h_p + h_e + h_f$

TDH = total dynamic head (ft)

h_p = operating head (pressure) required by fixture (ft)

$h_e = h_2 - h_1$ = elevation difference between pump and fixture (ft)

h_f = friction loss in system (ft)[4]

Once the required flow and total dynamic head are determined, consult a pump vendor for information on specific pumps that are best suited for system demand. On-Demand, Irrigation, transfer, sallow well pump and submergible pumps all have different features. Select one that works best for the site, system and customer. A pressure tank is required for some systems.

Back-Up Water

If the catchment area is not large enough to collect enough water for irrigation, a supplemental water resource is required. Supplemental water or Back-up water is from another water source, municipal or groundwater. Cross contamination with potable water must be avoided using a

backflow prevention device. Attached the supplemental water near the top of the cistern with a six inch air gap between the opening for the back-up water to the top of the overflow pipe. Check with the city to see if they also require a backflow prevention device in the potable water line.
There are several companies with devices to automate back-up water so the entire cistern will not fill up with potable water. Check with a Rainwater Harvesting Professional for selection of these different devices.

Maintaining Your Rainwater Harvesting System

Inspect water harvesting systems monthly to assure the system operating properly.

Use this maintenance checklist to keep your system in top condition:

- Develop a maintenance checklist
- Develop and use a schedule for maintaining system
- Keep a Diary of maintenance –and Usage
- Trim tree branches away from roof
- Keep debris out of gutters and downspouts
- Clean filters/screens going into and out of cistern
- Inspect tanks, lines and connections for leaks. Repair any leaks
- Empty First Flush after each rainfall or install an automatic or semiautomatic drain
- In colder climates, empty first flush before a freeze and protect pipes from freezing temperatures
- Flush debris from cisterns if necessary
- Clean and maintain filters, especially those on drip irrigation systems
- Lower level in system before each rainfall
- Lower level in cistern to allow for freeze expansion in cold climates

Rainwater Harvesting for Irrigators
Rainwater harvesting is an option irrigators, landscape management companies, and property managers should offer commercial and residential clients. Familiarize yourself with all options for rainwater collection systems and the calculations. Contact rainwater collection professionals to design and install rainwater collection systems. The American Rainwater Catchment System Association (ARCSA) and Texas A&M AgriLife Extension is the education and certifying organization for rainwater professionals. Their web site is http://www.arcsa.org/. Visit this web site for a list of professionals. Many states have rainwater collection state associations that umbrella under ARCSA, so check for state associations. Texas Rainwater Catchment Association is at http://www.texrca.org/. Texas A&M University AgriLife Extension Rainwater Harvesting Team is a leader in education about rainwater harvesting. This team has created a web site with information including pictures, videos and many fact sheets and publications. Visit this informative site as http://rainwaterharvesting.tamu.edu. Check these web sites often because new technology for rainwater harvesting is developing daily as the demand for systems increase through the county and the world.

‘**Conclusion**
A RWH model based on mass-balance method for solving the complex storage-use dynamics of RWH system and investigating the effectiveness of RWH system as a SCM was developed and evaluated in this study. There were two standards for determining the effectiveness of the system: reduction of the total volumes of potable water used for irrigation and, reduction of the total runoff from an irrigated turfgrass plot. The evaluation was done for four soil types, comparing three irrigation scheduling methods, and four cistern sizes. A series of simulations showed that all cistern sizes were efficient in reducing total runoff and potable water used for irrigation as compared to a NO RWH system. When moving from coarse soil texture such as sandy soil to fine soil texture such as Silty Clay soil the total water runoff predicted increased and total supplemental water predicted decreased. While RWH cistern provided adequate storage for irrigation demand for the studied area and contributed to reducing potable water used for irrigation, it overflowed frequently during stormwater events and especially when water was not released for irrigation purposes. A controlled release program based on predicted rainfall amounts from upcoming storms would improve the efficiency of RWH as an SCM. Predictive equations were developed to assist users in selecting an appropriate cistern size to save water and/or reduce runoff from their residence. Decentralizing the urban stormwater runoff problem to be on a household scale by implementing RWH system could result in financial savings as well as enhance both human and environment quality.’[5]

Rainwater harvesting is one of many landscape water conservation practices to consider. Landscape design, plant selection, soil preparation, mulch, irrigation efficiency and proper maintenance are also essential.

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Irrigation Water Balance Modelling:
Better Landscapes Through an Improved Design Process

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Abstract. *It is generally agreed that water is a limited resources. 97% of the world's water is saline; we have a long and well documented history of abusing this resource/an almost exponential rise in human water use because of increases in population and per capita water use in the last 75 years. Climate change/global warming has simply exacerbated the problem.*

Landscape irrigation is based primarily on potable water sources. Recent initiatives to improve the efficiency of landscape irrigation design and products have reduced irrigation water consumption. Although admirable, these initiatives do nothing to address the problem/disease rather than the symptoms. The only way to start addressing the issue is to truly understand how much irrigation water will be required before the landscape design is finalized.

In its simplest form, Irrigation Water Balance Modeling, or IWBM, is an irrigation water consumption calculation based on plant water use, on a species by species basis, microclimate, soils and seasonally available precipitation information. This calculation allows us to accurately predict quantify daily, weekly, monthly and seasonal irrigation water requirements for a given landscape design early enough in the design process that the irrigation water design consumption can be quantified and potentially reduced through the elimination of irrigation in non-essential area and/or the substitution of less water consumption species. Only by understanding these factors can we design landscapes that are viable without continuing to overdraw on our water resources.

Keywords. Designer/Consultant, Policymaker, Water Manager, Water Provider, Turf/Landscape (Commercial), Turf/Landscape (Residential), Drip, Sprinkler, Deign, Conservation, Sustainability, Alternate & Alternative Water, Rainwater, Reclaimed & Recycled Water, Controllers, Turf/Landscape Smart Controller, Drip/Micro Systems, Turf/Landscape, Rain Sensor/Shut Off Switches, Rain Water Harvesting Equipment.

Introduction

What is Irrigation Water Balance Modelling (IWBM)?

- IWBM: Consumption calculation based on site specific criteria.
- Accurately quantifies irrigation water requirement.
- Accurately predict supply/availability with demand.
- New design parameters: L.I.D. and L.E.E.D.
- The rising cost of water.

Water Issues in General

About 1/3 of the world's population live in arid regions. That factor coupled with the acceleration of frequency of extreme weather events globally, as a function of climate change has resulted in extended periods of "atypical" weather everywhere. What does this mean? "The world is facing a crisis in water instability and is just walking up to the idea" (Dr. Howard Wheaton, 2013). In California the Sierra snow pack provides 75% of the annual freshwater supply. Similar to

Canadian Glaciers the Sierra snow peak is shrinking. If precipitation across the Sierras falls by 1% reservoir volumes by 32%.

The Prairie Provinces represent one of the most extreme “agricultural” climates in the world. 80% of Canada’s agriculture and important mineral resources are situated in the Saskatchewan Rivers basin. In some parts of the basin the water supply is already fully allocated and is additionally threatened by damaging floods and draughts as well as deteriorating water quality. “Water futures depend on what society chooses” (Dr. Howard Wheaton, 2013)

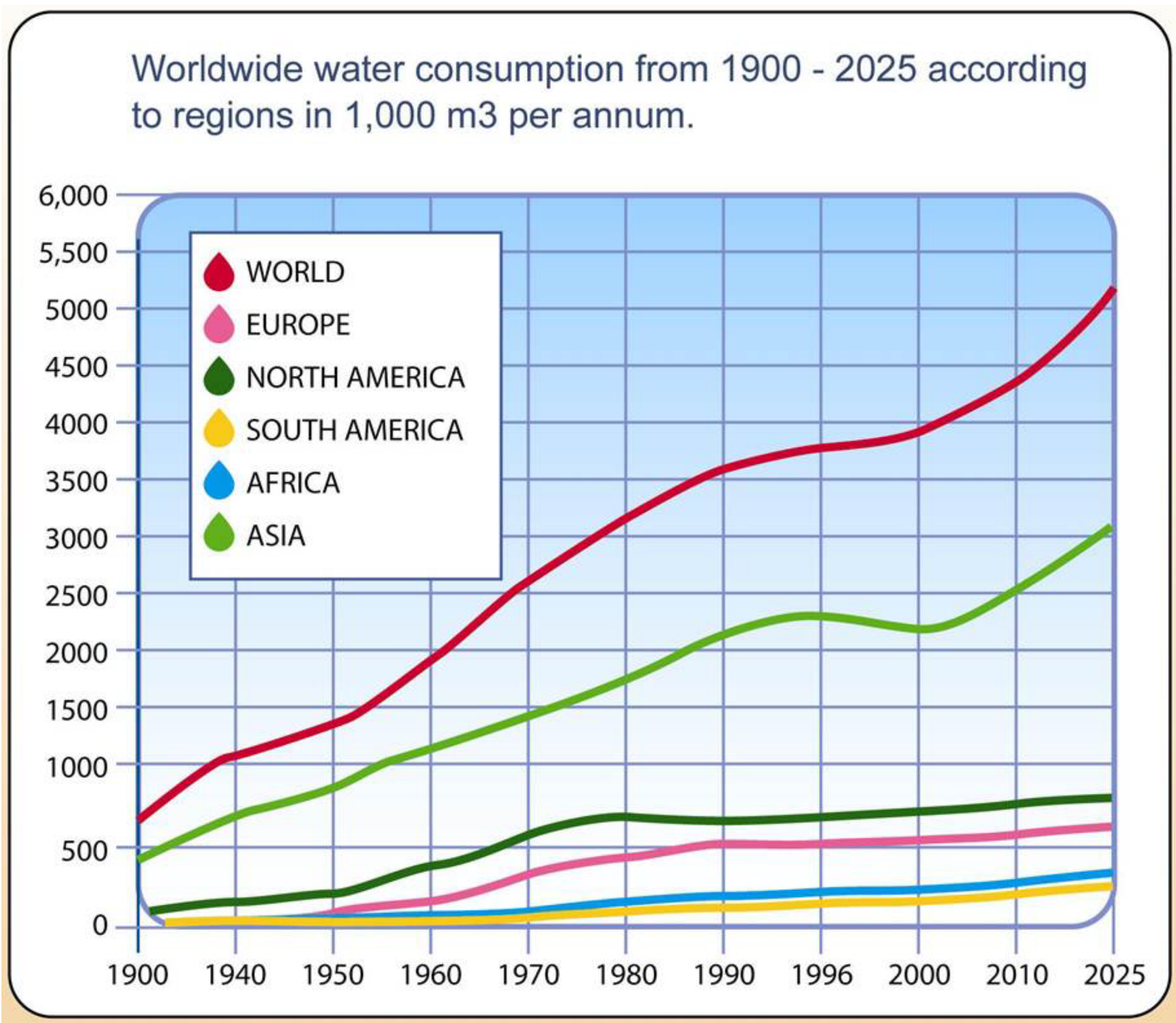

Figure 1. Worldwide water consumption from 1900 – 2015 according to regions in 1,000 m3 per annum.

In their report “GEO 2000,” the United Nations Environment Program UNEP states, that:
In the year 2000

- One third of the world’s population (more than 1 billion people in 21 countries) will not have a sufficient supply of potable water.
- Every year, more than 7 million deaths occur as a result of water pollution or scarcity.

In the year 2025

- Two-thirds of the world's population (more than 2.5 billion people) will not have sufficient potable water.
- 70% of crops worldwide will be produced with irrigation.
- China will consume 78% of its water supply for agricultural purposes, and India an even higher 93%

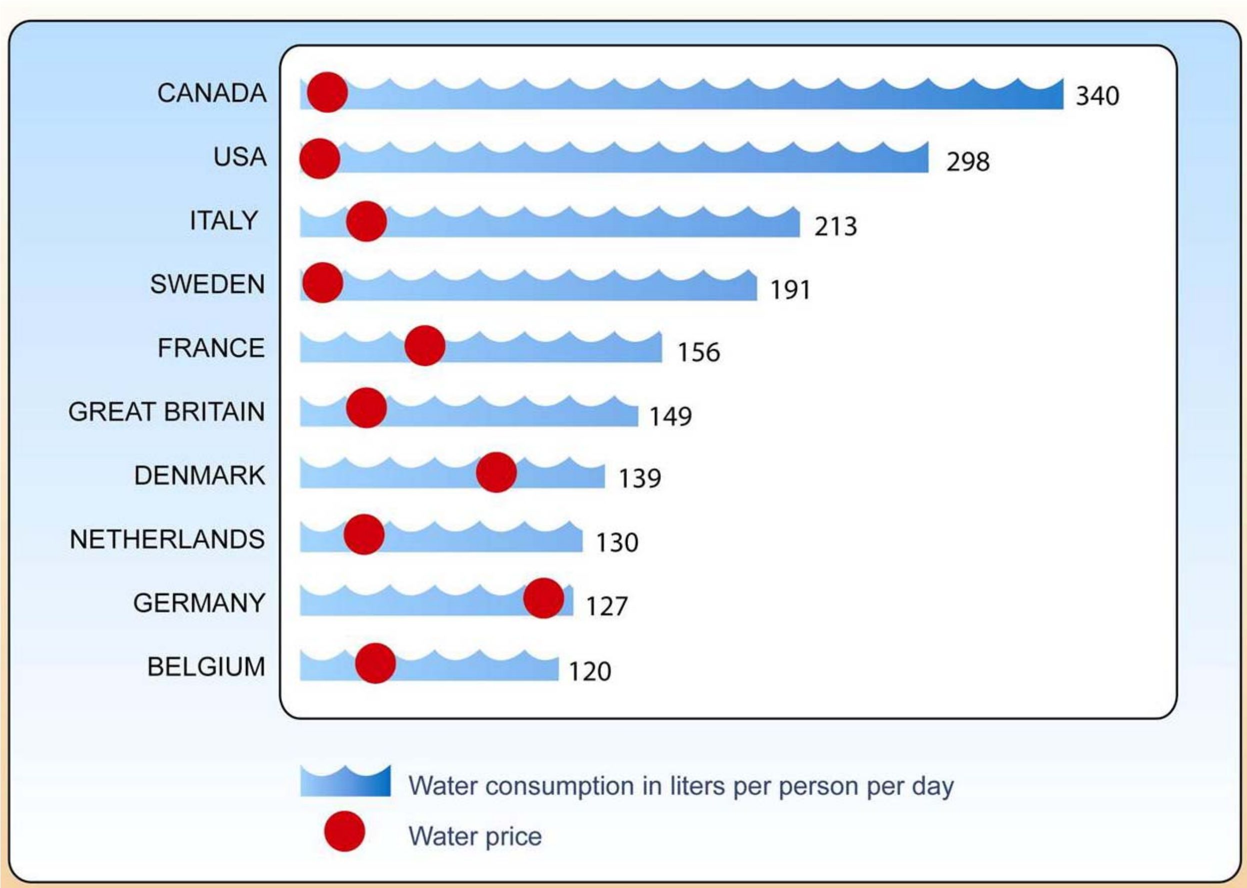

Figure 2. Regional Per Capita Water Use

The Amenity Landscape Industry

Every level of society is being sensitized willingly, or otherwise, to the increasingly precarious nature of our water reserves. In Canada we have been blessed with a historical surplus of freshwater reserves. Because of this, as a result public will continue to overdraw this reservoir (per capital Canadians triple the water use of most Europeans). Not specifically because of this issue, but over the last 20 years the major amenity irrigation manufactures have dramatically the efficiency and control potential factors of their product lines. Unfortunately as design industry landscape architects have not been as proactive as we could be in terms of translating these product improvements into more water "cautious" landscape designs. We are going to hit a wall in the not too distant future so my recommendation is to get in front of this challenge as soon as possible. Irrigation Water Balance Modeling has the potential to move us significantly in that direction.

Irrigation Product Innovations

In general these innovations can reduce or eliminates water waste and promote healthier plant growth:

- Match the water application to the specific needs of each plant.
- More closely match the application rate to the soil's infiltration rate.
- Apply water directly to the root zone to reduce overspray and evaporation.
- Reduces or eliminates runoff.

General Irrigation Design Considerations

- Available irrigation water volume
- Available water pressure
- Site soils
- Size and configuration of areas to be irrigated
- Type and number of obstructions within area to be irrigated
- Type of vegetation
- Physical activities within irrigated area
- Minimizing product variety within the site

The Landscape Design Process

Figure 3. Historically

Figure 4. Irrigation Water Consumption Calculation

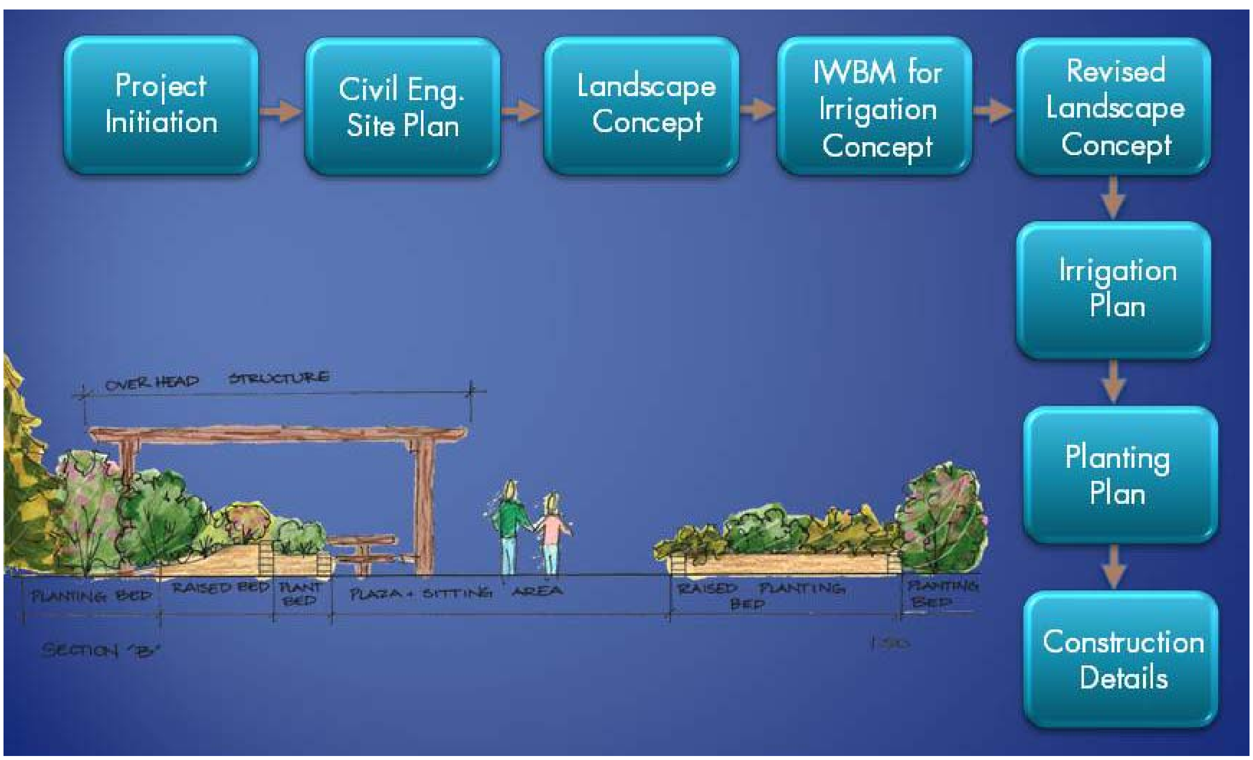

Figure 5. New Approach/Process

Figure 6. Landscape Concept

Figure 7. Irrigation Water Consumption Calculation

Environmental Considerations for IWBM

Climate/Microclimate

Table 1. General Climate Types in North America

Climate	Humidity	Avg. Max. Temp (°F)	ET (in.^{p}/day
Cool	Dry Humid	< 70 < 70	0.15 0.15
Moderate	Dry Humid	70 - 80 70 - 80	0.25 0.25
Warm	Dry Humid	80 - 100 80 - 100	0.35 0.30
Hot	Dry Humid	< 100 < 100	0.45 0.40

Microclimate Considerations

- Environmental conditions may also vary significantly within a single landscape
- “Average” microclimate: Adjacent structures, shade, surfaces, orientation and slope conditions do not influence the site.
- “High” microclimate: Sun (heat absorption/solar reflection and wind exposure overtly influence the site.
- “Low” microclimate: Shade and shelter overtly influence the site.

Precipitation

Table 2. Calgary police services 1 district weather data/site water balance

Month	Precipitation: Rain + Snowmelt (mm)	Precipitation on Site (m^3)	Harvested Water per Month (m^3)	Required Draw-down (m^3)	Obtained from Cistern (m^3)	Water Remaining in Cistern (m^3)
September Half	22.85	61.12	31.38	0.00	0.00	31.3822
October	13.90	37.18	19.09	0.00	0.00	50.4725
November	12.30	32.90	16.89	0.00	0.00	67.3653
December	12.20	32.64	16.76	0.00	0.00	84.1208
January	11.60	31.03	15.93	0.00	0.00	100.0522
February	8.80	23.54	12.09	0.00	0.00	112.1381
March	17.40	46.55	23.90	0.00	0.00	136.0353
April	23.90	63.93	32.82	0.00	0.00	168.8595
May Half	30.15	80.65	41.41	0.00	0.00	176.5000
May Half	30.15	80.65	41.41	-1.96	0.00	176.5000
June	79.80	213.47	109.60	-56.09	0.00	176.5000
July	67.90	181.63	93.25	-24.25	0.00	176.5000
August	58.80	157.29	80.76	0.09	0.09	176.5000
September Half	22.85	61.12	31.38	17.57	17.57	176.5000

Soils As

We can look at soil as a reservoir for water

Soil, in general, influences the plant's growth by:

1. Supporting and anchoring the plant
2. Supplying and storing the essential nutrients
3. Supplying and storing the plant's water needs
4. Supplying and storing the plant's oxygen needs

Soil Structure

1. Refers to the various arrangements of soil particles
2. Primary constituents/elements (sand, silt, or clay)

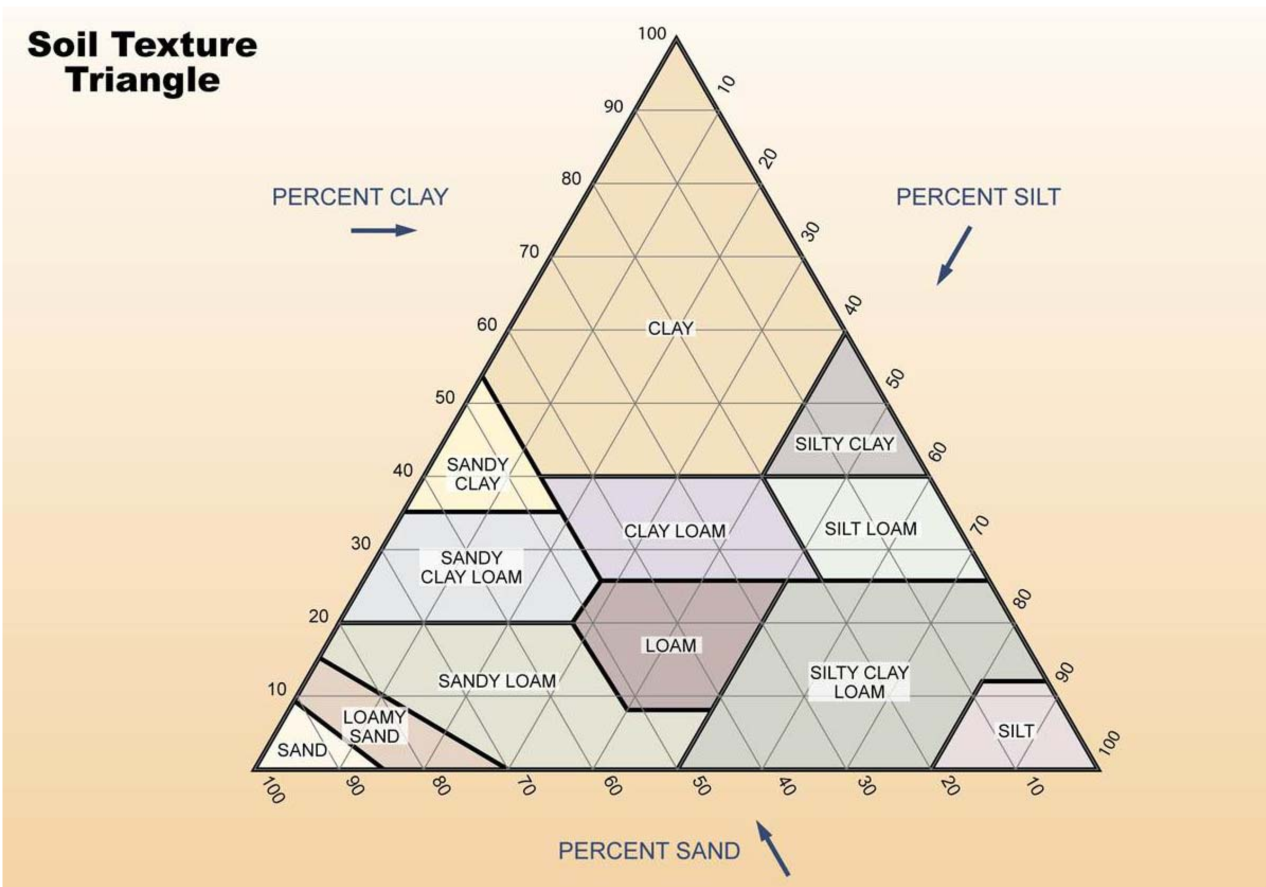

Figure 8. Soil Texture Triangle

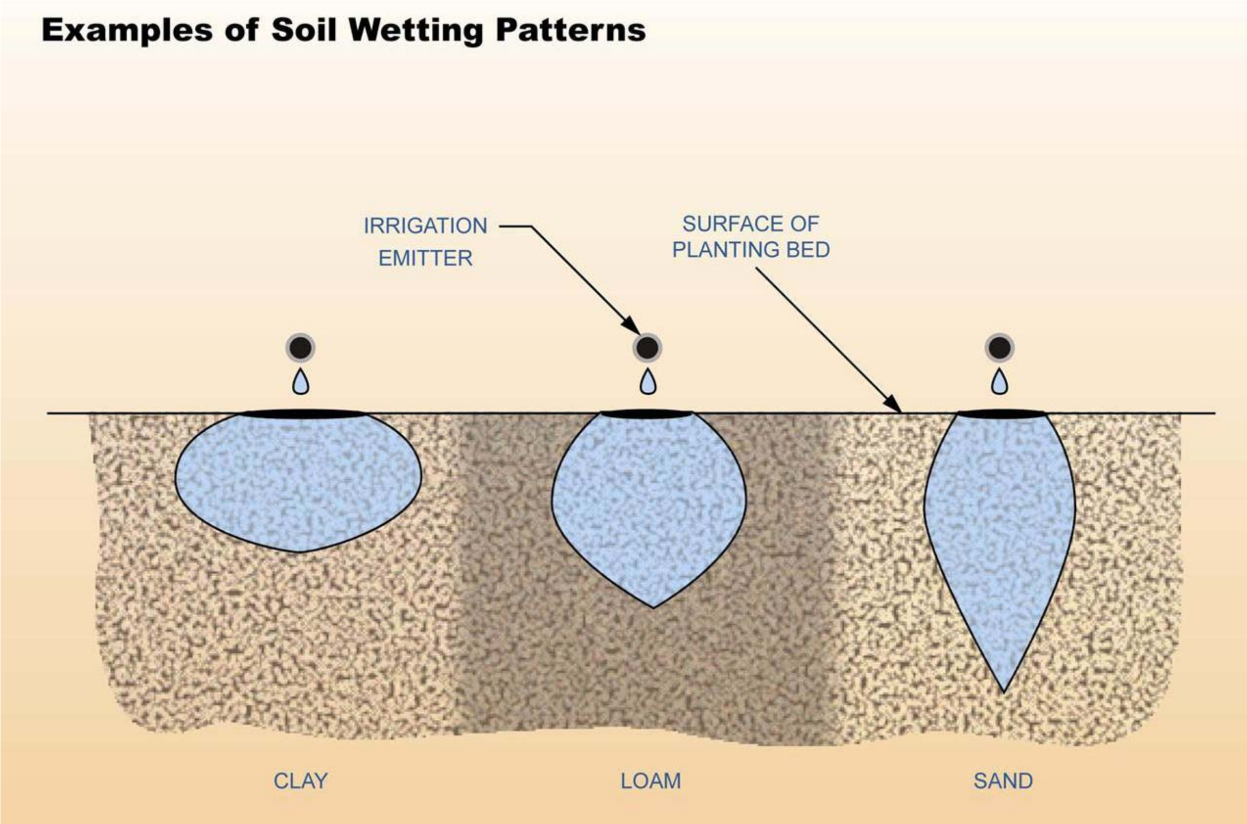

Figure 9. Examples of Soil Wetting Patterns

Plants/Plant Water Use

a) Factors which affect plant growth
b) General use characteristics

- High - Ornamented
- Average – Naturalized
- Low - Native

The difference between low water use and drought tolerance.

Plant Water Use Calculations

Plant water use is based on Irrigation Association design principals for soils, microclimate and planting density factors, as well as, plant species, character, and size at maturity.

Plant Landscape Coefficient: KL = Ks x Kd x Kmc

Where: KL = Landscape coefficient
Ks = Species factor
Kd = Density factor
Kmc = Microclimate factor

Different plant species can vary considerably in their rates of water consumption/evapotranspiration. Some species require/transpire large amounts of water, while others use relatively little.

Because there is such a wide range of water needs among different landscape plants, the water use is divided into three use groups: High, Medium, and Low, as shown below.

Table 3. Species Factor (Ks) for Different Plants

Vegetation	High	Average	Low
Trees	0.9	0.5	0.2
Shrubs	0.7	0.5	0.2
Ground Cover	0.9	0.5	0.2
Mixed Cover	0.9	0.5	0.2
Turf Grass	0.8	0.75	0.6

Calgary is classified as a cool, dry climate therefore our worst case Evaporation Rate is 0.15-0.20 inches/day. For calculation purposes species factors (Ks) for this project are keyed to actual values for local species/climate information.

The following formula is used to calculate the required maximum amount of water to apply on a per plant basis. For Trees we will assume the calculation at 75% of the plant's maximum size based on Landscape Nursery Trades Association information.

Plant Water Use: $ETp = Ks \times ETr$ (in./day)

Where: ETp = Plant Water Use (in./day)
Ks = Species Factor
ETr = Reference ET

Additional Considerations

How do LEED initiatives relate to irrigation design?

The US Green Building Council, as the governing agency for L.E.E.D. criteria in the United States, and its counterpart, the CaGBC in Canada, promote similar, but less specific, design criteria as the Irrigation Association in terms of irrigation water conservation.

LEED Design Considerations are divided into five key performance categories:

- Sustainable Sites
- Water Efficiency
- Energy and Atmosphere
- Materials and Resources
- Indoor Environmental Quality

A sixth category: Innovation and Design Process rewards exceptional environmental and/or design performance.

LEED Point System: Certified/Silver/Gold/Platinum

From an irrigation design standpoint, we can contribute to the Sustainable Sites, and Innovation categories, but most significantly in Water Efficiency category:

WE 1.1

The intent is to limit the use of potable water for landscape irrigation to 50%. To achieve this point, potable water consumption for irrigation purposes must be reduced by 50% over conventional means by using captured rain or recycled site water.

WE 1.2

The intent is to eliminate the use of potable water completely for landscape irrigation purposes. This point is achieved by using **ONLY** rainwater or captured site water as the source for irrigation water.

L.I.D. or Low Impact Development Parameters

What is L.I.D.?

In it's most basic sense and as it applies to this discussion, L.I.D. is the matching of post development storm water flows to pre-development storm water flows.

What does it mean?

In terms of storm water design it means an increase, on a community by community basis, in storm water retention/detension facilities and storm water engineers are generally looking for every means possible to lose volume out of these facilities without putting it directly into conventional storm water systems based on the general premise of recharging the groundwater system. What this means to irrigation design is that we need to look harder at non-potable irrigation water sources, such as storm ponds.

Non Potable Water Sources

- L.I.D. – Required drawdown vs. irrigation consumption
- Rain Water Harvesting – allowable drawdown vs. irrigation consumption

Irrigation Control

IRRIGATION SCHEDULE CHART

										JUNE 1 -- AUGUST 30					SPRING - FALL				
STATION/ ZONE	ZONE VALVE	PSI AT VALVE	HEAD TYPE	NOZZLE NUMBER	FLOW (GPM)	PRECIPITATION RATE (IN/HR)	SLOPE	ASPECT	SOIL	TOTAL RUN TIME (min)	DAYS OF THE WEEK	NUMBER OF CYCLES	CYCLE TIME (min.)	SOAK TIME (min.)	TOTAL RUN TIME (min)	DAYS OF THE WEEK	NUMBER OF CYCLES	CYCLE TIME (min.)	SOAK TIME (min.)
1	38mm	45	ROTOR	2.8/4.0	30	0.48	YES	SOUTH	CLAY LOAM	153	MWF	3	17	75	108	MWF	3	12	16
2	38mm	45	ROTOR	2.8/4.0	34	0.48	YES	SOUTH	CLAY LOAM	153	MWF	3	17	75	108	MWF	3	12	16
3	38mm	45	ROTOR	2.8/4.0	30	0.48	YES	NORTH	CLAY LOAM	153	MWF	3	17	75	108	MWF	3	12	16
4	38mm	45	ROTOR	2.8/4.0	34	0.48	YES	NORTH	CLAY LOAM	153	MWF	3	17	75	108	MWF	3	12	16

Figure 10. Irrigation Schedule Chart

How Do You Do It?

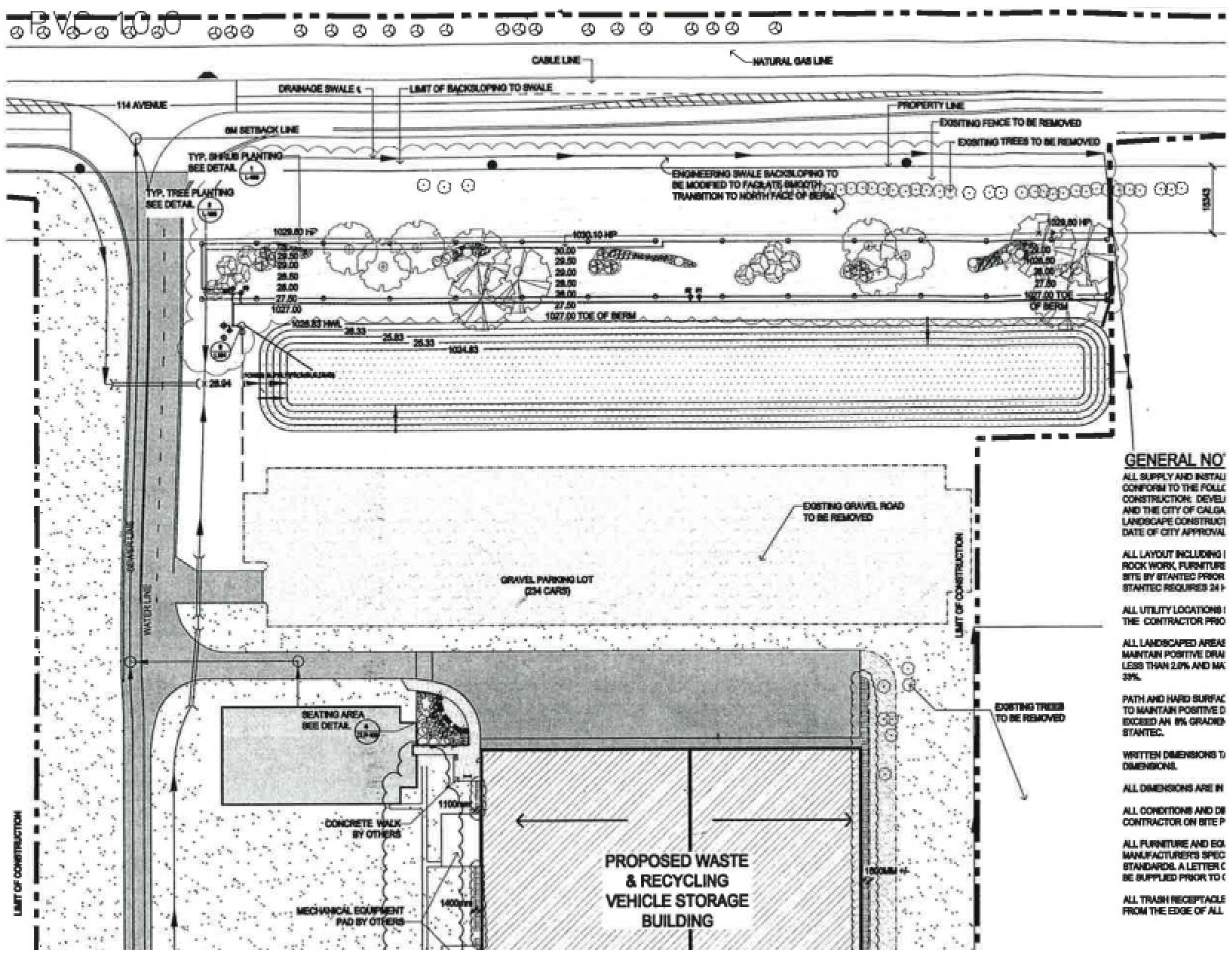

Figure 11. L.I.D.

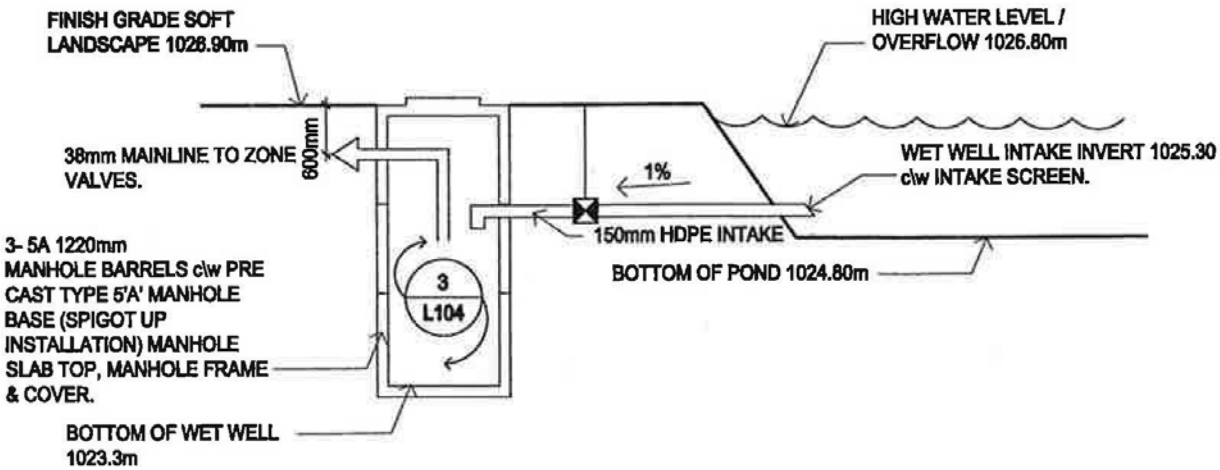

Figure 12. L.I.D.

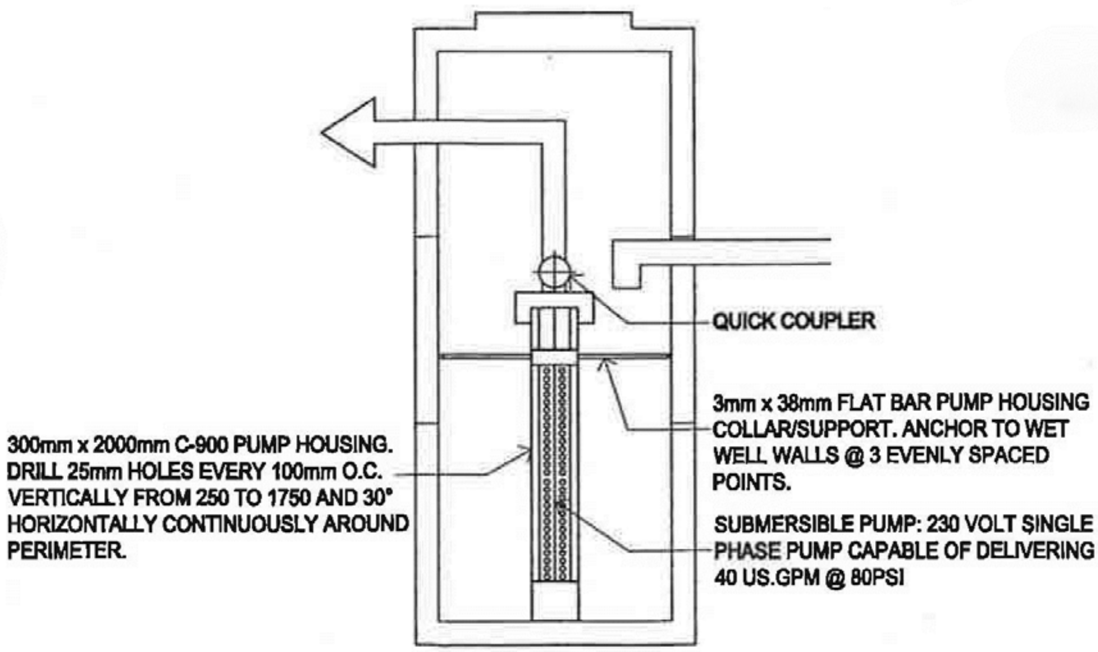

Figure 13. L.I.D.

Rainwater Harvesting

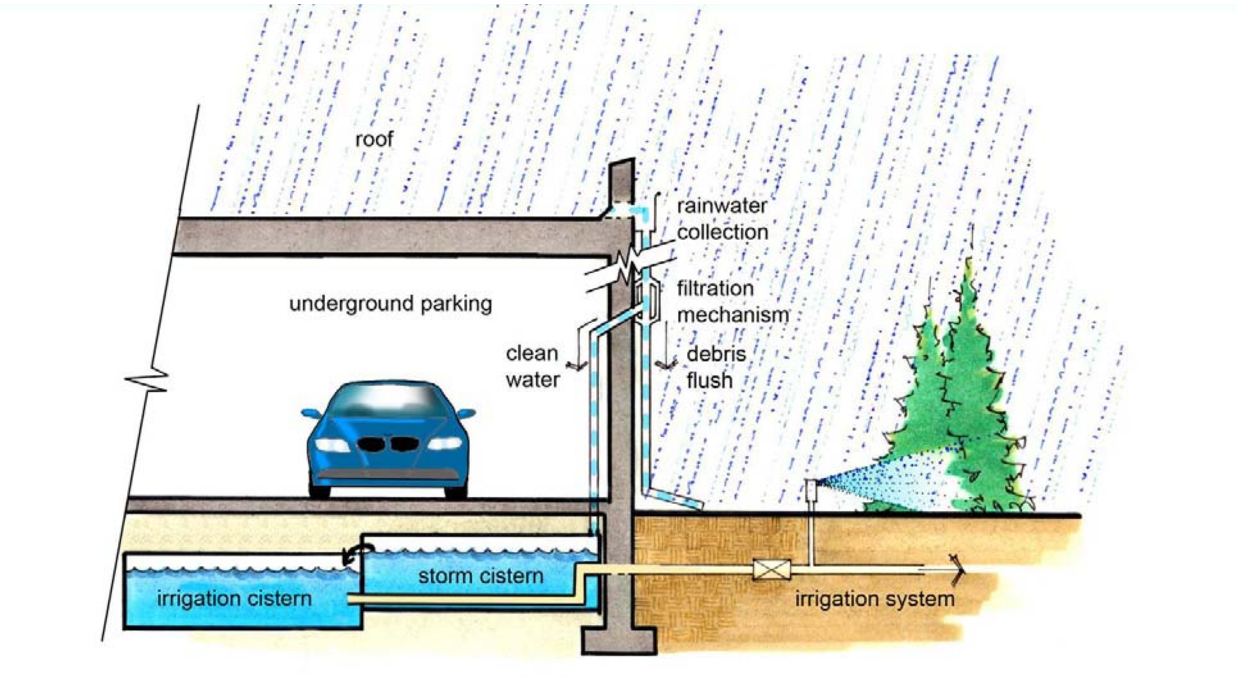

Figure 14. Rain Water Harvesting For Non-potable Use: Irrigation

Table 4. Non Potable Water Source Availability Calculation

Month	Precipitation: Rain + Snowmelt (mm)	Precipitation on Site (m^3)	Harvested Water per Month (m^3)	Required Draw-down (m^3)	Obtained from Cistern (m^3)	Water Remaining in Cistern (m^3)
September Half	22.85	61.12	31.38	0.00	0.00	31.3822
October	13.90	37.18	19.09	0.00	0.00	50.4725
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December	12.20	32.64	16.76	0.00	0.00	84.1208
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August	58.80	157.29	80.76	0.09	0.09	176.5000
September Half	22.85	61.12	31.38	17.57	17.57	176.5000

Irrigation Needs During Growing Season -64.64 m^3
Irrigation Needs Provided by Cistern 17.66 m^3

% of Irrigation Needs Provided by Cistern -0.27 m^3

Available Irrigation Water: A/W = TCA x CE x P x DWG = HW/M – DD = US Gal/m^3/month

Where:AIW = Available Irrigation water
TCA = Total Capture Area
CE = Capture Efficiency
P = Precipitation
DWG = Dewatering Water Generated
HW/M = Harvested Water per Month
DD = Draw Down

Conclusion

1) Irrigation Water Conservation: through a more interactive landscape/irrigation design process which gives consideration to plant species water use/requirements as an integral part of the landscape design species selection process.
2) Quantify Plant Water Requirements based on plant species selection & climate specificity as the basis of irrigation design: high water use species versus low water use or drought tolerant species.
3) Utilization of Non-Potable Irrigation Water Sources: improve LEED performance & increase compatibility with Low Impact Development principles.

References

Article in Serial Publication

"Water futures depend on what society chooses" (Dr. Howard Wheaton, 2013)

"The world is facing a crisis in water instability and is just walking up to the idea" (Dr. Howard Wheaton, 2013)

Conference, Symposium, or Workshop Proceedings and Transactions

"GEO 2000," the United Nations Environment Program UNEP

Overcoming the “water cycle” myth: Conserving water in Oklahoma City

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Abstract. *Stubborn drought in Oklahoma has been the precursor for water conservation programming in the City of Oklahoma City. Oklahomans have grown accustomed to plentiful water resources; however, due to persistent drought across the state, competition between municipalities, and population growth, water policy is becoming a serious concern. In 2013, the Oklahoma City Utilities Department contracted with the Oklahoma State University Department of Horticulture and Landscape Architecture (OSU) and the Oklahoma Cooperative Extension Service (OCES) to help promote outdoor water conservation throughout the city. Providing resources and education for homeowners and irrigation managers is a critical step to prepare for long-term drought conditions in a state with limited water restrictions. A citywide telephone survey revealed many barriers for educators to overcome including participants' uncertainty in their ability to conserve water outdoors and lack of confidence on how to determine water needs of the landscape. This program has created many educational tools and outreach opportunities for homeowners, golf course managers, and irrigation contractors.*

Keywords. Conservation, education, sustainability, turf/landscape, water provider, consumer preference

Background

Public water utilities across the United States are recognizing the value of water conservation awareness programs. Cities have seen both the direct and indirect benefits resulting from water savings including decreased pressure on operating systems and increased capital. Some water districts have found that water conservation programs decrease the need for additional water supply storage and infrastructure expansion (Kennedy and Goemans, 2008). The Western Resource Advocates determined that “Urban water conservation is often cheaper, faster, and smarter than traditional ‘concrete and steel’ water supply approaches; conserving water allows us to do more with less.” Currently, Oklahoma is experiencing a prolonged, four year drought which is predicted to remain in the western part of the state through December 31, 2014 (National Oceanic Atmospheric Administration, 2014). Drought is often the precursor for water conservation planning (Anderson-Rodriquez, 1996). In recent history, Oklahomans have experienced wetter than normal conditions from 1985 to 2010 creating a skewed viewpoint of climatic conditions across the state. Due to this viewpoint, many Oklahomans are accustomed to over-irrigating their landscapes with no repercussions, and the majority of Oklahoma City residents may be unaware of the importance of water conservation. Often times, the water cycle is cited to support why homeowners do not need to conserve water, and many Americans assume that their water supply is reliable and abundant (Attari, 2014). It has been shown that water consumption is dependent on many factors including attitudes and belief towards water use (Renwick and Archibald, 1998; Mayer and DeOreo, 1999; Renwick and Green, 2000). However, studies have shown water supplies will become more variable as climatic factors such as precipitation and temperature change. In Oklahoma City, approximately 30 to 50 percent of household water use is consumed in the landscape. Reducing water applied in excess of plant water need is crucial for conserving water supply. To help reduce peak water demand and promote water conservation the city implemented a mandatory odd/even water schedule. Once the combined lake supply drops to 50 percent, the water restrictions will go to 2 day per week watering restrictions.

Oklahoma City relies on water from the North Canadian River, Atoka Lake and McGee Creek Reservoir. The water rights are assigned by the Oklahoma Water Resources Board (OWRB). The Oklahoma City Water Utilities Trust (OCWUT) has the permitted rights for 423,334 acre-feet per year. Although this is the permitted right during years of drought, evaporation can reduce the surface water availability. Oklahoma City owns four water supply lakes including Overholser, Hefner, Atoka and Draper and water rights in Lake Canton and McGee Creek Reservoir. Lakes Overholser, Hefner and Draper are within city limits. Atoka and McGree Creek Reservoirs are in southeast Oklahoma and Lake Canton is located in northwest Oklahoma. The entire state has experienced a three year drought which has been detrimental to Lake Canton which is currently at 20 percent of maximum capacity. Lakes Canton, Hefner and Overholser receive water from the North Canadian River and Lake Draper receives water from Lakes Atoka and McGee Creek via a 100-mile pipeline. OCWUT currently serves approximately 600,000 municipal, domestic and industrial users with a current demand of 241,768 acre-feet per year (AFY). With a projected water demand of 353,965 AFY in 2060.

In 2013, the OCWUT approached Oklahoma State University Department of Horticulture and Landscape Architecture (OSU) to promote outdoor water conservation through education and outreach programs targeted at different customer groups. The current program is slated to end in 2015; however, OCWUT may continue the partnership with OSU for an additional three years.

Program objectives

The OKC program includes six distinct objectives: 1) Educate homeowners, managed property owners, irrigation installation companies, and golf course managers through workshops, publications and seminars; 2) Build outdoor water conservation demonstration research areas; 3) Develop a public service announcement campaign; 4) Assess overall educational program effectiveness; 5) Evaluate environmental impacts of recycled water irrigation water, and 6) Assess specific educational programs and landscapes using pre-and post-surveys. The following sections discuss the specific goals in detail.

Educate homeowners, managed property owners, irrigation installation companies, and golf course managers through workshops, publications, and seminars

Public support is crucial for water conservation program acceptance and success (Howarth and Butler, 2004). Typically public awareness campaigns are expected to reduce demand by 2 to 5 percent (Wang et al., 1999). Billing and Day (1989) found that the conservation effects due to publicity only exist as long as the publicity continues. Therefore, continued education and awareness campaigns are needed for long-term success. In Oklahoma City, education efforts are currently directed toward three distinct OCWUT customer groups; 1) Homeowners; 2) Commercial and managed property managers; and 3) parks and recreation, golf course, and sports field managers. Oklahoma State University has conducted multiple workshops geared toward homeowners. The workshops cover plant selection, turfgrass management, smart irrigation technology, and irrigation audits. Many publications have been created for use across the state and are utilized for homeowner education programs. In addition, OSU has visited with over two dozen homeowner and neighborhood associations to encourage responsible water use in the landscape. Many homeowners are unaware that they may be watering more than plant water need. A large proportion of homeowners do not know the source of their tap water, or that Oklahoma is in its fourth year of consistent drought conditions. Continuous education targeted towards irrigation companies and homeowners will increase best management practices in the landscape. The OSU team has created several publications that are free for the public, including a water conservation guide and a drought-tolerant plant guide for Oklahoma.

Build outdoor water conservation demonstration research areas

To effectively educate and promote best management practices in the landscape, OSU has created two demonstration areas and will construct three additional gardens. Each garden is located in very visible areas in high traffic locations. The largest demonstration garden is located at Oklahoma State University-Oklahoma City (OSU-OKC) and will be used for homeowner workshops and for OSU-OKC irrigation planning and design, and landscape planning classes. The OSU-OKC garden includes three irrigation controllers, a soil moisture sensor and an evapotranspiration sensor. The OSU-OKC garden was completed in May 2014 and the Myriad was completed in January 2014.The additional three gardens will be located at the OKC Zoo, Woodson Park, and Bluff Creek Park which are dispersed through Oklahoma City. The demonstration gardens provide homeowners with hands on training and easy ways to save water in the landscape. Oklahoma State University is focused on promoting the seven xeriscape principles, which are displayed throughout the demonstration garden areas. The gardens have been featured on *Oklahoma Gardening* which airs on Saturdays at 11:00AM and Sundays at 3:30PM on Oklahoma Educational TV Authority (OETA/PBS).

Develop a public service announcement campaign

A survey of 600 utilities customers in OKC found that 24 percent of those asked about the importance of water conservation stated that is was somewhat or not at all important. In general, Oklahoma residents may be less concerned with water conservation practices. To increase general water conservation awareness, the OSU team attends tradeshows, conferences and provides literature for a city-wide "Neighbors night out" event. The water conservation program is frequently highlighted in the water bill insert. Oklahoma City provides a water conservation website, SqueezeEveryDrop.com with information provided by OSU. The public service campaign has created a general awareness of the need for water conservation in Oklahoma and has provided tools for homeowners to utilize in their home landscapes. Public awareness campaigns have shown water use reduction. Eight urban California water agencies showed an average of 8 percent water savings due to public awareness campaigns (Renwick and Green, 2000). A remarkable 22 percent reduction in water use was determined due to San Diego's intensive education and advertising campaign (Shaw et al., 1992). Savings are typically only achieved for as long as the campaign continues. In the future, the OSU team will work with nurseries to provide informational leaflets to distribute to customers.

Assess educational program effectiveness through pre- and post- city wide surveys

A pre-telephone survey was completed in February 2014 and included 803 valid completed responses. The post-telephone survey will be replicated at the end of the program in 2015 to determine change in behavior. The pre-survey revealed that many of the respondents were unsure about how much water they actually use for irrigation. Only 9 percent of 529 respondents knew how much water they put on their lawns. Over 65 percent used their own judgment when watering the lawn and only 16 percent used the local weather. The majority of respondents, 77 percent out of 685, stated that they do not feel confident in their ability to conserve irrigation water. The survey revealed that there is an educational gap in Oklahoma City. Many homeowners could benefit from water conservation educational programing. Some other cities across the United States are mobilizing free or low-cost audit teams to educate the homeowners about proper watering techniques. Oklahoma City may benefit from this type of service. The majority of respondents, 51 percent out of 685, stated that they could tolerate a lighter green turf if it would result in a lower bill. While 16 percent stated they could not tolerate a lighter turf even if it lowered their bill. Results from the pre-survey showed that access to educational tools such as the Oklahoma Mesonet, the statewide weather monitoring system, and OSU websites and plant lists may help increase customer confidence and increase water conservation program success.

Evaluate environmental impacts of recycled water irrigation water

Reclaimed or recycled water is waste water that has been treated to levels suitable for reuse (Smith, 2011). Reclaimed water use reduces the need for purchasing water in other parts of the state, and decreases pressure on water municipalities during times of severe drought. Providing recycled water for irrigation and commercial purposes protects drinking water resources for human consumption. There are potential risks associated with the use of recycled water in urban environments; however, appropriate management and controls help reduce this risk (Toze, 2008). Reclaimed water contains various amounts of dissolved solids, nutrients and other elements (Qian and Mecham, 2005). Excess salts can build up in the soil profile and lead to plant mortality. Some of these nutrients are required for turfgrass growth and vitality, and should be considered in a landscape management plan. Starting in 1996, the City of Oklahoma City began offering recycled water to large industrial water users including OG&E, Redbud electric, and to the Gaillardia Country Club. Three out of the four wastewater treatment facilities in Oklahoma City can produce and deliver recycled water to industrial consumers, saving the city more than 1 billion gallons of drinking water per year (Chavez, 2012). The recycled water benefits the city as well as

Oklahoma City residents and businesses. To evaluate the environmental impacts associated with reclaimed irrigation water, five golf courses that receive irrigation water from various water sources including: reclaimed water, untreated surface/lake water, Oklahoma City treated water, and groundwater mixed with creek water were selected. Soil and water samples have been collected and results will be used to determine the effects of reclaimed water on soil properties. Reclaimed water could potentially be used to irrigate additional golf courses, athletic fields, and commercial industrial parks.

Assess specific educational programs and landscapes using pre-and post-surveys

On July 20 and August 10, 2013, two workshops were administered in Oklahoma City in order to provide homeowners with the tools to properly maintain their landscapes. During these workshops pre- and post-workshop surveys were administered. At the beginning of the workshop, prior to any presentation, participants completed a pre-survey to assess prior subject knowledge. At the end of the workshop, a post survey was administered to assess learning. As a third step, an internet follow-up survey was also conducted with willing participants a month after the workshops. The follow-up survey collected information on implementation of the home irrigation audits, barriers to auditing, and suggestions for improvement. In total, 70 and 30 people attended the first and second workshops with a response rate of 78 percent for the July workshop and 77 percent for the August workshop pre and post surveys, and 22 people responded to the follow-up survey.

In the pre-survey, 44 percent of respondents indicated understanding of the simple irrigation audit procedure. After the workshop, 68 percent of attendees understood how to do an irrigation audit, which was a major goal of the workshop.

Within 6 weeks of the workshop, participants were given a follow up survey. Forty percent of the 22 people who completed the follow up survey indicated that they audited their irrigation or watering systems, while 60 percent had not. When asked why the participants had not audited their irrigation systems, 11 percent of them indicated that they did not have enough time, 33 percent indicated that the weather kept them from conducting the audit, and 11 percent of them indicated that they needed an irrigation professional to help them. None of the workshop respondents indicated that not being able to remember how to conduct the audit and to program and run the irrigation system among the reasons for not auditing their system. However, 45 percent of them indicated other unnamed reasons for being unable to audit their system. Looking at the statement about whether they agree with the assertion that “The simple irrigation audit was easy to conduct,” 31 percent of people who took the follow up survey strongly disagree with the statement, 19 percent of them simply disagree, 13 percent neither agree nor disagree. Only 37 percent of them agreed or strongly agreed with that statement that the audit was easy to conduct, indicating the presentation or implementation could be tweaked or phone support provided after a workshop. More than half of the participants in the follow-up survey, 60 percent, indicated that their watering habits changed and over half, 67 percent, indicated that their watering schedule changed to late evening or early morning.

Homeowners many lack the understanding of how to maintain an attractive landscape while saving water. The goal of workshops and classes is to show, scientifically, that landscapes typically do not require irrigation every day or every other day. Through education, many homeowners change their habits and irrigate only when needed or during the correct time of day.

Conclusions

Many water users attribute the natural water cycle as proof that water is a renewable, abundant resource; unfortunately, the urban water cycle is often more representative of the actual process. Through education and increasing drought pressure, residents are becoming more aware of water issues facing Oklahoma. Awareness paired with changing regulations will prepare Oklahomans for continued drought conditions. Oklahoma municipalities should continue to work with irrigation contractors, universities, and extension to create a comprehensive program to change minds and overcome the “water-cycle” myth.

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Land Use Code Ordinance
to Support Water Conservation

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Abstract: *In 2009, Fort Collins Utilities adopted amendments to its Land Use Code to support landscape water conservation for new commercial developments. An extensive review process of the landscape plan was completed to address xeriscape principles of plant selection, water requirements, sun exposure and soil amendments.*

The irrigation plan review is the second step of the new process and needs to be designed with high-efficiency components to assure the most efficient performance of the landscape watering. Examples of the components, include a master valve, smart controllers and pressure-regulating heads. Once the irrigation plan is approved, periodic field inspections follow and an independent Certified Landscape Irrigation Auditor (CLIA) must performed catch can tests of selected turf zones before the project is complete.

Keywords: Land Use Code, water conservation, landscape water, Fort Collins, sprinkler efficiency, sprinkler design review process, inspections

Land Use Code Ordinance
to Support Water Conservation

Fort Collins Utilities provides water, wastewater, stormwater and electric services to more than 150,000 residents. Faced with a drought in 1977, Utilities created a part-time position dedicated to water conservation, which moved into a full time position by 1990. During this time frame, Utilities established specific goals design to lower the water use of its customers through a variety of educational programs and advertising campaigns.

An educational campaign targeting outdoor water use was put into place to identify high demand and provide opportunities for efficiency improvements. Among the conservation opportunities were improved irrigation efficiency, landscape transformation and customer education. A sprinkler audit program was developed at this time to help educate homeowners on outdoor water use.

Free xeriscape classes and workshops also were developed to help the community understand the essentials for healthy plants in our arid conditions. Offering sprinkler rebates and creating standards for new landscapes were the next steps to improve efficiency and lower landscape water use. Combined, these programs and services helped Fort Collins balance a growing community with a limited water source.

Landscape Standards

The first step to implement landscape standards was to assemble a team to identify the areas of the landscape that could be improved. These upgrades can be made through proper xeriscape principles and an irrigation system designed to eliminate water waste.

Installing a sprinkler system

The team was led by Water Conservation Manager, Laurie D'Audney. Members included local landscape designers, irrigation contractors, City of Fort Collins Parks and Planning Departments. These amendments were presented to City Council and adopted into the City's land use Code.

The following are the adopted amendments to the City's Land Use Code:

Landscape Review

All landscape plans must be designed to incorporate water conservation materials and techniques through application of xeriscape landscaping principles. Xeriscape landscaping principles include:

- Design. Identify zones of different water requirements and groups plants together with similar water needs ;
- Appropriate Use of Turf. Limit high-irrigation turf and plantings to appropriate high-use areas with high visibility and functional needs;
- Low Water-Using Plants. Choose low-water demanding plants and turf where practicable;

- Irrigation. Design, operate and maintain an efficient irrigation system;
- Soil Preparation. Incorporate soil amendments before planting
  - Three cubic yards of amendment per 1,000 square feet
- Mulch. Add mulch to planting beds to a minimum depth of 3 inches;
- Maintenance. Provide regular and attentive maintenance.

Landscape plans submitted must include:

- Accurate and clear identification of all applicable hydrozones using the following categories:
  - High Hydrozone: 18 gallons/sq.ft./season
  - Moderate Hydrozone: 10 gallons/sq.ft./season
  - Low Hydrozone: 3 gallons/sq.ft./season
  - Very Low Hydrozone: 0 gallons/sq.ft./season
- A Water Budget Chart that shows the total annual water use, which shall not exceed 15 gallons /sq.ft. over the site; including all hydrozones used on the landscape plan.

Irrigation Review

For any development provided water by the City, an irrigation plan must be submitted to and approved by the Utilities General Manager prior to the issuance of the building permit. The irrigation plan should incorporate the City of Fort Collins Irrigation System Standards for Water Conservation. In addition, the irrigation system must be inspected for compliance with the approved irrigation plan before the issuance of a Certificate of Occupancy.

Inspecting a new landscape

The irrigation plan is reviewed by the Utilities' Certified Irrigation Designer (CID). The City of Fort Collins Irrigation System Standards for Water Conservation are as follows:

- The irrigation system shall be designed according to the hydrozones shown on the landscape plan.
- Each zone shall irrigate a landscape with similar site, soil conditions and plant material with similar water needs.
- Turf and non-turf areas shall be irrigated on separate zones.
- On steep grades, an irrigation method with a lower precipitation rate shall be used in order to minimize runoff.
- Drip, micro-sprays, sprayheads and rotors shall not be combined on the same zone.

Irrigation Equipment

The irrigation plan components are essential to achieve the optimal performance from the system while limiting water waste.
The irrigation plan requirements are as follows:

- A backflow prevention assembly shall be installed in accordance with local codes.
- A master shut-off valve shall be installed downstream of the backflow device to shut off water to the system when not operating.

- Irrigation controller(s) shall be “smart” controllers, using climate-based or soil moisture-based technology, selected from the Irrigation Association’s current Smart Water Application Technologies (SWAT) tested products list or other similarly tested product list.
- A rain sensor shall be installed on each irrigation controller and installed according to the manufacturer’s specifications.
- All sprayheads and rotors shall be equipped with check valves and pressure regulating stems.
- Remote control valves shall have flow control.
- Properties with single or combined point of connection flows of 200 gpm or greater, shall have a control system capable of providing real-time flow monitoring and the ability to shut down the system in the event of a high flow condition.

Irrigation Inspections

After building permits have been approved and construction begins, periodic site inspections are performed to ensure installation follows the approved plan. These site visits are helpful in determining the number of zones necessary for catch can test audits and final inspections.

Performance Audit

A sprinkler performance audit must be performed by a landscape irrigation auditor certified by the Irrigation Association (CLIA). Other requirements of the field audit are:

Catch can test

- The auditor must be independent and not affiliated with the installation contractor.
- The audit shall include measurement of distribution uniformity (DU). Minimum acceptable distribution uniformities shall be sixty (60) percent for sprayhead zones and seventy (70) percent for rotor zones.
- The audit shall measure the operating pressure for one sprinkler on each zone to determine whether the zone meets the pressure requirements.
- Linking zones with similar heads nozzles and spacing can be done to gather an average value.
- A data input chart for the Smart Controller, including the precipitation rate from the audit, shall be posted at each irrigation controller.
- A copy of the sprinkler performance audit shall be submitted to and approved by the City before issuance of a certificate of occupancy (CO).

Final Submittals and Approval

Submit “as-built” of the irrigation plan, noting any minor changes of the installation. Complete smart controller input chart, sprinkler performance audit and catch can data forms to Fort Collins Utilities. The City inspector (CID) approves the installation and submittal documents before issuing a final CO.

Six-Week Inspection

Six weeks after the installation of new landscaping, the irrigation contractors are required to reset the smart controllers to the normal season watering schedule and remove the sod program from the controller. Fort Collins Utilities will inspect that the controller has been programmed for a normal watering schedule, the input chart has been posted and the weather station or rain sensor has been installed correctly and operating.

Conclusion

Fort Collins Utilities provides water, wastewater, stormwater and electric services to more than 150,000 residents. In order to continue providing water to a growing community, a water conservation division was established. Aggressive goals were set to control water demand by generating a series of educational programs promoting water efficiency and landscape transformations.

Free landscape and irrigation workshops, a free sprinkler audit program and sprinkler rebates contribute to managing the water use through proper water requirements and component upgrades.

New commercial developments are required to follow a strict review process for landscape and irrigation system designs. These adopted amendments ensure that new developments limit water waste by improved irrigation design standards and new water saving technologies.

Identifying Challenges and Improvements for the Water My Yard Program

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Abstract. *The WaterMyYard Program is an innovative new program launched in collaboration with the North Texas Municipal Water District (NTMWD) in May 2013. The program aims to help homeowners conserve water by providing them a weekly email with a recommended irrigation runtime rather than the amount of inches to apply. Homeowners create a profile by selecting on a district map the location of their residence and entering their sprinkler precipitation rate. However many homeowners do not know the precipitation rate of their sprinklers so an intuitive tool is used to allow them to pick their sprinkler type based on the sprinkler image, spacing and the manufacturer, thereby enabling manufacturers data be used to estimate precipitation rate. The program also incorporates local water restrictions such as days per week available for irrigation. Lessons from its pilot year have been incorporated into the WaterMyYard V2.0 program. This paper discusses the upgrades and challenges of the program as it evolves and becomes adopted by other. In 2014 we initiated a research project to investigate the spatial variability of ET drivers in an urban environment in order to determine the minimum number of weather stations needed. This paper will also provide an update on this project.*

Keywords. *Landscape Irrigation, Irrigation Scheduling, Homeowners, Evapotranspiration*

Introduction

The Water My Yard program and website (http://WaterMyYard.org) was developed using simple, intuitive images and information prompts for homeowners to receive recommendations on how long (in minutes) to run their irrigation systems. The program was launched in May 2013 as a joint effort of the Irrigation Technology Program of the Texas A&M Agrilife Extension Service (Extension) and the North Texas Municipal Water District.

The North Texas Municipal Water District (NTMWD) covers 1,600 square miles and provides to water services to 1.6 million residents of North Texas through 13 member cities. NTMWD provides the majority of water from Lake Lavon. With persistent drought over the last few years, lake levels have dropped resulting in mandatory outdoor water restrictions. Most restrictions have limited outdoor watering to two (2) days a week irrigation with recent restrictions allowing only one (1) day a week watering.

In the summer of 2014, WaterMyYard Program V2.0 was released. Stakeholder input was also incorporated into the new version to improve the homeowner experience with the program.

Water My Yard Program

Working with Extension, NTMWD purchased and installed seven (7) ET Weather Stations. Locations were chosen based on elevation, microclimates, district property, and variations in typical rainfall patterns. Weather station data is collected daily as a part of the TexasET Network (http://TexasET.tamu.edu) to calculate daily ETo. A customized interactive map was created (Figure 1.) for identifying homeowner location within the district in order to link the appropriate weather station.

Once the location is selected, confirmed or located, the homeowner is prompted to enter their precipitation rate (Figure 2.). If the precipitation rate is not known, they are given instructions on how to conduct a catch can test. Alternatively they can select their sprinkler type. Working with state and local irrigation associations and sprinkler manufacturer representatives, a list of irrigation systems was developed which describe the common irrigation systems used in the area (Figure 3.). These include spray heads, rotors, multi-stream rotors and drip irrigation (required in some landscapes as per Texas Rules and Regulations). After the sprinkler type is selected, the spacing between sprinklers (or emitters) and the manufacturer is selected in order to fine tune the precipitation rate for calculating runtime (Figure 4.). Once the precipitation rate is set, a runtime can be calculated.

In order to calculate the runtime, assumptions were made to keep this simple for homeowners. The first assumption is that the homeowner is watering a warm season turf grass with a kc = 0.6. Adjustment factor of “Normal Quality” or 60% of turf ETc was used. For NTMWD, a shift from Stage 2 water restrictions (2 days a week watering) to Stage 3 water restrictions (1 day a week watering) required a 10% reduction in water use as a part of the districts drought management plan. For this period the adjustment factor was reduced to a “Low Quality” or 50% of turfgrass ETc. This will keep the turfgrass alive but may result in some mild visual signs of turf stress during peak ET in the summer. Taking the adjustment factors into account along with user defined precipitation rate and localized weather station rainfall, the Water My Yard Program calculates weekly irrigation runtimes (Figure 5.). Once a runtime recommendation has been calculated, the homeowner can then sign up for weekly irrigation runtime emails to be received every Monday (Figure 6).

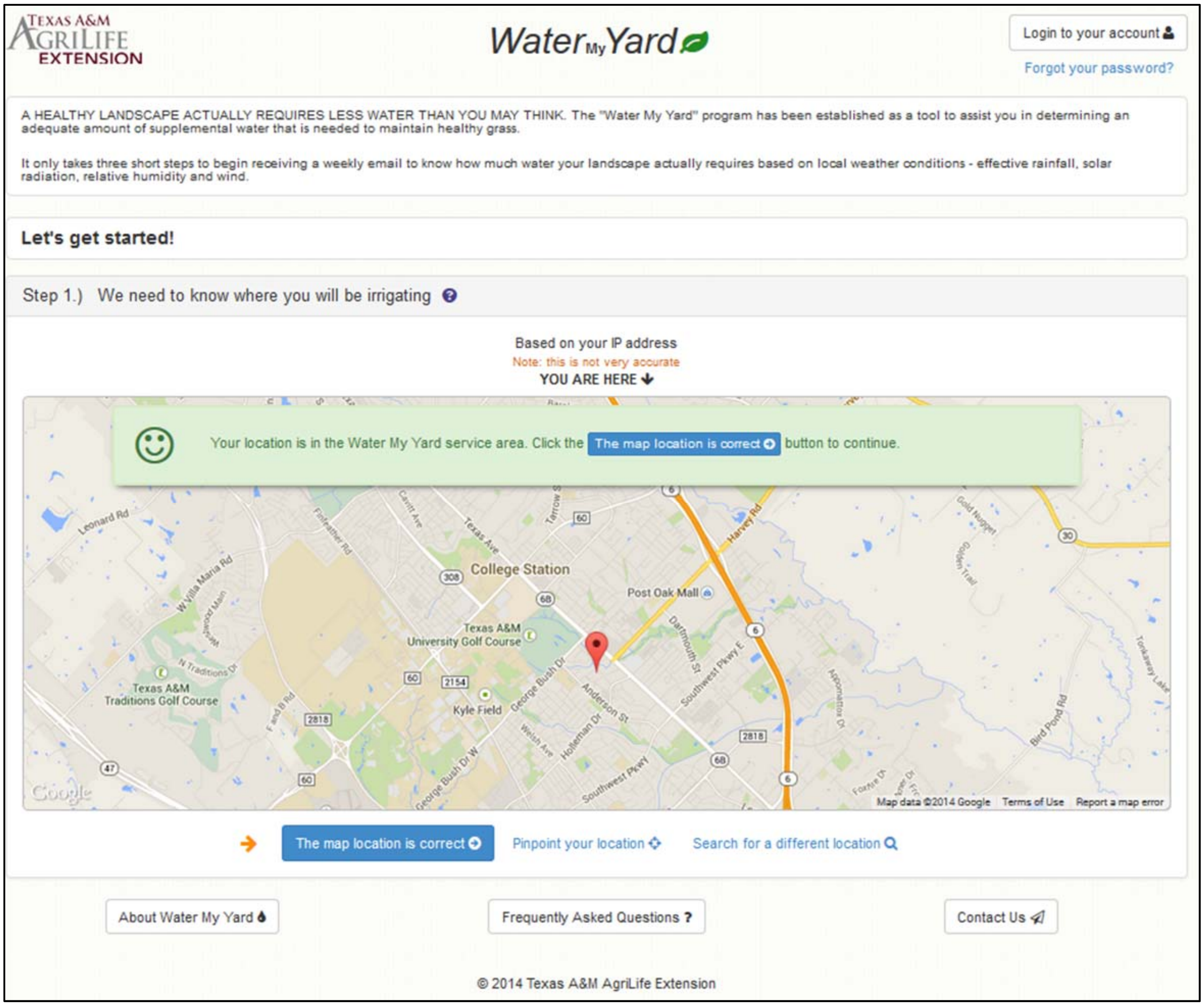

Figure 1. Water My Yard Homepage-Map

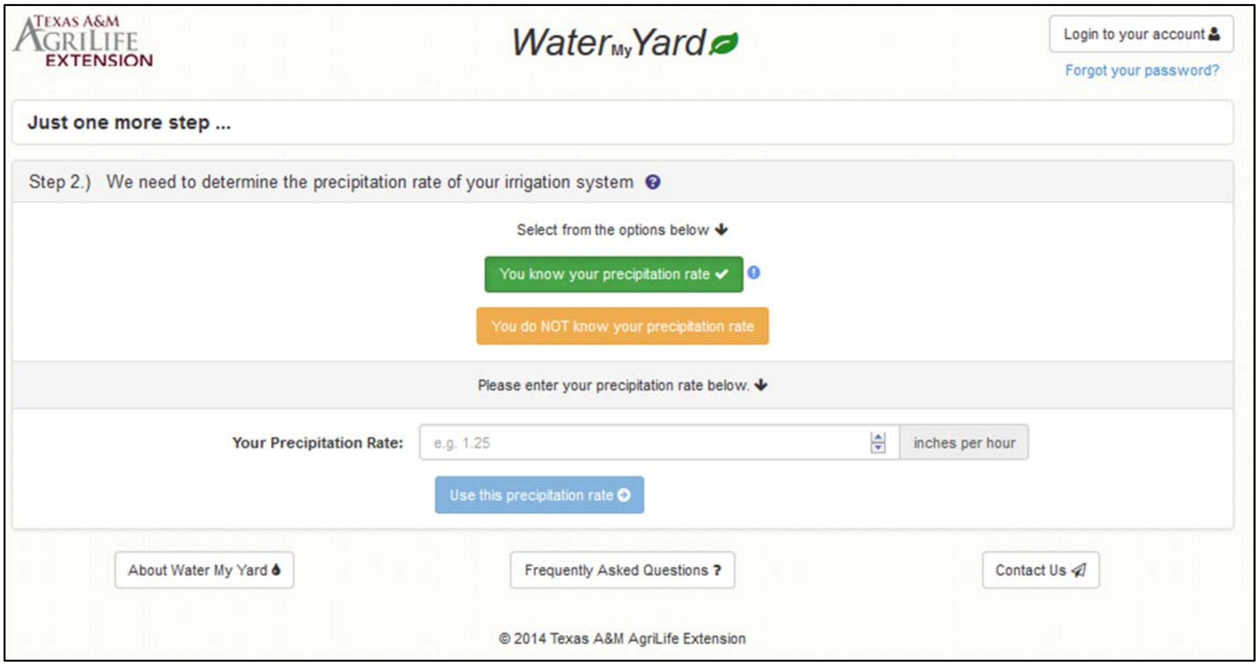

Figure 2. Water My Yard Step 2- Enter Precipitation Rate

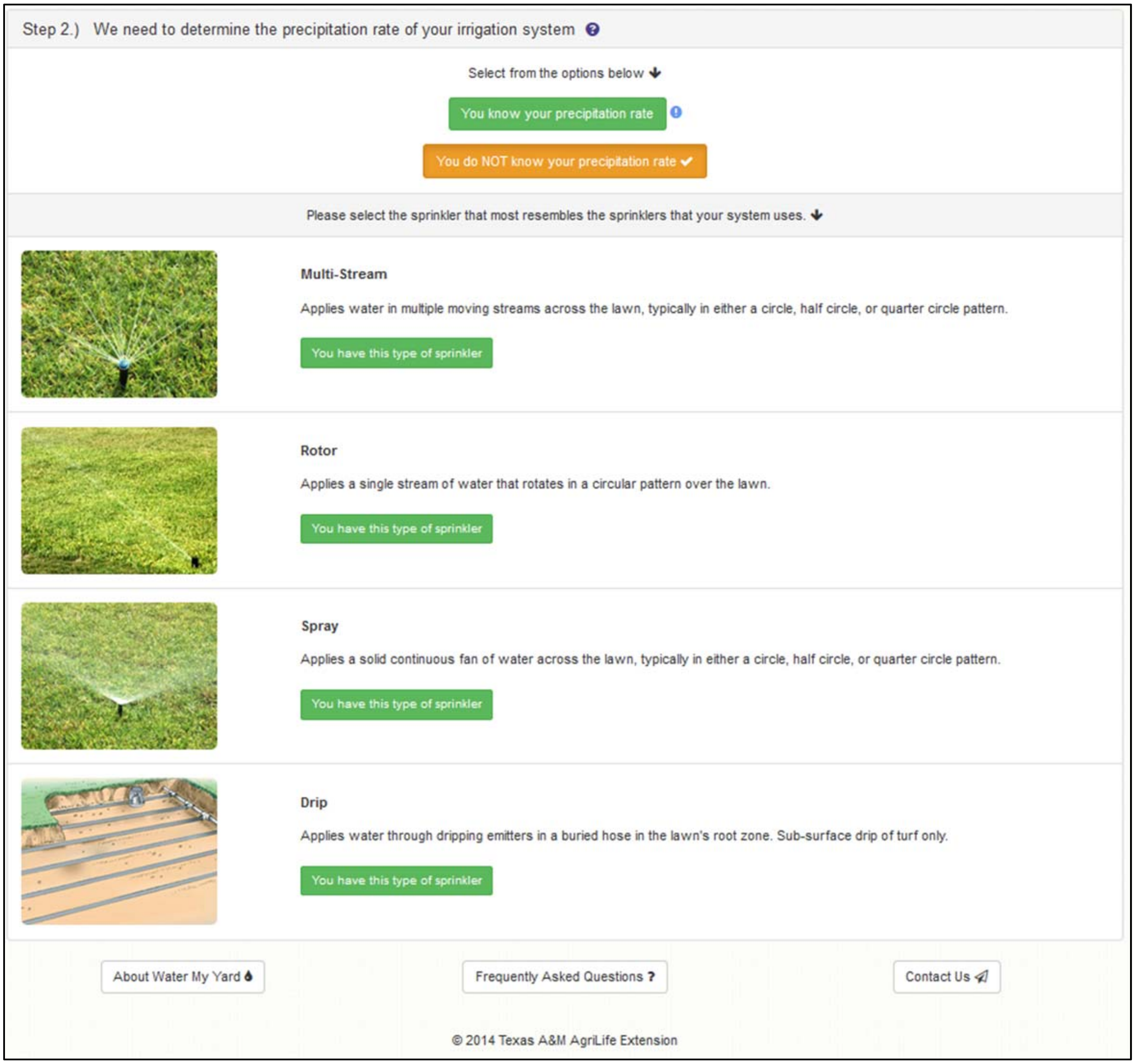

Figure 3. Water My Yard Step 2- Selecting Sprinkler Type

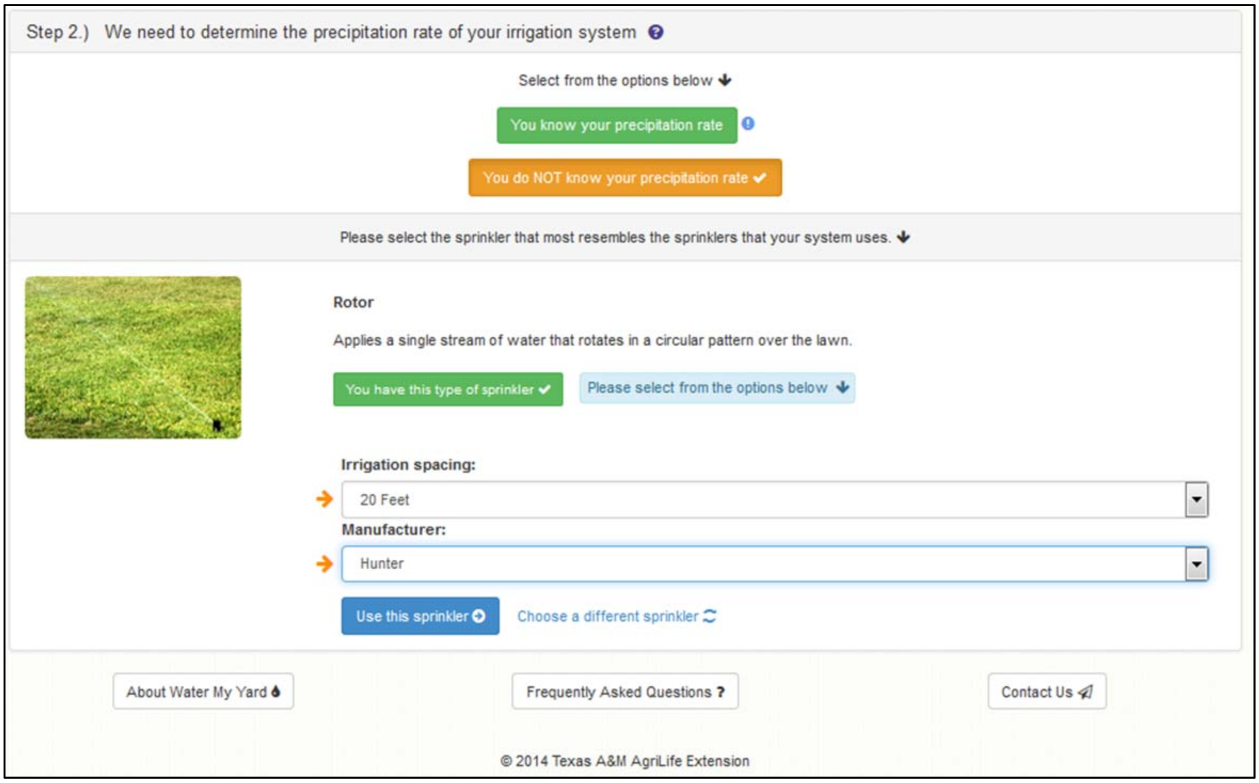

Figure 4. Water My Yard Step 2 – Selecting Sprinkler Installation Information

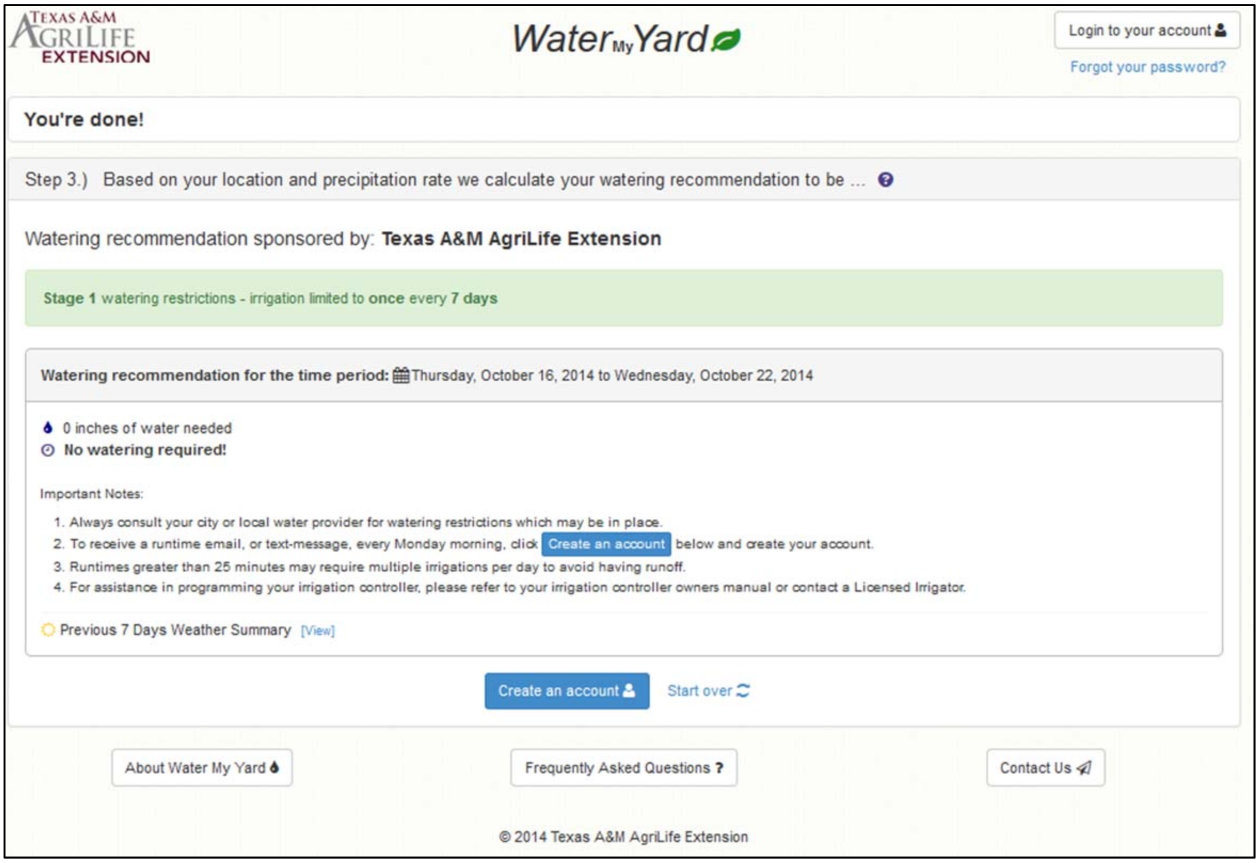

Figure 5. Water My Yard Step 3 - Select a Water Recommendation

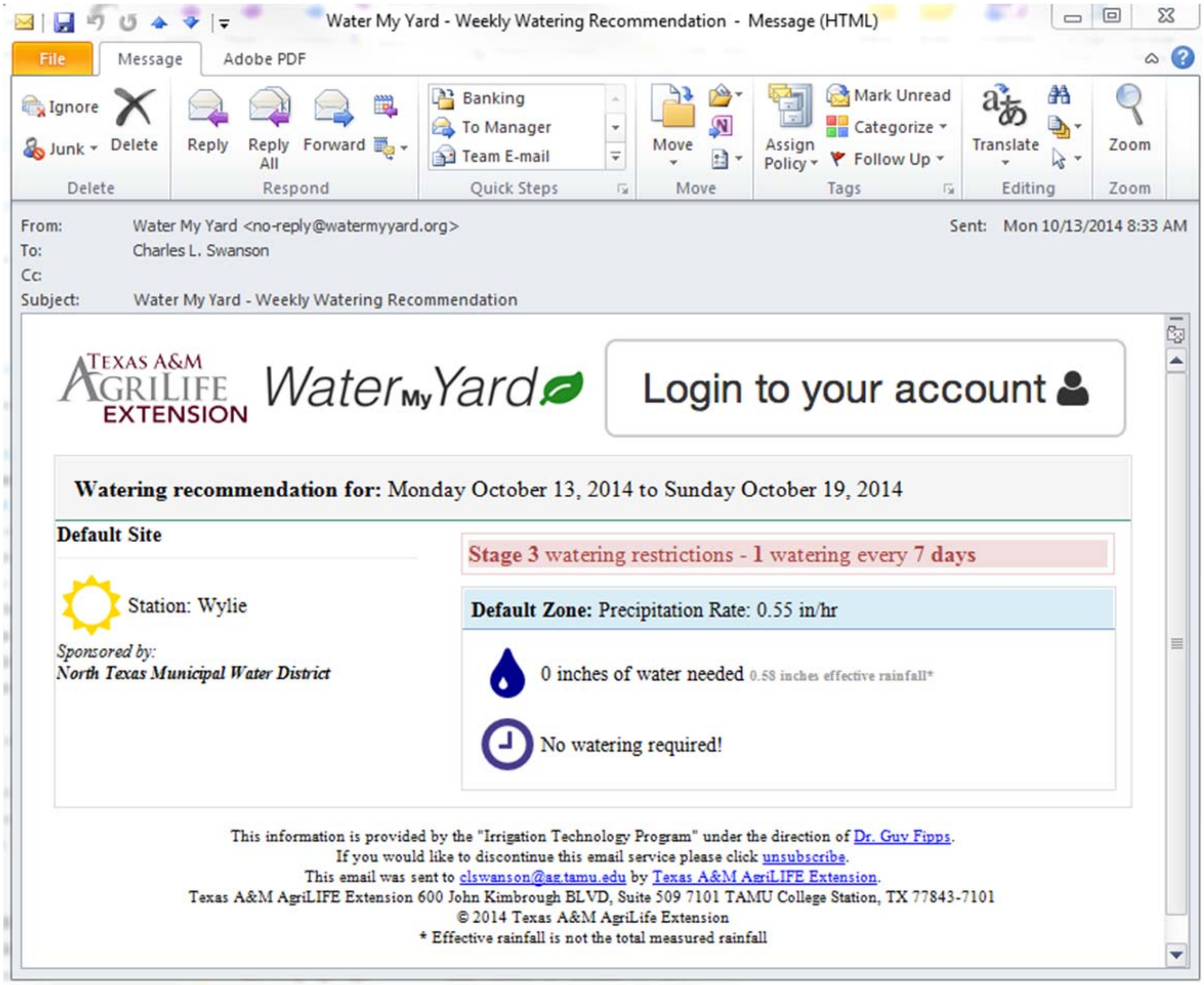

Figure 6. Water My Yard- Email Water Recommendation

Challenges and Improvements

During its first year of operation, challenges were identified by homeowners trying to use the program as well stakeholders recommendations. The first challenge was that some homeowners did not know where they live. This may seem strange, but some users found it difficult to click on the location of their home on the service area map. To address this issue, the service area map was replaced with an interactive google map which automatically pinpoints their location based on their IP address. Alternatively, users may enter their address. The homeowner would then verify their home location.

In V1.0, users were only allowed to set up one landscape zone at a time. This meant, for example if a home had spray heads in the front yard and rotor sprinklers in the backyard, they would have to create a profile for the first zone, then start over and create a profile for the second zone. Version 2.0 allows users to add multiple controllers and stations with different precipitation rates to a single account.

Managing Irrigation during water restrictions has been a major challenge of the program. When the program was first released, water restrictions allowed two irrigation days per week. However, as the drought progressed, restrictions increased only allowing one day per week for irrigation, then to one day every two weeks. The change in restrictions produced the needs for limits on the amount of irrigation water applied and the time frame upon which the irrigation recommendation is based. For weekly or biweekly water balance calculations, a limit is placed on irrigation which corresponds to the maximum amount of water that can be held in the soil. The maximum amount of water available for the plant was set at 0.67 inches of water which is the equivalent of a four inch effective root zone in clay soil, the most common landscape scenario in the areas.

The second challenge was producing an irrigation recommendation for the one irrigation every two week scenario. The initial solution was to use the previous two weeks evapotranspiration and rainfall. This methodology was found ineffective as rainfall is inconsistent and confusing to users. The decision was made to produce a “floating” two week irrigation recommendation every week. This allowed for the most recent rainfall to be included in the irrigation recommendation and address uncertainty over which week the homeowner chose or was allowed to irrigate.

Besides addressing these challenges, other improvements were made to the software to simplify ease of use and implementation of the program. These included a redesign of the program website to allow for a more clean and modern view with a smart device. Users are also able to input their cellular provider information during the account set up to allow for weekly text messaging of irrigation runtimes in addition to weekly emails.

Variability of ETo in Urban Environments

As the drought continues for much of Texas, the Water My Yard program is gaining attention from water stressed utilities around the state. As these utilities begin their inquiry into joining the program, one of the first questions is how many ET Weather Station or Rain Gages are needed. In 2014, a study began to address that question. Mobile weather readings are taken across urban areas to determine the variability of ET drivers: temperature, solar radiation, relative humidity, and wind speed. Data is also collected from permanent ET weather stations in each urban area as baseline measurements. Preliminary results show that temperature, solar radiation and relative humidity have very low variability across the tested urban areas. However wind speed values have shown some variability based on the varying fetch in urban areas, leading to higher calculated evapotranspiration in those areas. Rainfall continues to be a highly variable factor across areas. While predominate rainfall patterns may be used for siting of rain gages, intensity of rainfall amounts can vary quite significantly even in small urban areas.

Summary

Currently the Water My Yard Program provides runtime recommendations for three areas: the North Texas Municipal Water District, the City of Irving, and the Brazos Valley-Bryan/College Station area. Two addition utilities are interested in joining the program and are currently either procuring the necessary equipment or in the early planning stage. The Water My Yard program as of October 15, 2014 has over 1300 user accounts after its first year of operation. Preliminary analysis shows great potential for water savings. For example, the Wylie area only had an irrigation recommendation for 19 weeks of the year. When followed by homeowners in that service area, they would have applied zero irrigation for 34 weeks, or 64% of the year (See Figure 7). Currently volunteers are being sought in Water My Yard service areas to help document and verify the water savings potential of the program.

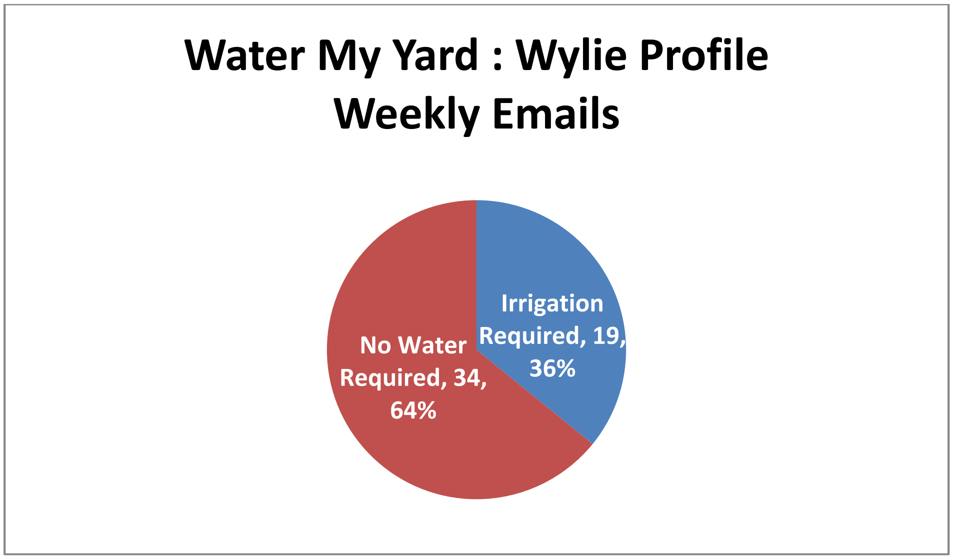

Figure 7. Water My Yard- Recommendation Summary for Wylie

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Water Utility Agency Aiming to Develop Partnership with the Green Industry

Denver Water has always considered the single family residential customers the primary target for water conservation. Denver Water's marketing and advertising campaigns are especially directed towards our single family residential customers. We then began to consider our commercial irrigation users. Recently we conducted a survey with our WaterSense smart controller rebate customers to determine how they heard about the rebate program. Only 6% had heard about the rebates from their contractor. A large majority of our customers heard about the rebates from the retail stores. Other sources of successful rebate information were achieved through the advertisement in the monthly water bill as well as the DW website. This knowledge further influenced our decision to develop marketing and programmatic options to engage the Green Industry to reduce water consumption in the commercial sector.

As a utility, we recognize there is a conflicting message the Green Industry receives between Denver Water and their employer. When reservoirs are low we request and even require reduction in water use. Then, there is the customer that just wants the grass to stay green. The role of the landscape professional is to maintain green grass and to keep the plants healthy and thriving which requires water. The added difficulty is the underbidding to keep contracts as budgets are continually tightening. Labor and irrigation technician hours are often cut to meet the demand. This leaves no room within the contract to maintain the irrigation systems (let alone manage the water) while trying to make a profit.

Conservation Programs

For several years, Denver Water has designed programs to encourage improved efficiency for commercial properties irrigation systems. We have provided free water audits where we go through the entire irrigation system, zone by zone creating a report with specific site information and recommendations. We can identify locations of broken heads or lines, mixed zones, tilted or obstructed heads, etc. and print out a report immediately on site for the contractor's information and use. The report also details zone by zone recommendations for other Denver Water programs such as native grass conversion, rebates and the water budget program. Our rebates include 25% purchase price of WaterSense ET controllers (product only, no labor) and precision nozzles at $2.00/nozzle.

As a result of the drought in 2012 we developed and piloted the Water Budget Program. It was designed for large commercial customers who had a significant amount of landscaping on their property. It is a free program and the customer just needs to sign up and provide specific site information along with the contact information for both the landscape contractor and the property or site manager. Each month a letter goes out with a graph showing the sites actual water use versus appropriate water efficient benchmark calculated by Denver Water based on irrigable area and outdoor water use. Using industry standards, 18 gallons per square foot (GPSF) per year was applied as the targeted use in a normal year. During the drought, we required a further reduction of 35% (or 12 GPSF). The program was developed to be informational and a tool for the landscape and manager to identify what the sites water use was so they can collectively determine the water use goals for the site. We also saw it as a helpful tool to identify possible breaks or spikes in consumption. The additional benefit of participating in the program is the site was exempt from any water day restrictions. However, they were still responsible to adhere to the no daytime watering rule. If the site exceeded the monthly expectations we would notify and work with the property but there was no penalty applied.

Communications and Marketing

Denver Water's "Use Only What You Need" campaign has been an award winning campaign with catchy billboards, bus stops, and commercials as well as antics such as the running toilet (a mascot like costume that runs around events and sports venues). Although successful, it was aimed almost exclusively at our residential customers. Our marketing team is working with the conservation field team, irrigation distributors and local professional organizations to create a message directly to the landscape contractor and irrigation industry audience. We have also successfully utilized social media to target the Green Industry audience. We participated in a landscape chat talking about Xeriscape and landscape conversion. The potential reach of this chat was 137,000 impressions.

Future Partnerships

At Denver Water, our future state is to continue developing programs that will acknowledge the Green Industry and encourage continued improved irrigation efficiency. Although it is just in the conceptual phase, we are considering a recognition program for properties that are conscientiously making an effort to use less water. The sites within the Water Budget program can be ranked and labeled efficient based on much water they are using. This gives us the opportunity to highlight the good work being done by managers, landscapers, and property owners. We can also look at what the site has done overall to bring their water use down, such as landscape conversion, Xeriscape, rebates or any other ideas implemented to reduce long term water use. We anticipate awards, signage or recognition on our website as some of our ideas for recognition.

Another future initiative we are considering is creating Water Management specifications to include as an addendum to landscape maintenance contracts. As previously stated, we understand contract labor is being cut due to continually reduced budgets. The contractor cannot be responsible to cut their costs without cutting labor. Often times, the irrigation technicians scope of work is reduced to keep the contract profitable. Again, here comes the conflict whereas we are asking them to do more work in terms of Water Management while they're being paid less. We would like to develop a scope of work that includes Water Management that can be included within the contract or as an addendum. The contractor would be able to bid the extra hours required to not only manage the landscape but also the irrigation system and water use. As a third party, Denver Water can endorse Water Management and objectively support management companies to include water management within all standard maintenance contracts.

It is widely acknowledged that water is a precious and finite resource. Water management is the future of the landscaping industry and Denver Water wants to partner with and support those that are currently practicing or trying to develop water management for their customers. Improved knowledge and efficiencies must be achieved within the Green Industry for a sustainable future.

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Conserve Water by Irrigating Deeply and Less Frequently

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Abstract. *During periods of drought, watering restrictions for many municipalities limit the days per week when landscape irrigation can occur. Additionally, many smart irrigation controllers for residential landscapes schedule watering on a weekly or more often basis. These constraints can result in watering more frequently than would be required by the depletion of plant available water in the root zone. Under limited or partial soil moisture depletion, the number of days between irrigations is reduced. This increases the potential for losses to surface evaporation and provides less latitude for managing soil moisture levels below the 'no water stress' fraction.*

This paper summarizes results derived from a soil water balance which calculates evaporation from wetted plant-soil surfaces, including drying of the surface soil layer. Comparison is made of the needed net irrigation under likely irrigation frequencies resulting from limited water availability and watering restrictions.

Irrigating deeply and less frequently provides significant benefits.

- *Supports landscape health.*
- *Promotes deeper root zones.*
- *Provides significant potential for water conservation.*

Deeper rooting depths make landscapes more drought resistant. They better support managed deficit irrigation practices which can achieve significant water conservation by reducing landscape water use rates during the 'dry down' period before subsequent irrigation or watering is applied.

This information should assist water providers and irrigation managers in determining what watering schedules may better conserve limited water supplies while still meeting the needs for healthy urban landscapes.

Keywords. Conservation, Deficit Irrigation, Evapotranspiration, Plant Factors, Scheduling, Sprinkler, Turf/Landscape (Residential), Water Budget, Water Manager, Water Provider.

Background and Methodology

Benchmark values for constructing crop water use curves are presented for a diversity of plants and agricultural crops in Irrigation 6th edition, 2011, Table 5.2, pp. 117-122. Included are typical values for $K_{c\ ini}$, $K_{c\ mid}$, $K_{c\ end}$, $K_{cb\ ini}$, $K_{cb\ mid}$, and $K_{cb\ end}$ all for sub humid climatic conditions characterized by an average minimum daytime humidity of 45 percent and average wind speeds at 2-m height of 2 m/s (4.5 mph). All these factors are intended to represent evapotranspiration or ET under growing conditions having a high level of management and with little or no ET reducing environmental stresses, such as delayed irrigation under managed deficit irrigation. Hence $ET_c = K_c ET_o$ would represent potential levels of crop ET, not necessarily actual ET under reduced watering restrictions.

The dual K_c approach presented in Irrigation 6th edition, 2011, pp. 132-139 utilizes (K_{cb} + K_e) to separately account for wet surface evaporation resulting from precipitation or irrigation events, rather than relying on the average surface wetting frequency incorporated into the single K_c factor. Utilization of a plant stress factor K_s further improves estimates of actual ET. Hence $ET_{c\ act} = (K_s K_{cb} + K_e)\ ET_o$ represents ET under any condition, ideal or non-ideal.

Actual ET for cool season turfgrass was calculate using the $ET_{c\ act} = (K_s K_{cb} + K_e)\ ET_o$ approach utilizing reference ET or ET_o calculated from weather data obtained from the meteorological station managed by Northern Water at their headquarters in Berthoud, Colorado. Various irrigation management strategies were assumed and the monthly actual ET and needed net irrigation depth applied were compared.

Landscape Plant and Soil Parameters

Cool season turfgrass dominates in the irrigated urban landscapes along Colorado's Front Range. Consequently turf accounts for the majority of the demand for outdoor watering during summer months and is specifically targeted by some municipal drought watering restrictions. However, because of turf's stand density and heavy shading of the soil surface, differences in wet surface evaporation losses are expected to be less significant for turfgrass than many other landscape plantings. Consequently, cool season turfgrass was selected for this comparison both for its being representative of Coloradr landscapes and also for its perceived immunity to high evaporative losses.

The soil at the Berthoud site is deep silty clay. Turfgrass study plots at this site are typically watered once per week with minimal evidence of water stress. The following parameters were utilized in the soil moisture balance.

Table 1. Plant and Soil Parameters.

Cool season turfgrass (bluegrass)	$K_{c\ min} = 0.15$, $K_{CB\ ini} = 0.81$, $K_{cb\ mid} = 0.86$, $K_{cb\ end} = 0.86$	
Depletion fraction for no stress, p	0.4	
Managed stress level, K_{sm}	Average = 0.80	
Maximum rooting depth, Z_r	12 inch	(305 mm)
Average crop height, h	3 inch	(76 mm)
Silty clay soil	Surface layer amended with compost	

Field capacity, Θ_{FC}	0.360 ft^3/ft^3	(0.360 m^3/m^3)
Wilting point, Θ_{WP}	0.230 ft^3/ft^3	(0.230 m^3/m^3)
Adjustment factor for soil matric potential	0.95	
Total available water in root zone, TAW	1.48 inch	(38 mm)
Uniform ground surface	slope < 2%	
Sprinkler irrigation	popup sprays	
Full sun exposure	No micro climate adjustment	
No salinity or drainage concerns	Ks factor reflects only water limiting stress	
No drainage concerns	No capillary rise from ground water table	

Irrigation Management Strategies

Utilizing weather data for Berthoud, Colorado from May to September of 2014, the following strategies were selected for comparison.

Table 2. Selected Irrigation Management Strategies.

	MAD	K_{sm}	K_{cb} x K_{sm}	Peak season irrigation interval	Effective root zone depth
No irrigation frequency restrictions	0.51	0.95	0.81	4 days	12 inch (305 mm)
No irrigation frequency restrictions	**0.71**	**0.80**	**0.68**	**7 days**	**12 inch** (305 mm)
No irrigation frequency restrictions	0.80	0.70	0.60	9 days	12 inch (305 mm)
Irrigation limited to every 5th day	**0.70**	**0.80**	**0.68**	**5 days**	**10.4 inch** (264 mm)
Irrigation limited to every 4th day	**0.69**	**0.80**	**0.68**	**4 days**	**8.8 inch** (224 mm)
Irrigation limited to every 3rd day	**0.68**	**0.80**	**0.68**	**3 days**	**7 inch** (178 mm)

The following equations were used in calculation of the daily soil moisture balance in the root zone:

$$ET_{c\,act} = (K_s \times K_{cb} + K_e) \times ET_o$$

$$K_s = \frac{TAW - D_r}{(1-p) \times TAW}$$

$$K_e = [F_t + (1 - F_t)K_r](K_{c\,max} - K_s K_{cb})$$

$$F_t = \frac{REW - D_{REW,j-1}}{K_{e\,max} ET_o}$$

$$K_r = \frac{TEW - D_{e,j-1}}{TEW - REW}$$

$$D_{REW,j} = D_{REW,j-1} - \left\{(1-f_b)\left[\left(P_j - RO_j\right) + \frac{I_j}{f_w}\right] + f_b\left[\left(P_{j+1} - RO_{j+1}\right) + \frac{I_{j+1}}{f_w}\right]\right\} + \frac{E_j}{f_{ew}}$$

$$D_{e,j} = D_{e,j-1} - \left\{(1-f_b)\left[\left(P_j - RO_j\right) + \frac{I_j}{f_w}\right] + f_b\left[\left(P_{j+1} - RO_{j+1}\right) + \frac{I_{j+1}}{f_w}\right]\right\} + \frac{E_j}{f_{ew}} + T_{ei,j}$$

Where:

$ET_{c\,act}$	= actual crop ET under any condition, ideal or non-ideal, mm
K_s	= stress factor computed for available soil moisture in the root zone
K_{cb}	= basal crop coefficient for dry plant/soil surfaces
K_e	= soil evaporation coefficient
ET_o	= short crop reference ET, typically clipped cool season turfgrass, mm
TAW	= total plant available water in the root zone, mm
D_r	= depletion of soil moisture in the root zone below field capacity, mm
p	= soil water depletion fraction for no plant stress
F_t	= fraction of calculation time step/interval that resides in stage 1 drying
K_r	= evaporation reduction coefficient - fraction wetted by precipitation only
$K_{c\,max}$	= maximum value of K_c following rain or irrigation
REW	= readily evaporable water during stage 1 drying, mm
$D_{REW,j-1}$	= cumulative depletion from soil skin layer at end of previous day, mm
$D_{REW,j}$	= cumulative depletion from soil skin layer at end of day j, mm
$K_{e\,max}$	= maximum value of soil evaporation coefficient
TEW	= total evaporable water – maximum depth that can be evaporated from a completely wetted surface soil layer, mm
$D_{e,j-1}$	= cumulative depletion from surface soil layer at end of previous day, mm
$D_{e,j}$	= cumulative depletion from surface soil layer at end of day j, mm
f_b	= fraction of precipitation and irrigation contributing towards evaporation during the current calculation time step/interval
P_j	= precipitation on day j, mm
RO_j	= runoff of precipitation from soil surface on day j, mm

I_j = irrigation depth that infiltrates the soil on day j, mm
f_w = fraction of ground surface wetted by irrigation and/or precipitation
E_j = evaporation depth from exposed soil surfaces on day j, mm
f_{ew} = fraction of soil both exposed to solar radiation and wetted
$T_{ei,j}$ = transpiration depth from the exposed and wetted fraction of the soil layer on day j, mm
$DP_{ei,j}$ = deep percolation from the soil surface layer on day j if soil water content exceeds field capacity, mm

Surface runoff of precipitation RO_j was estimated using the USDA-NRCS curve number method presented in Irrigation 6th edition, 2011, pp. 162-264.

Results

The soil moisture balance calculations indicate that more frequent wetting of landscape plants by precipitation or rainfall does increase water losses to evaporation and reduce soil moisture available for plant transpiration. More significant was the reduction of the effective plant root zone as irrigation frequency was increased while still maintaining a modest level of deficit irrigation for water conservation. Decreased rooting depths directly diminish drought resistance of the landscape.

More frequent irrigation events provide less latitude for managing soil moisture levels below the ‘no water stress’ fraction. Only when depletions exceed this fraction will landscape ET drop below the higher ‘well watered’ rate. Significant water can be conserved through management practices that provide a drier root zone before the next irrigation event. However, care must be taken to avoid deficits which could result in undesirable and damaging plant stress. Consequently, irrigations are commonly scheduled to occur on the day before soil moisture levels are expected to drop below the limit set for the management allowed deficit. Under managed stress, a shallow rooted landscape on a hot dry summer day can ill afford to go one day too long before watering occurs. As irrigation is typically scheduled as a daily event (not hourly), an allowable irrigation interval of 3½ days would be shortened to 3 days, an interval of 4½ days would be shortened to 4 days, etc. This ‘protection factor’ diminishes the water conservation potential proportionally more for short irrigation intervals than for longer, less frequent intervals.

Conclusions

Under limited water availability and watering restrictions, irrigating deeply and less frequently provides significant benefits.

- Supports plant and landscape health.
- Promotes deeper more extensive root zones.
- Provides significant potential for water conservation.

Deeper rooting depths make landscapes more drought resistant. They further support managed deficit irrigation practices which can achieve significant water conservation by reducing landscape water use rates during the ‘dry down’ period before subsequent irrigation is applied. The potential for water conservation may thereby be reduced with too frequent applications of irrigation water.

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Updates in ET Based Smart Irrigation Controller Performance: Results from 2013

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Abstract. *A smart controller testing facility was established by the Irrigation Technology Program at Texas A&M University in College Station in 2008. The objectives were to (1) evaluate smart controller testing methodology and to (2) determine their performance and reliability under Texas conditions from an "end-user" point of view. Based on the last 6 years of the ET controller testing program, many ET controllers currently being marketed in Texas remain inconsistent in their performance and continue to apply excessive amounts of irrigation. Some participating manufacturers have used the evaluation results to update and improve sensors and firmware to increase controller performance.This paper provides an update on the performance of 9 commercially available controllers and tries to identify reasons for poor performance of controllers by evaluating controller generated or recieved ET values.*

Keywords. *Landscape Irrigation, Irrigation Scheduling, Evapotranspiration, Smart Controllers, Water Conservation*

INTRODUCTION

The term *smart irrigation controller* is commonly used to refer to various types of controllers that have the capability to calculate and implement irrigation schedules automatically and without human intervention. Ideally, smart controllers are designed to use site specific information to produce irrigation schedules that closely match the day-to-day water use of plants and landscapes. In recent years, manufacturers have introduced a new generation of smart controllers which are being promoted for use in both residential and commercial landscape applications.

However, many questions exist about the performance, dependability and water savings benefits of smart controllers. Of particular concern in Texas is the complication imposed by rainfall. Average rainfall in the State varies from 56 inches in the southeast to less than eight inches in the western desert. In much of the State, significant rainfall commonly occurs during the primary landscape irrigation seasons. Some Texas cities and water purveyors are now mandating smart controllers. If these controllers are to become requirements across the state, then it is important that they be evaluated formally under Texas conditions.

CLASSIFICATION OF SMART CONTROLLERS

Smart controllers may be defined as irrigation system controllers that determine runtimes for individual stations (or "hydrozones") based on historic or real-time ETo and/or additional site specific data. We classify smart controllers into four (4) types (see Table 1): Historic ET, Sensor-based, ET, and Central Control.

Many controllers use ETo (potential evapotranspiration) as a basis for computing irrigation schedules in combination with a root-zone water balance. Various methods, climatic data and site factors are used to calculate this water balance. The parameters most commonly used include:

- ET (actual plant evapotranspiration)
- Rainfall
- Site properties (soil texture, root zone depth, water holding capacity)
- MAD (managed allowable depletion)

The IA SWAT committee has proposed an equation for calculating this water balance. For more information, see the IA's website: http://irrigation.org.

Table 1. Classification of smart controllers by the method used to determine plant water requirements in the calculation of runtimes.

Historic ET	Uses historical ET data from data stored in the controller
Sensor-Based	Uses one or more sensors (usually temperature and/or solar radiation) to adjust or to calculate ETo using an approximate method
ET	Real-time ETo (usually determined using a form of the Penman equation) is transmitted to the controller daily. Alternatively, the runtimes are calculated centrally based on ETo and then transmitted to the controller.
On-Site Weather Station (Central Control)	A controller or a computer which is connected to an on-site weather station equipped with sensors that record temperature, relative humidity (or dew point temperature) wind speed and solar radiation for use in calculating ETo with a form of the Penman equation.

MATERIALS AND METHODS

Testing Equipment and Procedures

Two smart controller testing facilities have been established by the ITC at Texas A&M University in College Station: an indoor lab for testing ET-type controllers and an outdoor lab for sensor-based controllers. Basically, the controllers are connected to a data logger which records the start and stop times for each irrigation event and station (or hydrozone). This information is transferred to a database and used to determine total runtime and irrigation volume for each irrigation event. The data acquisition and analysis process is illustrated Figure A-1 . Additional information and photographs of the testing facilities are provided in the Appendix.

Smart Controllers

Nine (9) controllers were provided by manufacturers for the Year 2013 evaluations (Table 2). Each controller was assigned an ID for reporting purposes. Table 2 lists each controller's classification, communication method and on-site sensors, as applicable. The controllers were grouped by type for testing purposes

Table 2. The controller name, type, communication method, and sensors attached of the controllers evaluated in this study. All controllers were connected to a rain shut off device unless equipped with a rain gauge.

Controller ID	**Controller Name**	**Type**	**Communication Method**	**On-Site Sensors[1]**	**Rain Shutoff**
A	ET Water	ET	Pager	None	✓
B	Rainbird ET Manager Cartridge	ET	Pager	Tipping Bucket Rain Gauge	
C	Hunter ET System	Sensor Based	-	Tipping Bucket Rain Gauge, Pyranometer, Temperature/ RH, Anemometer	
D	Hunter Solar Sync	Sensor Based	-	Pyranometer	✓
E	Rainbird ESP SMT	Sensor Based	-	Tipping Bucket Rain Gauge, Temperature	
F	Accurate WeatherSet	Sensor Based	-	Pyranometer	✓
G	Weathermatic Smartline	Sensor Based	-	Temperature	✓
H	Toro Intellisense	ET	Pager	None	✓
I	Irritrol Climate Logic	Sensor Based	-	Temperature, Solar Radiation	✓

[1] Rain shut off sensors are not considered On-Site Sensors for ET Calculation or runtime adjustment

Definition of Stations (Zones) for Testing

Each controller was assigned six stations, each station representing a virtual landscaped zone (Table 3). These zones are designed to represent the range in site conditions commonly found in Texas, and provide a range in soil conditions designed to evaluate controller performance in shallow and deep root zones (with low/high water holding capacities). Since we do not recommend that schedules be adjusted for the DU (distribution uniformity), the efficiency was set to 100% if allowed by the controller.

Programing the smart controllers according to these virtual landscapes proved to be problematical, as only two controllers (E and H) had programming options to set all the required parameters defining the landscape (see Table 4). It was impossible to see the actual values that two controllers used for each parameter or to determine how closely these followed the values of the virtual landscape.

One example of programming difficulty was entering root zone depth. Four of the nine controllers did not allow the user to enter the root zone depth (soil depth). Another example is entering landscapes plant information. Three of the controllers did not provide the user the ability to see and adjust the actual coefficient (0.6, 0.8, etc.) that corresponds to the selected plant material (i.e., fescue, cool season grass, warm season turf, shrubs, etc.).

Thus, we programmed the controllers to match the virtual landscape as closely as was possible. Manufacturers were given the opportunity to review the programming, which three did. Five of the remaining manufacturers provided to us written recommendations/instructions for station programming, and one manufacturer trusted our judgment in controller programming

Table 3. The Virtual Landscape which is representative of conditions commonly found in Texas.						
	Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
Plant Type	Flowers	Turf	Turf	Groundcover	Small Shrubs	Large Shrubs
Plant Coefficient (Kc)	0.8	0.6	0.6	0.5	0.5	0.3
Root Zone Depth (in)	3	4	4	6	12	20
Soil Type	Sand	Loam	Clay	Sand	Loam	Clay
MAD (%)	50	50	50	50	50	50
Adjustment Factor (Af)	1.0	0.8	0.6	0.5	0.7	0.5
Precipitation Rate (in/hr)	0.2	0.85	1.40	0.5	0.35	1.25
Slope (%)	0-1	0-1	0-1	0-1	0-1	0-1

Table 4. The parameters which the end user could set in each controller directly identified by the letter "x."									
Controller	**Soil Type**	**Root Zone Depth**	**MAD**	**Plant Type**	**Crop Coefficient**	**Adjustment Factor**	**Precipitation Rate**	**Zip Code or Location**	**Runtime**
A	X	X	X	X		X	X	X	
B[1]	-	-	-		X	-	-	X	X
C	X			X	X	X	X		
D[2]	-	-	-		-	-	-	X	X
E	X	X		X	X	X	X		
F[2]				X					X
G	X			X	X	X	X	X	
H	X	X	X	X	X	X	X	X	
I[2]	-	-	-		-	-	-	X	X

[1] Irrigation amount was set based on plant available water
[2] Controller was programmed for runtime and frequency at peak water demand (July).

Testing Period

The controllers were set up and run from March 4 to May 11 and from July 29 to December 1, 2013. Controller performance is reported over seasonal periods. For the purposes of this report, seasons are defined as follows:

- Spring: March 4 to May 11 (77 Days)
- Summer: July 29 to September 15 (49 Days),
- Fall: September 16 to December 1 (70 Days).

ETo and Required Irrigation

ETo was computed from weather parameters measured at the Texas A&M University Golf Course in College Station, TX which is a part of the TexasET Network (http://TexasET.tamu.edu). The weather parameters were measured with a standard agricultural weather station (Campbell Scientific Inc) which records temperature, solar radiation, wind and relative humidity. ETo was computed using the standardized Penman-Monteith method.

Irrigation Requirement

The irrigation requirement was calculated using a daily soil moisture balance model. Irrigation was applied through the model once the managed allowable depletion was reached or exceeded. The model used the following equation:

$SM_D = SM_{PD} – (ETo \times Kc \times Af) + Rain_{Eff}$ (eq.1)

Where:
SM_D = Soil Moisture of the current day, inches
SM_{PD} = Soil Moisture of the previous day, inches
ETo = Daily Evapotranspiration, inches
Kc = Crop Coefficient, %
Af = Adjusment Factor, %
$Rain_{Eff}$ = Effective Rainfall that can be stored in the root zone, inches

Irrigation Adequacy Analysis

The purpose of the irrigation adequacy analysis is to identify controllers which over or under irrigate landscapes. An uncertainty in calculating a water balance is effective rainfall, how much of rainfall is credited for use by the plant. Further complicating rainfall is the use and performance of rain shut off devices.

For this study we broadly define irrigation ***adequacy*** as the range between taking 80% credit for all rainfall ($R_e = 0.8$) and taking no credit for rainfall ($R_e = 0$). These limits are defined as:

Extreme Upper Limit = ETo x Kc (eq. 2)
Adequacy Upper Limit = ETo x Kc x Af (eq. 3)
Adequacy Lower Limit = ETo x Kc x Af - Net (80%) Rainfall (eq. 4)
Extreme Lower = ETo x Kc x Af - Total Rainfall (eq. 5)

The adequacy upper limit is defined as the plant water requirement (eq. 3) without rainfall. Irrigation volumes greater than the upper limit are classified as ***excessive***. The adequacy lower limit is defined as the plant water requirements minus Net Rainfall (eq 4). The IA SWAT Protocol defines net rainfall as 80% of rainfall. Irrigation volumes below than the adequacy lower limit are classified as ***inadequate***.

For comparison purposes, extreme limits are defined by taking no credit for rainfall (upper) and total rainfall (lower). These limits are the maximum and minimum possible plant water requirements.

RESULTS

Results from the Year 2013 evaluation periods are summarized in Tables 5-7 by season.

Irrigation Requirement Comparisons

Controller performance during the Spring evaluation period (March 4-May 11, 2013) was good.

Controllers Passing
None

Good Performers
Controller C had four stations that were within irrigation requirement

Poor Performers
Controllers D and I had irrigation applications greater ETo
Controller F had one station in excess of ETc

Controller performance during the Summer evaluation period (July 29-September 15, 2013) was good.

Controllers Passing
None

Good Performers
Controller G had four stations that were within irrigation requirement.

Poor Performers
Controllers D and I produced irrigation volumes in excess of ETo.
Controller D had four stations that were in excess of ETc.

Controller Performance during the Fall evaluation period (September 16-December1, 2013) was generally poor.

Controllers Passing
None

Best Performer
None

Poor Performers
Controllers D and I produced irrigation volumes in excess of ETo.
Controllers F and H produced irrigation volumes in excess of ETc.

Tables 8-10 show the irrigation ***adequacy*** analysis for each station during the three seasonal periods. During the Spring period, four (4) controllers applied excessive amounts of irrigation for one or more stations with one (1) controller applying excessive amounts for all six (6) stations. In the Summer period, four (4) controllers applied inadequate irrigation amounts with two (2) controllers consistently applying inadequate irrigation amounts. Six (6) controllers applied excessive amounts during the summer period with two (2) controllers consistently applying excessive amounts for all six (6) stations. No controllers applied inadequate amounts during the Fall period, however six (6) controllers consistently applied excessive amounts of irrigation with three (3) controller applying excessive amounts for all six (6) station.

Figure 1 and Figure 2 contain daily ET readings from controllers and the TexasET Network graphed with daily rainfall totals during the entire evaluation period (Figure 1) and as a percentage of daily ETo (Figure 2). Controller ET values appeared erratic and inconsistent compared to TexasET throughout the study period; however all controllers consistently show decreases in ETo values during days which rainfall occurred.

Controller Problems

Two controllers experienced problems during the course of the study.

1. Controller B had poor signal accuracy during the study dropping down as low as 17% at some times. The signal provider was notified and adjustments were made in the signal settings and an upgraded antenna was installed. Signal accuracy increased temporarily after adjustments but soon declined again. Signal provider stated controller was in a poor coverage area due to changes in signal/transmission towers. However Controller B does have local historic monthly ET data stored in its settings and continued to operate at low signal accuracy using the historic ET values and onsite rainfall measurements.

2. Controller H experienced communication problems multiple times throughout the study. Controller alerts (beeping) occurred on at least 2 occasions during the evaluation period. The manufacturer was notified of the problem and a signal amplifier was installed on the controller. However, it was later determined that the problem was a result of poor signal service by the signal provider company in the testing area (lack of towers). Controller will not be included in future evaluations at this location due to the continuous communication problems.

Table 5. Spring Performances. Irrigation amount (inches) applied for each controller station. Yellow denotes values within +/- 20 % of the irrigation requirement. Red indicates values in excess of ETc						
Controller	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	8.40	5.14	3.71	2.46	2.62	2.50
B	9.03	5.53	4.10	2.93	3.81	0
C	7.00	3.48	2.66	1.98	2.94	0.51
D	19.76	11.99	9.38	6.43	8.57	3.87
E	9.05	5.17	2.30	1.48	1.61	0
F	9.33	7.51	10.21	3.38	5.55	3.54
G	5.94	2.81	2.10	1.34	2.05	0.83
H	7.94	5.09	3.53	2.68	3.64	1.58
I	16.63	6.30	4.82	2.91	4.66	2.20
Total ETo[1]	14.14					
Total Rain[2]	8.58					
Irrigation Requirement	7.16	4.23	3.19	2.17	1.78	0
Total ET_{MAX}[3]	11.31	8.48	8.48	7.07	7.07	4.24
Effective Rainfall	0.10	0.51	0.65	0.50	1.98	1.64

[1] Total ETo calculated using the standardized Penmen-Monteith method using weather data collected at the Texas A&M University Turfgrass Lab, College Station, Texas.
[2] Total Rainfall collected from TexasET Network Weather Station "TAMU Golf Course"
[3] Rainfall and Adjustment Factor not included in this calculation

Table 6. Summer Performances. Irrigation amount (inches) applied for each controller station. Yellow denotes values within +/- 20 % of the irrigation requirement. Red indicates values in excess of ETc						
Controller	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	8.32	5.73	4.45	3.74	4.19	3.32
B	5.81	2.96	2.18	1.56	1.50	0
C	5.02	2.39	1.07	1.21	1.21	0
D	18.72	10.97	8.63	5.86	7.82	3.57
E	9.34	5.62	2.88	1.79	2.43	0
F	8.12	6.65	7.28	2.65	4.23	2.70
G	8.50	5.38	4.04	2.78	3.91	1.68
H	10.29	6.59	4.57	3.47	4.71	2.04
I	24.10	8.58	8.86	5.97	6.47	3.95
Total ETo[1]	13.20					
Total Rain[2]	0.86					
Irrigation Requirement	6.37	5.12	3.71	2.54	3.61	0
Total ET_{MAX}[3]	10.56	7.92	7.92	6.60	6.60	3.96
Effective Rainfall	0.17	0.10	0.23	0.19	0.52	0.61

[1] Total ETo calculated using the standardized Penmen-Monteith method using weather data collected at the Texas A&M University Turfgrass Lab, College Station, Texas.
[2] Total Rainfall collected from TexasET Network Weather Station “TAMU Golf Course”
[3] Rainfall and Adjustment Factor not included in this calculation

Table 7. Fall Performance. Irrigation amount (inches) applied for each controller station. Yellow denotes denotes values within +/-20% of the irrigation requirement . Red indicates values in excess of ETc.

Table 7. Fall Performance. Irrigation amount (inches) applied for each controller station. Yellow denotes values within +/-20% of the irrigation requirement . Red indicates values in excess of ETc.

Controller	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	6.13	2.57	1.67	1.46	1.05	0
B	3.84	1.39	1.02	0.73	0	0
C	3.27	0.79	0.19	0.38	0.59	0
D	15.40	10.58	8.26	5.25	7.02	3.40
E	5.97	3.25	1.87	0.49	0.18	0.62
F	6.52	7.01	6.44	2.57	4.09	2.62
G	5.26	3.56	2.66	1.73	2.43	1.13
H	8.53	5.46	3.79	2.88	3.91	1.69
I	22.47	8.52	8.48	6.25	6.62	4.40
Total ETo[1]	10.06					
Total Rain[2]	18.71					
Irrigation Requirement	4.79	2.45	1.52	0.98	0	0
Total ET_{MAX}[3]	8.05	6.04	6.04	5.03	5.03	3.02
Effective Rainfall	0.17	1.26	1.50	1.00	2.85	2.51

[1] Total ETo calculated using the standardized Penmen-Monteith method using weather data collected at the Texas A&M University Turfgrass Lab, College Station, Texas.
[2] Total Rainfall collected from TexasET Network Weather Station “TAMU Golf Course”
[3] Rainfall and Adjustment Factor not included in this calculation

Table 8. Irrigation adequacy during the Spring Period						
Controller	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
A	Adequate	Adequate	Adequate	Adequate	Adequate	Excessive
B	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
C	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
D	Excessive	Excessive	Excessive	Excessive	Excessive	Excessive
E	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
F	Excessive	Excessive	Adequate	Adequate	Excessive	Excessive
G	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
H	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
I	Adequate	Adequate	Adequate	Adequate	Adequate	Excessive

Table 9. Irrigation adequacy during the Summer Period						
Controller	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
A	Adequate	Adequate	Adequate	Excessive	Adequate	Excessive
B	Inadequate	Excessive	Inadequate	Inadequate	Inadequate	Inadequate
C	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate
D	Excessive	Excessive	Excessive	Excessive	Excessive	Excessive
E	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate
F	Inadequate	Excessive	Excessive	Adequate	Adequate	Excessive
G	Inadequate	Inadequate	Inadequate	Adequate	Inadequate	Adequate
H	Adequate	Excessive	Adequate	Excessive	Excessive	Excessive
I	Excessive	Excessive	Excessive	Excessive	Excessive	Excessive

Table 10. Irrigation adequacy during the Fall Period

Controller	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
B	Adequate	Excessive	Adequate	Adequate	Adequate	Adequate
C	Adequate	Adequate	Excessive	Excessive	Adequate	Adequate
D	Excessive	Excessive	Excessive	Excessive	Excessive	Excessive
E	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
F	Adequate	Excessive	Excessive	Excessive	Excessive	Excessive
G	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
H	Excessive	Excessive	Excessive	Excessive	Excessive	Excessive
I	Excessive	Excessive	Excessive	Excessive	Excessive	Excessive

DISCUSSION AND CONCLUSIONS

Over the past five years since starting our "end-user" evaluation of smart controllers, we have seen improvement in their performance. However, the communication and failures that were evident in our field surveys conducted in San Antonio in 2006 (Fipps, 2008) continue to be a problem for some controllers. In the past five years of bench testing, we have seen some reduction in excessive irrigation characteristics of controllers, however some controllers still have difficulty managing irrigations in some stations, particularly station 1.

Our emphasis continues to be an "end-user" evaluation, how controllers preform as installed in the field. The "end-user" is defined as the landscape or irrigation contractor (such as a licensed irrigator in Texas) who installs and programs the controller.

Although the general performance of the controllers has gradually increased over the last five years, we continue to observe controllers irrigating in excess of ETc. Since ETc is defined as the ETo x Kc, it is the largest possible amount of water a plant will need if no rainfall occurs. This year, one controller consistently irrigated in excess of ETc, even though 28.15 inches of rainfall occurred during the study. The causes of such excessive irrigation volumes are likely due to improper ETo values and/or insufficient accounting for rainfall.

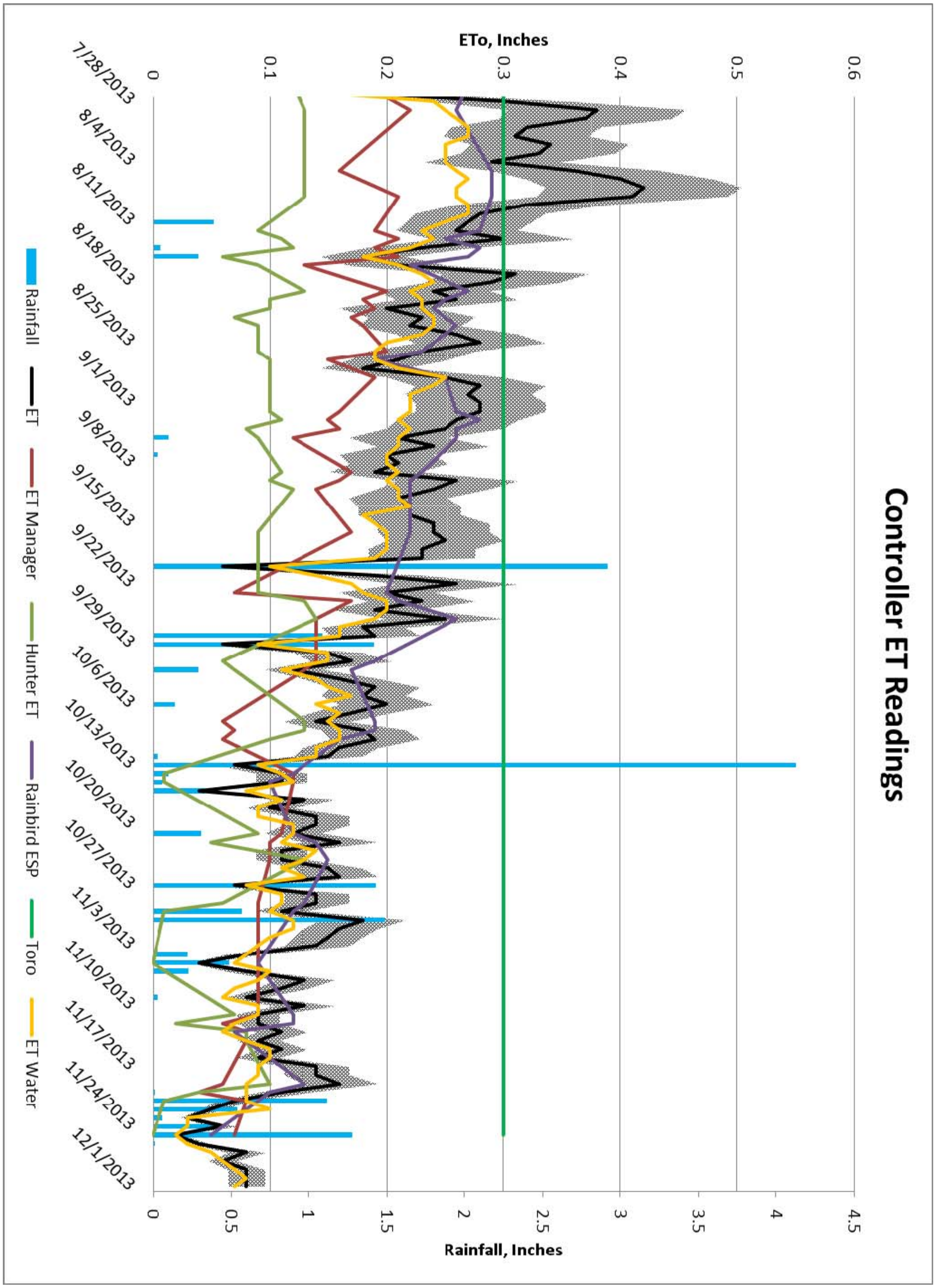
Three (3) controllers were equipped with tipping-bucket rain gauges which measure actual rainfall and six (6) controllers were equipped with rainfall shutoff sensors as required by Texas landscape irrigation regulations. Rainfall shutoff sensors detect the presence of rainfall and interrupt the irrigation event. During the 2013 evaluation period, a variety of rainfall conditions occurred across the three study periods. The fall period had the most rainfall (18.71 inches), and no major differences in performance observed between controllers using rain gauges and those using rainfall shutoff devices. This is in contrast to the 2010 study during which over 17 inches of rainfall occurred; and controllers using rain gauges applied irrigation amounts much closer to the irrigation requirements.

For a controller to pass our test, it would need to meet the irrigation requirements for all six stations. Of the nine (9) controllers tested, none successfully passed the test during the spring, summer or fall season. Results over the last five (5) years have consistently shown that some of the controllers over-irrigate (i.e., apply more water than is reasonably needed). This year, due likely to the variations in rainfall received during the study, four (4) controllers applied an inadequate amount of water compared to 2011 when six (6) controllers failed to meet minimum plant water requirements. Inadequacies appeared most common during periods with the least amount of rainfall while the most excessive amount appeared most common during the period with the highest amount of rainfall.

Generally, there was no difference in performance between controllers with on-site sensors and those controllers which have ET sent to the controller. Previous years evaluations had shown those controllers with on-site sensors to irrigate much closer to the irrigation requirements.

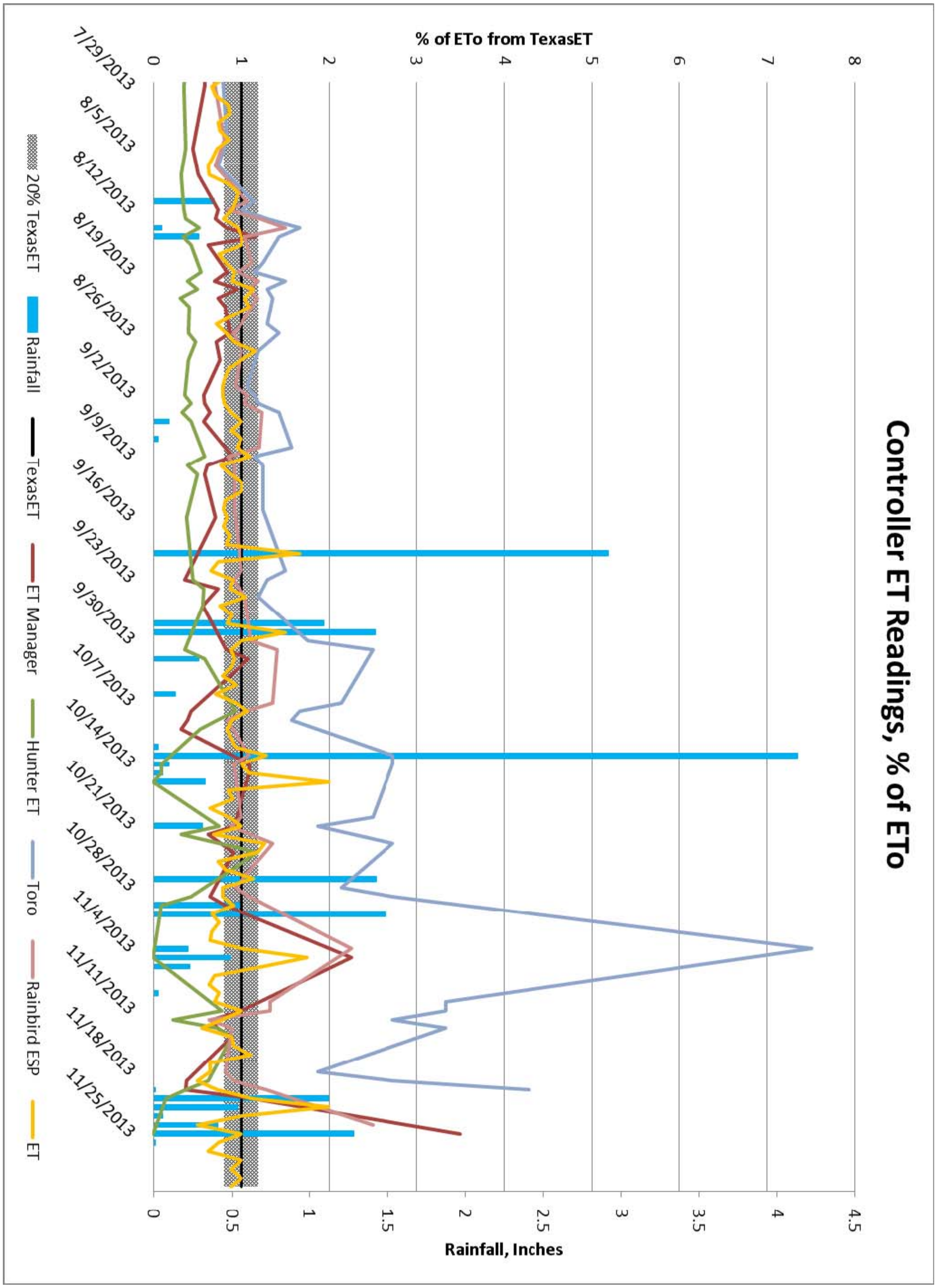
Current plans are to continue evaluation of controllers into the 2014 year and seek funding to expand the evaluation to program other regions in the state. While water savings shows promise through the use of some smart irrigation controllers, excessive irrigation is still occurring under some landscape scenarios. Continued evaluation and work with the manufacturers is needed to fine tune these controllers even more to achieve as much water savings as possible.

Figure 1



Controller ET Readings
ETo, Inches
0
0.1
0.2
0.3
0.4
0.5
0.6
Rainfall, Inches
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
7/28/2013
8/4/2013
8/11/2013
8/18/2013
8/25/2013
9/1/2013
9/8/2013
9/15/2013
9/22/2013
9/29/2013
10/6/2013
10/13/2013
10/20/2013
10/27/2013
11/3/2013
11/10/2013
11/17/2013
11/24/2013
12/1/2013
Rainfall
ET
ET Manager
Hunter ET
Rainbird ESP
Toro
ET Water

Figure 2


Controller ET Readings, % of ETo
% of ETo from TexasET
0
1
2
3
4
5
6
7
8
7/29/2013
8/5/2013
8/12/2013
8/19/2013
8/26/2013
9/2/2013
9/9/2013
9/16/2013
9/23/2013
9/30/2013
10/7/2013
10/14/2013
10/21/2013
10/28/2013
11/4/2013
11/11/2013
11/18/2013
11/25/2013
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Rainfall, Inches
20% TexasET
Rainfall
TexasET
ET Manager
Hunter ET
Toro
Rainbird ESP
ET

Distribution Uniformity of Multi Stream Multi Trajectory Rotary Nozzles Spaced Below Recommended Distance

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Abstract. *There are irrigation design and field situations where sprinkler spacings do not match conventional head to head spacing. A study was conducted to determine the effect of nozzle spacings at less than normal head to head spacing on distribution uniformity, DU. Also the effects on DU of adjusting and not adjusting the radius screw were measured. Three Multi Stream Multi Trajectory (MSMT) nozzles common in professionally installed systems were selected for this study. Nozzle spacings were 10% and 25% less than normal head to head spacing. Results show DU was basically higher at spacings of 10% and 25% less than head to head spacing for cases of adjusting or not adjusting the radius screw*

Keywords. Irrigation, distribution uniformity, multi stream nozzle

Introduction.

Urban landscape irrigation is an important water use issue in California as well as other areas in the US . The overarching-issue in California is "that Section 2 of Article X of the California Constitution specifies that the right to use water is limited to the amount reasonably required for the beneficial use to be served and the right does not and shall not extend to waste or unreasonable method of use." Use of this limited water supply has multiple advocates in agriculture, environmental, and urban (including landscape water users).

Legislative action in California based on extensive input from government, water agency, landscape, and environmental interest, resulted in AB 1881 Model Water Efficient Landscape Ordinance, and SB X7-7 Water Conservation Act of 2009. In AB 1881 the Maximum Allowable Water Applied (MAWA) is based on irrigation efficiency of 0.71 which is partially based on DU. A landscape irrigation system must possess a very high distribution uniformity (DU) to have an efficiency of 0.71. Baum et al. (2005) conducted a study on 15.1 ft. x 15.1 ft. (4.6 x 4.6 m) outdoor plots irrigated with spray nozzles under controlled conditions. They reported that the average DU_{LQ} for spray heads was 0.49. In this study, the researchers also audited residential spray landscapes and reported an average DU_{LQ} of 0.41 (DU ranged from 0.12 to 0.67). More recent designs of nozzles to replace spray nozzles have generally resulted in higher DU for systems (Solomon 2005).

High DU is critical to meet irrigation efficiency requirements of AB 1881. It states that irrigation efficiency "(IE) means the measurement of the amount of water beneficially used divided by the amount of water applied. Irrigation efficiency is derived from measurements and estimates of irrigation system characteristics and management practices. The minimum average irrigation efficiency for purposes of this ordinance is 0.71. Greater irrigation efficiency can be expected from well-designed and maintained systems." An irrigation system that has high DU of 0.80 and irrigation management efficiency of 95% has an estimated irrigation efficiency of 0.76 (if IE = DU x Irrigation Management Efficiency). In this case the estimated IE of 0.76 exceeds the required IE of 0.71 when the assumed sprinkler DU is 0.80.

Irrigation designers and contractor-installation methods may use various criteria for the sprinkler spacing and nozzle radius adjustments that may affect DU. In some landscapes, head spacing may vary from the head to head normal design; therefore the primary objective of this study was to measure DU of nozzles when spaced at less than head to head spacing.

Study Objective.

Measure the low quarter irrigation distribution uniformity (DU_{LQ}) of Multi Stream Multi Trajectory (MSMT) rotary nozzles using manufacturer's performance data and at smaller spacings than manufacturer's data. The effect on DU_{LQ} of adjusting and not adjusting the radius screw on the nozzle for head to head (HTH) coverage also was measured. An additional calculation of low half irrigation distribution uniformity (DU_{LH}) is also included.

Methods and Procedures.

The spacing of the nozzles for this study was based on the maximum radii listed in the manufacturer's specifications. The tests were all run at 40 psi (276 kPa) with pressure adjusted at the point of connection for the testing system. Pressure variation in the system was 5% or less. Nozzles were mounted on 6-inch risers with shrub adapters; there were no in-stem pressure regulators for the nozzles. The testing system (Figure 1) had 9 nozzles on a square spacing: 4 - 90 degree arc nozzles; 4 – 180 degree arc nozzles; and one 360 degree arc nozzle. Nozzles with arc adjustments were adjusted as needed for the testing system. This testing system which was constructed on turfgrass is also shown in Figures 2 and 3 (see pages 9 and 10).

Square Configuration

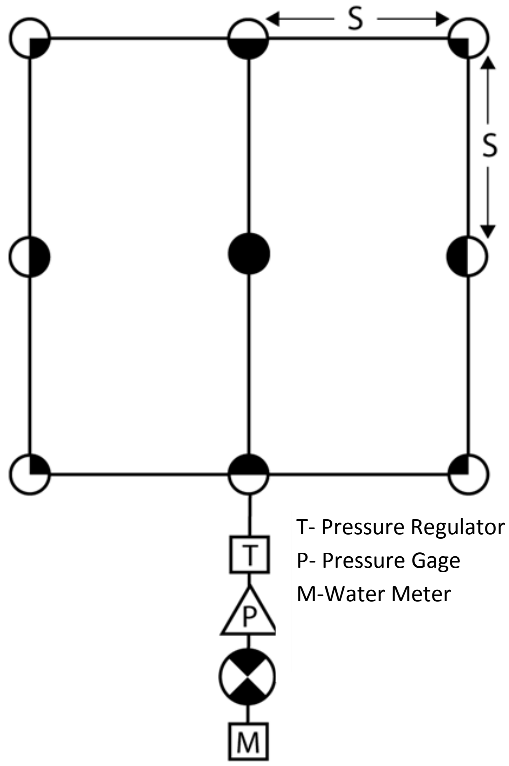

Figure 1. Testing system used in similar to configuration of nozzles and point of connection as shown here and referenced in Colasurdo (2010) and IA (2012).

Three Multi Stream Multi Trajectory (MSMT) nozzles common in professionally-installed systems were selected for this study. The first treatment factor **(spacing or spacing treatment)** was nozzle spacing distances in conjunction with adjusting and not adjusting the radius screw on the nozzle for head to head coverage (five levels) (Table 1). The second treatment factor was nozzle **(nozzle or nozzle treatment)** (three levels); they were labeled nozzle A, nozzle B, and nozzle C for this study. Distances between nozzles and between catch cans for the three test spacings are shown in Table 2.

Table 1. Five spacing and nozzle adjustment treatments.

Spacing Treatment	Nozzle spacing description	Abbreviated description[z]	Replications
1	Maximum Spacing, HTH	Max.	4
2	Minus10% of HTH, unadjusted	10% unadj.	4
3	Minus 25% of HTH, unadjusted	25% unadj.	4
4	Minus 10% of HTH, adjust radius to HTH	10% adj.	4
5	Minus 25% of HTH, adjust radius to HTH	25% adj.	4

[z] See Table 2 for HTH (Head To Head) spacing; unadj. = nozzle radius unadjusted at reduced spacing; adj. = nozzle radius adjusted for head to head coverage.

Table 2. Nozzles treatments, maximum nozzle spacing, nozzles treatment spacing, and catch can spacing.

Nozzle treatment	Max. nozzle spacing, ft(m)	Spacing % less than Max.	Nozzle treatment spacing, ft(m)	Total outside dimension of test system,[z] ft(m)	Catch can[y] inset from nozzle, ft(m)	Catch can spacing, ft(m)
A	18(5.5)	0	18.0(5.5)	36.0(11.0)	2.0(.6)	6.4(2.0)
A	18(5.5)	-10	16.2(4.9)	32.4(9.9)	2.0(.6)	5.7(1.7)
A	18(5.5)	-25	13.5(4.1)	27.0(8.2)	2.0(.6)	4.6(1.4)
B	21(6.4)	0	21.0(6.4)	42.0(12.8)	2.0(.6)	7.6(2.3)
B	21(6.4)	-10	18.9(5.8)	37.8(11.5)	2.0(.6)	6.8(2.1)
B	21(6.4)	-25	15.8(4.8)	31.5(9.6)	2.0(.6)	5.5(1.7)
C	20(6.1)	0	20.0(6.1)	40.0(12.2)	2.0(.6)	7.2(2.2)
C	20(6.1)	-10	18.0(5.5)	36.0(11.0)	2.0(.6)	6.4(2.0)
C	20(6.1)	-25	15.0(4.6)	30.0(9.1)	2.0(.6)	5.2(1.6)

[z] Distance between 90 degree arc nozzles in Figure 1.
[y] Catch cans were Cal Poly type.

The maximum spacings tested correspond to the maximum radius listed in product literature for nozzles B and C, and a spacing of maximum plus 1 foot (30.5 cm) for nozzle A for pressures of 40 psi (276 kPa). The spacing of maximum minus 10% selected for this study was based on conversations with irrigation designers who use this criterion in some designs. The spacing of maximum minus 25% as the second spacing selected was based on a common metric in the industry for the screw on the nozzle to adjust the radius to 25% less than the maximum recommended radius.

The five spacing treatments with four replications were run for each nozzle as listed in Table 1. To ensure independence between replications, a separate set of nozzles for the entire testing system was used for each replication. As an illustration, replication I of nozzle A used the first set of nozzles for the five spacing treatments, while replication II of nozzle A used the second set of nozzles for the five spacing treatments. The order of tests was: Maximum Spacing, HTH **(Max.)**, nozzle A, replications I to IV; nozzle B, replications I to IV; and then nozzle C, replications I to IV. This sequence of nozzle and replication tests was then used for the following spacing treatments in this order: Minus10% of HTH, unadjusted **(10% unadj.)**, Minus 25% of HTH, unadjusted **(25% unadj.)**, Minus 25% of HTH, adjust radius to HTH **(25% adj.)**, and Minus 10% of HTH, adjust radius to HTH **(10% adj.)**. A total of 60 individual tests were conducted.

Thirty six catch cans were used for each test. Catch can locations were changed each time the nozzle spacing was changed (see Table 2 for details). The 10% and 25% unadj. spacing treatments may have had overspray beyond the boundary of sprinkler heads. However, the catch cans for these treatments were only inside the boundary; catch can spacings are noted in Table 2. The nozzle height was the approximately the same as the top of the catch cans and the risers were visually aligned to vertical. The runtime was 15 minutes for all nozzles and spacing treatments. Wind speed measurements were taken near nozzle height and testing was terminated when wind speed exceeded 3 mph (4.8 kph) using a Kestrel 4000 Pocket weather tracker.

DU_{LQ} and DU_{LH} from 60 individual tests from the testing system were statistically analyzed. The experimental design was a 3 x 5 factorial completely randomized, in 4 replications, with nozzle (N) at 3 levels (A,B, and C) and spacing (S) at 5 levels (Max., 10% unadj., 25% unadj., 10% adj., and 25% adj.). A standard fixed effect model analysis of variance (ANOVA) procedure was used to test main effects and interaction and subsequently pre-determined single degrees of freedom contrasts (SAS 9.2). Because the N x S interaction was significant, ANOVA was conducted by N using a completely randomized design for 5 levels of the S treatment factor. Additionally, means were compared by using a Fisher's protected LSD test. It should be noted that a Univariate procedure showed that DU_{LQ} data were normally distributed.

Results and Discussion.

Two points of interest for this study were first, what effect does a decrease in nozzle spacing from head to head spacing (Max.) have on DU? Secondly, when the spacing is decreased, what effect does adjusting or not adjusting the radius screw have on DU? It should be noted that spacing treatments included both the treatments for physical distance between nozzles and the treatments of adjusting radius of the nozzle for head to head coverage (see Table 1).

Statistical analyses showed that spacing and nozzle treatments significantly affected DU_{LQ} and DU_{LH} and that the spacing x nozzle interaction also was significant (Tables 3 and 4, ANOVA effects). Due to the significant interaction, analysis of spacing treatments for individual nozzles was justified (Tables 3 and 4, Spacing treatment). The grand overall mean for DU_{LQ} for all spacing and nozzle treatments was 0.65 (Table 3, Overall column and Overall nozzle row) while the same for DU_{LH} was 0.78 (Table 4, Overall column and Overall nozzle row). The overall DU_{LQ} for the Max. spacing was 0.54 which was significantly lower than the overall DU_{LQ} for all other spacing treatments; 0.62, 0.66, 0.70, 0.72, 10% unadj., 25% unadj., 10 adj. and 25% adj., respectively (Table 3). Additionally, the overall DU_{LH} for the Max. spacing was 0.71 which was significantly lower than the overall DU_{LH} for all other spacing treatments; 0.76, 0.79, 0.81, 0.82, 10% unadj., 25% unadj., 10 adj. and 25% adj., respectively (Table 4). The DU for the Max. spacing was lower than expected for these types of nozzles which may be due to test conditions.

In context of the present study, contrasts are **predetermined** comparisons among selected spacing treatments which help refine information provided from a table providing spacing treatment means for individual nozzles and the overall, as shown in the upper portion of Table 3.

Contrasts for DU_{LQ}(see Table 3).

1. *(Max. vs. (10% and 25% unadj.))*: The DU_{LQ} for (10% and 25% unadj.) was significantly higher than Max. for the overall and for Nozzles B and C. This difference was not significant for nozzle A.
2. (Max. vs. (10% and 25% adj.)): The DU_{LQ} for (10% and 25% adj.) was significantly higher than Max. for the overall and for all nozzles.
3. (10% unadj. vs. 10% adj.): The DU_{LQ} for 10% adj. was significantly higher than 10% unadj. for the overall and for nozzles A and B. This difference was not significant for nozzle C. The overall DU_{LQ} for 10% adj. and 10% unadj. was 0.70 and 0.62, respectively.
4. (25% unadj. vs. 25% adj.): The DU_{LQ} for 25% adj. was significantly higher than 25% unadj. for the overall and for nozzles A and C. This difference was not significant for nozzle B. The overall DU_{LQ} for 25% adj. and 25% unadj. was 0.72 and 0.66, respectively.
5. *(10% adj. vs. 25% adj.)* The DU_{LQ} for 25% adj. was not significantly different than 10% adj. for the overall and for nozzle B. For nozzle A, 10% adj. was significantly higher than 25% adj.; for nozzle C, 25% adj. was significantly higher than 10% adj. Considering the above, a general difference between 25% adj. and 10% adj. is inconclusive and specific to nozzle type.

6. *(10% adj. and unadj.) vs. (25% adj. and unadj.)*: The DU_{LQ} for (25% adj. and unadj.) was significantly higher than (10% adj. and unadj.) for the overall and nozzles B and C. For nozzle A, DU_{LQ} was significantly higher for (10% adj. and unadj.) than 25% adj. and unadj.).

Contrasts for DU_{LH} (see Table 4).

1. *(Max. vs. (10% and 25% unadj.))*: The DU_{LH} for (10% and 25% unadj.) was significantly higher than Max. for the overall and for Nozzles B and C. This difference was not significant for nozzle A.
2. (Max. vs. (10% and 25% adj.)): The DU_{LH} for (10% and 25% adj.) was significantly higher than Max. for the overall and for all nozzles.
3. (10% unadj. vs. 10% adj.): The DU_{LH} for 10% adj. was significantly higher than 10% unadj. for the overall and for nozzles A and B. For nozzle C, 10% unadj. was significantly higher than 10% adj. The overall DU_{LH} for 10% adj. and 10% unadj. was 0.81 and 0.76, respectively.
4. (25% unadj. vs. 25% adj.): The DU_{LH} for 25% adj. was significantly higher than 25% unadj. for the overall and for nozzle A. This difference was not significant for nozzles B and C. The overall DU_{LH} for 25% adj. and 25% unadj. was 0.82 and 0.79, respectively.
5. *(10% adj. vs. 25% adj.)*: The DU_{LH} for 25% adj. was not significantly different than 10% adj. for the overall and nozzles A and B. For nozzle C, 25% adj. was significantly higher than 10% adj. Considering the above, a general difference between 25% adj. and 10% adj. is not substantiated and specific to nozzle type.
6. *(10% adj. and unadj.) vs. (25% adj. and unadj.)*: The DU_{LH} for (25% adj. and unadj.) was significantly higher than (10% adj. and unadj.) for the overall and nozzles B and C. For nozzle A, DU_{LH} was significantly higher for (10% adj. and unadj.) than (25% adj. and unadj.).

Table 3. The effect of spacing, radius adjustment, and nozzle on low quarter irrigation distribution uniformity (DU_{LQ})

	Nozzle[z]			
Spacing treatment	**A**	**B**	**C**	**Overall**
25% adj.	0.75 b[y]	0.74 a	0.67 a	**0.72 a**
10% adj.	0.81 a	0.76 a	0.52 c	**0.70 ab**
25% unadj.	0.59 cd	0.78 a	0.62 ab	**0.66 b**
10% unadj.	0.64 c	0.65 b	0.57 bc	**0.62 c**
Max.	0.58 d	0.58 b	0.45 d	**0.54 d**
Overall nozzle	**0.68 B**[x]	**0.71 A**	**0.56 C**	**0.65**
ANOVA effects (*P*)				
Spacing (S)	***	***	***	***
Nozzle(N)				***
S x N				***
Contrast (*P*)				
Max. vs. (10% and 25% unadj.)	NS	***	***	***
Max. vs. (10% and 25% adj.)	***	***	***	***
10% unadj. vs. 10% adj.	***	**	NS	***
25% unadj. vs. 25% adj.	***	NS	*	***
10% adj. vs. 25% adj.	*	NS	***	NS
(10% adj. and unadj.) vs. (25% adj. and unadj.)	*	*	***	**

[z] Nozzle spacing, feet: Max, 10%, & 25% respectively, Nozzle A: 18, 16.2, 13.5; B: 21, 18.9, 15.8; C: 20, 18, 15.

[y]Mean separation by Fisher's protected LSD test, $P = 0.05$. Means within the same column followed by the same letter are not significantly different.

[x]Mean separation by Fisher's protected LSD test, $P = 0.05$. Means within the same row followed by the same letter are not significantly different.

[NS,*,**,***]Nonsignificant, or significant at $P \leq 0.05$, 0.01, 0.001, respectively.

Table 4. The effect of spacing, radius adjustment, and nozzle on low half distribution uniformity (DU_{LH})

	Nozzle[z]			
Spacing treatment	**A**	**B**	**C**	**Overall**
25% adj.	0.83 a[y]	0.84 a	0.80 a	**0.82 a**
10% adj.	0.86 a	0.86 a	0.70 c	**0.81 ab**
25% unadj.	0.73 b	0.87 a	0.76 ab	**0.79 b**
10% unadj.	0.76 b	0.78 b	0.74 b	**0.76 c**
Max.	0.73 b	0.73 b	0.67 c	**0.71 d**
Overall nozzle	**0.78 B**[x]	**0.82 A**	**0.73 C**	**0.78**
ANOVA effects (*P*)				
Spacing (S)	***	***	***	***
Nozzle(N)				***
S x N				***
Contrast (*P*)				
Max. vs. (10% and 25% unadj.)	NS	***	***	***
Max. vs. (10% and 25% adj.)	***	***	***	***
10% unadj. vs. 10% adj.	***	**	*	***
25% unadj. vs. 25% adj.	***	NS	NS	**
10% adj. vs. 25% adj.	NS	NS	***	NS
(10% adj. and unadj.) vs. (25% adj. and unadj.)	*	*	***	**

[z] Nozzle spacing, feet: Max, 10%, & 25% respectively, Nozzle A: 18, 16.2, 13.5; B: 21, 18.9, 15.8; C: 20, 18, 15.
[y]Mean separation by Fisher's protected LSD test, $P = 0.05$. Means within the same column followed by the same letter are not significantly different.
[x]Mean separation by Fisher's protected LSD test, $P = 0.05$. Means within the same row followed by the same letter are not significantly different.

[NS,*,**,***]Nonsignificant, or significant at $P \leq 0.05$, 0.01, 0.001, respectively.

Summary.

This study's primary objective was to measure the effects of spacing and nozzle radius adjustment on the DU for Multi Stream Multi Trajectory (MSMT) rotary nozzles. There are irrigation design and field situations where sprinkler spacings do not match conventional head to head spacing. A previous study (Colasurdo 2010) on spray nozzles reported that DU values were not consistently highest at the Max. spacing compared to smaller and greater spacings. In this study, DU was basically higher at both 10% (adj. or unadj.) and 25% (adj. or unadj.) spacings than at the Max. spacings selected for this study for three nozzles.

A secondary objective was to determine the effect of adjusting or not adjusting the nozzles on DU when spacings were decreased from Max. Basically, data show adjusting the radius screw to achieve HTH coverage for smaller spacings resulted in a higher DU.

Several test procedures of this study should be noted. First, when nozzles are spaced at 25% unadj. there was overspray. This may be objectionable when nozzles are installed on landscape perimeters or other situations where overspray water is not used by plants. Overspray may occur to a lesser extent at 10% unadj. It should be reemphasized that all nozzles were tested at 40 psi (276 kPa) and wind speed did not exceed 3 mph (4.8 kph). Results may be different if field conditions vary.

When nozzle spacings are less than the maximum spacing the precipitation rate does increase (data not shown). In the field this would need to be considered in irrigation scheduling.

Future research could explore if these trends in DU are similar in actual landscapes where nozzle spacing may include a range of sprinkler head spacings.

Figure 2. Test system with nozzles , catch cans, point of connection, water meter, and pressure gauge.

Figure 3. Sprinkler nozzles on shrub adapters mounted on movable platforms to set required nozzle spacings.

Acknowledgements.

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The effect of approximating irrigated area on the gross irrigation requirement

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Abstract. *The gross irrigation requirement (GIR) is the estimated irrigation required to maintain the landscape considering evapotranspiration, rainfall, and irrigation system efficiency. Irrigation volume must be converted to depth to compare to the GIR. The objective was to evaluate the variation in irrigation using three methods to determine landscape area: A) irrigated area, B) turfgrass only, and C) parcel information. The irrigated area was defined as the area covered by the existing irrigation system observed during on-site visits. Irrigated areas were overlaid on aerial images to determine turfgrass only areas assuming that established ornamentals required no irrigation. The final method, irrigable area estimated from removing building footprints from total parcel area, is common when on-site visits are unfeasible, but can have significant error when large portions of outdoor space is unirrigated. The evaluation was conducted by determining differences in estimating irrigation application by smart controllers compared to GIR assuming an 80% efficiency factor using the three area methods. Results showed that estimating turfgrass only areas from aerial imagery was just as accurate as on-site area measurements whereas the parcel area estimation was more conservative. From the perspective of a targeted water conservation program, using parcel areas may be the best option due to directing resources concerning water conservation toward proven excessive irrigators for maximum program effectiveness.*

Keywords. Gross irrigation requirement, irrigation, landscape area, smart controllers

Introduction

In 2013, groundwater resources were considered insufficient in Central Florida to sustain projected population growth. Though landscape irrigation is proportionately small in water consumption compared to agriculture, research has shown that utility customers in Central Florida over apply landscape irrigation by 6 to 8 times the amount of irrigation required (Davis and Dukes 2014) and irrigation accounts for over half of total residential water use (Haley et al. 2007). Thus, reducing over-irrigation across the region may reduce the burden on the aquifer.

The total irrigated area is one of the most important factors needed to relate total water volumes to the calculated irrigation requirement. On-site measurements of landscape area are not feasible on a large scale, such as by a utility or water management district. Two different approaches to estimating landscape area include using satellite images to delineate green area and using readily available parcel data obtained through the property appraiser. However, the amount of error in these estimated methods is unknown. The objective of this study is to determine the best methods to estimate irrigated area in effort to identify over-irrigated landscapes for future targeted sustainable programs.

Materials and Methods

Study Description

In 2011, a smart controller study was implemented in Orange County, FL. Smart controllers are technologies that assist in recommended irrigation scheduling when installed and programmed properly. Current smart controllers on the market include evapotranspiration (ET) controllers and soil moisture sensors (SMS). The ET controllers use estimates of ETO to determine theoretical plant water needs. The SMS bypasses scheduled irrigation events when the soil has sufficient moisture.

There were a total of 167 homes chosen across nine locations that were distributed into five treatments per location with a minimum of three replications per treatment. The treatments were as follows: ET controller (ET; 28 households), ET controller with educational programming (ET+Pgm; 38 households), soil moisture sensor (SMS; 28 households), soil moisture sensor with educational programming (SMS+Pgm; 38 households), and monitored only (MO; 35 households). All technologies were installed by a licensed irrigation contractor. The treatments with educational programming received a one-on-one tutorial from the researchers, additional educational materials, and re-programming of their technology to match their specific site conditions. Only results from the MO, ET, and SMS treatments are presented in this paper.

The selected homeowners submitted to an intense screening process to determine applicability of using a smart controller. Initially, homeowners had to fall within 1.5 to 4 times above the gross irrigation requirement (GIR) on a monthly basis (Davis and Dukes 2014). Irrigation application was determined from estimated irrigation volumes using utility billing data and estimated irrigated area using available parcel information. Once selected as a potential participant, each household received an irrigation evaluation by the researchers to verify that excessive irrigation was due to improper irrigation scheduling that could be addressed by the smart technology and not due to faulty irrigation systems or already poor landscape quality.

On-site Area Measurements

During the irrigation evaluations, total irrigated area for each participant was measured using a walking measuring stick. The irrigated area was defined as the total area that the irrigation system was designed to target. Thus, impervious areas within a zone were not removed such as sidewalks and walkways. However, poor adjustments to sprinkler nozzles and other maintenance issues were not considered as irrigated area. Examples would include misaligned sprinklers that irrigate across property lines or into roads or driveways.

Turfgrass Only Area Estimations

When on-site irrigated areas are not available, an alternative method can be to spatially determine the potentially irrigated green space using satellite images imported into ArcGIS. The bird's eye view depicted the house and other building structures, turfgrass areas, and ornamentals. Polygons were formed around the dominant turfgrass areas since turfgrass is a water-intensive plant material (Romero and Dukes 2011). The ornamentals were not used in this estimation because established plants can maintain plant quality under normal rainfall conditions (Scheiber et al. 2008, Gilman et al. 2009).

Parcel Area Estimations

It has been proposed that using parcel level data available through the property appraiser to estimate irrigated area can be used to accurately predict trends of single-family residential irrigation application (Friedman et al. 2013). Each participating household was searched on the Orange County property appraiser site to determine total parcel size and gross parcel area that includes impervious areas such as the house and driveway. The proposed irrigated area was the difference between the total and the gross estimates.

Data Collection and Analysis

Weather data was collected from three installed weather stations and one Florida Automated Weather Network (FAWN) weather station located near the treatment groups across the county. Two additional rain gauges were installed to have more accurate rainfall measurements in locations that did not receive weather stations. Precipitation, air temperature, relative humidity, and wind speed were collected at 15 minute intervals throughout the study period. The data was used to calculate reference evapotranspiration (ETO) for use in the soil water balance equation in order to determine GIR.

Hourly outdoor water volumes were collected from each household using an automatic meter recording (AMR) device installed and maintained by Orange County Utilities. Irrigation application as a depth was calculated from water volumes using estimated irrigated areas. As a result, three estimations of irrigation application were produced for each participant from December 2011 through July 2013. The analysis was separated into four seasons due to significant differences in rainfall throughout the study period.

Statistics were conducted using Statistical Analysis Systems (SAS) software (Cary, NC). Results were modeled using the GLIMMIX procedure with treatment differences determined using least mean square differences for type of area by treatment for each season within the study period. Significance was determined at a 95% confidence level.

Gross Irrigation Requirement

The net irrigation requirement (NIR) is the amount of water required to reach the root zone to maintain plant water needs. It is calculated using a daily soil water balance with inputs of ETO and rainfall. The root zone was estimated as having a depth of eight inches for turfgrass and available water holding capacity was determined from soil survey information based on treatment location.

The gross irrigation requirement (GIR) is the amount of irrigation that must be scheduled to achieve NIR due to inefficiencies in the irrigation system. The preferred achievable efficiency was selected as 80%. Thus, the GIR was calculated using 80% efficiency as a comparison. A detailed description of how the GIR is calculated can be found in Davis and Dukes (2014).

Results

In all seasons and treatments, there was no difference in estimated irrigation application between the measured landscape area and the turfgrass only areas determined using ArcGIS (Figs. 1-4). This resulted in an average error of 3% - 7% in monthly irrigation application estimations across treatments (Fig. 5). This was not surprising considering turfgrass is the dominant plant material in most landscapes within the study.

In all seasons and treatments, the irrigation application determined using the parcel area was not different or was significantly less than the irrigation application estimated using the measured area. More often than not, using parcel area was significantly less than measured area. As a result, average error ranged from -12% to -18% across treatments.

Except in one instance occurring in the wet 2013 season for the comparison treatment (Table 4), the irrigation application estimated using the turfgrass only areas was significantly different than when estimated using the parcel areas. The parcel areas over-estimated the irrigated area resulting in lower estimates of irrigation application.

Except during the wet 2013 season (Table 4), the irrigation application by the MO treatment using all three area estimates resulted in significantly different irrigation application than GIR. This indicates that the participants without technological changes remained excessive irrigators throughout most of the study. Though it is unknown why there was no difference during the wet 2013 season, it is possible that the frequent rainfall resulted in many participants switching their timers to the off position for short periods of time. These potentially missed events may have counteracted the over-irrigation during the events that actually occurred.

The SMS was not significantly different when using the parcel area compared to the GIR during both wet seasons (Table 2, Table 4).

Conclusion

There is a need for a methodology to efficiently target habitual excessive irrigators for intervention in effort to increase water conservation and sustainability. One of the important inputs to accurately determine irrigation application is the irrigated area. Estimating irrigated area by direct measurement on a large scale, such as by a utility, would be too expensive and time consuming to make it a feasible option. Investing in estimating turfgrass area using ArcGIS was just as accurate as on-site area measurements, so it may be a good option if it is economically feasible. Using parcel data was less accurate, typically resulting in under-estimations of irrigation application. However, from a water conservation program perspective, this may be the best option due to its relatively low cost in obtaining the areas and generally errs on the conservative side. This way, resources concerning water conservation can be directed toward proven excessive irrigators for maximum program effectiveness.

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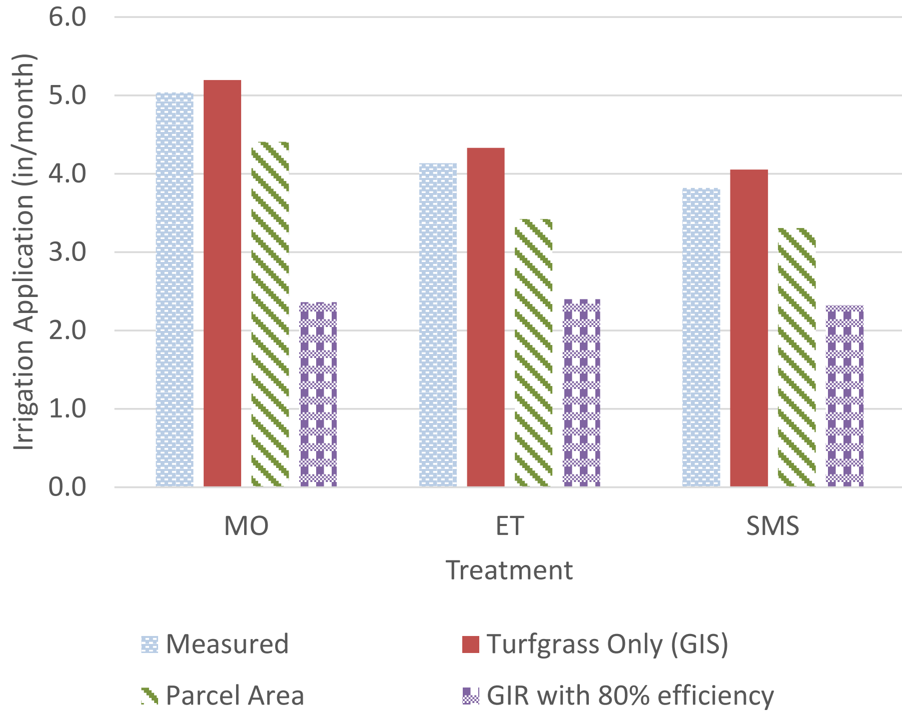

Figure 1. Average irrigation application during the Dry 2012 season using three different landscape areas compared to the gross irrigation requirement.

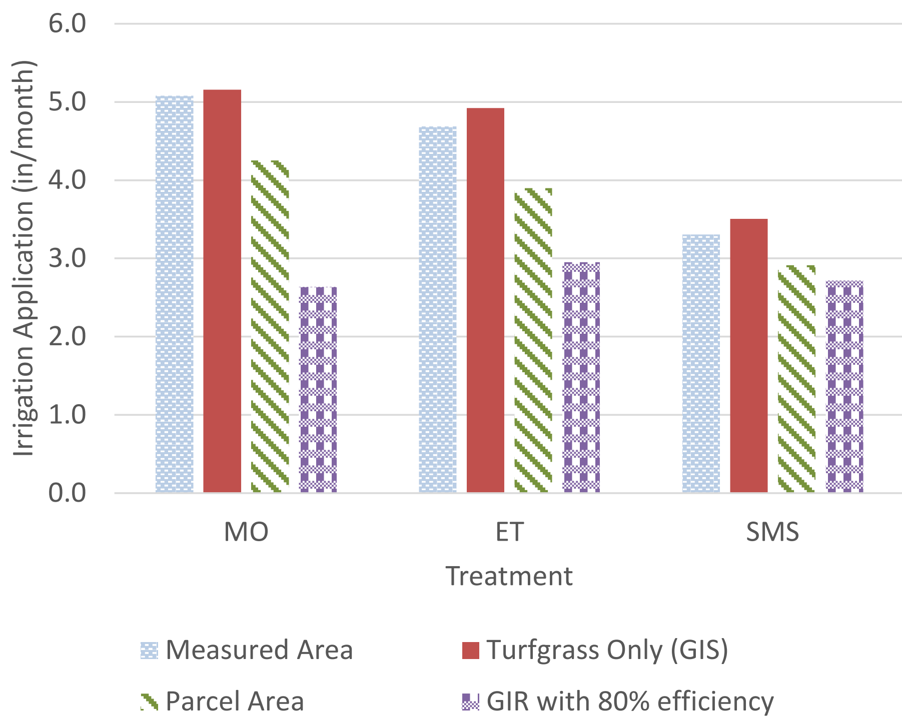

Figure 2. Average irrigation application during the Wet 2012 season using three different landscape areas compared to the gross irrigation requirement.

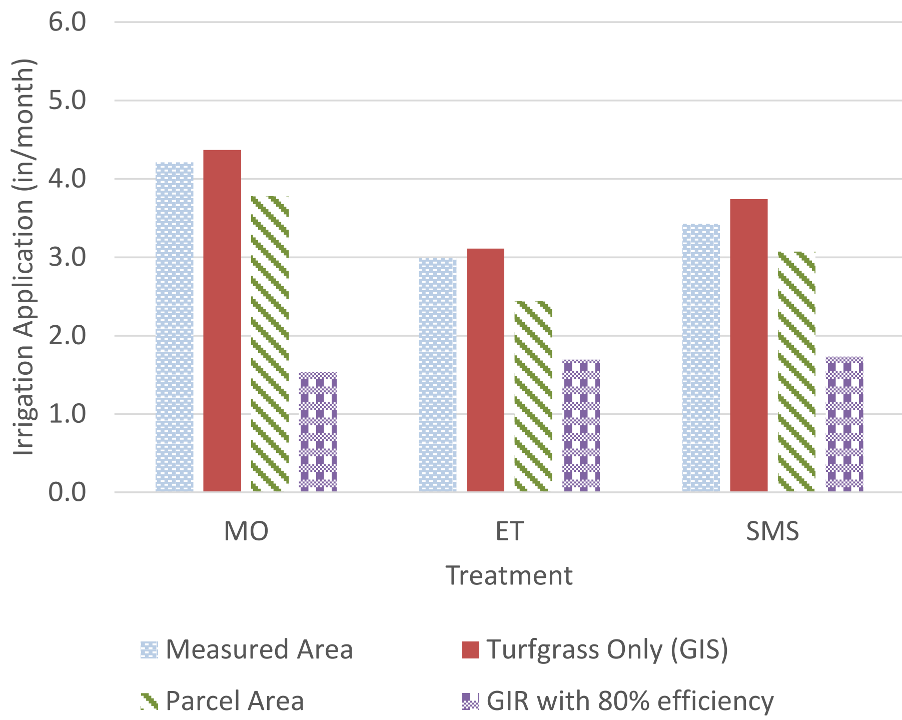

Figure 3. Average irrigation application during the Dry 2013 season using three different landscape areas compared to the gross irrigation requirement.

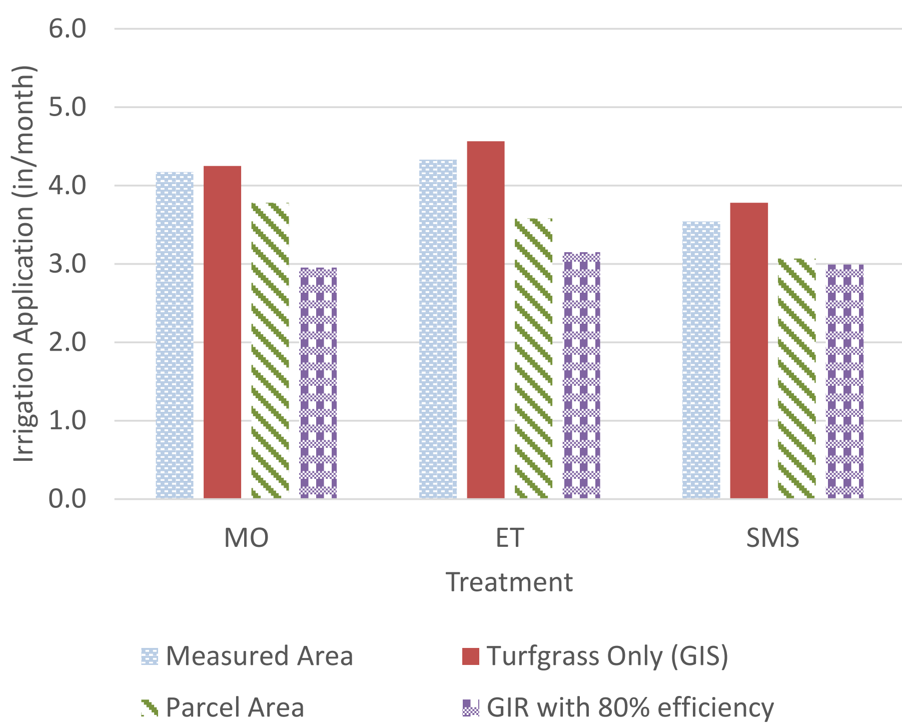

Figure 4. Average irrigation application during the Wet 2013 season using three different landscape areas compared to the gross irrigation requirement.

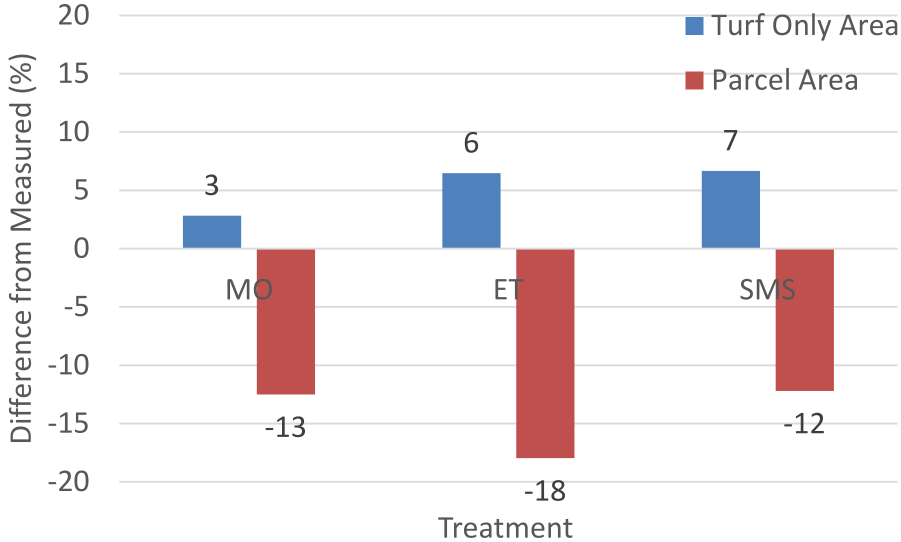

Figure 5. Average error of irrigation application on a monthly basis when determined using the turfgrass only and parcel area estimations, both compared to the measured landscape areas.

Surfactant Effects on Municipal Sports Fields

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Abstract:

For turf managers, soil surfactants are important tools for improving water-use efficiently, maintaining turf quality and reducing expenses. The overall goal of this field trial was to evaluate the addition of three EO/PO block copolymer surfactants as a component of a sports field water management strategy in West Deptford, New Jersey, USA. Three irrigated soccer fields were split down the center, and treated with one of the three surfactants. An unirrigated softball field was also tested. Turf quality (TQ), volumetric water content (VWC) and chlorophyll content (CC) were measured weekly for a total of 24 weeks. The softball field treated with surfactant showed the greatest improvement. Turf quality, VWC and CC were higher in the surfactant treated area. On one of the soccer fields, the surfactant significantly reduced VWC when there was too much water on the field.

Keywords. Sports Turf, Soil Moisture, Distribution Uniformity, Turf/Landscape

Introduction:

Water restrictions and budget cuts are making it more difficult to maintain municipal sports fields in the United States. With the majority of the western USA being classified as in a severe drought or worse, using water as efficiently as possible is becoming increasingly important (Hiem, 2014). Cost is also a large factor in water savings. In 2013, municipal water costs in 30 US major cities saw an average of a 7% increase over the previous year, and between 2010 and 2014 increased 25% (Walton, 2013). These large price increases in water are opening up a lot of potential markets for surfactant use as a way to save water and money.

Surfactants are organic molecules that act as wetting agents by reducing the surface tension of water (Laha et al., 2009). For turf managers, soil surfactants could be an important tool for improving water-use efficiently, maintaining turf quality and reducing expenses (Oostindie et al., 2008). They have a wide variety of uses including sports turf, golf courses, agriculture and horticulture. Surfactants have been shown to increase soil water holding capacity, as well as, increase nitrogen use efficiency (Kostka, 2000; Lowery et al., 2002; Arriaga et al., 2009). These effects on soil physical properties may make them ideal to use in an environment that does not have the resources to allocate to high maintenance costs.

Surfactants improve water conversation in two ways; by reducing to soil water repellency (SWR) and preferential flow (PF). Soil water repellency and PF can significantly reduce irrigation efficiency and cause water and nutrient loss (Oostindie et al., 2008). Surfactants have been shown in golf course turf systems to reduce both SWR and PF patterns in soil (Tucker et al., 1990; Hallett et al., 2001). The majority of surfactant research is focused on highly managed golf course conditions. The site was chosen because it was maintained by the local government. The resources allocated to maintain this park declined due to budgetary cuts. The purpose of this experiment was to test the effectiveness of these three surfactant chemistries under these sports field conditions.

Materials and Methods:

Site Description:

Figure 1: Overview of the park and the fields that were treated. The soccer field is labeled 1-3 and the softball field is labeled number 4. (Google maps)

Surfactant	**Rate**	**Frequency**	**Total Applications**
EP/PO Block Co-Polymer 1	24oz/Acre	Every 3 Weeks	7
EP/PO Block Co-Polymer 2	16oz/1000sq/ft	Every 12 weeks	2
EP/PO Block Co-Polymer 3	6oz/1000sq/ft	Every 4 Weeks	5

Figure 2: Surfactant rates and number of applications.

The field site was scouted, and the optimal fields for the trail were chosen during the first visit. The EP/PO block co polymers were set to correspond with the number field. The fields (Figure 1) were then split in half and marked with spray paint. The surfactant was tank mixed and spray applied with a 20 foot Toro commercial sprayer according to Figure 2 by the facility manager. Each surfactant was spray applied on one half of each of the three soccer fields in a split bock. Due to adequate rainfall none of the products were watered in. The total area of each of the fields was about two acres, making one acre treated and one control. The soil was a native sandy loam. The field was a mix of perennial rye and creeping bent grass that was reseeded yearly following aeration. The fertilizing regiment was extremely minimal. Urea was applied only when the turf appeared to be showing signs of nitrogen deficiency, and a starter fertilizer was applied following aeration and reseeding. The field was aerated, reseeded and fertilized during the 19th week of this trial.

The layout of the softball field made consistent treatment complicated. The field (Figure 1) had two light poles approximately 200 yards apart, which were used as a reference points to ensure the same area was treated. The EP/PO block copolymer 1 was tank mixed and spray applied with a 20 foot Toro commercial sprayer according to Figure 2 by the facility manager. The sprayer was lined up with one side in line with pole, driven in a straight line to the opposing pole and back. Foam dots were used to ensure a straight line and that there was no overlap. This made a 40 foot section treated with controls on either side. The soil was a native sandy loam with a very large, dry, problem area centrally located in the outfield. The 40 foot treatment divided the problem area in half. The field was a mix of perennial rye and creeping bent grass that was reseeded yearly following aeration. The fertilizing regiment was extremely minimal. Urea was applied only when the turf appeared to be showing signs of nitrogen deficiency, and a starter fertilizer was used following aeration and reseeding. The field was aerated, reseeded and fertilized during the 19th week of this trial.

Evaluations:

The field was evaluated weekly for 24 weeks. Turf quality was visually rated using a 1 to 10 scale (1=poor turf and 10=ideal turf) on the treated and untreated sections of each field. Soil VWC was measured with a Spectrum FieldScout TDR300 (Spectrum Technologies, 3600 Thayer Court, Aurora, IL 60504) moisture meter with the 3 inch (8cm) probes installed. Thirty readings were taken on a straight tangent across the treated and untreated sections of the field. Turf grass CC readings were taken at the same time using the Spectrum CM1000 (Spectrum Technologies, 3600 Thayer Court, Aurora, IL 60504) meter beginning at week three. Ten random soil cores at a depth of surface to four inches (10cm) were taken at the beginning and end of the trial on each section of the field and were sent to Harris labs for nutrient analysis.

Environmental Conditions:

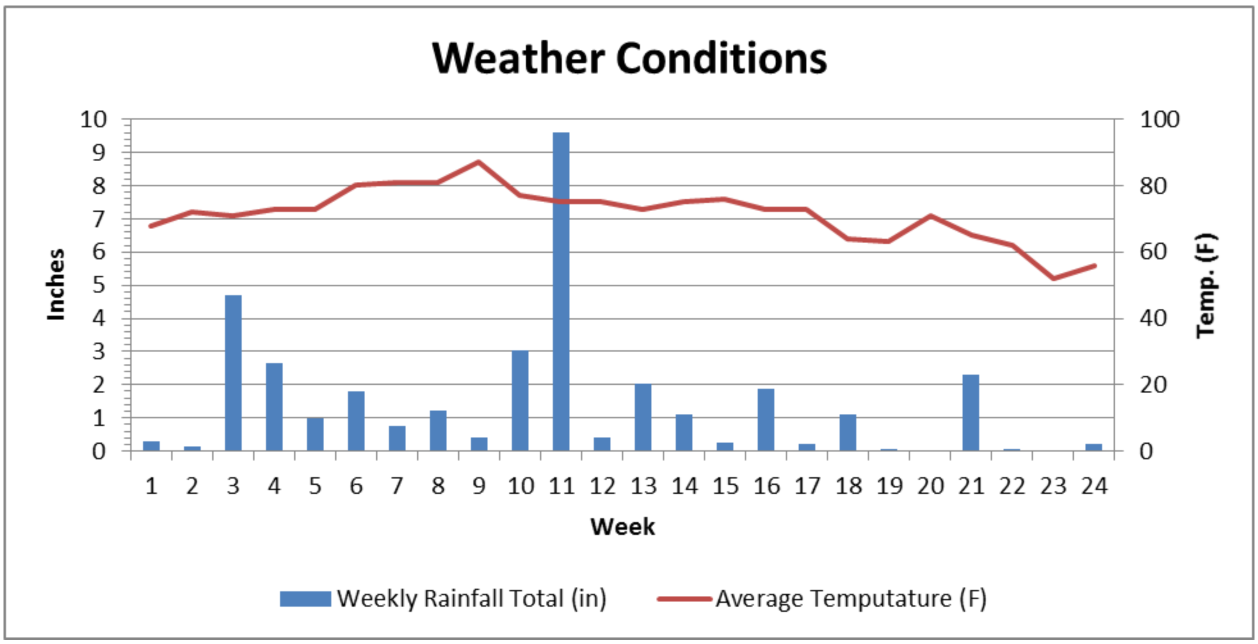

Figure 3: Weather conditions according to weather underground.

Figure 3 shows the weather conditions during summer months in Philadelphia, which is the closest recorded weather station. The summer of 2013 was one of the wettest summers on record for the Delaware Valley. A little over 35 inches of rain fell during this field trial. During the same time period in 2012 a little over 17 inches of rain fell in this area. The area typically averages 0.75 inches of rain per week and 41 inches for the year. The weather conditions made it challenging to see results because the turf grass was not under water stress during the trial.

Statistical Analysis:

After the data were collected, the results were graphed and data were analyzed. A two paired t-test was run on the volumetric water content and the chlorophyll content data. An asterix on the graph indicates that the P value is less than 0.05.

Results:

Soccer Field One:

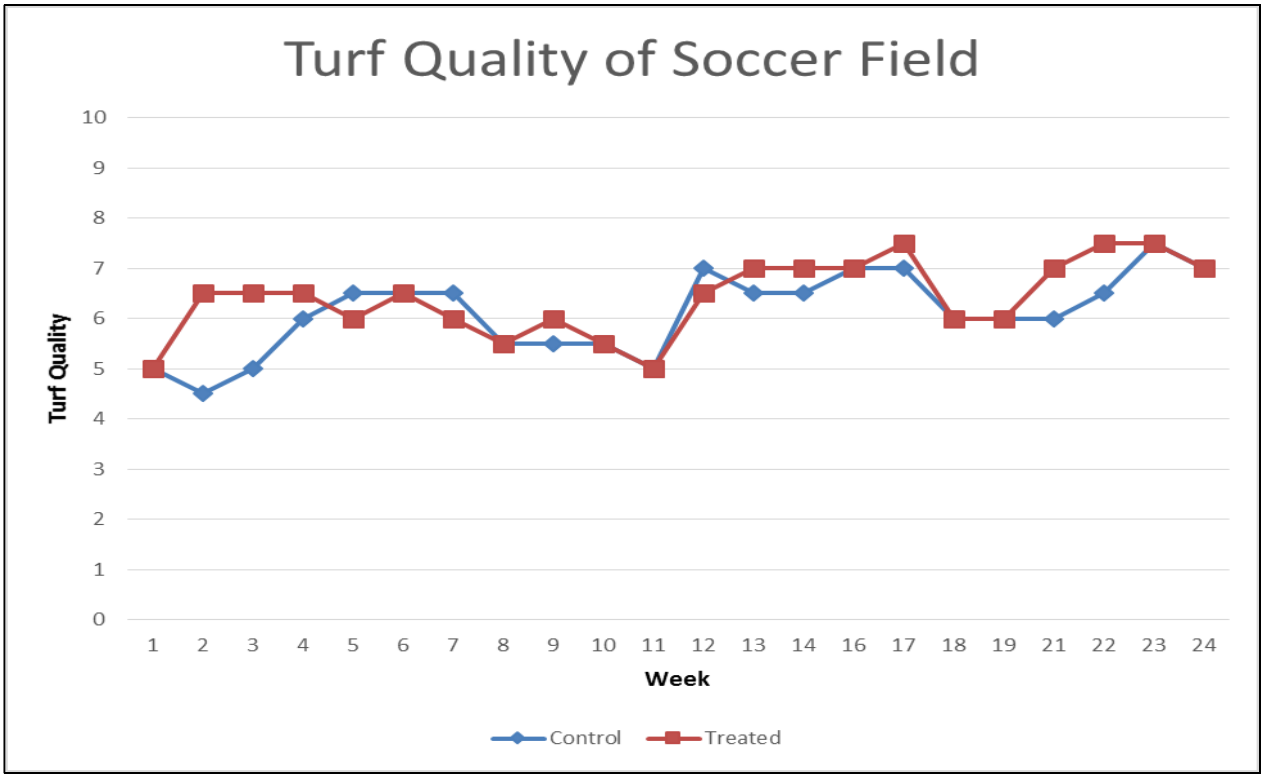

Figure 4: Turf quality of a soccer field treated with an EP/PO Block Co-Polymer

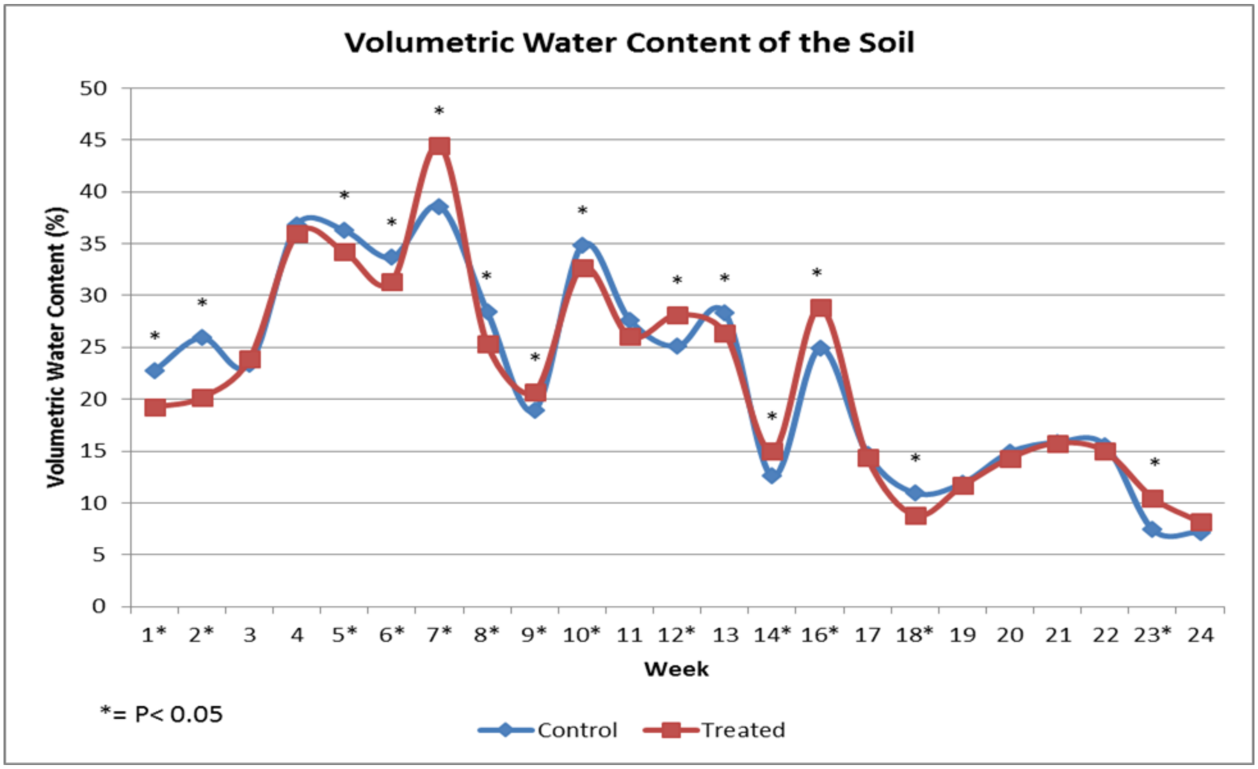

Figure 5: Volumetric water content of the soil on a soccer field treated with an EP/PO Block Co-Polymer

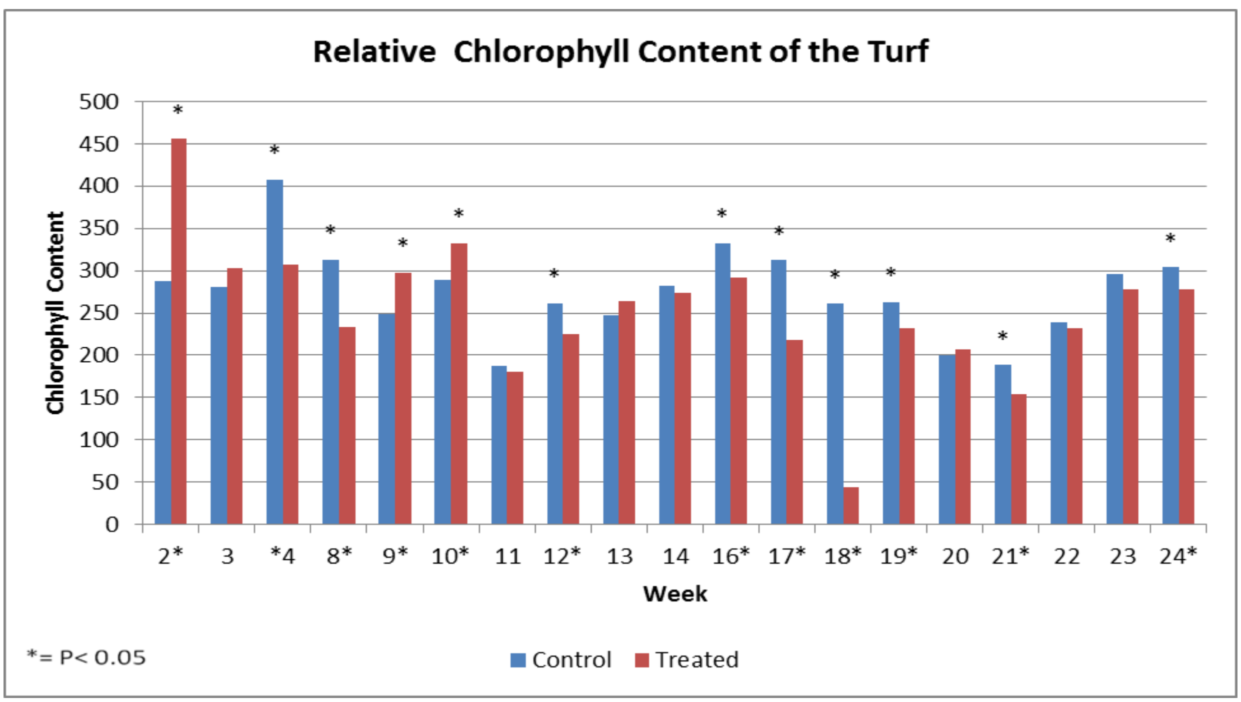

Figure 6: Relative chlorophyll content of the turf on a soccer field treated with an EP/PO Block Co-Polymer

The two sides of the field started the same and then the treatment exhibited a trending effect at week 2 (Figure 4). The TQ of the control area eventually improved after about 4 weeks. The two sides of the field demonstrated similar TQ for the majority of the trial. The treated side of the field exhibited a secondary trend toward improvement after the field was aerated and reseeded at week 19. The treated areas appeared to demonstrate a faster recovery. The control side eventually showed equal TQ after three weeks.

Many similarities in TQ were due to how this field was split. The control area was not nearly as worn as the treated area. There was significant wear around the goal areas, and these exhibited improvement throughout the season. These improvements were apparent in the pictures, but did not improve the treated side of the field enough to show up on in the overall turf quality.

Although there were statistical differences in VWC (Figure 5) no trends were seen in the data. The soils did appear to be very wet during the majority of the season and did not dip below ten percent on either side until the last week. The CC (Figure 6) seems to be closely in line with the VWC data and there were no trends in the data.

Soccer Field Two:

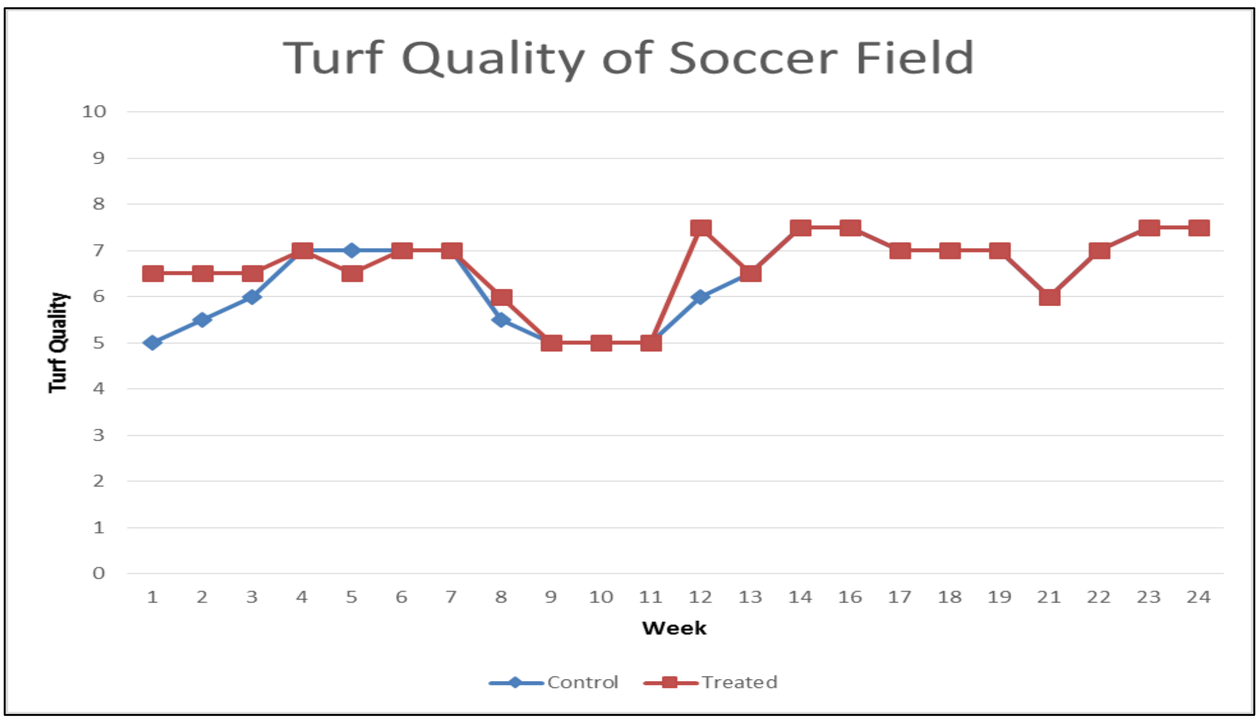

Figure 7: TQ of a soccer field treated with an EP/PO Block Co-Polymer

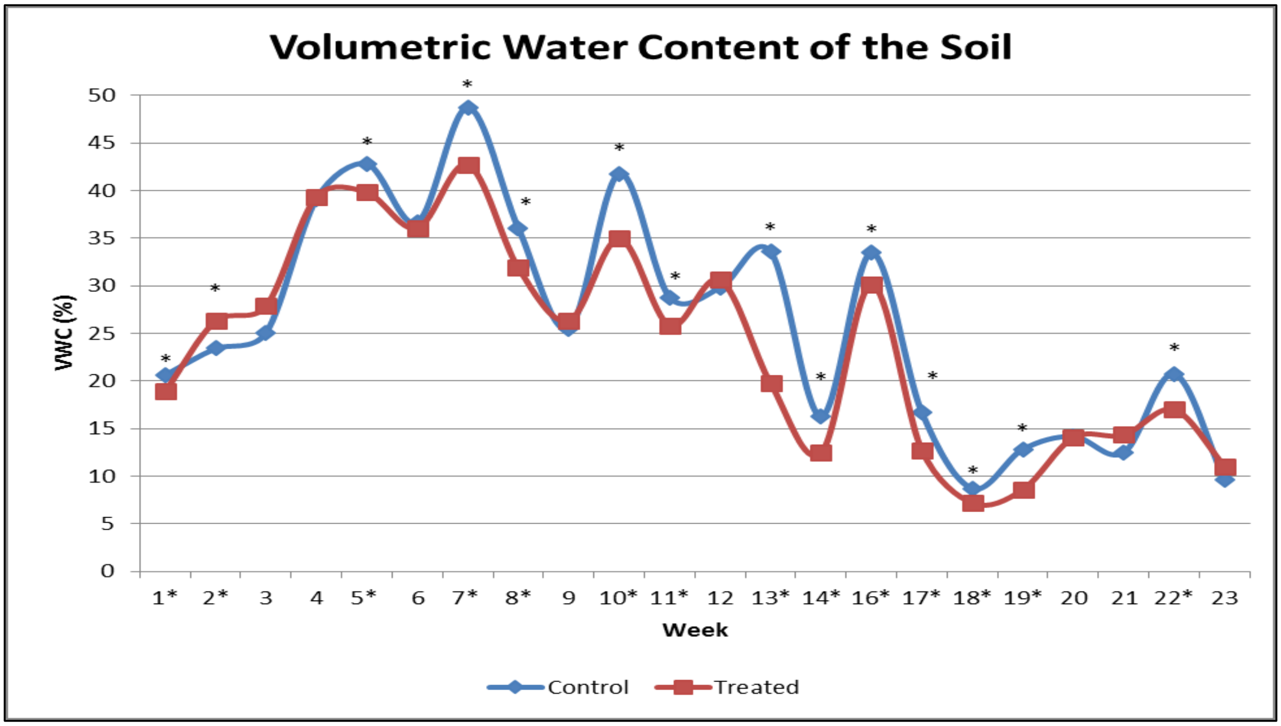

Figure 8: VMC of the soil in a soccer field treated with an EP/PO Block Co-Polymer

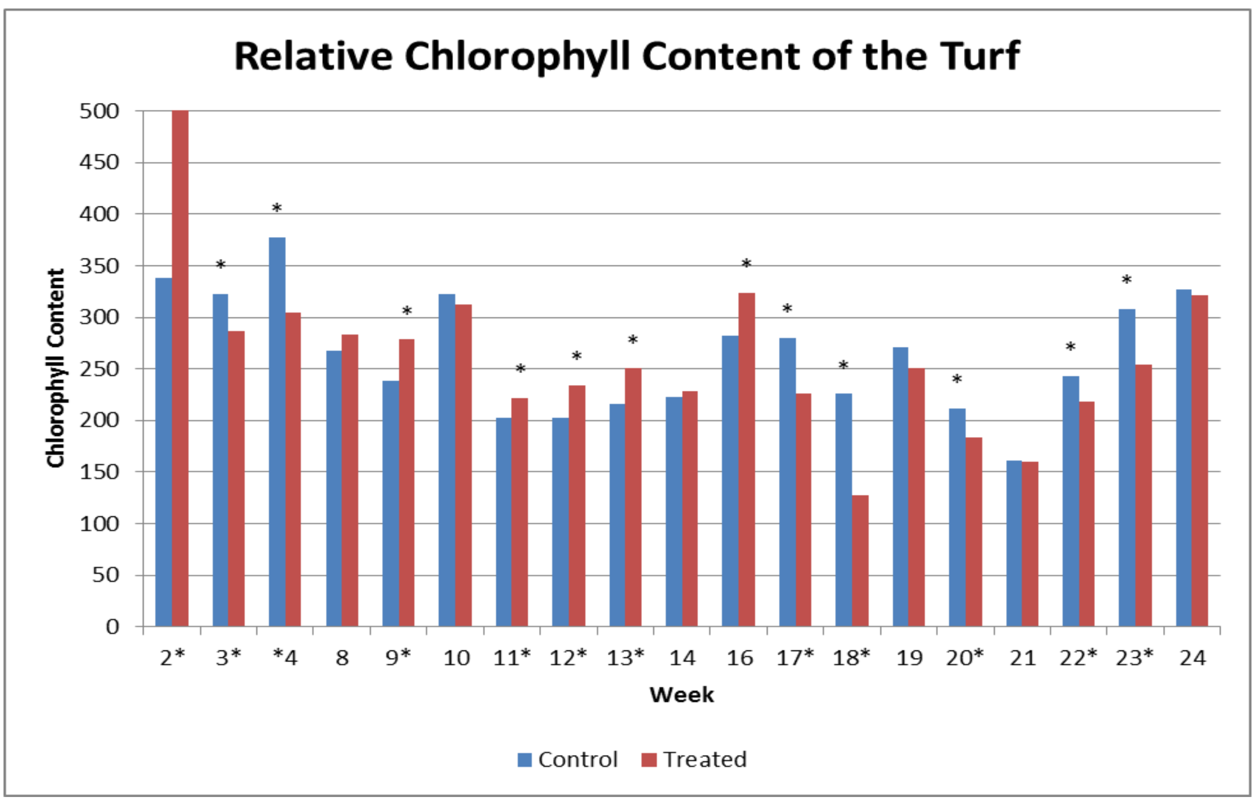

Figure 9: Relative CC of the turf on a soccer field treated with an EP/PO Block Co-Polymer

The treatment side initially had higher TQ (Figure 7). The control area eventually improved after about 3 weeks. The two sides of the field demonstrated similar TQ for majority of the trial. No overall differences were seen on the field.

The VWC was significantly lower on the treated side of the field throughout the season (Figure 8). The field started the same on both sides. The surfactant may have helped this field to drain excess water. Also, the treatment significantly improved the CC (Figure 9) on weeks 11, 12, 13, and 16. Weather conditions (Figure 3) indicate that these were particular wet and hot with week 11 receiving 9.5 inches of rain. The VWC (Figure 8) was also significantly lower during Week 11, 13 and 16. Indicating that the turf exhibited less stressed due to the presence of less water in the treated area of the field. Week 17 and 18 the CC significantly dropped and this is consistent with a significant drop in VWC on the treated side of the soccer field. Indicating that while under wet conditions the surfactant helped with drainage, however when the field dried out it put the plant under water stress.

Soccer Field Three:

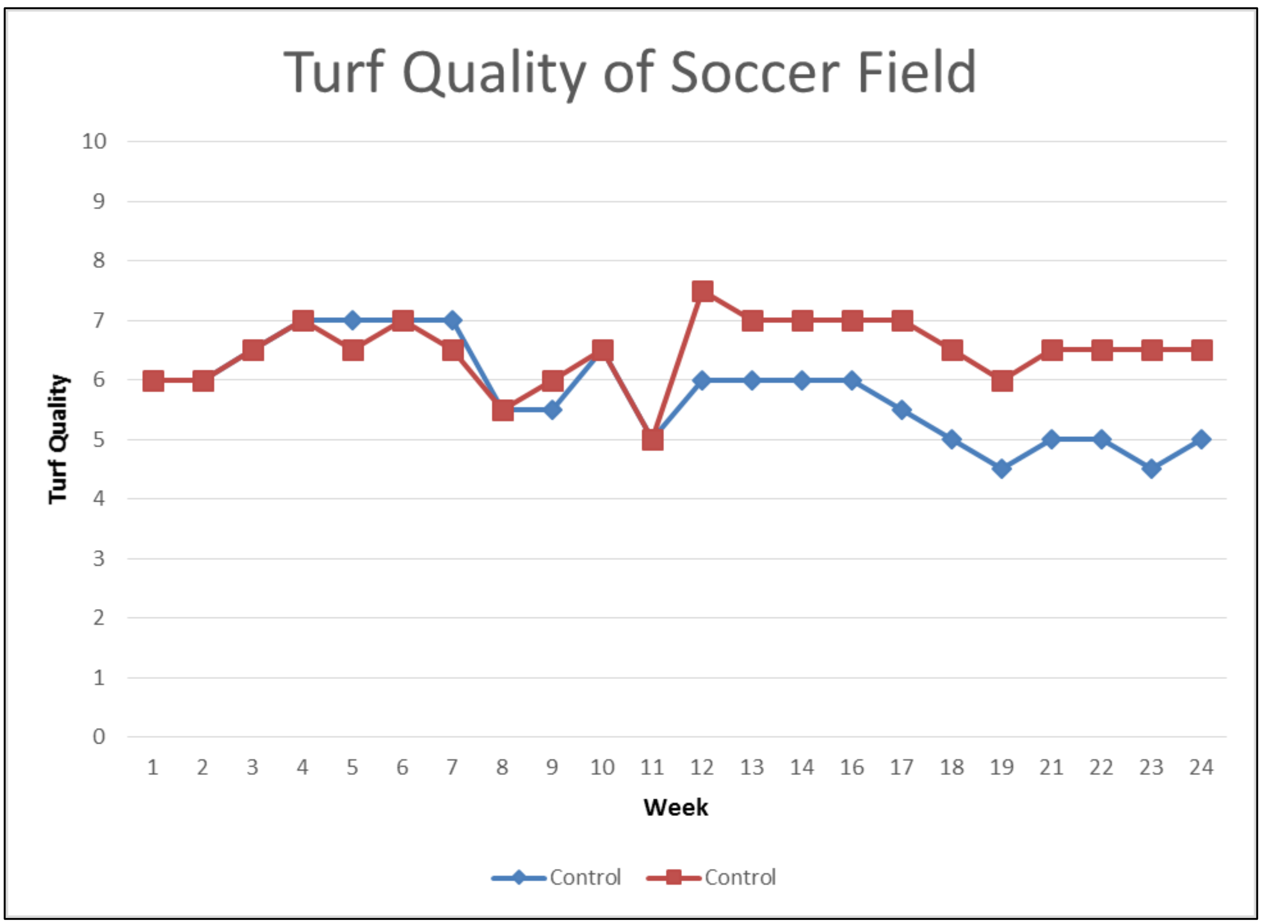

Figure 10: Turf quality of a soccer field treated with an EP/PO Block Co-Polymer

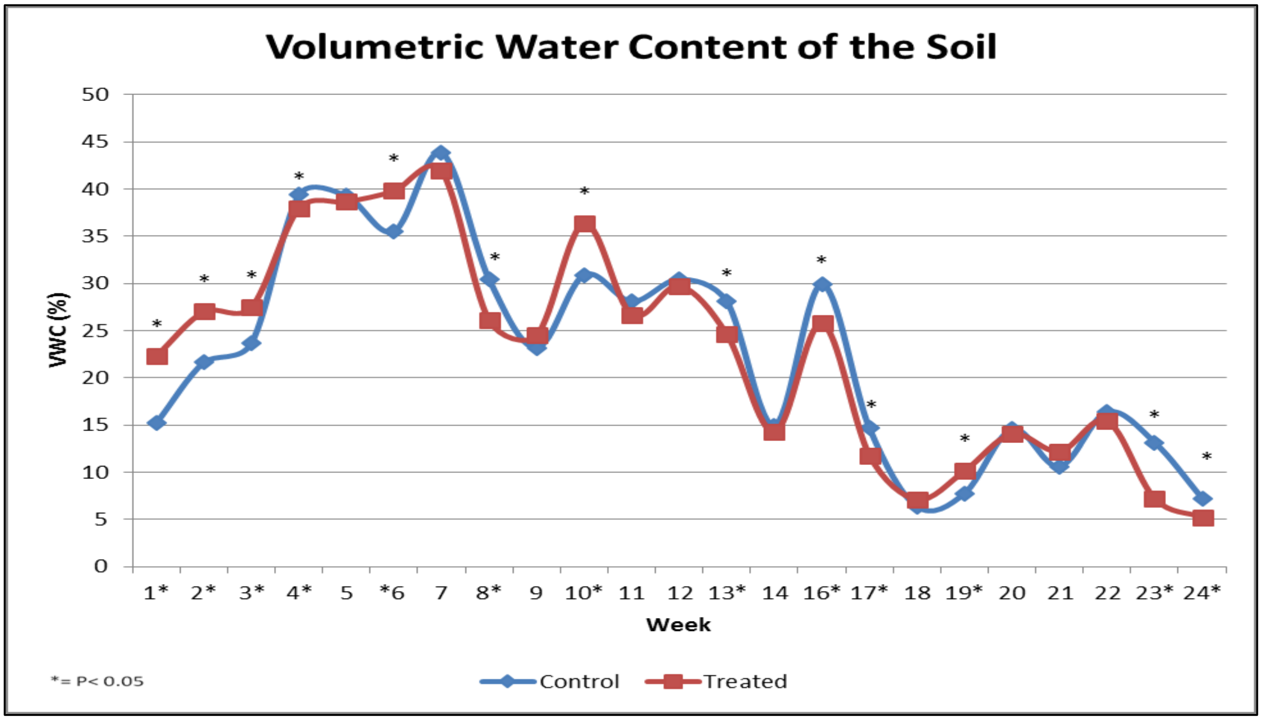

Figure 11: Volumetric water content of the soil on a soccer field treated with an EP/PO Block Co-Polymer

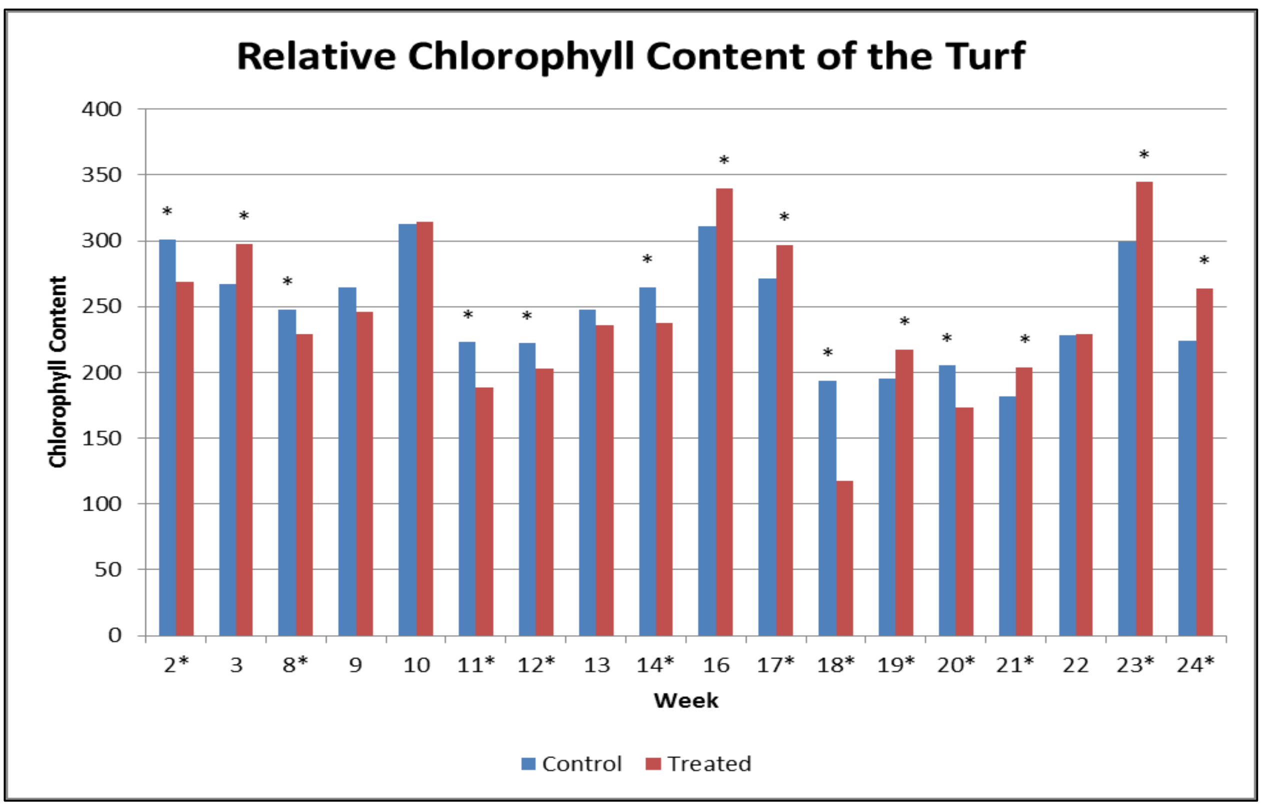

Figure 12: Relative chlorophyll content of turf on a soccer field treated with an EP/PO Block Co-Polymer

Turf quality (Figure 10) on the treated and untreated sides of the field started the season equal. This field was heavily infested by crab grass. It was then treated with an herbicide to try to combat infestation. After the treatment, the surfactant treated side trended to recover faster and maintained that trend of higher TQ through the duration of the trial.

There were no treatment effect on soil VWC (Figure 11). The CC (Figure 12) on this field exhibited some interesting trends when compared to the weather data. The beginning 14 weeks of the trial were the wettest, and during this time the control section exhibited significantly higher CC compared to the treated side. During five of the nine weeks data was collected the control was significantly higher. After 14 weeks, six of the final nine weeks the treated area had significantly higher CC. The VWC (Figure 11) decreased 50% on both sides during this time, indicating, that as the summer dried out the turf may have been less stressed on the treated side.

Softball Field Four:

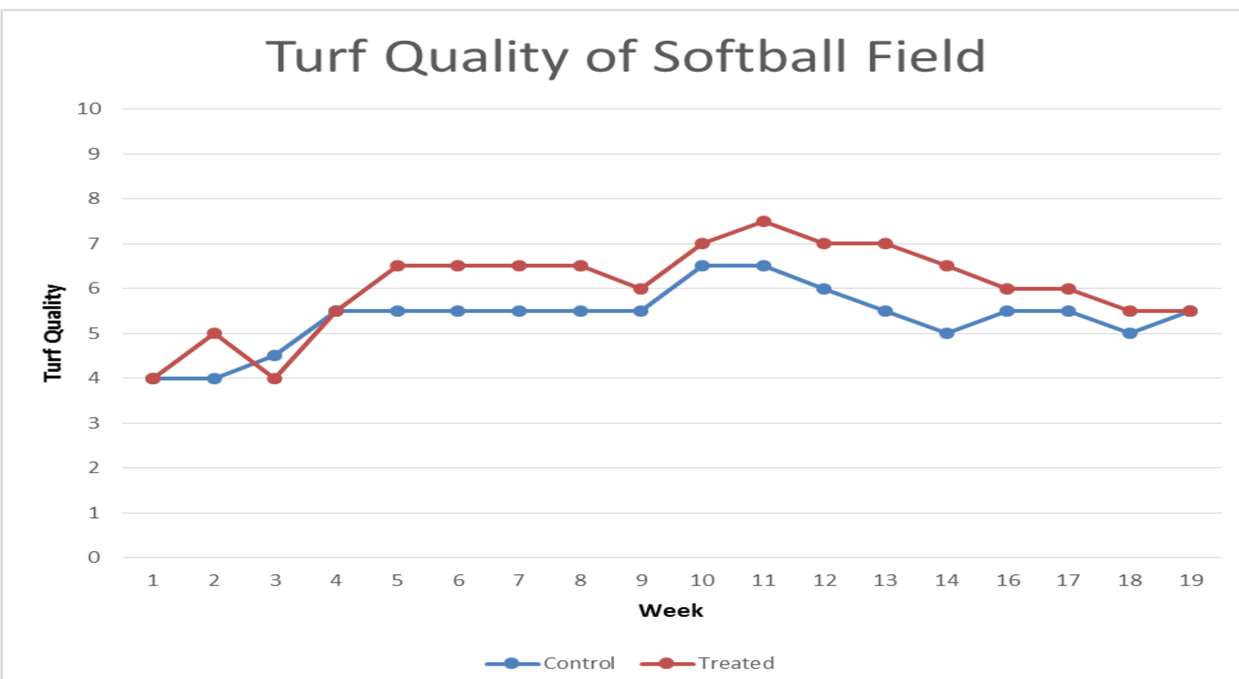

Figure 13: Turf quality of a softball field treated with an EP/PO Block Co-Polymer

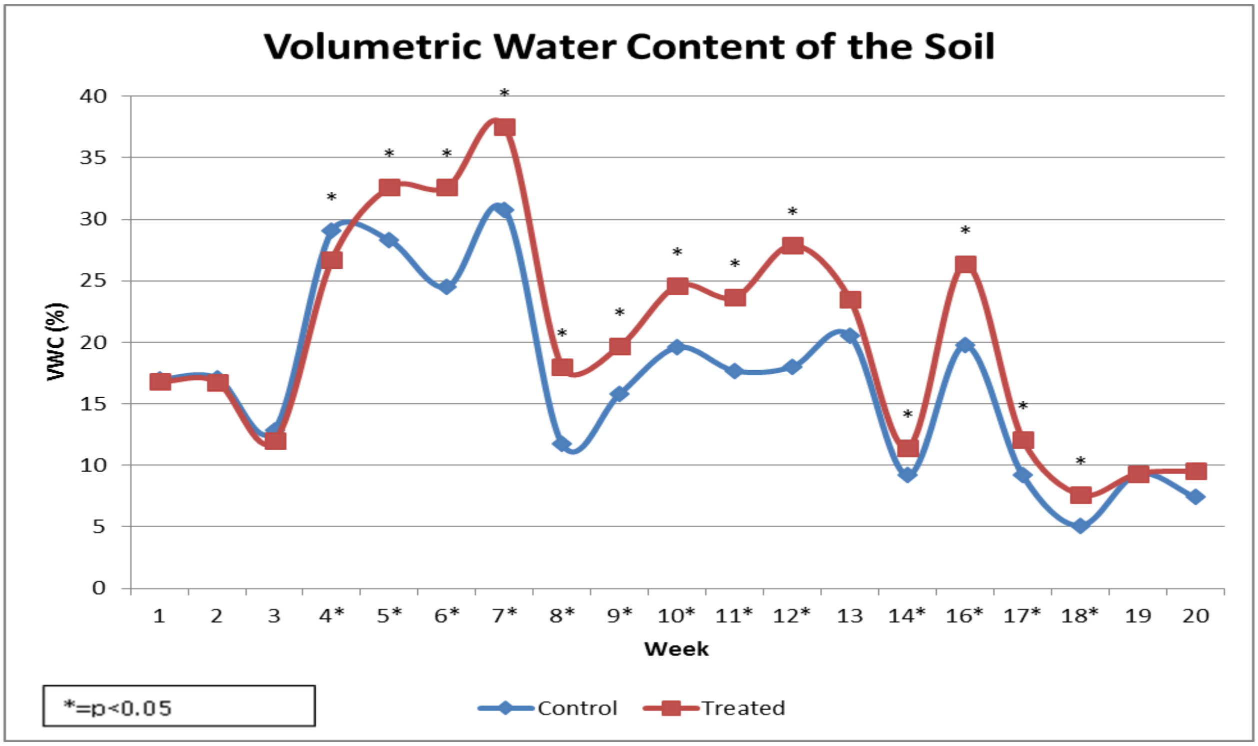

Figure 14: Volumetric water content of the soil on a soccer field treated with an EP/PO Block Co-Polymer

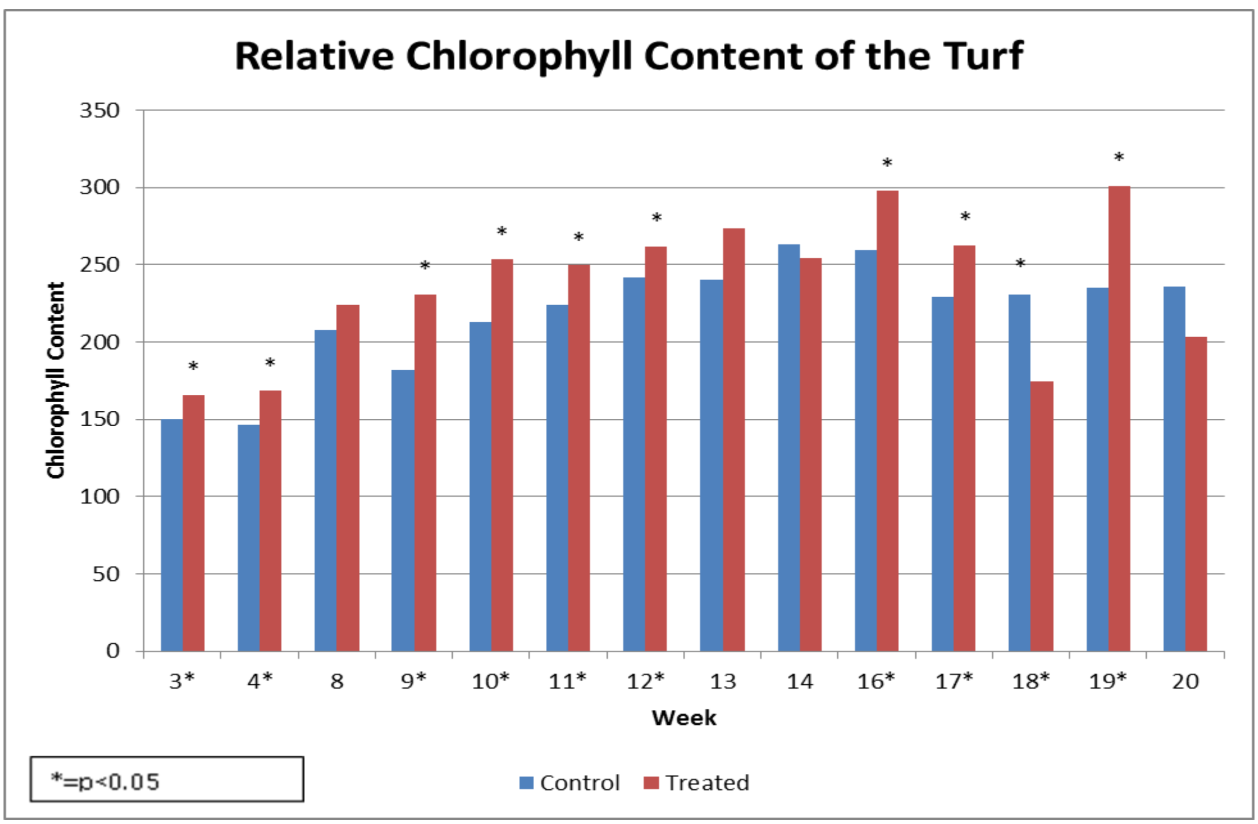

Figure 15: Relative chlorophyll content of the turf on a softball field treated with an EP/PO Block Co-Polymer

At the start of the season TQ (Figure 13) on the treated and untreated side of the field were equal. After about five weeks a trend in improvement was observed in the surfactant treated areas. The difference between treatments remained until the final week when the surfactant and control areas were similar. This observation suggest that this product may influence TQ.

At study initiation, soil VWC (Figure 14) were equivalent in the treated and untreated sections. Beginning at week 4 the VWC was significantly higher in the treated portion of the field and remained significantly higher than the control for all but two of the subsequent measurement dates. The surfactant treatment helped to retain soil water throughout the growing season.

On 10 of the 14 measurement dates, the CC (Figure 15) was significantly greater in the surfactant treated portion of the field, compared to the untreated area. Higher CC supports the visual TQ rating and indicates greater photosynthetic efficiency. It is also an indicator that the plants were less stressed throughout this trial.

Conclusions:

In conclusion, this trial demonstrates that all three of EP/PO block co-polymers would fit into a water management program at West Deptford Park, NJ. EP/PO block co-polymers 1 proved very effective on the unirrigated softball field. It improved TQ, soil VWC and turf CC. The chemistry demonstrated the largest treatment effects seen on any field during this trial. EP/PO block co-polymer 2 statically decreased soil VWC when the field was to wet and would be useful for draining a field that holds to much water. EP/PO block co-polymer 3 improved overall TQ and CC during the driest portion of the summer.

Acknowledgments:

I would like to personally thank Matt Moore, Acting Public Works Manager, for allowing us to use the park to conduct this trial. I would also like the thanks Mica for her continued guidance and support.

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Selling End Users on Water Efficient Improvements.

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Abstract

In an effort to drive uptake of water conserving products, an irrigation professional must “sell” their client on the value of water conservation. The purpose of this paper is to evaluate the effectiveness of an alternative method to data collection compared to catch can data collection and analysis. While irrigation professionals typically want to help their clients reduce water use, the only methodology they are trained on is the use of catch cans and collection of data such as, precipitation rates and Distribution Uniformity (DU) – (Distribution Uniformity, Coefficient of Uniformity and Scheduling coefficient). The objective of this study is to (evaluate the use of) use an alternate method of irrigation analysis to produce useful information that can be used to drive client uptake of water saving products.

This study was carried out over 5 irrigation seasons (2010-2014) and consisted of evaluating multiple irrigation systems using an alternative irrigation assessment technique. Trained irrigation professionals used this alternative method to quantify water use, identify water use, annual water cost and water savings potential. This information was then used to sell end-users on the advantages to investment in irrigation system performance improvements. The intent was to achieve and sustain significant outdoor water use reductions.

Results indicate that it is Return on Investment (ROI) and total water use savings volumes that drive consumer behaviour when it comes to investment in irrigation system improvements. While DU is one way to measure zone performance, DU is not something that the end user cares about (or understands). These findings indicate that irrigation professionals can provide end users with useful information that can be collected in (approximately) half the time of a traditional (catch can) irrigation assessment. In five years of practical, hands-on, real-world experience, the assessment findings led directly to the improvement of irrigation systems resulting in the conservation of millions of litres of potable water and hundreds of thousands of dollars in water cost savings. If more assessments can be performed in significantly less time but achieve the same results, this would indicate a potentially significant revenue opportunity for irrigation professionals. If significantly greater economies of scale can be achieved with this new approach to irrigation assessments while assisting the irrigation professional in demonstrating a solid business case for irrigation water conservation, then a very promising business opportunity exists for irrigation professionals in marketing irrigation water conservation assessments and retro-fits.

Keywords

Water manager, consultant, designer, water resource management, water utility, water conservation, audit, irrigation assessment, inspection, water budget, distribution uniformity, scheduling, return on investment, water conservation audits, data collection, retro-fit.

Do we need to sell water conservation?

Water conservation generally makes sense to consumers and irrigation system end users. In the case of low flush toilets it is fairly simple. Converting a standard toilet 3 GPF (Gallon per Flush) to a 1 GPF will save water every time you use your fixture. Another example of a water saving fixture is a high efficiency shower head. These are probably the most widely used and observed conservation techniques used in the home or in commercial buildings. The savings realized from the employment of these fixtures is easy to measure, understand and "sell" to consumers. Unfortunately, selling irrigation water conservation is not as simple. Sure, the manufacturers such as Hunter, Rain Bird and Toro all have invested heavily in R&D for creation of new irrigation products that can help irrigation system owners save water, but a problem still exists. These products are not as highly used as needed since end-users do not really know exactly how much water they can save by installing these new high efficiency products.

Manufactures claims of 30% for pressure regulation, rotary nozzles, etc sound great, but in reality, a contractor does not have the information they need to answer the most common question from a homeowner or decision maker. How much water am I using right now and how much will installation of these products cost me and save me? Claims of 30% water savings are great but 30% of what? In order to sell water conservation in irrigation systems, we need more verifiable information.

Typically, an irrigation professional will attempt to gain experience and knowledge in water conservation by becoming a Certified Landscape Irrigation Auditor (CLIA). There are thousands of CLIA professionals in North America. This professional learns how to use and collect irrigation performance values and metrics such as DU, lowest quarter DU, etc. If you speak to some of these CLIA professionals you will hear consensus that typically, they are seldom paid to perform this work. Irrigation professionals regard this work as time consuming and expensive. As a result, the cost of a "catch can" audit falls outside the budgets of what a homeowner or HOA (home owners association) might consider as cost effective. It is true that if there is limited budget, spending a large portion of the budget on the audit makes little sense. The majority of irrigation assessments currently being performed are being done by not for profit organizations that have funding to carry out irrigation assessments as part of the overall "water conservation" mandate. Typically these agencies are performing this work for cities and towns as part of their water conservation strategy. If a more efficient and cost effective method of performing irrigation assessments existed, irrigation professionals would start to perform more assessments, and this in turn, will result in the implementation of water conserving products and behaviours.

Typically irrigation improvements do have to be "sold". An HOA, for example, may know that they have a high summer water bill but typically they do not know why. They are likely aware that sprinklers are the cause but they don't really know if they "are they using more water than they need too". The consultative selling aspect is necessary to explain where the saving opportunities are and what level of investment is necessary to achieve a desired water use reduction outcome. The selling part of this process is demonstrating that an investment in water conservation makes financial sense. Sure there are other benefits to water conservation but usually it comes down to money. Traditionally an irrigation audit sets out to determine the level of performance for an irrigation system. Irrigation performance is described in terms of Distribution uniformity (how evenly water is applied) and precipitation rate (depth of water per unit of time). These operating characteristics are then used to program proper irrigation schedules. Neither of these performance metrics are helpful to the end user if making an investment decision. From personal experience, an end user will get a "glazed over look in their eyes" as soon as there is mention of distribution uniformity and other industry "jargon". The end user just wants to know how they can save water (while maintaining a healthy landscape) and how to prioritize their investment dollars.

A change in approach

After initial consult with a local water utility conservation department, it was clear that in order to meet their goals for the number of irrigation assessments performed, a new approach would have to be used. Since system assessment reports were going to be sent directly to the property management team, a new method of communicating water conservation potential had to be determined. The aim of this assessment program was to give property managers the information they needed to review the water savings opportunity with their contractor and then act on the recommendations.

After consideration, it was decided that savings potential would be identified by setting a weekly target of .50" (inches) per week. Using historical billing data and landscape size estimates it was hypothesized that over a 20 week irrigation season, on average, the landscape would require no more than a total of 10" of precipitation supplied by irrigation. While Evapotranspiration during this time period (May-September) typically totalled over 20 inches, rainfall was typically over 15" during the same period. Any weekly zone irrigation application amount in excess was deemed to be waste. ***Note- the .5" target is applicable for the climate of the study. In Hot arid climates this number would need to me raised.***

In order to achieve reductions in application rate to .5" per week, irrigation deficiencies such as leaks, mixed precipitation, over-pressurization and overspray would need to be corrected. If corrected, it was believed that an additional savings of .15" per week could be achieved with installation of a smart controller and .20" of savings with installation of an irrigation management system that included flow sensing.

The Methodology

Once a landscape had been selected, an irrigation assessment would be scheduled and an assessment performed. During the irrigation assessment key information was collected using an ultra-sonic flow sensor, measuring wheel, soil probe, sprinkler pressure gauges, and camera. During the inspection of each zone, the following information is collected:

1. Zone flow rate
2. Zone area of the landscape only (no hardscape)
3. Sprinkler head dynamic pressure
4. Sprinkler head count and type
5. Documentation of deficiencies (leaks, etc)
6. Picture of gauges, soil probe, leaks, overspray and landscaped areas
7. Irrigation program run times, start times and days of operation

Panametric/Ultra-sonic flow sensor

Soil sample

Example of a leak

Example of a leak- Some deficiencies are more visible than others.

Pressure gauge

Overspray- visible waste

With the above information, zone weekly application amounts were determined and used as the evaluation metric of performance. A zone with over .5” of weekly application was deemed to be over watering. Over watering can be a result of a leak, improper scheduling or other infrastructure problems. Identifying zones with over .5” per week of application leads the irrigation professional to zones that potentially require a closer look to determine the cause of the over watering.

Here is an example of an irrigation system assessment data chart:

Table 1 - Zone Summary: IMAX - 2010

Zone Number	Zone Location	Area, m^2	Landscape Type	Rotors	Sprays	PSI	Flow rate, L/min	run time min/cycle	cycles/week	mm/week	inches/week	m3/year	Leak Observed	Potential Savings, m^3/yr: Hardware Savings[1]	Additional w/ Smart Controller[2]	Additional w/ Central Controller[3]
1	NE corner of bldg	1,171	TURF/TREES	15	•	38	120	40	4	16	0.65	384		87	119	149
2	E side of bldg	471	MIXED	12	•	40	108	45	4	41	1.62	389		269	48	60
3	Boulevard between driveways	1,310	TURF/TREES	20	•	22	130	45	4	18	0.70	468	✓	135	133	166
4	S boulevard	641	MIXED	19	•	26	122	45	4	34	1.35	439		276	65	81
5	E side of pond	2,137	MIXED	14	•	45	108	45	4	9	0.36	389			63	117
6	N and S of pond	1,918	TURF/TREES	9	•	46	115	45	4	11	0.43	414			122	170
7	N of pond, S of bldg	2,731	TURF/TREES	14	•	34	147	45	4	10	0.38	529			113	182
8	S side of bldg	676	MIXED	9	•	33	112	45	4	30	1.17	403		231	69	86
9	Planting Beds at bldg entrance	552	SHRUBS/TREES	•	18	35	160	15	4	17	0.68	192		52	56	70
10	Lunch courtyard	487	SHRUBS/TREES	•	12	38	115	10	4	9	0.37	92			18	30
11	S side of bldg	1,076	TURF/TREES	13	•	32	125	40	4	19	0.73	400		127	109	137
12	NW side of shipping driveway	279	TURF	•	17	25	150	30	4	65	2.54	360	✓	289	28	35
13	W side of parking lot	242	TURF	•	14	36	120	30	4	59	2.34	288		226	25	31
14	N side of parking lot	166	TURF/TREES	•	12	35	104	30	4	75	2.95	250		207	17	21
15	E side of parking lot	230	TURF	•	10	32	86	30	4	45	1.77	206		148	23	29
16	N boulevard	1,479	TURF/TREES	13	•	34	105	45	4	13	0.50	378			153	190
17	E side parking lot and around naturalized area	2,146	TURF/TREES	15	•	34	108	45	4	9	0.36	389			62	116
18	POND FILLER VALVE															
19	N corner of bldg	914	TURF/TREES	15	•	40	150	40	4	26	1.03	480	✓	248	93	116
											Total Annual Irrigation Demand, m3/year =	6,450				
													Total Estimated Annual Savings, m3/year =	2,296	1,315	1,788
													Percentage Savings =	36%	20%	28%

Potentially over-watered zones

1 Via fixing leaks, replacing spray heads with rotors, and adjusting run times/schedule to achieve 0.5 inches/week for 20 weeks

2 Via reducing average irrigation application rate to 0.30 inches/week for 20 weeks.

3 Via reducing average irrigation application rate to 0.25 inches/week for 20 weeks.

The above chart is then sent to the property manager as part of a comprehensive report with cost estimates of the recommendations on total costs per zone and an anticipated return on investment (ROI) from water savings in each zone assuming repairs are made, performance enhancements are made and scheduling is adjusted. Once the system changes are implemented, a return to the site is necessary to verify “new” water use information. The purpose of the post inspection is to verify that changes had been made and to document the results. Here is an example of a post monitoring data collection chart:

Comparison between 2010 water use and 2011 water use

Changes were made to sprinkler nozzles, zones changed from sprays to drip, run-times adjusted

Average savings equal 27%

Zone Number	mm/week in 2010	inches/week in 2010	m3/year in 2010	mm/week in 2011	inches/week in 2011	m3/year in 2011	Overall reduction m3/year	Overall reduction Gallons/year	Percent Reduction
1	16	0.65	384	12	0.46	276	108	28,531	28%
2	41	1.62	389	27	1.07	257	132	34,871	34%
3	18	0.70	468	11	0.45	298	170	45,015	36%
4	34	1.35	439	22	0.87	283	156	41,211	36%
5	9	0.36	389	9	0.35	378	11	2,853	3%
6	11	0.43	414	10	0.41	396	18	4,755	4%
7	10	0.38	529	9	0.35	490	40	10,461	7%
8	30	1.17	403	31	1.20	414	-11	-2,853	-3%
9	17	0.68	192	12	0.47	132	60	15,850	31%
10	9	0.37	92	10	0.40	98	-6	-1,691	-7%
11	19	0.73	400	10	0.38	206	194	51,144	48%
12	65	2.54	360	25	0.97	137	223	58,963	62%
13	59	2.34	288	28	1.09	134	154	40,577	53%
14	75	2.95	250	36	1.42	120	130	34,237	52%
15	45	1.77	206	24	0.93	108	98	25,995	48%
16	13	0.50	378	12	0.46	346	32	8,559	9%
17	9	0.36	389	8	0.31	342	47	12,363	12%
18	POND FILLER VALVE								
19	26	1.03	480	18	0.70	324	156	41,211	33%
						Total =	1,711	452,051	
						Cost savings at $1.525/m3	$2,610		

In total, an average savings of 27% annually was achieved through system infrastructure improvements and the repair of deficiencies.

When combined with scheduling change savings, the results are even more dramatic (see chart below):

Comparison between 2010 water use and 2011 water use

Changes were made to sprinkler nozzles, zones changed from sprays to drip, run-times adjusted

Watering days adjusted by SMART Controller

Average savings equal 45%

Zone Number	mm/week in 2010	inches/week in 2010	m3/year in 2010	mm/week in 2011	inches/week in 2011	m3/year in 2011	Overall reduction m3/year	Overall reduction Gallons/year	Percent Reduction
1	16	0.65	384	9	0.35	207	177	46,758	46%
2	41	1.62	389	20	0.80	193	196	51,831	50%
3	18	0.70	468	9	0.34	223	245	64,669	52%
4	34	1.35	439	17	0.65	212	227	59,914	52%
5	9	0.36	389	7	0.26	284	105	27,817	27%
6	11	0.43	414	8	0.30	297	117	30,908	28%
7	10	0.38	529	7	0.26	367	162	42,796	31%
8	30	1.17	403	23	0.90	311	93	24,489	23%
9	17	0.68	192	9	0.35	99	93	24,568	48%
10	9	0.37	92	8	0.30	74	18	4,808	20%
11	19	0.73	400	7	0.28	155	245	64,775	61%
12	65	2.54	360	18	0.72	103	257	67,998	72%
13	59	2.34	288	21	0.82	101	187	49,453	65%
14	75	2.95	250	27	1.06	90	160	42,162	64%
15	45	1.77	206	18	0.69	81	125	33,127	61%
16	13	0.50	378	9	0.34	259	119	31,384	31%
17	9	0.36	389	6	0.24	257	132	34,950	34%
18	POND FILLER VALVE								
19	26	1.03	480	13	0.52	243	237	62,609	49%
						Total =	**2,896**	**765,016**	
						Cost savings at $1.525/m3	**$4,416**		

Combined with scheduling savings from installation of a smart controller, total annual water use reductions of 45% we achieved. This amounted to 2,896,000 litres per year (765,000 US Gallons) at a cost savings of $4,416.00 in 2011. At the 2014 current water rate, these savings now equal over $5,647.20 per year.

Here are some additional examples:

Microsoft	
PRE	
PRE Irrigation Demands per 20-week season	5,994 m^3
Area of Irrigation	10,073 m^2
Weekly Irrigation Demands	30 mm/week
Maximum Target (estimated) savings	4,715 m^3
POST	
POST Irrigation Demands per 20-week season	2,128 m^3
Weekly Irrigation Demands	11 mm/week
Savings	
Actual water savings	3,866 m^3
Percentage water savings	64%
Percentage of Target Savings Achieved	82%

Meadowvalve (2000 Argentia Road)	
PRE	
PRE Irrigation Demands per 20-week season	10,463 m^3
Area of Irrigation	21,125 m^2
Weekly Irrigation Demands	25 mm/week
Maximum Target (estimated) savings	7,244 m^3
POST	
POST Irrigation Demands per 20-week season	4,503 m^3
POST Irrigation Demands per 20-week season	11 mm/week
Savings	
Actual water savings	5,960 m^3
Percentage water savings	57%
Percentage of Target Savings Achieved	82%

With over 100 assessments performed using this methodology, here are some findings:

1. Over 50% of all zones were over watering (1000 zones)
2. On average there were 3 leaks per irrigation system
3. Overspray existed on every system
4. Scheduling responsible for approximately 50% of total savings
5. Very few functioning rain sensors
6. Over pressurization and mixed precipitation rates were commonly found
7. Irrigation contractors in general were happy with the results since it drove business for them.
8. Resulted in uptake from 50% of participants.
9. Over 50 new controllers installed.
10. Resulted in additional site visits for contractors for mid-season inspections.
11. Irrigation assessments could be completed in 5-7 minutes per zone compared to 20 - 30 minutes per zone using the catch-can approach.

Conclusion

Based on the findings from over 100 Industrial, Commercial, and Institutional (ICI) assessments using the alternative assessment methodology outlined above, it is clear that property managers are able to make irrigation water saving investment decisions without needing to know DU values or precipitation rates. Return on investment is a key performance metric for decision makers that are deciding on where to spend their "sustainability dollars".

While there was only 50% uptake of recommendations from assessment participants, the percentage of uptake was not believed to be influenced by the assessment methodology. In speaking with program participants, the typical reasons for lack of participation were:

1. Change in corporate priorities
2. Contractor not fulfilling request for proposals
3. Change in personnel that resulted in project being postponed
4. Funds not available due to unforeseen circumstances
5. Longer ROI than deemed acceptable for investment (typically the acceptable rate of return for an investment decision is 35%. ROI with over 4 years typically become a secondary priority)

Irrigation professionals that are looking to grow their business through system improvement within their existing clientele, would see a significant benefit from utilizing the assessment methodology outlined above. Time savings would be significant and challenges such as wind speed (that are a limiting factor in catch-can assessments), would not impede performance of irrigation assessments that are scheduled.

While not all irrigation professionals have access to an ultra-sonic flow meter, this assessment methodology has been tested using readily available flow rate calculators and manufacturers sprinkler nozzle charts. If an accurate estimate of flow rate is achieved, the results of the assessment are in line with an assessment performed using ultra-sonic flow readings.

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