TECHNICAL SESSION PROCEEDINGS

Irrigation Show 2007

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BALANCING BIOSOLIDS, NUTRIENTS, NITRATES AND RECLAIMED WATER – MULTI-TASKING ON NUMEROUS LEVELS

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Introduction

The City of Raleigh Public Utilities Department (CORPUD) operates the Neuse River Wastewater Treatment Plant (NRWWTP) in southeastern Wake County, North Carolina. During 2004, the flows treated by the NRWWTP averaged over 45 mgd. The facility is designed and permitted for 60 mgd with the discharge of treated effluent into the Neuse River. The treatment facility produces a very high quality effluent and, as a result, must manage a fairly large volume of biosolids produced by the advanced wastewater treatment process.

The City maintains Non-Discharge Permit No. WQ0001730 for management of biosolids produced by the NRWWTP. The program includes approximately 1,030 acres of farmland divided into agriculturally managed tracts. Biosolids are land applied at agronomic rates to use the receiving crops and soils to assimilate the biosolids and associated constituents. The site has been operated as a biosolids management farm since 1980.

Monitoring of groundwater at the biosolids farm revealed exceedances of the North Carolina 2L groundwater standards. As a result of the exceedances, the City was required by the NC Division of Water Quality (NC DWQ) to characterize and assess the extent of the groundwater issues. The City suspended land application of the biosolids on the subject lands in September 2002. The City also developed a Corrective Action Plan (CAP) that addresses the actions necessary to remediate the subject groundwater standard exceedances.

The City desires to resume use of the land application sites for the management of biosolids. In order to ensure that future practices do not result in any regulatory compliance issues, the City desires that resumption of land applying biosolids be done with the sensitivity to all potential controls of nutrient loading. In addition to careful analysis, recordkeeping, and application practices, the City wants to optimize the health of the receiving crops to ensure a vigorous uptake of applied nutrients. In order for the receiving crops to be vigorous, they must have water in addition to nutrients. The City's past experience with the sites' farming activities has indicated that during drought conditions, the crops become stressed and no means of irrigation has been available. There is one area of the site, approximately 120 acres in size, that has a solid-set irrigation system and farm personnel have recognized the value of providing water to all crops and fields. This project is to design and install irrigation equipment to irrigate an additional 130 acres of the farm.

Site Characterization and Considerations

Irrigation of treated wastewater from the NRWWTP is being designed at rates necessary to optimize the yield of the receiving crops. The traditional control for an irrigation application rate is the amount of water that can be applied to a site or specific soil series without causing ponding or runoff of the applied water. Transmissive or highly permeable soils in the Piedmont or central part of the State would have irrigation rates exceeding 60 inches per year. The traditional approach gave significant consideration to the underlying soil and its associated loading rate restrictions, but little consideration was given to the hydraulic needs or uptake of the receiving crop (secondary factor). In the current approach, the hydraulic need of the receiving crops is being given the higher priority, with the intent of providing a healthy, vigorous crop to ensure optimization of crop yield.

Wastewater Effluent Versus Reclaimed Water Irrigation

The principle drivers for choosing between reuse quality effluent (reclaimed water) and traditional land application of treated wastewater effluent are primarily:

- Effluent water quality or treatment requirements
- Setbacks or buffers

The North Carolina regulatory requirements for land application of wastewater treatment facility effluents are found in Title 15A of the North Carolina Administrative Code (NCAC) Chapter 2H .0200 – Wastes Not Discharged to Surface Waters. The rules lay out requirements for all types of Non-Discharge Systems but .0219(k) specifically addresses the reclaimed water requirements.

Effluent Water Quality and Treatment Requirements

Typically, the required effluent quality for land application of wastewater on a controlled access site is secondary treatment or better. Typical effluent parameters and their acceptable levels for secondary effluent and for reclaimed water are compared in Table 1.

Table 1. Secondary Effluent and Reclaimed Water Treatment Performance Levels

	Secondary Effluent	**Reclaimed Water**	
Parameter	**Monthly Average Maximum**	**Monthly Average Maximum**	**Daily Maximum**
BOD_5	30 mg/l	10 mg/l	15 mg/l
NH_3	20 mg/l	4 mg/l	8 mg/l
Total Suspended Solids (TSS)	30 mg/l	5 mg/l	10 mg/l
Fecal Coliform	200 colonies per 100 ml	14 colonies per 100 ml	25 colonies per 100 ml
Turbidity	Not Specified or Limited	Not Limited	10 NTU[1]
Total Nitrogen	Not Specified or Limited	Not Specified or Limited	Not Specified or Limited
Total Phosphorous	Not Specified or Limited	Not Specified or Limited	Not Specified or Limited

Note: 1 - Turbidity limit is actually an instantaneous maximum.

Since the NRWWTP produces an effluent that is tertiary in quality as opposed to secondary, the step to produce reclaimed water quality effluent is minimal. A review of existing effluent water quality data indicates that the NRWWTP currently consistently produces effluent that complies with the reclaimed water standards. In the event that turbidity or fecal coliforms are not met, the reuse stream could be diverted to the surface water discharge and still be in compliance with NPDES Permit discharge limitations.

Setbacks or Buffers

Treatment of the effluent to reclaimed water standards provides several attractive incentives from a regulatory perspective. A comparison of the setbacks required for land applied secondarily treated wastewater (non-reclaimed water) versus reclaimed water is shown in Table 2.

Table 2. Secondary Effluent and Reclaimed Water Setbacks

Distance Between Wetted Areas and…	Secondary Treated Wastewater	Reclaimed Water
Property Lines	150 feet	Zero (0) / Not Required
Surface Waters	100 feet	25 feet (Non SA Waters)
Adjacent Residences	400 feet	Zero (0) / Not Required
Public Water Supply Wells	100 feet	100 feet
Public Right-of-Way	50 feet	Zero (0) / Not Required

Other Factors to Consider

Site Access and Control

Wastewater effluent requires a controlled site that prevents access to the land application area. This is usually addressed by barbed wire or chain link fencing along with signage discouraging or preventing access. Reclaimed water utilization sites do not impose any fencing requirements but signage must be posted to ensure that the general public understands that the reclaimed water is not intended for drinking purposes. Inferred in the control of reclaimed water sites are that indirect contact with the reclaimed water is acceptable but long-term contact is not advisable.

Pipe Labeling and Cross Connection Controls

Since wastewater piping is typically color coded differently from potable water piping, no special requirements are imposed to ensure improper cross connections. Since reclaimed water is relatively new to North Carolina and the utility construction industry, reclaimed piping is required to be either color coded (purple pipe) or taped or wrapped in purple plastic labeling to prevent the inadvertent cross-connection between reclaimed systems and potable water systems. The increase in overall cost of the pipe or tape installation is negligible compared to traditional piping costs.

Regulatory Perspective
Management of wastewater effluents by non-discharge means are considered favorable compared to the discharge to surface waters (NPDES Permit). Land application of non-reclaimed effluents is still considered *disposal* whereas land application of reclaimed water is considered *utilization*. Utilization or recycling of water for a beneficial purpose is considered preferable and as such, several regulatory incentives exist. These include buffers or setbacks from irrigation areas and property lines, surface water features, residences; reduction or elimination of groundwater monitoring requirements; and site specific data such as hydrogeological borings and assessments. Overall, the NC DWQ considers reclaimed water utilization to be the *preferred* means of wastewater management and will treat such projects favorably in many cases.

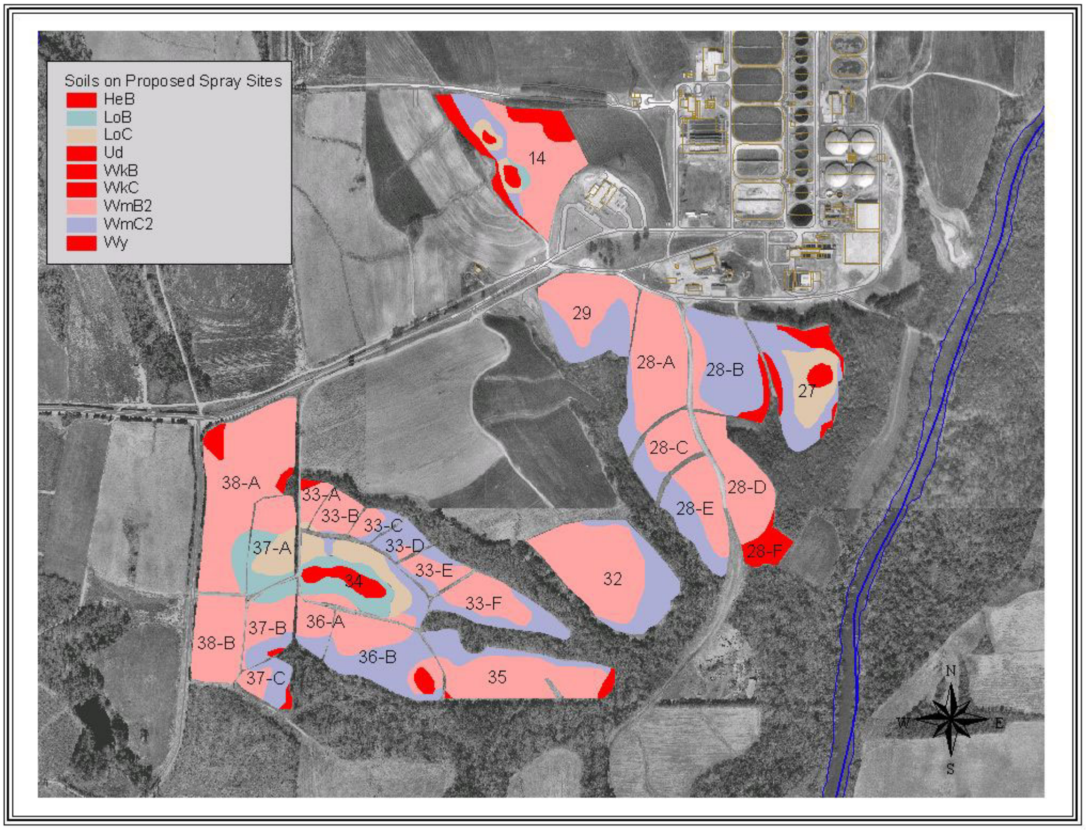
Soil Mapping
Although the site has been utilized for the management of biosolids since 1980, no record could be located of any detailed site assessment of the soils proposed for the irrigation system. Although the Soil Survey for Wake County prepared by the U.S. Department of Agriculture could provide a reasonable survey of the soils, an accurate and site specific soil map was prepared by Synagro Technologies, Inc. A Synagro staff soil scientist evaluated the proposed irrigation sites and developed a soil map and associated soils analysis. A digitized version of the soils map prepared by Synagro is shown in Figure 1. It should be noted that the areas highlighted in red are deemed unsuitable for irrigation due to either wetness (Worsham – Wy and Helena – HeB), shallow soils (Wake – WkB and WkC), or significant soil disturbance (Udorethents – Ud).

Hydrogeological Analysis
The firm of Edwin Andrews and Associates was utilized to prepare the hydrogeological evaluation of the proposed irrigation sites. Hydrology tests were conducted on the most restrictive horizons of the Louisburg, Wake and Wedowee soils. These tests, in addition to the soils mapping and agronomic evaluations prepared by Synagro provided information suitable for development of a water balance for the proposed irrigation sites.

HYDRAULIC AND NUTRIENT MANAGEMENT

Since the project objective is to optimize crop yield and subsequently nutrient uptake, it is very important to ensure that the spray irrigation system is designed and operated to meet these requirements. Historically, most land application systems have focused on the maximum hydraulic loadings of wastewater effluents. This is driven primarily because of the traditional approach of providing the minimum system to dispose of the maximum amount of effluent so that overall costs of the system are minimized. The City has recognized that there is a balance associated with this project between managing biosolids on the farm, attenuating (or at least not exacerbating) the nitrate levels on the site, and the benefits of using the effluent for irrigation.

Crop Schedule and Agronomic Considerations
Discussions with biosolids and farm management staff at the Neuse River Treatment Facility indicate that only three primary crops are utilized for biosolids management. These include corn, soybean and wheat. Synagro was employed by HDR to assist with the agronomic evaluations of the proposed spray irrigation system and to make recommendations as to the appropriate hydraulic loadings to meet the



project objective of optimizing crop yield. The current cropping system is understood to be corn, wheat and soybeans (double-cropped). A summary of Synagro's hydraulic loading recommendations can be found in Table 3.

Figure 1. Soil Map of Proposed Irrigation Area

Table 3. Synagro's Recommended Hydraulic Loadings

Crop	Month	Irrigation (inches / month)
Corn	April	1.1
	May	4.9
	June	7.5
	July	5.4
	August	1.0
	Total	**19.9**
Soybean	July	2.2
	August	4.7
	September	7.5

Crop	Month	Irrigation (inches / month)
	October	4.5
	November	1.0
	Total	**19.9**
Wheat	November	1.0
	December	1.0
	January	1.0
	February	1.0
	March	2.5
	April	5.3
	May	7.5
	June	3.7
	Total	**23.0**

It should be noted that these loading rates do not take into account precipitation or wet conditions and are more reflective of drought conditions. The water balance calculations and loading rate recommendations prepared by Edwin Andrews and Associates will address these matters in later sections.

Hydrogeological Considerations

Extensive hydrogeological evaluations have been conduced by ENSR Consulting and Engineering, Inc., (ENSR) related to the nitrate conditions at the spray site. For the proposed irrigation sites, there are no significant hydrogeological restrictions to irrigation. According to ENSR's Comprehensive Site Assessment Report *(December 2002)*, "Hydrogeology in the area of the application fields consists of a single aquifer system with subunits corresponding to geologic zones. The aquifer units are in descending sequence saprolite, a transition zone primarily of partially weathered rock and fractured bedrock. The fractured bedrock unit is the primary water supply zone for drinking water wells. Groundwater flows from ridge top and side slope recharge areas towards discharge areas along perennial streams such as Beddingfield Creek and the Neuse River.

The objective to only use irrigation as a means to meet the crop water needs is in conformance with the corrective actions recommended by ENSR. By optimizing crop yield in conjunction with the biosolids management program, nutrient migration to the underling aquifers will be minimized, if not eliminated.

Recommended Hydraulic Loadings

The conventional approach to spray irrigation design and operation is to focus on the hydraulic loadings with a given site while ensuring that no ponding or run-off of applied water occurs. Crop nutrient loadings or hydraulic considerations are rarely a factor since soils themselves are primarily the restriction to water adsorption or movement into the aquifer. Since the irrigation project objective is to balance biosolids nutrient management, groundwater nitrate attenuation, and to prevent any further nitrate issues, the irrigation system will be designed and managed to minimize nitrate migration to the underlying aquifer.

Edwin Andrews & Associates conducted an irrigation analysis for the proposed irrigation sites. The Andrews' Report analyzed the hydrogeology of the site, the soils, and the agronomic considerations and recommendations prepared by ENSR and Synagro, respectively. The Andrews' Report details water balance calculations and analyses to determine the appropriate hydraulic loading rates to meet the project objectives. These analyses take into account the various crops utilized and associated agronomic hydraulic loading recommendations plus expected precipitation and evapotranspiration rates for three general cases – dry, typical and wet years. Actual irrigation system design will not be affected by these seasonal characteristics but operation of the system will be affected. The primary operational constraint will be the length of irrigation (duration) which will have a direct impact on the total hydraulic loadings. A summary of the hydraulic loading recommendations from the Andrews' Report is contained in Table 4.

Table 4. Andrews' Recommended Hydraulic Loadings

Type of Season	Crop	Total Seasonal Irrigation (inches per season)	Maximum Required Irrigation (inches/month)
Dry Year	Corn	7.3	4.5
	Soybean	6.9	4.0
	Wheat	7.7	4.6
	Total	**21.9 inches per year**	**-**
Average Year	Corn	4.7	3.6
	Soybean	4.6	2.9
	Wheat	5.2	3.7
	Total	**14.5 inches per year**	**-**
Wet Year	Corn	3.4	2.9
	Soybean	3.3	2.1
	Wheat	3.9	3.0
	Total	**10.6 inches per year**	**-**

In addition to the seasonal hydraulic loading rates, an application or precipitation rate must be specified. This is the actual rate that water is applied to the ground surface. Too rapid an application can cause ponding or run-off of the irrigated water. Another variation of this application rate is to limit the amount of water applied during a given dose or irrigation event. Short irrigation events allow the soils to effectively drain and promote water uptake by the receiving crops through evapotranspiration. The Andrews' Report recommends that irrigation events be limited to a 0.2 inch dose and at no greater than

0.5 inches per hour. The ideal operating condition would be to irrigate the 0.2 inch dose in a 15 – 30 minute interval and allow the system to rest for several hours before any subsequent irrigation doses. The irrigation system should be designed to accommodate two 0.2 inch doses in a day and on two separate zones simultaneously.

Follow-up conversations with Mr. Andrews *(Safrit personal communications)* have indicated that from a traditional hydraulic perspective, these soils should be able to accommodate a hydraulic loading rate in the vicinity of 30 inches per year. This is important because at some point in the future when it is demonstrated that groundwater issues no longer dictate strictly an agronomic loading rate control, the CORPUD may pursue a hydraulic loading based on the soil characteristics alone.

Crop Nutrient Management

Nutrients applied to the crops will come from two major sources – the biosolids and the reclaimed water. No other sources of nitrogen or phosphorus such as commercial fertilizers are anticipated to be used. Some additional agronomic practices may occur such as pest management, disease control or pH adjustment. It is important that nitrogen and phosphorus be properly managed in order to avoid any over-application of nutrients that may "leak" from the soil profile and exacerbate the current nitrate conditions. For this reason, the nutrients from the irrigation of reclaimed water must be accounted for and included in the overall nutrient budget associated with the biosolids management program.

Surface Water Discharge Nutrient Load Reductions

Based upon effluent data obtained from the Neuse River Wastewater Treatment Facility and the anticipated hydraulic loadings, approximately 2,005 pounds (911 kg) of nitrogen and 16 pounds (7 kg) of phosphorus will be managed on the biosolids farm during a dry year. This also equates to an identical reduction of nutrients discharged to the Neuse River. The potential nutrient load reductions associated with the proposed spray system is summarized in Table 5. Ultimately, as much as 10,200 pounds (4,636 kg) of nitrogen and 3,400 pounds (1,545 kg) of phosphorus could be managed on the farm if all reasonably available sites (690 acres) are utilized for reclaimed water irrigation.

Table 5. Potential Neuse River Nutrient Load Reductions

Dry Year	Corn	590	197
	Soybean	551	184
	Wheat	615	205
	Total	**1,756 lbs per year**	**586 lbs per year**
Average Year	Corn	378	126
	Soybean	370	123
	Wheat	418	139
	Total	**1,166 lbs per year**	**388 lbs per year**
Wet Year	Corn	271	90
	Soybean	267	89
	Wheat	313	104

	Total	851 lbs per year	283 lbs per year

Irrigation System Design

Irrigation Demand

As reported in Table 4, the Andrew's Report identified a maximum crop irrigation demand of 4.6 inches/month during drought conditions, which is equivalent to an average daily irrigation demand of slightly less than 0.2 inches/day. In addition, the Andrews' Report recommends that irrigation events be limited to a 0.2 inch dose and at no greater than 0.5 inches per hour. Based on these requirements, the irrigation system was sized to provide a maximum dose of 0.2 inch per field at an irrigation rate of less than 0.5 inches per hour on two zones simultaneously. Time associated with irrigation of the existing fields was estimated assuming that CORPUD may irrigate fields up to two times per day at 0.2 inches/dose provided that the seasonal irrigation rates are not exceeded. Figure 2 illustrates the proposed irrigation sites.

Pumping System

The NRWWTP has an existing effluent pump station and 12-inch ductile iron mainline that delivers irrigation water to the existing 120-acre spray irrigation fields. The pump station includes four vertical turbine pumps (40 hp, 75 hp, 125 hp, and 250 hp) with a total flow of 3,400 gpm with all pumps in service. The effluent pump station also provides non-potable water for the NRWWTP.

CORPUD has initiated a project to modify the existing effluent pump station to separate pumps serving the majority of the non-potable plant demands from pumps servicing the spray irrigation fields to eliminate competing pump demands. This project includes addition of approximately 4,800 gpm of pumping capacity to the effluent pumping station which will allow the irrigation of two irrigation zones simultaneously at a rate of 2,000 gpm as well as run one of the water cannons at the equalization basin.

For sizing of the spray irrigation system, it was assumed that average effluent flow of 4,000 gpm would be available for irrigating existing and new irrigation fields. A 4,000 gpm effluent flow is adequate for irrigation of both the existing and proposed fields. However, additional effluent flow would be required to irrigate all of the farm fields in the future, since the total estimated irrigation time is in excess of 24 hours. A 4,000 gpm effluent flow dedicated to irrigation could irrigate a maximum of approximately 354 wetted acres at the maximum dose of 0.2 inches twice daily within a 16 hour timeframe. In order to irrigate the future maximum anticipated quantity of 688 acres of farm land within a 16 hour window, an effluent flow of 7,785 gpm dedicated to irrigation would be required.

Irrigation System Layout and Design Details

A solid-set spray irrigation system will be used to irrigate the proposed spray fields. The existing spray fields use SR100 Nelson Big Gun Sprinklers, which can operate of a pressure range of 40 psi to 110 psi with nozzle sizes ranges from 0.5-inch to 1.0-inch for taper bore nozzles. Proposed irrigation zones were developed for the fields shown in Figure 2 assuming continued use of Nelson Big Gun Sprinklers with an assumed delivery pressure of 70 psi.

NRWWTP effluent will be delivered to each zone through a 12-inch distribution main. Table 6 provides a summary of the identified zones. An automated control valve assembly will be provided for each irrigation zone. The valve assembly will include a gate valve for manual isolation of the zone and an automatically-controlled pressure reducing valve that will maintain a delivery pressure of 70 psi to the irrigation nozzles during irrigation periods. Each irrigation zone will consist of an array of full-circle and part-circle sprinklers aligned to provide irrigation over the spray fields within the zone. Submains (10-inch, 8-inch, 6-inch, and 4-inch, depending on number of sprinklers serviced by the submain) will distribute effluent from the valve assembly to the individual sprinklers located within the zone. Proposed spacing between the sprinklers is based on 60 percent of the manufacturer's published wetted diameter for the nozzle size in use.

Figure 2. Irrigation Sites

Table 6. Irrigation Zones

Zone	Field No.	No. of Sprinklers	Flowrate (gpm)	Wetted Acres
1	28B, 27	25	1,917	7
2	29, 28-A	21	2,034	11.8
3	28C, 28D, 28E	21	1,920	11.5
4	33-F, 35-A, 35-B	21	1,638	12.2
5	33-A, 33-B, 33-C, 33-D,	27	2,478	18.6

Zone	Field No.	No. of Sprinklers	Flowrate (gpm)	Wetted Acres
	33-E, 34, 36-A, 36-B			
6	37-B, 37-C, 38-B	19	1,699	8.3
7	37-A, 38-A, 38-C	24	2,358	13.5
13	32	17	1,611	10.9
25	14	8	710	5.5
Total	-	183	-	103.1

PRELIMINARY COST ESTIMATE

Table 7 provides a summary of the estimated construction cost for the proposed irrigation system. The cost estimate includes the 12-inch distribution main, ten irrigation zones with associated automatically-controlled valve assemblies, irrigation sub-mains within each zone, and a total of 183 sprinklers. The equipment cost for the solid set irrigation system is estimated at approximately $8,000 per wetted acre.

Table 7. Irrigation System Construction Cost Estimate

Item Description	Estimated Cost
11,120-lf of 12-inch DI Forcemain (including fittings / valves)	$509,000
Solid Set Sprinkler System (risers and valve assemblies)	$352,000
PVC Irrigation Sub-mains (includes fittings)	$340,000
General Site Work	$80,000
Electrical / Instrumentation & Control	$40,000
Contingency (10%)	$132,000
Construction Subtotal	**$1,453,000**
Engineering, Legal, and Administration (15%)	$218,000
Total Project Cost	**$1,671,000**

Conclusions and Recommendations

The benefits of the proposed reclaimed water irrigation system are not just for the Neuse River Wastewater Treatment facility but include other valuable benefits that may not be readily apparent as follows:

- The use of reclaimed water is a sustainable approach that meets the needs of the present without compromising the ability of future generations to meet their own needs.

- Each gallon of reclaimed water utilized reduces both nutrients (nitrogen and phosphorus) and oxygen-consuming demands on the receiving stream at a time when the receiving stream is typically at its most critical stage – during hot dry periods when stream flows and associated assimilative capacity are at their lowest point.

- The reclaimed water can provide a vigorous and healthy crop to ensure that applied nutrients are properly assimilated by the plants and those nutrients do not migrate below the root zone.

- Reclaimed water can displace use of potable water, thus off-setting need for new water sources or expansion of existing supplies.

- Reclaimed water can be a dependable, reliable, clean source of water, even in cases of severe drought.

- Reuse is the *preferred* means of wastewater management by regulatory agencies, environmental groups, and the general public.

- Allows a sustainable approach to minimize or avoid inter-basin transfers by reusing water in the basin from which it is derived.
-
- Reuse helps avoid dramatic "swings" in water plant operations due to irrigation demands or other peaks – creating an opportunity for a "steady state" mode of operation.

- Reclaimed water can be a source of revenue to offset or cover the cost of additional treatment and distribution.

- It makes sense to use non-potable water for non-potable needs and preserve potable water for its highest and best use – for human consumption, culinary purposes, and bathing.

- The use of reclaimed water from the Neuse River WWTP can help to off-set the groundwater extracted from the Biosolids Farm Corrective Action Plan (CAP) and introduced into the treatment facility.

Effluent Nitrogen Management for Agricultural Re-Use Applications

Daniel J. Howes[1], Franklin Gaudi[2], Donald Ton[3]

Abstract
Utilizing treated domestic wastewater to grow forage crops is becoming commonplace in regions that cannot release effluent into oceans or rivers. A key concern when using disinfected secondary treated water is nitrogen percolating below the root zone and reaching the groundwater. A 2,000-acre wastewater reuse site with 27 center pivots in Palmdale, California is being utilized by the County Sanitation Districts of Los Angeles County to reuse approximately 8 to 9 million gallons per day of treated wastewater from the city of Palmdale. Through the development of a daily soil water/nitrogen balance model, combined with an overall cropping and monitoring strategy, the nitrogen deep percolation has been minimized throughout the reuse area to levels that are below Regional Board requirements.

Introduction

In the western United States, scarce fresh water supplies have led to increased utilization of treated wastewater for a multitude of purposes. Historically, wastewater was treated and either put into rivers or oceans, percolated into the groundwater, or allowed to evaporate. However, water quality and quantity concerns have led to more innovative disposal techniques. In many areas treated wastewater is being utilized to irrigate landscapes in parks and golf courses. In communities surrounded by agriculture, the treated wastewater is being used to irrigate crops that are not used for direct human consumption (such as forage crops).

In Palmdale, California, the County Sanitation District No. 20 of Los Angeles County (District) received a Cease and Desist order from the California Regional Water Quality Control Board, Lahontan Region (Regional Board) in 2004 regarding application of secondary treated domestic wastewater with high nitrogen concentrations on agricultural fields near its treatment facility. At that time, the District had several center pivots and a flood irrigated field. The Regional Board objected to the volume of water and the concentration of nitrogen in that water, which was being measured in vadose zone measuring devices at the reuse area. In response to the order the Districts contacted the Irrigation Training and Research Center (ITRC) at California Polytechnic State University, San Luis Obispo, for recommendations on reducing the amount of nitrogen percolating below the crop root zone.

The recommendations provided by ITRC involved expanding the reuse area, replacing the flood irrigated field with additional center pivots, improving the distribution uniformity of the existing pivots and the overall design and sprinkler packages for new pivots, and improving the scheduling of irrigations using a daily irrigation scheduling program that allows users to plan for future irrigations using both a soil water and nitrogen balance.

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This paper will focus on the irrigation scheduling and annual crop planning aspects of the District's Effluent Management Site (EMS). The physical components of the system such as center pivot design, modifications, and maintenance will be addressed in a separate paper.

The following sections will:

- provide background for nitrogen and soil water balance components
- show how the individual components are brought into a real-time scheduling, planning, and monitoring strategy
- present the results of the strategy

Nitrogen Balance

The benefit of using treated domestic wastewater on agriculture and landscapes is that nutrients that are in the wastewater can be taken up by the plant and are removed from the reuse area. These nutrients – nitrate in particular – can pollute ground and surface water in high concentrations. The nitrogen cycle is depicted in **Figure 1**.

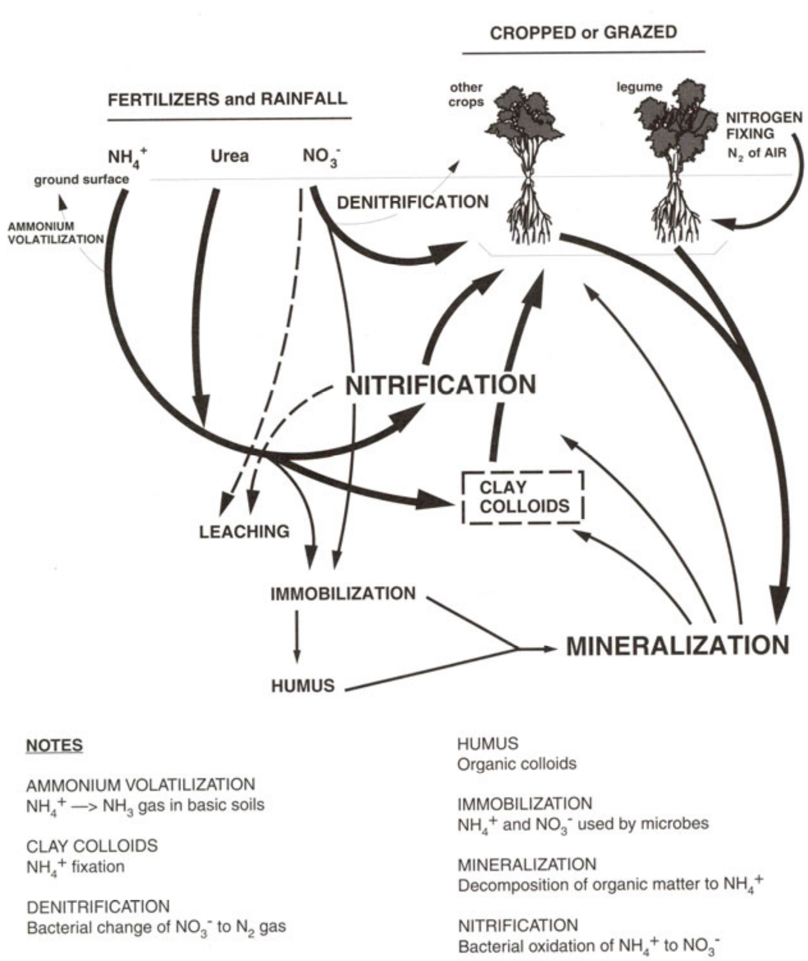


Figure 1. Nitrogen cycle (from Burt et al, 1998)

Sources of Nitrogen

There are two main sources of nitrogen at the Palmdale EMS:

1. Nitrogen from the effluent applied through the irrigation system subsequently taken up by the roots. This nitrogen can take three forms:
   - Organic nitrogen
   - Ammonium-nitrogen
   - Nitrate-nitrogen

   Organic nitrogen added to the soil via the effluent is converted by microbial mineralization processes into ammonium-nitrogen during the year. This ammonium-nitrogen will be rapidly converted into nitrate-nitrogen by the microbial process of nitrification.

2. Nitrogen from N_2 gas fixed during biological nitrogen fixation in the alfalfa crop by the *Sinorhizobium meliloti* bacteria. During biological nitrogen fixation, the microorganisms found in the symbiotic relationship with legumes such as alfalfa take the dinitrogen (N_2) gas out of the atmosphere and convert it into ammonium-nitrogen inside the alfalfa plants. This new ammonium-nitrogen is converted into amino acids and proteins to be used by the alfalfa plant. Nitrogen formed by biological nitrogen fixation within the alfalfa root not used by the plant is released into the soil and converted into nitrate-nitrogen as the roots die.

Nitrogen Removal

Nitrogen is removed from the EMS cropping system through four methods:

1. *Crop harvest* is the largest method of nitrogen removal in most cases. This is especially true with forage crops, because the majority of vegetation is removed at harvest. At the EMS, forage crops like small grain crops (wheat, barley, oats, etc.) are harvested for hay (vegetation and grain are removed from the field) along with sudangrass and alfalfa. Harvested tissue is analyzed at every harvest for nitrogen content. In addition, each load of harvested material is weighted so that the total tonnage of crop and nitrogen contained in that crop can be accurately estimated.

2. *Ammonia volatilization* occurs when ammonium converts to ammonia and enters the atmosphere. High temperatures, high pH, and high concentrations of ammonium and ammonia in the irrigation water can all contribute to higher percentages of ammonia volatilization.

3. *Denitrification* occurs when certain denitrifying bacteria commonly present in the soil are stressed for lack of readily available atmospheric oxygen gas (O_2) in the soil air. When the soil is irrigated or when rain falls, the water moves into the soil pores and tends to exclude the air from these same soil pores (Dinnes, et al, 2002). This water reduces the amount of oxygen gas in the soil. The nitrate-nitrogen (NO_3^-) contains an alternate source of oxygen (O) these special denitrifying bacteria can use for growth. As a result, the nitrate-nitrogen is converted into dinitrogen gas (N_2).

4. *Leaching or deep percolation* of nitrate below the crop root zone and eventually into the groundwater is a major source of pollution. The amount of nitrates leaching below the

root zone is one of the most difficult nitrogen destinations to measure. It is not reasonable to expect an accurate direct field level leaching measurement with today's technologies. Measurement units are limited by point measurements in a field that may not be "representative". Therefore, deep percolation is computed as a closure term in a water balance.

Calculations
The following equation shows the basic nitrogen balance calculation. Due to the topography, climate, and irrigation methods used at the EMS site, runoff is not a concern in this case; therefore, runoff is not included in the calculations.

$$\Delta Rz_{Storage} = \sum N_{inputs} - \sum N_{outputs} \qquad \textbf{Eq. 1}$$

where,

$\Delta Rz_{Storage}$ = Change in nitrogen storage in the root zone

$\sum N_{inputs} = N_{effluent} + N_{fixation}$

$\sum N_{outputs} = N_{Harvest} + N_{Volatization} + N_{Denitrification} + N_{Leaching}$

Method 1 – Limited Method
Since nitrogen leaching below the root zone cannot be accurately measured on the field level, it is moved to the right side of the equation (also known as the closure term). This modified equation will be referred to as **Method 1** for calculating nitrogen leaching or nitrogen remaining in the soil profile.

$$\Delta Rz_{Storage} + N_{Leaching} = \sum N_{inputs} - \sum N_{outputs} \qquad \textbf{Method 1: N Balance}$$

where,

$\sum N_{outputs} = N_{Harvest} + N_{Volatization} + N_{Denitrification}$

An accurate nitrogen mass balance in the field is complicated by the difficulty of determining the amount of biological nitrogen fixation in the alfalfa crop. Therefore, although the $N_{Harvest}$ is easy to measure, we do not precisely know what percentage of that nitrogen was fixed by the plant from the atmosphere, and what percentage originated with the wastewater. Because of this limitation with Method 1, Method 1 is only used for crops that do not fix nitrogen (grain hay and sudangrass at the Palmdale EMS).

Method 2 – Estimated Nitrate Leaching
No easy field test is available to monitor the amount of biological nitrogen fixation by the alfalfa. Since this can be a major source of nitrogen for alfalfa, the alfalfa fields require a different method (other than Method 1) of estimating nitrogen leaching below the root zone. This second method relies upon a detailed daily soil water balance to track water destinations and nitrate concentrations measured in soil water below the crop root zone.

Using the daily irrigation scheduling program with real-time data and accurately measured pivot distribution uniformity, the amount of deep percolation can be estimated across the field. Using the actual distribution uniformity, the program applies differing amounts of water across the field and can then determine the amount of deep percolation (leaching) that occurs at the different points. The program looks at five computed, hypothetical points in the field: the wettest, mid-level wet, average, mid-level dry, and the driest points. The distribution uniformity concepts and the irrigation scheduling program are described in the following sections.

Water Balance

Figure 2 shows "perfect" irrigation scheduling. It is "perfect" because the average depth of the lowest quarter (d_{lq}) equals the target depth of infiltration (usually the soil moisture depletion). As can be seen in the figure, even with a "perfect" irrigation schedule, deep percolation is inevitable – deep percolation exists on 7/8^{ths} of the field (Burt, et al, 1997). If the distribution uniformity (DU_{lq}) is improved, the amount of deep percolation will be lower. It is also important to note that with a "perfect" irrigation schedule, the lowest 1/8th of the field is being under-irrigated. This will cause some crop stress, but only minimally.

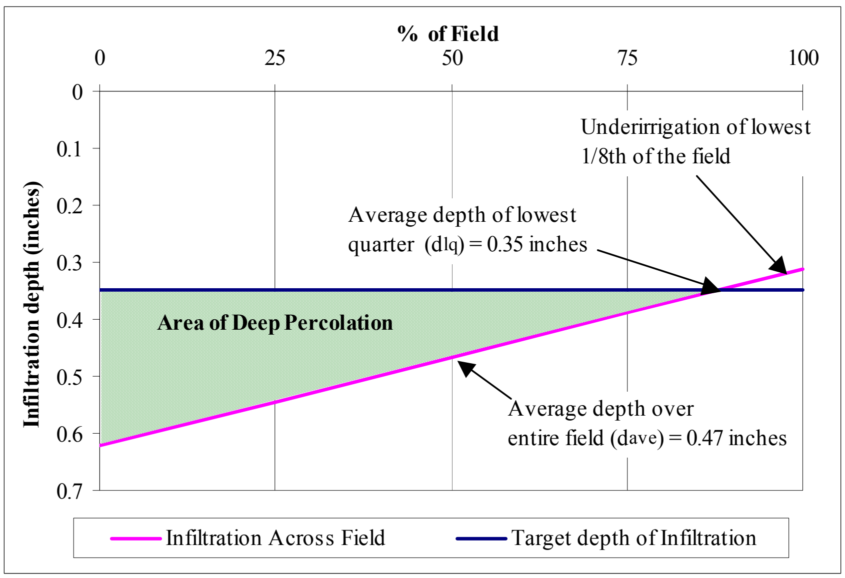


Figure 2. Simplified case of "perfect" irrigation scheduling. The DU_{lq} = (0.35/0.47) = 0.75. Note that the depth is the depth of water, not soil depth (from Burt, et al 1997).

In real-world applications, it is difficult to precisely estimate the target amount that should be applied (i.e., irrigation is not a perfect science). Soil moisture sensors and irrigation scheduling programs are two tools that are frequently used to help estimate the target. However, these tools have their limitations. For example, soil moisture sensors should be placed at representative points in a field – but unless the distribution uniformity is excellent, one never knows if the selected point is "representative". Making irrigation decisions by using weather data alone to estimate crop water use also has its limitations.

One can achieve very reasonable results using a combination of (i) excellent local weather data with a crop ET model, (ii) soil moisture measurement devices, and (iii) good records of the actual volumes and timing of water applied. This assumes that the irrigation system has been designed and managed for a good distribution uniformity. At the EMS, distribution uniformity and accurate water application records have been improved significantly since ITRC began providing technical assistance. The details of these endeavors will be saved for another paper.

Accurate weather data is considered the most important part of a good irrigation scheduling program. Initial ITRC recommendations included installing a California Irrigation Management Information System (CIMIS) weather station on-site. Prior to this, the closest station was in Victorville, CA, over 30 miles away. The California Department of Water Resources (DWR) installed the CIMIS station at the Palmdale EMS (Station #197) in the spring of 2005. This site is managed by EMS and ITRC personnel. Station #197 now provides weather data and the calculated ASCE Standardized (2000) Penman-Monteith grass reference evapotranspiration (ET_o).

Dual Crop Coefficient

Historically, crop evapotranspiration was calculated by adjusting the ET_o based on the actual crop in the field using a crop coefficient (K_c). A more accurate method actually adjusts the K_c values based on soil evaporation and crop stress that can occur. This preferred method of determining a crop coefficient (K_c) splits the computation into two components: transpiration and evaporation. This is called the "dual crop coefficient methodology" and is outlined in *FAO Irrigation and Drainage Publication No. 56* (Allen et al, 1998). An additional component – lack of soil moisture and its impact on transpiration reduction – must also be included in the transpiration calculation. More detailed information on this dual crop coefficient can be found in Allen et al (1998), Burt, et al (2002), and Walter et al (2000) but the basic concepts will be summarized in the following paragraphs from Burt, et al (2002).

> The basal crop coefficient (K_{cb}) is the fraction of reference evapotranspiration that will equal the potential transpiration of a certain plant plus a small component of evaporation from a dry soil surface. The K_{cb} value will vary with the growth stage of the plant; for an annual crop it typically has a value of 0.15 near planting, and reaches a maximum value of 0.9 - 1.2 or so at full cover. The product of ($K_{cb} \times ET_o$) equals the crop evapotranspiration under a well-watered condition with no stress and a dry soil surface, also referred to as crop basal evapotranspiration (ET_{cb}). These conditions are very rare in a field application. The K_{cb} has no irrigation management component or soil type component (it assumes perfect irrigation scheduling and a small water vapor evaporation component from the subsoil). Therefore, in concept it is transferable to anywhere in the world with minor adjustments. The minor adjustments are based on monthly average minimum relative humidity and wind speed (Allen et al, 1998).
>
> For actual estimates of crop evapotranspiration (ET_c), the basal crop coefficient is adjusted based on the amount of water stress that occurs, and an additional computation accounts for wet soil surface evaporation. Most crops undergo some water stress throughout the growing period. Water stress occurs at a certain moisture depletion level. This level varies depending on the crop and its resistance to water stress. The dual crop coefficient method uses a crop stress coefficient (K_s) as a multiplier to reduce the potential transpiration because of the plant response to water stress. Therefore, the actual transpiration is $[K_s \times K_{cb}] \times ET_o$, minus a small amount of evaporation inherent in K_{cb}.
>
> The evaporation component of the crop coefficient is the evaporation coefficient (K_e). It is calculated based on soil type and the evaporable water in the upper region of the soil. The evaporable water in this upper region is determined using a soil water balance. The overall equation using the dual crop coefficient to calculate ET_c is:

$$\mathbf{ET_c = [(K_s \times K_{cb}) + K_e] \times ET_o} \text{ (Allen et al, 1998)}$$

In order to utilize the dual crop coefficient method to calculate crop evapotranspiration, a daily root zone soil water balance is needed. This model tracks soil moisture depletion, irrigation and precipitation events and past crop water usage to determine the current ET_c.

Irrigation Scheduling Program – Daily Water Balance
A spreadsheet irrigation scheduling program was developed for the Palmdale EMS site that tracks daily data on crop development, weather, ET_o, irrigation, etc. to accurately determine ET_c, as well as predict weekly irrigation demands for the following week. The irrigation scheduling program tracks each of the 27 center pivots at the EMS. Inputs include:

1. Planting and harvest dates
2. Weather data including ET_o, precipitation, temperature, and wind speed
3. Actual volume of effluent applied to each center pivot
4. Soil types
5. Pivot distribution uniformity
6. Crop type and crop specific inputs such as root zone depth, soil moisture depletion at the start of stress, crop height, etc.

On a weekly basis the spreadsheet program outputs the estimated volume needed to meet ET_c demands and refill the next week's soil profile for each pivot. In addition, the program tracks the amount of nitrogen applied to each pivot through the effluent.

Verification
With any model or irrigation scheduling program, verification is necessary to confirm that the program is functioning correctly. This requires field measurements and should be considered the most important part of the management process. The field verification ensures that the program/model is accurately tracking what is occurring in the field.

Soil moisture and vadose zone sensors have been installed throughout the EMS. At least one site is located in each pivot. Each site consists of 3-4 soil moisture sensors located at different depths in and below the root zone and a vadose zone monitor to analyze the amount of water percolating below the root zone. However, again, the location of the sensor may not be "representative". Therefore, the data recorded at the monitoring sites is not taken as "absolute". The data is used to ensure that the soil monitoring equipment is working, and is not necessarily used to make sure the measured soil moisture depletion values in the root zone match up exactly with the irrigation scheduling program.

In addition to soil moisture measurements, having personnel visit the center pivots daily to make qualitative observations is very important for a practical irrigation scheduling regime. The daily field visits also provide information on physical operations at the EMS.

Matching Supply and Demand
The components of the water and nitrogen balance have been discussed. The pieces must be put together in order to maximize effluent utilization and minimize deep percolation of nitrate. A major issue when using effluent for plant water requirements is that effluent supply is relatively

constant throughout the year but plant water demands vary. **Figure 3** shows the relative plant demand by month versus the effluent supply (Note: The ET_o and effluent supply are in inches per month and million gallons per month (MGM), respectively).

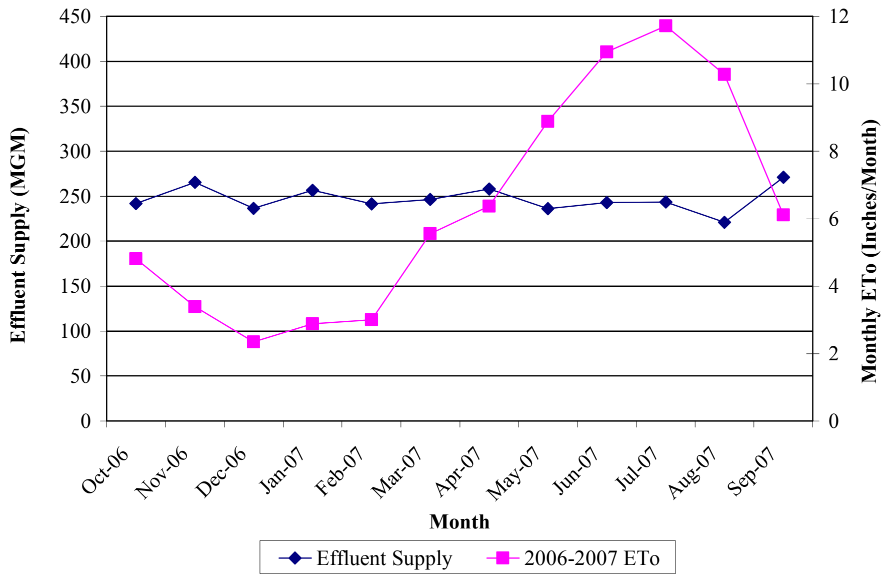


Figure 3. Average grass reference evapotranspiration (ET_o) compared to effluent supply over a recent year

Figure 3 shows that the effluent supply is relatively constant throughout the year, while the demand fluctuates. To overcome the supply and demand dilemma at the EMS, crop acreage is varied over the season. During the winter when ET_o is lowest, the entire 2,000-acre site is planted with crops (alfalfa and winter grain hay). During the summer when ET_o is highest, only the alfalfa is grown (approximately 900 acres) along with a small amount of sudangrass (approximately 30 acres). Even with this acreage reduction, the alfalfa is still under-irrigated to ensure that soil moisture is utilized and deep percolation is minimized. **Figure 4** shows the actual crop evapotranspiration (ET_c) compared to total effluent supply (both in million gallons per month (MGM)).

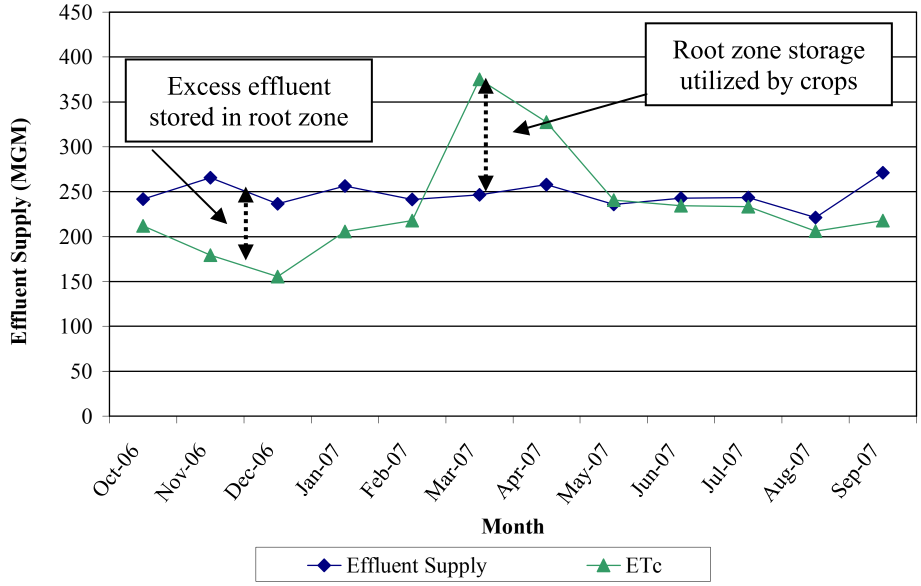


Figure 4. Actual ET of applied effluent compared to effluent supply

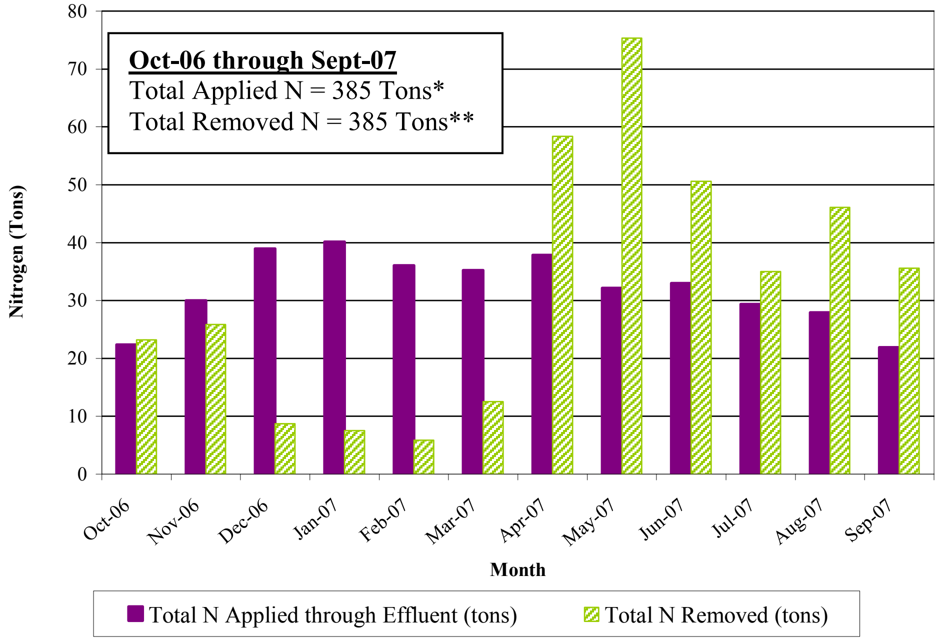
From **Figure 4**, a discrepancy still exists between effluent supply and crop demands even with crop acreage adjustments. During the fall and winter there is more effluent available than can be utilized by the crops. This is where the soil profile reservoir is fully utilized. By September the soil's available water reserves are fully utilized. The crops' water requirements are being met solely by applied water. As the water applications begin to outpace water utilization in October the root zone soil profile in each of the center pivots begins to refill, acting as a reservoir. This reservoir holds excess water from October through February. By March the crop water demands outpace applications and the soil reserves begin to deplete. Winter grain hay is harvested in April through May, decreasing the crop acreage and ET_c across the EMS, so that by summer the supply and demand match up.

The cropping strategy at the Palmdale EMS is a well choreographed plan that maximizes effluent utilization by minimizing water and nitrate loss through deep percolation. The cropping plan is created by November for the following year and lays out the basic strategy for the entire next season. This strategy accounts for each individual pivot, estimating the planting and harvest dates, daily irrigation applications, total nitrogen applied and removed, soil moisture content, etc. using a daily model with historical data. Then, using real-time data collected during the year, modifications are made to the plan to account for unforeseen events such as snow and ice damage to pivots.

Results and Conclusions

There are a number of items that must be considered when measuring success or failure in this type of field application. In most agricultural applications, crop yield is the major consideration in determining success along with some analysis of inputs, to ensure waste is minimized. However, at the EMS, yield is secondary to ensuring that nitrates do not leach below the root zone and effluent water use is maximized. Fortunately, yield, nitrogen utilization, and effluent utilization are all connected.

Meeting Regulatory Requirements
Figure 5 shows the nitrogen applied (does not include N fixation) and removed over the year. Nitrogen removed in **Figure 5** only includes volatilization, denitrification, and harvest (not leaching). Harvests typically occur from April through October, when the majority of nitrogen is removed from the EMS. Nitrogen is applied through irrigation. The variation in applied nitrogen is due to differing concentrations in the effluent.



* The total applied nitrogen does not include nitrogen fixed by alfalfa
**Total nitrogen removed does not included nitrogen leaching below the root zone

Figure 5. Nitrogen applied and removed over the year

Interestingly, the total nitrogen applied and removed from the EMS from October 2006 through September 2007 was equal. However, this is misleading because the N applied does not include nitrogen fixed by alfalfa and the N removed does not include nitrogen leached or percolated below the root zone.

Using the nitrogen balance equations (Methods 1 and 2) on a center pivot by center pivot case, the calculations indicate that approximately 75 tons of nitrogen either remains in the soil profile or percolates below the root zone from October 2006 – September 2007. It is inevitable that some nitrogen will be lost below the root zone in a productive irrigation application because distribution uniformity and irrigation timing cannot be perfect. With this understanding, the Regional Board has set a limit of tons of nitrogen that can be applied in excess of what is removed. Utilizing an intensive irrigation scheduling regime with proper monitoring, planning, and improved distribution uniformity (physical infrastructure) the actual excess nitrogen is within the prescribed limit.

Improving Past Performance
It can be difficult to compare current with past performance at any particular site when there have been modifications in operation or physical infrastructure. This is the case at the EMS. The site was expanded by over 1,000 acres in the last two years. Five of the center pivots have

been operating since the EMS started with the same operational rule of limiting effluent application to crop water demands plus reasonable losses from imperfect distribution uniformity and normal agronomic needs (such as seed germination irrigations and water applied to prevent wind erosion). However, only limited data on actual applications, soil moisture, and irrigation scheduling existed prior to ITRC's involvement at the EMS. The vadose zone monitoring devices that measure water percolating below the root zone did not pick up any deep percolation in 2006 or 2007 in the 5 pivots. One monitoring device did pick up a relatively significant volume in 2005 prior to ITRC's involvement. The accuracy and location of the equipment was questionable, however, so additional sensors have since been installed along with improved datalogging technology.

The only reliable data that is available prior to 2006 is harvested tonnage. However, the alfalfa crops on the 5 pivots in question were only 2-3 years old in 2004/2005. Crop tonnage is typically highest at 2-3 years of age, and declines in years 4-5 (2006/2007 for the 5 pivots shown in **Figure 6**). In addition, harvested tonnage does not necessarily relate to a reduction in nitrate leaching. Nevertheless, it is important to show that tonnage is approximately the same if not improved even though the crop is older.

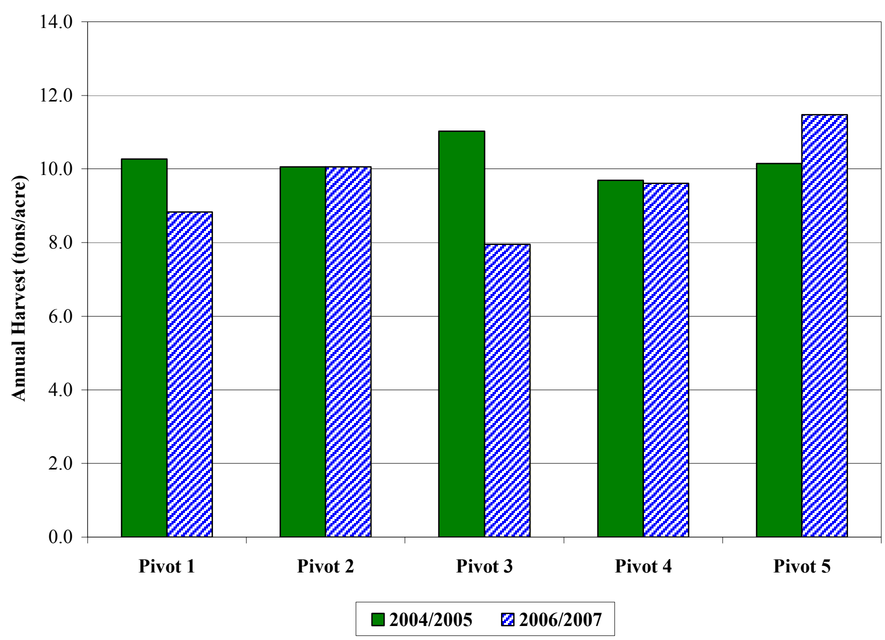


Figure 6. Harvest tonnage comparison from past to present (alfalfa)

The Districts have plans to install storage reservoirs as well as a tertiary treatment facility to decrease nitrate leaching even further. Additionally, the District's efforts have been so successful the Regional Board is in the process of lowering their limits based on new recommendations from the Districts and ITRC.

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Effluent Nitrogen Management for Agricultural Re-Use Applications

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Abstract

Balancing the continuous supply of domestic wastewater from effluent treatment plants with fluctuating crop water demands requires unique irrigation design strategies. A key design consideration when utilizing disinfected secondary treated city water is to maximize the re-use of effluent in winter months, when forage crop water demands are low, yet still produce minimal deep percolation. Twenty-seven center pivots in Palmdale, California required new custom-designed sprinkler packages to dispose of approximately 7,000 gallons per minute of treated wastewater. Through innovative design efforts, extensive testing and field experimentation, a standardized package has been adopted by the County Sanitation District of Los Angeles County that enables a highly efficient application of re-use city wastewater without groundwater degradation throughout the year. Many factors influenced the selection of the sprinkler package components including infiltration rates, application rates, soil moisture storage, distribution uniformity, pressure regulation, wind, and debris buildup.

Introduction

Currently in the United States, many locations use reclaimed water. Reclaimed water is treated effluent which is typically for non-potable uses, such as irrigation. Historically, treated effluent from wastewater treatment facilities was discharged directly into a stream, river, or other natural body of water. However, the continued demand for fresh water supplies has increased need for reuse of treated wastewater. Using reclaimed water for non-potable use saves potable water for drinking, since less potable water will be used for non-potable uses.

The County Sanitation District No. 20 of Los Angeles County (District) in Palmdale, California, re-uses approximately 8.5 million gallons per day (MGD) of secondary treated wastewater within the Palmdale Effluent Management Site (EMS) for irrigation. Wastewater irrigation has been proven to be a viable alternative to point source discharge of treated wastewater. However, to beneficially reuse the wastewater, an efficient and effective land application system with minimal environmental ramifications is vital. In addition, public acceptance depends upon a reliable and robust design and management strategy.

To achieve these objectives, the Palmdale EMS presently utilizes 27 center pivots providing water to over 2,000 acres of forage crops, a tree nursery, a pistachio orchard, and 11 tree barriers. A general map of the Palmdale EMS is presented in **Figure 1**.

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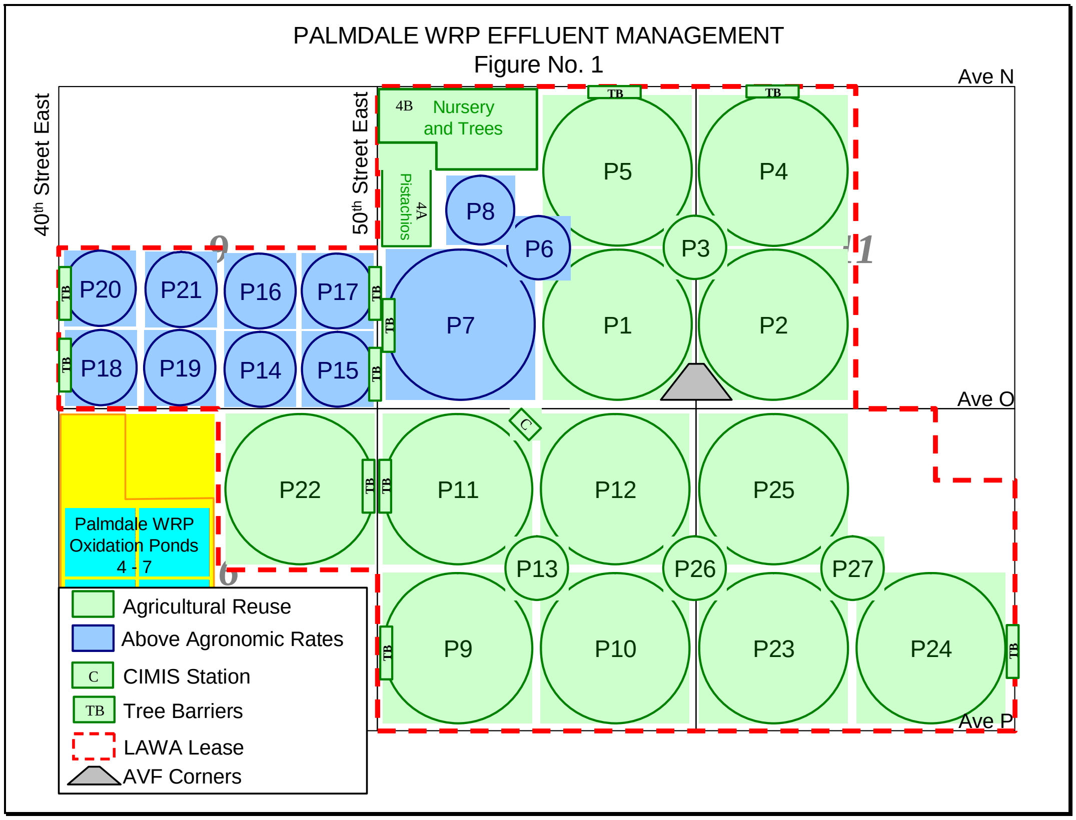

Figure 1. Palmdale center pivot layout

The District contracted with the Irrigation Training and Research Center (ITRC) at California Polytechnic State University, San Luis Obispo, for technical assistance to improve and monitor the Palmdale EMS irrigation distribution system. One of the key objectives of the contract was to provide real-time irrigation scheduling and representative soil moisture monitoring throughout the year. This is important because irrigation demands fluctuate monthly and wastewater supply is fairly constant. Several unique aspects of irrigation scheduling and annual crop planning for the Palmdale EMS are addressed in a separate paper.

As an early part of the technical assistance program, ITRC performed two evaluations of a "representative" center pivot irrigation system within the Palmdale EMS. The first evaluation was the baseline distribution uniformity (DU), which was conducted on the representative center pivot to provide an indication of the existing performance or "as-is" performance. The second evaluation (the improved DU) was performed following a number of modifications to the representative pivot, including:

a. Raised and/or staggered sprinklers to manufacturers recommended heights
b. Installed new nozzle package
c. Cleaned the sprinkler rotators and replaced the plates
d. Replaced broken rotators and/or rotator bodies
e. Leveled tilted sprinklers

These evaluations/modifications were performed to provide the District with a practical DU that could be used in annual cropping plans. A minimum DU benchmark of 0.80 had been set forth by the California Regional Water Quality Control Board, Lahontan Region (RB), and conducting the evaluations provided a benchmark by which the District could standardize each machine to meet the RB requirements. Both evaluations were conducted with the correct design pivot inlet pressure.

This paper outlines how a single machine, with the proper hardware and adjustments, can achieve a high DU. Additionally, all center pivot packages were standardized to provide matched precipitation rates and meet all center pivot pressure requirements, in order to make operation and management simpler and more systematic.

The following sections will:

- provide background on DU
- show how the modifications to the original design packages impacted DU
- demonstrate the improvement in DU through simple modifications
- lay out the current general package for all machines and system components

This paper will focus on the physical components of the water disposal system involving center pivot design, structural modifications, and maintenance practices—all of which are highly important, because not even good irrigation scheduling and soil moisture monitoring can turn a poorly-designed irrigation system into an effective tool.

Distribution Uniformity (DU)

Distribution uniformity is a measure of the uniformity with which irrigation water is distributed to plants throughout the field. It is defined as:

$$DU_{lq} = \frac{d_{lq}}{D_{avg}} = \frac{\text{average low quarter depth}}{\text{avg depth of water accumulated in all elements}}$$

The practice of using the least-watered 25% of the area (low quarter) as the reference standard has gained wide acceptance (Burt et al., 1997). The uniformity described by DU_{lq} (and all terms involving the low quarter) leaves about $1/8^{th}$ of the area at less than the value of the numerator. If the DU_{lq} is used to compute the necessary gross application depth, this "under-irrigation" varies from zero at the $1/8^{th}$ point to the minimum depth applied at the extreme. This term can be applied to all irrigation methods.

The following are the major factors influencing center pivot DU:

1. Different application rates along the pivot length. Ideally, the sprinkler nozzles will be sized properly along the pivot to account for pipe friction, sprinkler spacing, and the area covered (the first tower covers a much smaller area than the end tower).
2. Uneven overlap of sprinkler patterns between sprinklers. This is influenced by wind, the proper angle of sprinklers, the cleanliness of the sprinkler spray mechanism, and the height of the sprinklers, all of which were considered and/or corrected as part of this evaluation.
3. Uneven application patterns in different quadrants of the field. This is primarily caused by uneven wind patterns, and is especially important if the pivot is always in the same location at the same time every day.

To accurately evaluate the DU_{lq} of the center pivots, an irrigation evaluation procedure that was designed by ITRC to work with all of these factors was used (Burt et al, 1999).

Evaluating a "Representative" Center Pivot

Pivot 2 was chosen as the "representative" center pivot because it was one of the first center pivots installed within the Palmdale Effluent Management Site (EMS) and most (if not all) of the modifications made to Pivot 2 were needed at the other center pivots. In addition, the original pivot system sprinkler chart was available and modifications fit within the operation of the EMS.

The key to effectively evaluating the specific modifications (outlined in this paper) made to Pivot 2 was ensuring that everything else (such as system flow rate, system pressure, pivot speed and wind conditions) remained constant. All of these factors are easily manipulated and controlled except for wind conditions, which can vary from minute to minute and can have large effects on uniformity.

Wind Effects on Uniformity

To make certain that the wind conditions were as uniform as possible during each of the evaluations, the Palmdale WRP CIMIS station was utilized to find any patterns in wind speed and direction that may have existed. Data from the month before the initial evaluation were analyzed and plotted to identify tendencies in the weather. Wind speed data for typical 24-hr period is shown in **Figure 2**.

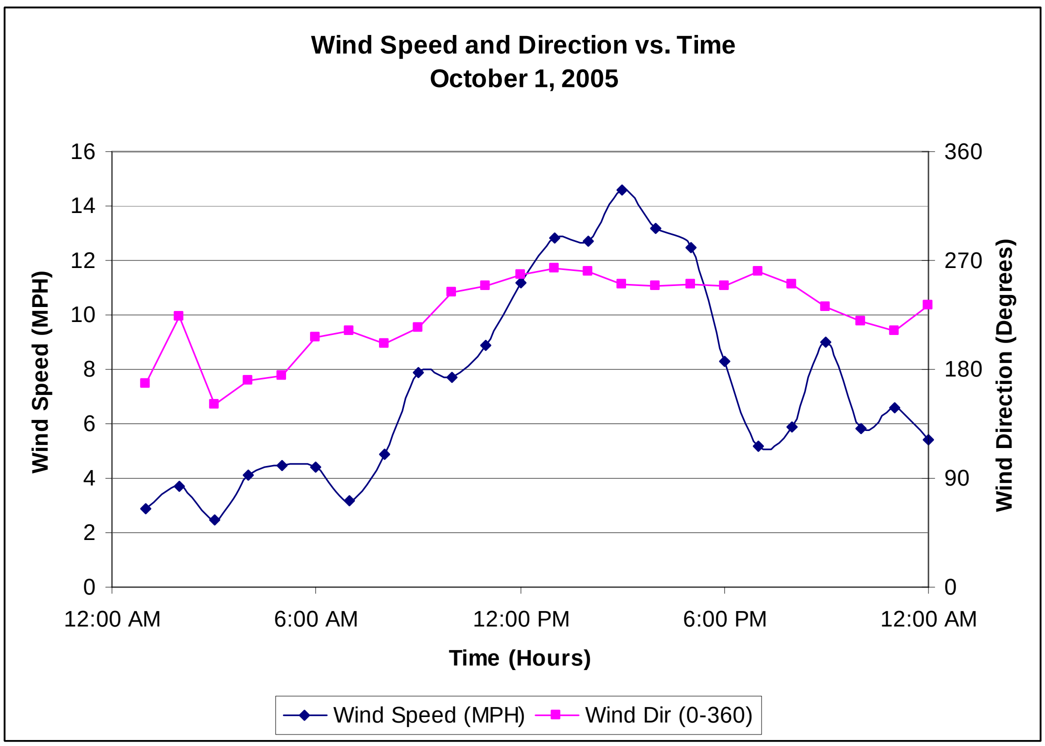

Figure 2. Graph of wind speed and direction for a typical day in October 2005

Figure 2 illustrates how the wind has a tendency to increase significantly between 9 am and 6 pm. The evaluations were conducted when the wind speed was at a 3-6 mile/hr velocity.

The tests were conducted at a 45-degree angle to the prevailing wind direction. This allows for a representative DU without having to conduct multiple evaluations on the center pivot if the wind had started blowing.

Since the center pivot rotations tend to follow a 12-hour increment and typically start at the same time every day, the effect of wind on distribution uniformity at certain points in the field will always be the same. For example, if the wind blows so that one point in the field does not receive any water, that point is likely not to receive any water on any rotation, or at least not on every other rotation.

Initial DU Evaluation

Prior to making any modifications to the "representative" center pivot a DU evaluation was conducted to verify the pivot package design in an "as-is" state. This provided a good estimate for the DU values that could be expected within the EMS. The resulting DU was 0.73. **Figure 3** illustrates the catch can volumes in relationship to the pivot center.

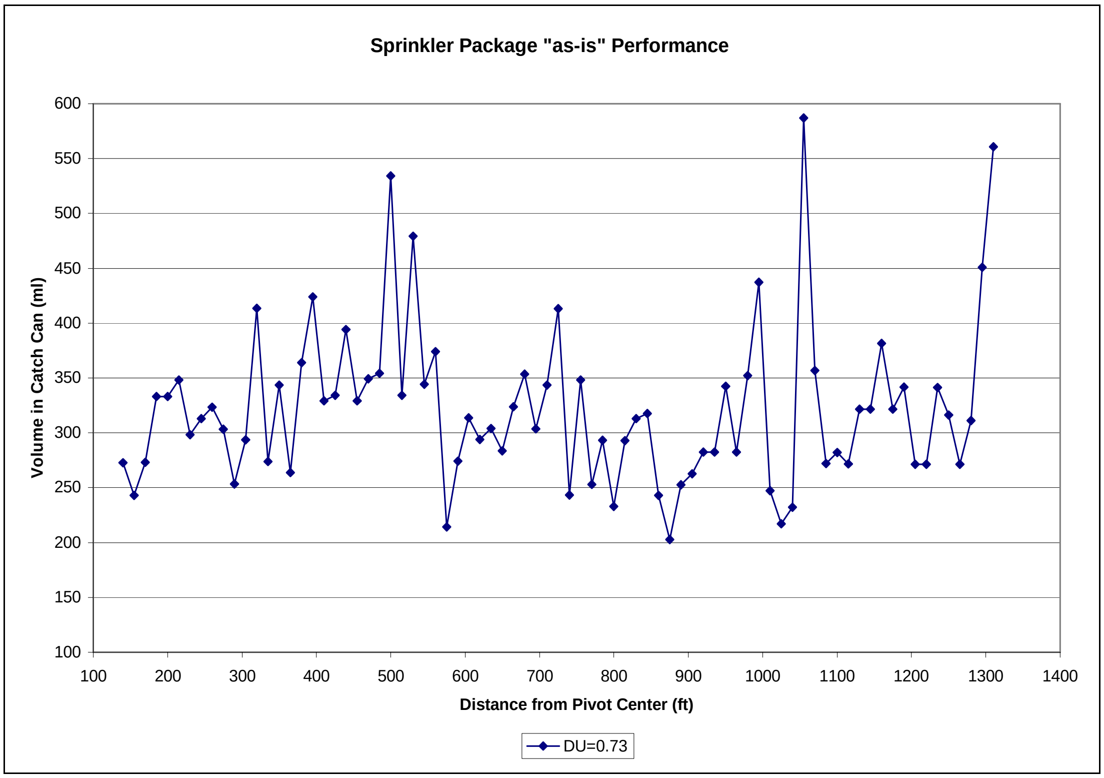

Figure 3. Catch can values along the length of the machine (non-weighted)

The pivot sprinkler package designed DU is 0.90. To achieve this goal modifications to the center pivot and sprinklers needed to be made. The improvements were selected to decrease the variations between catch cans.

Individual Center Pivot Modifications/Improvements

To provide the District with a distribution uniformity (DU) value that was obtainable and realistic, ITRC made the following modifications to Pivot 2 (listed by priority):

1. Raised the sprinklers from an average of 3.5 feet to an average of 5.5 feet
2. Staggered the heights and leveled the sprinklers to prevent water streams from colliding
3. Removed debris between the rotator and the rotator plate to allow free rotation
4. Cleaned the rotator plates to improve water trajectory
5. Replaced broken rotator bodies

6. Replaced nozzles to ensure design flow rates during the test

Points 1-3 (above) were the primary causes of the sub-par DU (of 0.73, compared to a pivot package design or target DU value of approximately 0.90).

Sprinkler Heights

Sprinkler spacing for center pivots are designed for a certain amount of overlap. This overlap ensures the proper distribution uniformity during irrigation. In previous years, the District had focused on limiting and/or preventing drift from the pivots from leaving the field by lowering many of the sprinklers (typically near the end of the machine) to an elevation just above the canopy height just before harvest (**Figure 4**). Unfortunately, this process negatively affected the DU of the pivot.

Figure 4. Original sprinkler heights – average 3.5 feet

The manufacturer of the sprinklers, Nelson Irrigation, was consulted to verify the correct mounting height for the sprinklers. The original pivot package for Pivot 2 utilized the R3000 rotator with green plates. This plate is designed to operate in a pressure range between 20-50 psi and at a height of 6 to 9 feet (Nelson Irrigation Corporation, 2005).

The sprinkler heights for the initial DU test (before modifications) ranged between 30 inches and 48 inches and had an average sprinkler height of approximately 42 inches. This limited the throw diameter and ultimately the overlapping of each sprinkler. To correct this, the sprinklers were modified so the average height was 66 inches (**Figure 5**); half at 60 inches and half at 72 inches. Prior to raising the height of the sprinklers, however, the District had mitigated drift concerns through chlorination of the secondary treated wastewater.

Figure 5. New sprinkler heights – average 5.5 feet

The R3000 rotator sprinklers were not placed as high as the manufacturer recommended because the pivot was operating at about 40 psi and wind drift is still a bit of a concern – even though the District now uses secondary treated chlorinated wastewater. In addition, maintenance of the sprinkler is more difficult at a high setting; this is discussed further in a later section.

Leveling and Staggering the Sprinklers

During the initial evaluation, adjacent sprinkler streams were commonly hitting one another, further impacting the overlap effect (**Figure 6**).

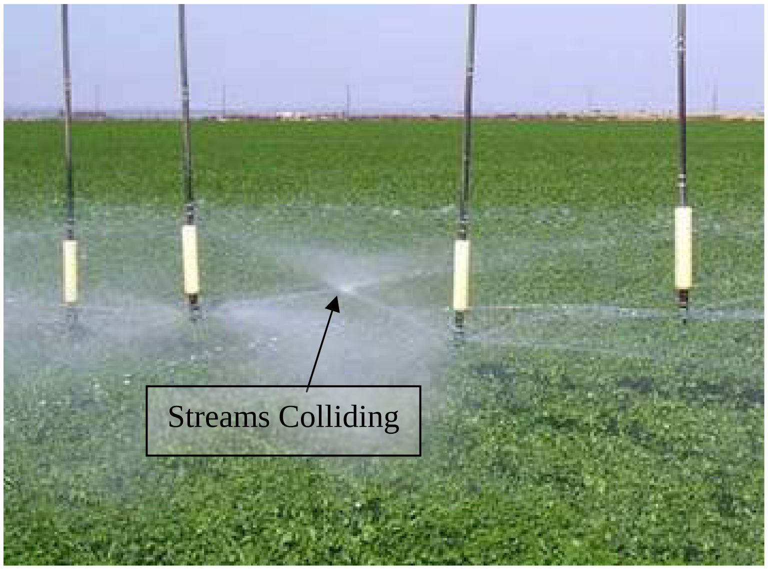

Figure 6. Sprinkler streams colliding during initial evaluation decreasing the pivot DU

In order to minimize stream collisions, drop hose heights can be staggered. For example, one sprinkler is set at 5 feet and the two adjacent sprinklers are set at 6 feet. This amount of stagger also prevents the water streams from colliding into the sprinkler weight – causing the sprinklers to swing while operating.

As part of the modifications every other sprinkler was staggered vertically by one foot to minimize the spray patterns hitting each other and to minimize sprinkler swinging (**Figure 7**).

Figure 7. Staggered sprinklers to minimize spray pattern collisions and swinging

<u>Cleaning Debris from Sprinkler Rotators</u>

Partial nozzle plugging and debris buildup on sprinkler nozzle plates was evident during the initial evaluation. Plastics, feathers, and algae in the irrigation water were the primary cause of this problem. Debris buildup on and under the rotator plate and nozzle plugging (even partial plugging) can have a significant negative impact on the distribution uniformity of the irrigation system. The debris impacts the nozzle spray pattern and prevents proper spinning of the rotator plates. This, in the end, results in poor application coverage. **Figure 8** illustrates an example with a rather heavy debris load.

Figure 8. Sprinklers with trash on rotator plates

As part of the modifications, each of the rotator plates was removed from the rotators and thoroughly cleaned (**Figure 9**).

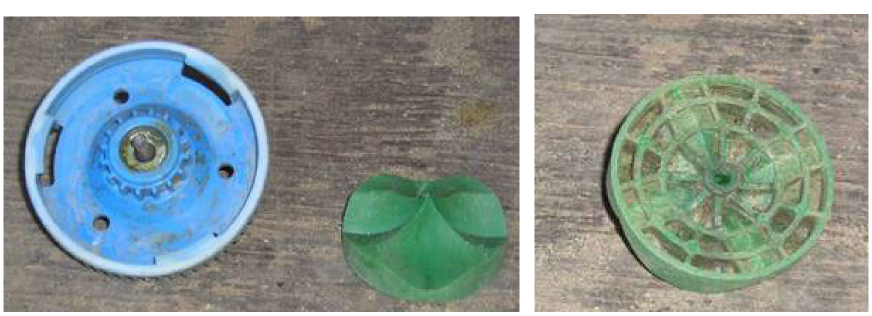

Figure 9. Clean rotators and rotator plates

Nearly all of the sprinklers had algae or debris buildup between the rotator plate and rotator. Inadequate filtration was the cause of these issues. Therefore, the District decreased the maintenance interval between servicing and cleaning the sprinklers and filters.

Replacing Rotator Bodies
Approximately 25 sprinkler bodies had to be replaced because they were either cracked, broken, or bent. The rotator body that is utilized at the Palmdale WRP is the “Trash-Buster”. The open-body architecture allows for debris to pass through more easily, alleviating buildup of material on the plate and body of the sprinkler. Replacing cracked and broken rotator bodies was also part of the increased maintenance program.

A majority of the bad rotator bodies had cracked braces that support the rotator and rotator plate. This prevents the water stream from striking the rotator plate correctly. This in turn can prevent the sprinkler from operating properly, if at all (as shown in **Figure 10**).

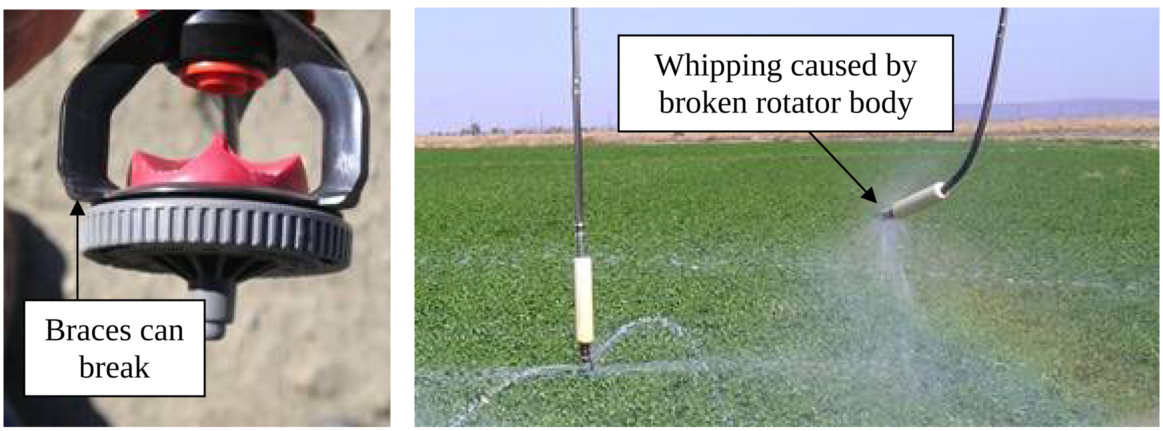

Figure 10. Non-functioning sprinkler because of broken rotator body

New Sprinkler Nozzles
The final modification made as part of the evaluation was the installation of new nozzles based on the pivot system sprinkler chart provided by Reinke Manufacturing and Rain for Rent. Each of the nozzles was removed from each sprinkler and replaced with the nozzle specified in the system sprinkler chart. The nozzles were replaced to guarantee that the proper (or design) sprinkler flow rates were being delivered at every point along the pivot and to replace any nozzles that may have any wear or plugging – reducing the DU of the system.

The original pivot sprinkler package utilized flow compensating (FC) nozzles, a plug-resistant sprinkler on the inner six spans of the pivot. The outer two spans utilize the 3TN nozzle – a fixed orifice with standard drill sizes. The FC nozzle uses a flexible orifice, which contracts as pressure increases, allowing the flow rate discharge to be held fairly constant, regardless of pressure fluctuations. The flexible nature of the rubber also allows for relaxation of the orifice at low pressure. FC nozzles are labeled by flow rate (GPM) and 3TN nozzles are labeled and color coded by drill size (in 64ths of an inch).

Flow control nozzles are NOT recommended on flexible drops because the orifice is continually adjusting/changing and the jet (or stream) of water from the nozzle may not strike the rotator plate perfectly. This could have negative implications on the system DU because of whipping as well as the life of the rotator and rotator plate. For this reason, all the FC nozzles were replaced with standard drill size 3TN nozzles per the new sprinkler package chart.

Results from the Modifications

A comparison of catch can volumes (non-weighted) before and after modifications is shown in **Figure 11**. The results were:

The initial DU = 0.73
DU with improvements = 0.89

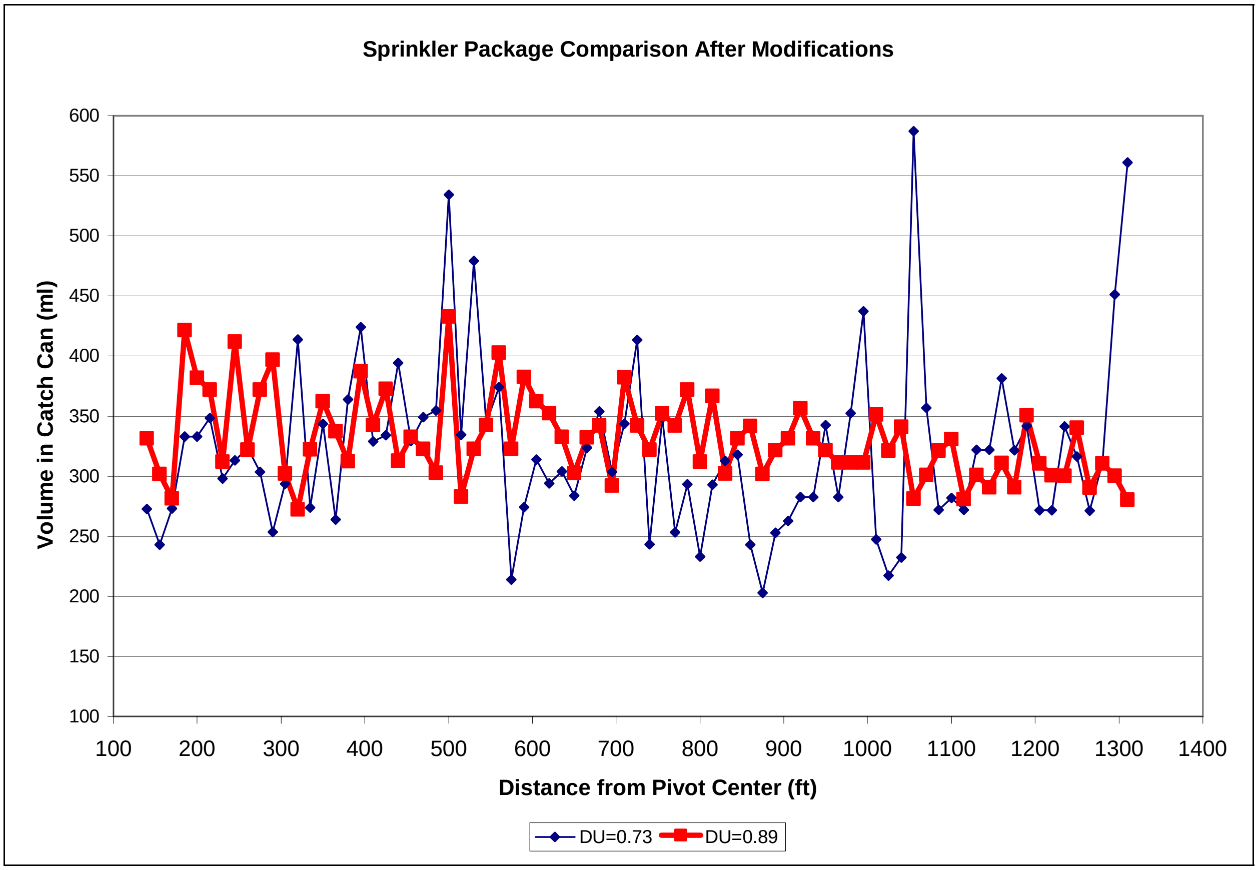

Figure 11. Catch can volumes from pivot center to edge of field (non-weighted)

Although there appears only to be some improvement between evaluations, the difference in DU is linked to the points on the right half of the figure. These points, when weighted, improve the DU because they represent a large portion of the field. For this reason, the modifications proved to be very effective at improving the DU for an individual pivot and ensuring that a majority of the pivot is representative of the entire field.

Comparing the Results of the "Representative" Center Pivot

For comparison purposes each of the points from both DU evaluations was weighted based on the location from the center of the pivot (the points farthest from the center are more important because they cover more area). These points were then plotted with a relative value of 1.0 to visually display the differences between the two evaluations.

Figure 12 illustrates that the number of points that fall within +/- 10% of the weighted average is greatly improved as the DU approaches 1.0. This equates to:

1. improved application uniformity
2. increased water efficiency (assuming good irrigation scheduling) minimizing deep percolation
3. simpler irrigation scheduling
4. an increase in representative sampling locations throughout the pivot
5. improved soil sensor reliability because its location is most likely more representative

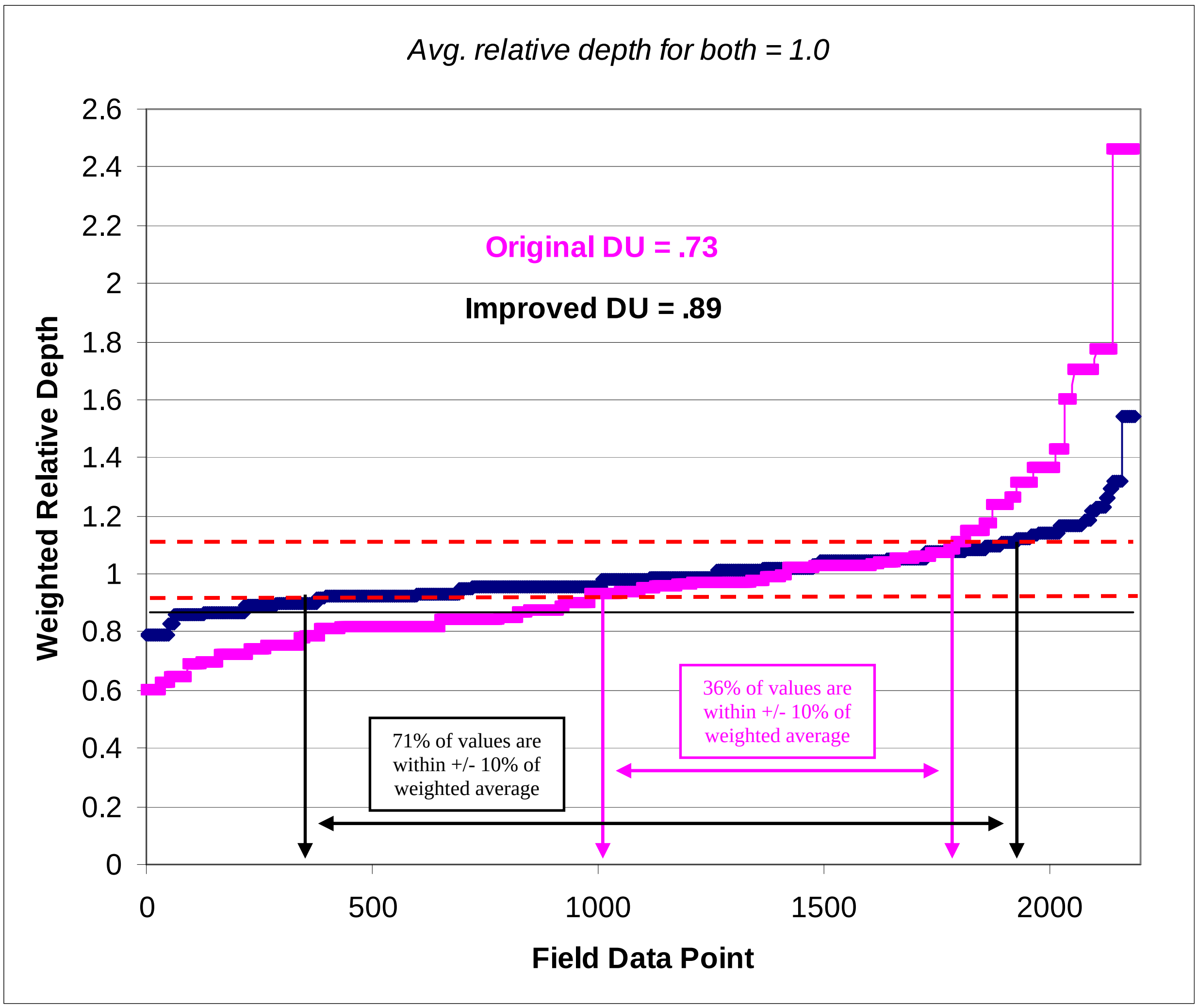

Figure 12. Improved performance in DU

Figure 12 demonstrates that with the original package, approximately 36% of the field is representative of the entire field. However, increasing the DU from 0.73 to 0.89 improves the representative segment of the field to about 71%. This simplifies management and operation by improving the likelihood that a plant tissue sample or soil moisture sensor station is within a representative portion of the field.

Standardizing the Entire Distribution Site

With a practical value for an obtainable DU many additional improvements were made at the Palmdale EMS to make the operation of the entire center pivot distribution systems simpler and more systematic. These operational improvements included modifying the pivot sprinkler package to:

1. match precipitation (application) rates for all pivots
2. provide a precipitation rate that would work in both the summer and winter months without runoff
3. minimize pressure requirements to reduce operating costs
4. add pressure regulation to stabilize pressure to sprinklers
5. make maintenance of the pivots and sprinklers simpler without negatively impacting DU

All of the operational improvements above work in correlation with one another. To provide improved operation of the system as a whole, each of these topics needed to be addressed. Implementing them individually would only have yielded mediocre benefits.

Matching Precipitation Rates for All Center Pivots

An analysis of the center pivots' design flow rates compared to the peak evapotranspiration (ET) requirement for alfalfa in the Antelope Valley indicated that most of the large pivots did not have enough flow rate capacity. On the other hand, the small pivots had application rates nearly three times what is required, making irrigation scheduling more difficult. The peak evapotranspiration of alfalfa irrigated using center pivots will vary depending on the speed at which the center pivot moves.

For example, running a pivot on a 14-hour rotation will lead to higher evaporation because the plant surface is wetted more frequently than when using a 48-hour rotation. The estimated peak evapotranspiration rate of alfalfa in July in Palmdale, assuming a 24-hour rotation, is about 0.4 inches/day or 7.5 GPM/Acre (940 GPM/125 Acres). After incorporating a minimum distribution uniformity of 0.80, the required system flow rate is 0.5 inches/day or 9.4 GPM/Acre (1200 GPM/125 Acres) with no under-irrigation.

To simplify irrigation management all pivot packages were designed with the same 9.5 GPM/Acre requirement. That way, the same depth is applied per hour, regardless of what machine is operating. **Figure 13** shows that the original application flows varied from 7.3 to 27.3 GPM/Acre and the current application flow range varies from 9.4 to 9.6 GPM/Acre. In most cases the District had to re-nozzle each individual pivot. However, making these modifications greatly simplified the operation and irrigation scheduling for each center pivot.

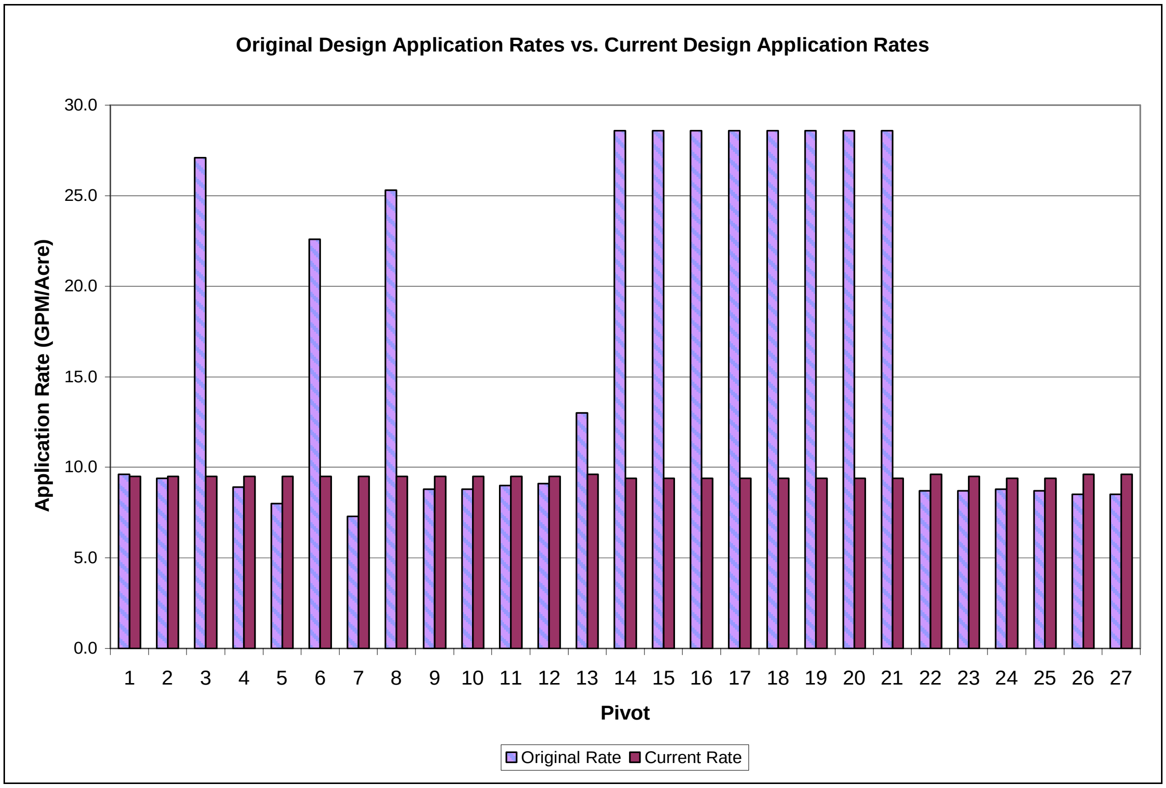

Figure 13. Original design precipitation rates vs. current design precipitation rates

One Package Year-Round

The pivot packages need to support both summer and winter crops without runoff. This would typically be a major task. However, because the DU is very good and the soils are classified as loamy sand and range to a sandy loam, the application rates do not exceed the infiltration rates. These factors reduce the likelihood of runoff even during the winter months. Furthermore, the installation of a single application rate simplifies operation of the pivots.

In areas where the soil is somewhat heavier (sandy loam) the drops were strung over the truss rods to increase the wetted area (reducing the instantaneous application rates) without replacing the nozzles (**Figure 14**).

Figure 14. Drops strung over truss rods to increase the wetted area

Pivot Operating Pressure
The nozzle pressure near the pivot center should be within 1-2 psi of the designed operating pressure. In most cases, the operating pressures and flow rates were originally below their design recommendations. During the DU evaluations several valves had to be adjusted to get the center pivot being evaluated up to its design flow rate and pressure recommendations. To do this, valves to other center pivots had to be throttled back, causing their flow rate and pressure to be nearly half of what they are designed to operate at. The practice of manipulating one center pivot's pressure to adjust another could not continue.

To reduce under-pressurizations the pivot sprinkler packages were reduced from about 50 psi to about 35 psi. This has several benefits, including larger nozzles that will pass debris more easily and less stream break-up due to increased droplet size – improving the sprinklers' wind fighting abilities to maintain a reasonable DU even during high wind events.

Figure 15 illustrates how the pressure requirements were adjusted. Pivots 22-25 needed increased pressure to compensate for the increase in flow rate and the addition of end guns.

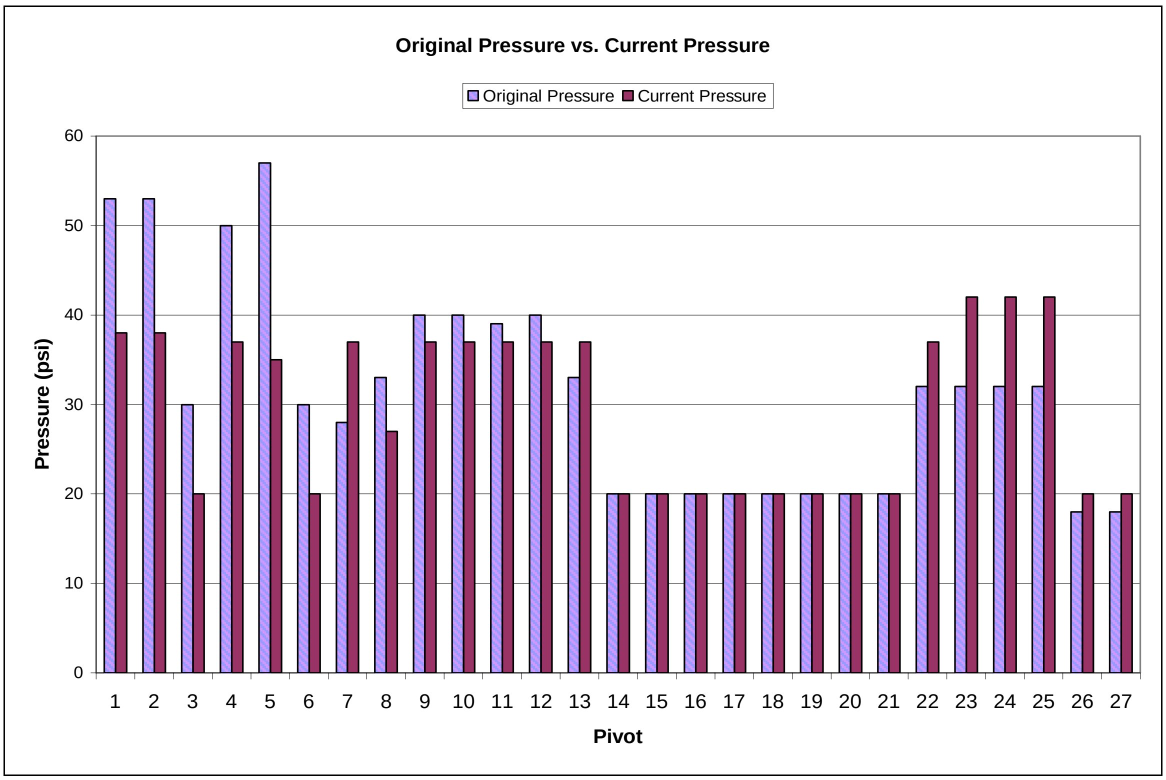

Figure 15. Original pressure vs. current pressure requirements

Pressure Regulation
It is difficult to accurately schedule irrigations when the flow rate varies from irrigation to irrigation or is different than expected when scheduling the irrigation. To combat this problem pressure regulation was installed on all center pivots. Pressure regulation ensures that the pressure does not exceed a preset limit. It does not, however, guarantee that the pressure is available. Therefore, booster pumps are run to provide slightly more pressure than is required at the most critical spots and pressure regulators are used to meet the designed pressure requirements of the center pivot.

All mini pivots (shorter than 700 ft in length) have individual sprinkler regulators and all large pivots (greater than 770 ft in length) have one in-line pivot regulator. The decision to use two types of pressure regulation was linked to economics. **Figure 16** shows both types of regulators. Both options provided adequate results and helped stabilize the flows onto each field.

Figure 16. In-line pressure regulator (left) and individual pressure regulators (right)

Center Pivot Maintenance

A major component of managing the site is to not only have a good DU but to maintain it. The inherent debris conditions of secondary treated chlorinated wastewater require a regular maintenance schedule for not only the filter stations but also the center pivots themselves. Between each harvest (or at least once a month) the pivots sprinklers are thoroughly cleaned. To make sprinkler maintenance easy, the sprinklers were positioned to an average height of 4 ft from the ground – staggered 3.5 to 4.5. This enables the sprinklers to be cleaned easily by operations personnel.

To overcome the slight reduction in DU caused by the lower sprinkler heights the rotator plates were changed to brown (see **Figure 16**). The brown rotor plates replaced the green plates for a number of reasons:

- Higher application uniformity – even at the lower height
- 10 water streams vs. 4 for the green plate
- Varying stream trajectories
- Gentler impact on the soil surface

In addition, a flush valve with a battery-operated automatic timer was installed at the end of most machines to flush large debris from the pivot twice daily. Because the process is automatic the system is flushed during operation and not just at startup, which was the previous standard protocol (**Figure 17**).

Figure 17. Automatic center pivot end flush

Conclusions

Providing real-time irrigation scheduling and achieving representative soil moisture monitoring throughout the year is important because irrigation demands fluctuate monthly and wastewater supply is fairly constant year-round. Therefore, it is easy to over-apply in winter months when crops demands are low and have a deficit in summer months when crops demands are high. Achieving a high DU reduces the possibility of deep percolation in the winter and improves the yield during the summer because water is more evenly applied to the entire field.

The results of the "before" and "after" DU evaluations of a "representative" center pivot show that a single machine, with the proper hardware and adjustments, can achieve a high DU. However, standardization for all pivots was needed to operate the whole system easily and uniformly. To achieve that, all precipitation rates needed to match, a single application rate was required year-round, pressure requirements needed to be adjusted and pressure regulation utilized, and a frequent maintenance program was put in place to sustain the high distribution uniformities.

All of the operational improvements described in this paper needed to work in correlation with one another. In order improve the system operations as a whole, the entire system must be examined and all factors must be addressed. Implementing any one of these factors individually would have provided little, if any, benefit.

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Soil Moisture Controlled Effluent Disposal by Subsurface Drip Irrigation in the Alabama Black Belt Soil Area

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ABSTRACT

Conventional onsite septic systems are not suitable for many soils of the Blackland Prairie in Alabama; however this rural wastewater treatment and disposal system has been widely applied in this region for decades. A soil survey of the Alabama Black Belt area indicates a wide spread environmental threat from conventional onsite septic systems. An alternative integrated sewage treatment system consisting of subsurface drip irrigation and crop uptake is proposed as a small community based decentralized system in this region. The system proposed uses volumetric soil moisture controlled subsurface drip irrigation (SDI) together with selected crops to dispose and treat pre-filtered septic tank effluent in a high clay drain field.

The goal of this study is to maximize the seasonal hydraulic dosing rates of a synthetic pre-treated septic tank effluent on a Houston clay in the Alabama Black Belt area, while maintaining a favorable soil aeration level for biological nutrient treatment. One and half years field data indicated three distinct dosing periods throughout a year, during which the field hydraulic loading rate ranged from a maximum 4 times the state's dosing recommendation in summer to zero disposal during winter. Grasses from controlled experiment plots showed significant yield differences due to the nutrient contribution from the synthetic wastewater. Initial field data suggest a promising strategy using field moisture controlled dosing system in high clay soil areas. The real-time SDI control system can prevent overdosing to a wastewater drain field during unfavorable (i.e. saturated) field conditions.

KEY WORDS

Black Belt; Decentralized; Hydraulic dosing rate; Onsite sewage disposal; Soil; Subsurface drip irrigation; Wastewater.

INTRODUCTION

Onsite wastewater treatment systems are a major component, in addition to municipal wastewater treatment plants, of the modern wastewater treatment industry. In the U.S., about thirty percent of households are using onsite septic systems, while in Alabama this number is 47 percent (AOWT 2005). Site conditions are critical for the success of onsite septic systems, and soil is the most important factor. The environmental challenge for conventional onsite septic systems comes from the system's almost complete reliance on soil properties (Oron 1996). The soil in a drain field should have a percolation rate that allows wastewater to penetrate into soil at an appropriate speed so that soil can absorb the wastewater and provide aerobic treatment of the nutrients and contaminants brought in with the wastewater. The requirement of an adequate soil percolation rate (not too fast or too slow) makes heavy clay soils and very sandy soils generally unsuitable for conventional onsite sewage systems.

Charles *et al.* (2005) did an extensive septic effluent field survey in Australia and compared the results with published regulations in U.S. and Australia. Charles concluded that 80^{th} percentile of the effluent survey values (250 mg/L for TN, and 36 mg/L for TP) should be incorporated into new regulations in order to minimize the overloading which is associated with most onsite system failures. Lipp *et al.* (2001) demonstrated that the pathogen impact from onsite sewage systems to the coastal community was related to local onsite system density. Carroll and Goonetilleke (2005) confirmed that a high septic system density (290 systems/ km^2) significantly impacts shallow groundwater systems. Incidences of poor treatment performance from onsite systems, particular conventional septic systems, are quite common in U.S. and worldwide (U.S. EPA 2002; Carroll and Goonetilleke 2005), and are a significant source of water pollution (Beggs et al. 2004).

Conventional onsite septic systems have been used in the Alabama Black Belt area for decades. A preliminary soil survey (Figure 1) that rates the soils in the Alabama Black Belt area in terms of suitability for conventional onsite septic systems was conducted within a GIS using NRCS SSURGO digital soil data. The results indicated that although 78% of the Alabama Black Belt area is rated as unsuitable for conventional onsite septic systems, in fact conventional onsite septic systems are the most common and widespread system in this region (Dougherty 2006).

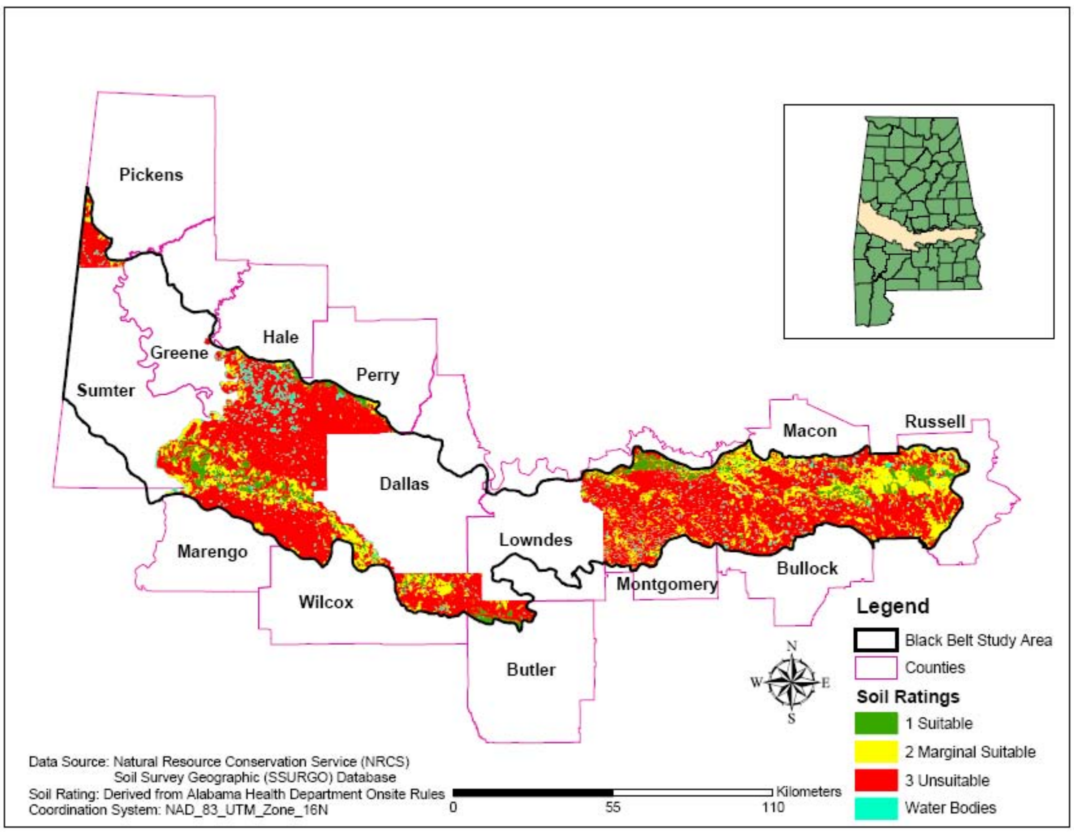

Figure 1. Soil ratings in Alabama Black Belt soil area.

The Alabama onsite sewage disposal rules (2005) exclude the use of conventional onsite septic systems in most Alabama Black Belt soils by regulating soil percolation rates for drain field design. Furthermore, all existing onsite systems installed after 2000 come under the influence of the new regulations. Those systems not meeting current regulations will not be allowed to renew their permits unless site conditions are improved or until disposal methods are upgraded. Therefore, the new regulations provide a strong incentive for alternative treatment and disposal systems in the Alabama Black Belt area.

An engineered wastewater dosing system is proposed uses a volumetric soil moisture controlled subsurface drip irrigation (SDI) system together with mixed grasses to dispose of pre-filtered septic tank effluent. Theoretically, a septic tank effluent is disposed into a drain field using SDI in series with engineered self-flushing filters (110 micrometers) to substantially remove septic tank effluent solids. The principal difference between the proposed SDI system and conventional septic systems is the self-regulated dosing and hydraulic control of the SDI system. The dosing of the septic tank effluent is controlled by soil moisture sensors buried in the drain field. Water disposal will be turned on when soil moisture content drops below 40% (v/v), and water disposal will be turned off when soil moisture content goes above 45% (v/v). In such dosing strategy, the real-time drain field moisture can prevent drain field overdose at or near field capacity. Selected grasses grown over the drain field provide additional uptake of water and nutrients thus providing more water and nutrient capacity in the drain field.

The objective of this study is to determine the hydraulic dosing rate of a pre-filtered septic tank effluent on a high clay soil (Houston clay) in Alabama Black Belt soil area, while maintaining nutrient levels in the drain field at an environmentally safe level.

EXPERIMENT METHOD

The testing site is at the Black Belt Research and Extension Station in Marion Junction, AL. The design drain field hydraulic loading rate is set to 0.05 gal/sq.ft./day and the design flow rate is 270 gal/day/household. The soil in the drain field is Houston clay which is rated as marginally suitable for conventional onsite septic system according to the new Alabama onsite rules. A 1000 gallon septic tank is used as a dosing reservoir. A 1/2 horse power pump with a capacity of 20 gpm supplies water from the tank to a $60' \times 90'$ drain field through subsurface drip irrigation tubing (Figure 2). The irrigation controller is installed onsite to datalog and control operating conditions and wastewater disposal in the drain field. Wheat (Jackson) and Ryegrass (Special effort) are grown during fall and winter, with hybrid Sorghum Sudangrass grown during spring and summer. During the first year, the SDI system was dosed using clean well water only, with the area surrounding the drain field used as a non-irrigated control. Nitrogen fertilizer at agronomic application rates was applied to both the irrigated and non-irrigated control plots. In the second year, the SDI drain field was divided into two plots, an irrigated nutrient plot and an irrigated non-nutrient plot. The area surrounding the drain field remained as a non-irrigated control. The irrigated nutrient plot received a synthetic wastewater with an N: P ratio similar to septic tank effluents. The irrigated non-nutrient plot received only clean water. Nitrogen fertilizer applied at agronomic application rates was applied to both the irrigated plot and non-irrigatedcontrol plot at the beginning of each plant season. Both the irrigated nutrient plot and the irrigated non-nutrient irrigated plot received the same amount of water each time the dosing pump operated. The collected field data, continuously logged at 15-minute interval includes soil moisture content, rain fall, soil temperature, pumping rate and volume, irrigation frequency and dosing time. Grasses nutrient content was analyzed by the soil lab in the Agronomy and Soil Department of Auburn University. Field suction lysimeters are placed in drain field with the sampling depths of 6", 12" and 18" to collect soil water samples periodically.

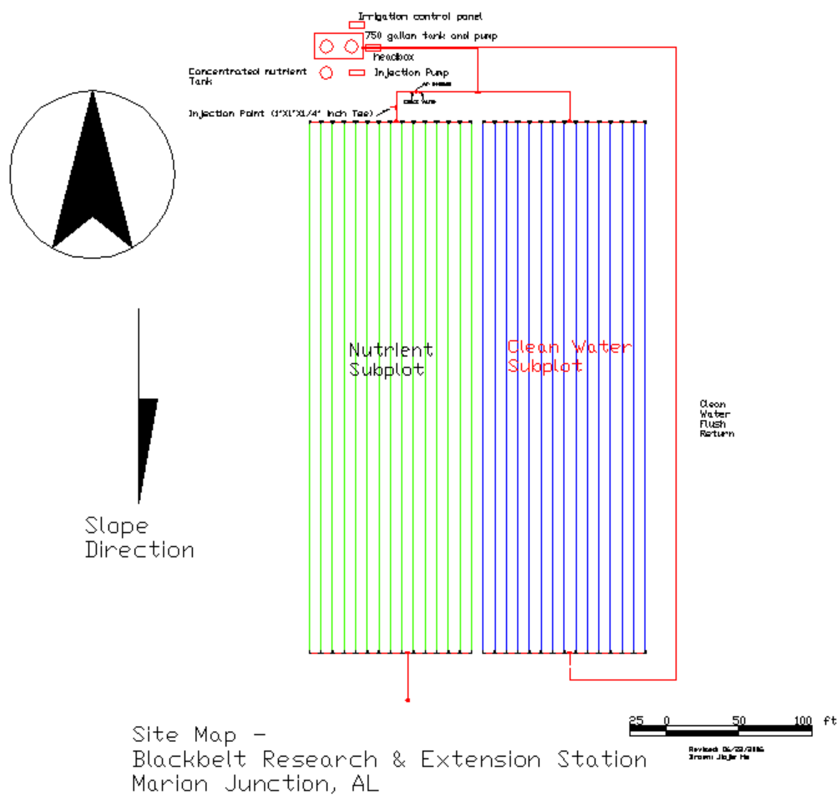

Figure 2. Field experiment sketch.

EXPERIMENT PROGRESS AND RESULTS

Clean water application (First year)

The field experiment was started on September 7, 2006. The drain field soil moisture went through a start up period before stabilizing (Figure 3). The total water applied to the drain field during the stabilized period was 15,618 gallons, approximately 1,115 gpd, four times higher than the design rate (270 gpd/household). During August and September, sufficient water in the irrigated drain field stimulated plant growth as expected. Evaluation of rainfall and flow data during August and September 2006 indicates SDI was the major contributor of the soil moisture. Due to an unexpected power outrage in the winter of 2006/2007, the dosing system was idle from October 6, 2006 untill January 09, 2007. Nevertheless, from soil moisture field data stored in the data logger, it is estimated that water disposal rate into the drain field would have been halted between October and September anyway due to naturally wet, rainfall-fed field conditions. In November, rain precipitation brought drain field volumetric moisture content above 45% (the set point to halt dosing) three times. Each time it took a longer time for the drain field volumetric moisture level to drop below 40% (the set point to begin irrigation after dosing is halted). In December 21, 2006, an intensive precipitation brought drain field moisture content above 45% again, and then the drain field moisture content stabilized above 45% with almost no variation till March 7, 2007.

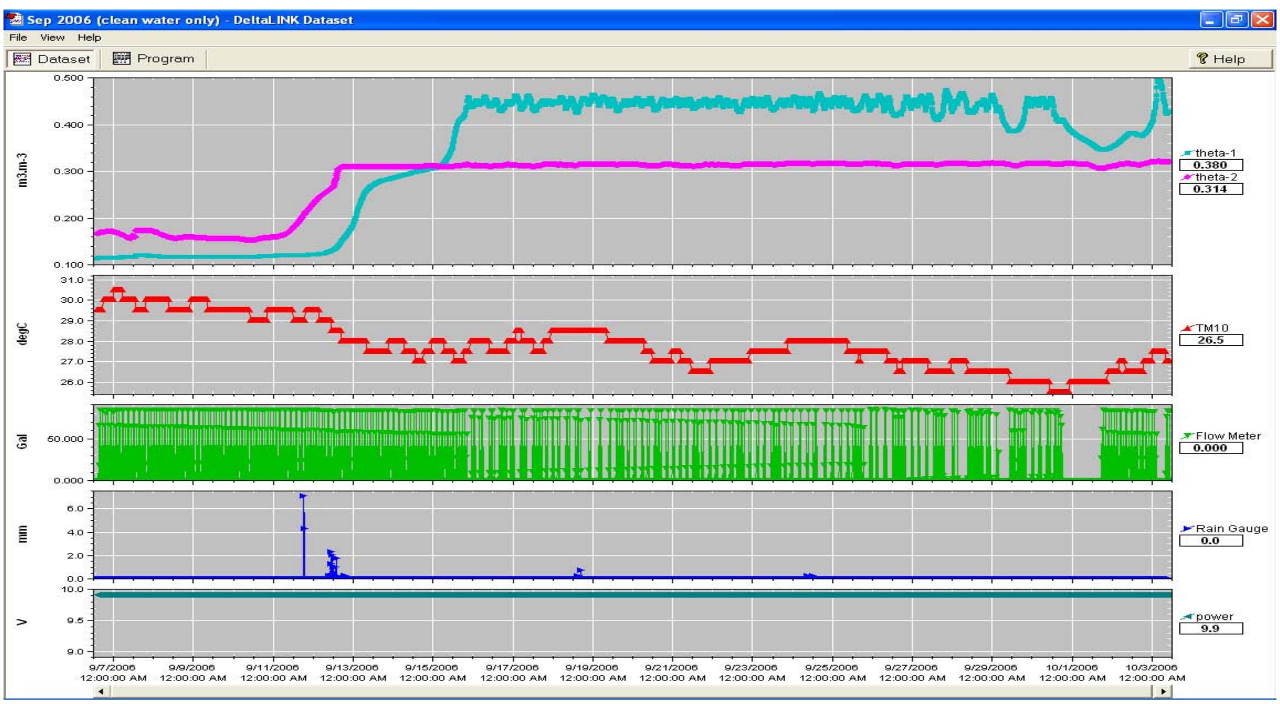

Figure 3. Field data from September 07,2006 ~ October 03,2006.

From late December 2006 to early March 2007, drain field moisture content stayed above 45%, which prevented SDI wastewater dosing. This indicats that there could be at least three months during which the drain field can not accept wastewater and a three month wastewater storage capacity would needed to store wastewater generated during those times when drain field moisture volumetric content exceeds 45%. After March 7, 2007, it was observed that the daily water dosing rate into the drain field was raised from 361 gallon per day in early March to 1056 gpd in late March due to dryer field conditions. The water disposal rate then stabilized untill early August at a rate between 1147~1223 gpd. After August 10, 2007, the daily water dosing rate stabilized at around 803~844 gpd.

Above results indicate a water dosing pattern that is comprised of a dormant season, two transition periods, and a growing season. The dormant season occurred when drain field volumetric moisture content maintained above 45%. The observed growing season between late March and early August is when the hydraulic dosing rate reached its peak value. Two transition periods lay between the dormant season and the growing season, one occurred between the dormant season to the growing season in March (less than one month), and a longer one occurred after the growing season but before the start of the dormant season (around 5 month).

The hybrid of Sorghum Sudangrass grown during the long transition period (August 03, 2006 ~ November 01, 2006) showed significant yield differences among the tested plots (Table 1). The irrigated plot had a field yield that was three fold that of the non-irrigated plot. Ryegrass and wheat grown during the dormant season (November 01,2006 ~April 20,2007) showed irrigated plot had a field yield 1.3 times higher than non-irrigated plot (Table 1). From the grasses elemental analysis, the N, P, K contents of different treatments were at fairly the same level with K has a 20% difference (Table 2).

In general, the soil moisture controlled dosing system operated in the drain field as designed. Seasonal moisture differences in the drain field influenced the effluent disposal rate as planned. Grasses yields in the drain field demonstrate the potential for grasses to increase water and nutrient uptake in the drain field.

Table 1. Grasses yield at different seasons

Grass Planted	Treatments	Date planted	Date harvested	pounds / acre	dry matter %	Dry matter lbs/acre
Sourghum/Sudan*	Irrigated plot	8/3/2006	11/1/2006	12,561	27.68	3477
	Non-irrigated plot	8/3/2006	11/1/2006	3862	28.36	1095
Wheat /Ryegrass**	Irrigated plot	11/1/2006	4/20/2007	22967	28.00	6431
	Non-irrigated plot	11/1/2006	4/20/2007	17522	27.50	4819
Sourghum/Sudan*	Irrigated nutrient plot	6/14/2007	8/9/2007	17494	30.14	5273
	Irrigated non-nutrient plot***	6/14/2007	8/9/2007	6594	31.00	2044
	Non-irrigated plot***	6/14/2007	8/9/2007	4073	35.47	1445

* Planted at 30 lbs seed /acre John Deere Drill 7" spacing, Fertilized 60# N 08/17/2006
**Fertilized 60# N 11/15/2006 &3/08/2007, Planted 60 LBS wheat & 20 lbs of ryegrass. John Deere drill 7" spacing
***Fertilized 60# N 07/20/2007

Table 2. Grasses element content

Grass Planted	Treatments	Date planted	Date harvested	N (%)	P (mg/kg)	K (mg/kg)
Sourghum/Sudan*	Irrigated plot	8/3/2006	11/1/2006	1.49	1732	5387
	Non-irrigated plot	8/3/2006	11/1/2006	1.91	1734	5007
Wheat /Ryegrass**	Irrigated plot	11/1/2006	4/20/2007	1.88	1534	10005
	Non-irrigated plot	11/1/2006	4/20/2007	1.90	1522	8869

Synthetic wastewater application (Second year)

A positive displacement injection pump (Neptune Inc.) was put in place on June 16, 2007 and started to inject synthesized, TSS fee, wastewater into the drain field. The simulated nutrient level was around 250 mg N/L and 36 mg P/L. As expected, the dosing record indicated a gradually reduced disposal rate after August 2007. This result confirms that this transition period will likely continue for a longer period than the March transition period. Grasses and soil nutrient levels are currently being analyzed. The most recent data for the hybrid Sorghum Sudangrass (June 14, 2006 ~August 09, 2007) show that the irrigated nutrient plot had a field yield 3.65 times higher than irrigated non-nutrient plot and 2.58 times higher than clean irrigated plot (Table 1). The grass elemental analysis is still under analyze.

CONCLUSION

The seasonal hydraulic dosing rates on a Houston clay soil in central Alabama were field observed through almost two years field study. During typical dry summer conditions, the hydraulic dosing rate can reach as much as four times the state's recommendation (0.05 gal/sq.ft./day). During fall and early spring, the hydraulic dosing rate dropped to around two times the state recommendation. During winter, the drain field was in a saturated state and could not safely accept any more wastewater. Field grasses harvested during each season indicate that grasses content was not influenced by the addition of synthetic wastewater. However, the yield in the soil moisture controlled drain field was five times as much as the non-irrigated control. It is expected that nutrient uptake results will show comparable increase in nutrients removal from the field. Soil water analyses taken from suction lysimeters 6", 12", and 18" (not yet available) will quantify the nutrient residence and balance in the drain field due to the synthetic wastewater application. HYDRUS-2D soil moisture modeling, developed by U.S. Salinity Laboratory, U.S. Department of Agriculture, will be incorporated to simulate the collected field data to better quantify and validate drain field water and nutrient conditions during each season.

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ENSURING EQUAL OPPORTUNITY SPRINKLER IRRIGATION

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ABSTRACT

Equal opportunity to water applied by sprinkler irrigation to each plant must be carefully considered by crop producers, irrigation consultants, and the industry that supplies the irrigation equipment. Equal opportunity can be negated by improper marketing, design, and installation of equipment, as well as through improper farming operations, and irrigation mismanagement. These issues have greater significance when the irrigation is applied within or near the crop canopy. Key issues that must be addressed to ensure equal opportunity to sprinkler irrigation applications are irrigation application symmetry, spatial orientation of sprinkler travel with respect to crop rows, and the seasonal longevity of the sprinkler pattern distortion caused by crop canopy interference. There are both producer and industry roles in providing equal opportunity for the crop to the applied sprinkler water.

INTRODUCTION

Mechanical-move sprinkler irrigation systems are typically designed to uniformly apply water to the soil at a rate less than the soil intake rate to prevent runoff (Heermann and Kohl, 1983). In the U. S. Great Plains, there is a growing use of in-canopy and near-canopy sprinkler application because of reduced evaporative losses, however these application devices introduce a much greater potential for irrigation non-uniformity and run-off and/or run-on (i.e., surface redistribution). Some of the earliest descriptions of in-canopy sprinkler irrigation (Lyle, 1992) discuss the importance of all crop plants having equal opportunity to water, yet irrigators, designers and equipment manufacturers do not always follow this guideline. This paper will discuss the issue from a conceptual standpoint using both research and on-farm examples. The objective is attaining greater acceptance of this design criteria so that irrigator's can avoid the reduced crop production and runoff that occur when equal opportunity is violated.

SYMMETRY OF SPRINKLER APPLICATION

Uniformity of water application and/or infiltration is an important attribute in ensuring equal opportunity sprinkler irrigation (Zaslavsky and Buras, 1967; Seginer 1978; Seginer 1979, von Bernuth, 1983; Feinerman et al., 1983; Letey, 1985; Duke et al., 1991). Increased uniformity will often result in increased yields, decreased runoff, and decreased percolation (Seginer,1979). Improved sprinkler uniformity can be desirable from both economic and environmental standpoints (Duke et al., 1991). Their study shows irrigation non-uniformity can result in nutrient leaching from over-irrigation and water stress from under-irrigation. Both problems can cause significant economic reductions. Returning to the first sentence of this paragraph, the careful wording can be noted of “uniformity of water application and/or infiltration”. This wording suggests that the primary goal is for the plants to have equal opportunity to root-zone soil water.

Sprinkler irrigation does not necessarily have to be a uniform broadcast application to result in each plant having equal opportunity to the irrigation water. Equal opportunity can still be ensured using a low energy precision application (LEPA) nozzle in the furrow between adjacent pairs of crop rows provided runoff is controlled (Figure 1).

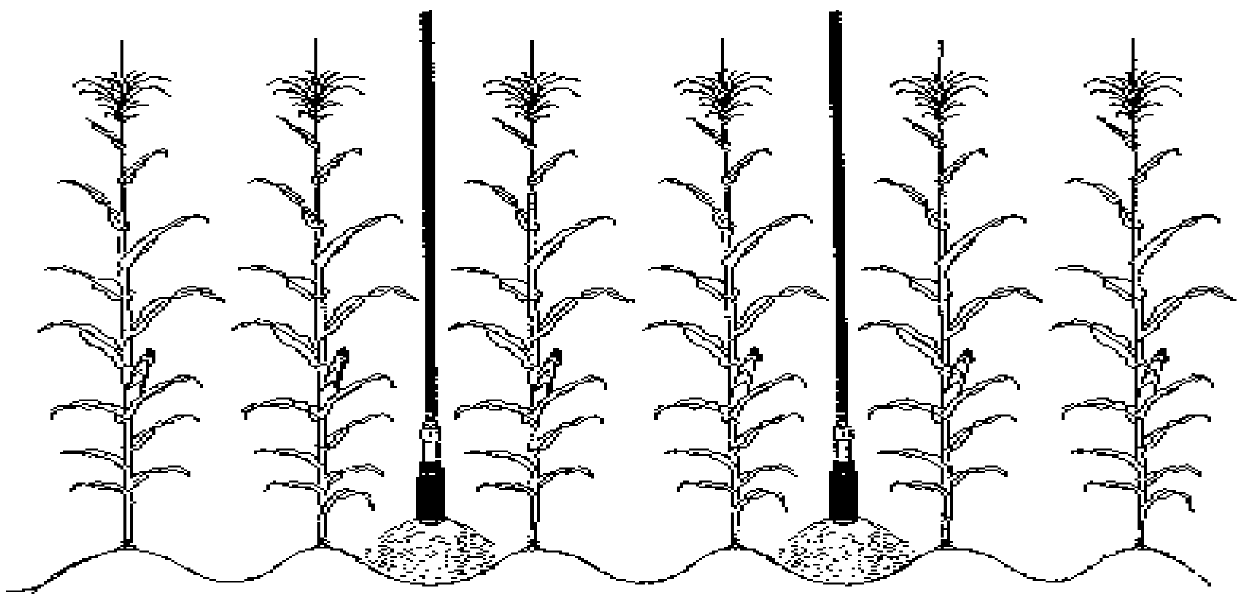

Figure 1. LEPA concept of equal opportunity of plants to applied water. LEPA heads are centered between adjacent pairs of corn rows. Using a 5–ft nozzle spacing with 30-inch spaced crop rows planted circularly results in plants being approximately 15 inches from the nearest sprinkler. After Lamm (1998).

Some sprinkler application non-uniformity can also be tolerated when the crop has an intensive root system (Seginer, 1979). When the crop has an extensive root system, the effective uniformity experienced by the crop can be high even though the actual resulting irrigation system uniformity within the soil may be quite low. Additionally, when irrigation is deficit or limited, a lower value of application uniformity can be acceptable in some cases (von Bernuth, 1983) as long as the crop economic yield threshold is met.

Some irrigators in the U. S. Great Plains are using wider in-canopy sprinkler spacings (e.g., 7.5, 10, 12.5 and even 15 ft) in an attempt to reduce investment costs (Yonts et al., 2005). Spray heads which perform adequately at a 10 ft interval above bare ground have a severely distorted pattern when operated within the canopy (Figure 2).

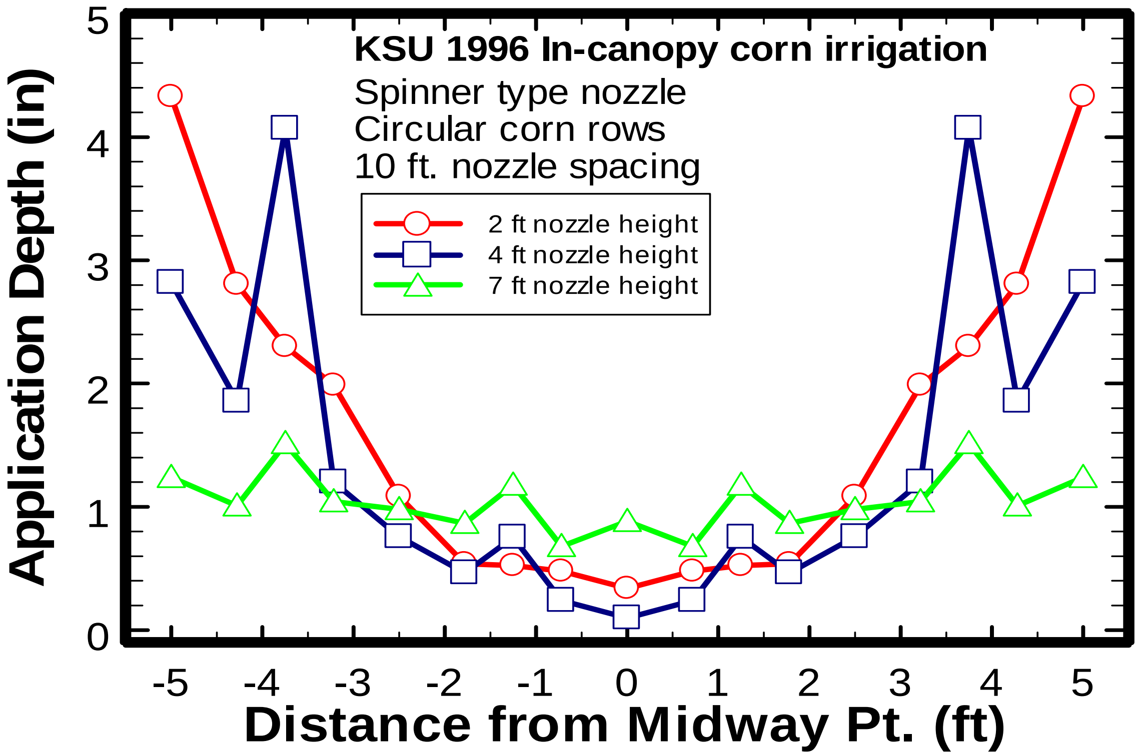

Figure 2. Differences in application amounts and application patterns as affected by sprinkler height that can occur when sprinkler spacing is too wide (10 ft) for in-canopy application. Center pivot sprinkler lateral is traversing parallel to the circular corn rows. Data are from a fully developed corn canopy, July 1996, KSU Northwest Research-Extension Center, Colby, KS. Data are mirrored about the centerline for display purposes.

Although Figure 2 indicates large application non-uniformity, these differences may or may not always result in crop yield differences, but they should be considered in design. Hart (1972) concluded from computer simulations that differences in irrigation water distribution occurring over a distance of approximately 3 ft were probably of little overall consequence and would be evened out through soil water redistribution. Some irrigators in the Central Great Plains contend that their low capacity systems on nearly level fields restrict runoff to the general area of application. However, nearly every field has small changes in land slope and field depressions which do cause field runoff or percolation when the irrigation application rate exceeds the soil infiltration rate. In the extreme drought years of 2000 to 2003 that occurred in the U. S. Central Great Plains, even small amounts of surface water movement affected sprinkler-irrigated corn production (Figure 3).

Figure 3. Large differences in corn plant height and ear size for in-canopy sprinkler application over a short 10-ft. distance (4 crop rows) as caused by small field microrelief differences and the resulting surface water movement during an extreme drought year, Colby, Kansas, 2002. The upper stalk and leaves have been removed to emphasize the ear height and size differences.

Mechanical-move sprinkler system manufacturers do not always provide nozzle spacings that ensure equal opportunity to the water. There are a host of nozzle outlet spacings available from industry, 30, 57, 90, 108 inches and the multiples of these spacings, but often a particular manufacturer will have their own limited selection which may be further limited in some span lengths. The industry may have valid reasons for this limitation related to overall inventory and international marketing but that does little to accommodate the various crop row spacings (e.g., 30, 36, 38, 40 inches, etc.) that are commonly used in the United States. Since irrigation is primarily a tool to increase crop production, maybe ensuring equal opportunity to the sprinkler irrigation water should be more important than marketing issues. After market suppliers have provided some solutions to this problem through furrow-arm goosenecks and hose draping devices but these “fixes” can be cumbersome to adjust and maintain in the proper position.

SPATIAL ORIENTATION

The direction of travel of the mechanical-move sprinkler lateral with respect to crop row direction can affect the equal opportunity issue when in-canopy application is used. It has been recommended for center pivot sprinkler systems that crop rows be planted circularly so that the rows are perpendicular to the sprinkler lateral. Matching the direction of travel to the row orientation satisfies the important LEPA Principles 2 and 5 noted by Lyle (1992) concerning water delivery to one individual crop furrow and equal opportunity to water by for all plants.

Some producers have been reluctant to plant row crops in circular rows because of the cultivation and harvesting difficulties of narrow or wide "guess" rows. However, using in-canopy application for center pivot sprinkler systems in non-circular crop rows can pose two additional problems (Figure 4). In cases where the CP lateral is perpendicular to the crop rows and the sprinkler spacing exceeds twice the crop row spacing, there will be non-uniform water distribution because of pattern distortion. When the CP lateral is parallel to the crop rows there may be excessive runoff due to the great amount of water being applied in just one or a few crop furrows. There can be great differences in in-canopy application amounts and patterns between the two crop row orientations (Figure 5).

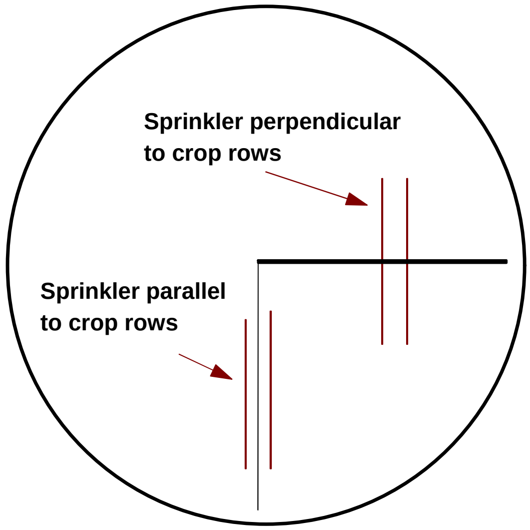

Figure 4. Two problematic orientations for in-canopy sprinklers in non-circular rows.

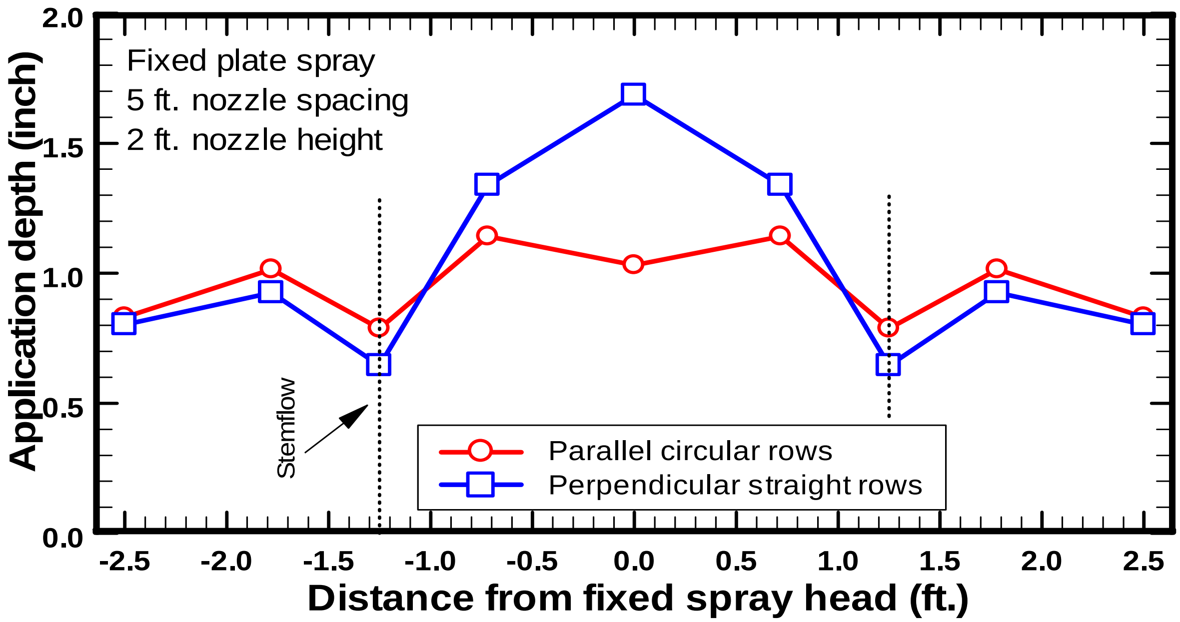

Figure 5. Differences in application amounts and application patterns as affected by corn row orientation to the center pivot sprinkler lateral travel direction. Dotted lines indicate location of corn rows and stemflow measurements. Data are from a fully developed corn canopy, July 23-24, 1998, KSU Northwest Research-Extension Center, Colby, KS. Data are mirrored about the centerline.

PATTERN DISTORTION AND TIME OF SEASON

Drop spray nozzles just below the center pivot sprinkler lateral truss rods (approximately 7-8 ft height above the ground) have been used for over 25 years in northwest Kansas. This configuration rarely has had negative effects on crop yields although the irrigation pattern is distorted after corn tasseling. The reasons are that there is only a small amount of pattern distortion by the tassels and this distortion only occurs during the last 30 to 40 days of growth. In essence, the irrigation season ends before a severe soil water deficit occurs. Compare this situation with spray heads at a height of 1 to 2 ft that may experience pattern distortion for more than 60 days of the irrigation season. Yield reductions might be expected for some corn rows in the latter case because of the extended duration of the pattern distortion. Lowering an acceptably spaced (10 ft) spinner head from 7 ft further into the crop canopy (e.g., 4 or 2 ft) can cause significant row-to-row differences in corn yields (Figure 6).

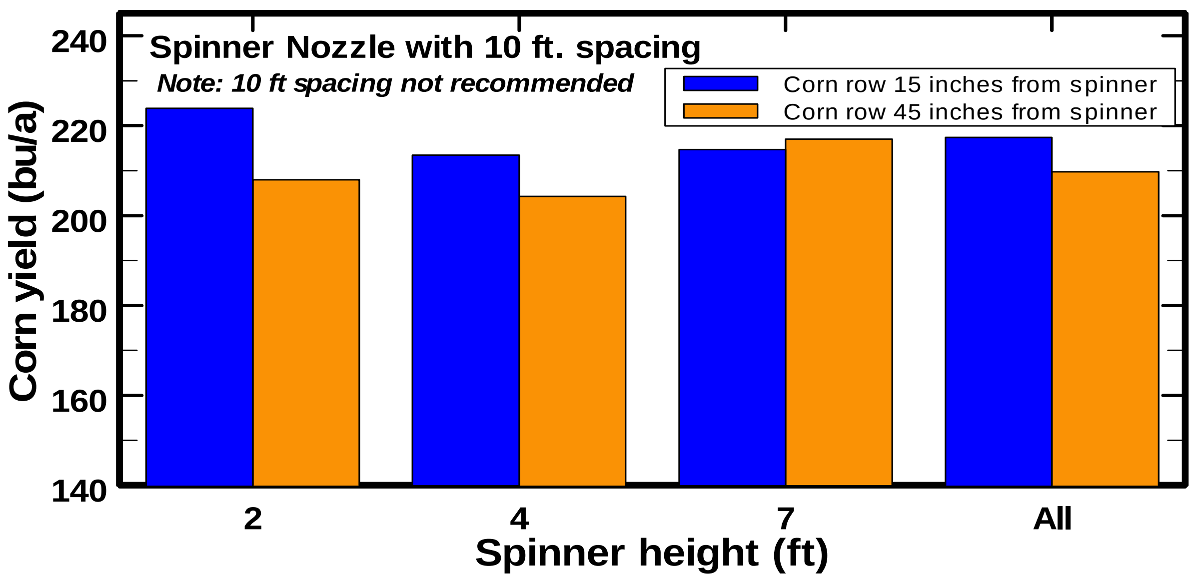

Figure 6. Row-to-row variations in corn yields as affected by sprinkler height for 10 ft. spaced in-canopy sprinklers. Sprinkler lateral travel direction was parallel to crop rows. Data was averaged from four irrigation levels for 1996 to 2001, KSU Northwest Research-Extension Center, Colby, KS.

CONCLUDING STATEMENTS

Short and long term water supply problems in the U. S. have forced those involved with irrigation to look for cost-effective, water saving techniques. Sprinkler irrigation is now the predominant irrigation method in the U. S. Great Plains because of both water and labor savings. Ensuring equal opportunity of crop plants to the applied water has long been recognized as an important tenet of irrigation, yet there continues to be a lack of appropriate attention to this rule particularly with the newer in-canopy and near-canopy sprinkler application techniques. Both end-users and industry have important roles in solving this problem. Neglecting this equal opportunity issue can easily waste more water and cause more crop yield reductions than other irrigation problems producers and industry are trying to avoid.

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Low-Pressure, Low-Cost Sprinkle Irrigation for Smallholders

By
Jack Keller[1] and JN Ray[2]

Abstract

This paper describes an affordable low-pressure sprinkle irrigation system, called *IDEal Rain*, developed in India by International Development Enterprises. It is ideally suited for millions of very small farms worldwide (it can even be powered using a manually operated treadle pump). A 0.4-hectare (1-acre) fixed system cost about $225 (and it can easily be shifted to serve another plot). Simple extruded plastic lay-flat tubing is used for the mains and laterals. Conventional impact sprinklers with specially designed nozzles are used at operating pressures of only 7- to 10-meter (10- to 15-psi). Only the sprinklers along with their unique tripods are shifted between sprinkler sets to provide an 8-meter by 10- or 12-meter (26-ft by 33-ft x 40-ft) sprinkler spacing. The system's water application efficacy is roughly 70 to 75%, which is more than three times as efficient as the classical surface irrigation systems typically used on small farms in developing countries.

Introduction

Efficient *affordable small-scale irrigation technologies* (ASITs) designed for farmers with land holdings of a hectare (2.5 acres) or less are needed for improving water use efficiency and the incomes of farmers in developing countries. To be most effective, based on the International Development Enterprises (IDE) experience, they should be delivered to resource poor farmers using a business development approach, but at minimum cost with little or no markup for property rights. This allows smallholders to purchase efficient irrigation technologies to irrigate and grow more intensive and high value crops and significantly boost their farming income. At the same time they also increase crop production per unit of both applied water and the water consumed by evaporative demands or losses to salt sinks (or water quality degradation).

Efforts to improve the on-farm performance of traditional surface irrigation of small fields have not succeeded because of the difficulties associated with trying to precision-level them. This has led to the use of pressurized irrigation systems, like drip and sprinkle. But simply downsizing the modern systems used in developed countries has usually resulted in systems that are technically and economically impractical for smallholders. To develop a successful ASIT, we have succeeded by: a) beginning with the fundamental aspects of a system such as drip or sprinkle; and then b) working in an environment similar to that of the smallholders to create a version of it that is practical for and attractive to them.

The need for developing improved water management strategies for small plots in developing countries stems form the fact that: most small holder farmers do not have access to a means for efficiently capturing and applying the available water to their small plots. We will focus on the

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general framework for developing ASITs and discusses the challenges encountered during the evolution of the developments leading to *IDEal Rain*, which is a new low-pressure overhead sprinkle irrigation system that only costs about US $225 for a fixed pipe system serving a 1-acre field. It provides good uniformity when operating at a 10-meter pressure head (15-psi) with sprinklers spaced on an 8- x 12-meter (26- x 40-foot) grid for close spaced crops such as alfalfa, or at a 7-m (10-psi) pressure head with sprinklers spaced on a 8- x 10-m (26- x 33-ft) grid.

Developing Technologies for Small Holder Farmers

In this section we will cover two key points. The first point is related to organization problem solving in general and the second on the general thinking processes involved in developing appropriate technologies for farmers with small land holdings.

Organizational Problem Solving

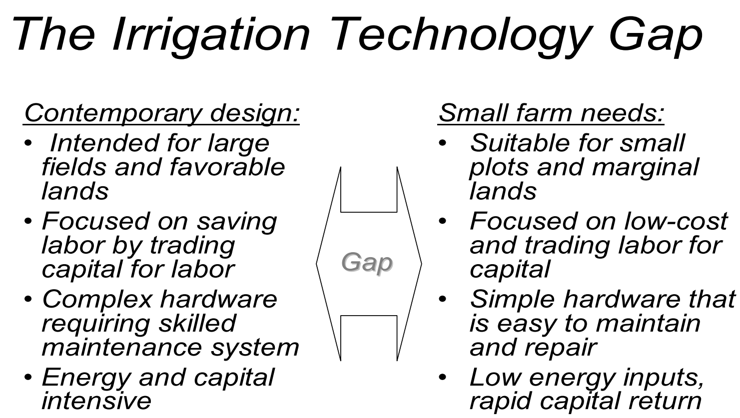
Why is it so difficult to develop appropriate technologies for small holder farmers? The general answer may lie just beneath the surface of a statement like Donald Rumsfeld's "You go to war with the Army you have", which is why the U.S. Military made serious blunders in Iraq that it cannot correct. It illustrates a familiar pattern of organizational problem-solving, that is - organizations usually proceed with whatever their strengths are and try to fit the problem to these strengths, rather than developing new or different strengths to fit the problem as pointed our by Schwartz (2005)[3]. Schwartz's editorial provides some examples of how this sort of organizational *idée fixe* has led to failures in business- and military-history. We also have similar examples of efforts to develop and promote *affordable small-scale irrigation technologies* (ASITs) that have failed as sustainable enterprises for small holder farmers, such as:

- The Netafin: *Family Drip System.* This is a very elegant system, which is a scaled down version of their commercial drip irrigation systems, and it cost US $240/1000 m^2 ex factory (Israel) in 2001. Furthermore, the laterals have in-line emitters that require careful filtration and cannot be cleaned when they become clogged.

- The Premier Irrigation Equipment or Jain Irrigation Systems: *Overhead Sprinkler Systems for Small Fields.* These are hand-move sprinkle irrigation systems that are similar to conventional commercial hand-move systems used through the world. The main system limitations are cost and operating pressures requirements. The 2005 smallholder cost in India was about US $600 for a system designed to serve 1-acre (4,000 m^2) even after receiving a 25% subsidy form the Government ($150/1,000 m^2). The systems need a minimum pressure head of 20 meters (30 psi) at the sprinklers for reasonable application uniformities. This usually requires a higher pressure well pump or a booster pump when converting a shallow well irrigation installation from surface to sprinkle irrigation.

The problem is there is a technology **gap** between contemporary irrigation system design and small farm needs.

[3] "Going to War with the Army You Have". TomDispatch.com, Posted March 5, 2005 at 11:25 am. http://www.tomdispatch.com/index.mhtml.



Challenge of Developing Low-Cost Systems

Developing ASITs requires focusing on affordability, while also improving the functionality and robustness of the equipment. We have found that the development work can best be accomplished in settings that have similar support systems and environmental conditions to where smallholders will use them. Ideally, prototypes should be developed and made at facilities that are typical in rural trade centers, not in highly professional workshops that have elaborate tools. Of course this may not be possible for all system components. But components that require sophisticated facilities to develop and manufacture should be held to a minimum of strategic parts, and normally not be major components of the system in terms of cost, volume or weight.

We believe all creative work requires some kind of meditation. Paraphrasing Pirsig (1974)[4], the first author expresses the meditative process he follows this way: "*When I approach a design and am stuck, I know this stuckness and a blank mind precede inventiveness. I don't try to avoid stuckness because I have found that the harder I try to hold on to it, the faster my mind will naturally freely move toward finding a good design. So I just concentrate on what I want to accomplish - live with it for a while. Study it like I study a line when fishing and before long, I will get a little nibble, a system design idea asking in a timid way if I am interested……*"

Another interesting point that we have learned is that beginning with the current modern equipment configurations designed for a given irrigation method, is usually not a very good starting point for developing an ASIT. It has usually been better to review the entire evolutionary path of the technology. Then select a more opportune place to start, which is usually nearer to its modern beginning than to where the technology has evolved to now. But this does not preclude picking and working with ideas and available materials from anywhere along the technology's evolutionary path. The techniques and strategies used for field-testing during past development stages have also proven to be very useful. We use this strategy and try to take full advantage of ours and colleagues' lifelong experiences and any other historic or new information we can find.

[4] R.M., Pirsig, *Zen and the Art of Motorcycle Maintenance* (New York: Bantam Books, 1974)

Affordable Low-Pressure Sprinkle System Development

We have already developed generic user friendly low-cost drip irrigation systems for small holder farmers and these are being widely promoted and marketed in India and in other developing countries (see Keller and Keller, 2003)[5]. However, drip is not very well suited for irrigation of forage, grain and other closed spaced crops, and the small-scale sprinkle systems promoted in developing countries (as mentioned earlier) are too expensive, cumbersome, and energy consuming for most resource poor farmers with small plots. In view of these limitations, we decided to start anew and design a sprinkle irrigation system that would be affordable and appropriate for millions of these resource poor farmers in Asian, African, and the Americas.

As a result of our efforts to date the *IDEal Rain* sprinkle irrigation system has been developed. This system is suitable for both larger fields as well as for small plots. (The system can even be operated with a manually powered pressure treadle pump.) It is capable of providing water application efficacies in the neighborhood of 75%, which is more than three times as efficient as the classical surface irrigation systems typically used on small farms in developing countries. We began by establishing the following design criteria to reduce cost and improve system functionality:

- Having an operating pressure head of between 7 and 10 meters (10 and 15 pounds per square inch, psi) at the sprinklers.
- Using thin-walled (500-micron or 20 mill) by 25-mm (1-inch) diameter layflat tubing for the sprinkler laterals with only one sprinkler operating on the lateral at a given time.
- Designing the system so that only the sprinklers along with their tripod-risers (not the laterals or long hoses) need to be shifted.
- Reducing the length of lateral tubing required by using a 10- to 12-meter (33- to 40-feet) wide lateral spacing and pulling the laterals back and forth (longitudinally) across the main supply line where convenient.
- Using simple low-cost locally manufactured (in India) system components, including standard impact-sprinkler bodies and developing special nozzles and other modifications to obtain good water distribution uniformity at low operating pressures.
- The cost to smallholders was targeted to be between 2.0 and 2.5 Indian Rupees (US \$0.05 and \$0.06/m^2) for fields of up to 1-hectare (2.5-acres or 10,000 m^2).

Using an intuitive strategy for new nozzle designs along with a breakthrough with a unique new tripod design, we succeeded in meeting our design criteria objectives. We have found from our field tests that this new overhead sprinkle irrigation system configuration performs well even when supplied by a treadle pump and has wide appeal. In the following sections we will describe the development and features of the system components and the complete system.

Sprinkler Selection

Designing viable sprinkle systems for irrigating field or vegetable crops on small farms required selecting or developing sprinklers that when operated at low pressures produce large

[5] Keller, Jack, and A.A. Keller. Affordable Drip Irrigation for Small Farms in Developing Countries. Proceeding of the 2003 Irrigation Association Conference. Paper No. IA 03-0415. pp: 14-25. Nov. 2003.

wetted diameters with uniform water distribution and small drops. To meet our sprinkler spacing and pressure head targets we needed a uniform water applications with small drops over a wetted area with a diameter of 12 to 16 meters when operating at between 7 and 10 meters of head pressure (0.7 to 1.0 Kg per square centimeter or 10 to 15 pounds per square inch, psi).

We tested sprinklers form various manufacturers and were unable to find one that could meet the above objectives. Some sprinklers that produced good application uniformities did not produce a sufficiently large wetted diameter while others produced large diameters, but poor distribution uniformities and large drops. As a result of observations made during these tests, we decided that:

- Impact sprinklers would have the best chance of satisfying the design criteria because they produce the greatest wetted diameter with good water distribution uniformity for a given nozzle configuration. This is because impact sprinklers have a specially designed spring loaded “impact arm” that is driven by the jet from the main nozzle. The impact arm periodically interrupts the jet and strikes the sprinkler body to rotate it. Between strikes the sprinkler’s body is stationary, so the wetted diameter is not shortened by having a tangential velocity component imparted to the jet as it leaves the nozzle.
- Rather than re-design or re-invent such a sprinkler, it would be best to locate a manufacturer of standard impact sprinklers who would work with us as technology specialists through IDE-India in developing a suitable sprinkler/nozzle package combination.
- The ideal sizes of available impact sprinklers for small farms would be a rather typical impact sprinkler with 1/2- or 3/4-inch male pipe thread base and bearing.
- The currently available sprinkler nozzles would need to be modified to produce the desired water break-up (giving small drop sizes) and distribution uniformity while still having a large diameter of throw at low operating pressure heads.

Considerable effort was made to determine what has been done by various sprinkler manufacturers to achieve good performance at low pressure. Several different impact sprinklers and nozzle configurations that are available in India were tested. These included metal and plastic bodied sprinklers with 1/2- or 3/4-inch bearings, but none of them met our design objectives. Essentially all of the sprinklers tested had similar nozzle and sprinkler body designs and either required pressures considerably higher that our targets, or produced wetted diameters of less than 10 meters even when operating at 10 meters of pressure head. But reviewing what others have tired was very helpful as it provided insights and guidance for moving forward.

As a result of our search for a suitable manufacturer in India who had field proven brass impact sprinklers and was willing to work with us and modify their sprinkler and nozzle configurations to meet our design criteria, we found L.M. Industries. This is a small sprinkler head and associated accessories manufacturer located in New Anaj Mandi, Nawana and Lehri is the brand name of their sprinklers. They agreed to work with us and that IDE-India will be the exclusive marketer of the sprinklers with the modified nozzles, and they will be marked under the *IDEal Rain* or *KB Rain*[6] brand names.

[6] Brand name used by IDE-India, the KB is short for “Krishak Bhandu”, which means “farmers friend” in Hindi.

Nozzle Design

The next step was to begin developing and testing nozzles of various designs in the Lehri sprinkler bodies. These included regular tapered round nozzles with special cross-cuts and nozzles with square and triangular shaped outlets. All of the nozzle configurations were machined out of brass bar stock and some configurations required special hand filing to finish shaping them. We used brass instead of plastic because it was the most cost effective and fastest way to proceed. Using plastic would have entailed making temporary molds, which would have been more time consuming and costly during the nozzle development and testing process.

To speed up the nozzle development and testing process we used radial-leg cup tests and operated the trial sprinkler nozzle configurations under low wind conditions. We then used a computer program, CATCH-3D[7], to convert the radial-leg data into grid data. Then the program overlapped the grid data to compute the distribution uniformity for various simulated sprinkler spacing configurations.

We found that the taper leading up to the discharge face of the nozzles was an important aspect that greatly affected sprinkler performance. Through a strategically guided "trial-and-error" process, sprinkler nozzle packages were developed that reached the design goal of: providing a relatively uniform depth of application over a wetted area with a diameter of 12 to 16 meters when operating at between 7 and 10 meters of head pressure (10 to 15 psi). Table 1 shows the catch values from a single 3/4-inch *IDEal Rain* sprinkler with the final nozzle design package. This nozzle package consists of an equilateral triangular (5.3 mm on each side) main driver nozzle and a 4.0 mm spreader nozzle with a "v notch" across its face.

Table 1. Radial-leg Catch Container Test Data of an *IDEal Rain* Sprinkler with a 5.3 mm Equilateral Triangular Main Driver Nozzle and a 4.0 mm v-cut Spreader Nozzle Operating at 10 and 7 meters of Pressure Head with a 10 m/s Wind from the SSW.

Pressure Head	*Radial Leg Position*	*Catch Container Volume - milliliters/hour (To convert to mm/hr multiply catch volumes by 0.45.)*															
		Radial Distance from Sprinkler – meters															
		0.5	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
10 m	West	15	13	13	12	12	13	13	14	15	16	14	14	10	2		
10 m	East	20	18	15	13	12	13	13	12	14	13	13	15	12	10	6	4
7 m	West	20	17	15	14	14	15	15	15	15	17	11	6	3			
7 m	East	22	17	14	14	13	14	14	14	16	15	14	14	8	5	1	

Two sprinklers were also operated as they would be in an actual farmer's field and the catch containers were laid out in a grid (instead of simulating the grid results from radial leg test data). The typical application uniformities with the *IDEal Rain* sprinklers spaced on an 8- x 12-meter (26- x40-foot) spacing with a 10 m/s cross wind and operating at a pressure head of 10 m were: CU = 84% and DU = 80%[8], which is quite good. Typical catch values obtained from these tests

[7] Developed by R.G. Allen and G.P. Merkley in the Biological and Irrigation Engineering Department, Utah State University several years ago and periodically upgraded, see http://www.neng.usu.edu/bie/software/catch3d.php
[8] The CU is the Christiansen's Uniformity Coefficient and DU is the Distribution Uniformity. These are statistical measures of sprinkler application uniformity and performance.

are shown in Table 2. The average sprinkler discharge rate is 1260 lph, liters per hour (5.55 gpm), which gives an effective average gross application rate of: 1260/(8 x 12) = 13.1 mm/hr over the 8- x 12-meter (0.52 in/hr over the 26- x40-foot) area. This is the gross application rate that is used for water management purposes when computing sprinkler set times. However, in the field the operating sprinklers are 12 meters apart (see Figure 1) and there is only a small amount of overlap between them, so the maximum field application rate is about 7 mm/hr (0.3 in/hr).

Table 2. Catch Container Test Data (2m x 2m grid) for the *IDEal Rain* Operating at a Pressure Head of 10 meters and an 8-meter x 12-meter Spacing in a 10 m/s Cross-wind.

Container Catch Values – mm/hour					
11.4	10.9	11.8	17.7	14.5	15.0
11.8	10.0	10.5	14.5	15.9	18.5
14.1	11.4	10.9	11.4	15.5	14.1
11.8	10.5	11.4	15.9	16.4	14.1

When operating at only 7 meters of pressure head (10 psi), the sprinkler spacing needed to be reduced to 8- x 10-meters (26- x33-feet) and the resulting CU = 80% and DU = 70%, which are still respectable values. The discharge is reduced to: $(7/10)^{0.5}$ x 1260 = 1050 lph (4.6 gpm), which also gives an effective average application rate of 13.1 mm/hr (0.52 in/hr).

Since it was not practical to hand fabricate the main nozzle with the triangular orifice, we had injection molds made for it so a sufficient number of plastic nozzles could be produced for the field and market testing phase of development. The spreader nozzles are machine made without any handwork so they are still being made out of brass because this is presently less expensive than having molds made so they can be fabricated out of plastic. We have patents pending on both the triangular main nozzle and the spreader nozzle as well as on the nozzle package.

Conventional 1-acre Sprinkle System in India

Conventional 1-acre systems in India have 75 mm diameter 6-meter long rigid plastic pipe sections. Regular brass impact sprinklers with 3/4-inch bearing are supported on 1-meter long metal "riser" pipes. The risers are fitted to the female end of each pipe section or attached to short (0.25 m long) quick coupling pieces that are inserted between adjacent (or every other) 6-meter long pipe sections. The portable line with the sprinkler along it is called the "lateral".

These conventional sprinkle systems now cost about 30,000 INR, Indian rupees ($750) per acre or 7.5 Indian rupees ($0.19) per square meter and require pump discharge pressure heads of at least 24 meters (36 psi). A typical 1-acre system has 6 sprinklers each discharging 1,600 lph giving a total system discharge of 9600 lph, which is 2.67 lps (42.3 gpm). With the system discharge of 2.67 lps the power required to operate a pump with an electric pumping unit that has an overall (wire-to-water) efficiency of 50% is:

Power = (2.67 x 24)/(102 x 0.5) = 1.26 kilowatts (kW)

The system can be operated with a 2-horsepower pumping unit if the water is available near ground level and the field is close to the water source (such as for pumping out of an adjacent canal). But in many cases the systems are operated with insufficient pressure and the application uniformity is very poor.

IDEal Rain 1-acre System Layout and Components

The best way to reduce system cost is to minimize the weight of plastic required. This can be done in three ways, by using smaller pipe diameters, by using thinner walled pipe, and by using recycled plastic for the mainline. We used all of these tactics to make the sprinkle systems as affordable as possible for use on small fields. Figure 1 shows the *IDEal Rain* irrigation system layout.

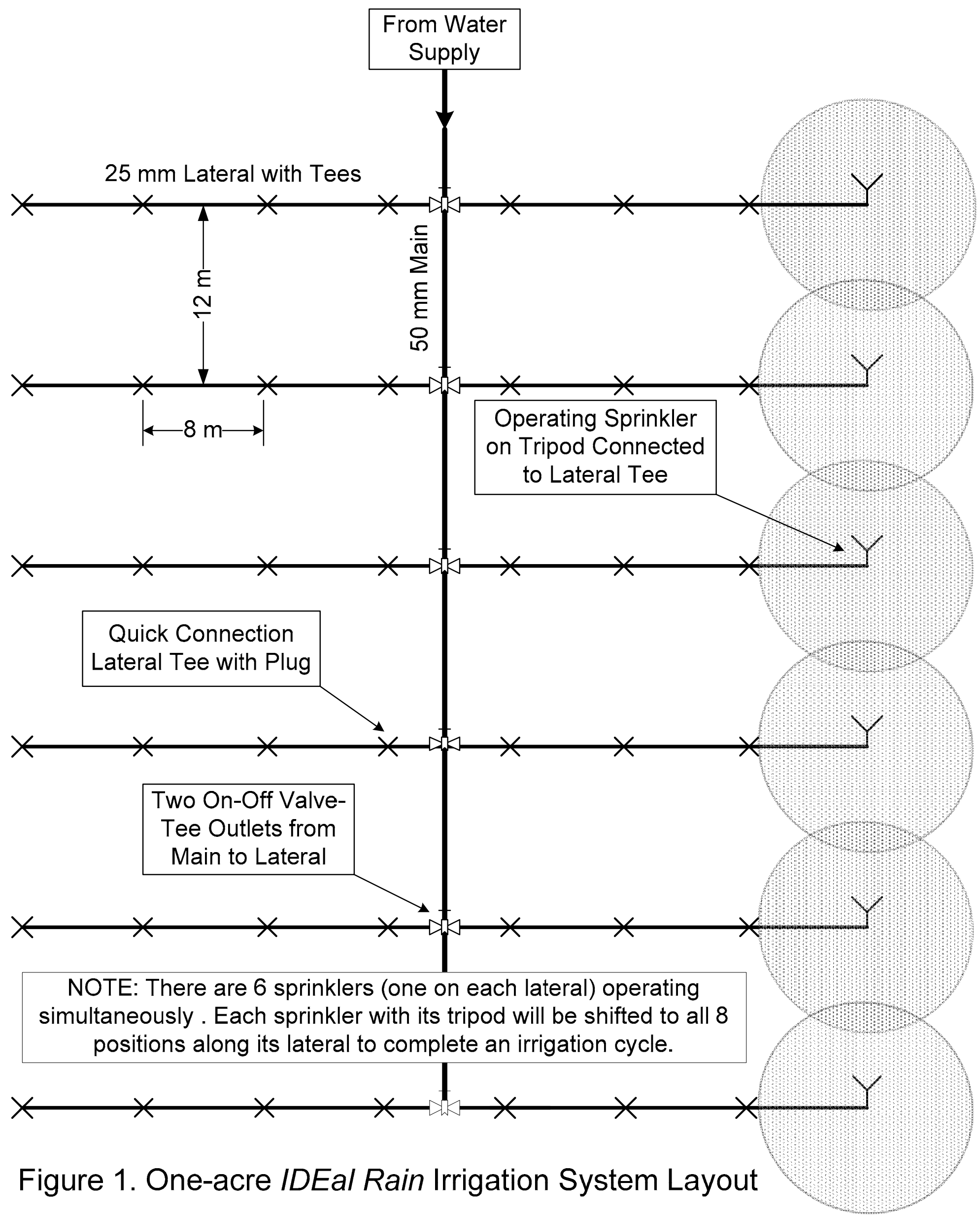


Figure 1. One-acre *IDEal Rain* Irrigation System Layout

Laterals. Rather than having the sprinklers mounted on a 75 mm (3-inch) diameter lateral and periodically moving the lateral, it was decided that it would be more convenient and less expensive to only have one sprinkler operating on each lateral. The sprinklers are then moved sequentially along each lateral (See Figure 1). This requires a lateral for each sprinkler, but the lateral pipe only needs to be 25 mm (1-inch) in diameter and the wall thickness can be as thin as 500 microns (0.5 mm or 20 mils).

For convenience of operation, the ends of each 8-meter (or 4-meter) length of lateral have quick (cam lock) connectors. Each length of lateral also has a Tee at one end (see Figure 1). Quick connection orange (for high visibility) plugs are provided for the Tees when they are not in use (rather than having a valve at each Tee). But an on-off valve is provided for each lateral at its inlet. Figure 2 shows a sprinkler in operation at the end of an 8-meter section of lateral line. There is an orange plug in the Tee at the other end, which can be seen in the foreground.

Figure 2. An 8-meter Section of 25-mm Lateral Line with an Operating Sprinkler Mounted on a Tripod and a Side Outlet Tee with an Orange Plug to Block the Flow Until the Sprinkler is Moved to that Position.

Tripod Sprinkler Stands (patent pending**).** The sprinklers are mounted 1-meter above the ground on sturdy metal tripod riser stands (see Figure 2). The tripods have two movable legs and one fixed leg so they are easy to handle and set up, even on uneven ground. The sprinklers are mounted on short pieces of riser pipe supported by the tripods. A short piece of hose is attached to the lower end of each tripod's riser pipe and a quick connector is provided at the inlet end of the hose so it can be conveniently attached to the Tees along the lateral. Farmers report that it takes less than a minute to move a sprinkler and its stand from one Tee to the next.

Mainlines. 0nly six sprinklers are needed for a 1-acre system (see Figure 1) and the total flow rate based on 1260 lph per sprinkler is: 6 x 1260 = 7,560 lph, which is 2.10 lps (33 gpm). Thus if the area irrigated is near the pump 50 mm (2-inch) diameter tubing with a wall thickness of 1000 microns (1.0 mm) can be used for the mainline. (If the distance to the irrigated area is much greater than 25 meters, it is better to use 63-mm (2.5-inch) tubing for the supply line to the field to reduce the pressure loss due to pipe friction.)

System Operating Pressure Head and Power Requirements

The total dynamic head at the pump discharge needed to operate the 1-acre *IDEal Rain* system with the pipe network shown in Figure 1, which has a 50-mm diameter main and 25-mm lateral pipe, is only 15.0 meters. Following is a breakdown of the system inlet pressure head requirement:

Pipe friction loss between pump and first lateral (25 m)		1.0 m
Pipe friction loss between first and last lateral		0.6 m
Pipe friction loss in lateral with sprinkler operating on end		0.9 m
Miscellaneous friction losses and pump lift		1.5 m
Sprinkler height above ground level		1.0 m
Sprinkler operating pressure head		10.0 m
	TOTAL	15.0 meters

With the system discharge of 2.10 liters per second, the power required to operate a pump with an electric pumping unit that has an overall (wire-to-water) efficiency of 50% is only:

Power = (2.10 x 15)/(102 x 0.5) = 0.62 kW

Thus the system could be operated with a 1-horsepower electric or engine-driven pumping unit if the water is available near ground level and the field is close to the water source (such as for pumping out of a shallow well or an adjacent canal).

System Cost

The cost of the 1-acre *IDEal Rain* system with the pipe network shown in Figure 1 and a 25 meter long 50-mm (2-inch) diameter main and supply line from the pump to the first lateral is 8,888 Indian rupees (~$225). The numbers, sizes and cost of the individual items are presented in Table 3. The area served based on a sprinkler spacing of 8- x 12-meters and 6 laterals to either side of the main supply line with 8 sprinkler positions per pair of laterals is: 8 x 12 x 6 x 8 = 4,608 m^2. Assuming the net (of edge effects) area served is 1-acre, which is 4,000 m^2, the cost per square meter is: 8888/4000 = 2.22 Indian rupees ($0.056).

Table 3. Item Description and Cost Breakdown of the 1-acre *IDEal Rain* Sprinkle Irrigation System Shown in Figure 1.

Item		*Size*	*Quantity*	*Unit Cost*	*Cost*
No.	***Description***			***Indian Rupees***	
1	Supply line tubing	50-mm x 1000 micron	25 m	20/m	500
2	Mainline tubing	50-mm x 1000 micron	60 m	20/m	1200
3	Tee couplers	50-mm x 25 mm	6	50 each	300
4	Valve Tee outlets	25-mm	12	29 each	348
5	Valve connectors	25-mm	12	4.5 each	54
6	Lateral tubing	25-mm x 500 micron	336 m	5/m	1680
7	Cam lock coupler sets	25-mm	48	26 each	1248
8	Lateral Tee outlets	25- x 20- x 25-mm	48	9 each	432
9	Plugs for Tee outlets	20-mm	42	7 each	294
10	Hose connectors	20-mm	6	7 each	42
11	Hose for tripods	20-mm x 0.6 m long	6	25 each	150
12	Metal tripod sprinkler stands	1 m high with 3/4 inch female pipe thread	6	200 each	1200
13	Impact sprinklers	3/4-inch brass bearing	6	240 each	1440
				TOTAL	**8,888**

The cost could be considerably reduced if instead of having enough 25-mm lateral tubing so only the sprinkler with their tripods needed to be moved, only half as much lateral tubing was used and it was shifted from one side of the main to the other side during each irrigation cycle. If this was done the cost of the system would be reduced by: (1680 + 1248 + 432 + 294)/2 = 1,827 Indian rupees. So the total cost would be reduced to: 8888 – 1827 = 7,061, which is 1.77 Indian rupees ($0.044) per m^2.

Field Evaluation of IDEal Rain and Conclusions

IDEal Rain sprinkle irrigation systems provide an important breakthrough in irrigation technologies that are affordable and efficient for use on small farms. Following are some of the unique features and advantages of the *IDEal Rain* irrigation systems that small holder farmers realized during the field tests:

- The systems operated efficiently with the pressure head between 0.5 and 1.0 Kg/cm^2 at the sprinklers, where as the classical sprinkle systems used in India on small farms normally required sprinkler operating pressures of at least 2.0 Kg/cm^2 to obtain similar performance.

- The innovative nozzles designs give good water distribution uniformity and produce reasonably small droplets even at these low operating pressures, which result in an overall irrigation application efficiencies of 70 to 75%.
- Farmers indicated that they used one-third less water and got almost double the yield of forage crops when using the *IDEal Rain* system as compared to classical flood irrigation.
- Because of the low sprinkler operating pressures, the systems only required half as much power to operate compared to classical systems, thus saving energy as well as conserving water. Furthermore, most farmers could operate their *IDEal Rain* system with the same pump they were used for flood irrigation.
- Farmers greatly appreciated not needing to move the pipes as each irrigation cycle progresses, since the only things that needs to be moved are the sprinklers and the tripods that support them. They felt that this resulted in two important advantages:
    - The sprinkler positions could be accurately established when the tubing network was laid out at the beginning of the crop cycle, whereas with classical systems, this laterals must be moved after each sprinkler setting.
    - Moving the sprinklers and their tripods was much easier and quicker than moving the large heavy lateral lines following each sprinkler setting.
- Farmers found the systems to be easy to layout and install, so they were able to use them for supplemental irrigation on more than one field.
- Since the systems utilize thin wall pipe that can be rolled in a coils, farmers were able to easily transport and store the systems, whereas classical systems, typically utilized 6-meter long rigid pipes that were difficult to transport.
- Farmers appreciated being able to space their sprinklers closer together where the discharge pressure from their wells was very low. This is practical because the thin wall tubing comes in rolls and can be cut to the desired length rather than being restricted to having standard (for example, 6-meter) pipe lengths.
- Farmers appreciated having the sprinklers on sturdy tripods that held them in the proper upright position, whereas with classical systems, the risers do not hold the sprinklers firmly upright and they often tip partly or all the way over.
- Farmers greatly appreciated the low cost of a 1-acre system, less than 9,000 Indian rupees or about 2.25 per m^2 (\$225 or \$0.056) as compared to the cost of classical sprinkler systems, which cost about 30,000 Indian rupees or about 7.5 per m^2 (\$750 or \$0.19).
- The systems are modular, so a small initial investment can be made to buy a system with only one sprinkler to irrigate a 600 m^2 plot, and then it can be expanded in the future.
- Because of the low operating pressures, a pressure treadle pump can be used to supply systems with one or two sprinklers to irrigate 0.3- to 0.5-acre plots.
- We have elected to patent the *IDEal Rain* sprinkler nozzles, as well as the unique tripod that support the sprinkler, and allow royalty-free manufacturing to assure that the system remains affordable to small holder farmers and to protect the property rights from exploitation by others.

Center Pivot Simulator for Evaluating System Design and Management Effects on Infiltration and Erosion

B.A. King and D.L. Bjorneberg[1]

Abstract
A 4-wheeled commercial irrigation boom was modified for use in investigating center pivot design and management effects on infiltration, runoff and erosion of specific soil types. The center pivot simulator used a hydraulic winch attached to the front of a tractor for mobilization and controlled travel speed. A 3 inch diameter 300 ft drag hose is used to supply water to the center pivot simulator. The center pivot simulator was used to conduct two studies to investigate infiltration, runoff and erosion differences of common commercially available center pivot sprinkler types on a Portneuf silt loam soil. Sprinklers used in the first study were: 1) Nelson R3000 with brown plate, 2) Nelson R3000 with red plate, 3) Nelson S3000 with purple plate, and 4) Senninger I-Wob with standard 9-groove plate. Measured runoff was highly variable despite the controlled experimental conditions. Runoff from all sprinkler types increased with number of irrigations indicating that soil surface sealing continued to increase without reaching a maximum after five irrigations. Measured runoff tended to be the highest for the S3000 and I-Wob sprinklers. Sediment loss tended to be highest for these sprinklers as well. The second study investigated differences in runoff and erosion related to kinetic energy of sprinkler droplets from commercial center pivot sprinklers. The sprinklers used in the study were: 1) Senninger I-Wob with standard 9-groove plate, 2) Nelson R3000 with brown plate, 3)Nelson D3000 spray with flat plate and 4) sprinkler 3 with the runoff plot covered with 20-mesh nylon window screen suspended about 1 inch above the soil surface to eliminate sprinkler droplet impact on the bare soil surface. Covering the plot with screen to eliminate sprinkler droplet impact resulted in significantly ($p \leq 0.05$) less runoff and sediment loss for all four irrigation events. The D3000 and I-Wob sprinklers tended to have the greatest runoff and sediment losses. Sprinkler type and configuration had a significant ($p \leq 0.05$) effect on runoff and erosion of a Portneuf silt loam soil.

Introduction
Center pivot irrigation is currently used on approximately 5.2 million acres in the ten western states of the U.S. Center pivot irrigation is a popular choice for many producers due to its large area of coverage, ease of use and degree of automation. The USDA NRCS Environmental Quality Incentives Program (EQIP) commonly cost shares new center pivot irrigations systems used to replace less efficient surface irrigations system as a means to increase irrigation efficiency and reduce ground and surface water degradation. Center pivot irrigated acreage will likely continue to increase in the near future.

Center pivot irrigation is popular with producers but is not necessarily the best irrigation system choice for all conditions. Water application rates often exceed soil infiltration rates for medium- and fine-textured soils, which can result in substantial runoff, erosion and spatial non-uniformity in water application depth on rolling topography. Over the past two decades center pivot sprinkler manufacturers have, and presently, continue to develop sprinklers that reduce peak water application rates and droplet kinetic energy as a means to sustain infiltration rate and reduce runoff hazard. As a result there are numerous center pivot sprinkler choices available for the producer but little quantitative information that relates these choices to performance on a particular soil type.

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Mention of trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the authors or the USDA and does not imply approval of product to the exclusion of others that may be suitable.

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

Runoff under center pivot irrigation systems tends to be quite variable due to spatial variability in soil texture, roughness and slope (Kincaid, 2002). The effect of small differences in the operating characteristics of commercially available sprinklers on infiltration, runoff and erosion is likely to be small as well. Thus to experimentally evaluate any effect under field conditions, uncontrollable extraneous factors due to spatial variability must be minimized. One approach to accomplish this is to have evaluation measurements collected in close proximity to each other in order to minimize slope and soil physical and chemical property differences. This is virtually impossible with field scale center pivot systems due to their large size and overlapping of sprinkler patterns needed to achieve high water application uniformity. The objective of this study was to overcome this limitation by developing a center pivot simulator that will allow experimental treatments on small replicated field plots for evaluation of center pivot design and management effects on infiltration, runoff, and erosion for specific soil types.

Methods and Materials

A 4-wheel commercial irrigation boom 154 ft in length (Briggs Irrigation, Northhamptonshire, UK) was used as the basis for the center pivot simulator. The irrigation boom was modified by increasing the boom height 18 inches and adding additional sprinkler outlets along the boom length. Two additional sprinkler outlets were added between each existing outlet to provide a 48 to 51 inch spacing between adjacent outlets. The commercial irrigation boom uses a hose reel to mobilize the system and supply water to the mobile boom. However, we used a cable winch system to mobilize the irrigation boom and a 3 inch, 300 ft drag hose to supply water to the irrigation boom. The cable winch system consisted of a hydraulic winch (Series 15, Warn Industries, Inc., Clackamas, OR) mounted on the front of a John Deere 1020 tractor. The tractor hydraulic system was used to power the hydraulic winch.

Travel speed of the irrigation boom (towing cable speed) was controlled using a closed-loop electronic control system. Hydraulic fluid flow rate to the winch hydraulic motor was controlled by a electro-hydraulic proportional flow regulator (PFR72-33BM-L160-12T-N-12DL, Hydraforce, Inc., Lincolnshire, IL). The proportional flow regulator controlled hydraulic fluid flow rate proportional to input current to a 12 VDC solenoid supplied by a proportional valve controller (4000046, Hydraforce, Inc., Lincolnshire, IL). The valve controller used a 0-5 VDC input to control output 12 VDC current to the solenoid. A programmable data logger (CR21X, Campbell Scientific Inc., Logan, UT) was used to supply the 0-5 VDC control input. Irrigation boom travel speed was determined by passing the towing cable over a 3 inch diameter rubber roller 16 inches wide mounted on a four-legged metal stand placed about 8 ft in front of the hydraulic winch. An incremental hollow shaft encoder (MEH30-1000P-F1-P-38, CUI, Inc., Beaverton OR), with 1000 pulses per shaft revolution, attached to one end of the rubber roller shaft was used to measure irrigation boom travel speed. A proportional-integral closed-loop control algorithm programmed into the data logger was used to control cable speed to a set value. The control algorithm measured cable speed and updated the 0-5 VDC output to the valve controller once every second to maintain a set travel speed.

The effect of water application and management decisions on runoff and erosion were measured using 3.3 feet (1 m) wide by 6.6 feet (2 m) long plot areas. A metal frame border was used to collect runoff and prevent plot runon from the surrounding area. The metal frame was made of 3/16-inch thick steel 3-inches in width orientated vertically on three sides. The bottom edge of the metal frame was driven into the ground to a depth of about 1.5 inches to channel the runoff and prevent runon. The down slope outlet end of the frame had a horizontal metal lip along its length about 2.5 inches in width for runoff to leave the frame without excessive erosion due to head cutting. Along the down slope length of the metal lip was a metal trough sloped to one edge of the metal frame to collect runoff and channel it to a collection bucket in a hole dug near the corner of the metal frame. The depth of water in the bucket was measured with a ruler to determine runoff volume. The bucket was covered to prevent water from sprinklers contributing to runoff water volume. The combined horizontal width of the lip and trough was about 3.25 inches. Water application to the lip and trough adds to the total runoff volume and was accounted for when calculating plot runoff volume. Average soil moisture in the top 8 inches of the soil profile in each runoff plot was measured using time domain reflectometry (TDR100, Campbell Scientific, Inc., Logan UT) prior to each irrigation event.

The center pivot simulator was used to investigate runoff and erosion of a Portneuf silt loam soil from common commercial sprinkler types found in Idaho. Sixteen runoff plots were installed in a four row by four column arrangement as shown in figure 1. The field area slope ranged from 4 to 6%. The field was roller harrowed prior to establishment of the runoff plots. The metal plot frames were installed at a constant slope of 5%. The soil surface within the metal frames was graded to a 5% slope and smoothed. The rather steep slope and smoothed soil surface of the plots was selected to minimize the unknown and variable surface storage component of the infiltration-runoff-erosion process. Four common commercial sprinklers were used in this first study to investigate infiltration, runoff and erosion differences, if any. They were: 1) Nelson R3000 with brown plate (Nelson Irrigation Corp., Walla Walla, WA) with a 20 psi regulator, 2) Nelson R3000 with red plate with a 20 psi regulator, 3) Nelson S3000 with purple plate with a 15 psi regulator, and 4) Senninger I-Wob with standard 9-groove plate (Senninger Irrigation Inc., Clermont, FL) with 15 psi regulator. Sprinkler nozzle sizes were selected to be representative of those used on the outer end of ¼-mile center pivot systems in Idaho. The sprinkler nozzle sizes were also selected to provide approximately the same flow rate per sprinkler regardless of operating pressure or manufacturer. The selected sprinkler nozzle sizes and corresponding flow rates were; 1) 0.297 inch (#38) rated at 11.28 gpm, 2) 0.297 inch (#38) rated at 11.28 gpm 3) 0.320 inch (#41) rated at 11.48 gpm, and 4) 0.328 inches (#21) rated at 11.36 gpm, respectively. Sprinkler height was approximately 5 feet above ground level. Sprinkler spacing along the boom was 96 to 102 inches. Five consecutive irrigations were applied to the runoff plots with an irrigation interval of 7 to 15 days to allow the soil surface to dry and soil profile to drain between irrigations. All irrigation applications were to bare soil conditions. Only half the length of the irrigation boom was used to apply water to the runoff plots.

The four sprinkler configurations (treatments) were randomly assigned to the sixteen plots with one treatment per row and column in order to obtain a Latin Square statistical design. Twelve of the sixteen plots were covered with waterproof polyethylene tarps when the center pivot simulator passed over the plot area with a particular sprinkler treatment. Then the center pivot simulator sprinklers were changed, the tarps repositioned and the simulator repositioned and towed upslope over the plot area again to apply a different sprinkler treatment. Two irrigation treatments were completed in a given day with the remaining two the following day. All the tarps were installed and removed at the same time to minimize differences in soil drying between irrigation events. There were four washouts at the lower end of the metal frames underneath the overflow lip that prevented accurate measurement of runoff during two irrigation events. A tractor problem prevented accurate runoff data collection for the R3000 sprinkler with the red plate on the fourth irrigation event. For irrigations events where loss of runoff data occurred, the results were analyzed using a Randomized Block experimental design with uneven sample sizes.

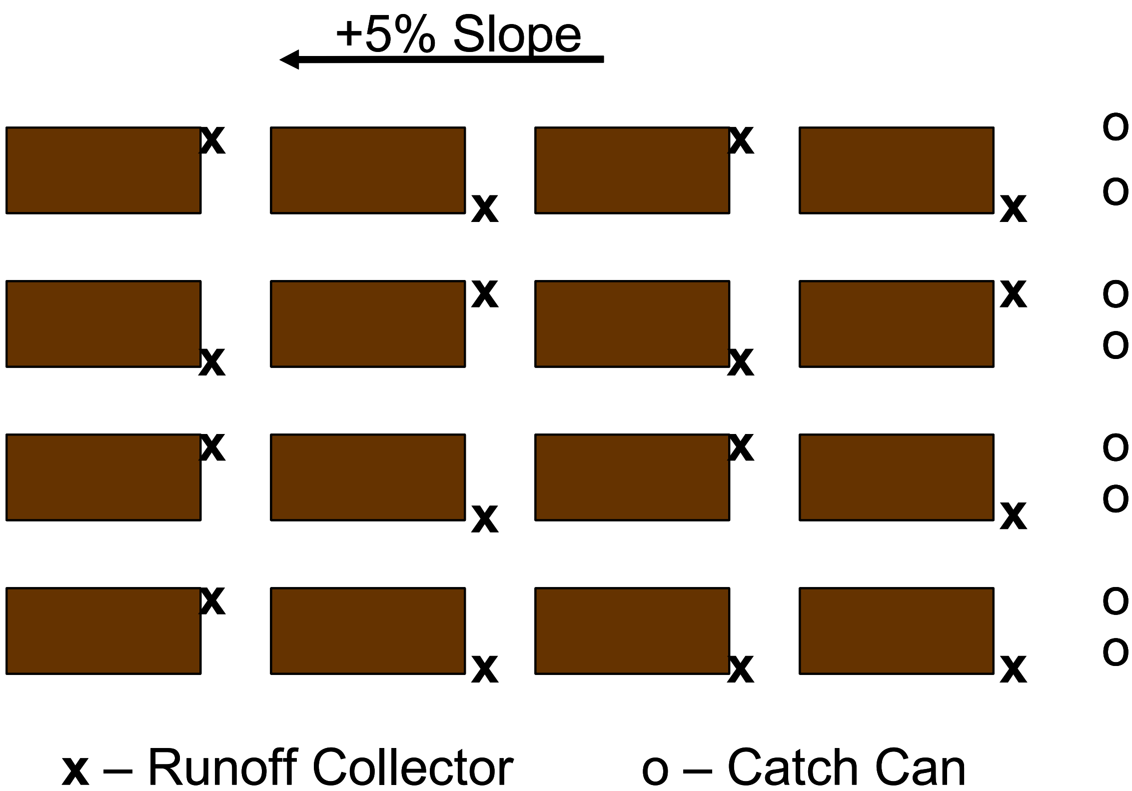

Figure 1. Runoff plot layout used in both field studies.

Statistical analysis was conducted using the SAS GLM procedure and Duncan's Multiple Range test for comparison of treatment means (SAS, 2007). Sediment mass in runoff was measured using vacuum filtration and filter paper.

The center pivot simulator was also used to investigate the effect droplet kinetic energy from common commercial center pivot sprinkler types has on infiltration, runoff and erosion of a Porrneuf silt loam soil. The same sixteen runoff plots used in the first study were used in the second study. The soil within the metal frames was tilled with a garden-type rear-tined rototiller and the soil surface graded to a 5% slope and smoothed. The sprinklers selected to provide a range in sprinkler droplet kinetic energy were; 1) Senninger I-Wob with standard 9-groove plate (Senninger Irrigation Inc., Clermont, FL) with a 15 psi regulator, 2) Nelson R3000 with brown plate (Nelson Irrigation Corp., Walla Walla, WA) and a 20 psi regulator, Nelson D3000 spray with flat plate with a 15 psi regulator, and 4) sprinkler 3 with the runoff plot covered using 2 layers of 20-mesh nylon window screen to eliminate sprinkler droplet impact on the bare soil surface. The 20-mesh screen had openings about 0.05-inch square and was suspended about one inch above the soil surface on a coarse grid of ¼-inch diameter wire paneling. Droplet kinetic energy was dissipated on the nylon screen above the plot surface. Sprinkler nozzle sizes were selected to provide approximately equal flow rate per sprinkler regardless of sprinkler type or manufacturer. The selected sprinkler nozzle sizes were; 1) 0.328 inch (#21) rated at 11.36 gpm, 2) 0.297 inch (#38) rated at 11.38 gpm, 3) 0.320 inch (#41) rated at 11.48 gpm and 4) 0.320 inch (#41) rated at 11.48 gpm, respectively. Sprinkler height was approximately 5 feet above ground level. Sprinkler spacing along the irrigation boom was 96 to 102 inches. Four consecutive irrigations were applied to the runoff plots with an irrigation interval of 7 to 10 days to allow the soil surface to dry and soil profile to drain between irrigations. All irrigations were to bare soil conditions. Only half of the boom length was used to apply water to the runoff plots. Irrigation events were completed in a single day.

The four sprinkler configurations (treatments) were randomly assigned to the sixteen plots with one treatment per row and column in order to obtain a Latin Square statistical design. Statistical analysis was conducted using SAS GLM procedure and Duncan's Multiple range test for means comparison (SAS, 2007). During the first irrigation event ponding on the layers of the nylon screen was observed which caused some uneven water application over the plot area. One layer of the nylon screen was removed for subsequent irrigation events, which alleviated ponding on the screen cover.

Results

Percent runoff (runoff volume / application volume x 100) for each sprinkler type and irrigation event in the first study are shown in figure 2. Application depths for the five irrigation events were 0.96, 0.8, 0.6, 0.6, and 0.6 inches, respectively. Soil moisture in the top 8 inches of the soil profile measured prior to each irrigation event averaged 0.15, 0.15 0.14, 0.15, and 0.13 inches/inch for the five irrigation events, respectively. Runoff measurements were highly variable despite the controlled experimental conditions and small distances between plots, limiting detection of significant differences in runoff among sprinkler types. In general, percent runoff increased with the number of irrigations. This result is attributed to reduced infiltration rates caused by soil surface sealing due to sprinkler droplet impact on the bare soil

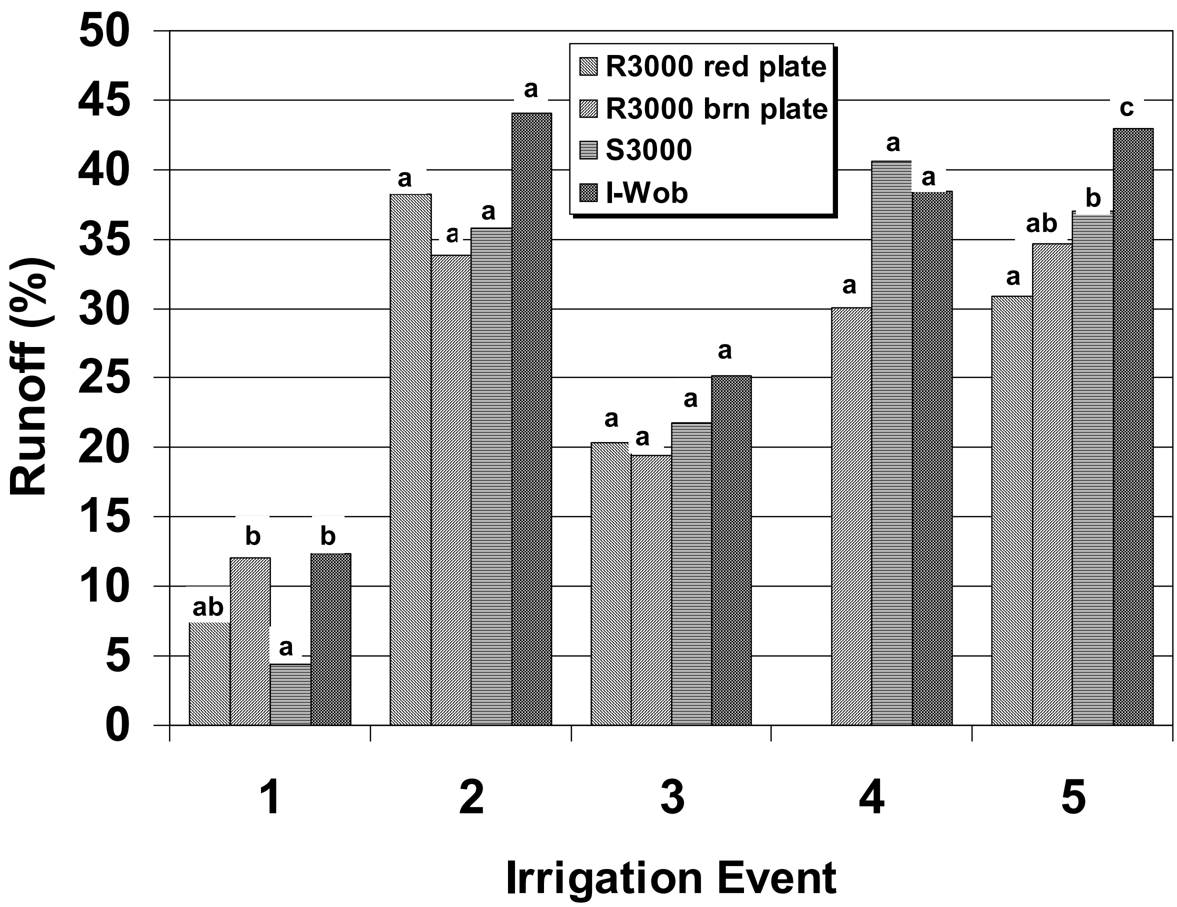

Figure 2. Percent runoff measured for the five irrigation events in the first field study. Columns with the same letter are not significantly different at the 0.05 level.

surface and consistent with the findings of Thompson and James (1985), DeBoer et al., (1988), Agassi et al., (1994) and Lersch and Kincaid (2000). Percent runoff continued to increase for irrigations three through five indicating that soil surface sealing increased with continued irrigation without reaching a maximum. By the fifth irrigation event a trend in runoff percentage differences between sprinkler types began to appear but additional testing is required to verify this result.

Sediment losses for each sprinkler type and irrigation event in the first study are shown in figure 3. In general, sediment loss was positively correlated with runoff volume. Since measured runoff was highly variable, so was measured sediment loss. However, for irrigation events three through five a trend starts to emerge where the I-Wob produced the highest sediment loss of the four sprinkler types even though runoff was not necessarily the highest. The S3000 sprinkler produced the next highest sediment loss. These two sprinkler types appear visually to spread the sprinkler droplets out more evenly over the wetted diameter with respect to time than the R3000 sprinkler. This functional difference may cause sediment to remain in suspension in overland flow for a longer duration allowing it to be more readily transported down slope. Average sediment concentration in the measured runoff for each sprinkler type is shown in figure 4. For irrigation events two through five, sediment concentration tended to be lowest for the R3000 sprinklers and was significantly ($p \leq 0.05$) less for irrigation events three and four. The very high

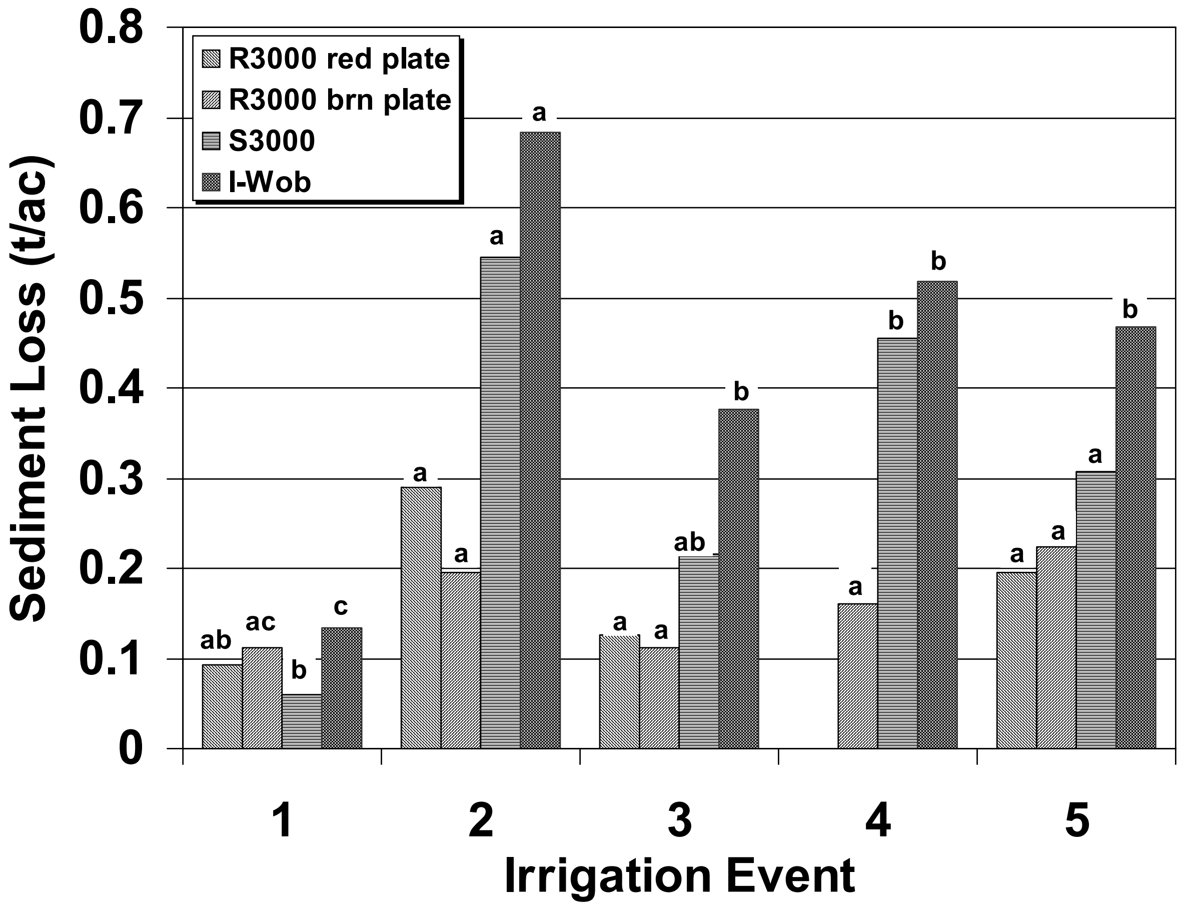

Figure 3. Sediment loss measured for the five irrigation events in the first field study. Columns with the same letter are not significantly different at the 0.05 level.

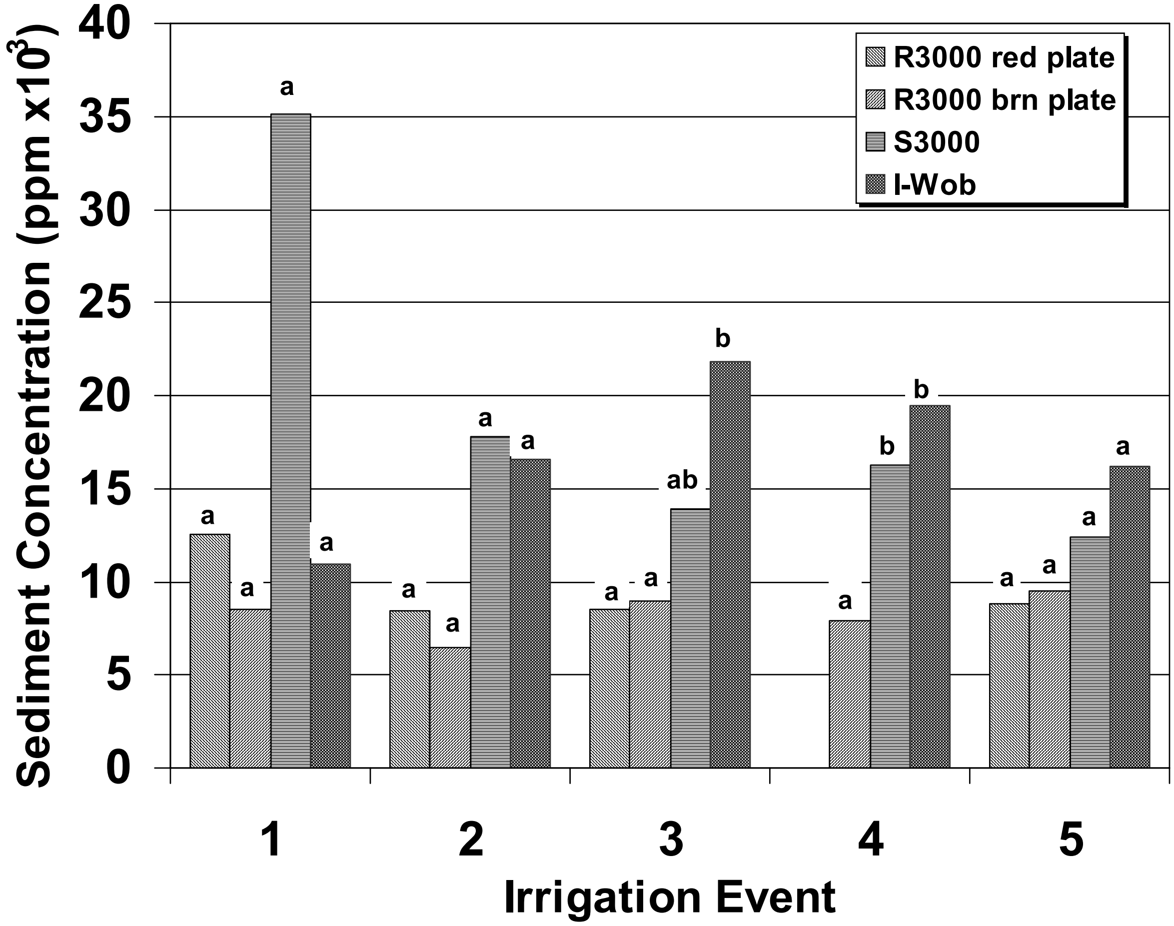

Figure 4. Sediment concentration measured for the five irrigation events in the first field study. Columns with the same letter are not significantly different at the 0.05 level.

sediment concentration for the S3000 sprinkler for irrigation event one is the result of a single runoff measurement with an extremely high sediment concentration (0.19 pounds) associated with a very small runoff volume (0.1 gallon). Another possible explanation for the differences in sediment concentrations in the measured runoff is a difference in breakdown rate of soil surface aggregate structure releasing fine grain material at different rates between sprinkler functional types.

Percent runoff for each sprinkler type and irrigation event in the second study is shown in figure 5. Application depths for the four irrigation events were 0.96, 0.6, 0.6, and 0.6 inches, respectively. Soil moisture in the top 8 inches of the soil profile measured prior to each irrigation event averaged 0.12, 0.13, 0.14, and 0.15 inches/inch for the four irrigation events, respectively. The measured runoff was again quite variable. However, for irrigation events one, three and four the I-Wob and D3000 spray sprinklers produced the highest runoff volumes. The peak application rate of the D3000 spray was about 50% higher than the I-Wob or R3000 sprinklers due to its smaller wetted diameter. The higher peak application rate of the D3000 spray is largely responsible for the high measured runoff despite the lower kinetic energy of the droplets due to there smaller size. For irrigation events one, two, and three, measured runoff for the R3000 sprinkler was not significantly different than that of the covered plot with

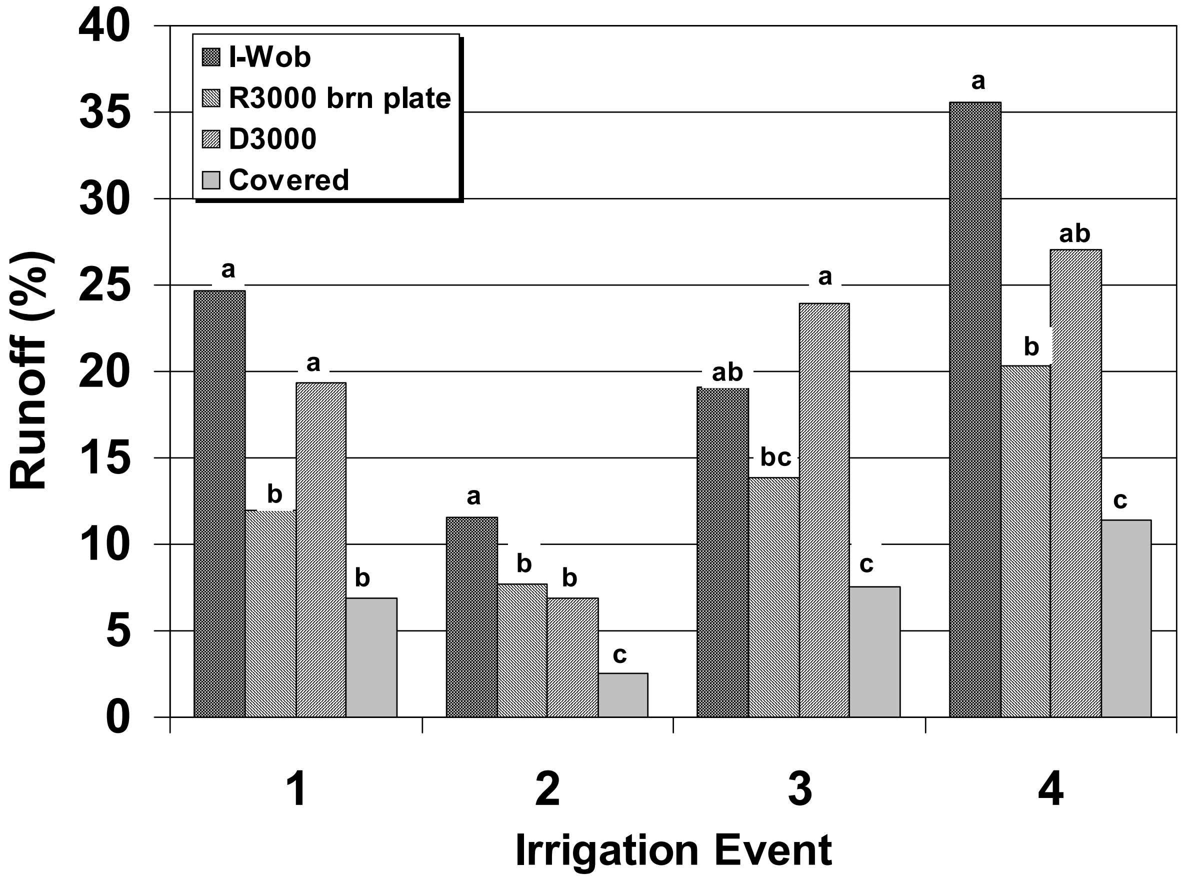

Figure 5. Percent runoff measured for the four irrigation events in the second field study. Columns with the same letter are not significantly different at the 0.05 level.

the D3000 spray sprinkler. Percent runoff continued to increase for irrigations two through four indicating that soil surface sealing increased with continued irrigation regardless of kinetic energy level.

Sediment losses for each sprinkler type and irrigation event in the second study are shown in figure 6. In general, sediment loss is positively correlated with runoff volume. The I-Wob and D3000 sprinklers produced the highest sediment losses. This is consistent with the results of the first study were sprinkler types that visually appear to more uniformly distribute sprinkler droplets over the wetted area with respect to time produce the highest sediment losses. For the first two irrigation events the R3000 and covered plot treatment had significantly ($p \leq 0.05$) less sediment loss than the I-Wob sprinkler. For irrigation events two through four, all the sprinklers resulted in significantly higher sediment loss compared to the covered soil surface.

Summary and Conclusions

A 4-wheeled commercial irrigation boom was modified and used to simulate center pivot irrigation to small replicated runoff plots. The center pivot simulator uses a hydraulic winch attached to the front of a tractor for mobilization and as a means to provide controlled travel speed. A 3 inch diameter 300 ft drag

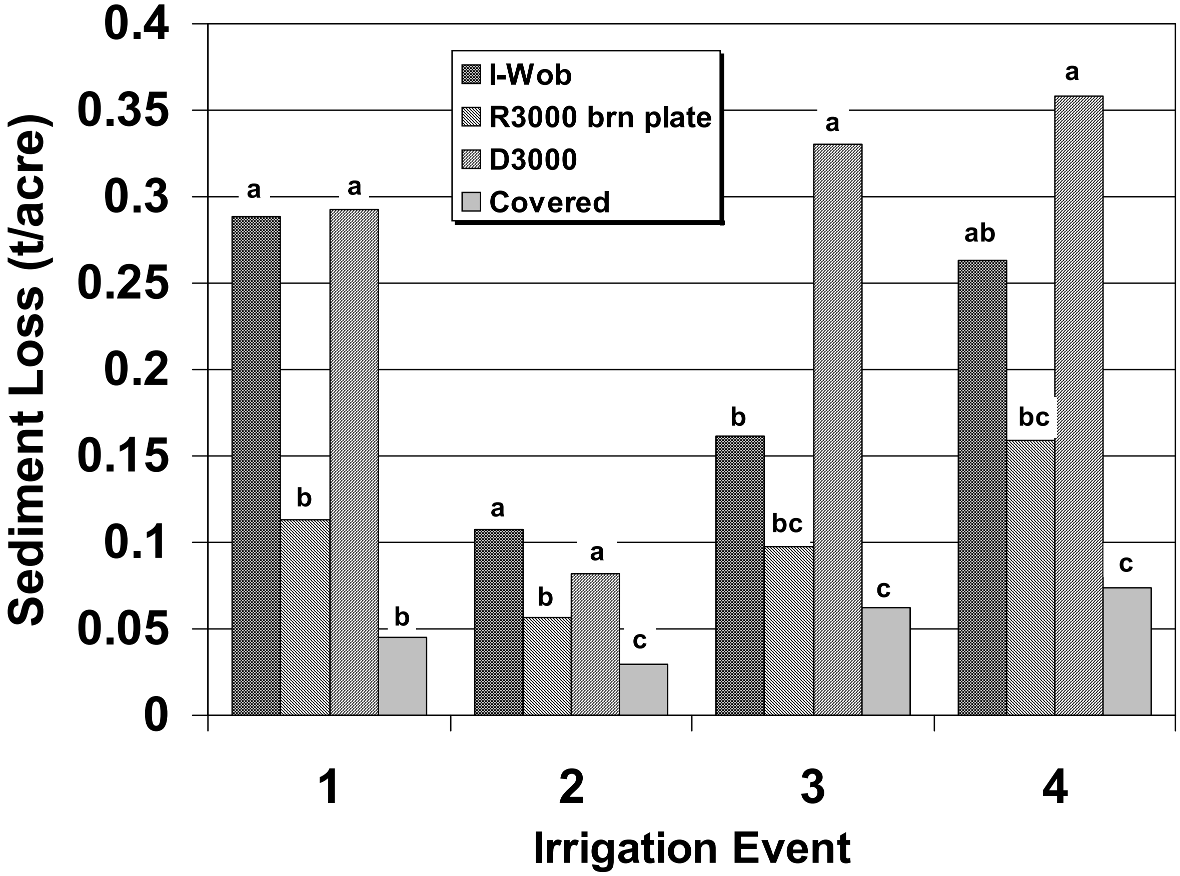

Figure 6. Sediment loss measured for the four irrigation events in the second field study. Columns with the same letter are not significantly different at the 0.05 level.

hose is used to supply water to the center pivot simulator. The center pivot simulator was used to conduct two studies to investigate infiltration, runoff and erosion differences of common commercially available center pivot sprinkler types on a Portneuf silt loam soil.

The results of the two runoff studies on a Portneuf silt loam soil indicate that center pivot sprinkler types that visually appear to more uniformly distribute droplets over the wetted area with respect to time tend to produce more runoff and sediment loss. This may be due to detached soil particles remaining suspended in overland flow for longer periods of time resulting in greater transport down slope and/or faster breakdown of soil aggregate structure releasing fine grained soil particles sooner. The results also show that sprinkler type and configuration has a significant effect on runoff and sediment losses for a Portneuf silt loam soil. Runoff experiments need to be conducted on additional soils and varying water application depths to validate these results.

Acknowledgement
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IRT WIRELESS INTERFACE FOR AUTOMATIC IRRIGATION SCHEDULING OF A CENTER PIVOT SYSTEM

S. A. O'SHAUGHNESSY[1] AND S. R. EVETT[2]

ABSTRACT

Infrared thermometers (IRTs) have been widely used in agricultural research as a method to measure canopy temperatures, an indicator of crop water stress. Although IRTs have proven to be reliable within the critical range for plant stress, they would be cumbersome for the grower to set up, maintain, and dismantle each irrigation season in a commercial system. A wireless sensor network of IRTs integrated into a center pivot lateral can facilitate the implementation of a fully automated irrigation system with sensors that can easily be mounted and dismounted from the system lateral line. The objectives of this study were to build an economical wireless interface for IRTs using radio frequency (RF) mesh networking modules and to investigate the network characteristics in a field application comparing mesh networking and simpler point-to-point networking. Our main hypothesis was that the mesh networking system was best suited for installation on the pivot lateral and its self-healing capabilities would overcome the majority of interference issues associated with the pivot's metal trusses, pipeline, and towers. The mesh networking architecture was expected to outperform the non-mesh network.

Relatively inexpensive integrated silicon circuit components were utilized to construct the sensor interface module; the approximate cost was $150, which included the signal conditioning electronic circuit that interfaced the IRT with the microprocessor and the RF module, the battery, and the solar panel. As part of the network testing, the received signal strength index (RSSI) for two different antenna types was tested at two different heights above grade under the pivot and at thirteen different distances from the pivot point. The RSSI using a whip antenna was superior to that of a dipole antenna.

Wireless sensor networks were deployed in the field (Field-WSN) and along the pivot lateral (Pivot-WSN) in point-to-point topologies using both non-mesh and mesh firmware, respectively. The Field-WSN outperformed the Pivot-WSN. Data packet retrieval was more than 90% successful for 93% of the growing season using the non-mesh networking firmware for the WSN

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established in the field crop. The Pivot-WSN data packet retrieval was more than 90% successful for 70% of the time using mesh-networking firmware, but data packet retrieval dropped significantly to < 80% success for 100% of the time when the firmware was changed to a non-mesh networking protocol during a trial period after the growing season. These results indicate the potential role of mesh networking and wireless sensors in agricultural field settings.

KEYWORDS. Automated irrigation, crop water stress, infrared thermometry, wireless sensors

INTRODUCTION

Earlier research showed that the timing of drip irrigation applications could be triggered by a signal that is positive if the crop canopy temperature is greater than a threshold temperature for greater than a region-specific threshold time (Evett et al., 1996, 2000). Crop stress can be detected non-invasively by using infrared thermometers (IRTs) to measure canopy temperature (Wanjura et al., 2003). The Time Temperature Threshold (TTT) method has been successful in automatically scheduling irrigations based on the needs of well-watered corn and soybean crops (Evett et al., 2006; Peters and Evett, 2006a,b).

Commercialization of a fully automated center pivot system using the TTT method will require the elimination of sensor wiring to reduce costs and complexity, and to improve system robustness while avoiding conflicts with farming operations. Challenges inherent in any wireless system include adequate bandwidth, efficient routing protocols, power usage, electromagnetic interference, radio range, and battery life (Zhang et al., 2004). A wireless network for industrial applications based on the IEEE802.11 standard was investigated by Ferrari et al. (2006). The network architecture investigated was a master-slave configuration that demonstrated connectivity between a personal computer and three remote sensors. The network demonstrated a received signal strength indication (RSSI) of 80% and an indoor range of 60 m with no obstructions; however, the power consumption for their protocol sensor module was relatively high at 350 mW.

The XBee and XBee-Pro modules (MaxStream®, Orem, Utah)[2] are off-the-shelf, low cost, low power (~100 mW) modules that use the IEEE802.15.4 standard for wireless communication. These modules transmit in the 2.4 GHz range and take advantage of direct sequence spread spectrum channel selection where the bandwidth per channel is 2 MHz and the channel spacing is 5 MHz. Recently, two new versions of firmware for the XBee-Pro modules became available and enabled the use of the I/O ports and mesh networking capabilities. The objectives of this study were to build an economical wireless interface for IRTs and test the network behavior of the radio frequency (RF) modules in a field application for automated center pivot irrigation.

MATERIALS AND METHODS

A prototype signal conditioner module (Fig. 1), using through-hole integrated silicon circuit chips (ICs) and electronic components, was designed to condition the small analog voltage (μV)

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

from an infrared thermometer (model IRt/c.5, Exergen, Inc., Watertown, Mass.) to a digital output of 10 mV ºC^{-1}. Other main components in the circuit included a cold conjunction compensation IC (Analog Devices, Mass.) specific to type ‘T’ thermocouples, operational amplifiers to provide isolation and buffering, a precision centigrade thermometer to measure sensor body temperature, and analog to digital converter (ADC) ICs. Use of an 8-bit microprocessor (Parallax, Inc., Rocklin, Calif.) enabled collection of several data outputs and control of the power mode (“sleeping”) of the RF module for each wireless sensor.

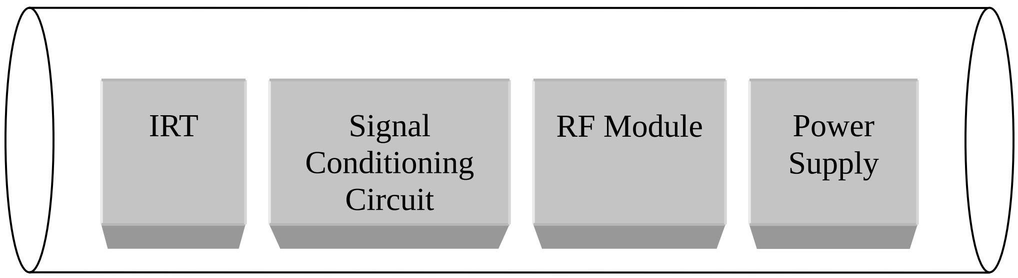


Figure 1. Prototype sensor module shown (within outline of plastic housing) was comprised of the infrared thermometer; signal conditioner module; RF module consisting of the XBee platform and a UART device; and power supply consisting of a battery, recharge circuit and external solar panel.

The digital output from the signal conditioning circuit was interfaced with the XBee RF modules, XBee/XBee-Pro Zigbee. Data from the microprocessor were fed to the RF module through an octal buffer that provided logic levels compatible with the XBee modules. The criteria for the RF module were low power consumption and possession of a practical transmission range, e.g., a minimum of 300 m, or 100 m with mesh networking capabilities. Meeting the criteria was critical to providing reliable transmission from the furthest remote module (at the end of the pivot lateral) to an embedded computer located near the control panel of the center pivot point.

The calibration of the wireless IRTs was completed using a black body calibrator (BB701, Omega Engineering, Stamford, Conn.) as the target temperature. The temperature of the IRT was held constant while the black body was varied from 0ºC to 45ºC. The temperature of the sensor body was incorporated into the calibration equation to adjust for drift. A datalogger (model 21-X, Campbell Scientific, Logan, Utah) was used to record the temperature of the blackbody and ambient room temperature. Sensor body temperature measurements were made using input from an LM35 digital temperature IC mounted to the body of the IRT. The circuit board and IRT were then placed into three controlled environments to obtain paired data sets. Calibrations were performed using wireless communications between the sensor module and a personal computer. Table 1 lists the outputs of the sensor module during the calibration process and to the base station (during field deployment) when polled by the base computer.

Similar to Kalma et al. (1988) and Bugbee et al. (1999), a calibration equation (Eq. 1) was developed for the IRTs using methods that included the IRT sensor body temperature, T_b (ºC). The difference between the IRT sensor temperature reading, T_s (ºC), and T_b was converted to thermoelectric voltage, E_d (mV) using

$$E_d = \sum_{i=0}^{3} c_i \left(T_s - T_b\right)^i \qquad \text{(Eq. 1)}$$

where the c_i are the coefficients for type-T thermocouples for the subrange, 0.000˚C to 400.00˚C (NIST, ITS-90 Thermocouple Database, 1995). A linear relationship was found between E_d and the energy radiated by the target, $\sigma(T_t + 273.16)^4$ (W m^{-2} K^{-4})

$$\sigma(T_t + 273.16)^4 = E_d m + b \qquad \text{(Eq. 2)}$$

where T_t is target temperature (˚C), the Stefan-Boltzmann constant σ = 5.67E-8 W m^{-2} K^{-4}, and m is the slope and b the intercept of the relation. IRT readings were taken at three sensor body temperatures (T_b = 44˚C, 23˚C, and 10˚C) and a range of target temperatures (0 to 45ºC).

Table 1. Wireless Sensor Module Output

Source	Purpose	Units
Infrared thermocouple	Measure crop canopy temperature	mV
Precision IC thermometer	Measure sensor body temperature	mV
Voltage divider	Monitor power supply	mV
RF address	Identify data source	ASCII

The XBee modules were evaluated for their range and consistency in transmission using a prototype white, rigid polyvinyl chloride (PVC) plastic enclosure for the signal conditioner circuitry and RF module. Testing included the use of the two types of modules (the X-Bee and the X-Bee Pro), four different power levels (programmable) and three different types of antenna designs [chip, wire and dipole] (Table 2). The sensor modules were positioned at two different heights under the pivot lateral, 0.6 m and 1.8 m, to simulate the range of required height above crop canopy over the growing season; the base modem (containing the XBee-Pro module) and the remote sensor modules were kept in line-of-sight of one another during the testing.

Table 2. Variables Used in the Antenna Evaluation

Antenna Type	Chip, XBee-Pro Wire, XBee Wire, XBee Dipole
RF power level (DB†)	0 (10 dbm), 1 (12 dbm), 2 (14 dbm), 3 (16 dbm), 4 (18 dbm)
Sensor height (m)	0.61, 1.83
Horizontal distance from base modem (m)	15, 30, 45, 61, 77, 91, 106, 122, 213, 243, 260

† Power dissipation ratio, $X_{DB} = 10\log_{10}\left(\frac{X}{X_0}\right)$, where X was the distance of the XBee and XBee-Pro transceiver from the modem and X_0 was the reference distance (1m).

A total of 14 bytes of data were transmitted from each wireless sensor node, including the sensor node address, the temperature reading of the IRT, the body temperature of the IRT sensor and the battery voltage supplying power to the sensor module. Using notation similar to Andrade-

Sanchez, et al., (2007), we defined this total package of 14 bytes as a data packet and the packet reception rate as:

$$PRR_x = \left[\frac{RR_x}{TR_x}\right]100$$

where PRR is the packet reception rate, RR is the number of records received during the time interval *x*, and TR_x is the total number of records transmitted during the interval time *x*.

To test the reliability of data transmission and compare mesh-networking protocol to non-mesh networking protocol, eight wireless sensors for each wireless sensor network (WSN) were deployed in the field and along the pivot lateral in a point-to-point topology (Fig. 2). Each WSN transmitted data on its own specific channel to a specific coordinator (base modem); data were collected using an embedded computer located at the pivot point. The programming of the microcontrollers was accomplished with PBASIC (Basic Stamp Editor, 2005; Parallax, Inc., Rocklin, Calif.); and communication between the XBee base RF module and the embedded computer was accomplished with Visual Studio 2005.

Network Topology

Pivot-WSN

Initially, all RF modules associated with this network were configured using the Zigbee firmware and the broadcast mode of communication. This mode entailed the coordinator sending its outgoing messages to all of the sensor nodes in the network at the same time; each message contained a node identifier code identifying the target sensor. However, only the targeted sensor returned data back to the coordinator while utilizing the other nodes as routers.

In the alternative unicast mesh-networking mode, the coordinator sent a message to a specific sensor node and the other nodes performed as routers to transmit the data back and forth to the targeted node; the network established the pathways. Again, only the sensor node, whose address was encrypted in the message, acted on the message and returned data to the coordinator through the network pathway (Fig. 2a).

Field-WSN

Firmware (802.15.4) was downloaded to each of the RF modules that comprised the Field-WSN. In this experiment, the Field-WSN coordinator individually polled each of the remote sensor devices using unicast addressing; the coordinator sent a message directed to a specific sensor node; the outgoing message and returning data packet traveled from the coordinator to the sensor node and back; the other nodes did not play an active role in the data routing (Fig. 2b).

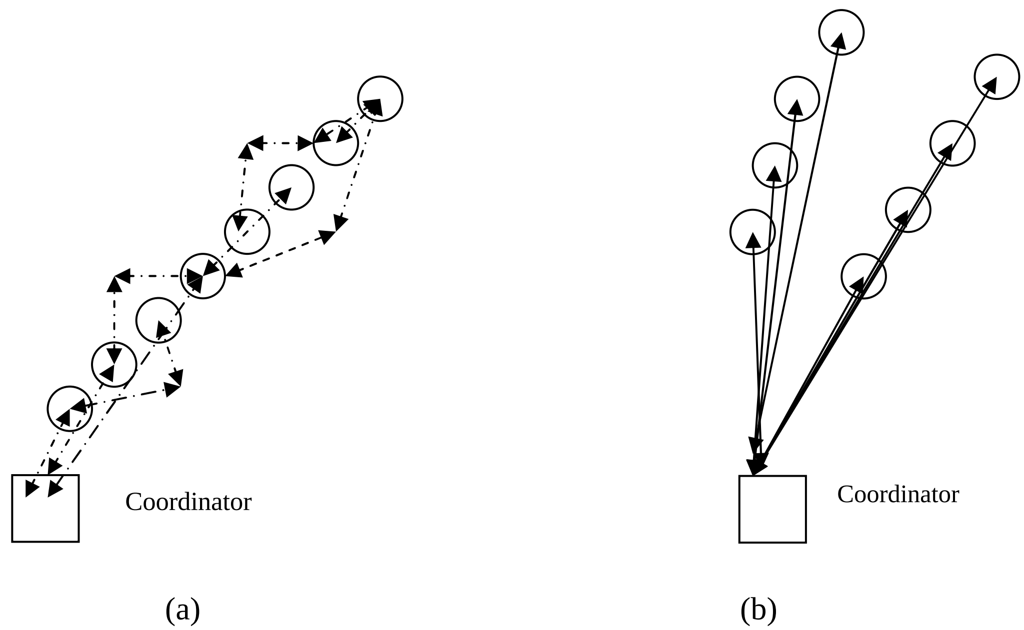


Figure 2. Network topologies showing: (a) Pivot WSN: unicast, mesh-networking where each sensor node acts as a router; (b) Field-WSN: unicast, non-mesh networking protocol where data is sent from the coordinator to each sensor node and back, the sensor nodes do not act as routers.

RESULTS

Sensor Module Calibration

An example of the calibration results is shown for a single wireless sensor module in Fig. 3, where residual error is the difference between the predicted temperature and the measured temperature. The largest error occurs when the sensor body is near 10ºC and the least amount of error occurs when the sensor body is near 24ºC. In both cases, the sensor reading and sensor body temperature are nearly the same.

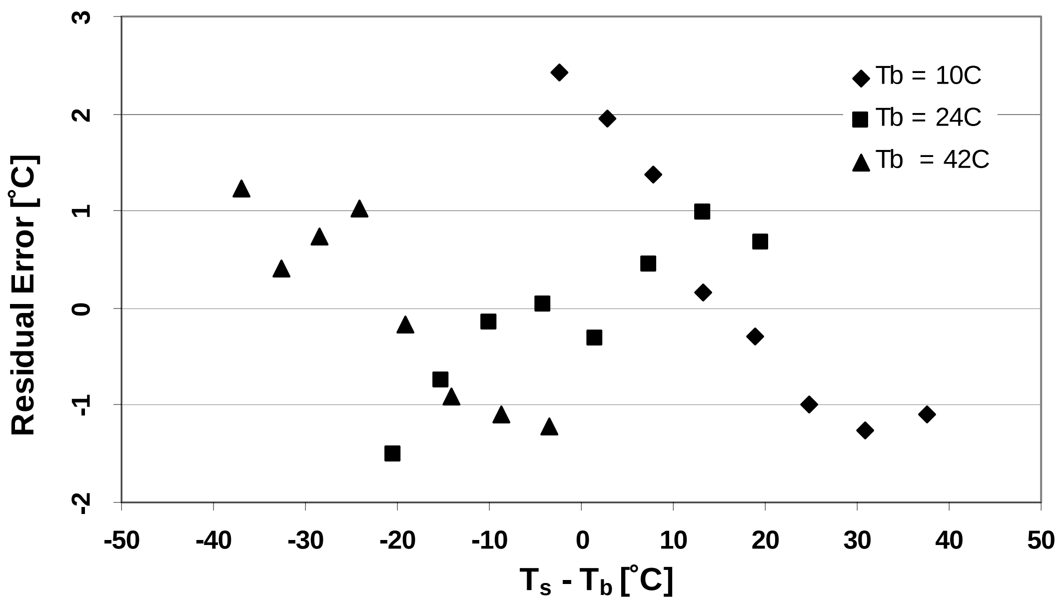
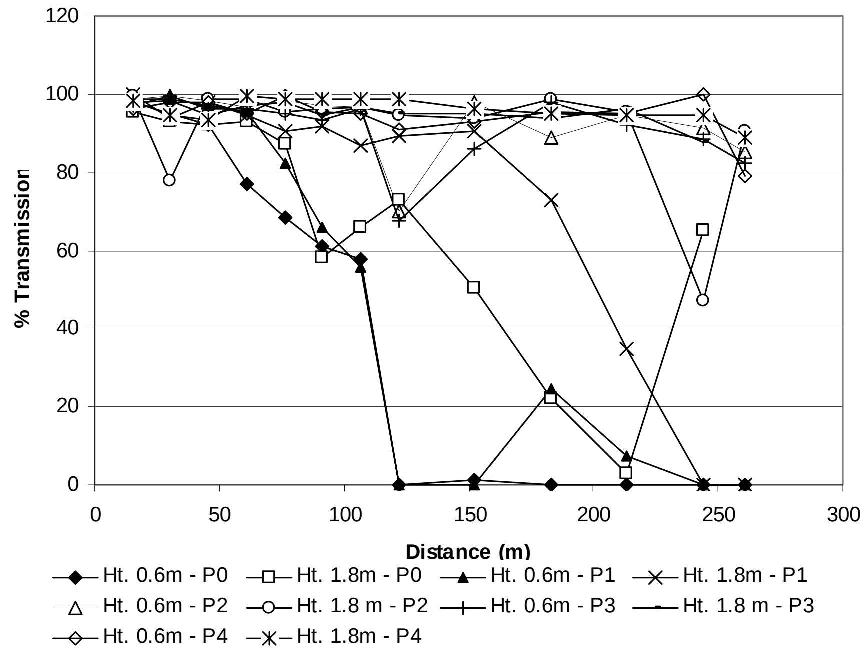


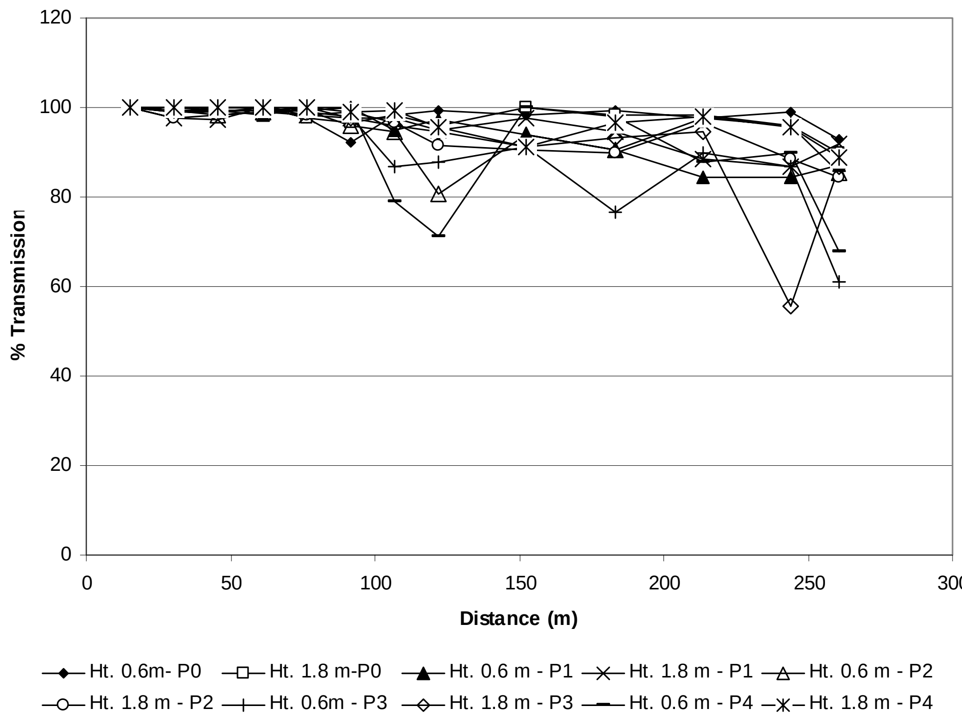
Figure 3. Graph showing residual error between the predicted and measured infrared sensor reading vs. the difference between the target temperature (T_t) and the sensor body temperature (T_b).

RF Antenna Testing

Received signal strength indication (RSSI) was compared for wire type and dipole antennas (Fig. 4). Transmission of data with the XBEE-Pro RF modules using a loop-back range test and X-CTU software (MaxStream2®, Orem, Utah) provided an RSSI of 95% at outdoor ranges > 500 m. Wire type antennas at a power level of 2 (on a scale of 0-4) were determined to be better suited than the dipole antenna for mounting on the center pivot lateral due to the superior performance of the XBee/XBee-Pro modules incorporated in evaluation boards supplied by MaxStream. The transmission of the dipole antenna may have been adversely affected by interference from the metal hardware of the center pivot trusses and towers compared with the wire antenna (Fig. 4).



(a)



(b)

Figure 4. Received signal strength indication (RSSI) for data received during the loop-back range test using: (a) the dipole antenna; and (b) the wire antenna. The RF module was placed at 0.6 m and 1.8 m above grade to simulate the range of the sensor height during a growing season.

Network performance:

Overall, the Field-WSN (unicast, non-mesh network) performed superior to the mesh networking system on the pivot lateral, probably due to interference from the pivot lateral on the mesh network. The Field-WSN required 8 seconds to collect data reliably from all eight sensors. However, it is important to note that using a non-mesh networking protocol on the Pivot-WSN resulted in a less than ideal level of reliability for data transmission, <80% reliability, 100% of the trial period (Table 3). The information below breaks down the results for the different network configurations.

The time required to collect data from a set of 8 sensors, using the broadcast communication mode and mesh networking, increased the latency of transmission of the entire network by 400% as compared to the Field-WSN. After reconfiguring the communication mode to a unicast method, while maintaining mesh networking capabilities, the latency was reduced to only 37% of the transmission rate of the Field-WSN.

The firmware installed on the RF modules for the Field-WSN was the 802.15.4, which enabled “sleeping” and therefore reduced energy consumption (Table 3). However, this firmware did not allow for mesh networking. On the other hand, the Zigbee protocol was installed on the RF modules comprising the Pivot-WSN and did allow for mesh networking but did not enable us to “sleep” the RF modules. Energy consumption for the sensor devices located on the Pivot-WSN was 300% greater than that for the Field-WSN.

Power issues

The wireless sensor module is currently powered by a nominal 6 V sealed lead acid battery that is trickled charged by a 5 watt, 6 V solar panel through a voltage regulating and isolation recharge circuit. The power consumption of the prototype sensor module is 360 mW when transmitting and less than 180 mW during its idle state. Power savings of 66% were realized by the ability to configure the “sleep mode” for the RF modules (Table 3).

Table 3. Results of deployed wireless networks.

Network System (# of devices)	Communication	Average % Packet Reception Rate	Energy Consumption
Field-WSN (8)	Unicast, non-mesh networking	>90% for 93% of the time (42 day trial period)	0.72 AH (sleep mode enabled)
Pivot-WSN (9)	Unicast, mesh networking	> 90% for 71% of the time (42 day trial period)	2.10 AH (sleep mode not available)
Pivot-WSN (9)	Unicast, non-mesh networking	< 80% for 100% of the time (6 day trial period)	Not assessed

CONCLUSION

The production of a wireless interface with an infrared thermometer for integrating the sensor into a commercialized center pivot system is critical to realizing a fully automated sprinkler system. It is possible to design an economical signal conditioner to interface with an "off-the-shelf" infrared thermometer and RF modules. The comparison of data packet reception rates in the mesh and non-mesh networking protocols demonstrated the beneficial application of wireless sensor networks in agricultural applications. The Field-WSN, installed as a non-mesh networking system in a point-to-point topology, out-performed the Pivot-WSN (configured with mesh networking firmware) in terms of reliability of data transmission; however, this was probably due to the interference that the pivot lateral caused in the Pivot-WSN. Supplementary benefits of the non-mesh networking system were speed (relative) of data transmission and the ability to "sleep" the RF modules and thereby significantly reduce total daily power consumption. However, it is significant to note that the mesh capabilities enable the wireless sensor network mounted on the pivot lateral to operate in a reliable manner. The manufacturer of the RF module is expanding the memory and "sleep" capabilities of its on-chip microprocessor. With these enhancements, the scalability and reliability of WSNs are expected to improve. In addition, further refinement of the signal conditioner components and the power supply module for the wireless sensor devices will be addressed to reduce maintenance of the electronic hardware, decrease total daily power consumption, and improve the accuracy of the sensor readings. An in depth investigation must occur with the wireless modules in a field setting during a growing season with the combination of new firmware and power conservation methods to determine the extent of the improvements and the feasibility for integrating the WSN into the center pivot system.

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Western Kansas Center Pivot Survey

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Abstract

Center pivot sprinkler systems are the dominant irrigation system type in Kansas, representing over 85 percent of the irrigated land. The State of Kansas requires annual water use reports from all irrigators as part of the water appropriation process. The report includes information on system type, crops grow and the amount of water applied. This provides a broad brush view of irrigation in Kansas. However, the types of nozzles and the nozzle configurations are not well documented and this information is often requested. A center pivot road survey was conducted in several western Kansas counties. The results will be compared to a previous survey conducted in south central Kansas.

Introduction

A road survey of center pivot irrigation systems was conducted in eight western Kansas counties in 2005 and 2006. The purpose of the survey goal was to obtain information that would be useful in characterizing the types of center pivot nozzle packages in currently use in the area and potentially be used as a baseline data set for tracking trends should additional surveys be conducted. The counties surveyed were Finney, ford, Grant, Gray, Haskell, Scott, Stevens and Thomas. A county road map was divided into three north/south transects and three east/west transects. All observations on the center pivot systems were made from the road; the fields were not entered by the surveyor.

The survey information consisted of observations on field location, degree of rotation, number of spans, nozzle type, pressure regulation, general nozzle type, nozzle height, number of spans and overhang, outlets on overhang, end gun presence and type, and the current or previous crop, if only stubble was present in the field.

Survey Results

The total number of systems observed in the survey was 659 with the number of observations in each county and the reported number of center pivot irrigated acres shown in Table 1. Center pivot irrigation is the dominant irrigation method in Kansas as reflected by the acreage report of the surveyed counties. The span length of the systems ranged from 4 to 19, (see Table 2). Most of the systems were probably typical standard quarter section sized systems (483 of 659 were either 7 or 8 spans in length). Only ten were six or fewer in span length. Seventy-six systems were either 9 or ten span length. Almost 15 percent of the observed systems were 15 spans or larger. There was a tendency for the larger span length systems to be operated as partial circles, as about 50 percent of the systems that were 11 spans or larger were partial circles as compared to about 7 per cent for systems 10 spans or smaller.

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The 78 per cent of the systems were pressure regulated and 89 per cent used a fixed plated nozzle package (Table 3). End guns are not widely used with only slightly more then 15 per cent of the systems with end guns. End guns were defined as either as traditional big guns or impact sprinklers if different from the nozzles on the bulk of the system. Only seven systems used big guns (Table 4).

Table 1: Counties surveyed, Center Pivot Systems, Reported Irrigated Acres, Reported Center Pivot Irrigated Acres (2005 Kansas Irrigation Water Use Report)

Counties	Systems Observed	Total Irrigated Acres	Center Pivot Acres[1]
Finney	143	228522	180555
Ford	69	87088	79996
Grant	54	107038	86448
Gray	107	180467	164268
Haskell	112	195999	112566
Scott	16	54483	31833
Stevens	93	169311	155335
Thomas	65	101947	99045

[1]Does not include center pivot acres from fields where multiple systems are used; for example, center pivot with flood irrigated corners.

Table 2: Center Pivot Survey information on number of spans and degree of rotation (full or part circle)

Number of Spans	Number Observed	Number of Partial Circles
4	1	1
5	2	0
6	10	2
7	276	18
8	207	19
9	26	2
10	50	1
11	1	1
12	2	1
13	4	0
14	4	2
15	6	4
16	28	14
17	20	11
18	16	10
19	6	1

Table 3: Center pivot survey information on pressure regulation use and type of nozzle

Pressure Regulation	Number	Nozzle Type	Number
Yes	515	Fixed Plate	589
No	136	Moving Plate	62
Unknown	8	Impact	2
		Mixed	1
		Unknown	5

Table 4: Center pivot survey information on use of end guns

End Gun Type	Number
Big gun	7
Single large impact sprinkler	22
Double large impact sprinkler	73
None (Last nozzle same type as system)	557

Observations were made on the placement of the nozzle for both spacing and height as shown in Table 5. The largest observation was a mixed spacing configuration, which generally meant the first several spans had wider spacing then the outer spans, although these numbers were not recorded. Only three systems were observed to have wide spacing. The majority of the systems were observed to use drop nozzles located at less then 4 foot height; followed by heights above 4 foot above ground but more then 2 foot below the truss.

Table 5: Center pivot survey information on nozzle spacing and nozzle height

Nozzle Spacing	Number	Nozzle Height	Number
Close (< 8 ft)	214	Less then 4 foot	385
Medium (8-12 ft)	197	Greater then 4 foot	212
Mixed	245	Truss to 2 foot below	55
Wide	3	Within truss	4
		Top of lateral	3

Survey information was also collected on whether the center pivot could make a full revolution. Table 6 shows that 88 systems or 13 per cent could only make partial revolutions.

Table 6: Center pivot survey information on full or partial rotation

Degree of Rotation	Number
Full (360 degrees)	571
Partial (Less then 360 degrees)	88

Additional analysis looked at various combinations of observations. The selections shown are nozzle type verses nozzle spacing (table 7), nozzle height verses nozzle type (table 8), nozzle height verses nozzle spacing (table 9) and number of spans verses degree of rotation (table 10).

Ninety per cent of the systems had the nozzles placed in the two lower placement categories (< 4 ft or > 4 ft but less then 2 ft below truss) with the lowest placement representing about 58 per cent of the total. Sixty-three percent of all fixed plate nozzles were within 4 ft of the ground, while only 12 per cent of moving plate nozzles were that low. Sixty-two per cent of the moving plate nozzles were observed in the > 4 ft category as compared to 29 per cent of the fixed plate nozzle. As noted previously, the mixed spacing configuration was typically a wider spacing for the first several spans then a decrease in spacing for the remainder of the system. About three fourths of the fixed plate nozzles were observed in these spacing categories. Sixty-one percent of the moving plate nozzles used the medium spacing, with another 10 per cent in the mixed category with a wider spacing in the initial spans and wider in the outer. The trend, as would be expected is that moving plate nozzles tend to be used in higher and wider configurations as compared to fixed plate nozzles.

The larger sized center pivots (greater number of spans) are more likely to be associated with partial rotations. For number of spans 11 or less, about 7 per cent did not have full rotation. For span numbers greater then 11, approximately half could do full circles. This might be expected, due to the likelihood of more physical constraints in larger fields, water right and land ownership constraints for large systems and irrigation capacity issues for large systems.

Table 7: Center pivot survey information on nozzle type verses nozzle spacing

Nozzle Type	Nozzle Spacing	Total
Fixed Plate	Close (< 8 ft)	196
	Medium (8-12 ft)	155
	Wide (> 12 ft)	1
	Mixed	237
Fixed Plate Total		589
Impact	Close (< 8 ft)	0
	Medium (8-12 ft)	0
	Wide (> 12 ft)	2
Impact Total		2
Mixed	Medium (8-12 ft)	1
Mixed Total		1
Moving Plate	Close (< 8 ft)	18
	Medium (8-12 ft)	38
	Mixed	6
Moving Plate Total		62
Unknown	Medium (8-12 ft)	3
	Mixed	2
Unknown Total		5

Table 8: Center pivot survey information on nozzle height verses nozzle spacing

Nozzle Height	Nozzle Spacing	Total
< 4 ft	Close (< 8 ft)	131
	Medium (8-12 ft)	41
	Mixed	213
< 4 ft Total		385
> 4 ft above ground	Close (< 8 ft)	64
	Medium (8-12 ft)	118
	Wide (> 12 ft)	29
	Mixed	1
> 4 ft above ground Total		212
Truss to 2 ft below truss	Close (< 8 ft)	18
	Medium (8-12 ft)	35
	Mixed	2
Truss to 2 ft below truss Total		55
Within truss	Close (< 8 ft)	1
	Medium (8-12 ft)	2
	Mixed	1
Within truss Total		4
Top of Pivot	Medium (8-12 ft)	1
	Wide (> 12 ft)	2
Top of Pivot Total		3

Table 9: Center pivot survey information on nozzle height verses nozzle type

Nozzle Height	Nozzle Type	Total
< 4 ft	Fixed Plate Moving Plate Mixed	371 12 2
< 4 ft Total		385
> 4 ft above ground	Fixed Plate Moving Plate Unknown	183 27 2
> 4 ft above ground Total		212
Top of Pivot	Impact Fixed Plate	2 1
Top of Pivot Total		3
Truss to 2 ft below truss	Fixed Plate Moving Plate Mixed	41 13 1
Truss to 2 ft below truss Total		55
Within truss	Fixed Plate	4
Within truss Total		4

Table 10: Center pivot survey information on number of spans verses degree of rotation

Number of Spans	Number Observed	Number with Full Rotation	Number with Partial Rotation
4	1	0	1
5	2	2	0
6	10	8	2
7	276	258	18
8	207	188	19
9	26	24	2
10	50	49	1
11	1	0	1
12	2	1	1
13	4	4	0
14	4	2	2
15	6	2	4
16	28	12	14
17	20	9	11
18	16	6	10
19	6	5	1

A three way sort of observations on nozzle spacing by nozzle height by nozzle type is shown in Table 11. The tendency is for fixed plate nozzles to be spaced more closely and lower to the ground then moving plate nozzles, as would be expected due to the operational characteristics of the two nozzle types. Moving plate nozzles were most commonly used with medium spacing in the > 4 ft height category.

Table 11: Center pivot survey information for nozzle spacing verses nozzle height verses nozzle type

Nozzle Spacing	Nozzle Height	Nozzle Type	Total
Close (< 8 ft)	< 4 ft	Fixed Plate	126
		Moving Plate	5
	< 4 ft Total		131
	> 4 ft above ground	Fixed Plate	55
		Moving Plate	9
	> 4 ft Total		64
	Truss to 2 ft below truss	Fixed Plate	14
		Moving Plate	4
	Truss to 2 ft below truss Total		18
	Within Truss	Fixed Plate	1
		Moving Plate	0
	Within Truss Total		1
Close (< 8 ft) Total			214
Medium (8-12 ft)	< 4 ft	Fixed Plate	36
		Moving Plate	5
	< 4 ft Total		41
	> 4 ft above ground	Fixed Plate	90
		Moving Plate	26
		Unknown	2
	> 4 ft above ground Total		118
	Truss to 2 ft below truss	Fixed Plate	26
		Moving Plate	7
		Mixed	1
		Unknown	1
	Truss to 2 ft below truss Total		35
	Within Truss	Fixed Plate	2
		Moving Plate	0
	Within Truss Total		2
	Top of Pivot	Fixed Plate	1
	Top of Pivot Total		1
Medium (8-12 ft) Total			197
Mixed	< 4 ft above ground	Fixed Plate	209
		Moving Plate	2
		Unknown	2
	< 4 ft Total		213
	> 4 ft above ground	Fixed Plate	26
		Moving Plate	3
	> 4 ft above ground Total		29
	Truss to 2 ft below truss	Fixed Plate	1
		Moving Plate	1
		Mixed	0
	Truss to 2 ft below truss Total		2
	Within Truss	Fixed Plate	1
		Moving Plate	0
	Truss to 2 ft below truss Total		1
Mixed Spacing Total			245
Wide (>12 ft)	> 4 ft above ground	Fixed Plate	1
	Top of Lateral	Impact	2
Wide (>12 ft) Total			3

A similar survey was previously conducted in the south central region of Kansas (Rogers and Clark, 2004). This survey was conducted in the fall of 2003 in Barton, Edwards, Pawnee, and Stafford counties using the survey technique described previously. There would be a tendency for higher capacity irrigation systems in this region as compared to the western systems due to generally sandy soils in south central and generally non-declining water tables.

Seventy-three percent of the SC systems were of 7 or 8 span length which was essentially identical to western systems. About 21 per cent of the systems in either region were of greater then 8 span length, however, in SC only two systems were greater then 10 spans in length, whereas 13 per cent of the western systems were of greater then 10 span length. This might be expected since the terrain of the SC area may be less conducive to larger systems and the higher irrigation capacity requirements for systems serving sandy soils would be problematic with regards to friction losses and well capacities. More of the SC systems (95.1%) completed full circles as compared to western systems (86.6%), although this trend is likely related to the number of larger systems in the west.

The most common type of sprinkler package in the SC survey was a moving plate type nozzle (Table12) as compared to the fixed plated nozzle in western Kansas. The nozzle placement in the SC survey was higher then in the western survey, as might be expected due to the difference in the most common type of nozzle in use.

End guns (Table 13) are in common use in SC Kansas with only about 13 per cent of the systems not having some type of end nozzle as compared to only 15 per cent of western systems having an end gun. Over one-third (37.5%) of the SC systems were equipped with a big gun (traditional end gun). About half (48.9%) were equipped with either double or single large impact sprinklers.

Summary

The dominant center pivot nozzle package of western Kansas is fixed plate nozzle positioned near to the ground using a drop tube. This was different type and configuration observed in the south central region of Kansas, where moving plate nozzles positioned higher above ground were more common.

Acknowledgements

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Table 12. Survey results of types and numbers of sprinkler nozzles on center pivot systems in south central Kansas – 2003.

Nozzle Type	Number of observations	Percentage
Fixed Plate	19	5.8%
Impact	22	6.8%
Mixed	5	1.5%
Moving Plate	244	75.1%
Unknown	35	10.8%

Table 13. Survey results of sprinkler vertical position for center pivot sprinkler systems in south central Kansas – 2003.

Nozzle Height	Number of observations	Percentage
< 4 ft	25	7.7%
> 4 ft above ground	42	12.9%
Top of Pivot	27	8.3%
Truss to 2 ft below truss	221	68.0%
Unknown	8	2.5%
Within truss	1	0.3%

Table 14. Survey results of end gun type on center pivot sprinkler systems in south central Kansas – 2003.

End Gun Type	Number of observations	Percentage
Big Gun	122	37.5%
Double Large Impact	78	24.0%
None	42	12.9%
Single Large Impact	81	24.9%
Unknown	2	0.6%

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Evaluation of Water Distribution Uniformity Under a Traveling Ggun Irrigation System

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The water distribution uniformity under a traveling gun irrigation system where evaluated using three type of sprinkler (Komet, Nelson 100 and Nelson 150) under two operation managements; the sprinklers moving with an constant speed during the irrigation (T1) and the sprinklers was stopped in different position along the travel direction based on the water distribution pattern (T2). The sprinklers were tested with 270o operation angle and 3 working pressures of 7, 8, and 9 bar under T1 and that was 360o, 5, 7, 8 bar for sprinklers under T2. Distribution pattern were simulated for different operation angles of 180o, 225o, 270o, and 315o, travel lines distance, and moving speed of sprinkler. According to the results, 180o operation angle showed highest distribution uniformity in most of the travel lines distance. The maximum distribution uniformity was measured when travel line distance was about 75-80% of distribution diameter. The impact of sprinkler operation angle on distribution uniformity was not considerable when travel line distance was optimum. Increase in working pressure, increased the distribution diameter and induce the maximum distribution uniformity under higher travel line distance.

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Using Saline Groundwater for Large-Scale Development and Irrigation of Pistachios Interplanted with Cotton

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ABSTRACT

A 9-year small-scale trial (ending 2002) in the southern San Joaquin Valley found that established pistachios can tolerate an irrigation water salinity up to 8 dS/m (similar to cotton) without a reduction in yield.

In 2004, a shallow subsurface drip tape system was installed in two 155 acre fields to irrigate future pistachio tree rows 22 feet apart with 4 rows of cotton interplanted on 38 inch beds. Replicated 19.5 acre blocks were arranged to test plant response to fresh (canal) water, blend and saline well water treatments with EC of 0.5, 3.0 and 5.4 dS/m and boron @ 0.3, 6 and 11 ppm, respectively. Fresh water was used to germinate cotton, which was planted in 2004, 5 and 6. Pistachios were planted in 2005. Cotton yields were unaffected by salinity, until 2006; showing a half bale loss for the well water (3.12 bale/ac) compared to the canal water (3.68 bale/ac). Pistachio growth is unaffected by salinity after 3 years.

INTRODUCTION

Cotton has long been known as a salt tolerant crop, but despite many small-scale field trials over 30 years almost no marginally saline water in the San Joaquin Valley is used for long-term production Over this same period water costs have increased four to tenfold while acala cotton prices have increased little since the early 1960's. At the same time, the population of California has grown by 10 million people and ag demand has dropped from 26 to 25 MAF mostly due to the adoption of micro (drip) irrigation systems (Figure 1). Farmers are looking for less expensive, more secure water supplies and more profitable crops.

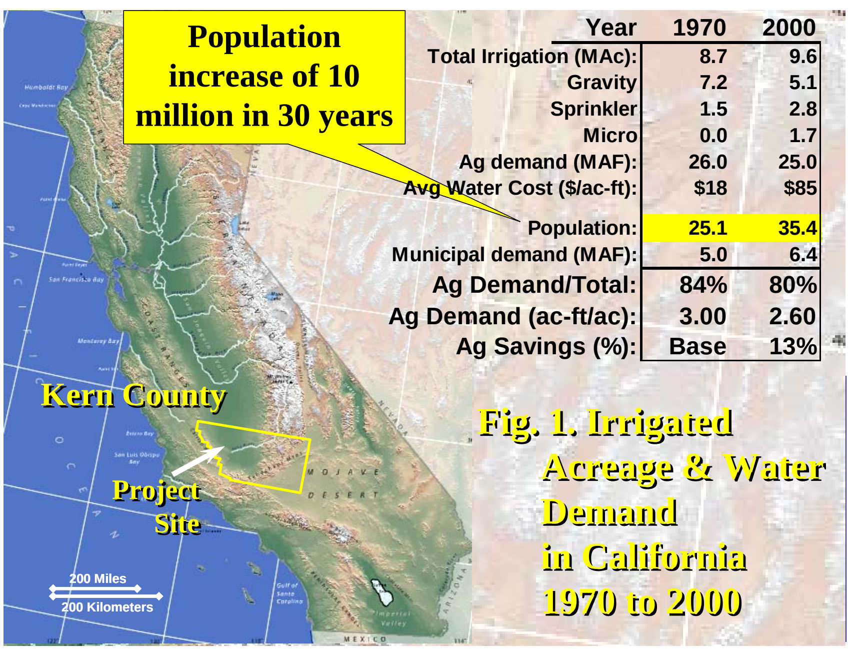

Fig. 1. Irrigated Acreage & Water Demand in California 1970 to 2000

A recently completed nine year field study on the salt tolerance of pistachios on the Westside of the San Joaquin Valley (Ferguson et. al., 2003 and Sanden, 2004), and previous pistachio studies in Iran (Fardooel, 2001) have shown the viability of using saline water up to 8 dS/m for irrigating these trees (Figure 2). A rootstock trial in sand tanks at the USDA Salinity Lab in Riverside (Ferguson et al., 2002) showed a significant increase in leaf burn when 10 ppm boron was added to irrigation water but no reduction in the biomass of year old trees. The salinity and B tolerance of cotton has been reported at similar levels in tank trials (Ayars and Westcott, 1985) and investigated in long-term field trials (Ayars et al., 1993).

Emphasizing the need for alternative water supplies, State Water Project allocations to Westside irrigation districts went to zero in 1990 due to extended drought; unleashing California's infant water market with the establishment of "Emergency Pool" water that could be bought for $100/ac-ft. Given the salt tolerance of cotton and other rotation crops on the Westside (such as processing tomatoes), some studies investigated utilizing fresh water blended with drainage from tile systems as a means of boosting available water supplies for furrow irrigation (Ayars et al., 1993, Sheenan et al., 1995). This approach generated some interest, since yields were maintained at similar levels to fresh water irrigations, but required a high degree of management with the possibility of long-term residual salinity problems that growers did not want to deal with.

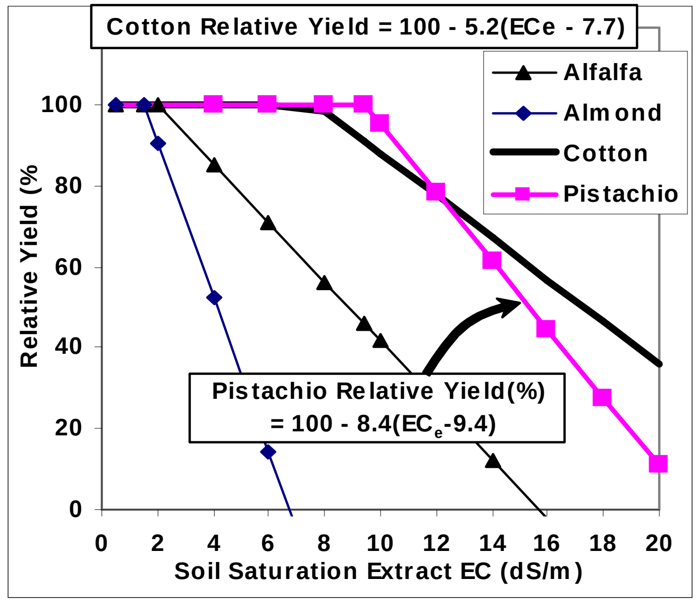

Fig 2. Comparison of salt tolerance thresholds and relative yield for various crops (Sanden, et.al., 2004)

At the same time water supplies have decreased and costs have soared, subsurface drip irrigation (SDI) systems using improved, thin-walled drip tape have become cheaper and more profitable than the earlier prototypes of the mid 1990's (Fulton et al., 1991), with capital costs as low as $800/acre for grower installed systems. With a much lower energy requirement than sprinklers, greater uniformity and reduced loss to evaporation (a total savings of 6 to 8 inches) this type of system becomes the most cost effective in this setting. All these factors have combined to make the time right for developing irrigation system management approaches that can use hybrid fresh and saline water supplies to irrigate salt tolerant crops.

PROJECT OBJECTIVES

- Assess the viability of large-scale cotton production and pistachio interplanting using saline groundwater (up to EC 5 dS/m and B @ 10 ppm) and optimal irrigation scheduling with SDI.
- Determine crop ET as a function of salinity using simple water and chloride balance.
- Maintain acceptable soil salinity levels for cotton stand establishment/production and maximum growth of young pistachios.
- Compare total project profitability under SDI using 3 different levels of salinity: saline water, non-saline CA Aqueduct water and a 50/50 blend. Compare the economics of drip tape SDI with typical Belridge Water District cotton production using sprinklers.

PROCEDURES

Irrigation system and treatment replication: Two, 155 acre blocks were designed for irrigation with TSX 708-12-220, 0.875 inch diameter drip tape injected at 10-12 inches below field grade using a 38 inch row spacing with two 54 inch skips every 22 feet between the tape used for future pistachio rows and the 4 adjoining 38 inch rows for cotton.. A separate underground manifold connected to the two hoses that irrigate the pistachio rows was installed to allow for separate scheduling. Hose runs are 1280 to 1300 feet long with the manifold connected at the high side of the field with the outlets connected to a common flush line. Each block has 16 separate pressure regulating subunit valves. The grower's booster and filter station are designed to irrigate 8 subunits at a time (~78 net acres); making for 4 set changes to irrigate

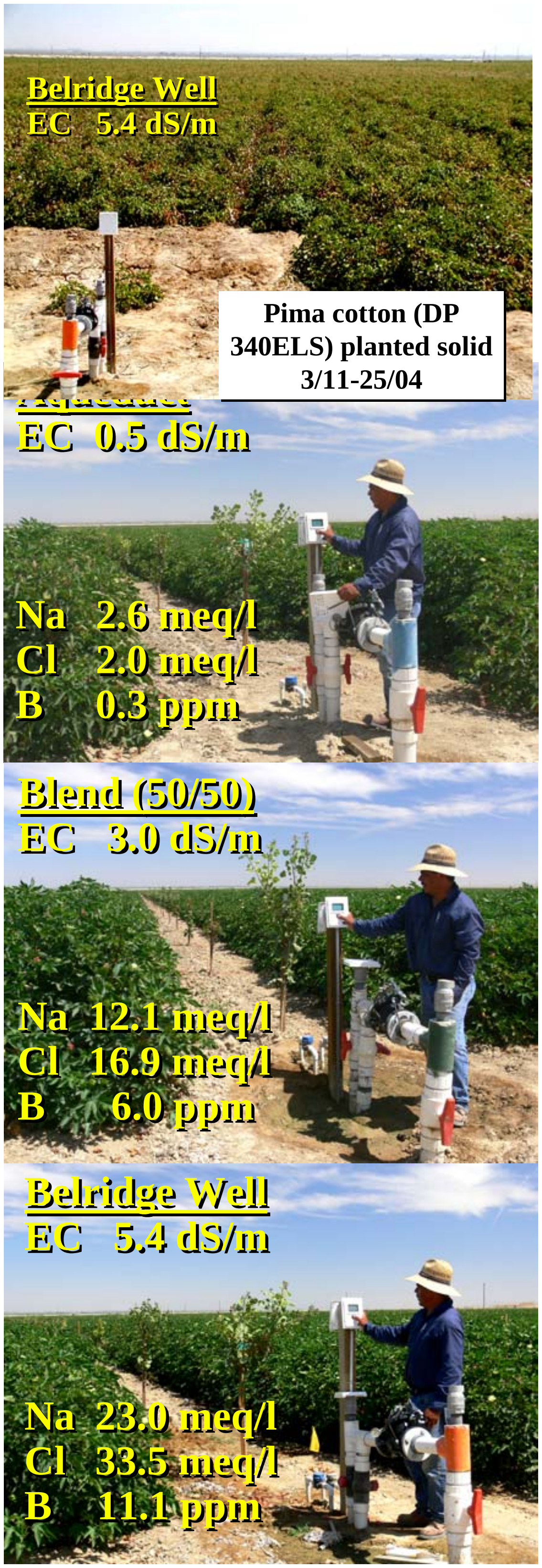

Fig 3. Solid planted cotton (Well treatment) July 2004 and comparison of irrigation treatments with third year of cotton and two year old pistachios (8/17/06).

310 acres. Treatments are applied to a total of twelve 19.5-acre plots (2 subunit valves each) arranged in a randomized complete block design with four replications.

Treatments: Aqueduct water (a 6 to 12 inch depth) is used for winter recharge of the rootzone and the germination irrigation for optimal cotton stand establishment and leaching in pistachios in all subunits. Subsequent irrigations are applied using 24 hour sets (2 inches) as required over the season using the following treatments:

Control: Aqueduct water only: EC ~ 0.5 dS/m

Blend: 50/50 mix Aqueduct and Well: EC ~ 3.5 dS

Well: Groundwater only: EC ~ 5.5 dS/m

2004 Season: Delta Pine 340 ELS pima cotton was planted over the entire field 3/11-25/04 (Figure 3, top).

2005-2006: Pistachio Pioneer Gold (PG1) rootstock was planted 3/5-11/05 with DP340 ELS pima interplanted 3/25-4/15/05. Pistachios were planted to a 17 x 22 foot spacing with 4-38" rows of cotton in between tree rows. Sub-blocks of 20 UCB1 rootstocks were planted in each plot to compare the vigor of both varieties under varying salinity. Separate orchard manifolds feed two drip tape hoses placed 19 inches from the tree trunk allow for optimal irrigation scheduling for trees in order to satisfy ET and some leaching even after cotton irrigation ceases. Phytogen 810RR pima was interplanted 4/12-14/06 (Figure 3, left).

2007: Pistachios only using the 2 adjacent drip tape hoses. Cotton was to be planted a 4th year, but severe reductions in irrigation district allocation forced the grower to cancel his Westside cotton program.

Data Collection and Analysis -- Soil water content and applied water: One neutron probe access tube for weekly measured water content depletion/ET estimation was installed in each plot, 150 feet from the head and, in Block 1 only, 250 feet from the tail ends of the drip tape. In one block for each treatment, matric potential at the 12, 24 and 48 inch depths adjacent to neutron probe access tubes was monitored using a Hanson AM400 data logger with six electrical resistance blocks (Watermark®). Small flow meters were installed at the entrance to each replicated run of drip tape in both cotton and pistachios.

Soil and water salinity: Replicated soil samples were taken each year from the area adjacent to access tubes from 0-6, 6-18, 18-36 and 48-60 inch depths at planting and post harvest and analyzed for EC, Ca, Mg, Na, Cl, HCO3, and

B. Treatment water samples were collected over the season. A transect of closely spaced samples perpendicular to the drip tape was used to characterize salinity patterns at the time of stand establishment.

Plant data: Replicated measurements of cotton leaf water potential were taken biweekly during the season. Pistachio trunk diameter was measured at the end of the season. Leaf tissue was analyzed for Ca, Mg, Na, Cl, B, N, P, K (pistachio) and petiole NO3, P, K and B (cotton) mid-season. Cotton lint yield and quality were monitored for all plots.

Data analysis: All data was tested for significance using 2-way ANOVA for a completely randomized block design.

RESULTS AND DISCUSSION

2004 cotton yield was excellent at around 4 bale/ac (Table 1). In 2005, all cotton yields were disappointing at around 2 bale/acre due to a very cold spring. Yields were unaffected by irrigation water salinity. Comparison of digital aerial analysis of the Normalized Difference Vegetation Index (NDVI) for August 2004 and 2006 showed no treatment impacts on crop vigor across the field. However, final 2006 cotton yields showed a half bale loss for the Well compared to the Aqueduct treatment (3.12 and 3.68 bale/ac, respectively). Again, cool spring temperatures combined with significant increased seedbed salinity in the Well treatment (ECe of 8 to 11, Figure 4) reduced plant population and early season vigor.

Table 1. Plant tissue nutrients, selected salts, growth characteristics, yield and applied salts for cotton and pistachio.

PLANT TISSUE ANALYSIS	Na (ppm)	Cl (%)	B (ppm)	Root-zone EC_e to 5 ft (dS/m)	[1]Cotton Ht, Pistachio Circum (inch)	Cotton Lint Yield (lb/ac)	[2]Total Salts Applied in Irrigation (lb/ac)
2004	Cotton Petioles 8/27			**10/6/04**	**9/14/04**	**10/6/04**	**Cotton'04**
Aque	570	2.58	34	2.71	42.2	1933	2,343
50/50	712	**3.23	37	*4.08	*35.8	1928	11,390
Well	574	*3.00	37	*4.68	38.8	2016	21,444
2005	Cotton Petioles 9/15			**10/18/05**	**9/15/05**	**10/19/05**	**Cotton'05**
Aque	605	2.71	42	1.42	41.6	954	2,305
50/50	539	*3.13	46	3.71	43.1	1129	10,144
Well	546	**3.38	**50	*4.74	42.1	999	16,975
	Pistachio Leaves 9/15			**10/18/05**	**10/19/05**		**Pistach'05**
Aque	222	0.27	194	2.87	2.31		1,742
50/50	220	0.27	**492	4.12	2.17		8,570
Well	314	**0.38	**673	*4.44	2.18		14,782
2006	Cotton Petioles 9/21			**10/30/06**	**9/21/06**	**10/27/06**	**Cotton'06**
Aque	885	1.95	48	1.01	44.9	1835	1,967
50/50	937	1.91	55	*3.61	45.0	1615	11,046
Well	1143	2.21	*56	**4.63	40.9	*1560	15,832
	Pistachio Leaves 10/31			**10/30/06**	**10/19/06**		**Pistach'06**
Aque	171	0.52	531	2.65	2.58		1,022
50/50	140	*0.58	**954	4.34	2.55		8,994
Well	201	*0.62	**1096	*4.61	2.49		11,104
2007	Pistachio Leaves 6/19				**10/18/07**		**Pistach'07**
Aque	99	0.24	167		4.65		
50/50	108	0.28	**315		4.59		
Well	*133	0.30	**384		4.45		

*Significantly different from Aqueduct @ 0.05, **Significant @ 0.01

[1]Cotton height @ irrigation cuttoff.

[2]Cotton cover = 12.7 foot width/tree row Pistachios = 9.3 foot width/tree row

Plant tissue analysis showed a significant 0.5 to 3 fold increase in chloride and boron levels in both cotton and pistachio (Table 1), but produced no toxicity symptoms in 2005. Some marginal burn was seen in the Well treatment in 2006. In 2007, some marginal leaf burn could be seen in all treatments, but did not seem to impact scaffold development or rootstock circumference. Due to small caliper rootstocks at planting and extremely high July 2005 temperatures, a significant number of trees needed to be rebudded Fall 2005 so that only 40% of the PG1 and 4% of the UCB trees had a full set of Kerman scaffolds by the end of 2006.

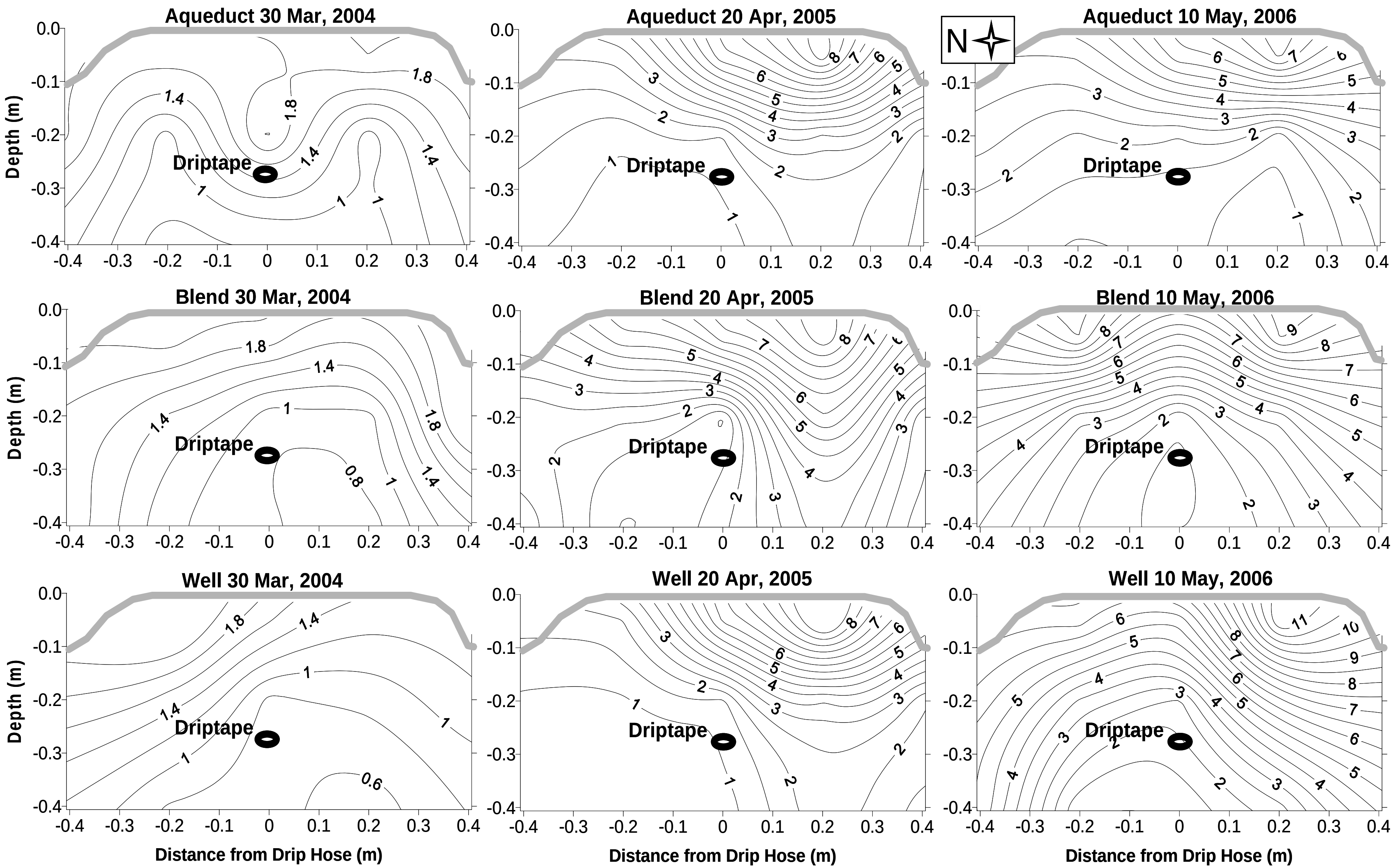

Fig. 4. Contours of saturation extract **soil salinity (ECe, dS/m)** in **cotton** beds (0.96m, 38 inches) at emergence after spring recharge and post-plant irrigation of 200 mm (8 inches) low salinity canal water (Aqueduct, 0.5 dS/m). Kerman rootstock planted 5-11 March, 2005 following cotton irrigated with the same treatment waters.

UCB rootstocks, however, were significantly larger than the PG1 rootstocks, but this difference has disappeared as of the end of this third season of 2007 (Figure 5). Scaffold development is complete on all trees (save a few replants), but the orchard as a whole is behind on development of tertiary branches stemming from the primary scaffolds. This is partially the result of two years of interplanted cotton, and the main reason why interplanting new orchards is rarely seen anymore. However, pistachios do not come into commercial bearing until their 7th year; allowing more time for this orchard to "catch up".

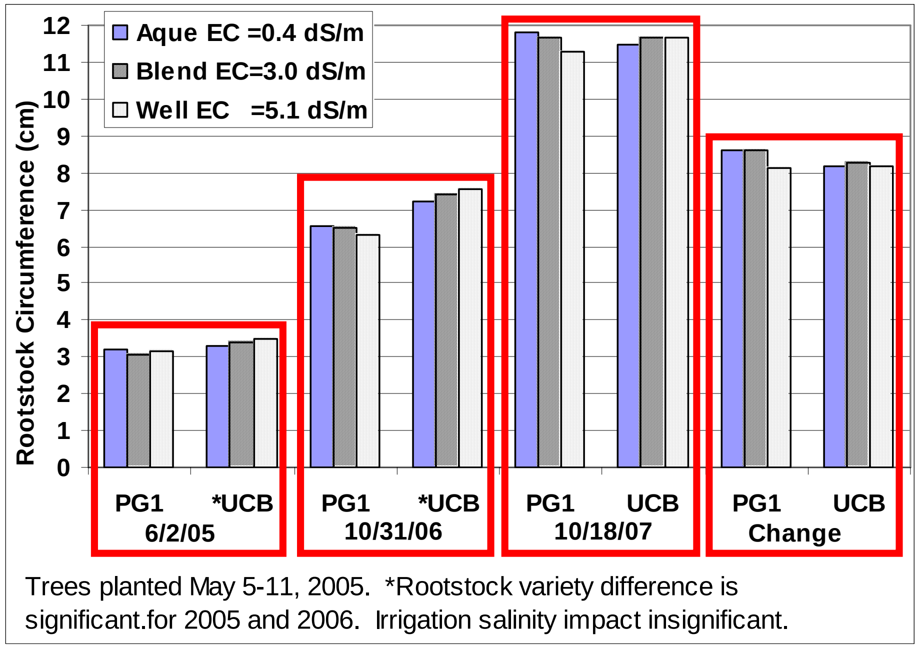

Fig. 5. Mean circumference for PG1 and UCB rootstocks from 40 trees (10 per plot) for all treatments and net increase after three seasons.

After three seasons of cotton irrigation this program results in about 6,600 lb/ac applied salt in the Aqueduct treatment and about 54,000 lb/ac in the Well treatment (Table 1). The final salt load in the 9 foot band along the pistachio drip tape after 3 years will be about 4,000 and 40,000 lb/ac for the Aqueduct and Well treatments, respectively. Total salt loads applied to pistachios would only be half of this if cotton had not been interplanted for the first two years as the cotton pulled substantial amounts of water from the pistachios. Net leaching from the pistachio rootzone is estimated at 5 to 20%.

The current trial is scheduled to run through 2008. Given sufficient funding, the pistachios will be monitored at least until 10 years of age (2014).

CONCLUSIONS AND PRACTICAL APPLICATION

The final verdict is not yet in on the long-term viability of this project. In addition, only sites with sufficient drainage allowing a 15 to 25% leaching fraction will be suitable for this strategy. But if proven successful, the eventual savings in water costs will be about $120/acre for mature tree ET. This equals $37,000/year for the 310 acre orchard. This doesn't even take into account the fact that planting this acreage would be impossible without using the "substandard" water. At this writing there are about 4,000 additional acres of pistachios planted or scheduled for 2007 in Buttonwillow and NW Kern County on saline ground with marginal well water that would not have been developed three years ago. Between marginal groundwater and blended drain water there is more than 150,000 ac-ft/year of additional "alternative" water supply on the Westside that appears suitable for pistachios. The aggregate value of this water and the potential development of 30 to 40,000 acres of pistachios replacing cotton and wheat rotations could easily exceed a benefit of $30 million/year over the value of the field crops.

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Irrigation Load Control Credit Rider Dispatch Pilot

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Abstract

As regulated entities, electric utilities are required to build infrastructure and generation to meet the annual peak. For nearly all electric utilities the biggest contributor to peak is summer heat. Increasingly, electric utilities have turned to Demand-Side solutions in lieu of expensive infrastructure / generation build-out. The reason Demand-Side solutions are attractive are twofold. First, expensive assets are not sitting idle for all but 40 hours per year. Second, Demand-Side is a far more environmentally friendly solution. Since 2003 Rocky Mountain Power has offered a 'Scheduled Forward' Irrigation Load Control Program to its 2,500 customers (4,700 agricultural pump sites) in southeast Idaho (service territory ≅10,000 sq miles). Since inception the Idaho Irrigation Load Control Program has grown to roughly 100MW (25% of the 400MW customer base). In 2007 a large-scale Dispatchable pilot was approved by the Idaho Public Utilities Commission and made available to growers. The 2007 pilot complemented the on-going 'Schedule Forward' initiative. Nationwide there is a growing appetite for utility-sponsored irrigation load control. This article describes what growers and/or or those in a position to advise growers need to know before leaping into utility sponsored irrigation load control programs.

The Rocky Mountain Power system

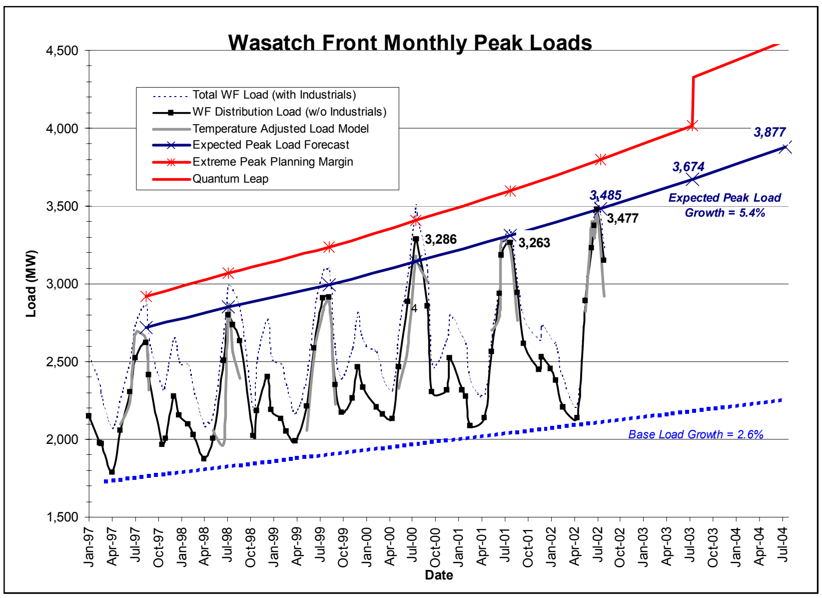
PacifiCorp is a regulated electric utility serving ≅1.6 million customers. The Company does business under the *Rocky Mountain Power* brand in the states of Utah, Wyoming and Idaho. The 'western' part of the PacifiCorp system serves Oregon, Washington and California and does business under the *Pacific Power* brand. The Utah / Idaho portion of the system has been and continues to experience significant load growth. Infrastructure assets are 'stressed' and all efforts are being directed to do more with less. Environmental entities level pressures that make it difficult to add infrastructure. Recently environmental organizations have taken legal action to prohibit the expansion of existing resources. It is with this background that the Idaho Irrigation Load Control Program was born.

The peak problem

There is a desire on hot summer afternoons (usually between 4:00p and 6:00p) for nearly everyone to want to use devices driven by electric power. This desire for power within the space of a narrow two to three hour window creates a 'peak' (think top of the bell-shaped curve). Illustration One provides actual Wasatch Front (Salt Lake City and surrounding cities) load profile data from 1997 through 2002. The illustration depicts a typical electric utility peak.

Keep in mind that ‘needle peaks’ such as that shown in Illustration One means that a significant portion of system resources (transformers, substations, poles, peak generation plants, conductor, switching gear and so on) must be sized, in place and operationally ready to meet just roughly 40 hours per year (that’s one-half of one percent). The costs for those idle assets are huge. Like it or not (and most don’t like it) those costs are deemed ‘prudent’ by regulatory bodies and are passed along to consumers in the form of rate increases. To the extent that growers can, as a group, mobilize and participate in well designed irrigation load control programs, they can reduce the amount that irrigation contributes to peak. By so doing environmental and economic savings could be realized.

Illustration One
Wasatch Front 1997–2002 Load Profiles



Until recently utilities have simply added more ‘supply stuff’ to meet the peak. Today the emphasis of electric utilities is increasingly directed to meet the peak via Demand-Side solutions which drives the need for irrigation load control.

But before you or someone you know jumps headlong into a utility sponsored program there are a few things that deserve a second look. The recommendations below arise from having designed, implemented and operated an irrigation load control initiative for the past five years.

Do participation credits off-set the risks?

Growers cannot and should not be easily dissuaded by the lure of participation credits. Instead, the value proposition itself should be the primary reason for participation and the deal workable within the grower's parameters of reasonable agri-business operations. In 2003 when Rocky Mountain Power first brought the load control initiative forward there was a single participation option–2 x 6-hour dispatches a week. Growers were required to participate for the full irrigation season (14 weeks or 168 hours). The offering was attractive for growers raising field crops (wheat, barley, grain, and alfalfa). Water sensitive row crops such as potatoes and corn were noticeably absent from participation.

Preparatory for the 2004 growing season the Irrigation Management Team introduced a 2 x 3-hour dispatch option and a 4 x 3-hour dispatch option in hopes of gaining additional participation. Both options were miserable failures. We later learned that 3-hour blocks failed to carry sufficient participation credit to outweigh the labor and fuel cost of having to manually re-start the pump. Subsequently the Irrigation Team has implemented a 1 x 6-hour option which seems to have found favor with some growers producing field crops but still almost no row crop sites found their way into program participation.

Only with the introduction of the 'Dispatchable' option in 2007 did we find high water-use crop participation. By tariff the Dispatchable offer was constrained by the following parameters:

- Available Dispatch Hours: 2:00 PM to 8:00 PM MDT
- Maximum Dispatch Hours: 65 hours per Irrigation Season
- Dispatch Duration: Not more than three and one-half hours per *Dispatch Event*
- *Dispatch Event* Frequency: limited to a single (1) *Dispatch Event* per day
- Dispatch Days: Monday through Friday (inclusive)
- Dispatch Day Exclusions: July 4 and July 24 and/or their respective designated weekday official holiday

Under the Dispatchable offer growers were able to receive the same participation credits for only one-third of the total hours. Moreover, and as part of the value proposition, growers also had the opportunity to 'opt-out' of any given *Dispatch Event* but would have their credits reduced by the amount Rocky Mountain Power would otherwise have to pay for power during the *Dispatch Event*. The 'opt-out' alternative proved pivotal in increasing program participation. The terms and conditions of the 'opt-out' provision provided financial protections to both Rocky Mountain Power and to growers. Under 'opt-out' circumstances, Rocky Mountain Power would otherwise be subject to market price vagaries. Growers, on the other hand were often faced with equipment or weather considerations which did not permit them to participate in a specific *Dispatch Event*. The opt-out provision mitigated the risks for both parties.

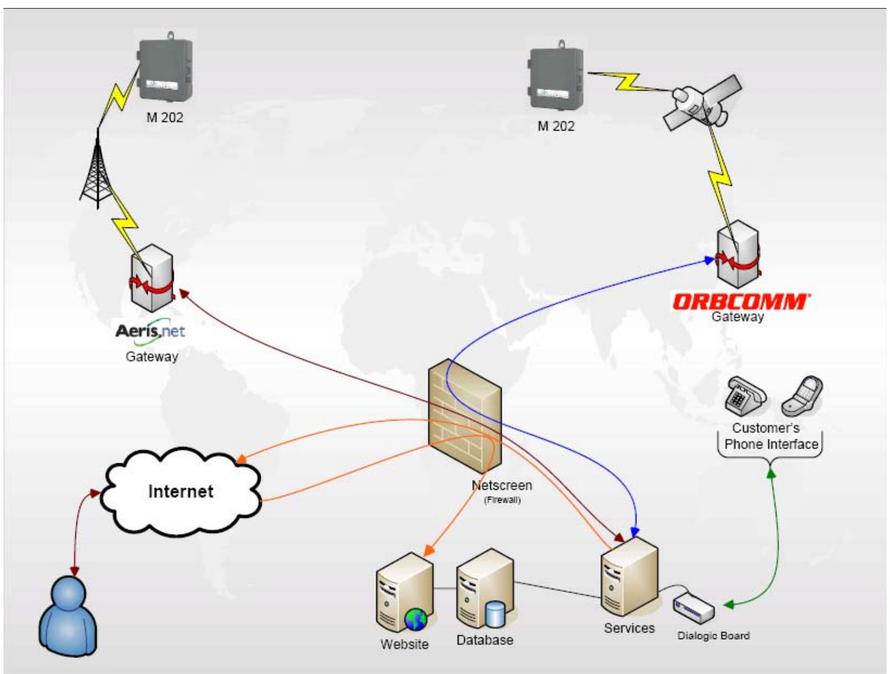
The Dispatchable option provided an acceptable value proposition. The option was bounded by utility considerations which were tolerable for the rewards growers were being asked to take. In short, the deal was both realistic and appropriate. And because Rocky Mountain Power had sufficient financial protections their interests were similarly protected. The bottom line is this: growers would be well advised to NOT engage in an irrigation load control program that fails to meet their core agri-business needs. If avoided capacity is valuable to the utility they will come and listen to you. The utility will then find ways to cobble together an acceptable value proposition. It is not simply about the participation credit but rather how well the value proposition fits with the agri-business circumstances and whether or not the risk / reward metrics pencil out.

Is the enabling control technology familiar to agriculture?

Prior to 2006 off-the-shelf generic electronic programmable timers were used to control pump / pivot systems according to pre-arranged participation schedules. Beginning in 2006 Rocky Mountain Power tested 25 advanced 2-way communication control units. These units were engineered and produced by the developer / manufacturer of the *Valley Tracker* control system. The *Valley Tracker* and subsequently, the Rocky Mountain Power units provided remote 2-way interface to the pump / pivot site through the Internet or the public cellular network. Illustration Two (*M2M Communications System Interface Diagram*) provides a graphical presentation of the system interface and associated communication networks.

Illustration Two

M2M Communications System Interface Diagram



Although the Illustration depicts a satellite communication channel, we found that with nearly 450 installations the cell coverage was sufficiently robust and the satellite system was never implemented. However, during the 2007 pilot roll-out, field installation teams did have to install a half-dozen high gain omni-directional antenna to effectively 'reach' cell towers. The cell system was surprising robust and a complete surprise to the entire Irrigation Load Control Team given that the southeast Idaho service territory is extraordinarily rural.

Field installations required a bit of a learning curve in developing the appropriate protocols systems and routines. Once units got installed in the field they didn't seem to work as nice or as neat as they did in the laboratory or even in simulated field conditions (this shouldn't surprise anyone who has every been involved in introducing a new technology). Fortunately, and with the exception of an occasional surface mount resistor that got damaged in the assembly process all changes / settings were:

- Accommodated in version-controlled Operating System (OS) releases and/or
- The retrofitting of external antenna that eliminated the rare signal attenuation issue.

Re-flashing units with new OS's while in the field could have proven to be very costly as irrigation sites were spread over vast distances…often requiring 45 minutes travel (one-way) to reach a single site had it not been for one extraordinary grower. This grower had a keen interest in the technology and stepped-forward offering their farm managers and their 51 participating sites as 'guinea pigs' for the entire pilot population.

Solving the technical issues with a single grower first allowed the Irrigation Management Team to solve the technical and operational challenges presented by the new technology without jeopardizing customer relations should complications arise. Focusing on a single grower at a time allowed installation teams to focus resources, resolve problems in a single geographic area, and communicate coherently with the grower before taking on another grower. Instead of installing all 448 participating sites in parallel with multiple installation teams. The project was rolled out one grower after another. The emphasis would be on getting the installation process, technology settings and database components correct with this single grower before moving on to parallel installations with subsequent growers.

A key point is that this particular grower had previously investigated the *Valley Tracker* remote control system. The system was not a stranger to the irrigation industry. It was an easy 'leap-of-faith' for growers to accept the Rocky Mountain Power control unit that would be affixed to their pump panels. Electronic timers while a relatively stable platform were woefully inadequate for the harsh agricultural environment. Timers simply did not work reliably. Timers were a case of an acceptable application not targeted to the correct application. Year-over-year timer failures (one year as much as 38%) meant that field technician teams were routinely deployed in the spring to perform maintenance on all units. The program would simply not continue to operate with the volume of customer complaints that was being generated.

The 2-way M2M unit, on the other hand, is designed exclusively for agricultural applications. Similar models have been offered by Valley Irrigation for years and maintenance has been practically nil. Moreover, the M2M technology offers a variety of functional capabilities that are recognized and valued by growers. Some but not all of those feature sets include:

- Controls and monitors pivot or linear irrigation systems by phone or Internet
- Receive phone-based notifications when changes or problems occur
- Report AC power outages, water usage, and run times
- Saves time and fuel
- Works with all brands and models of irrigation equipment (Valley, Zimmatics, Reinke, L&T, Lockwood, etc.)

Selling growers on using the technology was not difficult. In fact, when growers learned we would be installing this type of product interest in the pilot out-stripped resources.

Throughout the service territory there are a number of sites where a single large pump (say 800Hp) will serve multiple pivots. Over the years the irrigation team learned that an additional constraint to participation was being able to independently control the pivots and/or linears configured to a single pump. Working with M2M Communications, an innovative master / slave design was implemented. The 'master' communicates to the web site via a digital cellular modem. The 'master' also communicates to its associated 'slave' units through a radio frequency (RF) channel. This means that the grower has full 2-way interface / control with each separate piece of equipment on any given site. When the standard control panel is configured with auto re-start the grower can completely remotely-manage their irrigation operations.

The point is that the core M2M technology was conceived, designed, built and implemented for agricultural irrigation equipment. It was not and is not a 'bolt-on', kludged to interface with the pump panel. While we are not promoting a particular brand, what we are suggesting is that any self-respecting load control initiative should deploy equipment that is specifically designed to work with the specific load. Utilities and their potential end-use growers will be well advised to heed this council.

It has been our experience that while you can get a non-load specific control system to work reasonably well with the underlying equipment there will be enormous time and expense to ensure its operational integrity and often the economics or customer service issues simply make that decision more bothersome than beneficial. Equipment that fails the grower once is understandable. On-going inability to maintain tolerances is a guaranteed formula for failure. Growers, steer clear of equipment and systems inadequately designed for your agricultural applications.

On a side note, but still every bit as important, proprietary (utility built and maintained) communication systems for customer-centric programs are fraught with extended 'down time'. Here, as in elsewhere, we have unfortunately learned from our own mistakes. We strongly suggest that before you participate in a load control program that you make sure the communication channel take advantage of pervasive public communication networks. These networks and the folks that manage them do this for a living. They are professionals.

Proprietary systems are a sideline to the utility and should not be used when the risks, as they are in irrigation applications, are huge to the end-user.

Are operational components grower friendly?

With nearly 100 megawatts (MW) participating on the Irrigation Load Control program and 78 MW derived from the Dispatchable option there has been a fair amount of interest generated by Rocky Mountain Power executives. Recently a Rocky Mountain Power executive was wanting to get a better understanding of the value proposition. In an e-mail he asked whether growers appreciated (1) the benefits of the M2M control technology? (2) were only interested in the participation credits? or (3) some combination of the two? Part of my response to this executive is excerpted below:

> *The equipment we use and provide to the grower for their use does provide a convenience. In fact, Valley Irrigation sells the equipment based largely on fuel and labor savings. But it is not an 'over night' conversion. In talking with Valley they told me it takes 3-years before the grower gets comfortable (aka, trusts) the equipment to perform as expected. Over-time we anticipate Idaho growers to get there also. What we are talking about here is a technology transformation. Not unlike going from sailing ships to steam ships, horse-drawn carriages to horseless carriages, passenger trains to interstate travel and airplanes and so on.*
>
> *Some growers are early adopters, others are more skeptical in their tolerance for change. We are attempting to introduce change with the idea that the change will benefit both the grower and the Company. This initiative was designed for the grower to gain benefit and for the Company to realize gain also. We have been and are in the business of 'shaping' customer behavior away from electric use during on-peak periods, no ifs, ands or buts! In short we are attempting to teach growers to help the Company. In so doing both parties benefit.*

From Rocky Mountain Power's perspective there are two foundational program drivers. First and foremost, the irrigation initiative has had an eye to shaping behavior as to how power is used. Second, customer service reigns supreme. Irrigation Load Control is not a quick fix to peak problems. The Irrigation Team has taken the approach that a customer-centric design will have impacts surpassing the credits provided. Accordingly, program design has focused on providing an agri-business solution that has a load control component and not a load control program that may have some interest for irrigation management.

How does this translate? Customers are first consulted on their irrigation requirements. Next, the load control system is engineered to complement those needs. All Internet logins and phone system access are set-up and configured for the grower. The grower only has to learn how to access and navigate operational menus. To learn those systems, growers are provided detailed training to themselves and their farm managers. Laminated 'cheat sheets' are provided as reminders to growers as they master menus and systems operations. To accommodate the large population of Spanish speaking labors leave-behind materials are provided in Spanish. Training is provided in a classroom setting at the grower's operation. That is followed by physically going to the grower's pivot site where participants are given the opportunity to issue various control commands to the pivot via their cell phone.

Initial training is followed by field installation teams providing regular 'circuit rider' interface to the grower. 7 x 24 help line service is made available by these same field installation teams. Growers and their farm managers are encouraged to call day or night regardless as to how 'trivial' their question or concern may be. The Irrigation Team determined that for the program to succeed it would be important that the grower not spend hours struggling with the website or phone system.

Upon first encounter we are only asking growers to become familiar with system operations. We assumed that in subsequent years growers would be better prepared to address advanced system components. Growers should expect utilities to provide help in the use of remote control equipment on irrigation pump sites. Assuming or trying to make the change overnight is a recipe for failure. We suggest that utilities plan on helping growers make the adjustment and keeping it simple. To the point: the solution needs to be easily understood and implemented over time.

The proprietary 2-way technology had a distinct advantage over the electronic timers. Control commands could be sent to the field installed units and the units could report various state conditions and settings. For the purposes of the Rocky Mountain Power sponsored Irrigation Load Control initiative, units could be dispatched on-demand. Participating customers' equipment would no longer be turned off from 2:00p–8:00p on summer weekdays. Instead *Dispatch Event*s could be called only when it was necessary to help off-set peak load requirements. However, the 'random' dispatch schedule meant that a communication system, to inform the grower of *Dispatch Events*, had to be implemented. This communication system would send day-ahead notification to growers so they could make operational plans. In fact, growers were notified on a day-before (no later than 5:00p) and again on the morning-of (by 10:00a) the *Dispatch Event*. Without advance, predictable notifications, chaos would have dominated the random dispatch schedule.

Another advantage afforded by the 2-way technology is information timeliness. The amount of time that passes between the initial need to make a decision and having all the information necessary to make a decision is information timeliness. Our experience has shown that the 2-way technology facilitates information timeliness. Getting information to appropriate parties is critical to high customer service ratings. Consider this scenario.

A grower is experiencing some problem with irrigation equipment on which a load control device is installed. The natural thing to do is to suspect the load control device. The grower calls customer support. Within moments, customer service representatives can make an initial prognosis before the call is ended. The grower can be given an indication of what the problem is and the customer service representative can dispatch a technician to service as needed. It is also possible with the 2-way units for the grower to logon to the website and diagnose the problem himself.

Compared to a timer control device, 2-way technology can significantly reduce customer service time-to-resolution. Also, the incident of unnecessary trouble calls or false trouble calls can be reduced to near zero. For the growers, this means less time on the phone, definitive troubleshooting, and less trips to irrigation sites.

Why would a grower elect to participate in the Load Control Program? First and foremost, of course, are the participation credits. In 2003 the credits totaled $6.48/kW-yr. By 2007 and as a result of the overwhelming customer support and the impact to peak load reductions credits had risen to $11.19/kW-yr. By participating in the Load Control initiative growers had effectively transformed a portion of their pump costs into revenue producing assets.

Second, growers could now remotely communicate with their pivots and linears, receive notification of unanticipated changes in pump status and issue commands to their irrigation equipment. The benefit of the change-in-status notification option was vividly brought to light by one grower who reported that soon after installation his phone rang at 1:00a. On the phone was a robotic-like voice message telling him that a certain pump had turned off. At first he thought there must be some computer error. His curiosity got the better of him. So he got dressed and went out to check. Sure enough lightening has interrupted the power supply and the pump which was previously running had now turned off. Prior to the installation of the 2-way technology a grower would not discover the pump had turned off until the next day when checking his units. He would have likely lost eight hours of valuable irrigation.

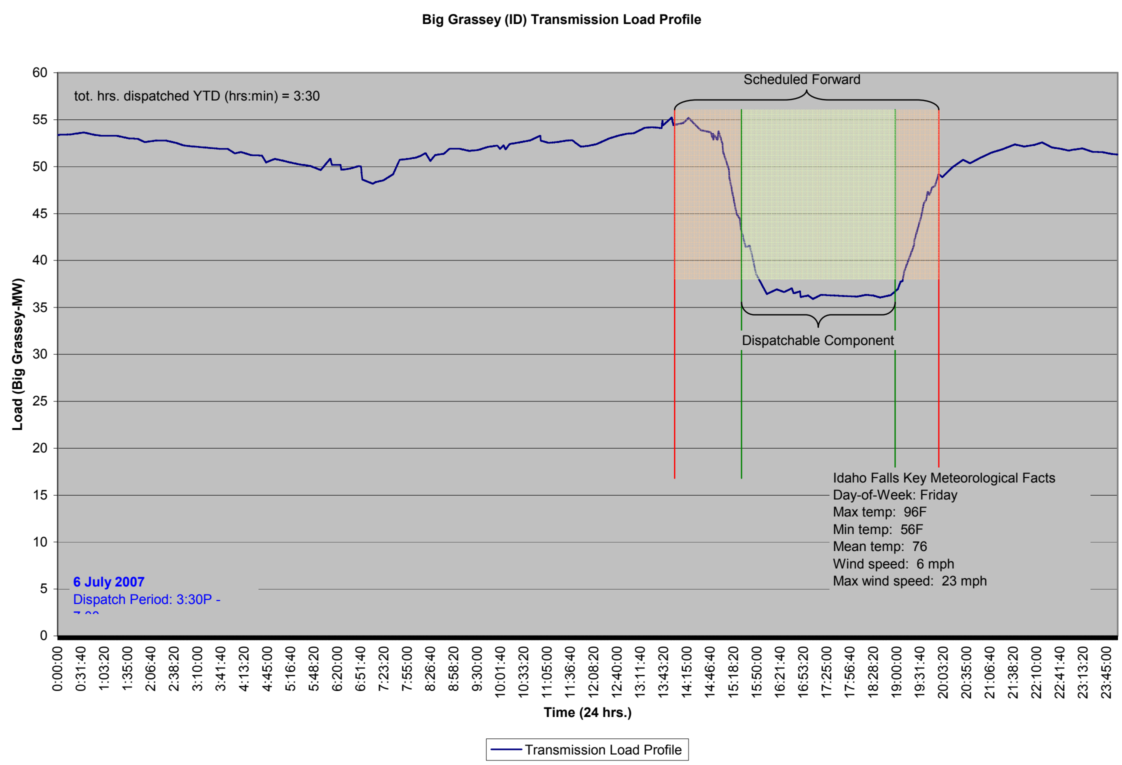
So what has been the results?

17 customers (448 sites) participated in the full-scale Dispatchable initiative using the proprietary (cellular / RF) M2M 2-way control technology. In 2007, 78 MW were aggregated under the Dispatchable pilot. Based on standard utility tests that compare total program benefits (avoided peak demand) against total program costs (equipment, labor, administration, customer service support, database and so on) the program calculated to be extraordinarily ‘cost-effective’.

Throughout the control period, Rocky Mountain Power SCADA data were collected and used in preparing impact analyses. Log data from Circuit Breaker #67 which was known to have a significant number of Program participants was mined for this analysis. A significant portion of the participants in this area where Circuit Breaker #67 resides participated in the Dispatchable program. Due to the impact of the Dispatchable initiative the results of the Scheduled Forward component is difficult to observe. Nevertheless, SCADA values were taken and logged at 20-second intervals for periods when dispatches were executed. Virtually all of the 13 ‘Dispatch Events’ had identical profiles.

Illustration One depicts Circuit Breaker #67 grid impacts as a function of both Scheduled Forward and Dispatchable options. What is noteworthy is (1) the magnitude of the load shifting effect as depicted in the difference between control and non-control hours and (2) the impact of 'load shaping' as a function of the combined impacts of the Scheduled Forward and Dispatchable program components. This shaping capability is important as it provides Rocky Mountain Power with more options and greater control over the grid in systematically meeting load requirements during summer peak periods.

Illustration One
Big Grassey Transmission Load Profile July 8, 2007)



Concluding thoughts and recommendations: some parting thoughts

Utility irrigation load control programs can and do deliver measured impacts to electric grids which can measurably assist in improving reliability, reducing operating costs, provide important environmental benefits and, in some cases, delay build-out of expensive infrastructure / generation resources. Before utilities offer or growers decide to participate in such an effort there are a handful of considerations you will want to keep 'top-of-mind'.

First, what utilities need to know / do…

- Utility sponsored irrigation load control programs can deliver SCADA-measured peak reductions.

- An option for grower ‘opt-out’ is pivotal in managing the risk to both growers and the utility offering the program. Without protections for both parties it will be difficult, if not impossible, for DSM to gain internal support for the initiative and for the grower to see his way clear to participate.
- Growers will participate with cash crop acreage if the ‘opt-out’ option and credits are appropriate for the risk.
- Putting customer service at the top-of-the-list of key operational considerations is pivotal to grower / farm manager training.

Second, what growers need to know / do…

- The advanced 2-way control system provides value-added convenience to optimize field operations and deliver labor, fuel, and equipment O&M cost savings.
- Make sure your farm manager(s) is/are comfortable with the use and operation of the equipment in managing regular irrigation turns. Require reluctant farm managers to jump in with both feet in learning how to manage irrigation systems by the 2-way equipment. Likewise require that farm managers learn how to appropriately navigate phone and secure Internet menus to accommodate ‘*Dispatch Event*s’.
- Be willing to invest in computer as well as remote Internet mobile connectivity technology. The above mentioned ‘guinea pig’ grower has eagerly taken to the installation of lap top computers in the pick-ups of each of his farm managers.

If you fail to see evidence of (1) an appropriate value proposition, (2) control equipment that can work seamlessly with irrigation systems and (3) systems, processes and procedures that make operations easy and efficient; work cooperatively with the utility promoting the initiative to translate these parameters into realities. The utility is new at the Demand Side game also. Chances are the utility will listen to your concerns, ideas, suggestions, opinions and recommendations and, where possible, incorporate them into the program design. After all, they have a vested interest in the success of their irrigation load control initiative as much as you do.

INTRODUCTION

Grand Valley Project

The Government Highline Canal is part of the Bureau of Reclamation, Grand Valley Project, located in Grand Junction, Colorado (figure 1). The canal construction was started in 1913 and completed during the Great Depression. The canal extends 52-miles from the diversion dam on the Colorado River flowing westward through the Grand Valley. Two Federal environmental programs spanning a 25-year period have had a dramatic impact on the modernization of the Highline Canal. This paper discusses the use of an operational pipeline spill near the canal head of the canal, in conjunction with a regulating reservoir and pump station near the canal end for reducing operational spills and improving canal water management.

The Colorado River Endangered Species Act funded the Highline Canal moderation program, with an objective of reducing canal diversions in the fall, to enhance Colorado River flows in a critical 15-mile reach, for the benefit of Colorado's endangered native fish population.

Historically canal flows ranged between 650 cfs to a minimum flow of 400 cfs. The minimum flow was necessary to maintain canal water surface levels for turnout deliveries. The addition of seven new check structures reduced the required minimum canal flow to 150 cfs.

Today the canal has 21 automated check structures in series, spanning 48 miles of the 52 mile canal. The check structures reduced the required minimum canal flows (figure 1). The combination of a controlled operational spill (Palisade Pipeline) near the start of the canal, and a reservoir pump-back station (Highline Lake) near the end, was envisioned to compensate for mismatches between water supplies from Colorado River diversion and irrigation water delivery demands.

HIGHLINE CANAL MODERNIZED FACILITIES

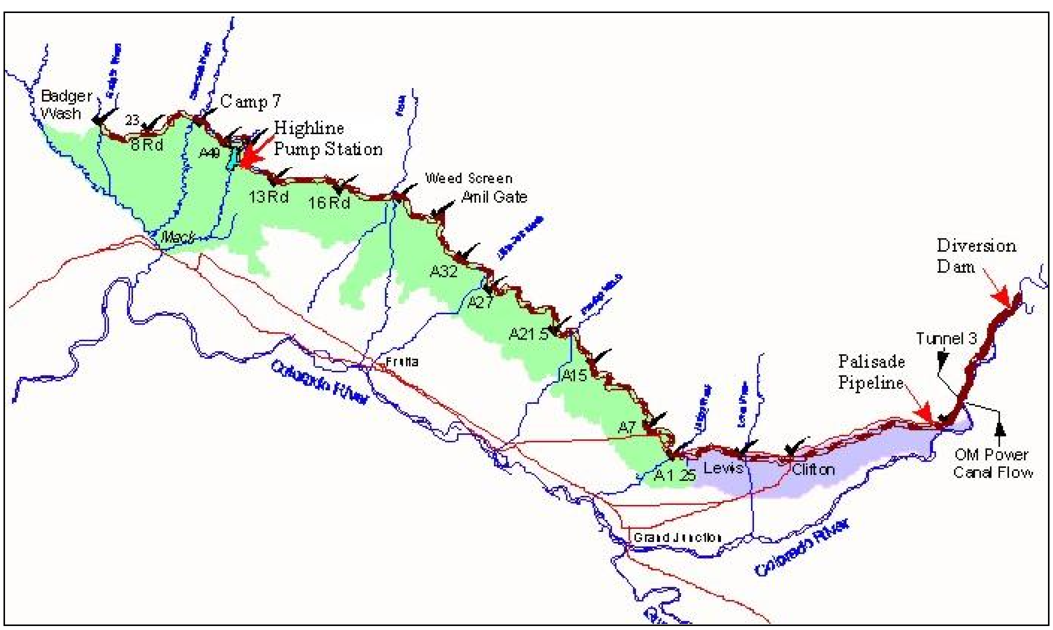


Figure 1: Grand Valley Project, Government Highline Canal

Palisade Pipeline Operation Spill

The Palisade Pipeline is designed to fine tune the flow in the Highline Canal. The pipeline (spill) is 6.5 canal miles downstream of the diversion dam, and is located below the four major turnouts that deliver water to three other irrigation districts and a power plant. The operational spill is a metered turnout structure from the Highline Canal, (figure 2), with a flow control gate and 1000 feet of 36-inch PVC pipe.

Figure 2: Palisade Pipeline Turnout from Highline Canal

The Palisade Pipeline spill discharges back into the Colorado River, (figure 3) above the critical 15-mile fish habitat reach of the river. The flow capacity in the pipeline is in excess of 100 CFS.

Figure 3: Pipeline Spill Returning 75 cfs to the Colorado River

Highline Lake Regulating Reservoir and Pump Station

Highline Lake is a recreation reservoir, with a surface area of 140 acres when full. The primary water supply for the lake is the Camp 7 spill, (figure 4) from the Highline Canal. The Camp 7 spill is 44 canal miles downstream from the Colorado River diversion dam. The historic flexibility for canal operation was achieved by diverting more water than required for irrigation deliveries, and spilling the excess water into the natural washes that intersect the canal throughout the Grand Valley, (figure 1).

Figure 4: Camp 7 Spill into Highline Lake

As part of the canal modernization program, a pump-back station was constructed in Highline Lake (figure 5). The pump station has a 200-horsepower lead pump, controlled with a VFD, and two additional 150-horsepower pumps, which are staged to supply additional flow. The total pumping capacity of the Highline pump station is 70 cfs (figure 6).

Figure 5: Highline Lake Pump Station

Reducing the operational spills in the canal will sometimes create a situation where the water delivery demands exceed the available water a particular canal reach. The purpose of the pumping station is to supplement these shortages, while more water is moved from the Palisade Pipeline spill down the canal, to cover the delivery shortage.

Figure 6: The Pump Station Delivering 70 CFS into the Highline Canal

<u>Pipeline Spills and Regulating Reservoir Operation from the Designer's Point of View</u>

The Palisade Pipeline allows the operator to fine tune the flow in the Highline Canal without adjusting the river diversion at the dam. By maintaining base flow of 50 cfs in the pipeline spill, canal flows can be increased or decreased by 50 cfs at the spill turnout. The time required to see a change in canal low at Camp 7 from a change in the pipeline spill is 13 hours. In other words, decreasing the flow by 25 cfs at 6:00 AM in the Palisade Pipeline will be seen as a 25 cfs flow increase at Camp 7 by 7:00 PM on the same day.

If the operational spill into Highline Lake is managed around 15 cfs, and the operational spill at the end of the canal, (Badger Wash) 6-miles downstream of the Camp 7 spill, is managed at 20 cfs; In theory, there is a 35 cfs spill buffer between canal supply and delivery demand. Add the 70 cfs automatically available from the Highline Lake pump station, and there is in theory a 100+ cfs buffer between canal supply and delivery demand. The design envisioned that the 35 cfs spill buffer could accommodate moderate increases in demand. If a demand increase exceeded the spill buffer, the pumping plant would turn on. When the pump was turned on, the flow of water in the Palisade Pipeline would be reduced, leaving more water in the canal. Within 13 hours, the additional flow would reach Camp 7 and allow the pumps to turn off.

Canal operation is not as simple as it seems to the designer. The canal is 52 miles long, with 21 check structures in series along the canal, operating in upstream water level control mode. All the check gates are automated. This is a perfect setup for a big wave tank.

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Pipeline Spills and Regulating Reservoir Operation from the Manager's Point of View

This part of the paper is based on an interview with Richard Proctor, Manager of the Grand Valley Water Users' Association. The Palisade Pipeline spill was the manager's idea during the modernization study in the late 1990's. The pipeline spill is used to fine tune the flow in the Highline Canal, and it has been operated for five years. This spill is used to match canal flows with water deliveries, and operational spills at the end of the canal, without changing the river diversion at the dam. The pipeline spill is operated during the spring to stay a head of increasing irrigation water demands. At peak demand, in July, the spill is off.

Then from August through the end of the irrigation season, the spill is used as a quick response to changes in water delivery demand. The indicators for a change in canal flow, are the amount of spill at Camp 7 and Badger Wash.

The manager's target spill, into Highline Lake at Camp 7, is about 90 cfs, and the target spill at Badger Wash is 40 cfs. Why is there such a large difference between the designer's spill targets and the manager's spill targets?

The water surface in the canal at the Camp 7 spill is controlled with a side-channel automated over-shot gate that spills into Highline Lake. The canal water surface is well controlled, but the spill into the lake fluctuates by about 60 cfs on a two hour cycle, (figure 7).

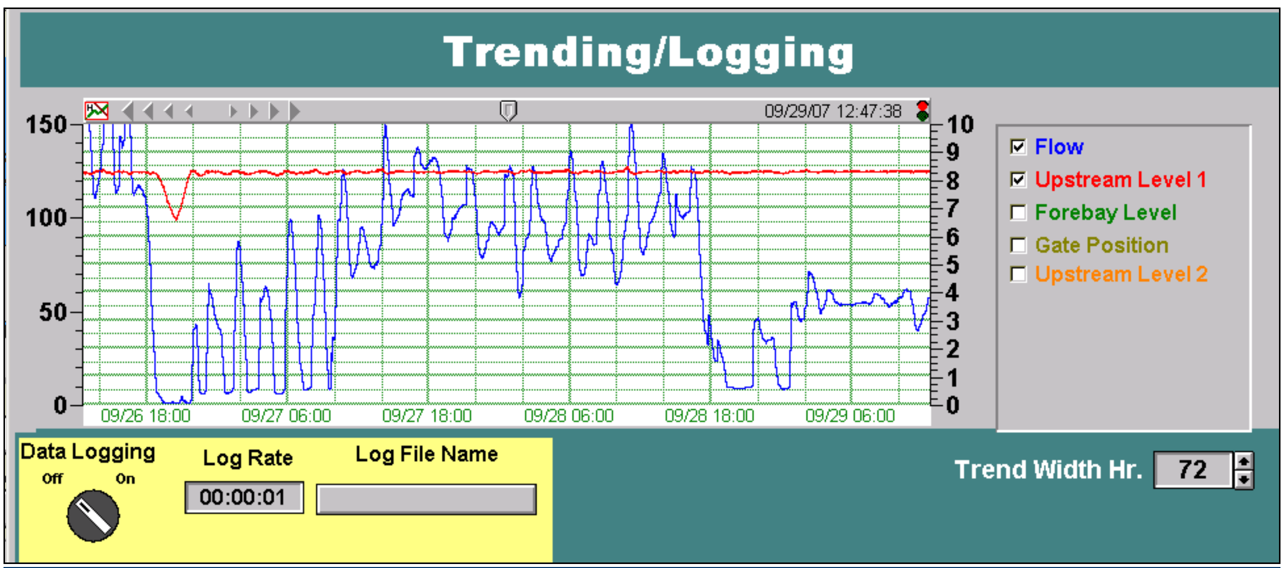

Figure 7: Log of the Camp 7 Spill into Highline Lake

When the Camp 7 spill target is at 90 cfs, the reliable buffer of extra water is about 30 cfs. The stable water surface level in the canal at Camp 7 produces a relative constant flow into the 6-mile end section of the canal. The trending log, (figure 8) is a three day log of the Badger Wash spill at the end of the canal.

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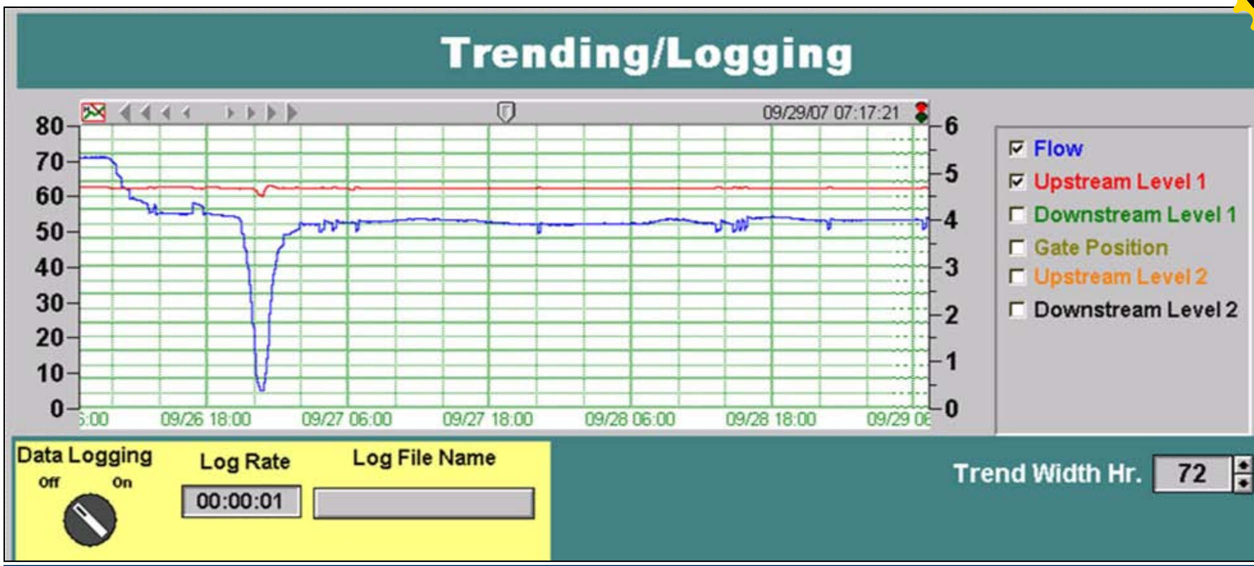

Figure 8: Log of Spills at the End of Highline Canal

The manager has had one full operating season with the automated pump-station, and is still on the learning curve. Currently the pump-station is used to compensate for operational malfunctions with canal equipment. The bumps, on the water surface trending lines (red), on the logs represent an accidental 50% (600 cfs) downward spike in canal flow at the diversion dam. At Camp 7, the spill dropped to zero and 45 cfs was pumped from Highline Lake into the canal. The regulating reservoir and pump-station respond well to large canal flow fluctuations, but why is the spill into the lake so unstable?

HIGHLINE CANAL AUTOMATION

Automated Canal Gates and Control Methods

Reclamation constructed the first motorized canal check structures in the Highline Canal as part of a canal lining, salinity control effort in 1979. The four new canal checks were automated as an afterthought in 1982, with surplus “Little-Man” controllers from a California Reclamation project.

Little-Man control logic uses an upstream canal water level as a target. If the water level moves a significant amount (up or down) from the target, the gate will automatically move in the appropriate direction to restore the water level to the target. Typically the gate move with Little-Man control is a fixed time length (5 seconds) and the control time step is also fixed (5 minutes). That means that if the water surface is off target, every five minutes the gate will move for five seconds to try to restore the water level to the target. The Little-Man controller will repeat the gate move process every five minutes until the target level is restored.

In 1986 the end of the Highline Canal was lined, under the salinity control program and four additional canal check structures were added. These checks were automated with an industrial ladder-logic controller, using Little-Man logic.

The Irrigation Training and Research Center (ITRC) and the Bureau of Reclamation partnered in a comprehensive canal modernization study starting in 1996. Construction of the canal structures from the studies recommendations began in 2000. The ITRC had developed a Proportional Integral Filtered (PIF) gate control algorithm. The ITRC modeled the Highline Canal system with the 14 existing and 7 proposed check structures on a hydrodynamic canal computer program.

The purpose of modeling all the gates in concert was to tune each PIF filter constants for overall canal stability, at various canal flow rates. If all of the gates are properly tuned, the gates should not induce waves in the canal.

When modernization construction was completed, the PIF logic was installed in the new check gates. Because of time and money constraints, the PIF logic for the older check gates was not implemented. These gates were already "automated". Performance of the old gates appeared to be fine. The Little-Man logic did not seem to be inducing waves into the canal and seemed to be able to hold the canal at the desired water levels.

We were aware of the fluctuations in the Camp 7 spill but believed these fluctuations were caused by the control on the overshot gate. In the summer of 2007 the control was changed to a PIF algorithm. This algorithm did a much better job of maintaining the desired water surface level in the canal, but the spill fluctuations persisted. Our current theory on the cause of the Camp 7 spill fluctuations is that the Little-Man control in the three old upstream canal checks are causing the problem.

CONCLUTION

Lessons Learned

Just because the canal water surface looks stable and the automated gates are working, don't assume the canal is under control.

The magnitude of the spill fluctuation was not believed by the designers until a SCADA system was implemented at the site, and data trending logs were examined.

It appears that Little-Man control can induce waves. Flow fluctuations are not observed in the canal in reaches with PIF control. One portion of the canal with Little-Man control appears to behave well, but in another portion Little-Man control appears to induce flow fluctuations.

The automated spill at Camp7 and the Highline pump station work very well, but the canal is not yet tamed.

The designer's operational point of view and the manager's operational point of view may merge, when the canal is brought under control

Upgrading the Flow Measurement System at the Tehama Colusa Canal Authority

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Abstract

The Tehama Colusa Canal System in northern California diverts water from the Sacramento River for use by various water districts across the region. The canal system is owned by the U.S. Bureau of Reclamation (USBR) and operated by the Tehama Colusa Canal Authority. The dam at Red Bluff is owned and operated by the USBR. Within this arrangement exists a network of release structures and pumps that frequently result in complex flow conditions in the canals and pipes that deliver water to the districts. Because of these dynamic conditions, automated flow instrumentation was needed to accurately measure the flow rate so that the total water volume could be accurately determined. We provide an initial description of the problem, the evaluation process of available technologies, and some results following the implementation of the new measurement technology at 23 sites.

Keywords

Doppler, canal, velocity, flow, shallow water, discharge, flow, Argonaut, irrigation, pipe

Introduction

The Tehama Colusa Canal Authority (TCCA)'s mission statement is: ". . to secure, protect, and develop dependable and affordable sources of water and to operate, maintain, and improve the works essential to deliver such water." Operating two canal systems for the USBR (the Tehama Colusa Canal, 110 miles long and the Corning Canal, 15 miles long), the combined system serves 17 water districts in northern California. For many years the system relied on gravity-fed Sacramento River water from releases at the dam at Red Bluff. However, because of regulations implemented in the late 1990's, the USBR could no longer rely solely on these releases and so installed four pumps with a total capacity of about 400 cfs. With peak irrigation demand between 800 and 1000 cfs, some creative hydraulics had to be implemented to assure uninterrupted delivery.

The solution involved installing an automated control system with both upstream and downstream control. Target elevations are maintained both upstream and downstream of the gates on any given pool. The resulting system is fairly stable and flows can reach 1700 cfs over the 110 mile stretch meeting the needs of the various districts. However, because the system no longer relies solely on gravity, complex flow conditions with reversals and stratification became the norm which required an evaluation of new discharge metering technologies that could work accurately under these conditions.

I. Metering Practices and Evaluation

Along the canal system there are more than 70 turnouts that presently use Venturi meters with Badger recorders as the principal measurement device. Each turnout is unique; however, they all have an undershot gate coming from the TCCA Canal. The entrance gate is typically fully opened and the flow controlled downstream of the gate. The turnouts have a straight run of large diameter (2-5 ft) pipe that varies in length. Some installations are greater than 15 diameters in distance between the gate and the first obstruction. Some turnouts have a common discharge manifold with other having up to three different discharge manifolds.

At each location there is a Venturi meter used for flow measurement. The Venturi meters have been in place since the installation of the turnouts over thirty years ago. The venturi meters are mostly located downstream of screens and pumps and are located in a vault 10-30 ft underground. The vaults have only limited room to access to the actual pipeline. Venturi meters work by measuring a differential pressure between two adjacent locations with different diameters. The field method for checking the accuracy of the Venturi system is by use of a Pitot tube that has an accuracy of +/- 3%.

While the installation, calibration, and maintenance of the Venturi system is a commonly understood practice, increasing human resources costs for service and training was causing concerns. Venturi systems frequently get clogged, must be purged of air at all times, and create limitations to the distribution system because of the requirement for a reduction in the channel diameter. In addition, new California safety regulations for work within confined spaces is adding to the ongoing costs. Thus, there was strong interest in moving away from this technology to reduce overall cost and maintenance.

II. Flow metering technologies considered

Several different technologies were considered for this project including acoustic, magnetic, and modified Venturi systems.

The first technology evaluated was a modified Venturi system with updated recording electronics as the Badger instrumentation was obsolete. The ongoing safety issues with accessing the vaults was the overriding reason to dismiss this option.

Electromagnetic technologies were also considered. Two basic types were evaluated:

1) Insertion
2) Full bore

Both types work using the principle of Faraday's law. Water flowing through a magnetic field of known strength will induce an electrical current proportional to the water velocity. The insertion type will measure the velocity (and level if equipped with a pressure sensor) at a specific point near the area where it is immersed. These instruments were trialed on site; however, they could not get a good reading due to the turbulent conditions that existed at the measurement point. There were also some concerns about their vulnerability to debris because they are installed near the center of the channel.

The full bore type was eliminated from consideration because the combined purchase and installation cost was prohibitive to what the project could realistically support.

The last type of technology to consider were acoustic methods – including two types of Doppler instruments as well as the travel-time velocity sensors.

Travel-time works by locating active and passive transducers on either side of a channel and measuring the amount of time it takes for the sound to travel between them. Knowing the fixed distance between the transducers as well as the speed of sound in water, the measured travel time is then proportional to the water velocity. This method is well known for providing highly accurate measurements. Installation and calibration requires good access to the inside of the pipe or channel. Because there were both safety and cost concerns about access, this option was dismissed.

Acoustic Doppler instruments work by reflecting sound energy off suspended solid matter that exists in the water. A transmitted pulse of a known frequency is emitted into the water and then a return frequency with a Doppler shift is received after reflection from these particles. The water velocity is directionally proportional to this Doppler shift. The technology works much in the same manner as police radars (tracking speeding cars) or weather radars (tracking clouds). For water velocity measurement, there are two general types: continuous wave, or pulsed.

Continuous wave instruments work by constantly sending out sound energy without regards to any timed interval. The return echo (and subsequent Doppler shift) is taken from whichever reflective target provides the strongest signal. In many cases this is the water's surface but it can also be the portion of the water column that has the most debris. In both these cases the speed measurement may be biased towards the stronger reflective area.

In contrast, pulsed Dopplers use a timing controller to emit sound at prescribed intervals. The instrument then "gates" the return echoes so it can tell where in the water column the reflection comes from. The advantage to this is that there is no bias on any particular portion of the water column and the instrument can automatically account for stratification in the velocity profile which is imperative for accurate velocity measurements under complex hydrological flow conditions. The disadvantage to this technology is that because it was developed for research/academic use, some of the useful features required for flow measurement are not yet developed or implemented for practical use in irrigation.

After some research and evaluation, TCCA settled on the SonTek Argonaut-SW instrument; however, only after SonTek agreed to some necessary modifications to the product to make it more suitable for the needs within TCCA. This involved incorporating a new feature into the firmware and software that would enable a minimum flow threshold for total volume. Thus, only flow values above this threshold would be reported as total volume.

III. Description of the Argonaut-SW

The Argonaut-SW is a bottom-mounted pulsed Doppler system that is ideal for complex flow sites (those with large stage variation or stratified flow), or for sites where purely theoretical discharge calculations are desired. One thing that makes the SW unique is that the entire instrument is self contained within one housing – there is no remote electronics unit like there are with all the other instruments evaluated. This greatly facilitated installation and set up.

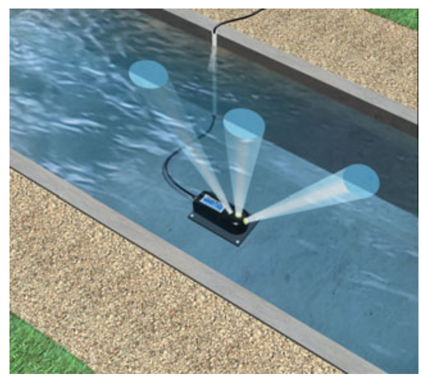

Figure 1 (left) shows the Argonaut-SW. Figure 2 (right) shows an installation site at an irrigation channel

The Argonaut-SW was designed with the following basic considerations:

- Operation in a wide range of water depths, with the minimum depth less than 1 ft.
- A vertically-integrated velocity cell covering most of the water column
- Accurate water level measurement
- Flow calculations for multiple channel types including trapezoidal, natural streams, and round/elliptical pipes

The Argonaut-SW uses two acoustic beams for velocity: one pointed upstream and one pointed downstream. The instrument is aligned with the axis of the channel. Small errors in alignment have negligible effect on velocity data since the velocity error is proportional to $(1-\cos(\theta))$ where θ is the error in alignment angle. Using two beams for velocity, instead of a single beam aimed forward, greatly reduces sensitivity to tilt angles in the installation. A third acoustic beam is aimed vertically up and is used to measure water level based on the timing of the reflection from the surface. The Argonaut-SW beam configuration is illustrated in fig. 2.

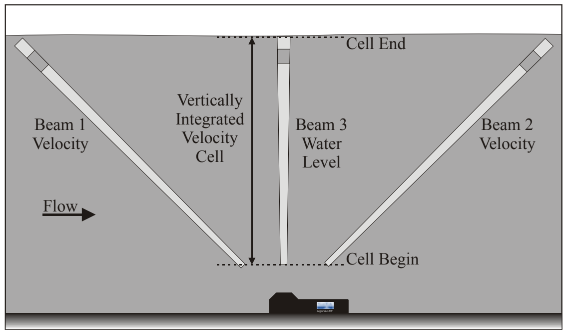

Figure 3. Argonaut-SW Beam configuration

To adapt to changing water level, the Argonaut-SW uses water level data measured by the vertical acoustic beam. The size of the sampling volume is automatically adjusted in real time to allow the Argonaut-SW to measure the greatest possible portion of the water column. The velocity measurement starts .23 ft (7 cm) above the sensor head (the acoustic blanking distance of the Argonaut-SW), and continues to the water surface. The instrument returns a single integrated velocity value representing an average over this portion of the water column. An optional feature is also available that returns velocity in up to 10 user programmable cells through the water column.

Because it was designed for small open channels, irrigation ditches, and culverts, the SW is as compact and low-profile as possible. Using an acoustic frequency of 3.0 MHz, its housing size is 9.7" x 4" x 2.5" (24.6 x 10.2 x 6.4 cm).

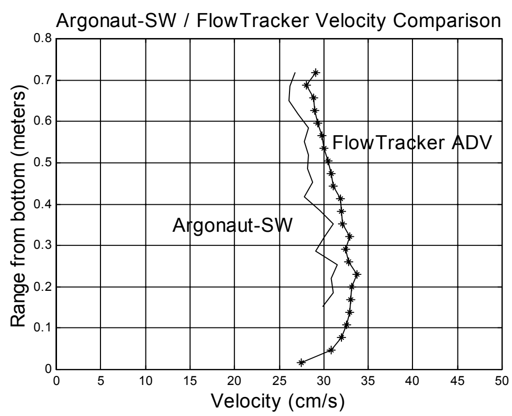

Figure 4. Velocity Profile Comparison

Because the SW is a pulsed Doppler instrument, it is able to provide a profile of the water velocity along the section of the water column where it is placed. This allows the SW to account for velocity stratifications in its internal flow calculations based on the channel cross-sectional area. Test data demonstrating this effect are shown in Figure 4.

These data were collected in a re-circulating flume with water depth of about 2.3 ft (0.7 m). The Argonaut-SW was mounted on the bottom, slightly off center. A FlowTracker ADV was manually raised and lowered to measure the current profile at the same location along the length of the flume; the ADV measurement location was 0.7 ft (0.2 m) to the side of the Argonaut-SW. The data shown in fig. 4 represent the average profile over a period of more than 1 hour.

The offset between Argonaut-SW and ADV velocity data (.0.07 ft/s or ~2 cm/s) is attributed to variations in the velocity field across the width of the flume, and is consistent with other flume data. The important comparison is the consistent shape of the velocity profile, particularly in the top half of the water column. In this case the Argonaut-SW is able to accurately measure water velocity all the way to the water surface, with no evidence of side lobe interference. Side lobe interference comes from undesired acoustic energy that propagates in direction other than the main beams. This is naturally occurring in any acoustic system; however, SonTek has taken steps to minimize this effect in their design. Tests in other flow conditions have shown similar results.

It is important to note that the SW can only make measurements all the way to the surface when the vertical beam can reflect off the free water surface only. In full pipe conditions, the hard reflective surface of the pipe wall contaminates the signal return. For these situations, a setting within the SW enables it to ignore that portion of the velocity profile near to the hard boundary. Velocity information is then extrapolated based upon the measured portion and accurate flow readings are still possible.

At its core, the Argonaut-SW measures water level and water velocity. To measure flow, the user is required to input the cross section of the channel (irregular, trapezoidal, elliptical, etc) and the SW will compute the area based upon the water level it measures. Velocity information is then applied and the SW computes flow in one of two methods:

1) Theoretical, based upon published flow formula
2) Empirical, based upon development of velocity index ratings

The empirical method is relatively new, deriving a specific flow equation for a given channel based upon independent flow measurements. If carried out properly, the end result is very accurate flow measurements with estimates of uncertainty based on the calculation method. The procedure is described by numerous papers including ITRC 006-003 *Non Standard Structure Flow Measurement Evaluation using the Flow Rate Indexing Procedure*. Once the proper equation is derived, the information is loaded into the SW for real time flow data output.

While the Argonaut-SW had a solid track record in the Western U.S. for flow measurement in open channels, TCCA could not make practical use of the device because of some shortcomings in the way it reports data. While the SW had been able to compute flow since its inception, it was never used for total volume measurements in such a complex flow setting. The basic problem TCCA was having had to do with timing of the pump operation and its effect on the flow in the pipes. At certain times between pump cycles or after one had shut down, the velocity of the water would start to acquiesce. This would often be accompanied by an event of back and forth motion at very low velocities. If the instrument would continue to accumulate volumetric data through this event, significant errors would be reported in the total volume. Thus the firmware modification to provide a low velocity threshold was necessary to provide a continuous record of accurate flow volume.

IV. Flow Meter test

In conjunction with Tehama Colusa Authority and Westside Water District, USBR personnel conducted two flow measurement tests. The initial test occurred December 21, 2005 using four different meters. A known volume of water was pumped into a holding tank and the accuracy of the meters was checked following each test. After extensive evaluation of the data collected, it was decided to conduct further testing isolating the SonTek Argonaut-SW Acoustic Doppler Meter. This testing occurred on January 13, 2006. The goal was to pump a continuous flow of water into the holding tank, varying the flow until a known volume of water was achieved. The SonTek and Venturi Meters were then compared to the known volume in the holding tank. Both meters recorded acceptable totals.

Based on the tests, Westside Irrigation District noticed that there were some discrepancies with their field current meters (mechanical) and decided to refurbish eight out of the nine field units. Their goal was to obtain volume totals similar to the Venturi Meter. Following the refurbishment, the field meters reported a negative 4% difference from the Venturi Meter. The time span allowed for the data to be collected was from April 30, 2006 to October 31, 2006.

USBR commends Westside Irrigation District for the work they have done refurbishing their field meters. The improvement from 9%-15% to 4% accuracy and the testing that was done confirms the fact that a maintenance program on all meters is the utmost importance for achieving acceptable results.

V. Installation, data and index velocity procedures

At the time of this writing, five SonTek SW instruments have been installed into the network and data has been collected and processed using index velocity procedures. The purpose of this limited deployment was to evaluate the instrument setup, and process some data to increase the users understanding of these devices so that some more standardized procedures can be applied to the remaining sites in the network. The present plan is to install an additional 45 meters into the TCCA network.

Figures 5 & 6: Photos show the installation into the one of the TCCA sites. The photo at right shows the Argonaut-SW cradled in a protective "shoe" that helps deflect debris away from the instrument

The TCCA currently calibrate flow measured by the SW using the Venturi meters which are recorded by Badger Instruments. As indicated previously, the Badgers are failing with replacement parts unavailable. Prior to undertaking the Velocity Index calibrations, ITRC personnel verified the accuracy of the Venturi meters, which is +/- 6% under the best of operating conditions. While a data review of the Venturi meters showed the instantaneous values to be very good, the Venturi showed some discrepancies under the constant flow tests.

Its believed that the discrepancies may be due to that fact that the flow was not actually at a constant rate due to water being pumped into the bottom of the tank.

For the velocity-index method, the measured velocity is sampled and recorded in programmed time intervals concurrently by both the device being calibrated (e.g., an Argonaut SW upstream of the pumps) as a continuous monitoring instrument and a second device or devices measures the simultaneous discharge measurement. In most cases these are portable devices which are capable characterizing the flow over the entire channel cross section. In this case because of access issues, the Venturi meter located downstream of the pumps was used. Mean velocities can also be obtained from other techniques such as pitot tube measurements, propeller meters, or other hydroacoustic instruments as long as the time periods are the same.

Using the SonTek FlowPack Velocity-Index Rating program, the resulting data for multiple sets of mean velocity and index velocity collected over a range of flow are analyzed using regression techniques. The resulting equation of the index velocity rating can then be utilized by the Argonaut-SW's internal flow computation feature. Every location will have its own specific index velocity rating, enabling data with the lowest uncertainty achievable.

Some data collected from an Argonaut-SW installed in a 42" pipe (107mm) at the Westside Irrigation District is shown below.

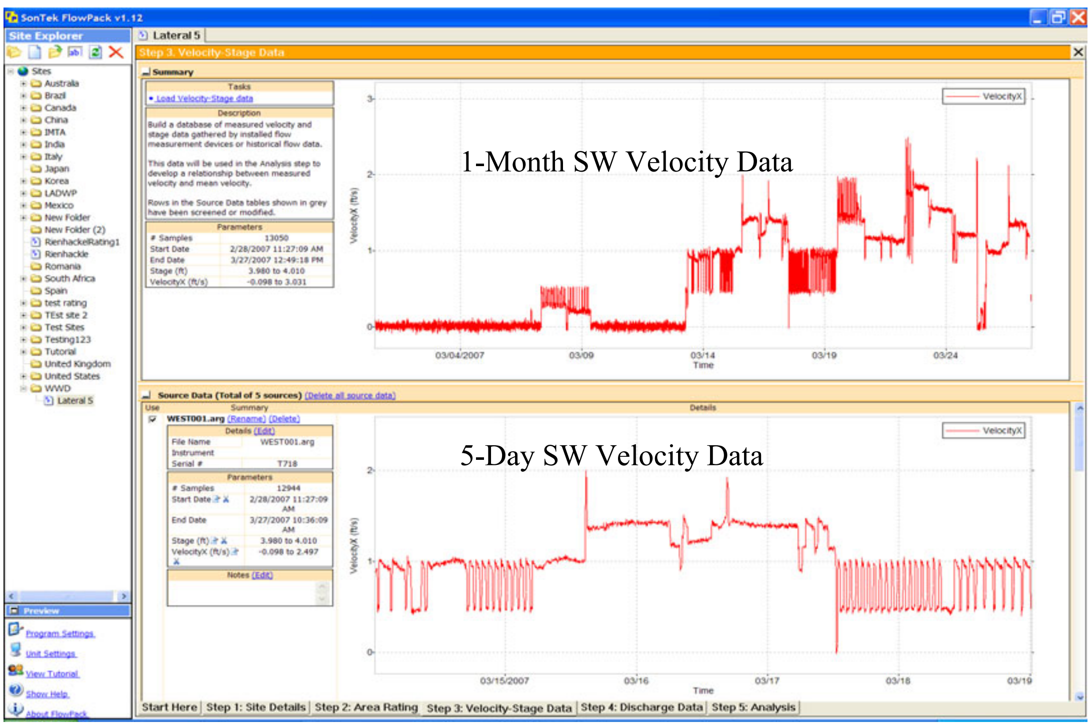

Figure 7: Plot showing velocity time-series data for Westside Water District Lateral 5.

Figure 7 shows the time-series velocity data measured by the Argonaut SW in a 42-inch pipe (Lateral 5) in the Westside Water District. The top velocity plot represents 1-month of continuous SW velocity data. The lower plot shows a 5-day excerpt of the 1-month data. The lower plot better shows the quick response of the Argonaut SW to the true variations in the pipe caused by changes in pump operating conditions.

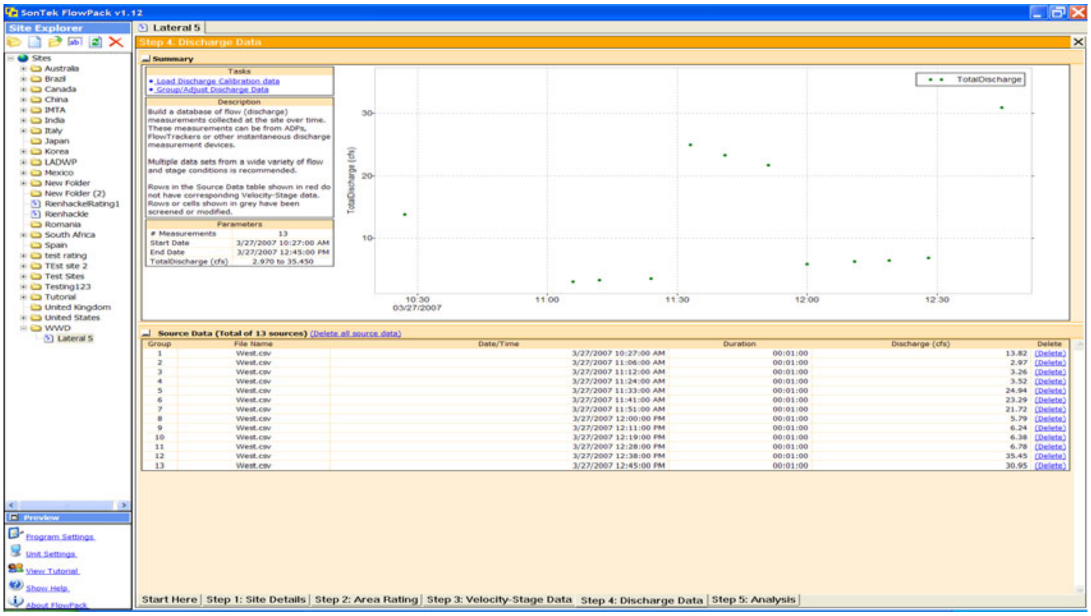

Figure 8: Discharge calibration data for Westside Water District Lateral 5.

Figure 2 shows the calibration data used to develop the mean-velocity rating for the Argonaut SW. The data were measured using a Venturi ranging in flows from 2.97 cfs to 35.45 cfs and were made concurrently to the operation of the Argonaut SW.

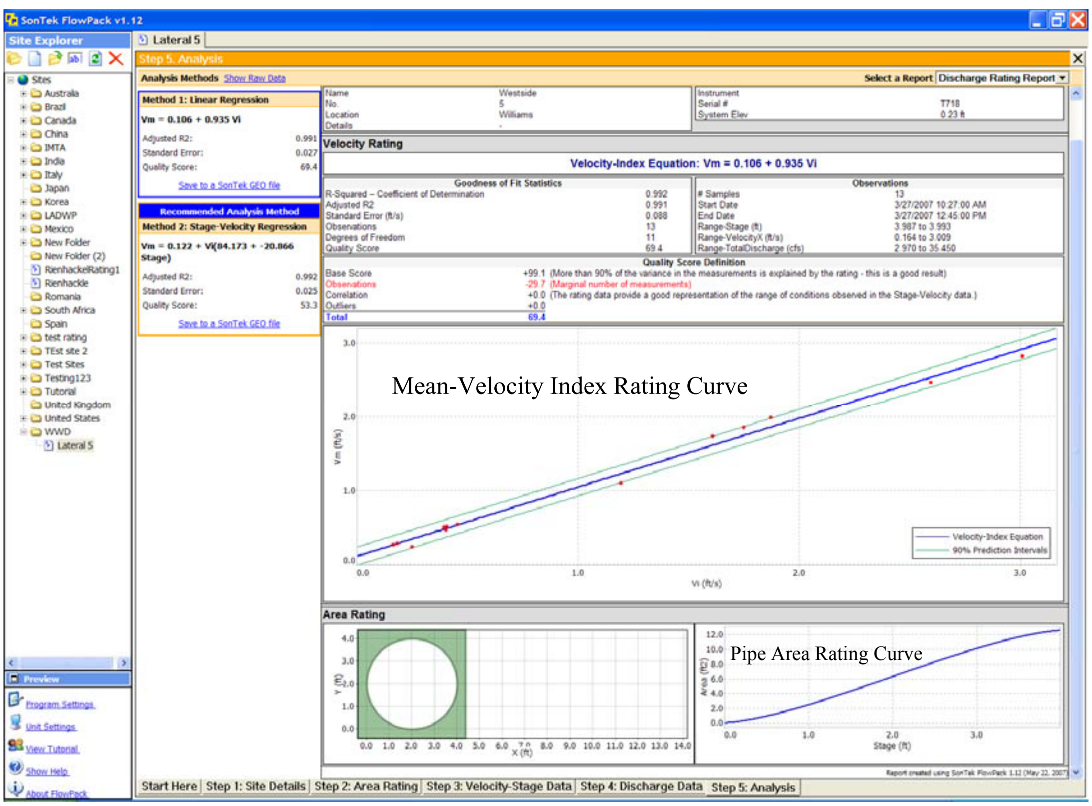

Figure 9: FlowPack discharge rating summary for Westside Water District Lateral 5.

Figure 9 shows the result of mean-velocity rating development using SonTek FlowPack Velocity index rating software. The figure shows the resulting mean-velocity and area rating curves used to calculate flow in the pipe (Lateral 5). Note that the linear regression is represented by the blue line and the light green lines represent the prediction intervals. One of the basic premises of velocity indexing is that the rating will improve over time with more concurrent measurements.

VI. Conclusion

More data needs to be collected and some of the procedures refined but from the USBR perspective, the data form the Argonaut-SW shows what was originally expected. That is, it very accurately characterizes what is going on inside the pipe and is able to properly exhibit the starting and stopping of the pumps. This is especially true when a pump shuts down, and then starts up again and the flow then sloshes back and forth for a period of time. The new features implemented by SonTek that set a flow measurement threshold for the recording of total volume worked perfectly in the applications thus far.

Though not shown within the data of this paper, we were also able to observe that the more pumps involved in a particular flow event, the more complicated the flow dynamics are within the pipe and this was exhibited in some of the data sets collected by the Argonaut-SW.

The velocity-index process is extremely valuable to an application such as this where there are numerous flow conditions to account for. Having a readily available software package like FlowPack that tracks ongoing data collection and provides the regression was highly useful to both the personnel in the field, and the operators who were evaluating the collected data.

The authors would like to thank the following individuals for their help in this project: Mr. Bryan Busch and Dr. Stuart Styles of ITRC for their work in both the initial evaluation of the project and the data collection portion, and Mr. John Sloat and Craig Huhta of SonTek/YSI for their ongoing technical support and data evaluation.

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"FLOW FROM FLEXIBILITY"

The Walla Walla Basin
The Water Management Initiative
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Gerald J. Anhorn
Walla Walla Community College

Introduction

The Water Management Initiative (WMI) is a unique opportunity, which has been presented to the people of the Walla Walla basin. Washington State Department of Ecology (Ecology) Director, Jay Manning, offered the initiative concept on a visit to the basin in 2005. He proposed to the people of the basin a different type of water management, one where the basin would be responsible for their own decisions and their own management of the resources in the basin. The offer had two requirements 1) instream flows had to be enhanced, and 2) any conflicts that would arise would be handled within the basin. In return Ecology would grant flexibilities, within the existing laws to help achieve the above-mentioned points. These flexibilities could demonstrate to the legislature the opportunity to enhance flows for fish if some permanent policy changes were enacted. If some flexibilities were identified as needed components but were not achievable because of the existing code, Ecology could use its existing authority to seek legislative changes to state law for a pilot program for the Walla Walla basin only. The Director also acknowledged that to achieve the ultimate goal of reaching identified instream flows a major storage project would have to be built. We could not reach the target flows with the initiative alone but the initiative would be a representation to the federal funding sources that this basin deserved such a project. In response to this offer the basin decided to enter into a partnership with Ecology to pursue further the notion of “flow from flexibility”.

The water management initiative in Walla Walla represents an attempt to recognize the need to use our resources for economic stability but also the need for preservation and protection of critical stream flows and riparian habitats. By identifying both critical elements, economic and environmental enhancements, the basin working as one entity can develop a management system that can achieve both desired goals. This management system will require the application and implementation of cutting edge technology. Integrating these technologies with new flexibilities can demonstrate greater environmental enhancements associated with the policy changes. This can then be used as a model and reproduced for other basins throughout the state and nation.

Background

This offer was extended to the Walla Walla basin because the basin has demonstrated the ability to work together on local issues and find solutions to those problems where other basins have not succeeded. This track record has gained the attention of the state and federal agencies and also has created a very good working relationship between the local people and these agencies. There have been countless numbers of volunteer hours in collaboration with the agencies developing science based conservation plans. These include a coordinated salmon recovery, watershed and sub-basin plan, a bi-state habitat conservation plan and others. These have all contributed to outcomes that both the community and the agencies can live with and have bought into because of the collaborative process used to developing then. This has contributed to “can do” attitude which has lead to some very creative out of the box thinking. It was this creativity and track record, which drew the Director of Ecology to put this offer on the table.

This collaboration has lead to many restoration projects which have already been implemented making progress towards the restoration of the stream flows, fish populations, and the riparian environments in the basin. These projects represent significant financial investment by both the funding agencies and the basin in the use of new technologies to reach desired outcomes. Projects such as the CREP (Conservation Reserve Enhancement Program) program have re-established over 150 miles of riparian habitat. Washington Department of Fish and Wildlife's Cooperative Compliance Program decreased juvenile fish mortality by installing compliant fish screens on over three hundred pump diversions throughout the basin. The irrigation efficiencies program has trusted over 6 CFS (summer flows) into the state trust with many more projects identified to save water. Other projects undertaken by the basin aimed specifically at increasing stream flows using cutting edge technologies include shallow aquifer recharge, and aquifer storage and recovery projects.

Current Situation

The Walla Walla basin is a very unique watershed due to the diversity and location of the area. The watershed (Watershed Resource Inventory Area, WRIA #32) includes portions in both Oregon and Washington. Roughly 2/3 of the basin is on the Washington side with the remaining 1/3 being in Oregon. The Oregon portion of the watershed is the upper region of the basin. This in itself can create cumbersome obstacles to overcome because of two sets of laws to deal with. Another issue at hand in the watershed is the fact that the water in the basin has been over allocated. A result of this over allocation had been the annual de-watering of tributaries and especially the main stem of the Walla Walla River. This problem was alleviated to some extent, for the mainstem, in 2000 by a negotiated settlement agreement between the three largest irrigation districts on the Walla Walla River with US Fish and Wildlife Services to bypass water. This has re-watered portions of the river, which in turn has kept the federal ESA regulators at bay. This re-watering has also lead to another identified problem relating back to the two different states. Water bypassed and protected in Oregon is not protected once it crosses the border and becomes Washington water. Two of the three irrigation districts are in Oregon while the remaining district is in Washington. Many of the smaller streams and tributaries of the mainstem are still dewatered today mainly due to the over allocation of water rights. These low or no stream flows have been identified in all the plans for the basin as a key limiting factor and a threat to ESA listed fish and other species. All these plans identify measures and actions that could improve flows throughout the basin. This information identified in these plans will be useful when the time comes to implement the demonstration projects for the WMI.

Other challenges identified have to do with the organization structure of entities working within the basin. At this time there are eight different organizations performing some type of leadership role. Although the intent of these organizations are always for the betterment of the resources and the people of the basin, many things are duplicated, activities performed are redundant and may at times represent inconsistent messages and activities. This has opened the door for funding agencies and policy makers to ask questions such as: Who speaks for the basin?: Are activities coordinated?: Who is accountable ?: and Are resources being used on the highest priorities? By establishing a set of needs for the basin, these and other challenges came be taken on and the basin can overcome then. The identified needs are as follows:

- Create local leadership and governance structure
- Formally organize all water users in the basin
- Define target flows and develop mechanisms to create and protect them
- Respond to legal disincentives through added flexibilities
- Set up a dispute resolution mechanism
- Establish performance measures and a tracking system for flow improvements

The flexibilities identified by the basin irrigators which they would like to see addressed through administrative relief or code adaptation could, if granted, greatly augment conservation efforts, including instream flows. Following are several examples:

- Use of surface and ground water conjunctively
- Simplified water right changes that benefit streams and users
- Share conserved water through the use of spreading
- Relief from relinquishment -"Use it or Lose it"
- Incentives rewarding innovation which lead to conservation
- Create a "water bank" within the basin
- Explore shared authority- (joint board of control)

By identifying the needs of the basin, and the flexibilities wanted, the basin has then been able to forward a performance task list which would need to be implemented to make the water management initiative successful. By establishing the first identified need: "Creating a local governance structure" the basin has a mechanism in which the tasks can be accomplished. The identified tasks are as follows:

- Ensure restored instream flows remain in stream
- Expedite water transfers and other water management measures
- Administer a water exchange or water bank.
- Manage agreements between water users
- Adopt and implement local water management policies
- Operate dispute resolution mechanism
- Track performance measures and flows
- Engage in water related economic development

As the basin has moved forward with the Water Management Initiative the governance mechanism has been identified as a major component to the success of the initiative. A very important issue is that of consolidating some of the eight different entities into this organization, thus streamlining many of the processes already in place. It has been delivered from the basin load and clear "Do not create a new organization, there are too many already". Because the basin has been heard, the organizational structure has expanded well beyond performing functions of the WMI. Not only can the governance structure serve to implement the initiative it can also overcome some of the legal challenges and some, if not all of the organizational challenges set forth in this paper. The governance organization could perform functions such as coordinating the implementation of projects, could be the one voice for the basin, be a single conduit for funding agencies, and resolve the bi-sate water issues. If authority was granted to this governance mechanism by the legislature, then Ecology as a partner could "hand off" some of its authority to this organization. This would in essence establish a shared-self governance organization which has some endowed authority from the state to make decisions on water management within its basin. This organization could then grant some of the administrative flexibilities identified by basin users and seek legislative flexibilities with Ecology as a partner. This allows the local people, who have the most at stake, a say in the decisions which affect their water and it creates an organization which can establish and operate a water bank, and a dispute resolution mechanism. Through the establishment and authorization of the shared governance mechanism, all the identified needs and challenges can be overcome because the tasks can be accomplished. This has focused the work on the initiative into the study of forming such an organization and the subsequent authorization from the legislature. This process is ongoing with the hope to have an organizational structure in place and authorized by the legislature in 2009.

On The Ground Implementation

Using technologies we can demonstrate how existing and new flexibilities can prove to be beneficial to both the environment and the users. A great example is the irrigation efficiency program. This program could benefit greatly by some minor policy adjustments, but it does work now on a limited basis and when it is implemented the results have had tremendous benefit to the environment and the user. The following is an example of a real project that was implemented in the Walla Walla basin.

This is an example of the existing irrigation efficiency program. To qualify for this program an irrigator must have an historical use that is greater than what he needs, usually due to low application efficiency. This creates a trustable component thus, the State is able to lease the saved water portion of the right. The example project is roughly 600 acres and has eight water rights associated with the properties, all eight being surface rights. The Walla Walla River splits the property with the majority of irrigated lands (424 acres) on the southern side. Of these 424 acres, 190 were being flood irrigated through an earthen lined ditch. This ditch contained all waters of a small tributary, which were diverted from the natural channel into the ditch two miles above the property and other waters delivered by a different ditch. In essence the tributary was dried up two miles above the property and all water was delivered to the farm via this ditch. Once the ditch water entered the property it followed the natural contours along the lower edge of a bench for approximately 1 mile where it discharged into a lower pasture never making it back to the river. This is the last property on this ditch but it has two of the most senior rights associated with these waters, and these rights contain stock water rights, hence water always was available to the user and it ran in the ditches roughly 49-50 weeks out of the year.

Of the 190 flood irrigated acres, 129 were converted to low pressure center pivot, another 49 acres were hand line and the remaining 12 acres would not be irrigated. By implementing new low pressure drop style center pivot technology the irrigation efficiency for these acres's changed from 50% to 85% and from 50% to 65% for new hand lines. A new pump station uses variable frequency technology to save more water and energy. Using these percentage numbers (NRCS standard efficiencies), soils information and crop consumptive use data a water management plan was developed with a net savings of 293 ac-ft year, or 1.63 CFS. Due to the complex nature of trust water programs the trustable components are usually less than the total savings. Total trustable components on this project were 257 ac-ft/year and .724 CFS[9]. These quantities were then trusted by the state. In return for the saved water the landowner received 85% cost share on the project. Total estimated cost for this project was $341,064.00 and was installed on budget. The landowner trusted all 100% of the documented savings.

On the books this project only shows the trusted savings, while in reality true saving and environmental benefit, especially on this project, cannot even be measured. The re-watering of two miles of a known salmonid spawning and rearing area and the elimination of a mile of ditch, running water 50 weeks out of the year, discharging into a field, are not shown as outcomes and are not measurable under this program. One can actually calculate the cost per ac-ft per year on this project (15year lease) but it is truly the un-documented increase to instream flows and riparian habitat that make this project a true win-win for all.

From the outset of this program this owner had been resistant to it. The reason, a complete validity and extent had to be done and he did not want to jeopardize any of his water rights. It was through an educational process that this landowner was shown, first he didn't need as much water as he was using, second all the excess water he was using was costing him money and third his production on his land would go up due to the efficiency of the new technology. This information and the financial incentive was all that was required to entice this landowner to step forward. Now conceive response to this program if some flexibility, such as changes to a water right which result in environmental benefit does not require a complete validity and extent, were granted. This flexibility could open the floodgates to restoration efforts because the fear of relinquishment could be reduced significantly.

Another great example of using precision application, drip irrigation, combined with flexibilities to enhance both economy and environment is the concept of spreading water. Spreading water is defined as using water on ground that is not associated with a water right. Simply put: irrigating land that does not have a water right. In prior appropriation doctrine the place of use is specific and uses elsewhere are illegal. If some flexibility was granted in this area the outcomes could have significant benefits to both the irrigator and the environment. The following is an example, if an irrigator is growing a high consumptive use crop, such as alfalfa hay, 4.5 Ac-Ft/year @ 60% efficient, the potential to convert to a low consumptive use crop such as wine grapes and integrate precision application, drip irrigation, can have a tremendous savings associated with the conversion. In this example the grapes would require 1.8 Ac-Ft @ 95% efficient. The associated 2.7 Ac-Ft savings could then be split between the landowner and the state each taking half. (These are example numbers and are representative only.) The States portion would be trusted to instream use while the landowner would be granted permission to apply the water to other lands which could then lead to greater production from the newly irrigated ground, resulting in economic benefit for the user and environmental benefit for all the citizens of the state. In return for the instream flow contribution a portion of the cost of the infrastructure conversion could be shared by the State, removing some of the economic burden of investment off the user. The establishment of a water bank could be the function used to accomplish the implementation of this flexibility.

One more combination of technology and flexibility would be the implementation of conjunctive use as a practice for water right holders. Conjunctive use is the ability to move from surface water to ground water and back again. The current code does not allow for this because the two sources of water are considered as separate and not interconnected. If irrigators would increase efficiencies through new technologies creating a quantity of savings as described above, the state could extend this flexibility when the stream flows dropped below the target flows for that particular reach. The irrigator would have a more reliable source of water to base their farming practices and crop rotations and any savings from the efficiency upgrade could be left instream. The final piece to this flexibility would be to implement an aquifer recharge program and recharge the amount of water used out of the aquifer. This recharge could be implemented in the winter months using excess waters, which normally just flow out of the basin. In essence we would be using the existing storage capacity in the ground to help hold the waters for use at a later time. To recharge the shallow aquifers water could be diverted during high flow times, onto the natural alluviums, allowing for percolation into these shallow gravels. To recharge the deep aquifer, all water must be treated to drinking water quality and then pumped back down the actual wells. This process is expensive, but the city of Walla Walla has already invested the infrastructure on five of their deep wells and have been implementing recharge for a couple of years. If the quantities of water used from each aquifer, during times of low flow, were monitored and measured we as a basin could create partnerships with the city to recharge the deep aquifer and with local landowners who's property could be flooded to practice the shallow aquifer recharge.

Another very important concept of the initiative is the concept of water banking. This concept requires all the identified components of the WMI. First you need an organization that can be the bank, then you need water saving technology to generate the deposits of water, then you need the flexibilities to spread that water to other ground. The concept is relatively simple: water is deposited through voluntary purchases, leases or donations. These would come from irrigators and other water right holders. Of the total quantity of water deposited an allocation would be made to the state for instream flows and a portion could be made available to users who want to expand production for that year. The bank could be monitored on a year-to-year basis, hence in low water years no excess water would be available for use, and likewise in a good water year there would be plenty in the bank for distribution to those who were willing to pay the highest for it. This concept is the accumulation of all the discussed points, with the organization being the key component. This is important because at this time only Ecology has the authority to establish water banks, thus this could be extended to the local organization as one of the flexibility granted to the basin.

These are all examples of how the use of water savings technology can be augmented by combining them with flexibilities. Many programs implementing technology exist today without the flexibility portion and most have had marginal results at best. By educating our users on the correct application and use of water, giving them the incentives to make the investments in these new tools and creating the needed flexibilities that can lead to economic benefits; the WMI will increase local stream flows and riparian habitats and enhance local economic stability. Only after the flexibilities have proven to work will the changes to policy be recommended for permanence, and then some that work in Walla Walla may not work in other areas simply due to the diversity between water users and watersheds throughout the state. The model of a local water management scheme could be the reproducible component and the changes to code to gain flexibilities, could be unique to each basin.

Conclusion

Many people and organizations have wrestled with the concept of change but few have succeeded. The bottom line is we have to do a better job of managing the water we have by using such tools as real time data from weather station networks, implementing high efficient application methods and educating users on how to schedule and plan for water use using these tools. By adding the flexibility component to the mix, the WMI, can achieve success were others have failed. The idea of integrating water saving technology with needed flexibilities to generate the positive environmental benefits and keep local economies stable will work because it is a true win-win scenario. By removing the investment barrier, through monetary assistance and displacing the perceived or real threat to relinquishment, through education and added flexibilities we will enable irrigators to once again be the stewards of the resource with out costing them the farm. It is time for this generation to step up and solve this issue and lead not with what we say, but rather in what we do, by creating this new water management system. A system in which local people are responsible for local decisions and everyone has a stake in the outcome. By accomplishing this the WMI can demonstrate that investment incentive combined with flexibilities, managed by local people, can generate the desired outcomes everyone in the west needs.

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EXECUTIVE SUMMARY REPORT

The Control of Algae In the Litani River Authority's Canal 900

Small Scale Testing and Validation and Scope of Work (SOW)

September 19, 2005

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EXECUTIVE SUMMARY REPORT

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Small Scale Testing and Validation And Scope of Work (SOW)

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Cover Photo: Application of Copper Sulfate to Canal 900 Near K2 Pump Station

1.0 Executive Summary

Canal 900 is operated by the Litani River Authority and is located in south central portion of Lebanon's Bekaa Valley. The canal's source water, Lake Qaraoun, contains high amounts of nitrogen and phosphorous. Nutrients in slow moving, shallow canal water provide ideal growing conditions for aquatic weeds and algae during the summer, resulting in clogged pump screens and poor water delivery capacity.
Algae control techniques were evaluated and copper sulfate was selected as safe and effective tool for algae control. Small scale testing in May and August 2005 proved that copper sulfate is an effective algaecide. The average concentration of copper sulfate in the canal will be less than the US Environmental Protection Agency (USEPA) drinking water standard and the annual amount of copper sulfate applied to land irrigated with canal water will be less than the European Union maximum allowable concentration for organic produce. LRA staff was trained in proper copper sulfate dosing estimates, application techniques and health and safety requirements.
As part of a comprehensive algae control Scope of Work for 2006, recommended activities this winter include cleaning the canal of debris, grading canal banks, repairing bridge abutments and footings to prevent soil from entering the canal, and evaluating operational changes in water delivery scheduling.

2.0 Background

Development Alternatives International (DAI) is providing advisory support services for the improvement of water quality management and remediation of wastewater and other pollution in the Litani River and Qaraoun Lake Basin.

The objectives of this scope of work were:

1. Recommendation for solution (s) for control of algae proliferation in Canal 900 (herein referred to as the "canal").
2. Preparation of a SOW and related costs for LRA to implement the recommended solution(s);

The tasks identified as necessary to accomplish the above objectives were:

1. Review and analyze the Canal 900 algae proliferation study carried out in 2003 and the algae identification study conducted in July 2004;
2. Based on the above review and analysis and using available data for flow/channel characteristics, recommend algae control solution (s) for canal 900 and prepare a concise plan and time schedule for:
    a. testing and validation of the recommended solution(s) during spring/summer 2005 and
    b. preparation of a Scope of Work (SOW) and related costs for LRA to implement a routine algae control program based on the validated solution(s).
3. Oversee, and conduct as feasible, field work to test and validate the recommended solution (s);
4. Prepare an SOW and estimated costs for LRA to implement a routine algae control program based on the validated solution(s).

Michael S. Blankinship, of Blankinship and Associates, was retained by DAI to execute the tasks described above. Mr. Blankinship is a California licensed professional Civil Engineer (PE) and Pest Control Advisor (PCA) in California with over 15 years of experience in the assessment and control of aquatic weeds.

3.0 Canal Characteristics

The canal is operated by the Litani River Authority and is located in south central portion of Lebanon's Bekaa Valley. Refer to **Figure 1**.

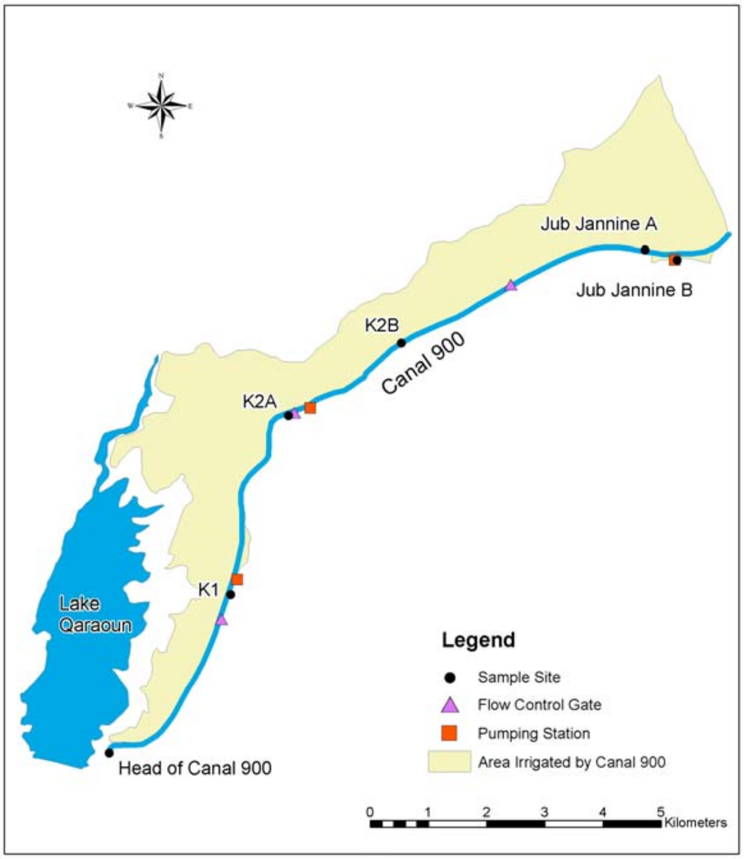

Figure 1. Project Location Map

Canal 900 an open, combination rectangular and trapezoidal, concrete-lined channel of approximately 18.5 km. It is divided roughly into 4 equal reaches of average slope of 0.2 % and delivers irrigation water from Lake Karaoun to approximately 1900 Hectares (Ha).

The canal is designed to deliver 30 million cubic meters per year (m^3/yr). Three pump stations deliver water to regulating reservoirs that subsequently service laterals that irrigate adjacent crop land totaling approximately 2,000 hectares (Ha). Water is delivered from May to September. The canal is dry the remaining 7 months of the year.

The main pump delivering water from Lake Karaoun to the south end of the canal delivers water at an average flow (Q) of 4.5 cubic meters per sec (m^3/s). Although not currently operational, the total delivery capacity of water from the 5 wells at the north end of the canal is 0.275 m^3/s. Water is delivered from regulating reservoirs to laterals at rates ranging from 0.170-0.890 m^3/s.

Crops in the Bekaa Valley irrigated by Canal 900 include, in order of predominance: wheat, potatoes, onions, water melons, tomatoes, and apples. Crops such as potatoes are sprinkler irrigated and other vegetables are drip irrigated.

4.0 Technical Documentation Review

We reviewed the following documents:

1.) Addressing Algae Proliferation in Canal 900 of the Litani River Basin in Lebanon. October 2003. DAI.
2.) Conveyor 800 Mission Report of the Algae Control Specialist. 09-12 February 2004.
3.) Litani River Authority, General Studies Department, South Bekaa Irrigation District Canal 900-Phase I (2000 Ha) Hydraulic and Technical Specifications. March 2, 2005

The following relevant facts were derived:

1.) Lake Qaraoun and the canal have hypereutrophic conditions highly conducive to the growth of algae.
2.) Reduction and/or treatment of Lake Qaraoun water to remove P and N is not feasible at this time.
3.) Unabated algae growth in the canal is blocking pumps, screens, and filters, clog drip emitters, limits water delivery to farmers, generate foul odors and attract mosquitoes
4.) LRA staff use nets and screens to manually remove algae.

5.0 Canal 900 Reconnaissance Findings

Site reconnaissance during both the May and August site visits revealed that the following aquatic weeds were present in the canal:

1. Filamentous green algae (*Cladophora* sp.) at all locations; most prevalent at and downstream of K1 pump station. Refer to **Figure 2**.

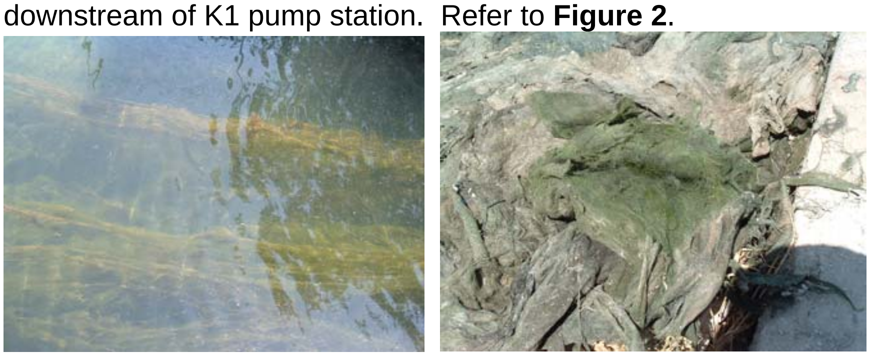

Figure 2. Filamentous Green Algae

2. Sago pond weed (*Stuckenia pectinatus*) and curly leaf pond weed (*Potamogeton crispus*) at and downstream of the K2 pump station. Refer to **Figures 3 and 4**.

Figure 3. Sago Pond Weed

Figure 4. Curly Leaf Pond Weed

The primary purpose of algae removal is to keep pump screens clean. Screens are located at each of the three pump stations and screen water prior to it being pumped to one of the three storage reservoirs.

Prior to reaching the screens, algae is currently removed from the canal by hand using rakes and boards placed across the canal. This technique is labor-intensive and must be repeated regularly.

6.0 Analysis of Suggested Control Options

Observations made during the site reconnaissance and data provided in the technical documentation reviewed suggest that a variety of aquatic weed control techniques may be considered. Each of these techniques is briefly discussed and evaluated below. Evaluation is based on past experience with these techniques in similar canal environments in California. A summary of the algae control options discussed above are presented in **Table 1**.

TABLE 1. Summary of Control Options

METHOD	POSITIVES	NEGATIVES	CONCLUSION
Chemical			
Various	See Table 2	See Table 2	Consider. See Section 5.0 below.
Mechanical			
Hand Removal	Available labor, past experience	Limited effectiveness, Labor intensive	Implement
Remove Canal Debris	Removes dirt, improves flow, prevents weeds next	Must be repeated every year	Implement
Bank Grading	Prevents Soil in Canal	None	Implement
Biological			
Apply Barley Straw	May slow algae production	Not proven; may clog pump screens	Do Not Implement
Use of Fish (Carp or Tilapia)	May eat algae and weeds	Must be repeated every year; may be removed by residents	Do Not Implement
Exclusion of Light (Trees)	May prevent algae from growing	Takes time to grow, only partial shade	Do Not Implement
Operational			
Agricultural Practices to Limit N & P	May prevent algae from growing	Control of the source of N & P is difficult	Implement if Possible; Provide education, extension and outreach
Exclusion of Light (Shade Structure)	May prevent algae from growing	Expensive, hinders canal maintenance	Do Not Implement
Improved Canal Flow Management	May prevent algae from growing	Current insufficient water demand to justify sustained high volume flow	Implement if Possible

7.0 Recommended Algae Control Solutions

Based upon the analysis of control options presented above, an IPM approach to the control of aquatic weeds in Canal 900 is recommended. Components of the recommended IPM approach include:

Mechanical Control:

1. The canal bottom should be thoroughly cleaned of all soil and debris. Weed seed may be present in canal cracks and joints and should be removed using pressure washing equipment or other suitable device
2. Retaining walls should be constructed at bridge abutments to prevent soil from entering the canal.
3. Ground on the side of the canal should be graded away from the canal so that during rain events no soil is washed into the canal.
4. Residents adjacent to the canal should be instructed on how to prevent soil from entering the canal from their property. Further, they should not be allowed to house animals close to the canal to prevent nutrients and bacteria in animal waste from entering the canal.
5. Algae should continue to be removed by hand from the canal and pump intake structures

Operational Control:

1. Consider decreasing flow during evening hours and increasing flow during daylight hours to decrease daytime water temperatures and increase shear stress on algae adhered to the canal banks.

Chemical Control:

1. Screen and select appropriate herbicide(s) based upon factors including ease of use, efficacy, toxicity to non-target organisms, and risks to applicators and residents near the application area.

8.0 Analysis of Chemical Control Options

As previously discussed, the climate, topography and growing season of Lebanon's Bekaa Valley is similar to that of the central Valley of California. Management of aquatic weeds in irrigation canals in California have historically relied on an IPM approach that includes the use of herbicides. Several herbicides have proven effectiveness and based on the screening and selection factors mentioned above, are evaluated and summarized in the **Table 2** below.

TABLE 2. Summary of Herbicide Control Options

Herbicide	Ease of Use	Efficacy on Algae	Toxicity to Non-Target Organisms	Risk to Applicators	Risk to Residents
Copper Sulfate	Easy	Good	None	Low	Low
Chelated Copper	Moderate	Good to Very Good	Low	Low	Low
Acrolein	Difficult	Excellent	High	High	High
Hydrogen Peroxide	Difficult	Good	High	Moderate	Low

At this time, copper sulfate is readily available to the LRA, has proven efficacy on the algae species present in the canal, and when used according to label directions will not likely cause adverse impact to aquatic environments in which it is used. It is a dry solid that is easy to handle and does not possess acute or chronic human health risks. Because the canal is concrete-lined and the water that it carries is not used for habitat for any species, the use of copper will adversely impact water quality. Further, when copper-treated water is used for crop irrigation, it is not known to be phytotoxic to the crops currently grown in the area.

In addition, the target concentration of copper in the canal will not exceed the US Environmental Protection Agency (USEPA) Maximum Contaminant Level (MCL) for drinking water of 1.3 mg/L.

Last, the anticipated amount of copper delivered annually per irrigated hectare of land per irrigation year is less than the maximum amount suggested by the European Union (EU) that can be added to soil annually for organic food production.

9.0 Algae Control Testing and Validation

Small scale testing and validation of algae control using herbicides was accomplished from 16-26 May 2005. Testing took place at three locations in the canal. A target concentration of between 0.5 and 1 milligram per Liter (mg/L or parts per million [ppm]) was initially targeted to evaluate the degree of algae control. Good to very good control of algae was noted in 3 days. Refer to **Figures 5 and 6**.

Figure 5. 20 May 2005

Figure 6. 23 May 2005

During the site reconnaissance done from 1-5 August, 2005, significant amounts of algae were noted, particularly from at and downstream of the K2 regulating reservoir. As a result, the dosing target was increased to 1 mg/L for the month of August.

On both the May and August field reconnaissance visits, LRA staff were trained to estimate the amount of copper sulfate required per location and date in order to achieve target copper concentrations. In addition, LRA staff were trained in appropriate techniques for safely and effectively measuring and applying copper sulfate to the canal.

10.0 Water, Crop and Soil Testing

Based upon water quality testing performed by DAI and LRA staff, canal water temperature increases from spring to summer and increases in chlorophyll concentration appears to precede observed algae counts. In addition, relative to other locations in the canal, high algae densities and chlorophyll concentrations were observed at the end of the canal at Jub Jannine and K2. This finding is consistent with the high water temperature and slow or non-existent flow that is present in these locations.

DAI staff performed soil and crop sampling. The data suggest that the soil in the area irrigated by Canal 900 has copper at a concentration that appears to be statistically significantly higher than the soil in background areas not irrigated by Canal 900. The reason for this is not known. This data does, however, provide background information for LRA staff so that the impact to area soils as a result of using copper in Canal 900 irrigation water can measured.

11.0 Cost Estimation

11.1 Summer Activities: Chemical Control

The estimated annual copper sulfate use is 1286 Kg and the estimated unit cost of copper sulfate of $3 USD/Kg, the cost to implement the control of algae in the canal is estimated at $3/Kg x 1286 Kg = $3,858.

Estimated labor costs for past manual control of algae were based on 10 men at a rate of $10 USD/day/man. This equates to a cost of approximately $15,000 USD for the 5 month irrigation season. Labor costs, however, are expected to less than this value when copper sulfate is used. Nonetheless, the need, if any, of continued manual removal of algae in conjunction with the use of coppers sulfate is not known and depends on the degree of control achieved with copper sulfate.

Therefore, a conservative estimate for the cost of implementing chemical control in the summer is $3,858 + $15,000 = $18,858 USD.

11.2 Summer Activities: Operational Control

Additional staff time will be required to execute changes in the operation of the canal to aid in the control of algae. The level of effort is not known.

11.3 Winter Activities: Mechanical Control

Additional staff time will be required to perform these tasks. Assuming 10 men at a rate of $10 USD/day/man for a 2 month mechanical control program, this equates to a cost of approximately $6,000 USD. In addition, the equipment such as skip loaders ($150/day) and backhoes ($150/day) will be required at a cost of $18,000 for the same 2 month period.

Therefore, a conservative estimate for the cost of implementing winter mechanical control is $6,000 + $18,000 = $24,000 USD.

This cost does not include the cost to design and build retaining walls around bridge abutments and footings. The cost for this work will vary and depend on the length, size and type of structure that is selected.

An Ecohydraulic Approach to the Modernization of Farmer Managed Irrigation Systems in Nepal

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Glossary of local terms used in this paper

kulo	canal
kula pani choudhari	The head of the farmers irrigation block

Abstract

This paper focuses on the optimization and expansion of farmer managed irrigation systems (FMIS) in Nepal. The three systems under concern namely the Majhara *kulo*, the Budhan *kulo* and the Raj *kulo*, situated at the left bank of the Babai river were constructed in the 1940s by the local community, using their indigenous knowledge. Actually the 5400 hectares (ha) area covered by these FMISs forms the head reach of the Babai Irrigation Project (BIP) which is aimed at providing irrigation water to an additional 8100 ha area after the construction of a new headwork and a 28 km long main canal in 2000. The annual volume of water to be claimed as "priority right" of the FMIS area is 86 million m^3, whereas the total available water volume is 682 million m^3.

In this paper it is shown that by replacing the old, leaking diversion constructions by new diversion weirs and control gates, a much better water distribution can be achieved during the low flow periods, while in periods of flood the newly designed irrigation system is able to continue acting as a flood management and protection system.

It is demonstrated that the approach of the FMIS modernization, besides being technically viable, is user as well as environment friendly due to its capacity to preserve the existing water management tradition of the farmers while at the same time, offering the opportunity to substantially extend the total irrigated area.

1 Introduction

Irrigation is vitally important in meeting the food and fibre needs for a rapidly expanding world population that reached six billion in 1999 and is expected to reach about 8.10 billion by 2030. The growing population will result in a considerable additional demand for food. Simultaneously, the water demand for the non agricultural sectors will keep growing in both developed and developing countries. To meet the food requirements of the growing population with growing water demand for the non agriculture sector there is a need to achieve a significant increase in water productivity. In the Nepal's context this challenge is expressed in terms of increasing the year round water supply from 41% to 90% of the total irrigated area in the period between 2002 and 2027 by means of enhancing the water use efficiency, ground water utilization and making storage arrangements (Water Resource Strategy, 2002 & Irrigation Policy, 2003).

In Nepal thousands of farmer managed irrigation systems (FMIS) have been developed and exploited by the local community over the centuries. It is estimated that there are about 15000 FMIS in the hills and nearly

1700 FMIS in the Terai (southern plain) of Nepal. More than 40 percent of the country's present food production is delivered by the FMIS which serve almost 70 percent of the irrigated area. Various studies have shown that FMIS generally achieve a higher level of performance than the agency managed irrigation systems (AMIS) with regard to the physical condition of the system, the water delivery effectiveness and the agricultural productivity (Lam Y.F., 1996). The farmers do a much better job of governing and organizing their own systems than government officials do on their systems (Ostrom E., 2002). The FMIS are the symbols of democratic values in Nepal. The community owing the system manages the resources on their own. They evolve the rules and regulations on their own and implement them with consensus within the community (Pradhan P., 2000). The diversion and other structures in the FMIS made by the farmers using local materials are normally of a temporary or semi permanent type with significant leakage occurring through these structures. That is why the farmers in the FMIS are bound to run their canals with a much higher discharge than actually required for crop growth. The proper rehabilitation and modernization of the FMIS can be considered as one of the pertinent ways to increase the water productivity and subsequent expansion of the irrigated area.

The goals of the rehabilitation project, discussed in this paper are to extend existing 5400 ha irrigation area with an additional 8100 ha while preserving the "priority water right" of the farmers exploiting the 5400 ha area. This will be realised by limiting the irrigation discharges during the low flow periods, by solving the actual leakage problems. At the same time the damage to the ecosystem, caused by erosion will be resolved by lowering the bottom slopes of the actual main irrigation channels. The quantity of water claimed by the farmers of the FMIS area as their priority right is 86 million m^3. In this paper we have carried out the analysis of a cascade arrangement of concrete weirs and the change in bed slope after the rehabilitation of the *kulos*. The US Army Corps of Engineers' river analysis system HEC-RAS has been used to simulate the performance of the *kulos* during high and low flow conditions before and after the rehabilitation of the system in order to determine an optimum user friendly structural arrangement of the permanent diversions.

2 The study area and unsolved problems

The study area is the FMIS part of the Babai Irrigation Project (BIP) in the Bardiya district of Nepal, which is located between 81°17' and 81°27' E longitude and 28°17' and 28°25' N Latitude. The East West Highway running almost parallel to the eastern main canal forms the northern boundary and the Babai river forms the southern and the western boundaries of the study area. The Vada river is located at the eastern boarder of the study area. The Babai river is the source river having a catchment area of 3270 km^2 and a high flood discharge of 7500 cubic meter per second (m^3/s). There are three FMIS in the study area, all located at the left bank of the Babai river namely the Majhara *kulo*, the Budhan *kulo* and the Raj *kulo*. Figure 1 shows the map of the study area with the headworks, the East West Highway, the main canal and the farmers' *kulos* with the names of the diversions.

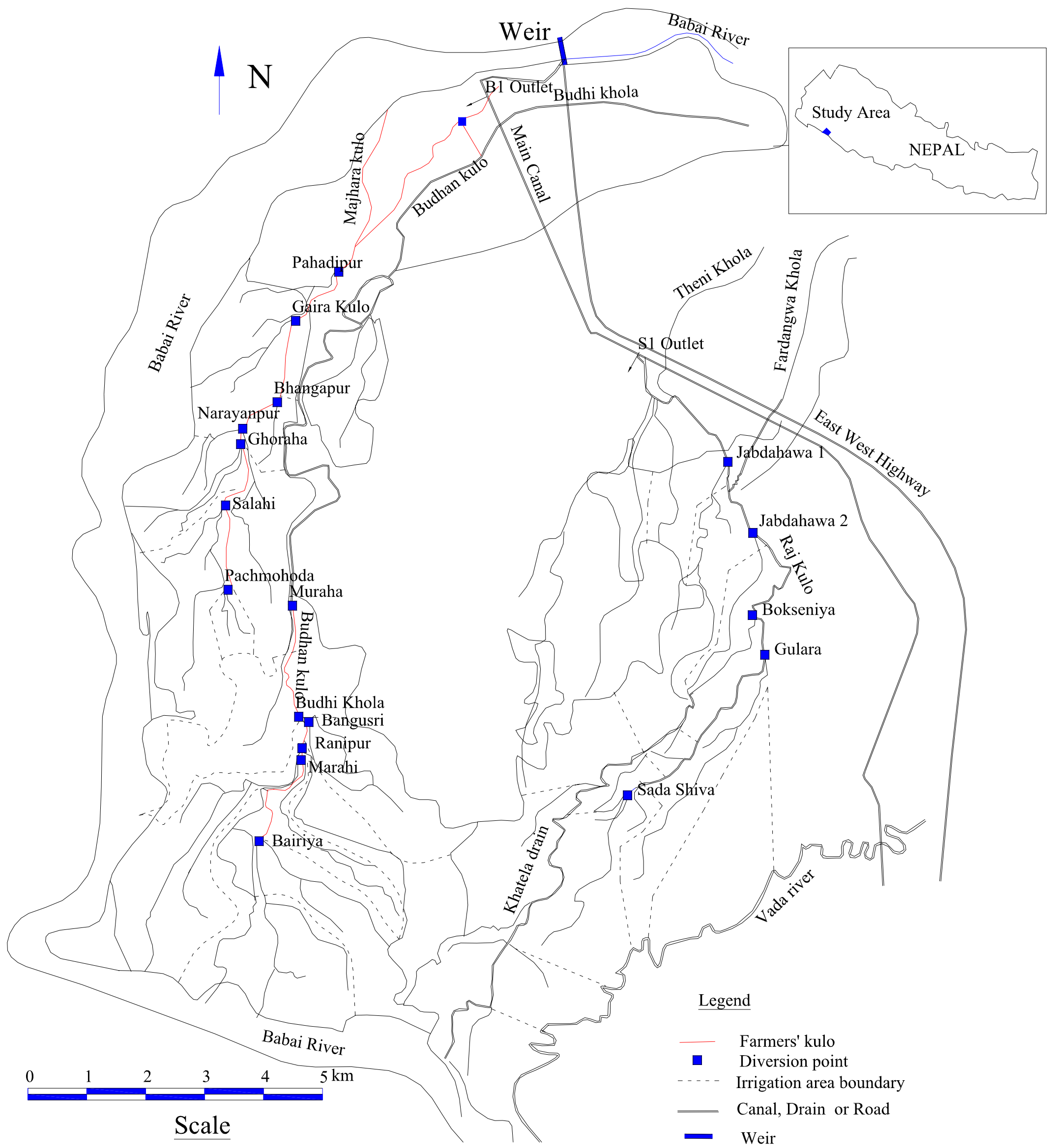

Figure 1: The map of the study area showing the headwork, the main canal, the FMIS *kulos* with diversions.

In 1992 the government constructed a weir cum bridge across the Babai river and the first 5 km of the east main canal as shown in Figure 1. As the bridge on the weir is a part of a national highway, the location of the bridge forced the designers to construct 5 km of the main canal to supply the Raj *kulo* and the Budhan *kulo*. In the period between 1995 and 2000 the BIP extended the east main canal from 5 km to 28 km bringing 8100 ha of dry area under irrigation. The government intervention and subsequent expansion of the irrigation area raised several questions among the farmers of the FMIS regarding their priority water right and modality of rehabilitation of their *kulos*. These questions are vitally important and need to be properly addressed in order to enhance the irrigation efficiency and to achieve better water management in the FMIS area as well as to guarantee sufficient supply of water to the extension area.

The BIP had designed a new canal system in 1982 for the whole eastern area including the FMIS part. However, the farmers of the FMIS area rejected the construction of new canals through fields which were already irrigated from another canal network. The rehabilitation of the existing *kulos* basically by replacing temporary diversions through concrete weirs was the farmers' main demand. In the nearby Rajapur area, the largest FMIS in Nepal, the farmers had rejected the design of diversions making more use of semi permanent gabion structures (Howarth S.E. et. al, 2002.) and the engineers were bound to change the design from crated boulder to concrete diversions. The farmers of the FMIS area being aware of the history of the Rajapur area, found that only permanent diversions were the appropriate solution to their problems.

The main concern of the farmers of the FMIS was to establish the "priority water right" of the existing FMIS before making any water sharing arrangement with the extension area. However, due to the absence of agreement on the modality of irrigation development at the FMIS part the BIP intensified the construction of branch canals in the new area since 2002. Many branch and secondary canals at the new area were completed by 2006 resulting into an increased water demand. The demand for water of both areas needs to be resolved properly in order to avoid the possible water use conflicts between the FMIS and the extension parts.

3 Field study and data collection

A field study was conducted by the first author in November, 2006. Participatory approaches were used to identify the irrigation related problems of the farmers, which included focus group discussions with the farmers of different *kulos*. Site visits accompanied by the head of the farmers' institution called *kula pani choudhari* were conducted along all three FMIS *kulos* during which the condition of existing temporary diversion structures, flood dispersion patterns and the existing leakages through the diversion structures were carefully observed. It was observed that the indigenous strategy of the local farmers in keeping completely open all the outlets to field channels during the rainy season is very effective in dispersing flood flows from the *kulos*. During the dry season the same *kulo* network is used for providing irrigation water to the fields. The farmers wanted to preserve their indigenous knowledge and the tradition of dual function of their *kulo* network.

The Environmental Impact Assessment study of the command area development works of the BIP conducted in 2004 had the requirement of presenting the project development plan to public hearing in order to get the farmers' consent on the plan. The cascade arrangement of permanent concrete diversions capable of preserving the flood dispersion tradition of the farmers and supplying water to the field channels effectively without leakage during low flows was accepted as a suitable solution to FMIS *kulo* rehabilitation by both the farmers and the BIP. The BIP provided the detailed longitudinal and cross section survey data of the Majhara *kulo*, the Budhan *kulo* and the Raj *kulo* and other designs and drawings prepared so far for this study. Several discussions were held with Water Users' Association WUA representatives and BIP officials regarding the FMIS rehabilitation and the increase of water use efficiency at the FMIS area. Previous study reports of the BIP and meteorological data were collected from the BIP, the Department of Irrigation and the Department of Hydrology and Meteorology.

4 Analyses and Results

4.1 Existing cropping pattern and its water requirement

The existing cropping pattern of the study area was determined in 2004 during the EIA study by means of questionnaire survey of 34 farmers from 4 villages representing the FMIS area. The cropping pattern was found to be 179% which is shown in Figure 2. The total cultivated area was 5400 hectare (ha), out of which 5100 ha was covered by rice and 300 ha by summer vegetables. In the winter lintel, wheat, pulses, winter vegetables and potatoes covered 700, 665, 1000, 600 and 200 ha respectively. Maize was the only crop cultivated in the spring season in 1100 ha of lands. The farmers of the FMIS area have been cultivating these crops since long ago with sole use of the east part's share of water from the Babai river and hence they claim the water needed to continue their present cropping pattern as their "priority right".

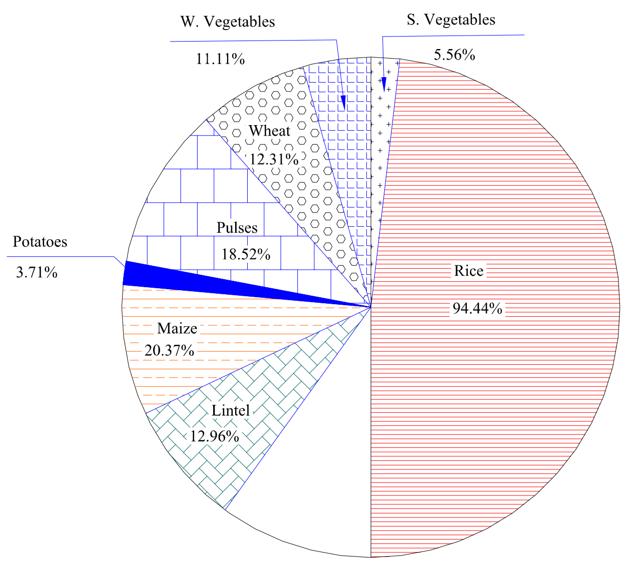

Figure 2: Existing cropping pattern in the FMIS area based on survey in 2004.

The crop water requirements (CWR) per hectare of different crops other than rice have been determined taking field application efficiency at 0.60. Due to the existence of a constant water pool in rice fields, the CWR calculation has been performed taking the deep percolation equal to 3 mm per day during the growth and 55 mm of water consumption during the two weeks needed in the preparation of the crop area. The combined main and branch canal efficiency has been taken at 50% in determining the intake water requirements. The CWR of each crop multiplied by the respective area gives the total water demand of particular crop and the sum of water demands for all crops resulting into the total water requirement. The monthly water requirement for the FMIS area and the available water in the main canal are presented in Table 1 and Figure 3. The total water requirement of the FMIS is 86.16 million m^3 (MCM) whereas the total available water for the eastern part is 683.2 MCM. Figure 3 indicates the plenty of surplus water from June to January. February and March are the most stressed months which is similar to the field situation.

Table 1: Water availability and requirement of the FMIS area, MCM

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Available	18.4	15.4	10.2	9.4	12.0	35.8	109.1	189.0	166.4	61.4	32.8	23.8	683.2
Required	5.11	9.84	10.41	2.64	3.63	1.27	21.15	5.29	9.33	15.09	0.16	2.24	86.16

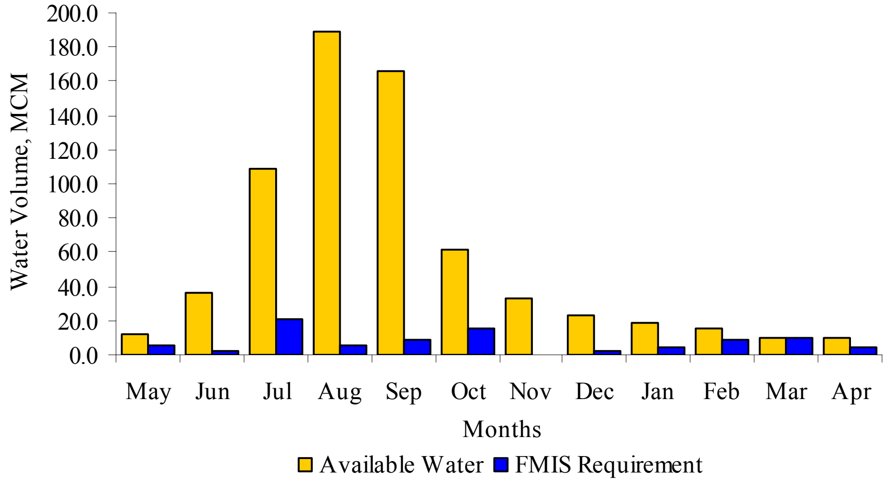

Figure 3: Monthly water supply and demand scenario at the FMIS area.

4.2 Arrangement of fixed constructions

The cascades of concrete weirs as a replacement of the temporary diversions in the FMIS *kulos* have been planned based on the longitudinal and cross section survey data of all *kulos* provided by the BIP. The cascade arrangement of diversions showing the name of each diversion, distance from the main canal in km, the drop height and the channel bed slope to be realized after the rehabilitation are presented in Figure 4. One of the important aspects to be considered is the change in bed slope before and after construction of the permanent diversions. In the Majhara *kulo* the steepest bed slope after the rehabilitation will be 0.00107 m/m (1:936) at the section between Bhangapur and Narayanpur, where the present average bed slope is 0.00236 m/m (1:423). In the Budhan *kulo* the future steepest bed slope will be 0.0012 m/m (1:833) in the sector between Padnaha and Ranipur instead of the present bed slope of 0.00175 m/m (1:570). Similarly in the Raj *kulo* the section between Bokseniya and Gulara will get a steepest slope of 0.00135 m/m (1:743) replacing the 0.00333 m/m (1:300) present situation. All these facts show that, after the rehabilitation, in addition to solving the leakage problems, the stability of the channel bed will also be enhanced, by this contributing to solving the erosion problem and to the overall ecological stability of the environment.

4.3 Simulations using HEC-RAS

4.3.1 Approaches and assumptions

The US Army Corps of Engineers' river analysis system HEC-RAS, a computer programme that allows performing one-dimensional steady and unsteady flow river hydraulic calculations, has been used for the steady flow simulations of all three FMIS *kulos*. The present and future water level characteristics of the *kulos* at different discharges have been studied through simulations of channels having leaky diversions at present and leak proof concrete diversions in the future. The existing diversion structures are made form crated boulders or a brushwood-boulders combination showing a similar leakage behaviour. In HEC-RAS they have been modelled as multiple obstructions of 1.25 m wide solid blocks with a 0.25 m gap between them.

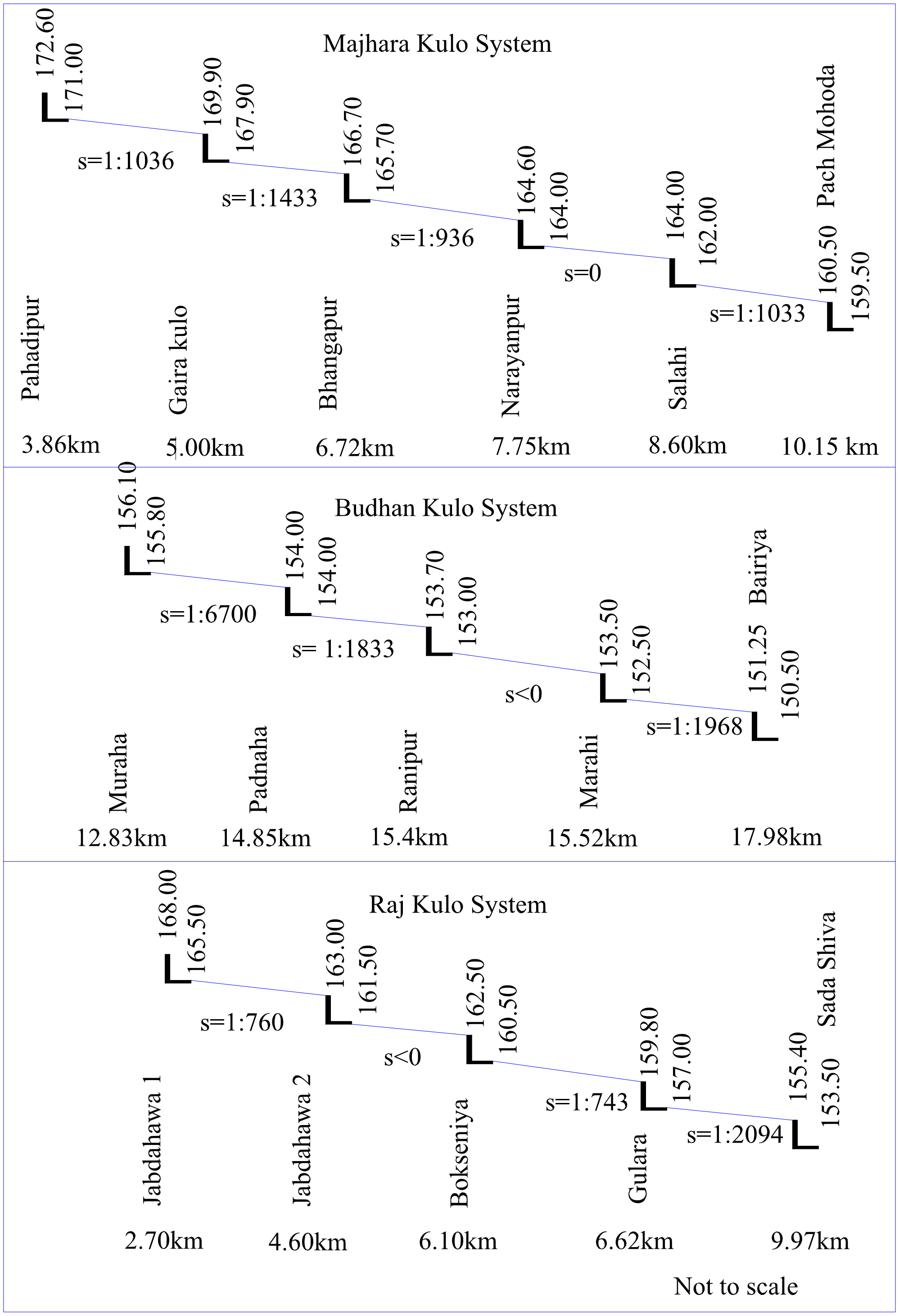

Figure 4: Schematic view of the proposed cascades of concrete weirs showing *kulo* system names, locations, levels and the bed slopes to be realized.

The top level of the obstruction has been set equal to that of the existing temporary diversion at each site as determined from the field survey. The lateral outlets have been modelled as free flow lateral weirs while the split flow optimization command of HEC-RAS has been used to assess the flow distribution between the lateral outlet and the *kulo*. The crest levels of weirs, scouring sluices and lateral outlets in the future situation have been worked out from the discussion with the farmers in order to fit the operation of the new structures to the farmers' demands. Based on these levels the design will be optimized using multi-criteria analysis. Figure 5 shows how the present situation and the future proposed situations of the diversion weirs have been simulated in HEC-RAS. The farmers will continue their tradition of high flow dispersion during the rainy season and providing the year round irrigation by their *kulo* network due to the long established social settings. Hence the main focus of the simulation is to find the structural arrangement giving similarity in flow dispersions at the present and future situations at all the diversion points, but while saving substantial amount of water in the dry season.

The peak discharges in the Budhan *kulo* and the Raj *kulo* are governed by the runoff from their catchments. The Majhara *kulo* is vulnerable to floods in the Babai river since it still draws water from its original intake at the Babai river, in addition to the regulated flow from the main canal. The Budhan *kulo* carries run off from the *Budhi* river and the Raj kulo carries the run off from the Theni and the Fradangwa rivers. The peak flows in these rivers have been estimated applying the in Nepal widely used Medium Irrigation Project (MIP) method (M3 Manual). The catchment areas of each river and the calculated peak discharges are presented in Table 2. The peak flows taken for the analysis at the Budhan and the Raj *kulos* are 25 and 85 m^3/s. For the case of the Majhara *kulo* the peak flow of 25 m^3/s is assessed based on the maximum carrying capacity of the upstream cross section. The peak and low discharges taken for the simulation are shown in Table 3.

4.3.2 Simulation Results

The water surface profiles obtained from the HEC-RAS analysis during the peak and low flows of the Majhara *kulo* at the present and future situations are presented in Figure 6a. At present, the low flow profile is almost parallel to the bottom without forming any pool at the diversion sites indicating the leakage through the pores, whereas the low flow profile for the future situation shows a significant rise in water level near the diversion sites indicating the presence of leak proof structures. The low flow profile at present downstream of the Salahi diversion shifts from below to above the future situation profile indicating the significant

Table 2: Estimated peak flows and catchment area of the natural drains

River	Budi river	Theni river	Fardangwa river
Catchment Area, km^2	6.5	5	16
Peak Discharge, m^3/sec	25	25	60

Table 3: Peak and low discharges used in the HEC-RAS analysis of different *kulos*, m^3/sec

Kulo	Peak Discharge, m^3/s	Low Discharge, m^3/s
Majhara	25.0	1.0
Budhan	25.0	2.0
Raj	85.0	1.5

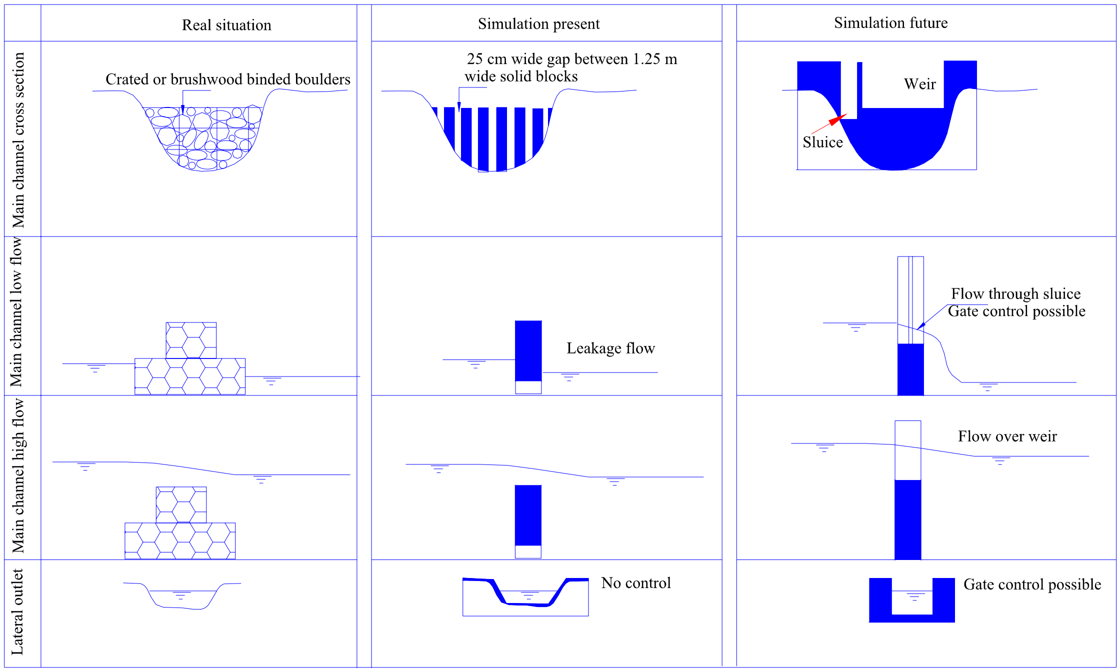

Figure 5: Real situation and HEC-RAS simulation of diversions and outlets at the present and future situations.

Leakage flow in the present situation. In the upstream reaches of the *kulo* the channel widths are higher, resulting in higher leakage flows and by this causing much difficulty to the farmers in diverting water to the fields during low flows. On the other hand, the downstream reaches get leaked water even if it is not needed. The low flow profile at the future situation has been simulated assuming free flow without any gate control. Gate operation at the lateral outlets and sluices will make it possible to run the branch canals in their full capacity on rotational basis. The upper two profiles in Figure 6a are the water surface profiles of the peak flow in the present and future situations. Closeness of both the profiles along most of the *kulo* length demonstrates similarity in flow situations at present and in the future. The biggest differences appear at the diversions where leakage flow is replaced by flow over the structures. Figure 6b and 6c represent the water surface profiles of the Budhan *kulo* and the Raj *kulo* showing much similarity with the profiles of the Majhara *kulo*. In the Raj *kulo* the future peak flow profile downstream of the spillway passes slightly above the present one, indicating the reduction of channel discharge after the spillway. The similarity in dispersion pattern in present and future situations proves the appropriate sizing of the permanent diversion structures for keeping the existing canal systems intact and functionally consistent with the farmers' tradition of water management and flood protection.

Figure 7 shows the dispersion pattern of peak flows in present and future situations for all 3 systems. The upstream discharge of 85 m^3/s at the Raj *kulo* is reduced to 20 and 21 m^3/s respectively in diversion number 5. In the Budhan and the Majhara *kulos* the peak discharge of 25 m^3/s is reduced to 6 m^3/s at diversion no 5 in the present as well as in the future situation. The discharge ratios between the "future" and the "present" situations at the Raj *kulo* during an upstream peak flow of 85 m^3/s are 0.72, 0.81, 0.79, 0.76 and 0.95 at the first to fifth diversions respectively. In the Budhan *kulo* during an upstream peak discharge of 25 m^3/s, the

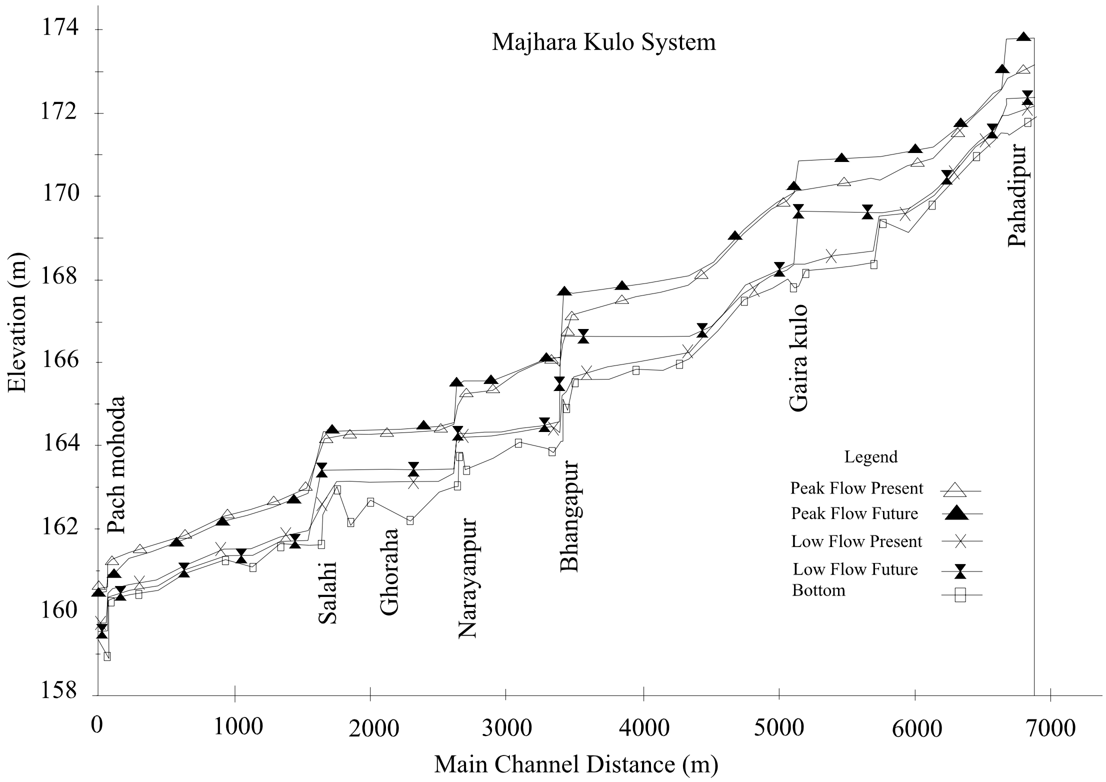

Figure 6a: Water surface profiles obtained from the HEC-RAS simulation of the Majhara *kulo* for present and future situations and for peak and low flow, respectively.

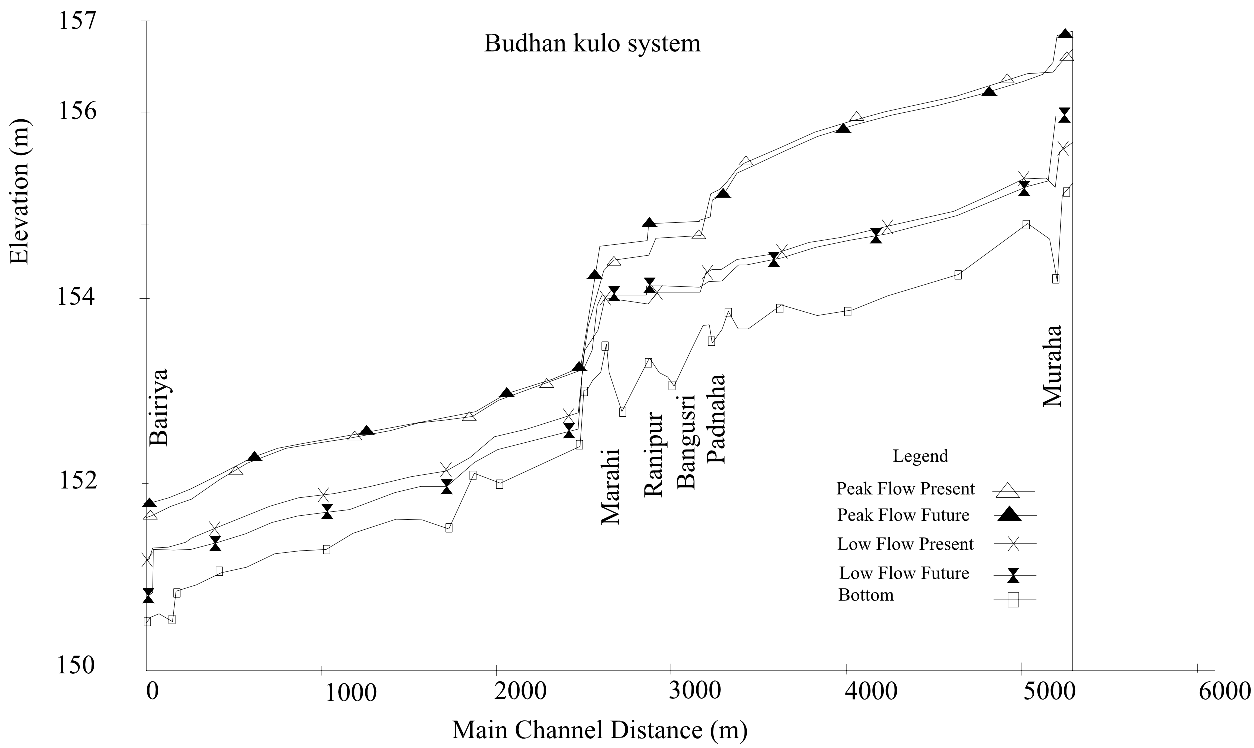

Figure 6b: Water surface profiles obtained from the HEC-RAS simulation of the Budhan *kulo* for present and future situations and for peak and low flow, respectively.

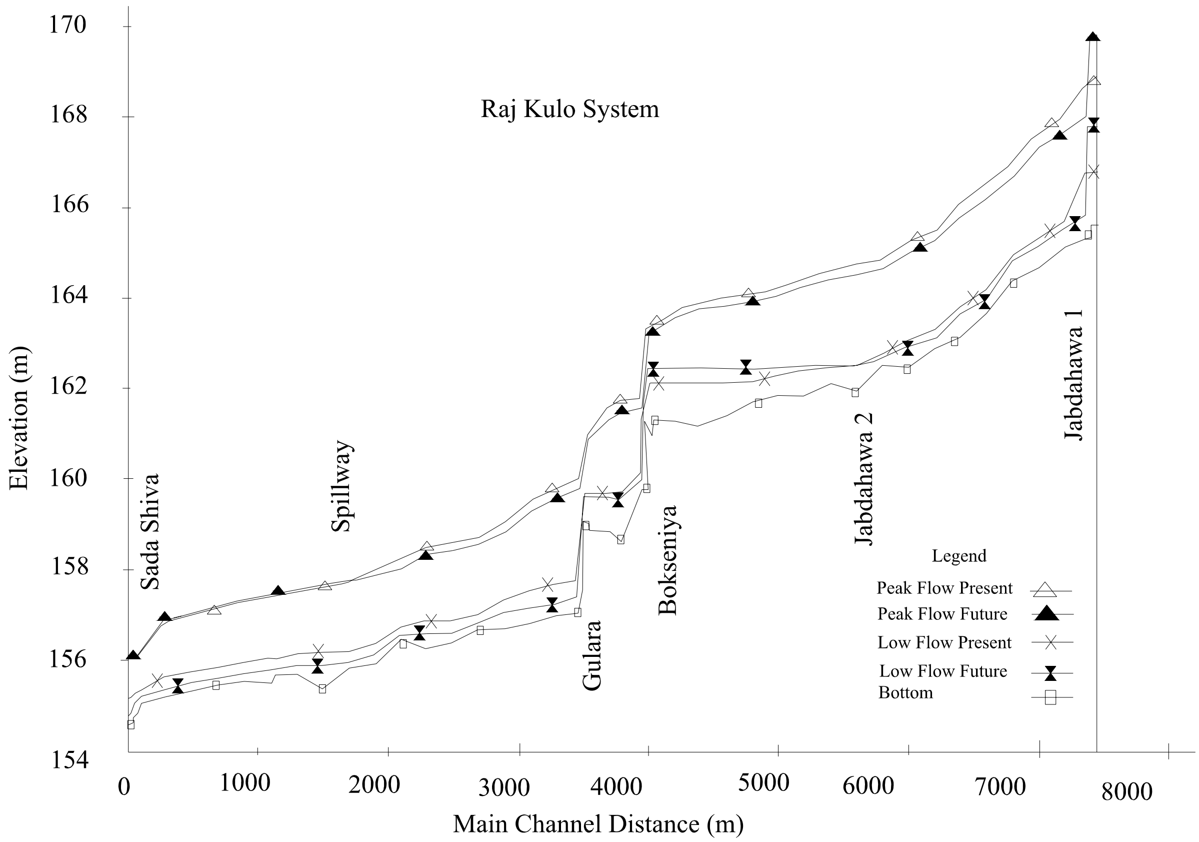

Figure 6c: Water surface profiles obtained from the HEC-RAS simulation of the Raj *kulo* for present and future situations and for peak and low flow, respectively.

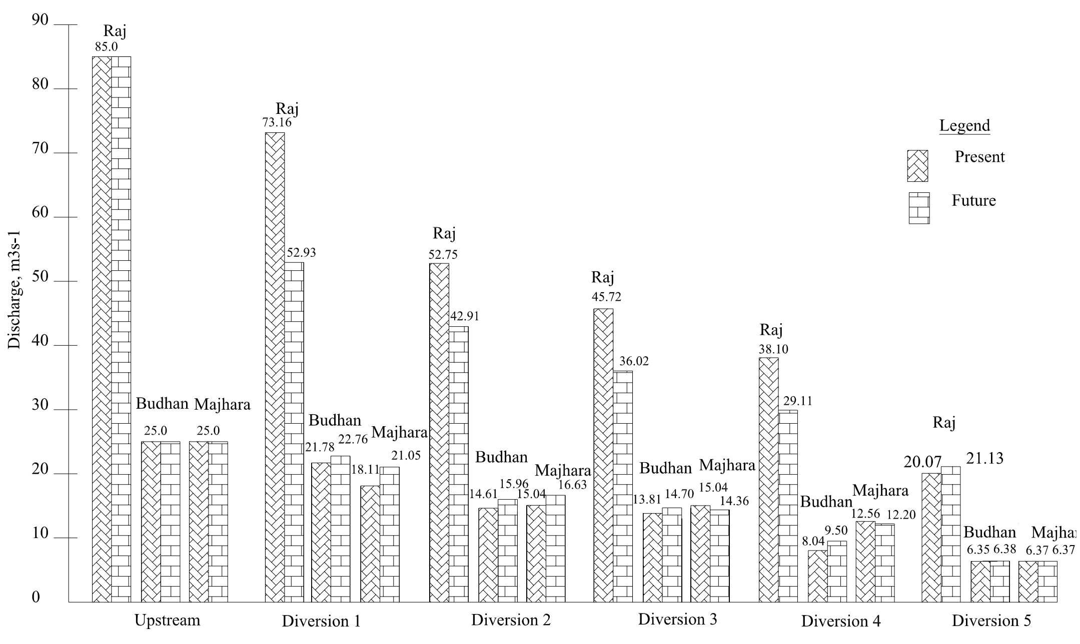

Figure 7: High flow dispersion patterns at present and future situations of the Majhara, Budhan and Raj *kulos*

respective ratios are 1.04, 1.09, 1.06, 1.18 and 1.00 whereas for the Majhara *kulo* with the same upstream discharge as the Budhan *kulo* the respective values are 1.16, 1.11, 0.95, 0.97, and 1.00.

5 Discussions and Conclusions

Our study has given an answer to the farmers' question of preserving their priority water right which is extremely important to determine the farming possibility at the new area using the remaining water. It has cleared ways for further water sharing arrangements between the FMIS and the new areas. There is a great possibility of saving water and increasing the production of winter and spring crops in the FMIS area even without additional abstraction of water controlling leakage and using efficient water management practices.

The HEC-RAS analysis of the present and future situations of all the three *kulos* has proved the appropriateness of the proposed arrangement of leak proof diversion structures while maintaining the farmers' tradition of flood dispersion practice. The solution of installing a cascade of diversion weirs similar to the existing diversion strategy was proven to be the most viable alternative from both social and technical considerations.

The similarity in dispersion pattern at the present and future situations proves the appropriate sizing of the permanent diversion structures which is important for keeping the existing canal systems intact and functional consistent with the farmers' tradition of water management and flood protection.

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Reduction of irrigation water consumption in the Colombian Floriculture with the use of tensiometer

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Key words: chrysanthemum irrigation, irrigation saving.

INTRODUCTION

In 1998, Jaramillo reported that water consumption per hectare in the chrysanthemum cultivation cycle (3 months) under greenhouse conditions in Bogota plateau (Colombia) was frequently 5 to 6 million liters. Some growers argued that had reduced consuming of water down to 2,5 million liters per hectare per cycle.

This research work started in 1998 with the objective to reduce even more the irrigation volume with the use of tensiometer. The preliminary results of the research achieved in 1999 showed that consumption was reduced to 1,4 million liters. The work was focused on reduction of water consumption and keeping or improving chrysanthemum quality and production.

MATERIALS AND METHODS

Experiments were conducted in a commercial production greenhouse in Bogota plateau, Colombia in 2001 and 2002 (Table 1). The control represents the farm traditional irrigation without use of the tensiometer, with 4 drip irrigation laterals per bed with 2 $L \cdot h^{-1}$ Agrifim® drippers, with 30 cm spacing. This treatment used manual irrigation hose for the first 21 days of crop development. For the rest of the stage, the crop was drip irrigated for 20 minutes, three times per week. Treatments with tensiometer had 5 Chapin® drip tapes per bed with 20 cm outlet spacing and 0,75 $L \cdot h^{-1}$ emitters. Drip tape treatments used Naan Dan® fogger irrigation with different number of pulses per day along the first three development weeks. Soil water tension was monitored with tensiometers 10, 20 and 30 cm below soil surface. There were taken into account field capacity values reported in 1990 by Boswell and in 2002 by Soilmoisture® from data presented by Wateright®.

Table 1: Treatments:

Treatment	Description
Control: Farm	Initial stage (21 days): Manual irrigation hose each other day without use of the tensiometer. Second stage (67 days): Traditional drip irrigation three times per week without use of the tensiometer.
T1	Initial stage (21 days): One fogger pulse each other day without use of the tensiometer. Second stage (67 days): Drip tape irrigation three times per week with use of the tensiometer.
T2	Initial stage (21 days): Two fogger pulses per day. Second stage (67 days): Drip tape irrigation three times per week with use of the tensiometer.
T3	Initial stage (21 days): Three fogger pulses per day. Second stage (67 days): Drip tape irrigation three times per week with use of the tensiometer.
T4	Initial stage (21 days): Five fogger pulses per day. Second stage (67 days): Drip tape irrigation three times per week with use of the tensiometer.

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Important: The use of trade names in this paper does not reflect the endorsement or criticism of a product.

RESULTS AND DISCUSSION

Reduction of water irrigation consumption

Treatments T2 to T4 saved irrigation water since the first week of cultivation (Fig. 1 and 2) showing advantages of use of the tensiometer.

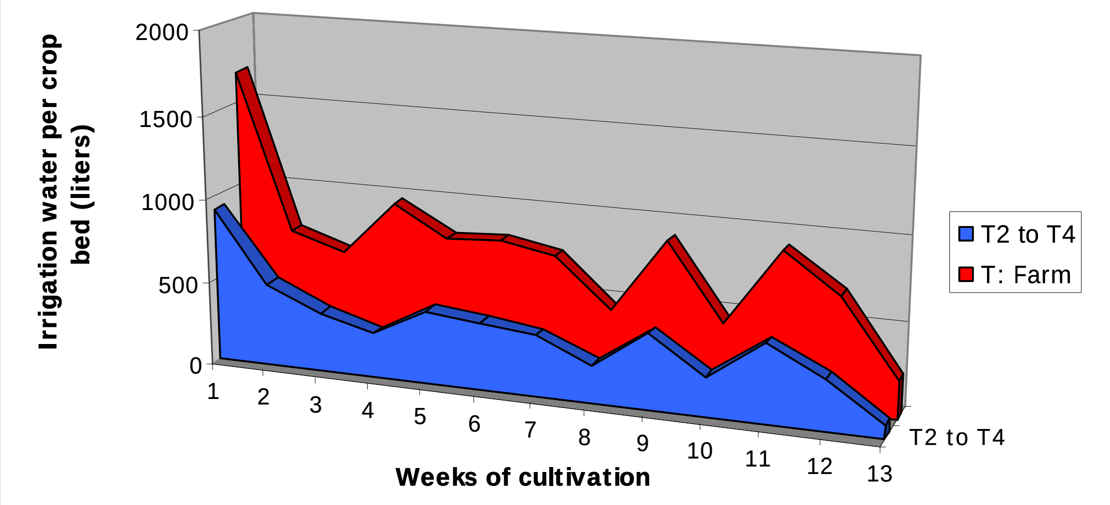

Figure 1. Irrigation water consumption (liters) per crop bed (36 m^2) for every week of cultivation

Farm treatment irrigation consumption totaled 9995 liters per 36 m2 bed, in 13 weeks of cultivation cycle. Treatments T2 to T4 with tensiometer support showed consumption of 5061 liters. Consumption went down from 3,15 (control) to 1,6 L · m^{-2} · day^{-1}. Savings of water reached 49,4%. Class A evaporation pan was installed inside of the greenhouse. Evaporation was 1,2 mm · day^{-1} (average for the 88 days cycle of cultivation). Water irrigation consumption obtained in this research work was smaller than requirements between 5 and 7 L · m^{-2} · day^{-1} reported by Fides in 1999.

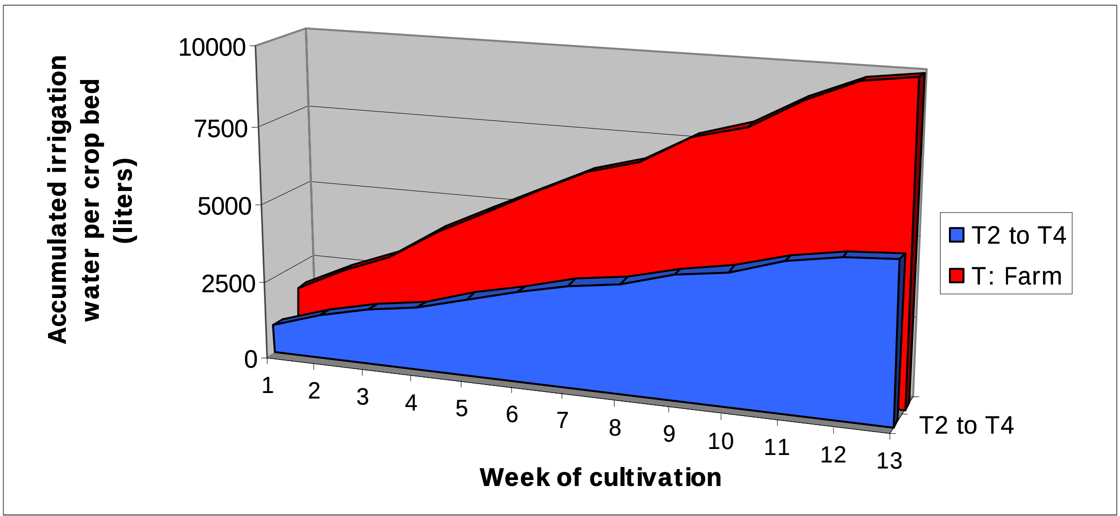

Figure 2. Accumulated irrigation water (liters) per crop bed (36 m^2) for every week of cultivation

Through all cultivation cycle, from 0 to 30 cm deep, farm untreated plot kept an average tension below field capacity, confirming over watering. Treatments T2 to T4 registered oscillating tensions between 10 to 35 centibars.

Vase life
Significant differences were found between treatments (Fig. 3), but no one was different from the farm treatment.

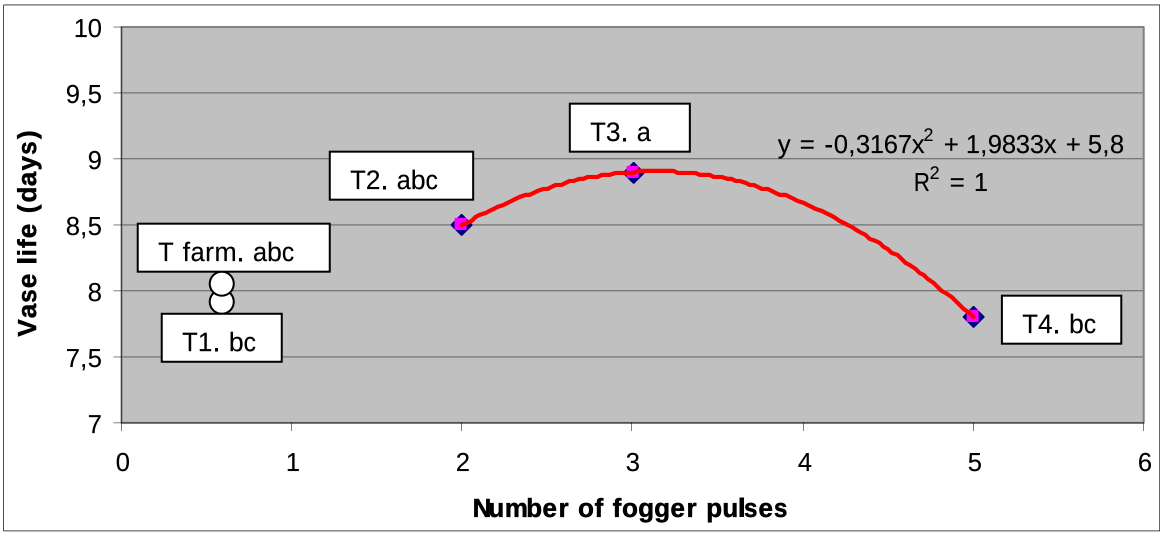

Figure 3: Effect of number of fogger pulses on vase life (days). Treatments with the same letter are not significantly different according to Duncan Test (p=0,05)

T3 treatment showed a better trend of vase life compared to the farm treatment. It can be seen in the following paragraph that T3 treatment had the better impact on root fresh weight.

Root fresh weight
There were found no differences among the treatments for the root fresh weight for 0 to 10 cm (Fig. 4). For 0 to 20 cm, highly significant differences were found between treatments. For 10 to 20 cm, T3 treatment virtually doubled the root fresh weight compared to the farm treatment (Fig. 4). T3 treatment showed an increase of 44,7% total root fresh weight (0 to 20 cm) compared to farm treatment.

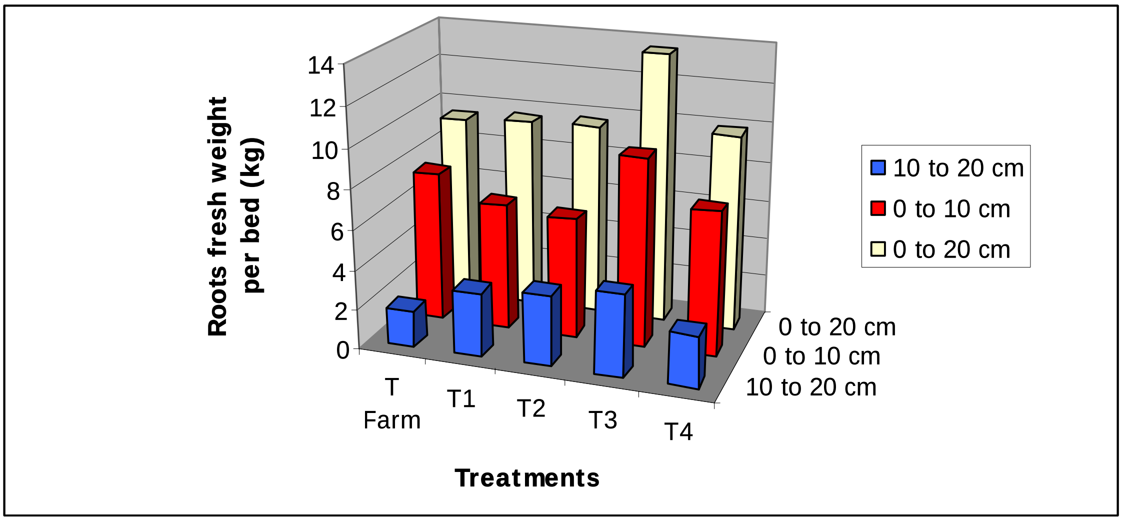

Figure 4: Effect of treatments with different number of fogger pulses on root fresh weight per bed (kg).

The excess of irrigation water applied in the farm treatment reduced the root system development compared with treatments with less irrigation water. Lack of oxygen in the soil diminished root system growth.

Number of bunches per bed

Significant differences were found between treatments (Fig. 5). The treatments T3 and T4 were significantly different from the control farm treatment and achieved an increase of 7,6 and 4,7%, respectively.

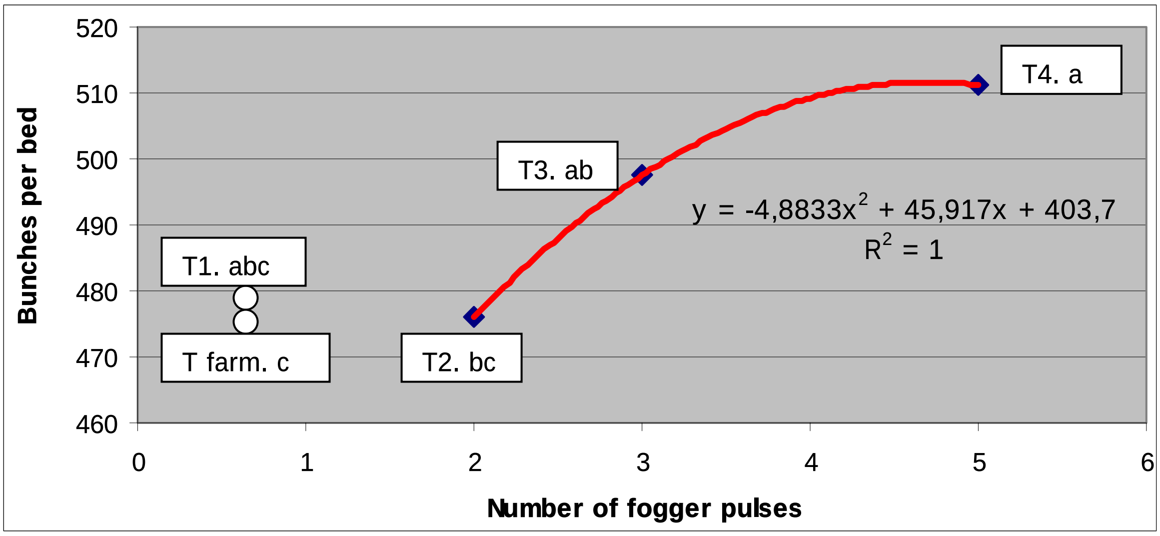

Figure 5: Effect of number of fogger pulses on bunches per bed. Treatments with the same letter are not significantly different.

Double ceramic tensiometer as innovation

At the final stage of this research work, an inexpensive double ceramic tensiometer (Fig. 6) was designed and proposed as innovation. The patent of this tensiometer model is pending on behalf of the Universidad Nacional de Colombia.

Figure 6: Double ceramic tensiometer. The independent vacuum gauges present information from two independent coaxial porous ceramics.

Conclusions

The greenhouse chrysanthemum growers in the Bogota plateau, Colombia can reduce water irrigation consumption to approximately 900.000 liters · ha^{-1} per crop cycle of 3 months. For the studied production area, water savings were approximately 50%.

Through combining benefits of use of the tensiometer to regulate moisture conditions to ideal levels and improving ways of water application with fogger and drip tape irrigation systems, the chrysanthemum grower gains production and quality advantages, compared with manual hose and traditional drip irrigation.

A trend of flower vase life improvement was observed with reducing consumption of irrigation water and employing of fogger with drip tape irrigation systems compared with that one when manual hose and traditional drip irrigation were used. The distribution and fresh weight of roots were also enhanced.

Allowing grower to take appropriate decisions on how much and when to irrigate, the tensiometer makes it possible to realize significantly increased chrysanthemum yields per hectare.

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Engineering factors effecting the performance of locally manufactured screen filters.

El-Tantawy, M. T.

ABSTRACT

The present study is to evaluate the engineering factors effecting on the performance of screen filters locally manufactured in Egypt. According to ISO 9912-2: **1992(E)**.The study reveals that some cylindrical screen filters can be used after sand filters when the source of water is surface water and located directly after pump station in Irrigation National Lab in Dokki – Giza governorate. The cylindrical screen filter materials are locally available. The evaluations included two solid concentrations in the water surface source (110 and 80 mg/l), two different external cartridge shapes (helically grooved and smooth) and three screen meshes (100, 160, and 200 mesh). The operating characteristics of cylindrical screen filters are predicated by knowledge of their mesh per linear inch, some hydraulic properties such as effect pressure loss, on flow rate, filtration efficiency, time, filtration cycle period, consumed for filtering cubic meter and flow rate reduction percentage.

The construction, measuring theory, operation, test, results and applications under pressure losses are described as follows:

1- The area ratio on the external cartridge surface for 65.0 orifices calculated according to **Keller (1949)**, were 33.16, 58.98 and 92.15 % with different orifice diameters perforated on the cartridge were 0.3 . 0.4, 0.5 mm, respectively.

2-The flow rate increased generally in all cases under helically-grooved cartridge surface due to path on the external cartridge surfaces and specially highest flow rate was 5.7 m^3/h with high area ratio 92.15 %, screen 100 mesh and low solid concentration 80 mg/l.

3-Generally helically-grooved cartridge with 200 screen mesh gave highest filtration efficiency and flow rate reduction percentage reached to 69.0% and 38.5 at pressure loss 0.2 and 0.5 bare respectively with high area ratio 92.15% and solid concentration 110 mg/l compared with all treatments.

4-The filtration cycle period increased generally in smooth cartridge and specially under low area ratio 33.16% and screen 100 mesh under solid concentration 80 mg/l compared with all treatments.

5-The time consumed for filtering cubic meter increased generally in all cases under helically-grooved cartridge surface due to path on the external cartridge surfaces and specially under low area ratio 33.16 %, and screen 100 mesh under solid concentration 110 mg/l compared with all treatments.

Key words: Screen filter, area ratio, pressure loss, flow rate, filtration efficiency, time consumed for filtering cubic meter, filtration cycle period, and flow rate reduction percentage

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Senior Res., Ag. Eng. Res. Ins., Dokki, Giza.

INTRODUCTION

Many different types of cylindrical screen filters are available on the local market at low cost, which are used mainly in pressurized irrigation systems. Use of these filters is increasing with increasing of the agriculture-irrigated area under pressurized irrigation systems (1.6 million fed.) El-Gindy 1997. **Kelley and Karmeli (1975)** mentioned that in screen filters, the whole size and total amount of open area determine the efficiency and operation limits. The screen filter is efficient for the removal of very fine particles from the irrigation water, but tends to be rapidly clogged by heavy loads of algae and other organic materials. It is customary to clean the filter when the pressure head drop is about 2.0 m, or at a fixed time determined in advance. The factors should be considered when estimating the appropriate discharge for a given screen filter are: quality of water, filtration area, desired volume of water to be passed between cleaning cycles, and allowable pressure drop on the filter surface. **Burce (1985)** mentioned that screen product in this category functions much like cartridges and strainers, expect that they are designed for much higher flow rates (about 91 $m.^3/h$) and are capable of greater solids retention. To accumulate higher flow rate, screen filters have more filtration surface area per inlet size than cartridges and strainers. Flushing is accomplished with little interruption to the operation of the irrigation system. **Pierce and Mancuso (1985)** said that exceeding recommended flow rates cause rapid build-up of collected contamination and excessive flushing or cleaning. Operation at higher than recommended pressure levels may cause damage to both the screen filter housings and filter cartridge. **Zeier and Hills (1987)** found that sand size is the main factor effecting the character of screen filter plugging. Fine sands cause a factor pressure drop across the screen filter than the coarse sand for similar quantities. Coarse sand needs a greater filter element storage volume in order to increase the time between filter cleanings, all other left the same. Increasing the volume available for sand storage would be more beneficial than increasing mesh area. The shape of the filter element should favor greater mesh surface areas for a given filter volume. **James (1988)** mentioned that cylinder screens made of stainless steel or nylon are the most commons types of screen filter used in trickle systems. The size of screens openings and hence the number of wires per inch determines the minimum particle size retained by the screen. The screen mesh should be selected that the screen retains all particles larger than one-sixth the size of the smallest passage (openings) in the trickle system. **Keller and Bliesner (1990)** said that the head loss in clean mesh filter normally rang between 2.0 and 5.0 kpa. The losses depend on the valving, filter size, percentage of open area in the screen (sum of the holes), and discharge. The head losses through a mesh filter will normally range between 5 and 10 kpa. A mesh filter with a high discharge in relation to the screen area may require frequent cleaning and have a short life. The factors that should be considered when selecting screen filters are: water quality, system discharge: filtration area and percentage of open area per filter: desired cleaning cycle and allowable pressure drop. The maximum recommended flow rate through a fine screen should be less than 135 l/s per m^2 of screen open area. **Awady (1991)** stated that many factors affect on the function and capacity of water filtration for trickle irrigation . They include: 1) source of water, and amount and nature of sediments and other causes of emitter clogging carried by water 2) area served, plant grown, micro climatology, and soil factors ; 3) type and size of filter; 4) time between successive cleaning services ; 5) fertilizers, pesticides and other water treatment additives which may result in precipitation of solids, or from compounds that precipitate ; and 6) type and size of trickler , and operation pressure. **Ravine et al. (1992**) explained that reliable long-term operation of most emitter types was achieved with filtration at 80 mesh (180-micron opening) combined with daily chlorination and bio monthly lateral flushing. The difference between the levels of emitter clogging at 80 mesh filtration and 120 mesh was found to be insignificant. Hence, 80 mesh is the level of filtration recommended for manual flushing check filter in drip irrigation systems using reservoir waters. **Ravina et al. (1993)** reported that the performance of filters after primary filtration by 120 mesh filters was better than after filtration with 40 mesh primary filters or without primary filtration. The performance of the manual downstream filters with non- filtered water and after 40 mesh filtration was similar. **Barbagallo et al. (1994)** stated that different screen filters have been used in experimental filtration equipment using primary effluent (with the diameter of the circle with the same area of the screen opening) and the area ratio (ratio between open area and total of the screen) . A support made of a size plated net has been set up in respect of the currently used perforated plate, this metal support increases filtration cycle duration (time to get a prefixed hydraulic head drop and the amount of filtered water volumes per screen area unit. **Chauhan (1995)** said that screen filters constitute an important component of drip irrigation system. Screen filters are useful for removing suspended inorganic materials but cannot remove large amount of suspended and organic particles without reducing the flow and thus requiring frequent flushing. **Niekerk (1995)** reported that most of the filters make use of internally filtered water to clean themselves, but if the water is so dirty, the elements of the filters are blocked before they themselves are clean, and cannot function any longer. **Parwal et al. (1995)** reported that, filtration of irrigation water in micro irrigation system is used for preventing clogging of individual parts of the system. Three types of filters, hydro cyclone's sand or media and screen are used individually or in combination to achieve the desired objective. The study relates to flow of clean water through screen filters, besides studying the applicability of a procedure for determining pressure drop. **Philips (1995)** reported that most filtration equipment installed in micro irrigation system is being operating at less than optimum levels. A screen filter has operational limitations. Screens utilize a single barrier of woven fabric or similar device to separate the suspended solids from the water. Any failures in the integrate of the filter barrier will allow contamination to pass down stream into the irrigation systems resulting in plugg age or obstruction of the water application device. **Sagi et al. (1995)** explained that filters installed at the head of the drip irrigation systems to prevent emitter clogging were not effective in the case of colonial protozoa and sulfur bacteria, regardless of the filter type.

El-Bagoury (1998) reported that increasing size of suspended particles from 125 to 375 um lead to increase in filtration efficiency from 90 to 97%, 80 to 94% and 70 to 90% at concentration of contamination 10, 250, and 750 PPM respectively. The optimum duration between back washings was 3.0 hours based on head drop of 5m with 15 PPM of contamination at discharge rates 9.5 $m.^3/h$ for river water. The duration can be increased to 10 hours daily by decreasing the filter inlet discharge rate to 3.5 $m.^3/h$. **Keller (1949)** defined two hydraulic expressions named: the area ratio (AR), less or equal to unity and slenderness ratio (LR) as follow: AR= Sum of areas of all discharge opening / cross sectional area of pipe. LR = Actual active length/ pipe diameter.

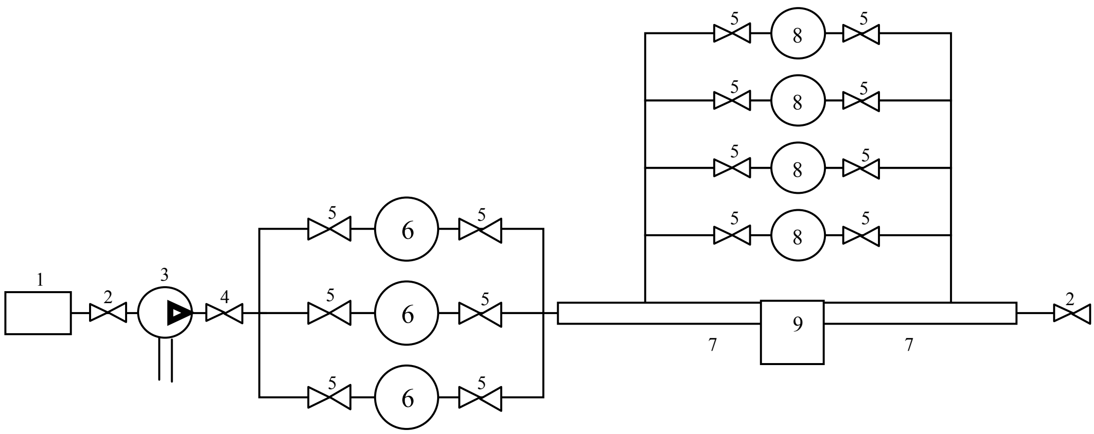
ISO 9912 (1992) specified that the pressure drop shall not be more than 10.0% greater than the pressure drop declared by the manufacturer. The strainer outlet shall not exceed 0.05 % of the maximum recommended flow rate. This leakage shall remain steady or lessen during the test. I n strainers containing several filter elements, perform the test on each filter element separately. **El-Tantawy (1999)** reported that screen filters are best selected for water source with low solid concentration as insurance for (clean water) or as secondary filter downstream of a pre-filter. Filtration efficiency tests can be easily and effectively done under laboratory and field condition (surface and ground) in all filters in two different qualities water. **Sharaf et al (1998)** found that using filter 150 mesh is a satisfactory filtration as a physical treatment of the drainage water without excessive clogging. **El-Berry et al. (2000)** found that increasing of screen filter aperture size has a negative effect on emitter discharge. This effect influences all types of emitters but not equally.

The aims of this work were to study the effect of area ratio and external surface of the cartridge, different solid concentrations in the water source and different screen meshs on pressure loss, flow rate, filtration efficiency, filtration cycle period , time consumed for filtering cubic meter and flow rate reduction percentage.

3-MATERIAL AND METHODS

The experiments were carried out in the Irrigation National Lab in Dokki – Giza Governorate with two different solid concentrations in the surface water with p^H (7.6) and E.C. (0.394 mmhos/cm). The control head used surface water in the irrigation and consisted of electrical centrifugal pump with maximum flow rate and head 100 m^3/h and 55 m respectively, two sand filters with diameters 90 cm , injection fertilizer pump, and screen filters with different flow rates. The present study is to evaluate the engineering factors affecting the performance of locally manufactured screen filters in Egypt. According to ISO 9912-2: **1992(E)**.The study reveals that some cylindrical screen filters can be used after sand filters when the source of water is surface water and located directly after pump station in Irrigation National Lab in Dokki – Giza governorate. The cylindrical screen filter materials manufactured from PVC with thickness 4.0

mm /10 bar are available locally. The evaluations included two different solid concentrations in the water surface source (80 and 110 mg/l), two different external cartridge shapes (smooth & helically-grooved) and three screen meshes (100, 160, and 200 mesh) respectively. The operating characteristics of cylindrical screen filters are indicated by knowledge of their mesh per linear inch, some hydraulic properties such as effect on pressure losses, on flow rate, filtration efficiency, time consumed for filtering cubic meter, filtration cycle period and flow rate reduction percentage effect of water quality on the operation duration. The pump unit was connected with filtration unit (media and screen filters). The screen filter was tested through pressure drop test facility and half cross-section helically –grooved cartridge in the Irrigation National Lab as shown in figs. (1 and 2) respectively.



(1) Water source (2) General gate valve (3) Pump (4) Discharge valve.
(5) Manual isolating valve (6) Electromagnetic flow rate (7) Set of straight pipes.
(8) Differential pressure gauge. (9) Screen filter to be tested.

Fig.(1) : General sketch showing the principle of the pressure drop test facility.

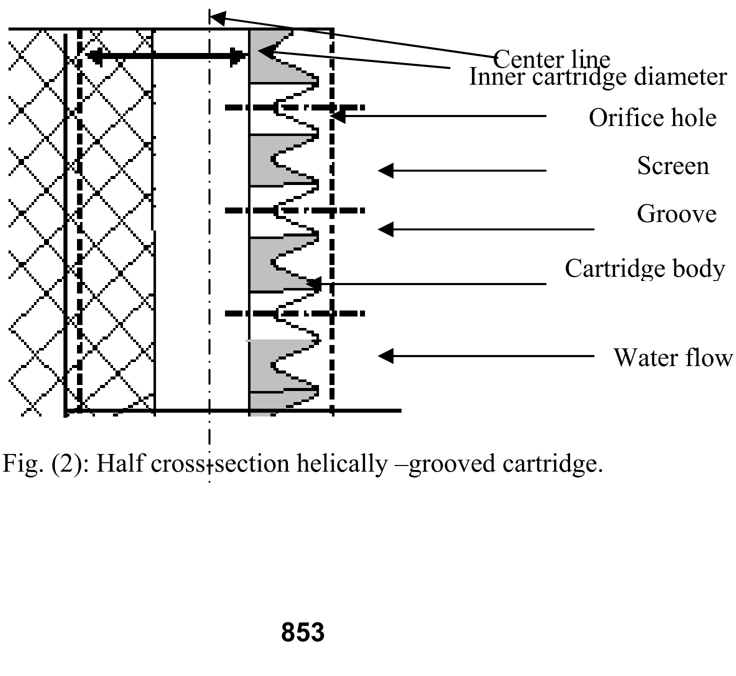


Fig. (2): Half cross-section helically –grooved cartridge.

The specifications of the screen filter tested as shown in table (1).

Table (1): Specifications of the screen filter tested.

Specifications	Filtration unit
-Hosing length (cm).	20.0
-Hosing outer diameter (mm)	60.0
-Hosing thickness (mm).	4.0
-Maximum discharge (m^3/h).	7.5
-Maximum pressure (bar).	10
-Screen cartridges outer diameter (mm).	50.0
-Screen cartridges thickness (mm).	4.0
-Cartridge area (cm^2).	13.854
-Number of mesh per linear (inch).	100, 160 and 200
-Screen material.	Stainless steel.
-Cartridge material	P.V.C.
- Cartridge surface area (cm^2)	125.6

The pressure loss ranged from 0.2 bar to 0.5 bar through filtration process under two different surface cartridge. The volume of filtered water ($m.^3$), filtration cycles (min) and flow rates (m^3/h) were measured and estimated time consumed for filtering cubic meter, and flow rate reduction percentage at increase pressure loss every 0.1 bar. One liter water samples were collected before and after filtration at each 0.1 bar pressure loss to estimates solid concentrations in (mg/l) in the two cases (110 and 80 mg/l) in surface water in National Irrigation Lab for calculating filtration efficiency (%) **El-Tantawy 1997**.

***Lab calculations through screen filter.**

- Cartridge area (cm^2) (Ac)

$$Ac = \Pi R^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

-Orifice area (cm^2) (a)

$$a = \Pi r^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots....(2)$$

-Cartridge external surface area (As) (cm^2)

$$As = 2 \Pi r L \ldots\ldots\ldots\ldots..... (3)$$

-Total orifices area($\sum a$)

$$\sum a = A * N \ldots\ldots\ldots\ldots\ldots\ldots .(4)$$

Where:

Π = constant (3.14).
R = inner cartridge radius (cm).
r = orifice radius (cm).
N = number of orifices.
L = cartridge length (cm).

-Area ratio (AR) (%)

$$AR= (\sum a/Ac) /?*100 \ldots\ldots\ldots(5)$$

- Opening area ratio (Ao)(%)

$$Ao = (\sum a/As) \ldots\ldots\ldots\ldots\ldots.. \quad (6)$$

Where:

$\sum a$ = Total orifices area (cm^2).
Ac = Cartridge area (cm^2).
As = Cartridge external surface area (cm^2).

-Filtration efficiency (%) (E_f)

$$(E_f) = (Ss - Si / Ss) * 100 \text{ ....(7)}$$

Where:

Ss= the solid concentration in the entrance of water before screen filter (mg/l).

Si = the solid concentration in the filtered water after screen filter (mg/l).

-Pressure loss (bar) (P)

$$P = Pi – Po \text{ ………………………(8)}$$

Where:

Pi = average pressure before screen filter (bar).

Po = average pressure after screen filter (bar).

-Flow rate (m^3 /h) (q)

$$q = V_f / T \text{ ………………………...(9)}$$

Where:

V_f = volume of water passing through screen filter.(m^3).

T = filtration cycle (min).

-Flow rate reduction percentage (Qr)

$$Qr = (Qs - Qi / Qs) * 100 \text{ ……….(10)}$$

Where:

Qs = flow rate at starting filtration process (m^3 /h).

Qi = flow rate at any time through filtration process (m^3 /h).

-Time consumed for filtering cubic meter (min/ m^3) (T)

$$T = (1 /q) *60$$

-Filtration cycle (h)

The time consumed between two successive back cleaning process (h).

RESULTS AND DISCUSSION

The main objectives of engineering laboratory tests are for calculating number and orifice diameters, measuring and evaluating the performance the selected six cartridges of screen filters (100, 160, 200 mesh) under three different area ratio percentage two solid concentration and two external cartridge shapes. The tests include pressure loss, flow rate, filtration efficiency, the filtration cycle period, time consumed for filtering cubic meter, and flow rate reduction percentage. All the measurements were taken during laboratory operation. The inlet pressure at starting filtration process was 2.0 bar and pressure loss under clean water were we 0.173 , 1.85, and 0.2 bar under different screen meshes 100, 160 and 200 respectively. The pressure loss through screen filter during filtration process range 0.2 bar to 0.5 bar after back washing at the inlet. When the pressure loss reached, 0.5 bar the screen filter needs cleaning, by washing the cartridge. The results of laboratory tests can be summarized as follows:

1-Calculation area ratio percentage , orifices numbers and diameters.

The cartridge area was 13.854 cm^2; the total orifices number distributed on the external cartridge surface on triangular spacing shape were 65.0 orifices with circular shape, so the maximum orifice diameter was 0.5 mm and cartridge surface area 125.6cm^2 according the calculation of the areas ratio **Keller (1949).** According to the calculation, six cartridges were tested in National Irrigation Laboratory as shown in table (2).

Table (2): Specification of screen cartridges tested in Irrigation National Laboratory.

No	Orifice diameter (cm)	Orifice area (cm^2)	Total orifices area (cm^2)	Area Ratio (%)	Opening area ratio (%)	External surface shape
1	0.3	0.0707	4.595	33.16	3.66	Smooth
2	0.3	0.0707	4.595	33.16	3.66	Helically-grooved
3	0.4	0.1257	8.171	58.98	6.51	Smooth
4	0.4	0.1257	8.171	58.98	6.51	Helically-grooved
5	0.5	0.1964	12.767	92.15	10.16	Smooth
6	0.5	0.1964	12.767	92.15	10.16	Helically-grooved

2- Effect of pressure loss on flow rate

The present study succeeded to prove the possibility of using local screen filters in pressurized irrigation system in Egypt, where the pressure loss through filtration units at starting time are 0.2 bar under surface water as shown in fig. (3):

At starting, of filtration process through screen filter 100 mesh with pressure loss 0.2 bar under solid concentration 110 mg/l (s 110) and 80 mg/l (s 80) , under cartridge of helically-grooved surface, the flow rates increase with 3.6 ,4.8 , 5.7 % and 3.1 ,4.3, 5.2 % respectively compared with smooth cartridge surface with orifices diameters 0.3, 0.4 and 0.5 mm respectively. Increasing solid concentration in the irrigation water from 80 to 110 mg/l, the flow rate decreased with percentage ratio under cartridge of helically-grooved surface were 3.5 to 7.1%, while under cartridge with smooth surface, ratios were 1.85 to 9.1% with orifice diameters 0.3, 0.4 and 0.5 mm respectively.

Same trend was observed at the end of filtration process at 0.5 bar pressure loss through screen filter. Increasing solid concentration in the irrigation water from 80 to 110 mg/l, the flow rate decreases under cartridge of helically-grooved surface, 3.5 to 11.1, while under cartridge with smooth surface, 1.92 to 10.7 % with orifice diameters 0.3, 0.4 and 0.5 mm respectively, and same trend in screens 160 and 200 mesh as shown in fig. (3).

3- Effect of pressure loss on filtration efficiency percentage

In fig.(4) at starting, of filtration process through screen filter 200 mesh with pressure loss 0.2 bar under solid concentration 110 mg/l (s 110) and under 80 mg/l (s 80) , under cartridge with of helically-grooved surface, the filtration efficiency increase with 2.0 to 6.0 % and 2.0 to 4.0 compared with smooth cartridge surface with orifice diameters 0.3, 0.4 and 0.5 mm, respectively. Increasing solid concentration in the irrigation water from 80 to 110 mg/l, the filtration efficiency increase with percentage ratio under cartridge of helically-grooved surface were 2.0 to 4.0 %, while under cartridge with smooth surface, ratios were 1.80 to 3.1 % with orifice diameters 0.3, 0.4 and 0.5 mm respectively.

Same trend was observed at the end of filtration process at 0.5 bar pressure loss through screen filter. Increasing solid concentrations in the irrigation water from 80 to 110 mg/l, the filtration efficiencies increasing with percentage ratio under cartridge of helically-grooved surface, 2.0 to 4.0, while under cartridge with smooth surface, decreases 1.0 to 3.0 with orifice diameters 0.3, 0.4 and 0.5 mm respectively, and same trend decreasing filtration efficiency with decreasing screen mesh from 160 to 100 mesh and decreasing solid concentration from 110 to 80 mg/l as shown in fig. (4).

4- Effect of pressure loss on filtration cycle periods

In fig.(5) at starting, of filtration process through screen filter 100 mesh with pressure loss 0.2 bar under solid concentration 110 mg/l (s 110) and 80 mg/l (s 80) , the filtration cycle periods under cartridge with of smooth surface increased of percentage ratio from 6.3 to 11.8 % and 5.6 to 10.5% compared with cartridge with of helically-grooved surface with orifice diameters

0.3, 0.4 and 0.5 mm respectively. When increasing solid concentration in the irrigation water from 80 to 110 mg/l, the filtration cycle periods decreased under cartridge of helically-grooved surface, ranging from 13.3 to 26.6 % and under cartridge with smooth surface from 5.9 to 25.0 % with orifice diameters 0.3, 0.4 and 0.5 mm respectively.
Same trend was observed at the end of filtration process at 0.4 bar pressure loss through screen filter. When increasing solid concentrations in the irrigation water from 80 to 110 mg/l, the filtration cycle periods decreased under cartridge of helically-grooved surface, ranged from 16.6 to 50.0 % and cartridge with smooth surface, were 13.3 to 42.8 % with orifice diameters 0.3, 0.4 and 0.5 mm respectively, and same trend decreasing the filtration cycle periods decreased with increasing screen mesh from 160 to 200 mesh and increasing solid concentration from 80 to 110 mg/l as shown in fig. (5).

5- Effect of pressure loss on times consumed for filtering cubic meter

In fig. (6) at starting, of filtration process through screen filter 100 mesh with pressure loss 0.2 bar under solid concentration 110 mg/l (s 110) and 80 mg/l (s 80), the time consumed for filtering cubic meter decreased from 3.7 to 5.7 % and 3.0 to 19.9 % compared with smooth cartridge surface with orifice diameters 0.3, 0.4 and 0.5 mm respectively. When increasing solid concentration in the irrigation water from 80 to 110 mg/l, the times consumed for filtering cubic meter increased with percentage ratio under cartridge of helically-grooved surface, increases from 6.6 to 9.9 %, while under smooth cartridge surface , increases were 1.67 to 9.9 %, with orifice diameters 0.3, 0.4 and .5 mm respectively.

Same trend was observed at the end of filtration process at 0.4 bar pressure loss through screen filter. When increasing solid concentrations in the irrigation water from 80 to 110 mg/l, the times consumed for filtering cubic meter decreased with percentage ratio under cartridge with helically-grooved surface, 2.67 to 10.25, while under smooth cartridge surface, decreases were 2.53 to 9.8 % with orifice diameters 0.3, 0.4 and 0.5 mm respectively and same trend decreasing the times consumed for filtering cubic meter decreased with increasing screen mesh from 160 to 200 mesh and increasing solid concentration from 80 mg/l to 110 mg/l as shown in fig. (6).

6- Effect of pressure loss on flow rate reduction percentage.

In fig.(7) at starting, of filtration process through screen filter 100 mesh with pressure loss 0.2 bar under solid concentration 110 mg/l (s 110) and 80 mg/l (s 80), under cartridge of helically-grooved surface, the flow rate reduction percentage increase with 0.7 to 2.0 % and 0.7 to 1.5 compared with smooth cartridge surface with orifice diameters 0.3, 0.4 and 0.5 mm, respectively. Increasing solid concentration in the irrigation water from 80 to 110 mg/l, the flow rate reduction percentage increase with percentage ratio under cartridge of helically-grooved surface were 1.0 to 2.7 %, while under cartridge of smooth surface, ratios were 1.0 to 2.7 % with orifice diameters 0.3, 0.4 and 0.5 mm respectively.

Same trend was observed at the end of filtration process at 0.4 bar pressure loss through screen filter. Increasing solid concentrations in the irrigation water from 80 to 110 mg/l, flow rate reduction percentage increasing with percentage ratio under cartridge of helically-grooved surface, 2.0 to 4.0, while under cartridge with smooth surface, decreases 1.0 to 3.0 with orifice diameters 0.3, 0.4 and 0.5 mm respectively, and same trend increasing flow rate reduction percentage with increasing screen mesh from 160 to 200 mesh and increasing solid concentration from 110 to 80 mg/l as shown in fig. (7).

7- Filtration cost

The present study recommended using local screen filter with cartridge of helically-grooved surface with available material in local market and lower than the foreign types for different diameters with ratio 50.0% and nearly same quality and efficiency.

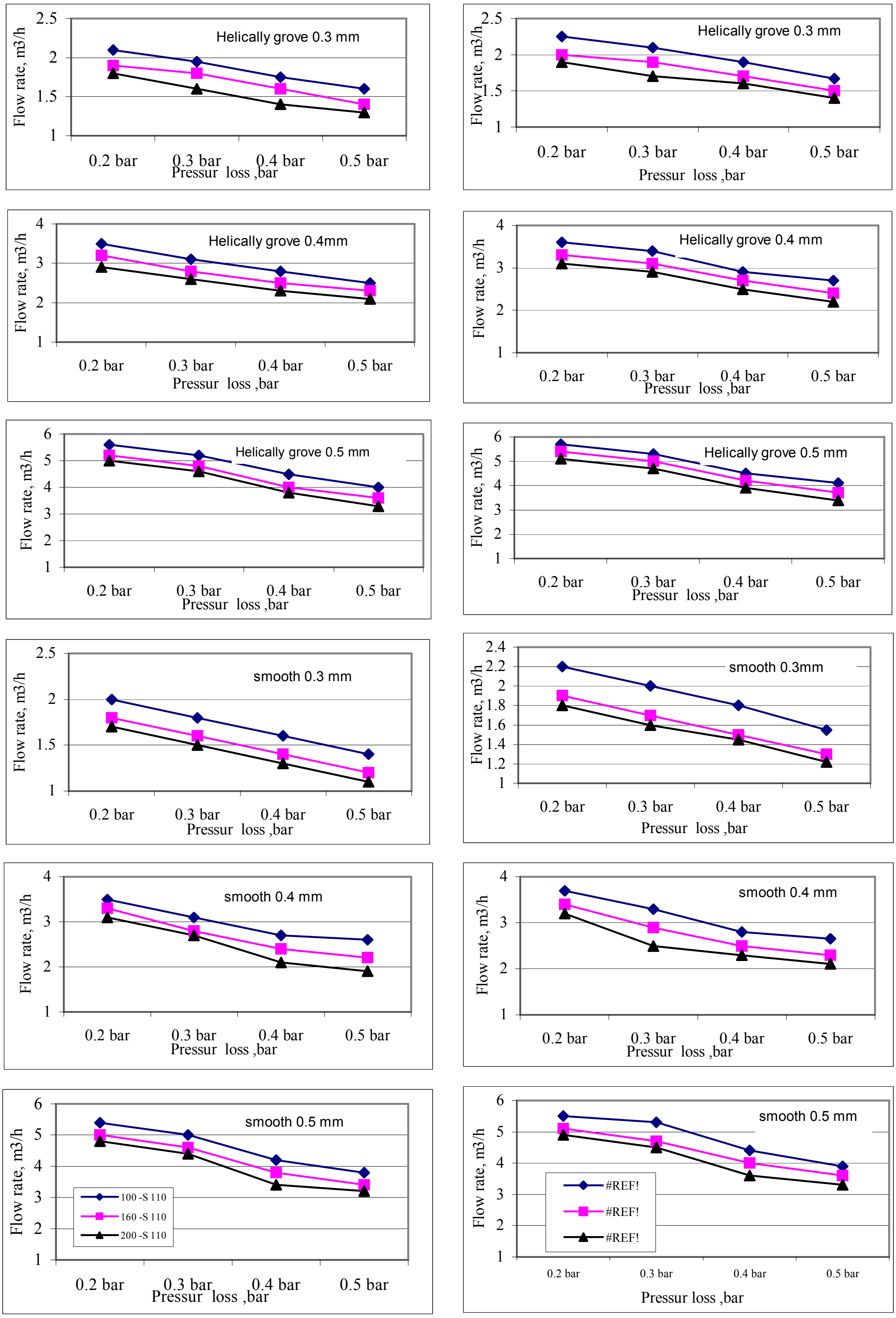


Fig.(3): The relationship between flow rate and pressure loss with surface water.

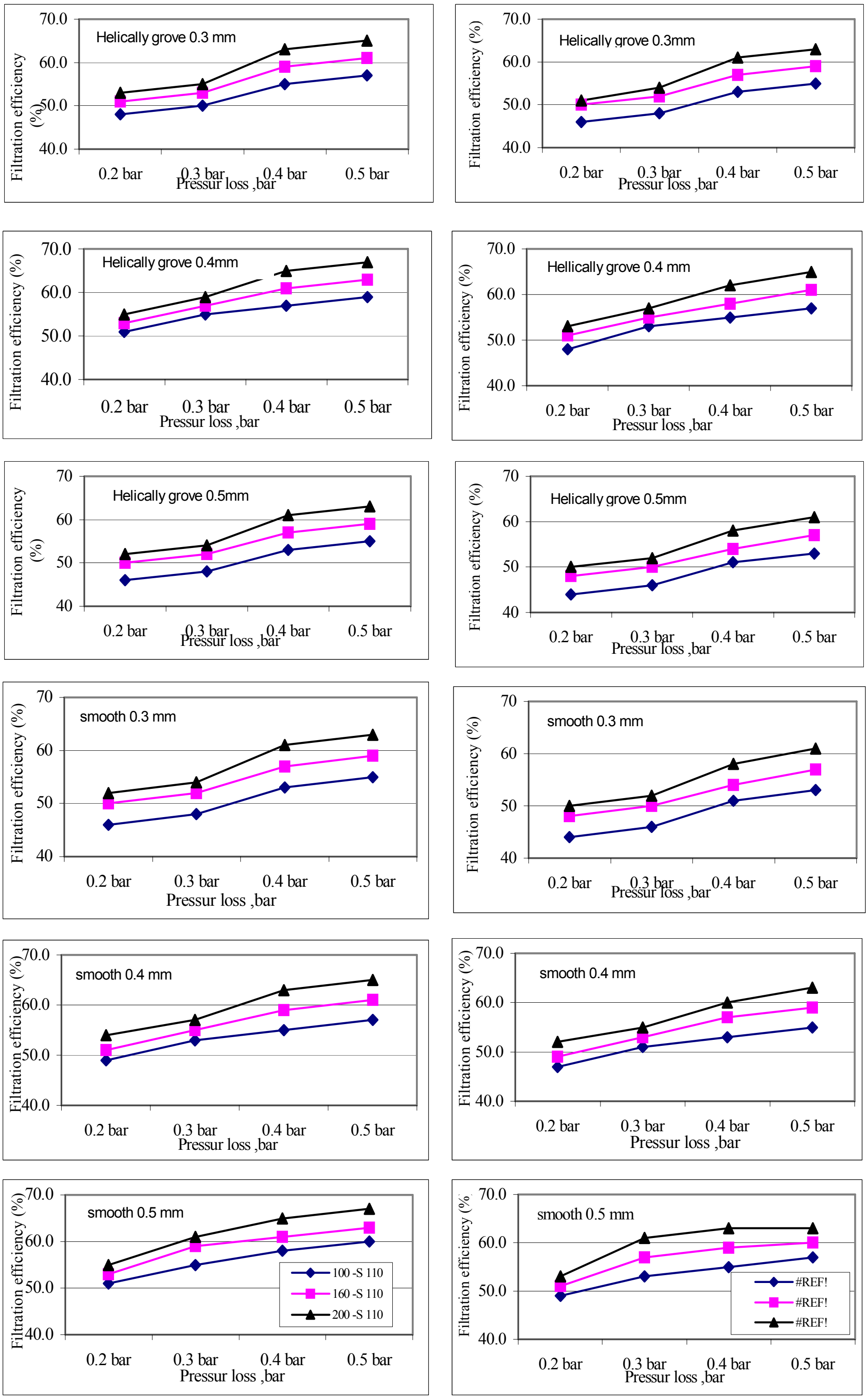


Fig.(4): The relationship between filtration efficiency and pressure loss with surface water.

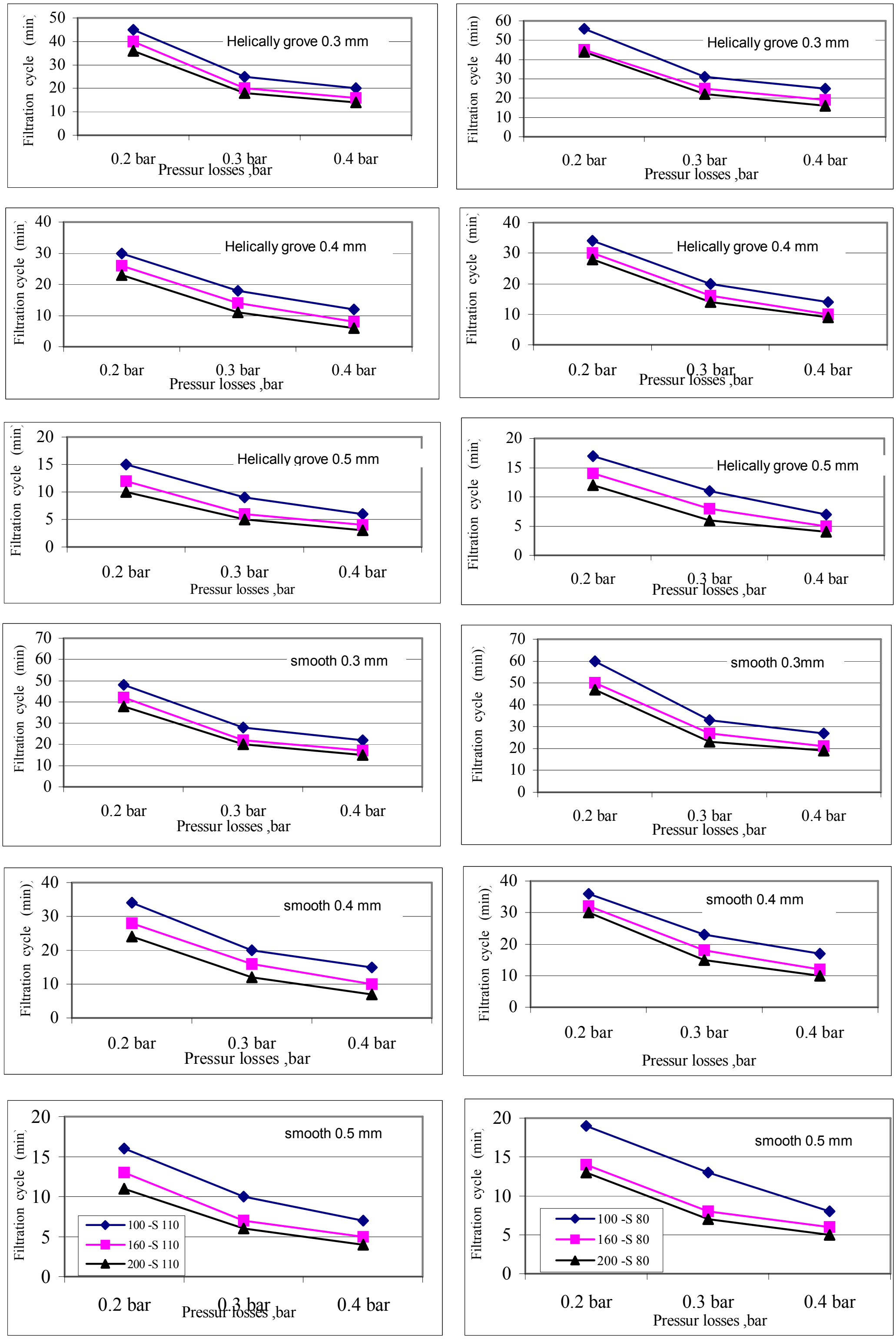


Fig.(5): The relationship between filtration cycle period and pressure loss with surface water.

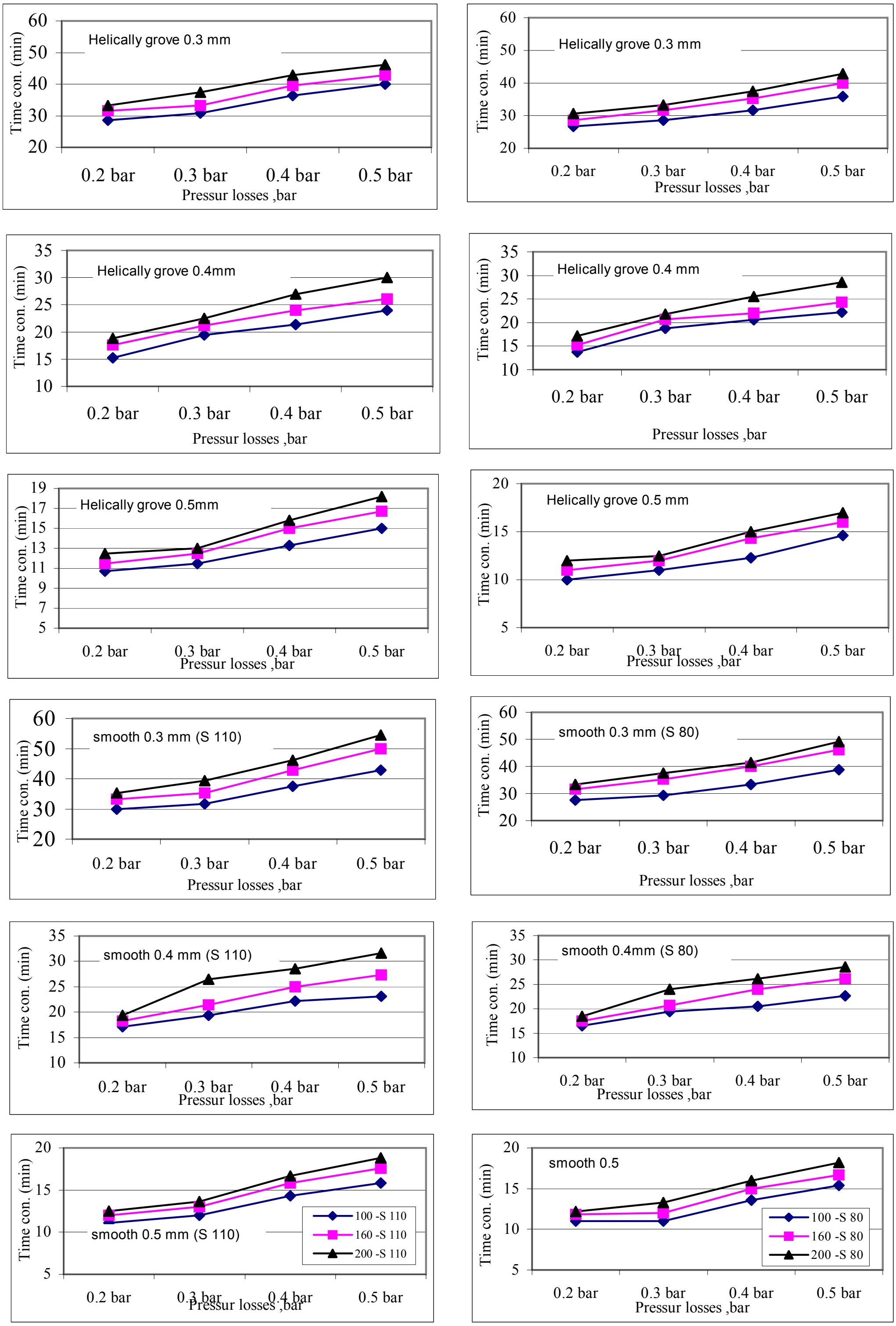


Fig.(6): The relationship between time consumed for filtering cubic meter and pressure loss with surface water.

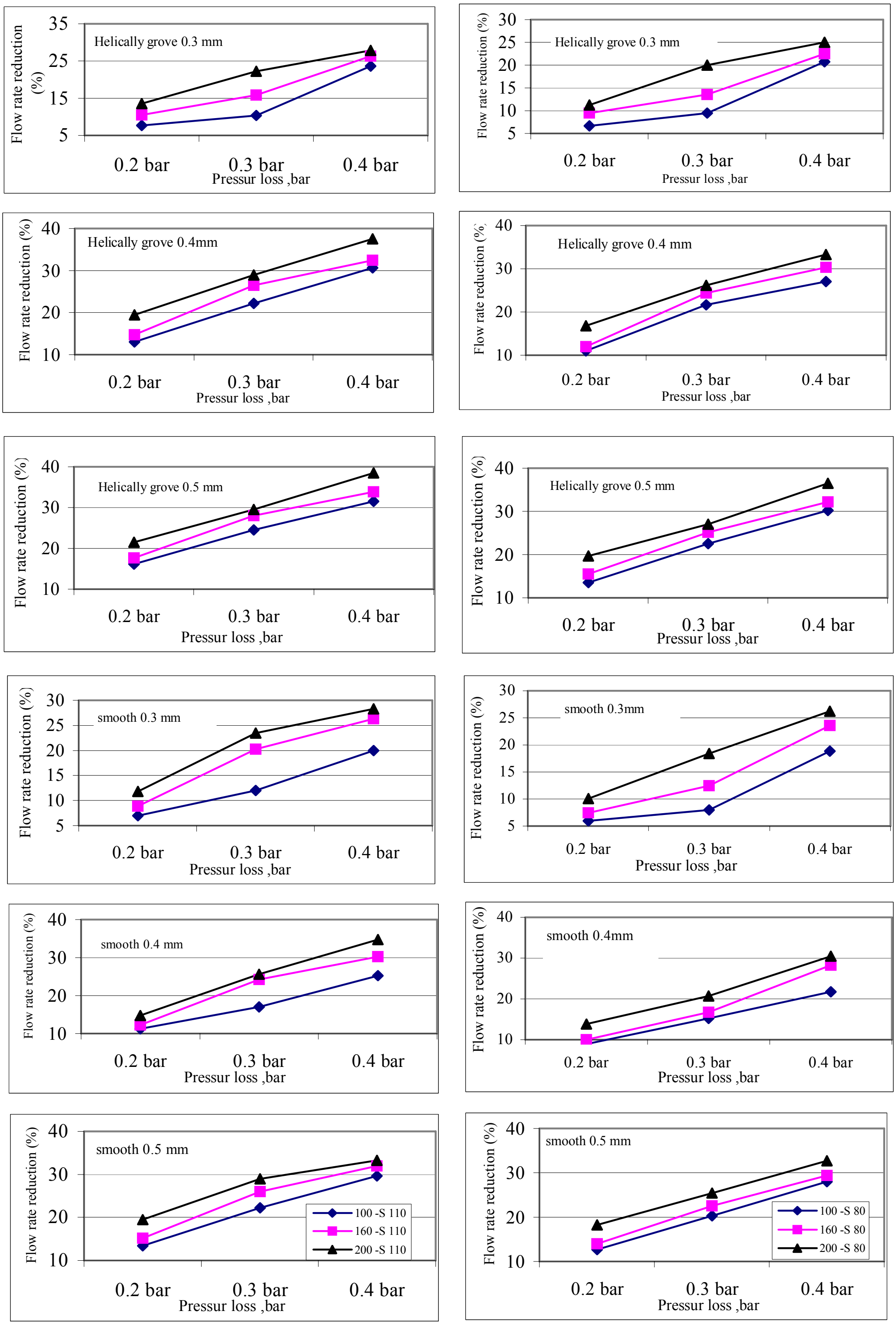


Fig.(7): The relationship between flow rate reduction percentage and pressure loss with surface water.

CONCLUSION

The present study is to evaluate the engineering factors effecting on the performance of screen filters locally manufactured in Egypt. According to ISO 9912-2: **1992(E)**.The study reveals that some cylindrical screen filters can be used after sand filters when the source of water is surface water and located directly after pump station in Irrigation National Lab in Dokki – Giza governorate.

The construction, measuring theory, operation, test, results and applications under pressure losses are described as follows:

1- The area ratio on the external cartridge surface for 65.0 orifices calculated according to **Keller (1949)**, were 33.16, 58.98 and 92.15 % with different orifice diameters perforated on the cartridge were 0.3 . 0.4, 0.5 mm, respectively.
2- Generally using cartridge of helically-grooved surface compared with smooth one increasing flow rate , filtration efficiency , time consumed for filtering cubic meter, flow rate reduction percentage, and decreasing filtration cycle period.

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OF SURFACE IRRIGATION SYSTEMS ON YIELD AND YIELD COMPONENTS OF AUTUMN SUGAR CANE AND TOMATO INTERCROPPED

El-Khatib S.I.[1] **Sahar.A. Sherif** [2]

ABSTRACT

This work was carried out to study the effect of modified surface irrigation by using gated pipes and intercropping patterns on yield and yield components of sugarcane and tomato. Two field experiments were conducted at Khreat farm, Kom Ambo city, Aswan Governorate in 2003/2004 and 2004/2005 seasons in clay soil.

The results are summarized as follow:

1- Values of stalk height, stalk diameter, number of millable stalks / fed, cane yield /fed, and W.U.E. were increased by using gated pipes irrigation. The cane yields were increased by 11.93 and 11.07% in the two seasons respectively. While the water applied m^3/fed were reduced by 13.94 and 14.85% also the W.U.E. were increased by 25.33 and 24.93% in the same seasons respectively.

2- The cane yield intercropped with tomato were reduced by 6.37, 13.52% and 7.48 and 15.98% less than the pure stand of one row and two rows tomato in both seasons respectively.

3- The cane yield were 52.67, 47.32 ton/fed and 51.27, 43.36 ton/fed when intercropped with one row and two rows of tomato in gated pipes system in the two seasons respectively compared with 48.38 and 47.15 ton/fed for pure stand sugarcane in traditional surface irrigation in the two seasons respectively. The water applied m^3/fed was reduced by using intercropping tomato with sugarcane under irrigation system. It was 7115, 7226.67 m^3/fed and 7065, 7073.33 m^3/fed for one row and two rows in the two seasons respectively compared with 8120, 8083.33 m^3/fed for pure stand sugarcane under traditional surface irrigation in the two seasons.

4- The fruits damage % was affected by interaction between gated pipes systems and intercropping it was 10.97, 11.48 and 12.48% and 11.07, 12.20 and 12.10% for one row, two rows and solid tomato in the two seasons respectively. Marketable yield ton/fed followed the same trend. It was increased by using gated pipes systems and intercropping, it was increased in the two seasons compared with solid tomato in the traditional irrigation. It was 23.16 , 24.95 ton/fed and 22.38 , 22.64 ton/fed for one row and two rows tomato in the two seasons respectively compared with 35.98 and 33.95 ton/ fed for solid tomato in the traditional irrigation in two seasons respectively.

5- The LER value for sugarcane intercropped with one row and two rows of tomato were 1.81 and 1.87 respectively for gated pipes system while it was 1.72 and 1.75 for one row and two rows tomato for traditional surface irrigation respectively.

6- The sugarcane intercropped with one row tomato under gated pipes gave the highest total income, (10663.35 L.E.) while the sugar cane intercropped with two rows tomato under traditional irrigation gave the lowest total income, (9113.30 L.E.).

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INTRODUCTION

Gated pipes is a way to increase the surface irrigation methods which has low on- farm water application efficiency (40 – 60%), also agricultural intensification is considered the main approach to achieve the economic growth. Also intercropping generally produces more total yields of the mixed crops per unit area.

Kholeif et al (1997) showed that modern irrigation systems in sugarcane under upper Egypt conditions gave the highest cane yield and quality. Also, he reported that the improved surface irrigation in strips as it was less in initial investment, easily managed and suits the skills in the sugarcane area. Meanwhile water saving was (31%) compared with conventional method. **Osman (2000)** concluded that good design of gated pipes with a precision land leveling improved the water distribution uniformity and saved irrigation water by 12% and 29.24% in cotton and wheat respectively. While cotton and wheat yield increased by 64.3 and 91.7% respectively compared by traditional surface irrigation systems. **El-Tantawy et.al, (2000)** showed that the water applied through perforated pipe decreased by (12.19, 18.64 and 23.22%) and (12.92, 18.91 and 23.50%) under different discharge of 0.6, 0.8 and 1.00 l/s, compared with traditional irrigation in both seasons respectively. He added that the crop yield increased by (9.0, 11.2 and 13.1%) and 14.9, 17.3 and 19.0%) under different discharge of 0.6, 0.8 and 1.00 l/s, compared with traditional irrigation in both seasons respectively. Also the water use efficiency for sugar weight increased by (17.5, 32.5 and 40.0%) and (30.23, 44.18 and 58.13%) under different discharge of 0.6, 0.8 and 1.00 l/s, compared with traditional irrigation in both seasons respectively. **Osman (2002)** showed that using gated pipes, acquired the highest cotton, wheat, corn and rice yield (61.1, 65.2, 116 and 53.6%) irrigation technique. Meanwhile water saving was (29.64, 29.9, 14.5 and 19.7%) in cotton, wheat, corn and rice compared with traditional system. **Eweida,et al.,(1996)** showed that yields of intercropped soybean, wheat, maize, and soybean with sugarcane raised the land use capacity by 50, 70, 30 and 40% respectively. Also the high values of the relative crowding coefficient (K) indicated a distinct yield advantage form intercropping these crops with sugarcane. **Zohry (1997**) concluded that sugar cane yield was significantly affected by onion intercropping. The average yield of cane was reduced by about 9.9 and 8.4 %compared with pure stand in first and second seasons, respectively. Birx, sucrose and purity percentages of sugar cane juice showed significant differences between treatments. Intercropping onion with sugar cane increased the land usage by 43- 59%. **Abd El_Aal and Zohry (2003)** mentioned that intercropping tomato with maize saved irrigation water by 40% compared with solid treatments. Tomato fruits were significantly affected by intercropping tomato with maize, phosphate source and doses. The damage of tomato fruits was decreased and marketable yield increased. These could be attributed to the height of maize plants that acts as shadow on tomato plants and protect fruits from sunrays and reduce the effect of direct burning on fruits. He added the most advantage for using intercropping is to maximize usage unit of land and water to produce a maximum production.

MATERIAL AND METHODS

Two field trials were conducted at khraat valley, Aswan Governorate in two successive seasons (2003/2004 – 2004/2005) to investigate the effect of using surface irrigation system with gated pipes and intercropping tomato (c.v. Castle rock) with sugar cane (c.v. G. T. C.54/9) on the water requirements, yield and yield components of sugar cane and tomato. Treatments were arranged in a split plot design with four replications. Methods of surface irrigation occupied the main plots, whereas intercropping occupied plots.

The treatments as follows:

1- Iintercropping one row of tomato on sugar cane ridge.
2- Iintercropping two rows of tomato on sugar cane ridge.
3- Pure stand sugar cane.
4- Solid tomato.

The plot was 2250 m^2 and consisted of 24 ridges.
Sugar cane was planted on October, 20th and 27th in the first and the second season, respectively, Transplanting of tomato were on 25th and 29th of November in the first and the second season, respectively.
All the experimental treatments received the same agricultural practices as recommended. Before starting the experimental work soil analysis was recorded. Table (1) shows the results of the mechanical analysis and the bulk density of the soil. Field capacity was 39.6 % by weight and the wilting point was 18 % by weight.

Table (1): Mechanical analysis and the bulk density of the different layers of the experimental area

Depth Cm	Coarse sand %	Fine sand %	Silt %	Clay %	Texture class	Organi %	$CaCo_3$	Bulk density cm^3
(0-15)	4.67	15.96	18.89	60.48	Clayey	5.50	3.50	1.10
(15-30)	4.50	13.50	19.0	63.00	Clayey	5.00	4.00	1.09
(30-45)	4.90	14.00	18.6	62.50	Clayey	2.00	3.90	1.15
(45-60)	3.50	15.50	16.0	65.00	Clayey	2.00	3.50	1.15

Methods of calculations:

Water use efficiency (kg/ m^3):

WUE = yield (kg/fed) / total applied water (m^3/fed)

Land equivalent ratio (LER)

Land Equivalent Ratio was calculated according to **Willey, 1979.** LER was determined as the sum of the fractions of the yield of the intercrops relative to their sole crop yields .LER was determined according to the following formula:

$$LER = \frac{Yab}{Yaa} + \frac{Yba}{Ybb}$$

Where:

Yaa = Pure stand yield of species a.
Ybb = Pure stand yield of species b.
Yab = Mixture yield of a (when combined with b).
Yba = Mixture yield of b (when combined with a).

Statistical analysis:

Data of the two seasons were statistically analyzed according to **Snedecor and Cochron (1988)** using Mstatc computer V_4 (1986). L.S.D. test at 0.05 level, was used to compare the differences between treatments.

Net return:

Net return was calculated according to prices by the Ministry of Agriculture economic publication for all land preparation practices and production articles and tools. Also, prices of main products were taken according to official prices issued by the Ministry of

Agriculture economic publication. (L.E.105/ ton sugarcane and L.E.200/ton tomato according to the prices of 2004). The cost of gated pipes for these experiments was L.E. 1200/ faddan

RESULTS AND DISCUSSION

1- Effect of surface irrigation systems on sugar cane.

Data presented in Table (2) and Fig (1) showed that characters under study of sugar cane were significantly affected by surface irrigation systems in the two seasons. Values of stalk height, stalk diameter, number of millable stalks / fed, cane yield / fed, and W.U.E. were increased by using gated pipes irrigation. The cane yields were increased by 13.55 and 12.05% in the seasons 2003/2004 and 2004/2005 seasons respectively. While the water applied m^3/fed were reduced by 13.94 and 14.85% also the W.U.E. were increased by 25.33 and 24.93% in the same seasons respectively. From Data presented in Table (2) it is clear that the T.S.S. and sucrose percentage were unaffected by using gated pipes, whereas it increased sugar yield/fed.

Table (2): Effect of surface irrigation systems on yield, yield components, Juice quality and yield of sugar cane in 2002/2003 and 2003/2004seasons.

Treatments	Stalk height cm	Stalk diameter cm	No. of millable stalks 1000/fed	T.S.S. %	Sucrose %	Water applied m^3/fed	Cane yield ton/fed	W.U.E. kg/m^3	Sugar yield ton/fed
2003 / 2004									
gated pipes system	264.56	2.61	33.49	20.14	18.15	7052.22	51.47	7.38	5.65
Traditional surface irrigation	258.33	2.56	32.06	19.93	17.95	8195.00	45.24	5.51	4.86
L.S.D. at 0.05	2.14	0.03	0.84	N.S	N.S	19.51	0.49	0.08	0.15
2004 / 2005									
gated pipes system	263.00	2.59	32.97	19.36	18.09	6971.11	49.95	7.22	5.26
Traditional surface irrigation	256.67	2.55	31.83	19.70	17.99	8186.67	44.42	5.42	4.79
L.S.D. at 0.05	3.87	0.04	0.69	0.23	N.S	31.08	0.46	0.46	0.14

2- Effect of intercropping on sugar cane.

Data presented in table (3) and Fig (2) showed that characters under study of sugar cane were significantly affected by intercropping patterns in both seasons. Values of stalk height, stalk diameter, number of millable stalks / fed, cane yield / fed were reduced by intercropped tomato. The reduction was grater when intercropped by two rows of tomato while the reduction was low when intercropped with one row of tomato. The cane yield / fed were reduced by 6.37, 13.52% and 7.48 and 15.98% from pure stand for one row and two rows tomato in the two seasons respectively. Also the W.U.E. had the same trend it was reduced by 7.98, 16.67% and 9.5, 18.53% from pure stand for one row and two rows tomato in the two seasons respectively. There was no relevance between T.S.S. and sucrose percentage and intercropping patterns. Sugar yield / fed of the pure stand surpassed that of intercropped by one or two rows of tomato. These results hold true in both seasons.

Table (3): Effect of intercropping tomato with sugar cane on yield, yield components, juice quality and yield of sugar of sugar cane in 2002/2003 and 2003/2004seasons.

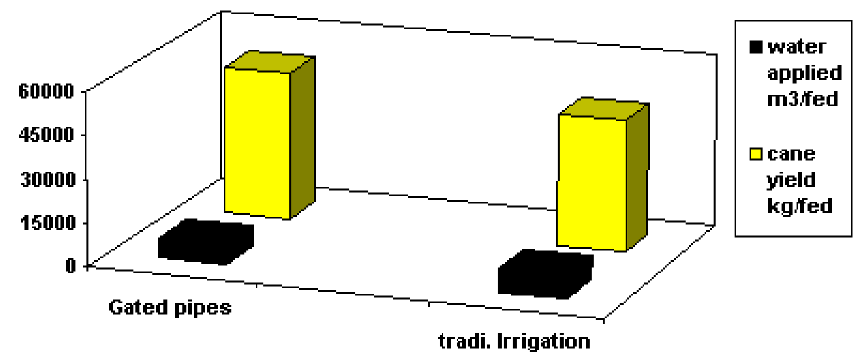
Treatments	Stalk height cm	Stalk diameter cm	No. of millable stalks 1000/fed	T.S.S. %	Sucrose %	Water applied m^3/fed	Cane yield ton/fed	W.U.E. kg/m^3	Sugar yield ton/fed
2003 / 2004									
Sugar cane + one row tomato	264	2.59	32.33	19.96	18.11	7665.83	48.54	6.46	5.19
Sugarcane +two rows tomato	254	2.54	31.33	19.96	17.93	7737.50	44.83	5.85	4.88
Pure stand sugarcane	266	2.63	34.57	20.19	18.11	7467.50	51.84	7.02	5.70
L.S.D. at 0.05	3.42	0.04	0.47	N.S	N.S	35.80	0.25	0.06	0.13
2004 / 2005									
Sugar cane + one row tomato	261.50	2.57	31.73	19.43	18.08	7667.50	47.36	6.33	5.01
Sugarcane +two rows tomato	253.17	2.53	31.28	19.23	17.99	7640.00	43.01	5.67	4.54
Pure stand sugarcane	264.83	2.62	34.18	19.33	18.03	7429.17	51.19	6.96	5.54
L.S.D. at 0.05	3.87	0.04	0.24	0.21	N.S	53.26	0.29	0.06	0.10

3- Interaction effect of irrigation systems and intercropping patterns on sugar cane.

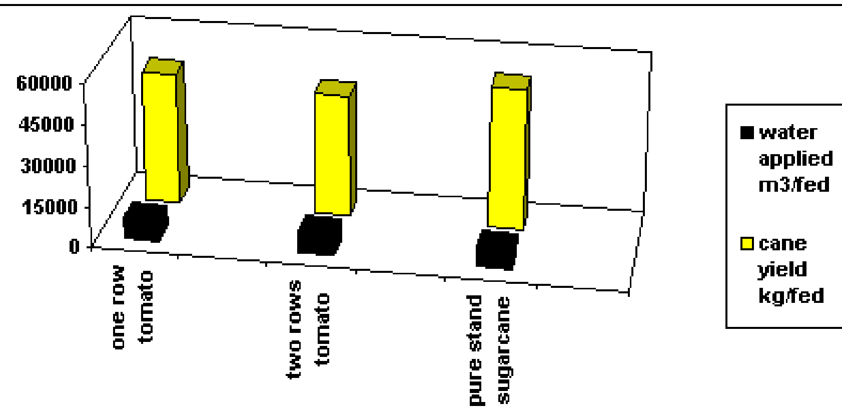
The interaction effect of irrigation systems and intercropping patterns on characters under study of sugar cane are presented in table (4). Data indicated that the characters under study of sugarcane were affected by using gated pipes system and intercropping tomato with sugarcane. Values of stalk height, stalk diameter, number of millable stalks/fed, T.S.S. % and sucrose % were higher than the same characters which in pure stand sugarcane in traditional surface irrigation. The cane yield was 52.67, 47.38 ton/fed and 51.27, 43.36 ton/fed when one row and two rows of tomato were intercropped with sugarcane in gated pipes system in the two seasons respectively, compared with 48.38 and 47.15 ton/fed for pure stand sugarcane in traditional surface irrigation in the two seasons, respectively. The water applied m^3/fed was reduced by intercropping tomato with sugarcane under irrigation systems. It was 7115, 7226.67 m^3/fed and 7065, 7073.33 m^3/fed when one row and two rows of tomato were intercropped with sugarcane in the two seasons, respectively compared with 8120, 8083.33 m^3/fed for pure stand sugarcane under traditional surface irrigation in the two seasons, respectively. The WUE for sugarcane under gated pipes system and intercropped with tomato was higher than the WUE for pure stand sugarcane under traditional irrigation. It was 7.42, 6.45 kg/m^3 and 7.37, 6.15kg/m^3 when one row and two rows of tomato were intercropped with sugarcane in irrigation system in the two seasons, respectively compared with 5.77 and 5.78 kg/m^3 for pure stand sugarcane under traditional surface irrigation in the two seasons, respectively.

4- Effect of surface irrigation systems on tomato.

Agronomic traits under study as well as fruits damage and marketable yield are statically analyzed and presented in table (5) and Fig (3). Data showed that plant height, No. of fruits/ plant, weight of fruits (kg)/plant, fruits damage %, total fruits yield (ton/fed) and marketable yield (ton/fed) were improved by using gated pipes. Fruits damage decreased by 2.12 and 1.99% in two seasons respectively.



Fig(1): Effect of irrigation systems on sugarcane water applied and yield.



Fig(2): Effect of intercropping systems on sugarcane water applied and yield.

Table (4): Interaction effect of irrigation systems and intercropping patterns on yield, yield components and juice quality of sugar cane which intercropped with tomato in 2002/2003 and 2003/2004 seasons.

Irrigation systems	Intercropping patterns	Stalk height cm	Stalk diameter cm	NO. Of millable stalk 1000/fed	T.S.S %	Sucrose %	Water applied m^3/fed	Cane yield ton/fed	W.U.E. kg/m^3	Sugar yield ton/fed
		2003 / 2004								
gated pipes system	Sugar cane + one row tomato	267.67	2.62	32.77	20.11	18.25	7115.00	52.67	7.42	5.65
	Sugar cane +two rows tomato	254.00	2.56	31.97	20.23	18.11	7226.67	47.32	6.45	5.11
	Pure stand sugarcane	272.00	2.66	35.57	20.37	18.22	6815.00	56.33	8.26	6.19
	Mean	264.56	2.61	33.44	20.14	18.15	7052.22	51.37	7.38	5.65
Traditional surface irrigation	Sugar cane + one row tomato	260.00	2.55	31.90	20.10	17.97	8216.67	45.12	5.50	4.72
	Sugar cane + two rows tomato	254.00	2.52	30.70	19.68	17.87	8248.33	43.24	5.25	4.64
	Pure stand sugarcane	261.00	2.60	33.57	20.01	18.00	8120.00	48.38	5.77	5.22
	Mean	258.33	2.56	32.06	19.93	17.95	8195.00	45.24	5.51	4.86
L.S.D. at 0.05		1.62	N.S	N.S	N.S	N.S	50.63	0.357	0.077	0.18
		2004 / 2005								
gated pipes system	Sugar cane + one row tomato	265.33	2.60	32.13	19.08	18.10	7065.00	51.27	7.37	5.39
	Sugar cane +two rows tomato	253.67	2.52	31.73	19.03	18.04	7073.33	43.36	6.15	4.48
	Pure stand sugarcane	270.00	2.64	35.03	19.97	18.12	6775.00	55.23	8.14	5.92
	Mean	263.00	2.59	32.96	19.36	18.09	6971.11	49.95	7.22	5.26
Traditional surface irrigation	Sugar cane + one row tomato	257.67	2.54	31.33	19.77	18.07	8270.00	43.46	5.29	4.63
	Sugar cane +two rows tomato	252.67	2.53	30.82	19.43	17.95	8206.67	42.66	5.18	4.60
	Pure stand sugarcane	259.67	2.59	31.33	19.00	17.95	8083.33	47.15	5.78	5.15
	Mean	256.67	2.55	31.83	19.70	17.99	8186.67	44.42	5.42	4.79
L.S.D. at 0.05		N.S	0.55	0.34	0.29	N.S	75.32	0.415	0.077	0.144

Table (5): Effect of irrigation systems on yield and yield components of Tomato in 2002/2003 and 2003/2004seasons.

Treatments	2003 / 2004			2004 / 2005		
	gated pipes system	Traditional surface irrigation	L. S. D. at 0.05	gated pipes system	Traditional surface irrigation	L. S. D. at 0.05
Plant height cm	62.31	60.16	1.34	59.54	57.53	1.59
No. of fruits/plant	40.81	38.31	1.67	39.49	38.31	N.S
Weight of fruits kg/plant	5.75	5.50	N.S	5.44	5.26	N.S
Fruit damage %	11.64	11.79	0.11	12.10	12.02	0.109
Total fruits yield ton/fed	28.88	25.68	0.481	27.81	24.11	0.713
Marketable yield Ton/fed	23.26	24.01	0.988	23.08	21.36	1.506
Water applied m3/fed	6277.78	6646.67	75.02	6347.78	6676.67	58.75
WUE kg/m^3	7.01	6.15	0.189	6.55	4.95	N.S

5- Effect of intercropping on tomato

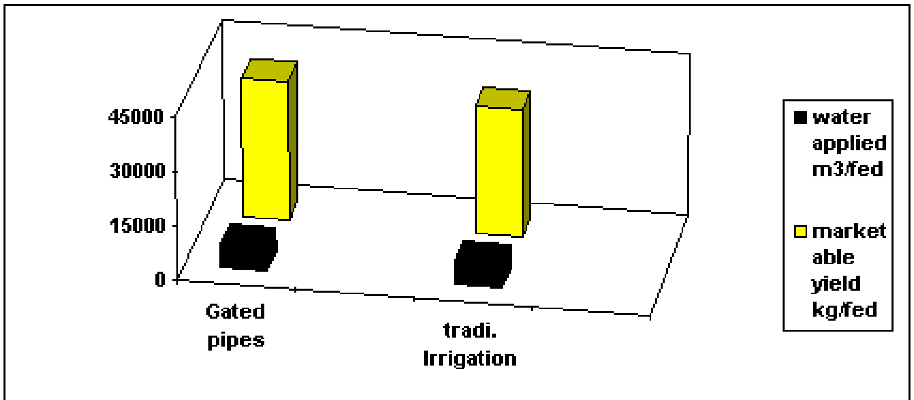
Intercropping tomato with sugarcane protect the tomato fruits from direct effect of sunrays and high temperature. This effect is important for collecting tomatoes with less damage and increasing marketable yield. Data in table (6) and Fig (4) showed that fruit damage decreased by 10.33 and 3.66 %, 13.50 and 2.43% when one row and two rows of tomato were intercropped with sugarcane as compared with sole tomato in the two seasons respectively.

Table (6): Effect of intercropping tomato with sugar cane on yield and yield components of tomato in 2002/2003 and 2003/2004seasons.

Treatments	2003 / 2004				2004 / 2005			
	Sugar cane + one row tomato	Sugar cane + two rows tomato	Solid Tomato	L. S. D. at 0.05	Sugar cane + one row tomato	Sugar cane + two rows tomato	Solid Tomato	L. S. D. at 0.05
Plant height cm	61.73	58.40	63.57	2.55	58.29	56.68	60.50	2.04
No. of fruits/plant	39.38	38.27	41.03	0.96	38.71	37.74	40.24	1.17
Weight of fruits kg/plant	5.71	5.17	6.00	0.44	5.15	4.95	5.95	0.30
Fruit damage %	11.02	11.84	12.29	0.35	11.02	12.43	12.74	0.42
Total fruit yield ton/fed	24.56	25.24	26.28	0.94	24.08	25.08	28.71	0.71
Marketable yield Ton/fed	21.82	23.01	26.08	0.94	20.71	21.88	24.08	0.73
Water applied m^3/fed	8027.50	8171.67	3187.50	69.77	8008.33	8203.33	3325.00	49.06
WUE kg/m^3	3.86	4.07	11.81	0.38	3.81	3.98	9.47	2.75

6- Effect of interaction of irrigation systems and intercropping on tomato.

The effect of interaction of irrigation systems and intercropping on the agronomic traits as well as fruit damage and marketable yield, also water applied and WUE are statistically analyzed and presented in table (7). Tomato plant height, No. of fruits / plant and weight of fruits kg / plant were not affected by the interaction between irrigation systems and intercropping pattern except in the case of weight of fruits kg / plant in the second season. Data show that the fruits damage % was affected by irrigation systems and intercropping, it was 10.97, 11.48 and 12.48% and 11.07, 12.20 and 12.10% for one row, two rows and sole tomato in the two seasons respectively. Marketable yield ton/fed followed the same trend. It were increased by using irrigation systems and intercropping, it was increased in the two seasons compared with solo tomato in the traditional irrigation. It was 23.16 and 24.95 ton/fed and 22.38 and 22.64 ton/fed for row and two rows tomato in the two seasons respectively compared with 25.98 and 23.95 ton/ fed for solo tomato in the traditional irrigation in two seasons respectively.



Fig(3): Effect of irrigation systems on tomato water applied and marketable yield.

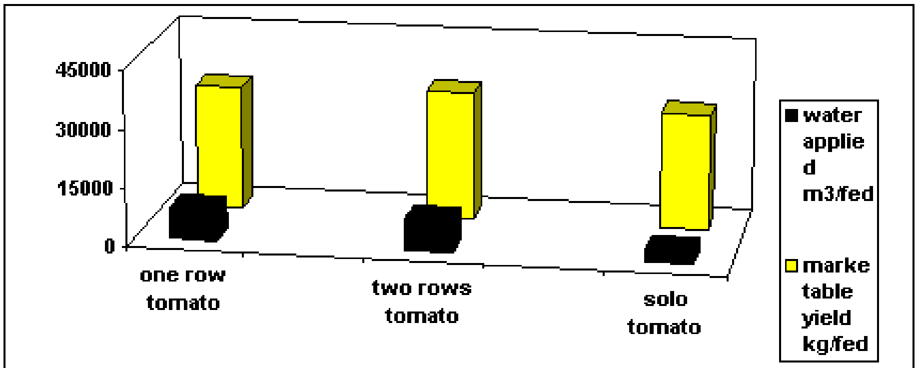


Fig (4): Effect of intercropping systems on tomato water applied and yield.

Table (7): Interaction effect of irrigation systems and intercropping patterns on yield and yield components of tomato intercropped with sugarcane in 2002/2003 and 2003/2004 seasons.

Irrigation systems	Intercropping patterns	Plant height cm	No. of f./plant	Weight of f. Kg/p.	f. damage %	Mark. Yield ton/fed	Total f. yield ton/fed	Water applied m^3/fed	WUE kg/m3
		2003 / 2004							
gated pipes system	Sugar cane + one row tomato	62.67	40.70	5.90	10.97	23.16	26.18	7813.33	4.18
	Sugar cane + two rows tomato	59.10	39.50	5.23	11.48	24.95	26.90	8076.67	4.43
	Solid tomato	65.15	42.23	6.13	12.48	22.90	27.83	2943.33	12.41
	Mean	62.31	40.81	5.75	11.64	23.76	26.97	6277.78	7.01
Traditional surface irrigation	Sugar cane + one row tomato	60.80	38.07	5.51	11.07	20.49	22.93	8241.67	3.54
	Sugar cane + two rows tomato	57.70	37.03	5.12	12.20	21.08	23.57	8266.67	3.70
	Solid tomato	61.98	39.82	5.87	12.10	22.46	25.53	3431.67	11.20
	Mean	60.16	38.31	5.50	11.79	22.50	25.68	6646.67	6.15
L.S.D. at 0.05		N.S	N.S	N.S	0.49	1.33	1.33	98.67	N.S
	2004 / 2005								
gated pipes system	Sugar cane + one row tomato	59.17	39.35	5.28	10.90	22.38	26.40	7736.67	4.13
	Sugar cane +two rows tomato	57.67	38.45	5.00	12.40	22.64	27.00	8166.67	4.19
	Solid tomato	61.80	40.67	6.03	13.00	24.21	30.03	3140.00	11.33
	Mean	59.55	39.49	5.44	12.10	23.08	27.81	6347.78	6.55
Traditional surface irrigation	Sugar cane + one row tomato	57.42	38.07	5.02	11.13	19.04	21.77	8280.00	3.48
	Sugar cane +two rows tomato	55.68	37.03	4.90	12.45	21.11	23.17	8240.00	3.76
	Solid tomato	59.50	39.82	5.87	12.48	23.95	27.38	3510.00	7.60
	Mean	57.53	38.31	5.26	12.02	21.37	24.11	6676.67	4.95
L.S.D. at 0.05		N.S	N.S	0.49	N.S	1.03	0.999	69.38	N.S

7- Interaction effect of irrigation systems and intercropping systems on LER and total income for sugarcane and tomato crops.

Data of LER values in Table (8) indicated that intercropping resulted in more yields advantage in both intercrop combinations compared with growing both crops in monoculture. Results also indicated that the highest LER values were obtained when sugarcane intercropped with two rows tomato while one row of tomato possessed the lowest value.

The LER values were 1.81 and 1.72 when one row of tomato intercropped with sugarcane was irrigated by gated pipes and traditional irrigation systems respectively but when the two rows of tomato intercropped with sugarcane the LER values were 1.87 and 1.75 when irrigated by gated pipes and traditional irrigation respectively. From these data it is clear that intercropping sugarcane with two rows tomato has the advantage from one row tomato. The data also indicated that the sugarcane intercropped with one row tomato under gated pipes gave the highest total income (10663.35 L.E.) while the sugar cane intercropped with two rows tomato under traditional irrigation gave the lowest total income (9113.30 L.E.) also the sugarcane intercropped with two rows tomato gave (1037.28 L.E.) under gated pipes system while the sugarcane intercropped with one rows tomato under traditional irrigation gave (8917.30 L.E.)

Table (8): Interaction effect of irrigation systems and intercropping patterns on LER and total income.

Irrigation systems	Intercropping patterns	Yield of cane ton/fed	Yield of tomato ton/fed	LER	Income of cane LE/fed	Income of tomato LE/fed	Cost of gated pipes L.E./fed	Total income LE/fed
gated pipes system	Pure stand sugarcane	55.23	----------	-------	----------	--------	1200	5799.15
	Sugarcane +one row tomato	51.27	26.40	1.81	5799.15	5280.00	1200	10663.35
	Sugar cane +two rows tomato	43.36	27.00	1.87	5383.35	5400.00	1200	1037.28
	Solid tomato	---------	30.03	-----------	4972.80	6006.00	1200	6006.00
Traditional surface irrigation	Pure stand sugarcane	47.15	-----------	----------	------------	-------	---------	4950.75
	Sugarcane +one row tomato	43.46	21.77	1.72	4950.75	4354.00	-------	8917.30
	Sugar cane +two rows tomato	42.66	23.17	1.75	4563.30	4634.00	------	9113.30
	Solid tomato	----------	27.38	----------	4479.30	5476.00	---------	5476.00

CONCLUSION

1- Values of stalk height, stalk diameter, number of millable stalks / fed, cane yield /fed, and W.U.E. were increased by using gated pipes irrigation. The cane yields were increased by 11.93 and 11.07% in the two seasons respectively. While the water applied m^3/fed were reduced by 13.94 and 14.85% also the W.U.E. were increased by 25.33 and 24.93% in the same seasons respectively.

2- The cane yield intercropped with tomato were reduced by 6.37, 13.52% and 7.48 and 15.98% less than the pure stand of one row and two rows tomato in both seasons respectively.

3- The cane yield were 52.67, 47.32 ton/fed and 51.27, 43.36 ton/fed when intercropped with one row and two rows of tomato in gated pipes system in the two seasons respectively compared with 48.38 and 47.15 ton/fed for pure stand sugarcane in traditional surface irrigation in the two seasons respectively. The water applied m^3/fed was reduced by using intercropping tomato with sugarcane under irrigation system. It was 7115, 7226.67 m^3/fed and 7065, 7073.33 m^3/fed for one row and two rows in the two seasons respectively compared with 8120, 8083.33 m^3/fed for pure stand sugarcane under traditional surface irrigation in the two seasons.

4- The fruits damage % was affected by interaction between gated pipes systems and intercropping it was 10.97, 11.48 and 12.48% and 11.07, 12.20 and 12.10% for one row, two rows and solid tomato in the two seasons respectively. Marketable yield ton/fed followed the same trend. It was increased by using gated pipes systems and intercropping, it was increased in the two seasons compared with solid tomato in the traditional irrigation. It was 23.16 , 24.95 ton/fed and 22.38 , 22.64 ton/fed for one row and two rows tomato in the two seasons respectively compared with 35.98 and 33.95 ton/ fed for solid tomato in the traditional irrigation in two seasons respectively.

5- The LER value for sugarcane intercropped with one row and two rows of tomato were 1.81 and 1.87 respectively for gated pipes system while it was 1.72 and 1.75 for one row and two rows tomato for traditional surface irrigation respectively.

6- The sugarcane intercropped with one row tomato under gated pipes gave the highest total income, (10663.35 L.E.) while the sugar cane intercropped with two rows tomato under traditional irrigation gave the lowest total income, (9113.30 L.E.).

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Development of a nomograph for scheduling irrigation for flood irrigated pecan orchards

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Abstract

For farmers to accurately schedule future water delivery for irrigations, a prediction method based on time-series measurements of soil moisture depletion and climate-based indicators of evaporative demand is needed. In New Mexico, pecan (Carya illinoinensis) farmers in the Mesilla Valley have been reluctant to adopt soil-based or climate-based irrigation scheduling technologies. In response to low adoption rates, we have developed a conceptually simplified, low tech, practical irrigation scheduling tool specifically for flood-irrigated pecan production. The information presented in the tool which is presented as slide rule nomograph was derived using 14 years of archived climate data and model-simulated consumptive water use. Using this slide rule, farmers can estimate the time interval between their previous and the next irrigation for any date in the growing season, in a range of representative soil types. An accompanying metric for extending irrigation intervals based on field-scale rainfall accumulation was also developed. In modeled simulations, irrigations scheduled with the tool while employing the rainfall rule were within 3 days of the model-predicted irrigation dates in silty clay loam and loam soil, and less than 2 days in sandy loam and sand soil. The simulations also indicated that irrigations scheduled with the tool resulted in less than 1% reduction in maximum annual consumptive water use, and the overall averaged soil moisture depletion was 45.14 % with an 18.1% coefficient of variation, relative to a target management allowable depletion of 45%. Our long term objective is that farmers using this tool will better understand the relationships between seasonal climate variation and irrigation scheduling, and will seek real-time evapotranspiration information currently available from local internet resources.

Introduction

Compared to other crops grown in the Lower Rio Grande Basin, pecan trees have the highest consumptive water use (Blaney and Hansen, 1965; Sammis et al., 1979). The reduction of water stress with correct timing of irrigations can have a significant impact on yield, nut quality, and precocity (Stein et al., 1989). An incentive for pecan producers to monitor water inputs should come from the perception that adoption of new soil moisture monitoring technologies will provide a means to increased profitability, which will in turn pay for the costs of those technologies many times over. However, in a

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limited study at five Mesilla Valley pecan orchards, growers were reluctant to adopt irrigation scheduling approaches that required measuring soil moisture with granular matrix sensors and data loggers, collecting bi-weekly tensiometer measurements, or tracking soil water-balance with an internet-based consumptive water use model (Kallestad et al., 2006). According to the Farm and Ranch Irrigation Survey (USDA 2002) only 2% of farms in New Mexico use soil moisture sensing devices, and less than 1% refer to daily crop evaporation reports or computer simulation models as methods in deciding when to irrigate; whereas 26% used a calendar, 23% use soil moisture “by feel”, and 62% of respondents said they use “crop condition” to schedule irrigation. Numerous recent articles and extension reports have concluded that instruments requiring high in-season labor input for field measurements are not likely to be used by farmers (Hill and Allen, 1996; Thompson et al., 2002; Sanden et al., 2003).

Simplified irrigation calendars based on historic reference evapotranspiration (ET_o), crop coefficients (k_c), plant phenology, and average seasonal rainfall, with intervals derived from modeled soil water balance, have been developed for a variety of annual crops. The simplest calendars provide fixed irrigation intervals with respect to a planting date, and have been used in developing countries where access to soil and climate-based scheduling technologies are limited (Hill and Allen, 1996). More flexible irrigation calendars account for the unreliability of rainfall and variability in seasonal temperature. Raes et al., (2000, 2002) devised calendars with irrigation intervals for specific crops using 15 to 25 years of historic climate data in a soil water balance model. Guidelines were also devised for delaying the irrigation intervals to account for rainfall. A delay factor is computed by the farmer by dividing the amount of accumulated rainfall by the typical irrigation depth. This factor is then multiplied by the recommended irrigation interval to determine the delay time in days.

ET calendars are primarily used in planning irrigation by employing the “checkbook method”. Similar to balancing a checkbook, the previous day's adjusted soil water depletion level (current balance) is adjusted by adding irrigation and rainfall inputs (deposits) and subtracting crop water use from ET tables for that period (withdrawals). Using this information, a farmer can track daily soil water balance to a management allowable depletion, based on crop root depth and soil water holding capacity.

Historical ET calendars are most appropriate for regions where climate is relatively consistent from year to year, and variability in seasonal rainfall and ET_o are small. Scheduling irrigation with historic ET has been advocated for some areas of California’s semiarid Central Valley (Hansen et al., 1999). Weekly ET calendars have been made available for California almond growers through the University of California Cooperative Extension (Sanden, 2006).

The objectives of this document are to describe the scheduling tool development and validation process for pecan irrigation scheduling, and elaborate on the potential for applying this process to other pecan growing regions, as well as for a broader scope of crops and irrigation methods.

Model description

The volume balance model used in this study is one component of an existing object-based growth and irrigation scheduling model (GISM) in spreadsheet format, modified for simulating irrigation management of a variety of crops including mature pecan orchards (Al-Jamal et al., 2002). The elements of this model were previously described in McGucken et al. (1987). In general terms, the volume balance model simulates daily available soil water in the rootzone by the relation:

$$SM_j = SM_i + USI_j + MSI_i + R_j - sf\left(ET_c\right)_i \tag{1}$$

where the soil moisture content in the rootzone at a particular timestep SM_j, is the sum of the soil moisture in the previous timestep (SM_i) plus any user-scheduled irrigation (USI_j), plus any model-scheduled irrigation (MSI_i) in the previous timestep, plus rainfall (R_j) inputs, minus moisture lost to crop evapotranspiration (ET_c), which may be modified by a water stress function scalar (sf). After an irrigation or heavy rainfall, when the soil moisture is in excess of the texture-specific water holding capacity (whc) in the user-defined rooting depth, the model sets volumetric soil moisture to the product of the whc times the rooting depth at that timestep, minus the ET_c for that period. The model assumes excess water is lost to drainage within the following timestep. Irrigations are scheduled by the model when $SM_{i,}$ diminished by sf x ET_c falls below the relative moisture content determined by the user-specified management allowable depletion (MAD).

The model requires daily meteorological input data collected from a user-selected weather station. Maximum and minimum humidity, temperature, solar radiation, wind speed, and soil temperature data from a network of local automated Campbell weather stations are gathered every night and made available on the New Mexico Climate Center's web site. The Climate Center also computes ET_o using a modified Penman-Monteith FAO-24 equation (Sammis et al., 1985), and accumulated growing degree days (GDD) for a variety of crops (Sammis et al., 1985). The daily GDD specific for pecan is calculated using an averaging method with no maximum or minimum cutoff temperatures, and a base air temperature of 60 °F as follows:

$$\begin{aligned} &GDD = T_{ave} - T_b \quad \mathit{if}\ T_{ave} > T_b \\ &\mathit{else} \\ &GDD = 0 \end{aligned} \tag{2}$$

where $T_{ave} = (T_{max} + T_{min})/2$, and T_b = crop specific base temperature. Station rainfall data can also be used in the computation of soil water balance.

The model requires user-defined physical parameters such as texture-specific soil water holding capacity, and irrigation amount; and phenological parameters such the starting and maximum rooting depth, and root growth rate. For mature pecan trees it was assumed that the starting and maximum root depths were the same.

The pecan crop coefficient (k_c) was computed from ET measurements collected in 2001 and 2002 at a mature pecan orchard 5.1 km south of Las Cruces using a one propeller eddy covariance (OPEC) system (Sammis et al., 2004). The model uses a fourth-order polynomial regression function of daily crop coefficient on an explanatory variable of GDD. The pecan crop coefficient polynomial is used to calculate daily ET_c by scaling ET_o input.

When soil moisture content falls below 45% of field capacity, the rate of ET in pecan trees can drop (Rieger and Daniell, 1988; Garrot et al, 1993). Below this stress threshold the trees close their stomata to use less water. At each time-step the model computes a variable scalar to modify ET_c according to the conditional function:

$$\begin{aligned} &If\ sf = m\left(\frac{SM_{i\ j}}{whc_j}\right) + b > 1 \\ &then \quad sf = 1 \\ &else \quad sf = m\left(\frac{SM_{i\ j}}{whc_j}\right) + b \end{aligned} \tag{3}$$

where the stress function scalar sf (dimensionless) is the product of a user-defined slope m multiplied by the relative soil moisture content at that timestep, plus a user-defined intercept. The function sets all sf values greater than 1 to 1. For pecans the slope value is set to 1.82 and the intercept to 0, which corresponds to a MAD of 45%.

Materials and Methods

STUDY AREA. The weather station located at the New Mexico State University Leyendecker Plant Science Research Center (PSRC), 9 miles south of Las Cruces New Mexico, was selected from among a network of local weather stations for its central location in the Mesilla Valley, and for the large and fairly reliable dataset archived from this site. Rainfall data from a second weather station located on the campus of New Mexico State University, which reports to the Western Regional Cooperative Network of the National Climate Data Center (NCDC), were used to derive the rainfall rule, and for tool validation studies.

DATA QUALITY. Archived climate data from the PSRC weather station for the years1988 through 2005 were collected and input in the irrigation scheduling model. To assess the quality of the meteorological data, time series plots of daily temperature minima and maxima, daily solar radiation, and daily relative humidity maxima and minima were examined to determine any sensor discontinuities or abnormalities and only good data was used in the analysis. All rainfall data came from the NCDC weather station because it is a hand read station with a high reliability factor.

INTERVAL DERIVATION. Each year's daily meteorological data including ET_o and pecan-specific GDD data was retrieved from the PSRC archive and input into the model, except for rainfall. For each model run, the soil water-holding capacity, root depth, and irrigation amounts listed in Table 1 were included as input parameters, with the user-defined MAD was set to 45%.The period (in days) between each model-scheduled irrigation was recorded and correlated to the date the irrigation was applied. This was done for each year in the dataset, for 4 soil water holding capacities and root depths corresponding to the 4 representative soil types. The dates were converted to Day of the year, and the mean irrigation interval for any application date (Day of the year) was determined by regression on a cubic polynomial function using Sigmaplot (Systat, Point Richmond CA). The minimum order polynomial was determined by maximizing the coefficient of determination for each regression.

Table 1. User-defined input parameters used in the irrigation scheduling model for each soil type.

Soil texture	Water holding capacity (inches/ft)	Beginning and maximum root depth (inches)	Irrigation amount (inches)
Sand	1.02	48	4
Sandy loam	1.42	48	5
Loam	2.02	42	6
Silty clay loam	2.53	42	6

RAINFALL RULE. Meteorological data collected at the PSRC weather station for all the dataset years, except rainfall, were input into the model. For each tool-defined interval, daily rainfall data retrieved from the NCDC station was sequentially input into the volume balance model. The difference (in days) between model-scheduled irrigation date with or without rainfall was regressed against the quantity rainfall using a linear function. This process was conducted with each of the four water holding capacities corresponding to soil type.

Results and Discussion

Random and systematic errors in solar radiation and relative humidity have been shown to have the greatest effect on the estimated mean daily ET_o using the FAO-Penman Montieth equations, followed by temperature, and least of all wind run (Meyer et al.,1989). However, as far as the output of the volume balance model and values used for the scheduling calendar are concerned, these errors are likely to be smaller than errors resulting from false assumptions about tree root depth, or the contribution of rainfall to soil moisture.

DATASET SYNOPSIS. Variation in the 14 years of meteorological data collected from the PSRC station is representative of larger time frames for this region. As shown in Figure 1A, annual rainfall for the data set years is approximately centered about the 47-year-average (1959 -2005). The dataset mean annual rainfall was 9.12 inches, with 2 years above, 3 years below, and 9 years within one standard deviation of the mean. The 47-year mean annual rainfall, measured at the NCDC station, was 9.28 inches. The 108-year-average (1892 to 2000) at the same site is 8.74 inches (Malm, 2003). Similarly, the variability in annual accumulative heat units with a 60 °F base temperature was distributed about a mean of 2487 °F, with 1 year above, 3 years below, and 10 years within one standard deviation of 151.7 °F. The 108 year average cumulative growing degree days was 2391 °F, with a maximum of 2994 °F and minimum of 1819 °F. Generally, the years 1991 and 2004 were particularly cool and wet, and the years 1996, 2001, and 2003 were hot and dry. Averaged monthly rainfall in the dataset years was also typical of the 47-year average (Figure 1B).

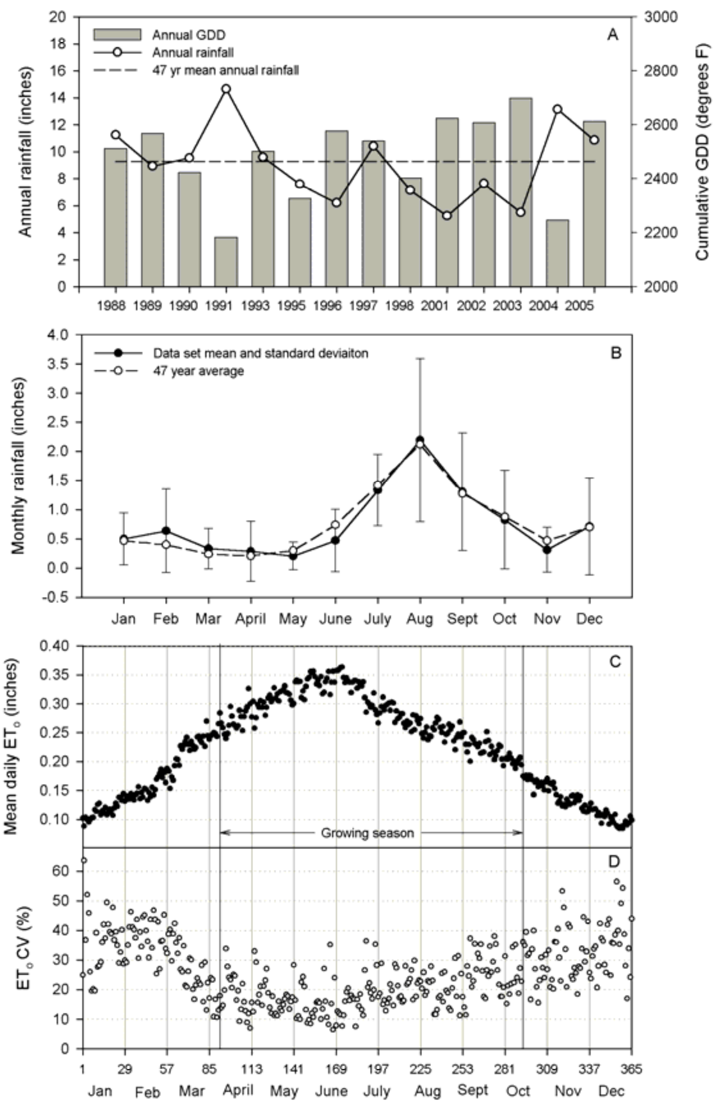

Figure 1. Synopsis of the meteorological data used in the development of the irrigation scheduling calendar. (A) Cumulative annual growing degree day (GDD) and rainfall data for years included in the data set, and 47-year average (1959 -2005) for annual rainfall. (B) Monthly rainfall averages for years included in the dataset, and 47-year monthly average. (C) Potential evapotranspiration (ET_o) averaged for each day from all years

included in the dataset. (D) Averaged coefficient of variation in daily ET_o, expressed as a percentage, for all years included in the dataset.

Daily ET_o averaged over the 14 years of the dataset for each date was fairly consistent (Figure 1C), with a year-to-year coefficient of variation (CV) for each day at approximately 20% in the beginning of the growing season, dropping to 15% mid-season, then rising to 20-25% at the end of season (Figure 1D). Daily ET_o variation exceeding 40% in the fall and winter months were likely due to temperature and cloud cover anomalies. Similar monthly variability in atmospheric demand for water was measured over a 9 year period for the Lower Rio Grande Valley by Enciso and Wiedenfeld (2005) who noted an averaged monthly CV of 14% from March to May, followed by an increase to as much as 30% after September.

INTERVAL DERIVATION. In 2005 we found the soil moisture depletion computed by volume balance model in agreement with field measurements at 3 orchards with different soil types (Kallestad et al., 2006). However, information about the depth and distribution of mature pecan roots in different soils is mostly anecdotal and in all likelihood variable. The model's rooting depth input parameter is the greatest source of potential error in the predicted moisture depletion. Decreasing the rooting depth from 48 to 42 inches for trees grown in the finer textured soils (Table 1) resulted in a decrease in the averaged irrigation interval of more than 2 days throughout the growing season. Other than general field observations about pecan root systems (Woodroof and Woodroof, 1934), there is a scarcity of literature specifically addressing the frequency and viability of deeper roots in different soils and moisture regimes.

The approach of deriving irrigation intervals using only atmospheric demand in the volume balance model was done for three reasons. The first was to increase the accuracy of the soil-specific regression function. Using this method, 87 to 93% of the interval variability is explained by the regression model (Figure 2). When rainfall is included, the coefficients of determination falls to between 0.77 and 0.87 for sand and silty clay loam respectively, and the function predicts an irrigation interval that is increased by 1 to 2 days in mid season. Second, by excluding rainfall and providing the user with a method for delaying irrigations in proportion to rainfall, the accuracy of the soil-specific regression models remain high as well as flexible. Finally, averaging model-derived irrigation intervals across all years for each soil type, instead of entering averaged climate data, provides a means to assess the year-to-year variability in the model-predicted intervals.

Post-harvest farm operations were considered when choosing an appropriate start date to begin model-scheduled irrigations. Pecan harvest is typically completed before mid January, after which farmers are involved in pruning and soil preparations up until mid March depending on the extent of winter rainfall. Many pecan farmers begin their first irrigation before the third week of March. We therefore forced the model to begin the irrigation sequence on March 15^{th}. In a separate analysis, there was no difference in regressed intervals using different start dates.

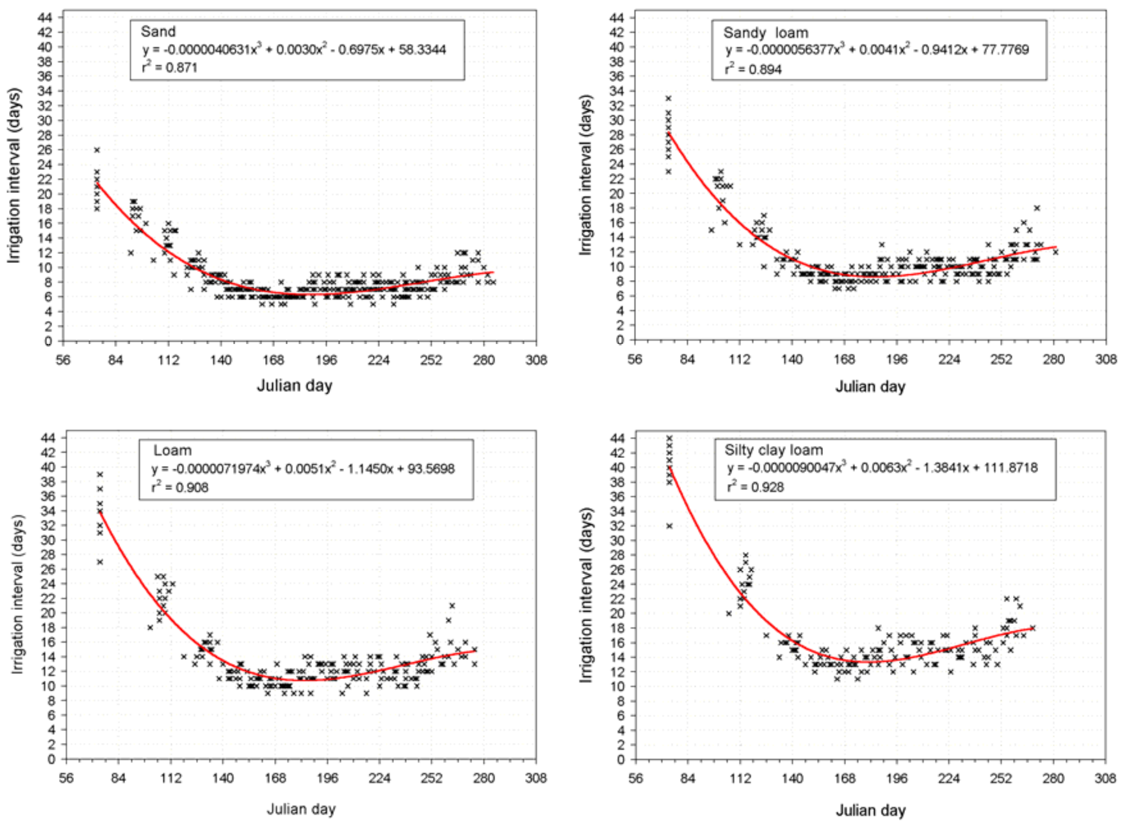

Figure 2. Model-derived irrigation intervals were plotted as a function of Julian date in four soil types. Each point represents the period of time to the next model-scheduled irrigation corresponding to the Julian date of the previous irrigation. Regression functions were used to derive intervals listed on the irrigation scheduling tool.

User-defined MAD is another source of uncertainty in the model. While there is some literature support correlating 45% MAD to water stress, there is little pecan-specific information correlating 45% MAD to yield. Changing the MAD levels from 45% to 55% delays the volume balance model-scheduled irrigations by 1 to 2 days in mid season, and longer at the beginning and end of the season.

RAINFALL RULE. The assumption built into the water balance model is that all of the station-reported rainfall contributes to soil moisture. Another assumption of the model is that water infiltration and drainage of soil moisture in excess of whc occurs within a single 24 hour time step. Any quantity of rainfall occurring immediately after a scheduled irrigation is allocated largely to drainage. In reality, for some fine textured soils, excess rain or irrigation water may stand on the surface for up to 72 hours, contributing to sustained field capacity moisture content in the root zone for several days.

The overall linear regression (Figure 3), which is approximately 3 days delay for every inch of rain, represents delay as a function of total rainfall. Erring on the side of caution, we devised the "one day increase for every half inch of rain" rule. Using this rule, users would measure rainfall accumulated at their location with a rain gauge. If accumulations exceed one half inch for the duration of the tool-defined interval then the irrigation could be delayed, but if accumulations for the interval were less than one half inch, the user would ignore the rule. Fractional values would always be rounded to the next highest interger. Users that choose not to delay intervals with rainfall will obviously over-irrigate.

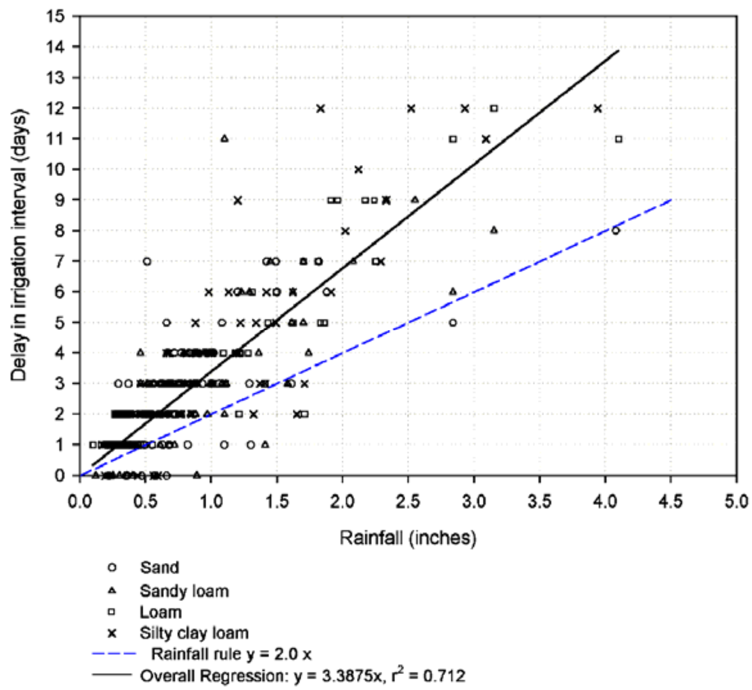

Figure 3. Model-derived irrigation intervals were plotted as a function of Day of the year for four soil types. Each point represents the period of time to the next model-scheduled irrigation corresponding to the Day of the year of the previous irrigation. Regression functions were used to derive intervals listed on the irrigation scheduling tool.

TOOL DECRIPTION. The tool is comprised of a printed card with the irrigation interval data for the four representative soil types arranged horizontally and listed below their corresponding calendar dates. The card slides through a printed jacket with cut out windows, instructions, and arrows to guide the user to the correct information. Also included on the tool is a description of the rainfall rule, and a table for calculating acre-inches of water to apply per irrigation based on acreage, soil type, and irrigation water salinity. The tool user slides the card through the jacket to the position where the calendar date corresponds to his last irrigation, and reads the irrigation interval from the line corresponding to his soil type (Figure 4).

Figure 4. The printed version of the irrigation scheduling estimator tool, with the irrigation interval data for the four representative soil types arranged horizontally and listed below their corresponding calendar dates on a sliding card, and information about delaying irrigations with rainfall accumulations. The user slides the card through a printed jacket with cut out windows that align the calendar date corresponding to his last irrigation, and reads the irrigation interval from the line corresponding to his soil type.

We evaluated 4 prototypes of the tool to determine a format that would be easiest for the growers to use and understand: 1) a wheel, with interval data for each soil type arranged radially, which spun inside a jacket with cut out windows aligning date with the interval; 2) a line graph of the intervals for each soil type as a function of calendar date printed on a card that slid through a jacket, which had a narrow cut out window aligning date with line position and the y-axis scale printed on the jacket; 3) a vertical list of the interval data printed on a card that slid through a jacket, 4) and a horizontal list of the interval data as described above. The prototypes were presented to the general public at the Southern New Mexico State Fair, to local pecan growers attending a New Mexico State University (NMSU) sponsored field day, and to various individuals attending or employed at NMSU. Study participants were guided through the operations necessary to obtain the information using each prototype, and then completed a short written survey to evaluate performance and rank preferences. The horizontal and vertical prototypes were favored over the wheel and graph.

TOOL VALIDATION. With regard to scheduling accuracy, tool-scheduled irrigations were on average within 1 to 2 days of water balance model-scheduled irrigations across all soil types, with the greatest inaccuracies occurring at the beginning and end of the growing season (Figure 5). Generally, the tool-scheduled irrigations were early before full leaf expansion, late during the spring when temperatures are highest and relative humidity is lowest, slightly early during the summer monsoon season, late again in late summer, then early in fall. Delaying irrigations with the rainfall rule resulted in greater scheduling accuracy, lower variability, and the elimination of 1 to 2 irrigations in the coarser textured soils.

The averaged annual soil moisture depletion (across all years and soil types) was 45.14 ± 8.2% when using the rainfall rule, and 43.5 ± 10.11% when the rainfall rule is ignored. The coefficient of variation was 18.2% with the rainfall rule delay and 23.3% without the rainfall rule delay. There were no significant differences when soil type and rainfall rule delay were considered separately.

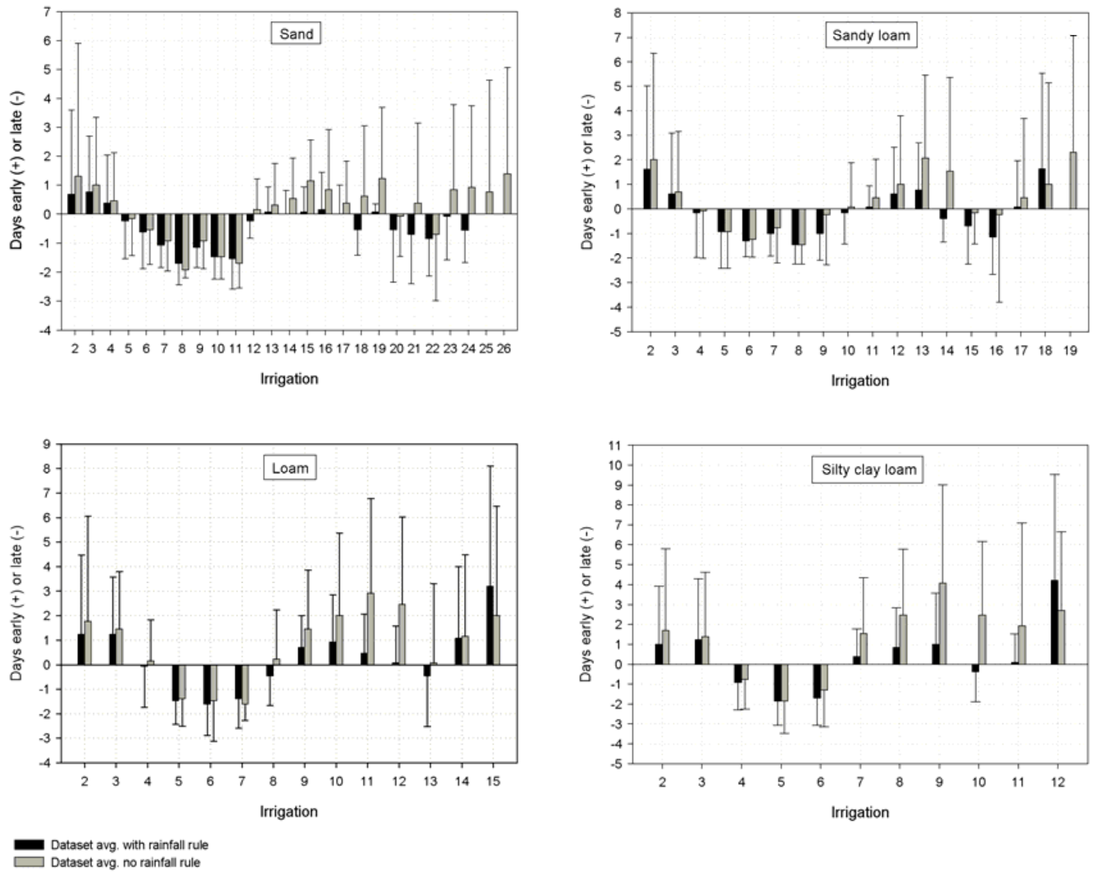

Figure 5. Averaged differences (days early or late) in irrigations scheduled with the irrigation scheduling tool and irrigations scheduled by the volume balance model. Differences were recorded using water holding capacities for the four representative soil types, and climate data for each year included in the dataset, with the rainfall rule (solid bars) and without the rainfall rule (shaded bars). Error bars represent one standard deviation.

Overall, the model-estimated annual loss in ET (the cumulative annual difference between stressed and non-stressed ET) resulting from irrigations scheduled late using the tool was less than 1% of the average non-stressed ET of 52.8 inches. As expected, ET losses were greater in the coarse texture soil, with lower water holding capacity, than in the fine textured soil. High estimated ET losses using the 1995 climate data occurred because summer monsoons were delayed approximately 4 weeks. High losses in 1996 resulted from higher spring temperatures and lower overall rainfall.

Conclusions

Producing a simplified irrigation scheduling calendar to circumvent labor-intensive soil moisture monitoring involves balancing a number of trade-offs. The tool needs to be conservative enough to minimize potential crop damage in hot dry years, yet accurate enough to minimize unnecessary irrigations. The information must be simple, straightforward, and readily understood; and versatile so that missing information can be easily interpolated. Ultimately it must provide a low risk compromise between either managing crop water in response to environmental variability with sensors, or simply guessing when to irrigate. The basic problem addressed in this calendar development process was determining the extent to which a 15% to 20% year-to-year variability in daily atmospheric demand for water translates into variability in model-scheduled irrigations, and how that variability in model-scheduled irrigations affects the accuracy of the calendar. Clearly, the availability of high quality local meteorological data has made development of this tool possible.

The tool developed was tailored for managing flood-irrigation in mature pecan orchards. The rapid application rate of flood irrigation is conducive, albeit simplistically, to a 24hr timestep model. For sprinkler or drip irrigation methods, more complex transport functions may required to model infiltration and lateral water movement in that time framework. Alternatively, water infiltration and extraction could be considered over longer timesteps, but such a model would require more generalizations to account for climate variability, and would therefore increase risk.

Tailoring the tool to account for different orchard maturity is also possible. Crop coefficient scaling factors have been developed for younger orchards with smaller canopy cover (Wang et al., 2007). However, we chose to avoid including additional scaling factors to reduce complexity.

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Experimental Verification of a Recursive Method to Calculate Evapotranspiration

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ABSTRACT

Recently, a recursive combination method (**RCM**) to calculate potential and crop evapotranspiration (ET) was given by Lascano and Van Bavel (*Agron. J. 2007, 99:585 – 590*). The **RCM** differs from the Penman-Monteith (PM) method, the main difference being, that the assumptions made regarding the temperature and humidity of the evaporating surface in the PM are not necessary when using the **RCM**. Rather, the **RCM** solves for ET by finding the temperature and the humidity by iteration and therefore satisfies the energy balance. We compared values of alfalfa ET measured with a large lysimeter at Bushland, TX, for a range of environmental conditions, to those calculated with the **RCM**. The **RCM** is based on the same physical principles as the PM except for the assumption that air and canopy temperatures are equal in the calculation of vapor pressure vs. air temperature relation. Unlike the PM, the **RCM** uses iteration to find an accurate answer for ET and can be easily be implemented using commercially available mathematical software such as Excel® and Mathcad®. Results for two days show that the **RCM** correctly calculates alfalfa ET and this conclusion is based on the close agreement between measured and calculated hourly values of ET.

INTRODUCTION

In agriculture, information on the amount of water that crops require is necessary to schedule irrigation and to maximize both the efficient use of water resources and crop production. Historically, methods used to estimate water evaporation have been a combination of empirical and theoretical approaches. Reviews of evaporative methods are given by Sibbons (1962), Brutsaert (1982), and more recently by Howell and Evett (2004), and Lascano (2007).

In 1948, *three* seminal papers were published that impacted our understanding of evaporation. *First*, was the paper of Charles W. Thornthwaite (1899 – 1963) (Thornthwaite,

1948) where he introduced and coined the term **potential evapotranspiration** (ET_p) and the concept that ET_p was the maximum rate of water loss by evaporation from the land and depended primarily on atmospheric conditions. A *second* paper was that of Howard L. Penman (1909 – 1984) (Penman, 1948) in which the **combination method** was introduced to ET from open water, bare soil, and grass. It was called the combination method because it combined the energy balance and an aerodynamic or diffusion formula to calculate ET and in doing so eliminated the surface temperature from the relevant equations (e.g., Sibbons, 1962; Milly, 1991). An almost exactly similar solution was obtained independently by Budyko (1951 and 1956) who termed the approach the *complex method* and by Ferguson (1952). The *third* paper was the work of Mikhail I. Budyko (1920–2001) (Budyko, 1948), where he summarized some of his pioneering work on evaporation.

It is clear that the methods proposed by Penman (1948) and by Budyko (1951 and 1956) to calculate evaporation were independent of each other. However, there is a *major* distinction between them in that the assumptions made by Penman (1948) regarding the temperature and the humidity of the evaporating surface are not required with the method proposed by Budyko (1951 and 1956). The method proposed by Budyko was *iterative* and his method consisted of an energy balance equation with two unknowns, ET_p and the surface temperature T_s, and the Goff-Gratch equation (Goff and Gratch, 1945) that relates the saturation humidity at a surface to the temperature at that surface. Starting with an initial value for T_s, the value of both unknowns is found by iteration, resulting in a value of T_s that satisfies the energy balance. An outline of this procedure is given by Budyko (1956, pp. 162 – 163) and by Sellers (1965, pp. 168 – 170). It is of interest to note that the Budyko (1956) publication was used as a graduate-textbook in a climatology class taught by Dr. William D. Sellers while a faculty member at the University of Arizona in Tucson (C.H.M. van Bavel, personal communication). Hereafter, we refer to the procedures based on Penman (1948) as the **E**xplicit **C**ombination **M**ethod (**ECM**) and those based on the iterative procedure first suggested by Budyko (1951 and 1956) as the **R**ecursive **C**ombination **M**ethod (**RCM**). Additional information on the **ECM** and **RCM** is given by Lascano and Van Bavel (2007).

The purpose of this paper is to two-fold. First, we provide a brief historical documentation on the development of **ECM** and **RCM** procedures used to calculate evapotranspiration. Second, using measured hourly values of air and dewpoint temperature, wind-speed, net irradiance, and soil heat flux we calculate ET using the **RCM**, and compare measured and calculated values of alfalfa ET. All measured values were obtained at Bushland, TX and alfalfa ET was measured with large weighing lysimeters (Marek et al., 1988: Howell et al., 1995). The purpose of the second objective was to experimentally verify the **RCM** as proposed by Lascano and Van Bavel (2007).

THEORY

In this section a brief history on the development of the **ECM** and **RCM** procedures is given. First, we start with the Penman (1948) combination equation, which eventually leads to the so-called Penman-Monteith (Monteith, 1965), the FAO-56 (Allen et al., 1998), and the ASCE (2005) procedures, which are all categorized as **ECM**. Second, we present the implementation of the **RCM** procedures based on Budyko (1951 and 1956). Please note that units of terms in most equations are intentionally omitted and if needed the reader should refer to the given references.

Explicit Combination Method (ECM)

Penman (1948) derived an explicit equation for ET_p by combining the energy balance of the evaporating surface with an aerodynamic diffusion equation to describe the flux of water vapor from the surface; thus, the term *combination method* is often used to describe his procedure. The fundamental assumption made by Penman (1948) was to assume that within the range of air and leaf water temperatures the vapor-pressure vs. temperature curve $(\partial e^*/\partial T)$ of water might be regarded as a straight line, which he took to be the derivative (tangent) of the vapor pressure curve at the air temperature T_a. This assumption allowed Penman (1948) to eliminate the leaf surface temperature T_s from the equations used to calculate ET_p. Mathematically, the linearity assumption is expressed by an approximation to $\partial e^*/\partial T$ and is given by:

$$\Delta = \frac{e_s^* - e_a^*}{T_s - T_a} \qquad [1]$$

where $\Delta = (de^*/dT)$ is the slope of the saturation vapor pressure curve $e^* = e^*(T)$, at the air temperature T_a, $e^*{}_a = e^*(T_a)$ is the corresponding saturation vapor pressure, and $e^* = e^*{}_s(T_s)$ the vapor pressure at the wet surface. Ferguson (1951) solved for ET_p from open water by solving a differential equation without the linearity assumption and derived an identical equation to that given by Penman's (1948) equation (16). A general form of the Penman (1948) equation to describe evaporative flux is given by Howell and Evett (2004):

$$LE = \frac{\left[\Delta\left(R_n - G\right)\right] + \left(\gamma\ LE_a\right)}{\left(\Delta + \gamma\right)} \qquad [2]$$

where LE $(\equiv \lambda E)$ is the evaporative latent heat flux (L and/or λ is the latent heat of vaporization); R_n is the net irradiance flux; G is the sensible heat flux into the soil; γ is the psychrometric constant; Δ is the slope of the saturated vapor pressure curve as defined in Eq. [1]; and E_a is the vapor transport flux also known as the aerodynamic evaporative term and empirically defined by Penman (1948) as:

$$E_a = W_f\,(e^* - e_a) \qquad [3]$$

where W_f is called a wind function, e^* is the saturated vapor pressure at mean T_a, and e_a is the mean ambient vapor pressure at a screen height above the ground surface. The evaporative term E_a in Eqs. [2 and 3], for a 24-h period, is expressed using a theoretical adiabatic wind-profile relation that defines the momentum surface aerodynamic resistance r_a, and E_a is given by:

$$E_a = \frac{\frac{\varepsilon\ \rho_a}{P}\ 86,400\ (e^* - e_a)}{r_a} \qquad [4]$$

where ε is the mole fraction of water in air (= 0.622), P is the barometric pressure, and ρ_a is the air density (e.g., Businger, 1956; Penman and Long, 1960; Van Bavel, 1966). The r_a for neutral atmospheric conditions is given by Evett (2002):

$$r_a = \frac{\ln\left[\frac{(z_w - d)}{z_{om}}\right]\ln\left[\frac{(z_r - d)}{z_{ov}}\right]}{k^2 U_z} \quad [5]$$

where z_w is the height for wind-speed measurement, z_{0m} is the momentum roughness length, z_r is the measurement height for humidity, z_{0v} is the vapor roughness length, k = 0.41 is von Karman's constant, d is the zero-plane displacement height, and U_z is the wind-speed at screen height z. The aerodynamic crop parameters are empirically estimated, as given by Evett (2002), with the following:

$$d = \frac{2}{3}\ h_c \quad [6]$$

$$z_{om} = 0.123\ h_c \quad [7]$$

$$z_{ov} = 0.1\ z_{om} \quad [8]$$

where h_c is the crop height.

The next step in calculating crop or actual ET was the recognition that an additional resistance to water vapor transport was involved causing $ET_a < ET_p$. For example, Penman (1953) recognized that the transpiration from well-watered vegetation involved a diffusion resistance due to leaf stomata and proposed that the expression for ET_p formulated in 1948 be modified as:

$$LE = \frac{ET_p(\varepsilon + 1)}{\varepsilon + 1 + \frac{r_c}{r_a}} \quad [9]$$

where ε is = Δ/γ, r_c is a canopy resistance term (bulk stomatal resistance), and r_a is the aerodynamic resistance defined in Eq. [5]. Equation [9] is analogous to Penman's (1953) equation (9), where he introduced the empirical concept of a stomatal (S) and a day-length factor (D), is the latter being equivalent to r_c given in Eq. [9]. The day-length factor D was defined as (Penman, 1953):

$$D = \frac{S_0}{24} + \frac{1}{2\pi}\left(\frac{(T_{a,\max} - T_{a,\min})/2}{T_{a,avg} - T_{d,avg}}\right)\sin\left(\frac{S_0\pi}{24}\right) \quad [10]$$

where S_0 is the day-length, $T_{a,max}$ is the daily maximum air temperature, $T_{a,min}$ is the daily air minimum temperature, $T_{a,avg}$ is the daily mean air temperature, and $T_{d,avg}$ is the daily average dewpoint temperature, and all temperatures are measured at a screen height above the ground surface. The stomatal factor S was defined as (Penman, 1953):

$$S = \frac{L_a}{(L_a + L_s)} \quad [11]$$

where L_a is an empirical function related to the molecular diffusion of water and wind speed at screen height, and $L_s \approx 0.16$, a value calculated for leaves with cylindrical tube stomata, and for a range of stomatal densities and epidermise thicknesses. A general method to calculate canopy resistance from leaf resistance does not exist and has lead to the formulation of theoretical (e.g., Jarvis, 1976) and empirical (e.g., Allen et al., 1989) approaches. Theoretical approaches are not described as they are beyond the scope of this paper.

Empirical equations to estimate bulk surface canopy resistance to water vapor flux based on crop height as a function of leaf area index LAI were given by Allen et al. (1989). For example, for a clipped grass:

$$LAI = 24\ h_c \quad [12]$$

where h_c is the height of the clipped grass for $h_c < 0.15$ m. For a non-clipped grass or alfalfa, Allen et al. (1989) proposed:

$$LAI = 1.5\ \ln(h_c) + 5.5 \quad [13]$$

with a surface or canopy resistance r_c for a reference crop calculated as a function of LAI by:

$$r_c = \frac{100}{(0.5\ LAI)} \quad [14]$$

The standard reference crop heights adopted by FAO-56 and ASCE are for a grass $h_c = 0.12$ m and for alfalfa $h_c = 0.50$ m, which result in $r_c = 70$ s/m for grass and $r_c = 45$ s/m for alfalfa.

Penman-Monteith

The resistance values suggested by Allen et al. (1989) were included in various derivations (e.g., Rijtema, 1965; Monteith, 1965) of the Penman (1948) equation and the resulting equation is known as the **Penman-Monteith** equation, which for daily values of LE is given by:

$$LE = \frac{\Delta(R_n - G) + \dfrac{86{,}400 \rho_a C_p \left(e_s^* - e_a\right)}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_c}{r_a}\right)} \quad [15]$$

where ρ_a is the air density, C_p is the specific heat of dry air, e^*_s is the mean saturated vapor pressure, e_a is the mean daily ambient vapor pressure, r_c is the canopy surface resistance, and r_a is the bulk surface aerodynamic resistance for water vapor. This equation is known as the ASAE Penman-Monteith equation (Jensen et al., 1990).

The ASCE-Standardized Reference Evapotranspiration Equation

The equation adopted and recommended by FAO-56 (Allen et al., 1998) and by ASCE (2005) to calculate crop evapotranspiration is based on the Penman-Monteith equation as given by Eq. [15]. Furthermore, to simplify and as an attempt to standardize the calculation ASCE adopted what is now termed as a Standardized Reference Evapotranspiration Equation, ET_{sz}, which for calculation of daily values is given by:

$$ET_{sz} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \qquad [16]$$

where ET_{sz} is the standardized reference crop ET for short (ET_{os}) or for tall crop surfaces (ET_{rs}), both in mm/d; R_n is the calculated net irradiance at the crop surface; G is the soil heat flux density at the soil surface, both terms in MJ/(m^2 d); T is the measured mean daily air temperature (°C); u_2 is the mean daily wind speed (m/s) measured at a screen height = 2 m; e_s is the saturation vapor pressure (kPa) calculated for daily time steps as the average of the saturation vapor pressure at maximum and at minimum air temperature; e_a is the mean actual vapor pressure (kPa); Δ is the slope of the saturation vapor-pressure temperature curve (kPa/°C), γ is the psychrometric constant (kPa/°C); C_n [K mm s^3/(Mg d)] is the numerator constant; and, C_d (s/m) is the denominator constant and both change with crop reference type and calculation time-step. The units for the coefficient 0.408 are m^2 mm/MJ. The screen-height for the measurement of T, e_s and e_a can vary between 1.5 and 2.5 m. Details on how to calculate R_n and G for daily estimates of ET_{sz} are given by Allen et al. (1998) and by ASCE (2005).

In practice, Eq. [16] is commonly used to calculate a daily reference ET for either a grass or an alfalfa crop, using values of short-wave irradiance, air and dewpoint temperature, and wind-speed, commonly measured at a screen height of 2.0 m above the ground surface. It is suggested that weather inputs used be based on hourly measurements of the weather variables (e.g., ASCE, 2005). This procedure is commonly used by regional weather networks, e.g., the Texas High Plains ET Network (http://txhighplainset.tamu.edu/), dedicated to providing information for the irrigation management of crops. The procedure is to calculate daily values of reference ET for a short grass using Eq. [16] and to multiply this value by crop-specific coefficients, thus providing a daily estimate of crop ET. In the Texas High Plains, this procedure is used to estimate the daily water requirements of crops such as, cotton, corn, soybean and wheat. This general method of using a crop reference ET in combination with crop coefficients to estimate crop ET, was termed the *engineering-approach* (Lascano, 2000) and was first suggested by Jensen (1968). For additional information see Lascano (2007).

Linearity Assumption

In Eq. [1], as T_s departs from T_a the error in the value of ET increases and this occurs under environmental conditions that are conducive to low and high rates of evaporation and high levels of solar irradiance (e.g., Sellers, 1965; Milly, 1991). This is important because conditions of high evaporation and solar irradiance are normally associated with arid and semi-arid environments where crop irrigation is normally practiced. Furthermore, the validity of the assumption of using a linear expansion of the curve of saturation vapor pressure curve vs. air temperature as introduced by Penman (1948) has been questioned by others (Sellers, 1965; Tracy et al., 1984; Paw U and Gao, 1988; McArthur, 1990 and 1992; Milly, 1991; and, Paw U, 1992). These authors suggested several approaches to eliminate the linearity assumption and thus minimize errors when calculating ET.

Paw U and Gao (1988) used a second-order Taylor expansion series of the approximation given by Eq. [1], i.e.,

$$e_s(T_a) = e_s(T_a) + \Delta(T_s - T_a) + \frac{1}{2}\frac{d^2 e_s}{dT^2}(T_s - T_a)^2 \qquad [17]$$

where the surface temperature T_s is eliminated (similar to Penman, 1948), yielding a quadratic equation for latent heat flux density (LE):

$$aLE^2 + bLE + c = 0 \qquad [18]$$

where coefficients a, b, and c are related to environmental parameters. This equation should have less error than the Penman (1948) equation because the saturation vapor pressure function is approximated by a quadratic curve instead of a straight line. Another solution to LE given by Paw U and Gao (1988) involved a quartic equation, expressing the saturation vapor pressure function by the approximation:

$$e_s(T_s) = \zeta + \alpha T_s + \beta T_s^2 + \psi T_s^3 + \mu T_s^4 \qquad [19]$$

where by algebraic manipulation and substitution into the energy balance equations T_s is eliminated and thus yielding a quartic equation to solve for LE:

$$kLE^4 + a^{'}LE^3 + b^{'}LE^2 + c^{'}LE + d^{'} = 0 \qquad [20]$$

where the coefficients k, $a^{'}$, $b^{'}$, $c^{'}$, and $d^{'}$ are related to parameters of the energy balance. The solution to Eq. [20] is complex and is given by Paw U and Gao (1988) in their appendix. Nevertheless, this solution still represents an approximation, although the error should be less than when a linear approximation is used. Additional information on Eqs. [18, 19, and 20] is given by Paw U (1992).

Milly (1991) went a step further and introduced a higher-order Taylor series to evaluate the saturation vapor pressure function using the expression:

$$T_s = T_a + \sum_{m=1}^{\infty} \frac{1}{m!}\left[\frac{d^m T^*}{de^m}\right]_a (e^*(T_s) - e^*(T_a))^m \qquad [21]$$

where T_a is the air temperature at an arbitrary level in the atmosphere, T_s is the air temperature near (adjacent) the evaporating surface, and m = 1,2,3 … ,. Specifically, the subscript a refers to conditions at an arbitrary level in the atmosphere above the surface. Again, by algebraic manipulation and substitution into general energy balance equations Milly (1991) derived a solution to calculate ET_a, which is given by his equation (23), although a simplification is given by his equation (25), which follows:

$$ET_a = \frac{\Delta_a (R_n - G)/L}{\Delta_a + \gamma^*}\left[1 + A + 0.44\frac{(1 - A\Delta_a/\gamma^*)^2}{A(1 + \Delta_a/\gamma^*)^2}\sigma\right] \qquad [22]$$

where ET_a is the evaporation rate; R_n is the net irradiance; G is the soil heat flux; L is the latent heat of vaporization, $\gamma^* = \gamma(r_a + r_c)/r_{ah}$, where γ is the psychrometric constant, r_a is the aerodynamic resistance to water vapor transport, r_c is the bulk canopy (stomatal) resistance, and r_{ah} is the aerodynamic resistance to heat transport; $\sigma = (d_a - d_{st})/e^*(T_a)$, where d_a is the vapor pressure deficit of the air, d_{st} is the vapor pressure deficit within stomatal cavities, Δ_a is the slope of the saturation vapor pressure curve; and, A is defined by:

$$A = \frac{\rho\, C_p (d_a - d_{st})}{\Delta_a (R_n - G) r_{ah}} \qquad [23]$$

where ρ is the air density, C_p is the specific heat at a constant pressure, and other terms are as previously defined. Milly (1991) through various manipulations also derived the quadratic equation, i.e., Eq. [19], given by Paw U and Gao (1988), leading to Milly's (1991) equation (29).

Another contribution of Milly (1991) was the derivation of a relative error term ε_r in evaporation rate ET_a calculated with **ECM** equations that use the linear assumption introduced by Penman (1948). The error ε_r is given by:

$$\varepsilon_r = -\frac{0.44(1 - A\Delta_a/\gamma^*)^2 \sigma}{A(1 + A)(1 + \Delta_a/\gamma^*)^2} \qquad [24]$$

showing that ε_r is always non-positive, i.e., the **ECM** to calculate ET_a can only yield smaller values of evaporation rate than does the **RCM**, but can never yield larger values than the **RCM**, but can never yield larger values than the **RCM**, all other factors being equal. In addition, it shows that ε_r goes to zero when the ratio A of the so-called 'wind term' to the 'radiation term' is equal to γ^*/Δ_a. This condition only occurs when LE ≡ (R_n – G), i.e., the sensible heat flux is zero and therefore $T_a \equiv T_s$.

The solutions to LE given by Paw U and Gao (1988) and Milly (1991) represent an improvement over the solutions given by the **ECM**, and used by FAO-56 (Allen et al., 1998) and ASCE (2005). Milly (1991) refers to these types of equations as *first-order combination equations*. However, the solutions are complex and convergence is not always assured. Tracy et al. (1984), McArthur (1992), and Milly (1991) stated that only by iteration can complete accuracy be obtained. Iterative methods are not new and have been used to calculate water evaporation from the soil and plant using energy and water balance simulation models (e.g., Lascano and Van Bavel, 1983 and 1986; Lascano, et al., 1987). Bristow (1987) used a Newton iterative procedure to find the surface temperature in solving the energy balance equation. However, none of these iterative techniques has been applied to provide general calculations of ET. Current data-loggers used with weather stations that measure the necessary weather input parameters have the necessary storage and processing capabilities.

Recursive Combination Method (RCM)

In addition to his earlier work (Budyko, 1951), Budyko (1956, pp. 162 – 163) suggested without any assumptions, an energy balance equation with two unknowns, ET and the surface temperature T_s, and the Goff and Gratch (1945) equations that relate the saturation humidity at the surface to T_s. The values of both unknowns (ET and T_s) are found by iteration starting with an initial value for T_s that satisfies the energy balance. Additional information is given by Lascano and Van Bavel (2007).

Lascano and Van Bavel (2007) used the mathematical software Mathcad[1]® v. 13 (Mathsoft Engineering & Education, Inc., Cambridge, MA) and Microsoft® Excel 2002, for the iterative solution of actual and potential ET. Mathcad® v. 13 uses the Secant or Muller method in the solution. In Mathcad® syntax the iterative calculation of T_s is given by Eq. [25], below:

$$T_s := root\left[\left[\left[0.80\times R_g - 5.67\times10^{-8}\times\left(T_s+273.2\right)^4 + R_l\right] + \frac{\left(T_a - T_s\right)\times\rho_d\times c_p}{r_a} - \frac{\left(1.323\times\frac{\exp\left(17.269\times\frac{T_s}{T_s+237.0}\right)}{T_s+273.2} - 1.323\times\frac{\exp\left(17.269\times\frac{T_d}{T_d+237.0}\right)}{T_a+273.2}\right)}{r_a+r_c}\times\lambda\right]\times\frac{r_a}{c_p\times\rho_d}, T_s\right] \quad [25]$$

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

where *root* is a built-in function given in Mathcad® where an initial value of T_s is given, e.g., T_s =10.0. In Eq. [25] inside the brackets is the energy balance of the crop, where the first term is the radiative component, the second term is the sensible heat flux, and the third term is the latent heat flux. All terms in Eq. [25] have been previously defined, except R_g the incoming short-wave irradiance, R_l the sky long-wave irradiance, and T_d the dewpoint air temperature at screen height. Once the implicit value of T_s is found, the latent and sensible heat fluxes are known as functions of T_s. We have also used *solver* (Excel® 2002) and compared results of T_s and ET to the solutions obtained with Mathcad® and the results from both solutions were identical.

METHODS

Experimental Data

Experimental weather and alfalfa ET data were gathered at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX (35° 11′ N, 102° 06′ W, 1170 m elevation above MSL) on a Pullman fine, mixed, superactive, thermic Torrertic Paleustoll soil. Half-hourly values of air (T_a) and dew-point (T_d) temperature, net (R_n) and incoming short-wave (R_g) irradiance, soil heat flux (G), wind-speed (U_z), and surface radiometric temperature (T_s) for 27 days with no rain in 1999 were selected and used as input data to calculate hourly values of ET_p using **RCM**. Half-hourly values of alfalfa ET were measured with large weighing lysimeters. Additional input data was the measured alfalfa height for the 27 selected days. Alfalfa variety Pioneer 5454 was seeded at a rate of 28 kg/ha on 13 – 14 Sep 1995, with a grain drill on 0.2-m spacing. Alfalfa was irrigated and fertilized to produce a reference ET vegetative surface (well-watered and without limitation of fertilizer or other inputs or management). A general description of the sensors and methods used to measure the above variables is given by Evett et al. (2000).

Lysimeter mass was measured every 0.5-h with 0.05-mm precision (Dusek et al., 1987). Weather variables were measured every 6-s and reported on 0.5-h averages. Over the lysimeter, R_n was measured with REBS net radiometers (Q*5.5, Seattle, WA), G was measured with four heat flux plates (REBS, HFT-1, Seattle, WA) buried 0.05-m below the surface with averaging thermocouples at 0.02- and 0.04-m above each plate. Also, T_s was measured with infrared thermometers (Everest, Model 4000, Fullerton, CA). Air and dew-point temperature, and wind-speed were measured at a screen height of 2.0 m in a nearby grass weather station using standard procedures as given by Evett (2002).

Procedures

For the purpose of this paper, only 3 days of measurement in 1999 were selected and used to validate the **RCM** of crop ET. A description of the procedure used in our calculations follows.

1. Crop ET was calculated using 0.5-h weather data using **RCM** of Lascano and Van Bavel (2007) as given by Eq. [25] and using the aerodynamic resistance (r_a) defined by Eq. [5]. Using the Mathcad® software (v. 14, Parametric Technology Corporation, Needham,

MA), canopy resistance (r_c) was defined as a *range-variable* and the measured values of crop ET and surface radiometric temperature (T_s) were used to estimate hourly values of r_c during daylight hours when stomata are fully open. In this procedure T_s, sensible heat flux, and ET were each calculated for values of r_c ranging between 10 and 100 s/m in 10 s/m increments. Data for Day of Year (DOY) 185 (4 July 1999), were used for this purpose.

2. Using the values of canopy resistance (r_c), as calculated with the previously described procedure, hourly values of alfalfa ET were calculated for two days (DOY 182 and 183) using as input measured values of weather variables, again using the **RCM**. The values of r_c calculated by this procedure are the values that satisfy the measured alfalfa ET values and corresponding radiometric surface temperatures.

RESULTS AND DISCUSSION

Calculation of Canopy Resistance (r_c)

The concept of using measured values of crop ET obtained with lysimeters to estimate canopy resistance (r_c) from a well-watered crop that is actively transpiring was first used by Ehrler and Van Bavel (1967), and Van Bavel and Ehrler (1968) on a sorghum crop. Using this procedure along with the **RCM** to calculate ET, the r_c was defined as a *range-variable* (10 – 100 s/m) and at 13:00 h on DOY = 185, the measured value of alfalfa ET was 1.026 mm, which yielded a value of r_c = 31.5 s/m (Fig. 1).

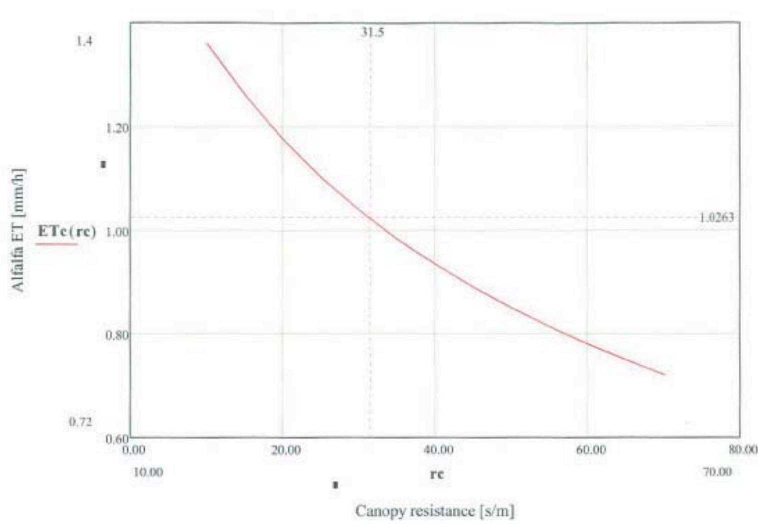

Figure 1. Calculated alfalfa-ET using **RCM** as a function of canopy resistance, defined as a *range-variable* in Mathcad® v. 14. The lysimetric measurement of alfalfa ET for this time-period was 1.026 mm, which yielded an r_c value of 31.5 s/m.

A second procedure that can also be used to obtain an estimate of r_c is to use the measurement of radiometric surface temperature (T_s) in a similar way as the measurement of crop ET (Fig. 1). Again, r_c was defined as a *range-variable* (10 – 100 s/m) in Mathcad® v. 14. At 13:00 h on DOY = 185, a measured T_s = 27.5 °C gives a calculated r_c = 33.5 s/m (Fig. 2).

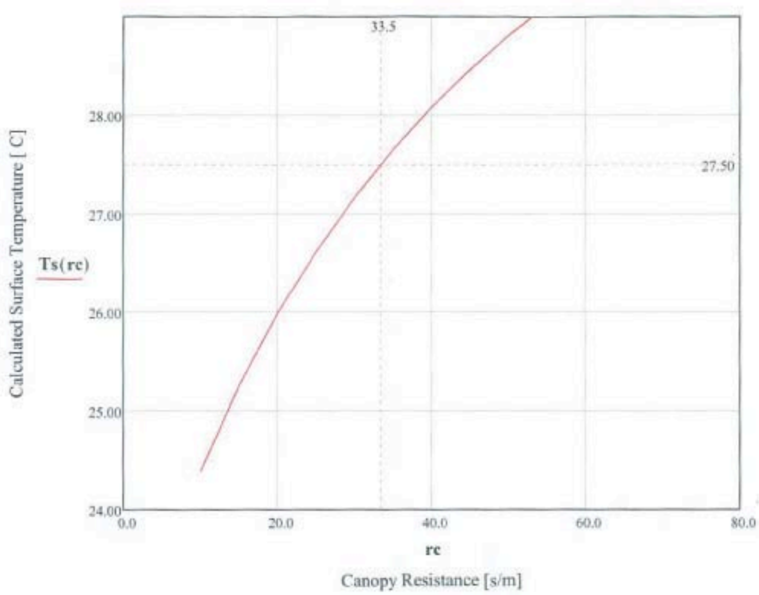

Figure 2. Calculated surface temperature (T_s) using **RCM** as a function of canopy resistance, defined as a *range-variable* in Mathcad® v. 14. The surface temperature measurement over alfalfa for this time-period was 27.5 °C, which yields an r_c value of 33.5 s/m.

A comparison between calculated values of canopy resistance (r_c) for DOY 185, 1999, between 8:00 – 19:00 h, for the two procedures used is shown in Fig. 3. The average between 10:00 – 17:00 h, for r_c from lysimetric measurements was 32 s/m (standard deviation = 2 s/m), and derived from surface radiometric temperature, it was 41 s/m (standard deviation = 8 s/m). Between 12:00 – 14:00 h, the calculated values of r_c from both lysimetric and radiometric surface temperatures are similar ~ 33 s/m. Therefore, we selected r_c = 33 s/m as the canopy resistance value to calculate hourly alfalfa ET using the **RCM** for DOY 182 and 183, and these values were compared to measured values of alfalfa-ET obtained with the lysimeter. The value of r_c reported by Ehrler and Van Bavel (1967) for three midday hourly values for sorghum was 28 s/m, i.e., 18% lower than that measured for alfalfa and shown in Fig. 3.

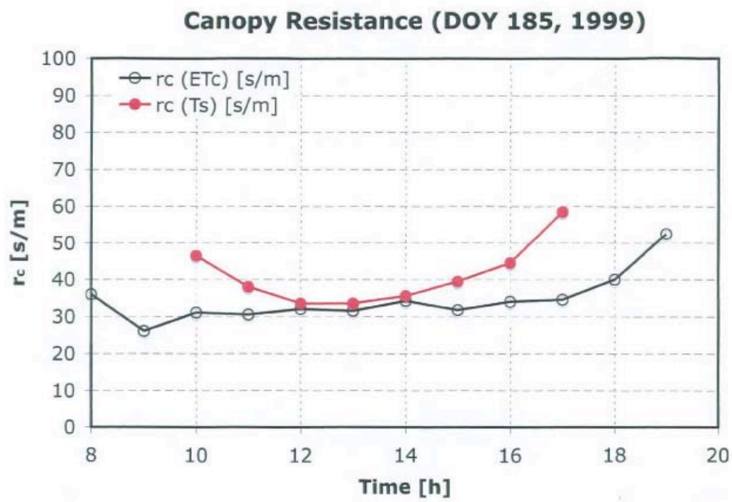

Figure 3. Calculated values of canopy resistance (r_c) from radiometric surface temperature T_s (●) and from lysimetric measurements ET_c (O) for DOY 185, 1999.

Weather-data for DOY 182

To illustrate the type of hourly input data used in our examples to calculate ET, we selected DOY 182, 1999. The hourly measured variables of air temperature (T_a), dewpoint temperature (T_d) and radiometric alfalfa canopy surface temperature (T_{can}) are shown in Fig. 4. The average daily T_a was 24.2 °C and average T_d was 18.0 °C. The corresponding measured hourly wind speed is shown in Fig. 5 and the daily average was 4.6 m/s. Hourly measured fluxes of net irradiance (R_n), soil heat flux (G), sensible heat flux (SH) and latent heat flux (LE) are shown in Fig. 6. The daily integrated fluxes were R_n = 17.14 MJ/m^2, SH = 14.51 MJ/m^2, LE = -32.04 MJ/m^2, and G = 0.39 MJ/m^2.

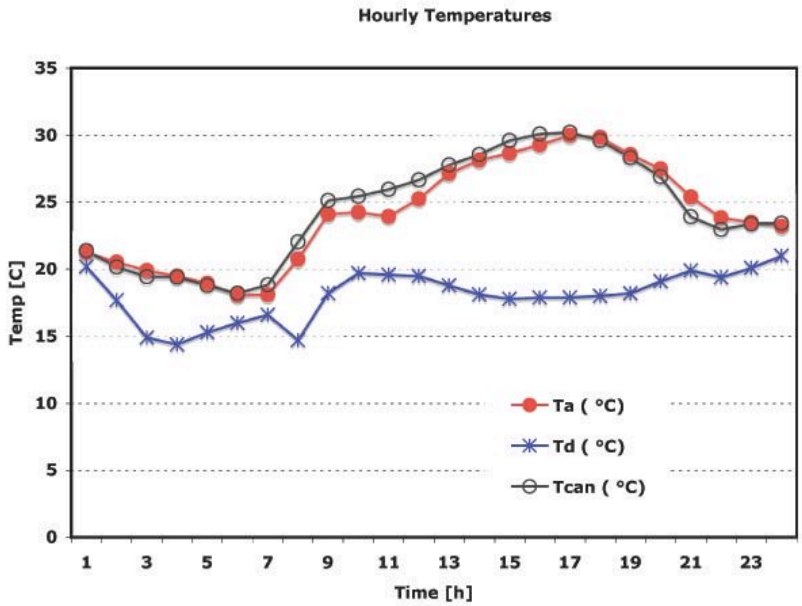

Figure 4. Hourly measured values of air temperature (T_a), dewpoint temperature (T_d), and radiometric alfalfa canopy temperature (T_{can}) on DOY 182, in Bushland, TX.

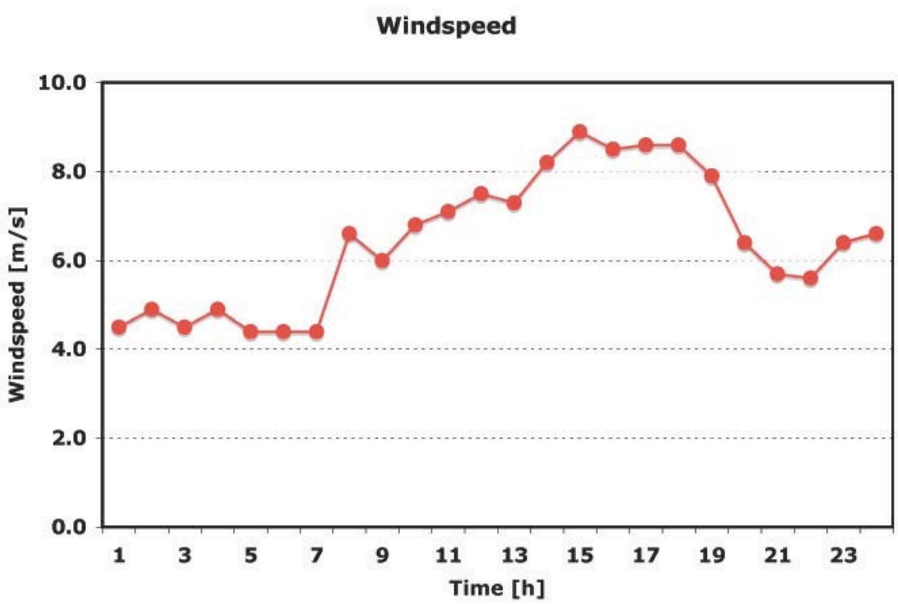

Figure 5. Hourly measured values of wind-speed for DOY 182, 1999 in Bushland, TX.

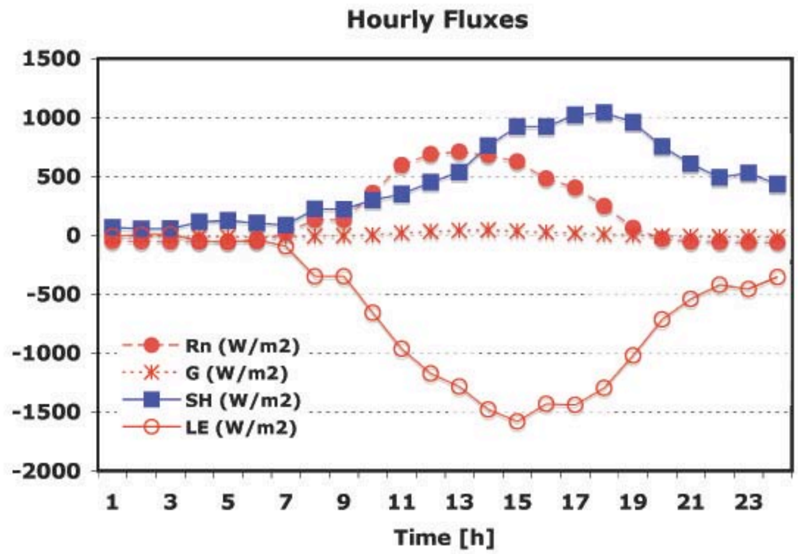

Figure 6. Hourly fluxes of net irradiance (R_n), soil heat (G), sensible heat (SH), and latent heat (LE) for DOY 182, in Bushland, TX.

The daily calculated value of potential ET_p obtained using the input weather data shown in Figs. 4 and 5, and using the **RCM** gave a total of 13.1 mm for DOY 182, 1999.

Comparison of Measured and Calculated Alfalfa-ET

Comparison of measured and calculated hourly values of alfalfa ET, between 8:00 – 18:00 h, assuming a constant values of r_c = 33 s/m throughout the day for the two selected days showed close agreement (Figs. 7 and 8). Furthermore, linear regression analysis (Fig. 9) indicated that the slope was not significantly different from 1.0 and the intercept was not significantly different than 0.0, with an r^2 = 0.98. From this comparison, we can conclude that the recursive combination method (**RCM**) first proposed by Budyko (1951 and 1956) and formulated by Lascano and Van Bavel (2007) is workable. The **RCM** is based on the same physical principles of the Penman-Monteith solution to ET, but uses iteration to find an accurate answer. It remains to be seen if the **RCM** compares well with the **ECM** for daily as well as seasonal estimation of alfalfa reference ET, which is work that we have in progress.

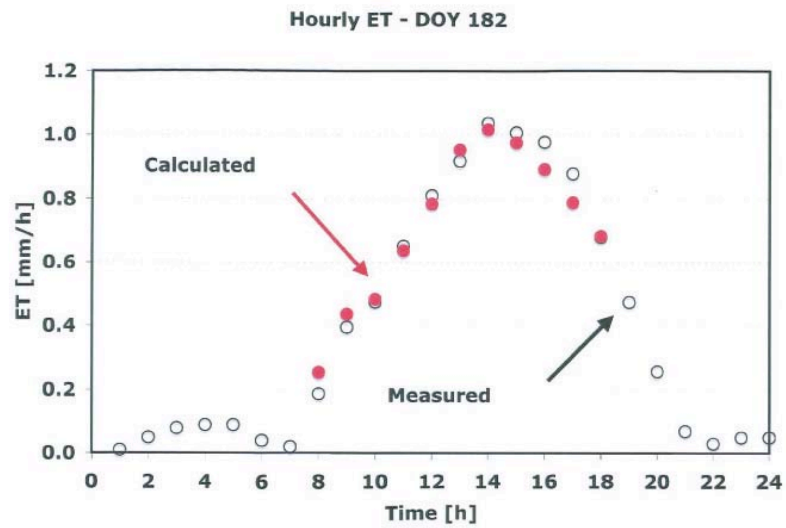

Figure 7. Hourly values of alfalfa ET measured with a lysimeter and calculated with **RCM** assuming r_c = 33 s/m, for DOY 182, 1999. Calculated values of ET were only done for daylight hours, i.e., 8:00 – 18:00 h.

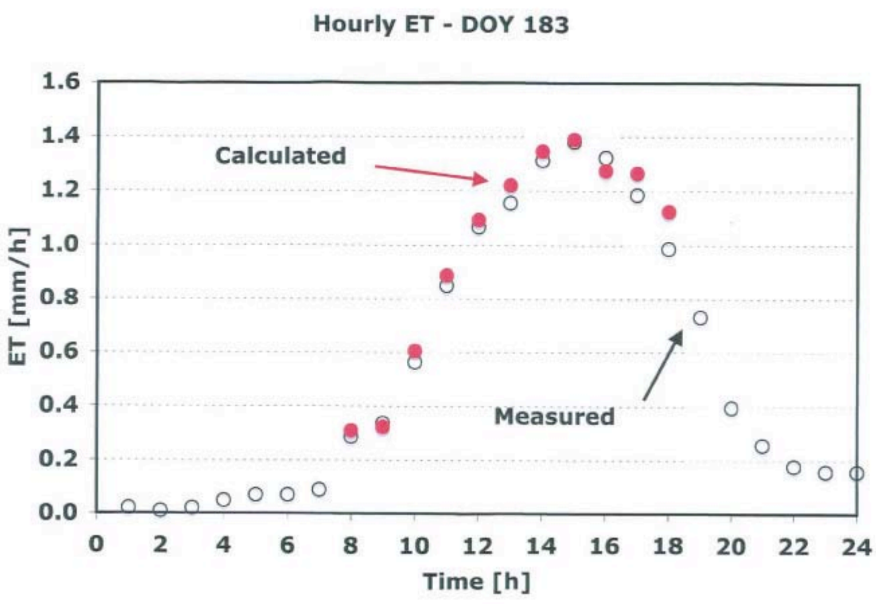

Figure 8. Hourly values of alfalfa ET measured with a lysimeter and calculated with **RCM** assuming r_c = 33 s/m, for DOY 183, 1999. Calculated values of ET were only done for daylight hours, i.e., 8:00 – 18:00 h.

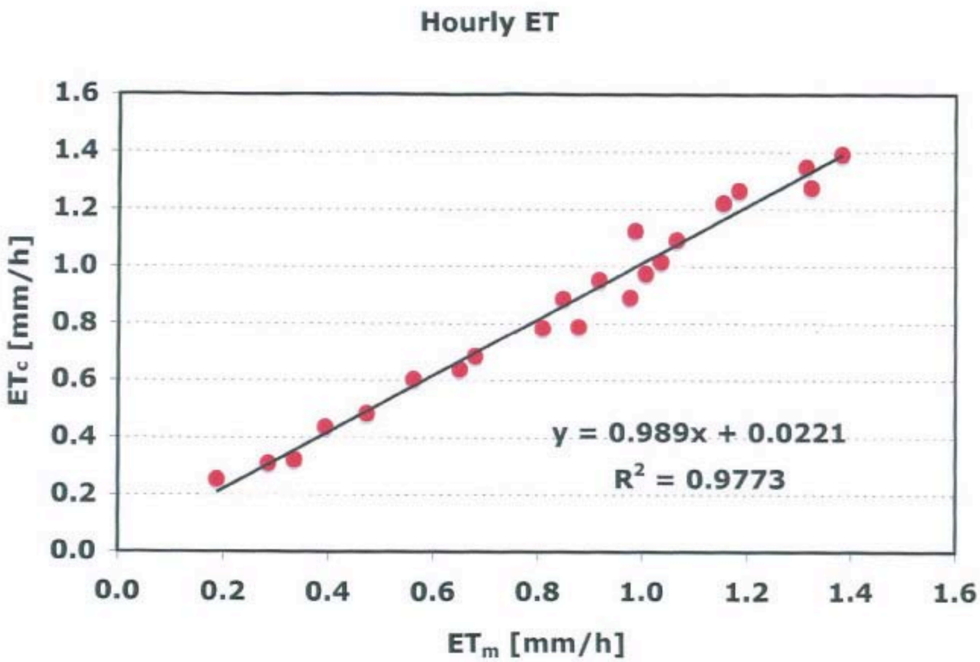

Figure 9. Linear regression between calculated values of ET (ET_c) and measured values of ET (ET_m) for the two days shown in Figs. 7 and 8.

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DETERMINATION OF CROP COEFFICIENTS (K_C) FOR IRRIGATION MANAGEMENT OF CROPS

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ABSTRACT

Weighing lysimeters are used to measure crop water use during the growing season. By relating the water use of a specific crop to a well-watered reference crop such as grass, crop coefficients (K_C) can be developed to assist in predicting crop needs using meteorological data available from weather stations. Seven lysimeters, consisting of undisturbed 1.5 x 2.0 x 2.2 m deep soil monoliths, comprise the Texas Agricultural Experiment Station - Uvalde lysimeter facility. Six lysimeters, weighing about 14 Mg, have been placed each in the middle of a one hectare field beneath a linear LEPA irrigation system. A seventh lysimeter was established to measure reference grass ET_O. Corn, sorghum, spinach, onion, cotton, and wheat were grown over the last five years in the lysimeter fields. Daily water use was measured on 5-min intervals. Crop water requirements, K_C determination, and comparison to existing FAO K_C values were determined over a 2 or 3 year period depending on the crop.

Keywords. Weighing lysimeters, ET measurement, Crop coefficients.

INTRODUCTION

In semiarid and arid lands and areas where water usage is regulated due to ecological protection programs, limited resources, and competitive demand (Barrett, 1999), agricultural water users must plan an annual water budget. Water for agricultural, urban and industrial use in the Austin – San Antonio – Uvalde corridor is pumped from the Edwards aquifer. This aquifer is in a class by itself being unique in terms of containment, recharge, and political sensitivity. The regulation of this aquifer, however, is portent to the regulation of all aquifers in Texas. In 2007, Senate Bill 3 of the 80th session of legislature imposed a maximum draw of 705.5 million m^3 of water per year from the Edwards aquifer. Since 50% of the water drawn from the aquifer is for agricultural use, agricultural water conservation strategies are of utmost importance in the Edwards region. Mild climatic conditions in this region allows for a variety of economically important crops to be grown year-round under irrigation, including corn, cotton, wheat, spinach, and onions. Determining crop water requirements specific to each crop is key in providing growers with information to a) select which crops to grow and b) determine the timing and quantity of irrigation events.

In 2000, growers in this region irrigated 40,000 ha (Texas Water Development Board, 2001). From preliminary studies carried on at the Texas Agricultural Experiment Station, it is estimated that approximately 62 million to 74 million m^3 of groundwater could be conserved each year by implementing proper irrigation techniques and scheduling. To optimize irrigation events, crop water requirements throughout the growing season must first be determined.

The use of on-site microclimatological data and crop coefficients enables the determination of crop water use and dissemination of such information to growers in a reliable, useable, and affordable format. Crop coefficients (K_C) are the ratio of the evapotranspiration of the crop (ET_C) to a reference crop (ET_O). ET_O may be measured directly from a reference crop such as a perennial grass or computed from weather data. Weighing lysimeters are employed to measure ET_O and ET_C directly by detecting changes in the weight of the soil/crop unit. Weather data is used to compute ET_O via equations such as the FAO Penman-Monteith. By utilizing the following equation, all that is needed to provide growers with real time irrigation recommendations (ET_C) are local weather stations.

$$ET_C = K_C \times ET_O \qquad (1)$$

According to Allen et al. (1998), crop type, variety, and developmental stage affect ET_C. The objective of this multiyear project is to determine crop water use (ET_C) and develop crop coefficients (K_C) specific to multiple phenological stages for row and vegetable crops grown in the Wintergarden region of Texas.

MATERIALS AND METHODS

The Wintergarden region of Texas is located on the South Texas Plains, receives approximately 660 mm yr^{-1} of precipitation, and has a growing season of approximately 214 to 275 d. The lysimeter facility at the Texas Agricultural Experiment Station located in Uvalde, Texas, USA (29° 13’ N, -99° 45’ W; elevation 283 m), includes seven weighing lysimeters constructed between 2001 and 2006. Construction details and resolution are described by Marek et al. (2006). Each lysimeter is 1.5 m x 2.0 m in surface area and 2.2 m deep. The surface area of the lysimeters accommodates the common row spacing utilized in the region. The soil monoliths in the lysimeters represent soils within an 80 km radius of the research station. Microclimatological data are collected every 6 s with 15 min output and the weight of each lysimeter is sampled every 1 s with 5 min output.

Microclimatological data are collected by a standard Campbell Scientific, Inc. (Logan, Utah, USA) weather station. (The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.) Changes in lysimeter weight are measured as changes in mV output of the load cell attached to the Avery Weigh Tronix (Fairmont, Minnesota, USA) scale beneath each lysimeter. The calibration of mV output to weight change represented as mm water is described in Marek et al. (2006).

A Campbell Pacific Nuclear Corp. (Martinez, California, USA) 503 DR Hydroprobe Moisture Depth Gauge was used to quantify volumetric soil water content of soil in the lysimeters during the growing seasons at 10 cm increments to a depth of 1.2 m. During the 2007 cotton growing season, one Agrilink C-Probe (Thebarton, South Australia, AU) sensor was added to each cotton lysimeter. The C-Probes measured volumetric soil water content at 10 cm increments to a depth of 1.5 m.

The crops grown over the last five years in the crop lysimeters used in the determination of K_C are reflected in Table 1.

Table 1. Crops grown at the Texas Agricultural Experiment Station – Uvalde for determination of K_C and associated seasonal data.

Crop	Variety	Planting Year	Plant-Harvest (M/D)	Precipitation (mm)	Irrigation (mm)	Growing Degree Days
Corn	32H39	2002	3/29 - 8/7	489	405	2426.8
	30G54	2003	3/18 - 8/11	322	349	2542.3
	30G54	2004	3/10 - 8/18	350	92	2598.7
Spinach	DMC16	2002	10/21 - 1/19	205	141	840.3
	DMC16	2003	11/20 - 2/27	60	130	821.7
Onion	Legend	2002	11/21 - 5/28	80	57	1808.8
Cotton	DP555	2006	4/12 - 9/7	75	604	2429.5
	DP555	2007	4/16 - 10/18	581	76	2547.7
Wheat	Ogallala	2005	11/18 - 5/19	58	434	3238.9
	Ogallala	2006	11/17 - 6/6	327	220	3365.3

RESULTS

The aim of this project is the determination of crop coefficients (K_C) for all crops grown in the Wintergarden region and to determine exact plant water usage or crop evapotranspiration (ET_C). Irrigation scheduling can then be improved for private consultants and growers to avoid water over use and to more precisely meet the crop water demand to produce greater yields, crop quality, and enhanced water use efficiency. Results from these experiments are in the following figures and tables:

Corn crop coefficients:

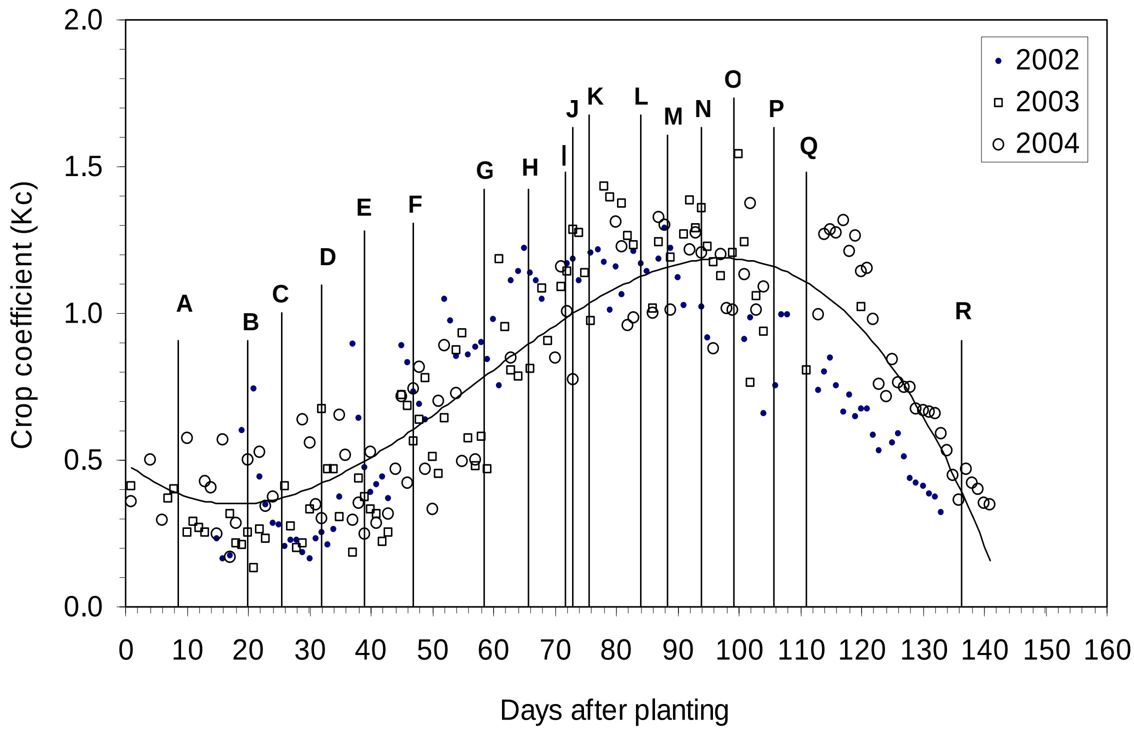

Figure 1. Corn crop coefficients as a function of days after planting in 2002, 2003 and 2004 at Uvalde, TX. Vertical lines represent 3-yr-average growth stages: A – emergence; B – 2 leaf; C – 4 leaf; D – 5 leaf; E – 6 leaf; F – 8 leaf; G – 10 leaf; H – 12 leaf; I – 14 leaf; J – tassel; K – silk; L – blister; M – milk; N – dough; O – dent; P – 1/2 mature; Q – black layer; R – harvest.

Table 2. Corn crop coefficients (K_C) determined at Uvalde, Texas in comparison to those from Bushland, Texas and from FAO.

Texas

Growth stage	Uvalde	Bushland
Emergence	0.35	0.35
2-leaf	0.35	0.45
4-leaf	0.40	0.70
6-leaf	0.45	0.85
8-leaf	0.55	1.00
10-leaf	0.70	1.15
12-leaf	0.80	1.20
14-leaf	0.90	1.25
Tassel	1.00	1.25
Silk	1.00	1.30
Blister	1.05	1.30
Milk	1.15	1.30
Dough	1.20	1.20
Dent	1.20	1.00
1/2 mature	1.20	0.90
Black layer	1.15	0.70

FAO

Growth stage	K_C
K_C ini	0.30
K_C mid	1.20
K_C end	0.35

Spinach crop coefficients:

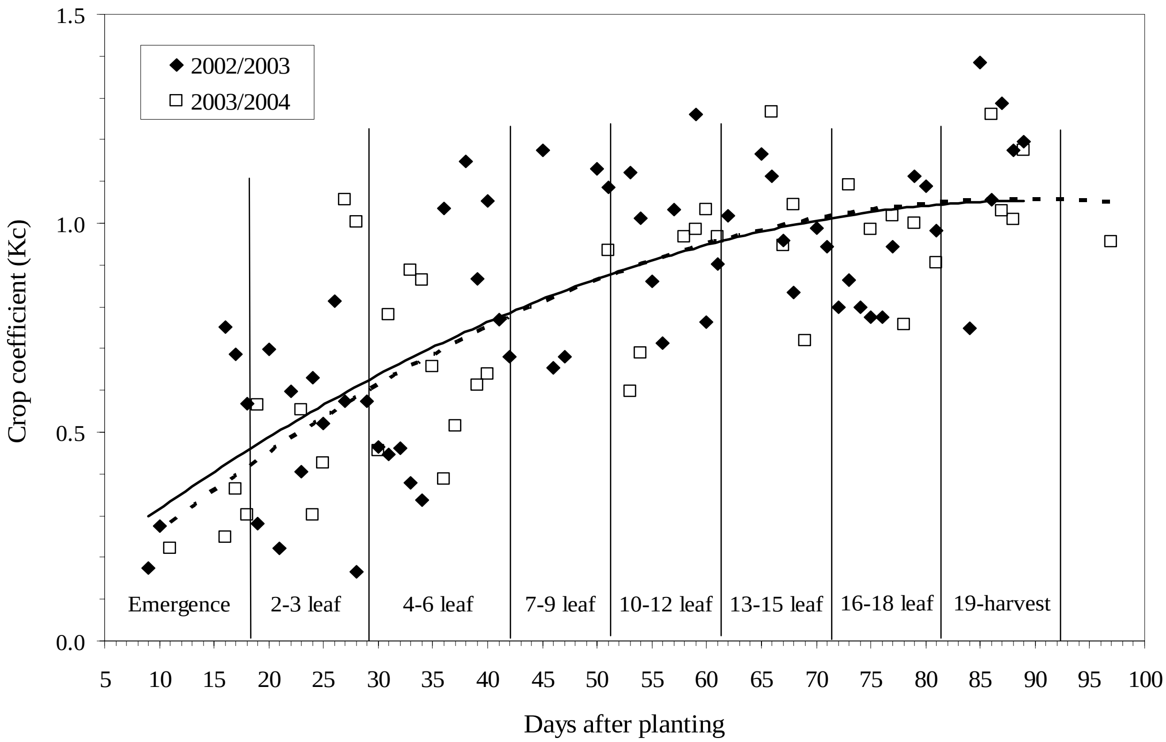

Figure 2. Spinach crop coefficients as a function of days after planting in 2002/2003 and 2003/2004 season at Uvalde, TX. Vertical lines represent 2-yr-average growth stages.

Table 3. Spinach crop coefficients determined at Uvalde, Texas in comparison to FAO.

South Texas

Growth Stage	2002	2003
Emergence	0.35	0.35
2-3 leaves	0.55	0.50
4-6 leaves	0.70	0.70
7-9 leaves	0.80	0.85
10-12 leaves	0.90	0.90
13-15 leaves	0.95	1.00
16-18 leaves	1.00	1.05
19 - harvest	1.05	1.05

FAO

Growth stage	K_C
K_C ini	0.70
K_C mid	1.00
K_C end	0.95

Onion crop coefficients:

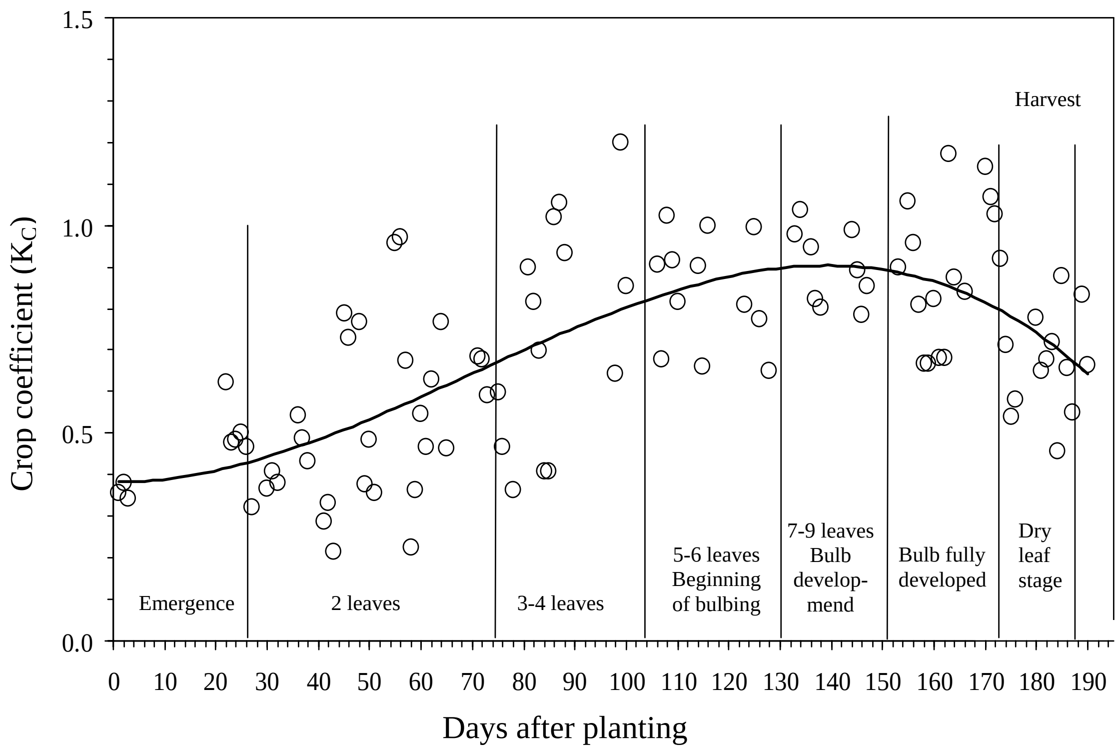

Figure 3. Onion crop coefficients of onion as a function of days after planting in 2002/2003 at Uvalde, TX.

Table 4. Onion crop coefficients determined at Uvalde, Texas in comparison with those from FAO.

South Texas

Growth Stage	Uvalde
Emergence	0.40
2 leaves	0.55
3-4 leaves	0.75
5-6 leaves Beginning of bulbing	0.85
7-9 leaves Bulb development	0.90
Bulb fully developed	0.85
Dry leaf stage	0.70

FAO

Growth stage	K_C
K_C ini	0.70
K_C mid	1.05
K_C end	0.75

Cotton crop coefficients:

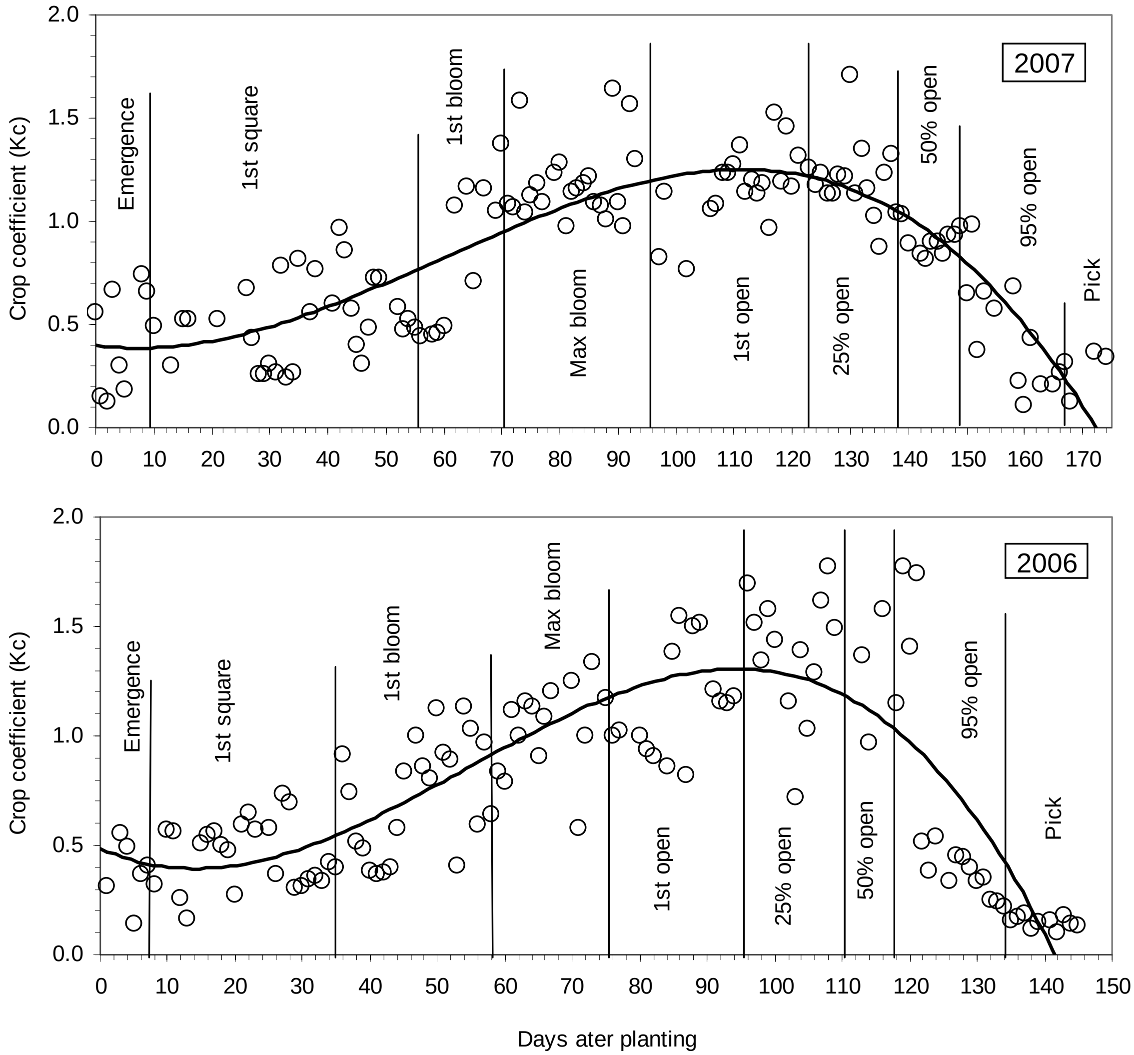

Figure 4. Crop coefficients of cotton as a function of days after planting in 2006 and 2007 at Uvalde, TX.

Table 5. Cotton crop coefficients (K_C) determined at Uvalde, Texas and comparison to those from Bushland, Texas and from FAO.

Texas

Growth Stage	Uvalde	Bushland
Emergence	0.40	0.22
1st square	0.45	0.44
1st bloom	0.80	1.10
Max bloom	1.08	1.10
1st open	1.23	0.83
25% open	1.25	0.44
50% open	1.05	0.44
95% open	0.60	0.10
Pick	0	0

FAO

Growth stage	K_C
K_C ini	0.35
K_C mid	1.15-1.20
K_C end	0.75-0.35

Wheat crop coefficients:

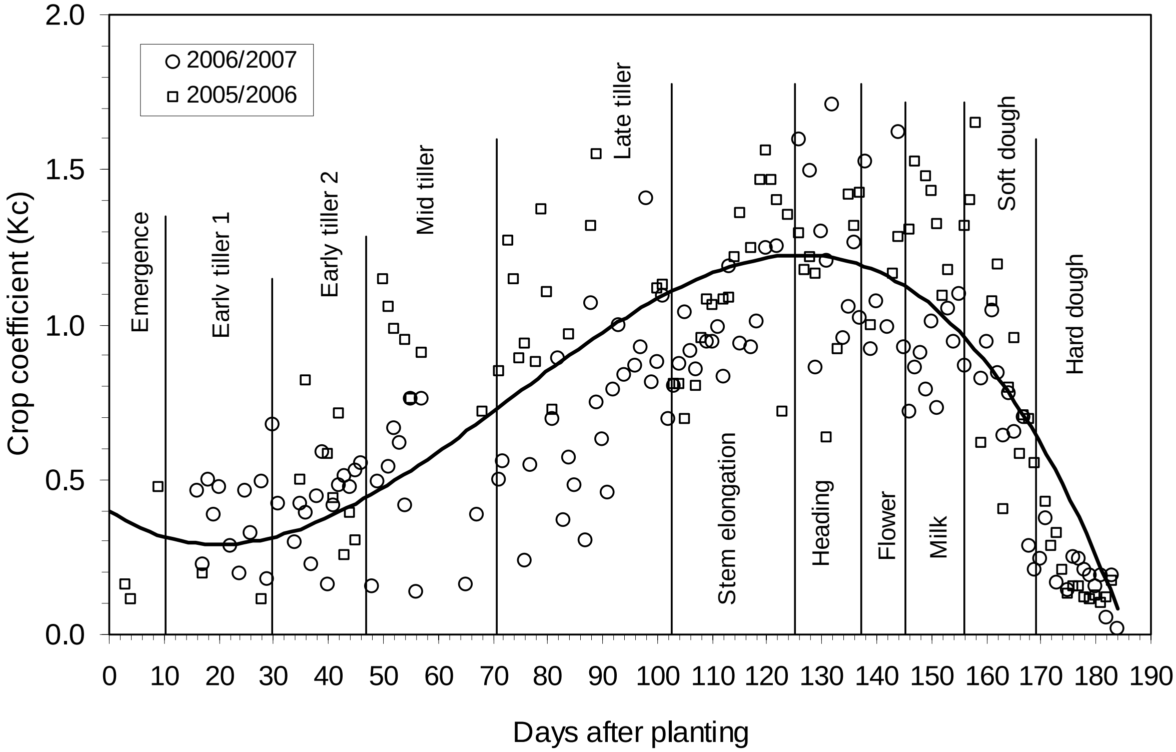

Figure 5. Crop coefficients of wheat as a function of days after planting in 2005/2006 and 2006/2007 at Uvalde, TX. Vertical lines represent a yr-average growth stages.

Table 6. Wheat crop coefficients determined at Uvalde, Texas in comparison to those from Bushland, Texas and from FAO.

Texas

Growth Stage	Uvalde	Bushland
Emergence	0.53	0.50
Early tiller 1	0.40	0.50
Early tiller 2	0.43	0.45
Mid tiller	0.63	0.90
Late tiller	0.93	1.00
Stem elongation	1.18	1.25
Heading	1.23	1.35
Flower	1.18	1.30
Milk	1.08	1.10
Soft dough	0.85	0.90
Hard dough	0.35	0.70

FAO

Growth stage	K_C
K_C ini	0.70
K_C mid	1.15
K_C end	0.25

DISCUSSION

Research has repeatedly shown that proper irrigation management is key to achieving profitable yields. PET networks and crop simulation models have proven to be reliable, inexpensive, and effective tools for estimating crop water needs in research settings. Recently, networks of weather stations have been established in many part of Texas for the purpose of supporting predictions of crop ET. It is estimated that, in the northern Texas panhandle, yearly fuel cost savings would exceed 18 million dollars if all irrigators used the PET network data. However to support predictions of crop evapotranspiration, generic crop coefficients will not fulfill the need for precise irrigation applications.

The need for regionalized crop coefficients (K_C) is demonstrated by the comparison between the K_C developed in Bushland and those developed in Uvalde. For example, corn crop coefficients from Uvalde are significantly lower than those from Bushland. This difference probably is due to elevated air temperatures that impede the plant to transpire at its full potential. In the Wintergarden region, the use of K_C developed in other regions will result in over-watering and consequently increased production costs and reduced profits.

In summary the development of regionally based K_C helps tremendously in irrigation management and furthermore provides precise water applications in those areas where high irrigation efficiencies are achieved by center pivot with LEPA (low energy precision application) systems or subsurface drip irrigation.

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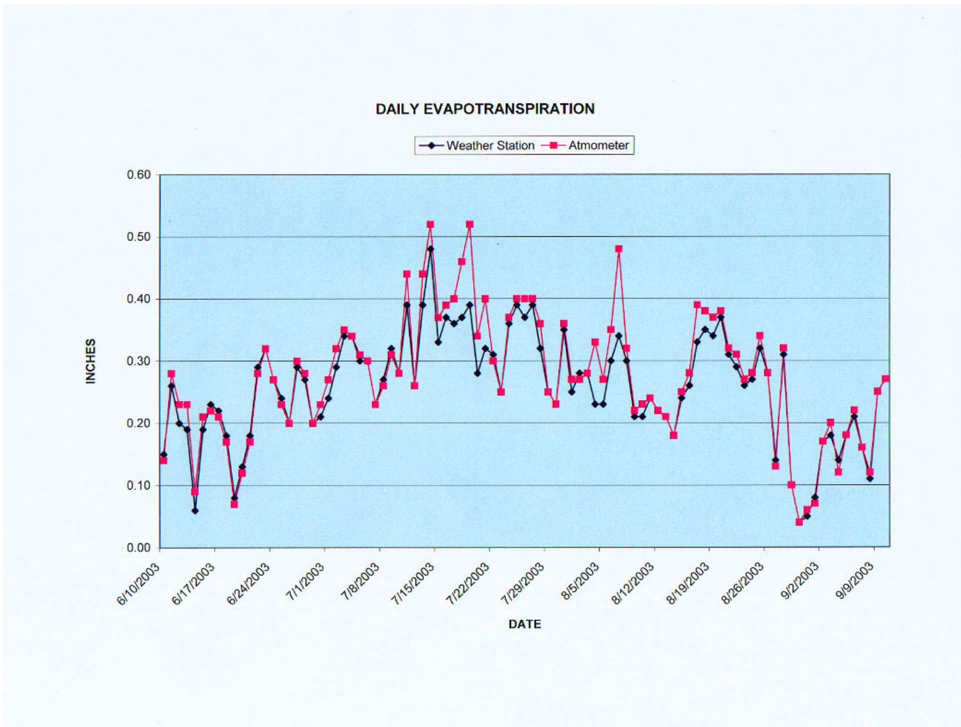
Using Atmometers for Irrigation Scheduling in Oklahoma

In the Spring of 2003, as the State Irrigation Engineer for USDA - Natural Resources Conservation Service in Oklahoma, I led an effort to educate Oklahoma irrigators in the value of evapotranspiration (ET) irrigation scheduling. In early 2003, I had discovered a research paper from Colorado State University on atmometers, which appeared to me to have potential as an economical tool for estimating evapotranspiration. I sought out resources for commercially available atmometers and found a source that sold the devices. The cost of a commercially available atmometer at that time was about $175.00. The atmometer is a device that acts as a mini-weather station. The commercial unit I found consists of a PVC container approximately 2 ½ inches in diameter by 16 inches tall. It is capped off with a ceramic evaporator surface and a disposable wafer that wicks up water to a canvas cloth of a specified weave. This device works by siphoning distilled water in the container through a straw connected to the ceramic cap. A site tube on the side of the PVC container has a direct scale to read the amount of water evaporated through the device.

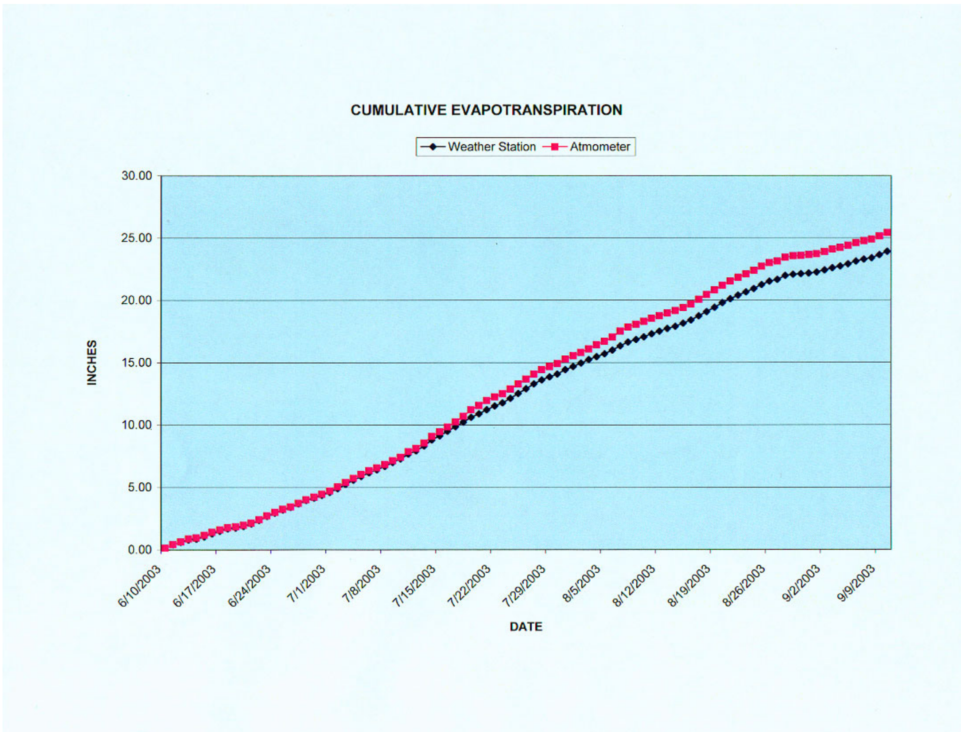
In the summer of 2003, NRCS in Oklahoma purchased a dozen atmometers to distribute to field offices for demonstration purposes. I set up an atmometer on site with a state operated Mesonet weather station at Woodward, Oklahoma. I located the atmometer on this site to compare evapotranspiration estimates from the two sources. I read the atmometer daily and recorded evapotranspiration estimates based on fully mature alfalfa. I also obtained daily evapotranspiration readings for the weather station from the Oklahoma Mesonet website. At this same time and in cooperation with Oklahoma State University, we located another atmometer on site with a weather station located at the OSU research station at Goodwell, Oklahoma. OSU researchers took daily readings from both sources and provided the data to NRCS. Readings at both sites were taken for approximately three months during the typical summer crop growing season. Daily evapotranspiration readings taken at the Woodward site is shown in Graph 1 below:

Graph 1



Graph 1 indicates that the atmometer estimated daily evapotranspiration very closely to what the Mesonet weather station estimated. The only exceptions to this appeared to be on days when temperatures exceeded 100 degrees Fahrenheit. In these cases, the atmometer had exaggerated readings that were greater than those from the weather station. Over the 2003 summer crop growing season, cumulative evapotranspiration from the atmometer at the Woodward site exceeded that from the Mesonet by only 1.49 inches or a difference of approximately 6.2% as indicated in Graph 2 below:

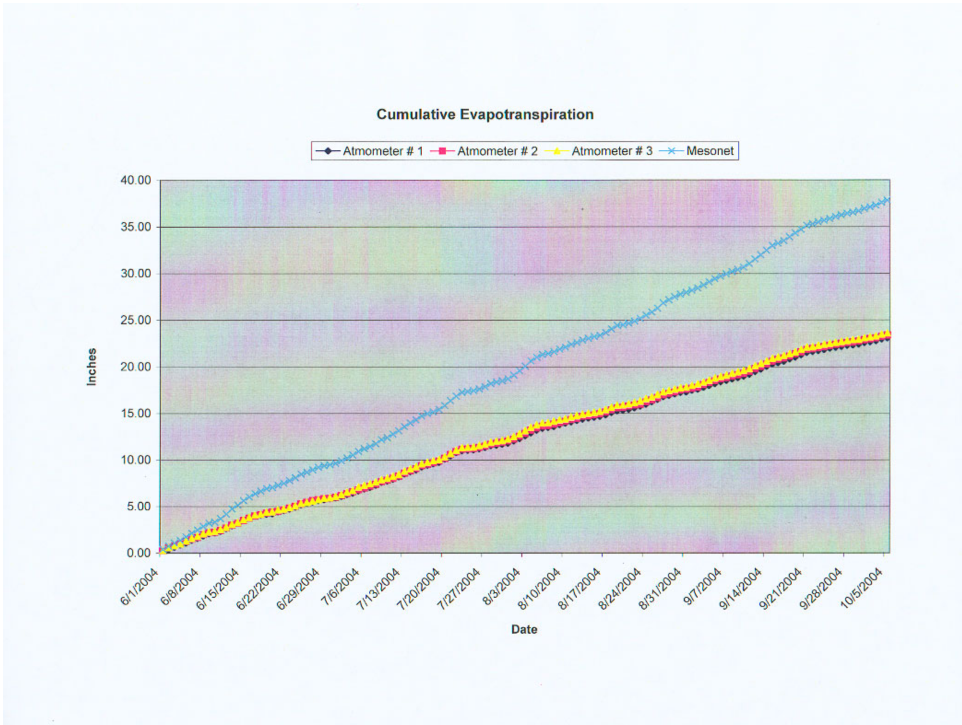
Graph 2



The field trial with OSU at Goodwell provided very similar results to the results in Graphs 1 and 2 above. The results in Graph 2 above indicated to NRCS that over a growing season, an atmometer can provide reasonable estimates of evapotranspiration similar to readings from a fully equipped weather station. Compared to a weather station costing thousands of dollars, the atmometer we found to be a simple and affordable device that could effectively be used by Oklahoma irrigators.

During this same time, NRCS ran a field trial with three atmometers at a single remote location to determine the consistency of readings between the devices. We also located these devices near a tree canopy to compare the readings of these 3 atmometers to the Woodward Mesonet site which is located on an unprotected short grass site. With the atmometers located in a different environment we anticipated that the readings would be less than those at the Mesonet site. Readings were taken daily with the cumulative evapotranspiration shown in Graph 3 as follows:

Graph 3



The results shown in Graph 3 indicated to NRCS that atmometers consistently provide accurate readings in comparison to each other when located at the same site. The results also indicated to us that an atmometer located in the same environment as an irrigators crop is a more valuable tool for scheduling than using readings from a remote weather station.

NRCS decided based on these field trials to move forward with promoting the atmometer as a tool for irrigation scheduling. Under the Environmental Quality Incentives Program (EQIP), Oklahoma NRCS in 2004 offered a ten dollar per acre incentive payment to irrigators to set up an evapotranspiration irrigation scheduling program using atmometers. The purpose of the program was to assist irrigators in the efficient use of irrigation water and to help conserve water resources.

Under this incentive program, an irrigation water management (IWM) plan is developed with the irrigator that identifies the irrigation system flow available to each field as well as the crops and soils in each field. This IWM plan establishes the management allowable depletion (MAD) for each field and a plan for saving water. I developed a “pocket sized” irrigation scheduling recordbook for irrigators to use to keep readings from the atmometer and to schedule irrigations based on the checkbook method. The recordbook also contains crop coefficient tables, a place to record monthly soil moisture readings, a place to record system flows, a scheme for scheduling, and other useful irrigation formulas to assist them in scheduling their irrigations. I also developed an automated version of the recordbook for the convenience of those irrigators that prefer to work with spreadsheets. NRCS in Oklahoma currently has thousands of acres and hundreds of irrigators in EQIP contracts receiving these irrigation water management (IWM) incentive payments.

Water savings is the ultimate goal of EQIP irrigation payment incentives. In Cimarron County, Oklahoma in 2004 NRCS worked with 8 irrigators in the Ogallala aquifer in a specific study to strictly use the atmometer as their scheduling tool versus their normal irrigation decision making process. In most cases the irrigators decision making process was simply based on their past experiences and they used no formal scheduling process. These irrigators selected fields near each other with the same crops and soils. On one field, they scheduled their irrigations using evapotranspiration estimates from the atmometer and the other field they used what they had used in the past to schedule their irrigations. The results of this study are shown in Table 1 below:

Table 1

Water Savings Achieved

1. 86 acres	alfalfa	20.8 acre feet	21% savings
2. 30 acres	corn	10.4 acre feet	26% savings
3. 125 acres	grass	20.9 acre feet	18% savings
4. 125 acres	corn	25.6 acre feet	14% savings
5. 63 acres	corn	1.4 acre feet	1% savings
6. 118 acres	wheat	2.0 acre feet	4% savings
7. 118 acres	corn	15.0 acre feet	15% savings
8. 116 acres	corn	10.0 acre feet	10% savings
TOTAL SAVINGS		106.1 acre feet	13.6% savings

These irrigators achieved an average of 13.6 % water savings during this crop growing season. These irrigators were quite impressed with the results of the study and saw the value of irrigation scheduling using evapotranspiration.

Conclusion:

Based on the work NRCS has done with irrigators in Oklahoma, atmometers are an easy to read, accurate, inexpensive tool for irrigators to use when scheduling their irrigations. NRCS in Oklahoma has concluded that notable water savings are realized using evapotranspiration irrigation scheduling methods and continues to promote this method using atmometers.

EPIC Model as a Decision Support System for Irrigation Management of Crops

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Interest is growing in simulation models to better assess crop water use and production with different management practices. EPIC was validated on corn and cotton under South Texas conditions and applied to evaluate the possibility of using it as a decision support tool for irrigation management of these crops. We measured actual crop evapotranspiration (ETc) using a weighing lysimeter and determined crop yields, then validated the model. Simulated ETc using EPIC agreed with the lysimeter measured ETc. EPIC also simulated the variability in crop yields at different irrigation regimes. The simulation results with farmers' field data allowed us to use the EPIC model as a decision support tool for the crops under full and deficit irrigation conditions. While growth stage specific crop coefficients can be used for making in-season decisions in irrigation scheduling, EPIC appears to be effective in making long term and pre-season decisions for irrigation management.

Keywords: crop model, EPIC, crop evapotranspiration, irrigation management

INTRODUCTION

The traditional solution to water shortages for plants has been irrigation, which has made agriculture possible in many otherwise nonproductive areas (Kramer and Boyer, 1995). In the Wintergarden area of Texas, irrigation is also one of the major limiting factors in producing corn, cotton, and other crops, as more than 90 % of the water for urban and agricultural use in this region depends on the Edwards aquifer. As the Texas Legislature placed water restrictions on the farming industry by limiting growers to a maximum use of 6,100 m^2 ha^{-1} of water per year in the Edward aquifer region, maximization of agricultural production efficiency has become a high priority for numerous studies in the Wintergarden area of Texas. For efficient water use, the irrigation amount should not exceed the maximum amount that can be used by plants through evapotranspiration (ET), which is the sum of the amount of water returned to the atmosphere through the processes of evaporation and transpiration (Hansen et al., 1980).

ET is very difficult to measure but several methods have been developed. One of the direct measuring techniques is a method using a weighing lysimeter, which constantly weighs the soil/vegetation mass and estimates gains and losses in water (Watson and Burnett, 1995). Because direct measurement of ET can be a difficult task, a wide rage of models have been developed for use in environments that lack either sufficient radiometric, meteorological, or lysimetric data. ET models tend to be categorized into three basic types: temperature, radiation, and combination (Jenson et al., 1990; Dingman, 1984; Watson and Burnett, 1995). Temperature models (e.g., Thornthwate, 1948; Doorenbos and Pruitt, 1977) generally require only air temperature data as the sole meteorological input; Radiation models (e.g., Turc, 1962; Doorenbos and Pruitt, 1977;

Hargreaves and Samani, 1985), designed to use some component of the energy budget concept, usually require some form of radiation measurement; and combination models (e.g., Penman, 1948) combine elements from both the energy budget and mass transfer models (Jensen et al., 1990).

Interest is growing in applying simulation models for conditions of South Texas, to better assess crop water use, and production with different crop management practices. One of these simulation models is EPIC, which was developed to determine the relationship between soil erosion and soil productivity in the U.S. (Williams et al., 1984). EPIC includes physiologically based components to simulate erosion, plant growth, and related processes. Model components include weather, hydrology, erosion, nutrient cycling, soil temperature, crop growth, tillage, pesticide fate, economics, and plant environmental control. The EPIC hydrology component includes runoff, percolation, lateral subsurface flow, ET, and snow melt. EPIC comes with five ET equations from which the user has to make a single choice for a simulation exercise. The equations include: Penman (Penman, 1948), Penman-Monteith (Monteith, 1965), Priestley-Taylor (Priestley and Taylor, 1972), Hargreaves-Samani (Hargreaves and Samani, 1985), and Baier-Robertson (Baier and Robertson, 1965).

The generic crop-growth subroutine in EPIC (Williams et al, 1989) facilitates the simulation of complex rotations and fallow-cropping systems, making the model useful for evaluating alternative crop management scenarios in South Texas. A variety of scenarios can be simulated with the model, such as evaluating crop water use. A critical step in constructing crop management scenarios with EPIC is to validate the model in the region of interest. The objective of this research was to validate and evaluate the model as a decision support tool for irrigation scheduling in South Texas.

MATERIALS AND METHODS

Field Experiment for Model Validation

Field studies for validation of EPIC crop model were conducted at the Texas A&M Agricultural Research and Extension Center in Uvalde, Texas (29° 13' 03", 99° 45' 26", 283m), in 2002, 2003, 2004, 2005, and 2006. Data were collected from two fields, one from a center-pivot-irrigated field with a low energy precision application (LEPA) system and the other from a linear-irrigated lysimeter field with a LEPA system. Crops used were corn and cotton. Their varieties and plant to harvest dates in each year are presented in Table 1. Soil type of both fields was an Uvalde silty clay soil (fine-silty, mixed, hyperthermic Aridic Calciustolls with a pH of 8.1). The experiment of the field under the center pivot was arranged in a randomized split-block design with each block replicated three times. A 90° wedge of the center pivot field was divided equally into 15° regimes, which were maintained at 100, 75, and 50 % crop evapotranspiration (ETc) values.

The lysimeter units used in this study had monolithic soil cores where soil structure and associated parameters remain unchanged (Marek et. al, 2006). The size of the monoliths is 1.5 × 2.0 × 2.1 m and each lysimeter is placed in the middle of a 1 ha field. The lysimeter field was managed under full irrigation based on measured daily crop water use. For the pivot experiment, irrigation scheduling and ETc regimes were imposed according to calculations of Penman-Monteith reference ET (ETo) and multiplied by available crop coefficient (Kc):

$$ETc = Kc \times ETo \qquad [1]$$

The total amounts of irrigation for each year are presented in Table 1.

Model Validation and Application

Parameters for the model validation were ETc and crop yields. In-field and simulated ET were calculated under unstressed crop conditions. Modified Penman-Monteith (Allen et al., 1998) ETo method in conjunction with crop coefficients developed at Bushland, TX (2002-03), and Uvalde, TX (2004), were used to calculate in-field ETc. EPIC makes users select one ET equation from five options. After preliminary test runs of the EPIC model, the Hargreaves-Samani (Hargreaves and Samani, 1985) ETo method was selected to simulate ETc in this study.

The model was applied to simulate the crop yields of 2006 from farmers' fields in South Texas (Fig. 1). Information regarding the fields and their cropping practices is presented in Table 2. In addition, the model was used to simulate the yields of each crop with various irrigation scenarios. These were 229, 306, 381, 457, 533, and 610 mm of irrigation, respectively.

Weather data used in the simulations were collected with a standard Campbell Scientific meteorological station (Campbell Scientific Inc., Logan, UT) at each location. Simple linear regression using PROC REG (SAS version 9.1, Cary, NC) was used to compare yields of simulated and measured data.

Table 1. Summary of cropping practices at Texas A&M Agricultural Research and Extension Center in Uvalde, Texas.

Crop	Variety†	Year	Plant-maturity (M/D)	Irrigation (mm)§		Rainfall (mm)
				Lysimeter	IFC	
Corn	30G54	2002	3/25-6/20	358.1	422.4	99.6
	30G54	2003	3/18-6/24	370.8	417.8	136.7
	30G54	2004	3/10-6/24	293.6	231.1	232.4
Cotton	ST4892	2003	4/02-8/11	N/A	253.5	318.3
	ST4892	2004	4/01-8/16	N/A	257.6	274.1
	ST4892	2005	4/07-8/07	N/A	337.3	140.7
	DP555	2007	4/16-9/07	76.2	N/A	575.8

† 30G54 from Pioneer (Johnston, IA 50121); ST4892 from Stoneville (Monsanto, St. Louis, MO 63167); and DP555 from Delta and Pine (Scott, MS 38772).

§ Total amounts of irrigation based on crop evapotranspiration using lysimeter-measured and in-field-calculated (IFC).

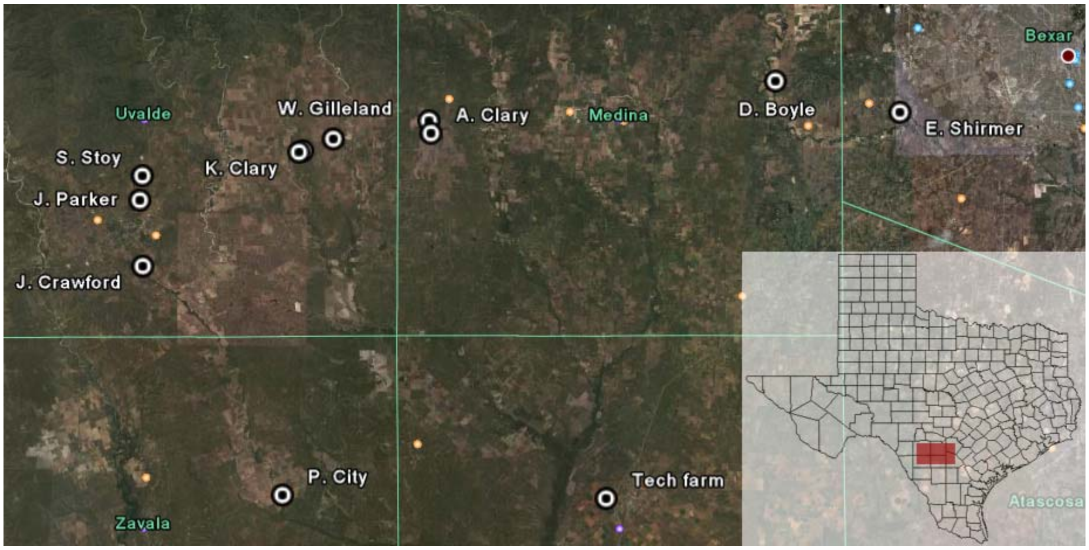

Fig. 1. Geological location of farms (open circle with a dot) used in crop simulation.

Table 2. Summarized information of farmer's fields and their cropping practices in 2006 used in crop simulation.

Crop	Farm's name	County	Soil type	plant to harvest (M/D)	N-P§ (kg ha^{-1})	Irrigation (mm)
Corn	Boyle, Duane	Medina	Knippa clay 0-1%	3/11-7/22	163-19	622
	Clary, Austin†	Medina	Montell clay 0-1%	3/03-8/01	101-90	427
	Crawford, Jimmy	Uvalde	Uvalde silty clay loam 0-1%	3/03-7/30	168-56	610
	Parker, Jimmy	Uvalde	Uvalde silty clay loam 0-1%	3/08-8/10	168-45	495
	Shirmer, Ernie	Bexar	Brayton clay 0-1%	3/10-8/26	163-46	533
Cotton	Panther City	Zavala	Uvalde silty clay loam 0-1%	4/10-8/29	103-0	425
	Clary, Kenneth†	Uvalde	Montell clay 0-1% Knippa clay 0-1%	3/30-8/29	56-0	406
	Gillerland, Weldon	Uvalde	Knippa clay 0-1%	4/04-8/29	50-129	464
	Stoy, Steve	Uvalde	Knippa clay 0-1%	3/21-8/29	123-45	419
	Tech Farm	Frio	Duval loamy fine sand 0-5%	4/05-9/02	123-0	533

§ Nitrogen-Phosphate applied.
† Two fields were used from these farms.

RESULTS AND DISCUSSION

Model Validation

Lysimeter-measured crop water use under unstressed crop conditions was previously compared to two different methods of irrigation calculation: 1) in-field-calculation with Penman-Monteith formula and 2) EPIC Hargreaves-Samani. This was performed as a preliminary validation of the EPIC model. No statistical difference was found between the ETc values of lysimeter-measured and the two different methods of irrigation calculation (data not shown). However, cumulative ETc varied during the growing seasons among the three methods of measurements (Fig. 2). In-season differences among ETc methods varied possibly due to inexact simulation growth curves or growth stage specific crop coefficients; however, the variations were within an acceptable range.

The EPIC model simulated the variability in grain corn yields with different irrigation regimes, with r^2 value of 0.69 and root mean square error (RMSE) of 0.50 Mg ha^{-1} (Fig. 3A). The regression line was close to the 1:1 line. For the three years, measured yields ranged from 4.71 to 7.62 Mg ha^{-1} while simulated yields ranged from 4.68 to 7.56 Mg ha^{-1}. The upper 95 % confidence interval of the means ranged from 6.08 to 8.14 Mg ha^{-1} while the lower 95 % confident interval ranged from 4.50 to 6.67 Mg ha^{-1}. For cotton, EPIC simulated the variability in lint yields, with r^2 value of 0.74 and RMSE of 0.70 Mg ha^{-1} (Fig. 3B). The regression line was close to the 1:1 line. For the three years, measured yields ranged from 1.82 to 2.67 Mg ha^{-1} while simulated yields ranged from 1.35 to 2.46 Mg ha^{-1}. The upper 95 % confidence interval of the means ranged from 1.81 to 2.86 Mg ha^{-1} while the lower 95 % confident interval ranged from 1.23 to 2.18 Mg ha^{-1}. Previously, Williams et al. (1989) reported that EPIC could accurately simulate crop responses to irrigation at locations in the western USA. Our validation results also demonstrate that the EPIC model can be used as a decision support tool for irrigation management of corn and cotton in South Texas.

Model Application to Corn

The crop model simulated the variability in grain corn yield from different farmers' fields at different irrigation regimes, with r^2 value of 0.67 and RMSE of 0.66 Mg ha^{-1} (Fig. 4). Reported yields ranged from 3.28 to 7.07 Mg ha^{-1} while simulated yields ranged from 3.83 to 6.86 Mg ha^{-1}. Since we are confident of reproducing the yield variation of corn using EPIC for the farmers' fields, the model was applied to simulate yield responses with various irrigation scenarios.

Grain yield as a function of irrigation + rainfall linearly increased until 800 mm and reached a plateau after that (Fig. 5A). With this result, we assume that the amount of water necessary to achieve 5 to 5.5 Mg ha^{-1} for corn is ~ 800 mm. In addition, yield versus crop evapotranspiration shows that grain yield linearly increased up to ~ 700 mm, which is considered to be a saturated crop evapotranspiration for corn in this region (Fig. 5B). Values of water use efficiency (WUE) versus grain yield linearly increased as grain yield increased until ~ 5 Mg ha^{-1} (Fig. 6A). WUE calculated with water input generally maintained a plateau after 5 Mg ha^{-1}. Our result shows that there is a positive correlation between WUE and grain corn yield up to a certain range of yield, which was ~ 5 Mg ha^{-1}. When the WUE values were plotted against values of ETc and water input, WUE sporadically increased as ETc or water input increased until ~ 700 mm (Fig. 6B). WUE versus water input decreased with a slow linear phase after ~800 mm. Therefore, it is considered that there is a negative correlation between WUE and water input after ~ 800 mm, which was determined to be the amount of water input needed to achieve the range of the highest grain corn yield in this study.

Model Application to Cotton

The crop model simulated the variability in lint yield, with r^2 value of 0.11 and RMSE of 0.22 Mg ha^{-1} (Fig. 7). The reported yields ranged from 1.40 to 1.61 Mg ha^{-1} while the simulated yields ranged from 1.18 to 1.74 Mg ha^{-1}. While present data were not statistically significant due to a narrow range of reported lint yields, simulated yields were arithmetically in general agreement with the reported yields. Assuming that EPIC can reproduce the cotton yield variation for the farmers' fields, the model was applied to simulate yield responses with various irrigation scenarios.

Lint yield as a function of irrigation + rainfall linearly increased until 700 mm and reached a plateau after that (Fig. 8A). With this result, we assume that the amount of water necessary to achieve 1.8 to 2.0 Mg ha^{-1} for cotton is ~ 700 mm. Likewise, the yield versus the amounts of crop evapotranspiration (ETc) shows that lint yield linearly increased up to ~ 600 mm, which is considered to be a saturated crop evapotranspiration for cotton in South Texas (Fig. 8B). Values of water use efficiency (WUE) calculated with water input versus lint yield linearly increased as the lint yield increased until ~ 1.7 Mg ha^{-1} and maintained a plateau after that (Fig. 9A). Meanwhile, WUE calculated with ETc versus lint yield increased with a slow linear phase until ~ 1.5 Mg ha^{-1} and maintained a plateau after that. Likewise for corn, the result shows that there is a positive correlation between WUE and cotton lint yield. When the WUE values were plotted against values of ETc and water input, WUE sporadically increased as ETc or water input increased until ~ 600 mm (Fig. 9B). WUE versus water input decreased with a slow linear phase after ~ 700 mm. This result shows that there is a negative correlation between WUE and water input after ~ 700 mm. This value corresponded to the amount of water input necessary to achieve the range of the highest cotton lint yield.

CONCLUSIONS

We validated and evaluated the EPIC crop model to use as a decision support tool for management of corn and cotton under various irrigation conditions in South Texas. The validation results of corn and cotton show reasonable agreement between simulation and measurement in terms of crop water use and crop yield. The simulation results with farmers' field data demonstrate that the EPIC model can be used as a decision support tool for the crops under full and deficit irrigation conditions in South Texas. EPIC specifically appears to be effective in long term and pre-season decision makings for irrigation management of crops. Using growth stage specific crop coefficients and/or the EPIC simulation model indicate the possibility of being effective tools in irrigation scheduling.

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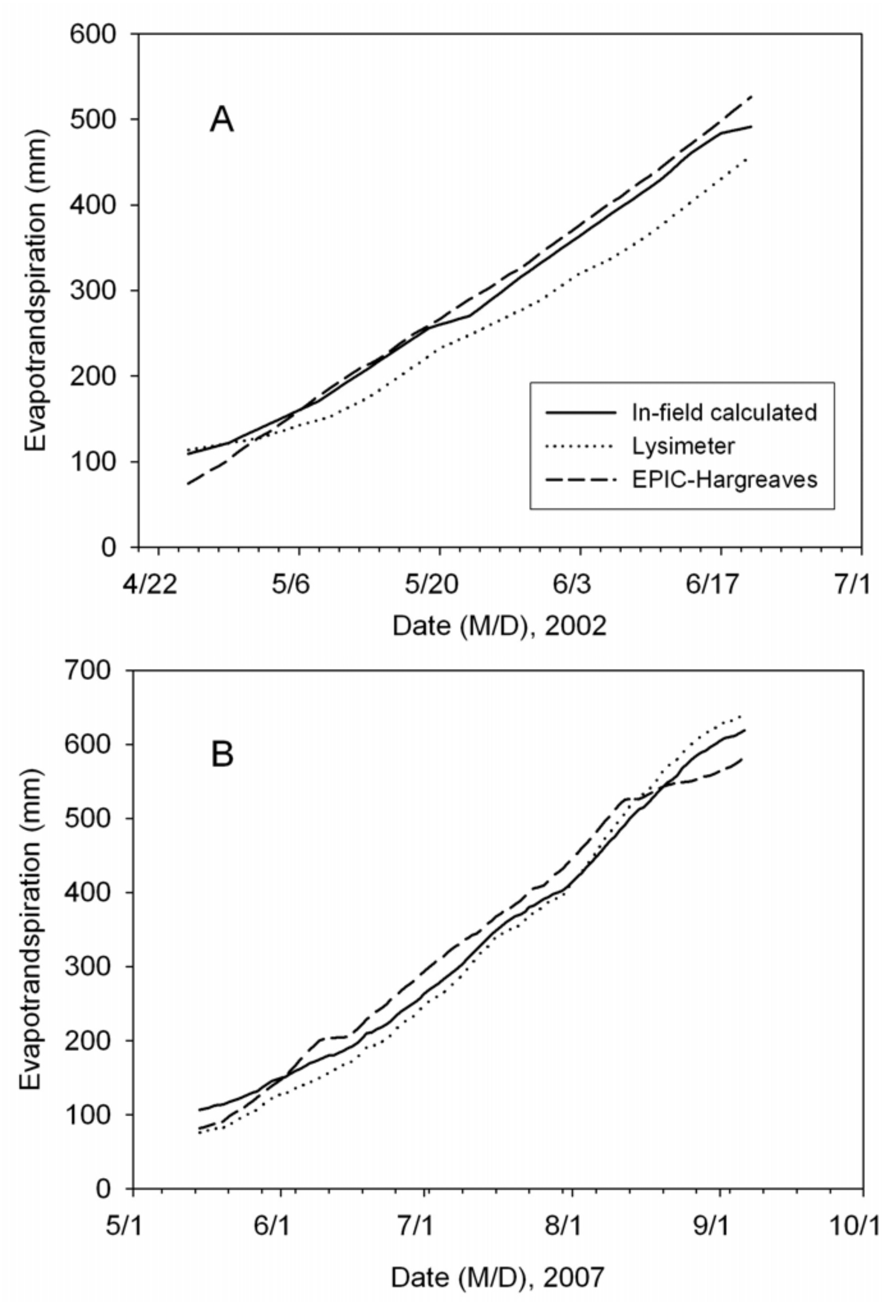

Fig. 2. Lysimeter-measured crop evapotranspiration (ETc) vs. two methods of estimating ETc (in-field-calculated and EPIC-simulated using Hargreaves-Samani) for corn (A) and cotton (B) in Uvalde, Texas.

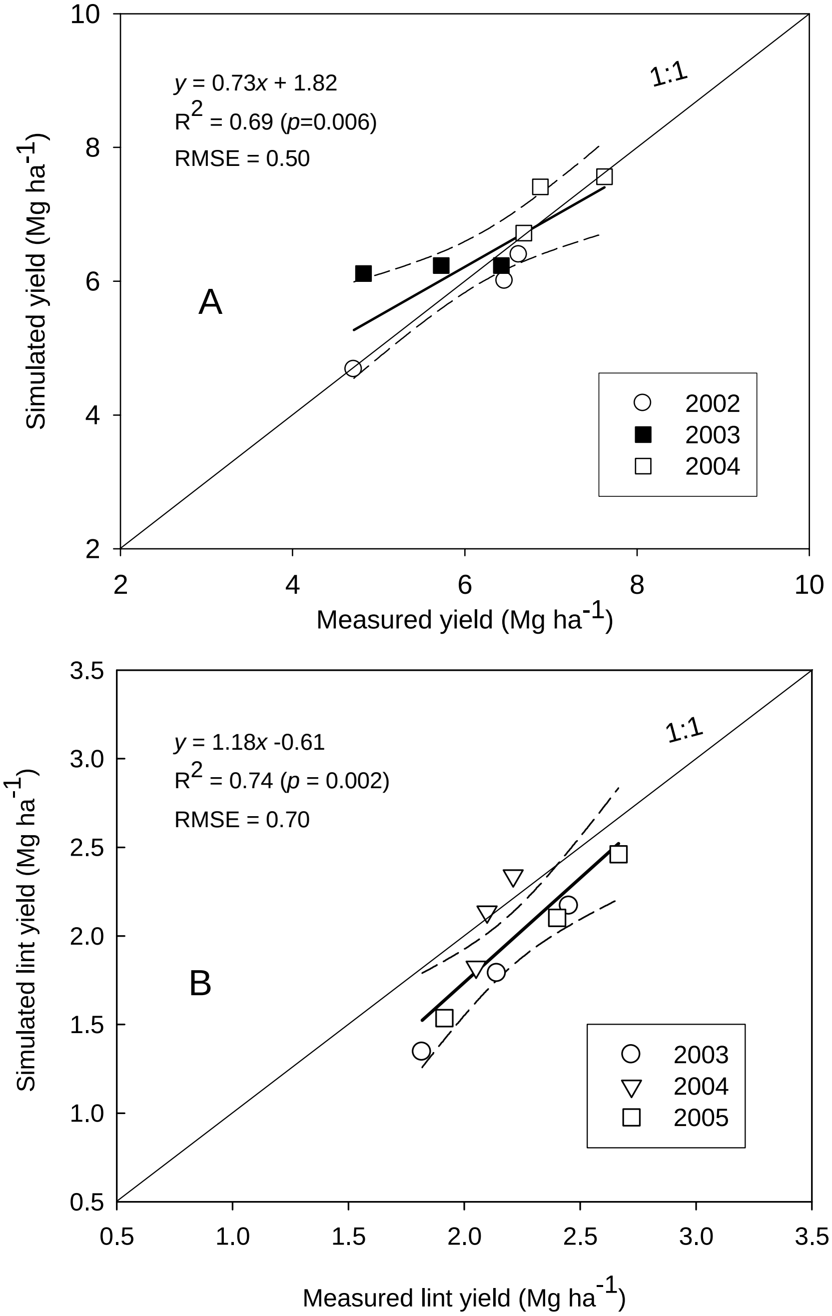

Fig. 3. Measured vs. simulated corn grain yields (A) and cotton lint yields (B) at the field of Texas A&M Agricultural Research and Extension Center in Uvalde, Texas. Dashed lines are 95% confidence interval for the mean of the simulated values.

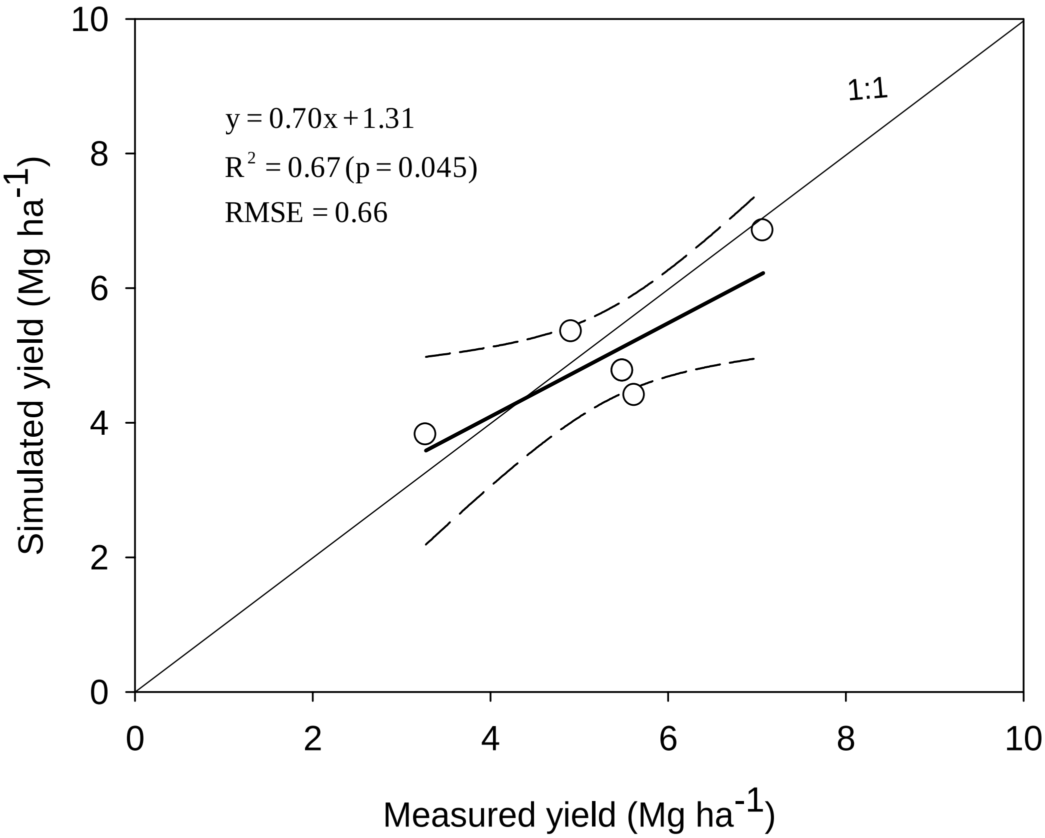

Fig. 4. Measured vs. simulated corn grain yields using farmer's field data, which were obtained from three counties of South Texas (Bexar, Medina, and Uvalde) in 2006. Dashed lines are 95% confidence interval for the mean of the simulated values.

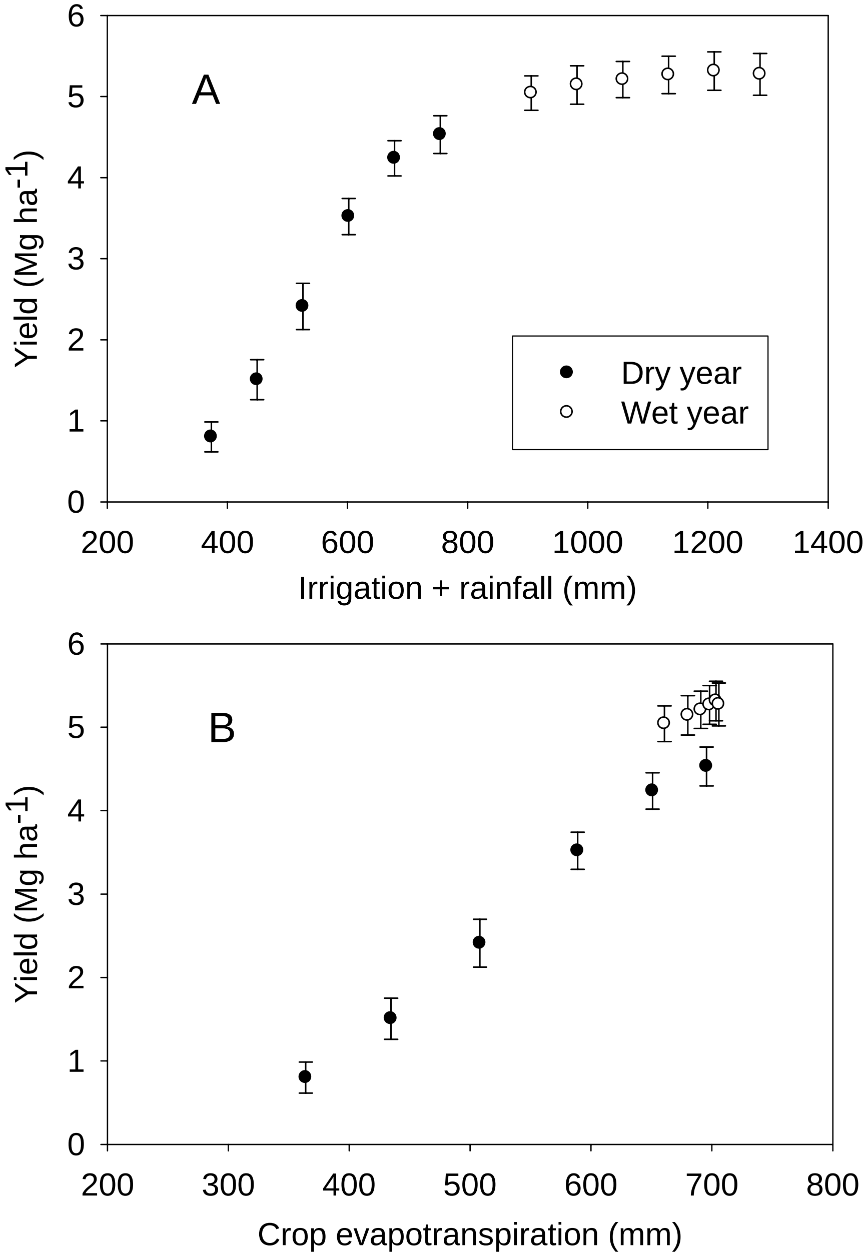

Fig. 5. Corn yield responses as a function of irrigation + rainfall (A) and crop evapotranspiration (B). Dry and wet year were chosen from 20 yr weather data (1987-2006) for each of 6 farmers' field data. Vertical bars represent standard errors at 95% confidence interval for the mean of each data point (n=6).

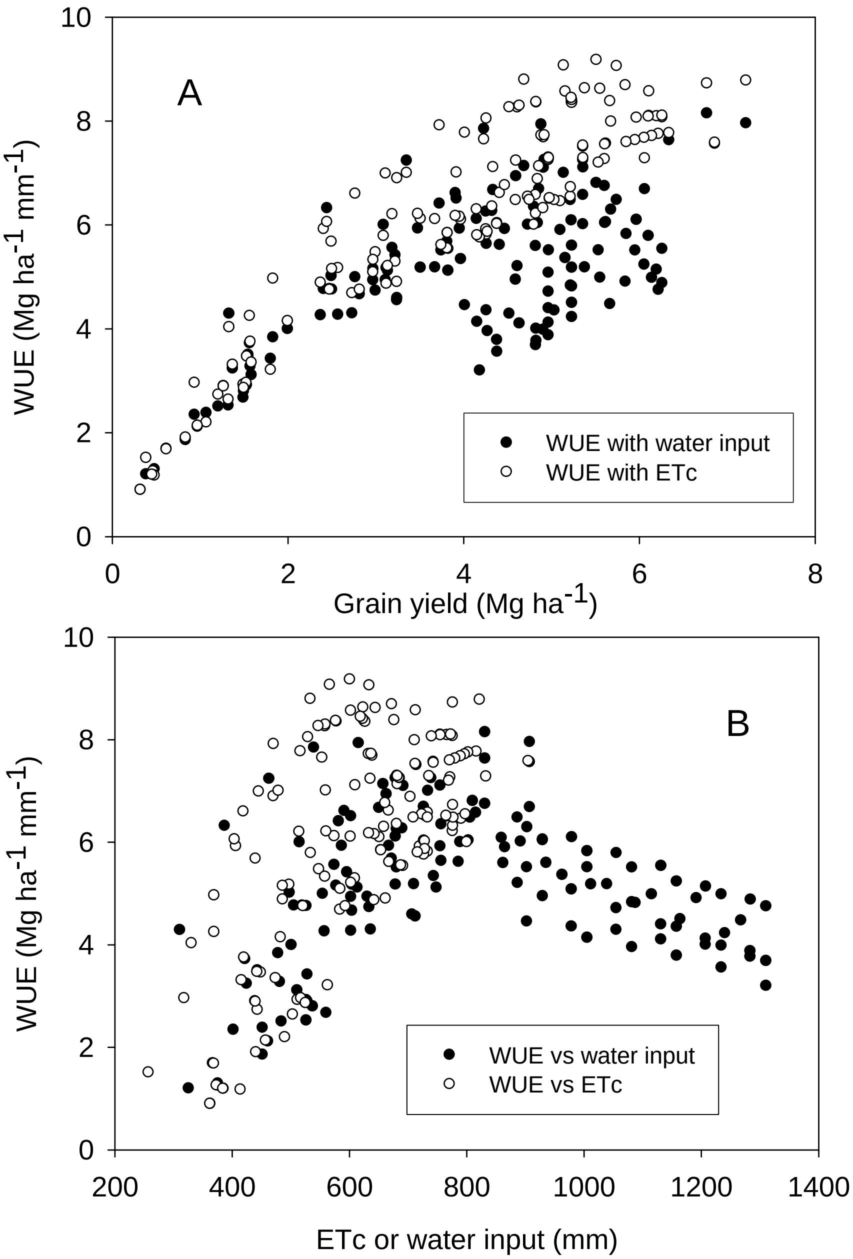

Fig. 6. Water use efficiency (WUE) vs. corn grain yield (A) and WUE vs. water input or crop evapotranspiration (B).

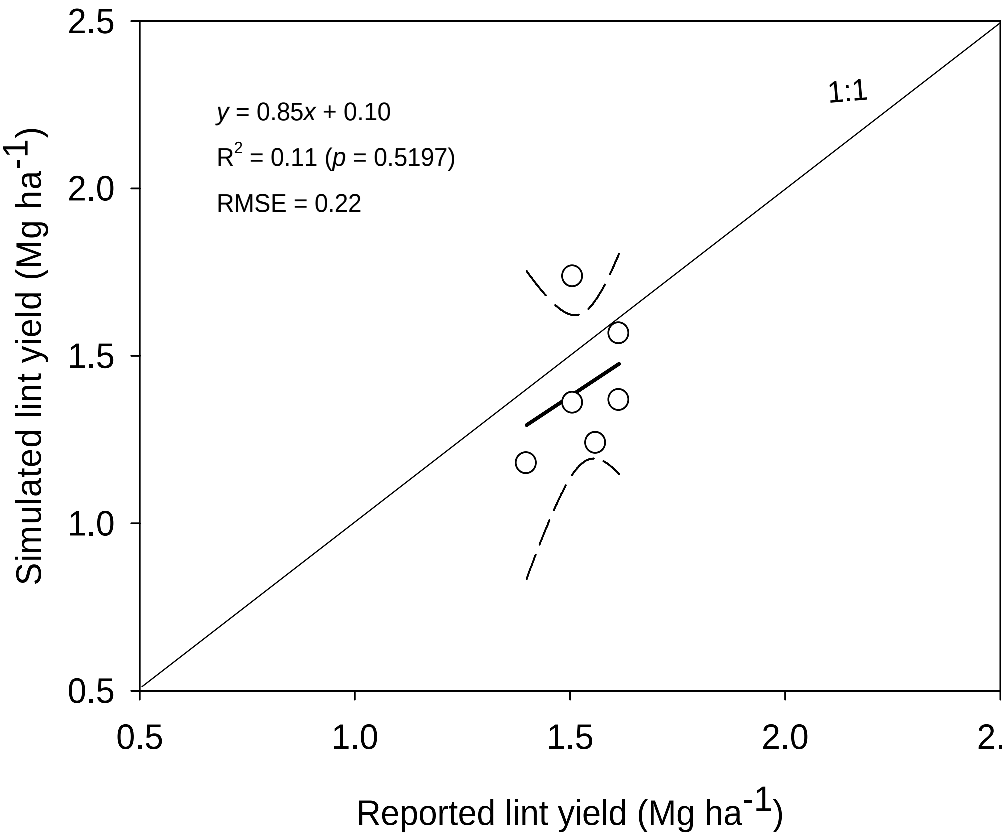

Fig. 7. Simulated vs. reported cotton lint yields using farmer's field data, which were obtained from three counties of South Texas (Bexar, Medina, and Uvalde) in 2006. Dashed lines are 95% confidence interval for the mean of the simulated values.

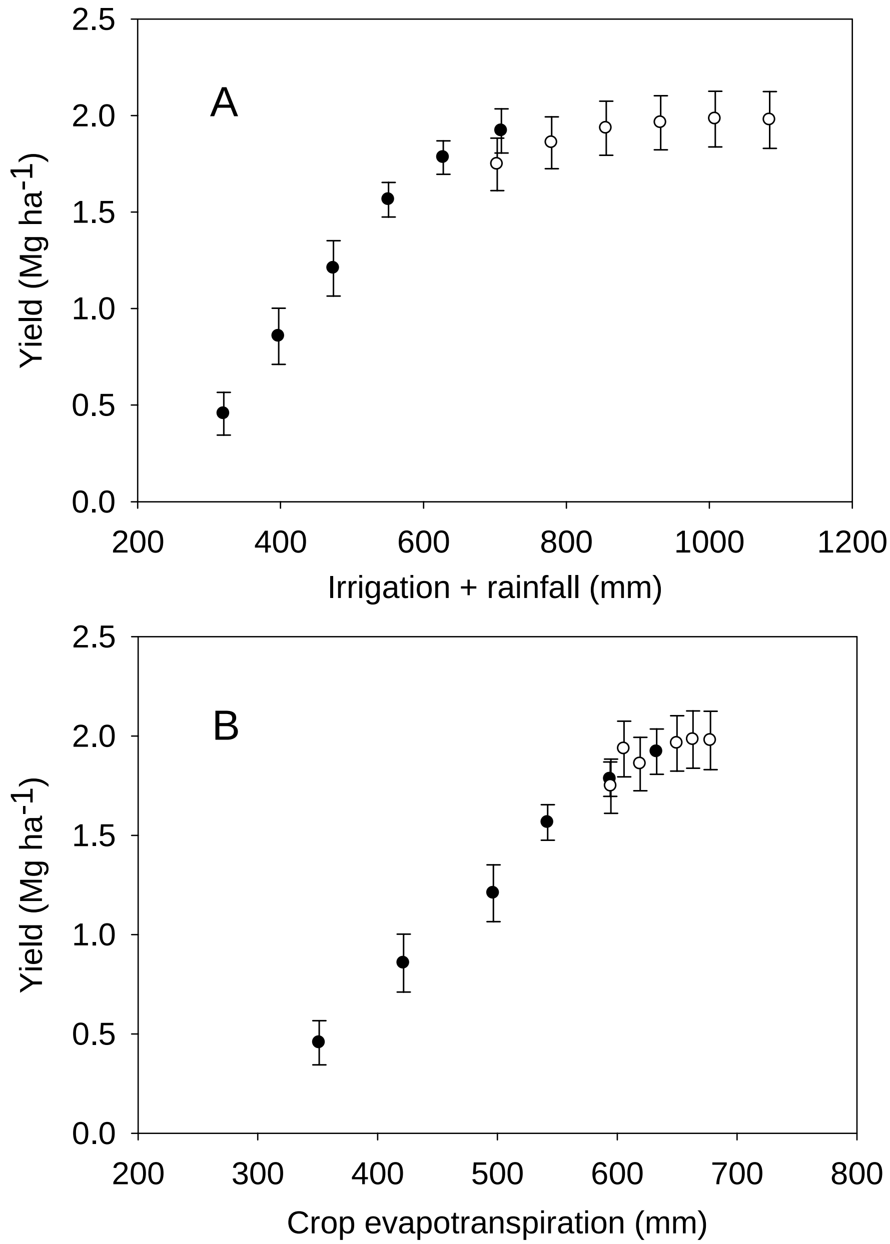

Fig. 8. Cotton lint yield responses as a function of irrigation + rainfall (A) and crop evapotranspiration (B). Dry and wet year were chosen from 20 yr weather data (1987-2006) for each of 6 farmers' field data. Vertical bars represent standard errors at 95% confidence interval for the mean of each data point (n=6).

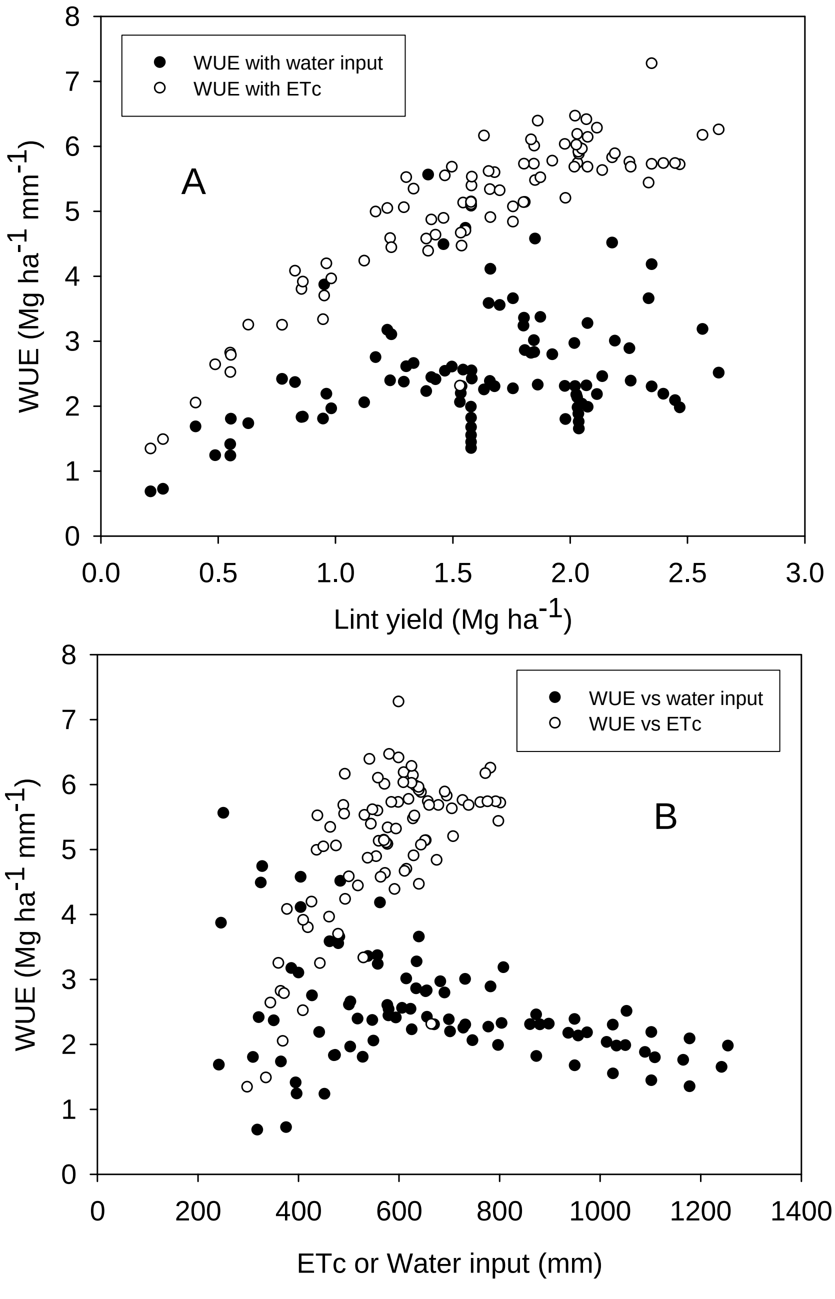

Fig. 9. Water use efficiency (WUE) vs. cotton lint yield (A) and WUE vs. water input or crop evapotranspiration (B).

A Web-based Advisory Service for Optimum Irrigation Management

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Abstract

Optimum irrigation management generally involves partial irrigation of some crops to maximize net returns, particularly when water supplies are limited. This management paradigm is substantially more challenging than full irrigation to maximize crop yields, and few irrigators have the resources or capacity to deal with it quantitatively. Oregon State University and NRCS have created a web-based irrigation advisory system for optimum irrigation management. The system is being developed in two phases. The first phase, now largely completed, supports conventional irrigation scheduling. Key features of the first phase are: (i) application efficiencies are explicitly analyzed for each irrigation strategy considered; (ii) When water supplies or delivery system capacity are limited, the system provides simultaneous scheduling of irrigations in all fields that share a water source; (iii) the user interface permits farm managers to participate directly in searching for an optimal strategy using a robust, interactive web interface to stipulate objectives and constraints of irrigation strategies. A pilot advisory service was initiated in Central Oregon in 2006 and will be made available on the USDA national web farm for use by NRCS cooperators in 2008. The second phase is incorporating new analytical tools that will enable the advisory service to ore effectively support optimal irrigation management, including management of partial irrigation when water supplies are limited. Key elements of the second phase are (i) a statistical model of crop development and potential yield to estimate yields under partial irrigation; (ii) a feedback system to reconcile conflicting estimators of soil moisture depletion. Incorporation of the second phase will begin in 2008, but it is expected that refinement of these tools will continue indefinitely.

Introduction

This paper describes an irrigation advisory service that was developed specifically to support implementation of optimum irrigation management strategies. Optimum irrigation management generally involves partial irrigation of some crops to maximize net returns, particularly when water supplies are limited. This management paradigm can be substantially more challenging than conventional, full irrigation for several reasons: (i) because the ultimate disposition of applied water is significantly effected by irrigation management strategies, system application efficiencies cannot be assumed *a-priori*. Efficiencies must be explicitly analyzed for each irrigation strategy and weather year considered; (ii) since partial irrigation implies reduced crop yields an advisory service needs to anticipate and estimate such losses; (iii) optimal allocation of limited water or limited system capacity may require simultaneous irrigation scheduling of multiple fields and continuous tracking of total demands and system capacities; (iv) because an irrigation strategy that is optimal for one farm may not be optimal for another, farm managers need to participate directly in the formulation and evaluation of alternative strategies. This insures that the analysis will account for specific farm circumstances and bring the manager's local experience and preferences into the analysis.

To deal with these issues Oregon State University and NRCS have developed a web-based advisory system for economically optimum irrigation management. The system estimates application efficiency by simulating the spatially variable disposition of applied water as ET, percolation, spray loss, surface runoff and redistribution. A statistical model of crop yields will estimate both the expected values and the uncertainties of crop yields. Uncertainties of other aspects of the analysis are simulated in a variety of ways. One important element of the uncertainty analysis is a set of algorithms to reconcile estimates of soil moisture derived from different sources. The system facilitates allocation of limited water supplies by simultaneous scheduling of multiple fields, forecasting daily water demands to the end of the season and flagging any dates when farm irrigation system capacities will be inadequate to meet total farm water demands. The allocation of limited water to different fields is based on an iterative, user-directed search in which the farm manager stipulates irrigation strategies and operational constraints. The advisory service is accessed through a robust, interactive web interface.

This work is proceeding in two phases. The first phase provides the capability for conventional irrigation scheduling. The second phase will provide additional analytical tools for making best economic use of water, including in particular a yield modeling capability and algorithms for refining soil moisture estimates based on measurements of various kinds.

The system can be described in terms of four primary elements. The first is a general model of irrigation efficiency (IEM) that analyzes the disposition of applied water as spray losses, surface retention, runoff and redistribution, infiltration, percolation, evaporation and transpiration. The second element is a robust, user-oriented, web-based 'expert' interface (OISO). The interface obtains Penman estimates of reference ET from a regional weather station network, uses IEM to forecast irrigation requirements and analyze the disposition of applied water, communicates advisory information to client farms and obtains operational data (irrigation events, measurements of soil moisture) from them. These first two elements have been in beta testing with cooperating farms and are expected to be installed on the USDA web farm in the coming year. These first two elements, which constitute Phase I of the overall project, are operational and have been in beta testing on a pilot basis for one year for 35 fields on 20 cooperating farms in Oregon.

The other two primary elements are a yield model and a feedback system for soil moisture determinations. The yield model will provide estimates of yield reductions when irrigation does not meet crop water demands. The feedback system will provide a way of systematically reconciling different estimators of soil moisture depletion. These two elements, which are the key features of the second phase of the project, are to be integrated into the advisory service gradually over the next two years.

The advisory service is conceived as a dynamic system. While it is ready for use for conventional irrigation scheduling today, it is really being developed for irrigation management 20 years from now. The intention is to continue refining the analytical tools and user interface indefinitely in anticipation of a more challenging future when accelerating competition for water compels more widespread use of partial irrigation.

Phase I: Advisory Service for Conventional Irrigation Scheduling

The irrigation efficiency model (IEM)

The Irrigation Efficiency Model is designed to model the relationship between irrigation intensity, water losses and crop water use. IEM was originally developed by Oregon State University and the New Zealand Ministry of Agriculture and Fisheries (English 1992), then further developed and refined with funding from a USDA National Research Initiative grant (Isbell 2005). The model is implemented in C# and uses a variant of the MODCOM simulation framework (Hillyer, 2003). The implementation is modular and was designed with the anticipation of future extensions and modifications.

IEM functions as a soil water balance model, tracking irrigation and precipitation inputs, estimating potential crop ET, adjusting the potential ET to account for low soil moisture or wet surface conditions, and partitioning ET into its component parts of evaporation and transpiration using the algorithms outlined in FAO 56 (Allen 1998). When soil moisture reaches a user specified level of allowable depletion the model calculates the gross irrigation requirement, expressed as the duration of irrigation required to bring soil moisture up to a user specified refill level. Calculations of gross irrigation requirements are based on net irrigation requirement and an *assumed* application efficiency provided by the user. Subsequently, when an irrigation event takes place, IEM simulates *actual* application efficiencies by modeling the principal determinants of irrigation losses, including spatial variability of soil characteristics, irrigation timing and adequacy, patterns of applied water, wind effects on spray losses, wind distortions of sprinkler patterns, variability of surface infiltration rates, and surface water accumulations and redistribution. By simulating these factors, the model analyzes the disposition of applied water in terms of evaporative losses, percolation, and runoff.

Simulation of the variability of soil moisture in a heterogeneous field with non-uniform water applications is a particularly important aspect of IEM. Such spatial variability has important implications for irrigation scheduling, and can be an important factor in yield modeling. These points are illustrated by Figures 1, 2, 3 and 4. Figure 1 shows a histogram of measured ‘field capacities’ in a small area (one acre) of a silt loam soil that illustrates the innate variability of soil water holding characteristics. That variability has two important implications. First, since net irrigation requirements are commonly based in part on field capacity, the variability indicated by Figure 1 implies that net irrigation requirements depend upon which part of a heterogeneous field is considered the ‘control’ sector for scheduling purposes. Secondly, since it is common practice to rely on soil moisture measurements to determine ‘true’ soil moisture, the variability shown in Figure 1 implies that such soil moisture measurements must be treated as highly uncertain. These two conclusions will not be news to experienced irrigation managers, but they illustrate the rationale for simulating spatial variability.

The variability in Figure 1 is less useful as an indication of crop water availability. Given the integrating effect of root distributions and lateral flow of soil water, the true variability of crop available water is likely to be less than this histogram would suggest. On the other hand, larger scale variations commonly seen in field soils may cause much greater variations than suggested by Figure 1. Figure 2, taken from the NRCS soil survey for Oregon, shows a field comprised of two distinctly different soils, one with an available water capacity of 2.3 in/ft to a depth of more than 5.0 feet, the other with an AWC of 1.7 in/ft to 2.0 ft. These imply much greater field-wide variation than that suggested by Figure 1.

Variations in crop available water imply corresponding variations in crop yield. Figure 3 shows an IEM simulation of the spatial variability of ET in a relatively homogeneous field irrigated at 90% of cumulative ET. Histograms of transpiration in Figure 4 show the changing spatial pattern of ET in a relatively uniform field irrigated at intensities of 60%, 80% and 100% of potential ET (Isbell 2005). The variance of ET at 100% irrigation is small, but as irrigation is reduced, the variance of ET increases and the shape of the probability density function changes. If crop yields are assumed to be more or less linearly related to ET or T, these spatial patterns of ET imply corresponding patterns of crop yield. The importance of such patterns, if any, is being analyzed at this time.

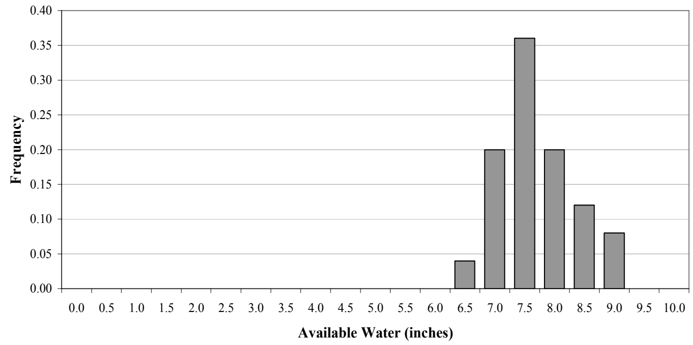


Figure 1. Variability of field capacity in a homogeneous silt loam soil

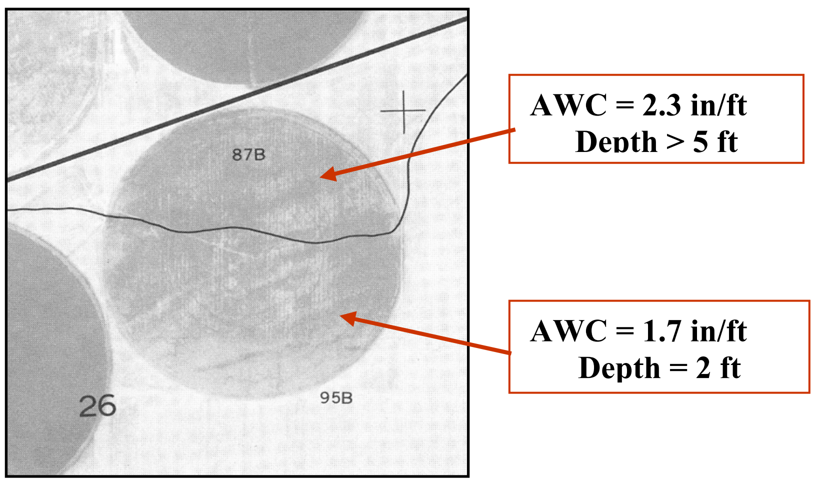


Figure 2. Two soil types in a single field

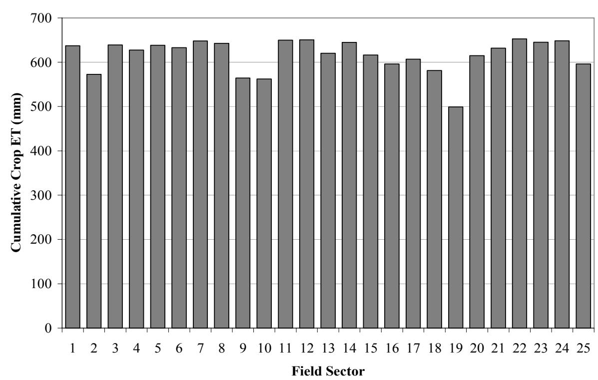


Figure 3. Distribution of Cumulative Crop ET

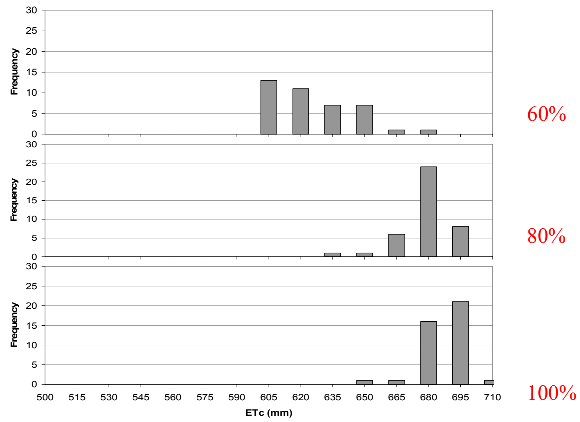


Figure 4. Simulated Distributions of Crop ET

Simulating the variability of soil water and crop available water provides a mechanism for explicitly accounting for these issues when formulating optimum irrigation strategies. That begs the question of how to determine the appropriate scale of variability for simulation purposes. At present that is left to the user's judgment, though default values are provided by the system.

Web based interface (OISO)

OISO analyzes operations for a single water management unit, or WMU, and multiple fields that share that are part of the WMU. By definition, fields that share a common water supply are part of the same water management unit. The program is initialized by specifying the WMU command area, delivery rates and volumes. The following inputs then define the fields and irrigation systems that share that water supply:

(i) area, crop type and development dates, soil depths, infiltration rates, water holding characteristics and antecedent moisture for each field

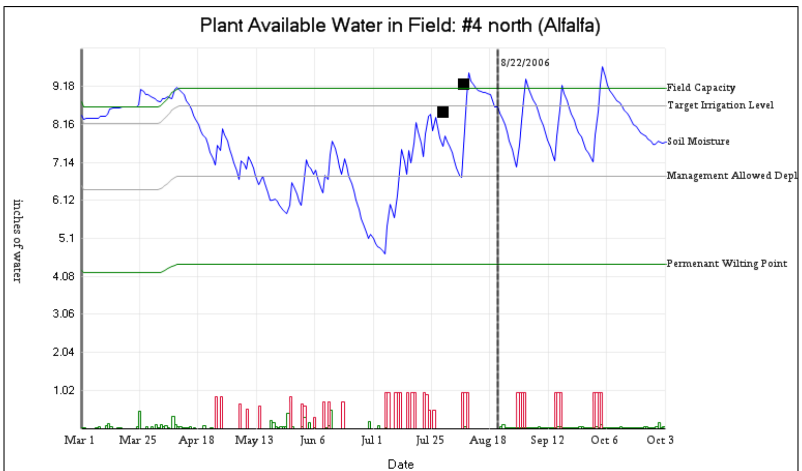
(ii) irrigation systems descriptions, including system type (e.g. pivots), application rates, nominal rotation times, estimated uniformity coefficients and sprinkler head configurations.

(iii) irrigation management strategies are described in terms of MAD, refill level, application efficiency (to be assumed for calculating gross irrigation requirements), and the field sector (defined by the total water holding capacity) to be used for scheduling purposes.

OISO downloads recent weather data, including daily Penman reference ET[1] then calls IEM to calculate spatially variable soil moisture on a daily basis, determine when irrigations are required and calculate the depths of water that need to be applied. When an irrigation event occurs IEM analyzes the disposition of the applied water as previously outlined. Outputs indicate current soil moisture status and recommendations for timing of upcoming irrigations. The program also forecasts crop water demand from the current date to the projected season end date. The system provides a daily email messages to individual clients.

[1] At present the system is linked to the USBR Agrimet network.

A typical output for a single field is shown in Figure 5. This output is delivered to the user via email and is also available on the website in an interactive form. The graph shows a history of soil moisture to date for a single field. A record of irrigation events (red) and precipitation (green) is shown along the horizontal axis. Below the graph is a calendar of recommended upcoming irrigation dates and rates (gpm). The vertical broken line represents today's date. A forecast of future irrigation dates and soil moisture to the end of the season based on historical weather conditions is shown graphically to the right of today's date. The e-mail communication also inquires about recent irrigation operations. By simply picking the *reply email* hyper link, the client can easily send back current operational information such as recent irrigation events, soil moisture measurements or alfalfa cuttings. Clients wishing to see more complete analyses can access their individual web pages by following the URL.



Field Name	Aug/ 20	Aug/ 21	Aug/ 22	Aug/ 23	Aug/ 24	Aug/ 25	Aug/ 26	Aug/ 27	Aug/ 28	Aug/ 29	Aug/ 30	Aug/ 31	Sep/ 1	Sep/ 2
#4 north					900	900	900	900						
#4 Southeast														
#4 Southwest	900	900	900	900								900	900	900
Total	900	900	900	900	900	900	900	900				900	900	900

Dear Mr. …..
The above OISO analysis is a summary for July 8th. The last irrigation date entered was June 28th. The last cutting of alfalfa was June 10th and the next assumed alfalfa cutting date is July 15th. If there have been more recent irrigations, or soil moisture measurements please let us know by *reply email*. For more complete details you can go directly to the web site:
http://oiso.bioe.orst.edu/Realtimeirrigationschedule/index.htm

Figure 5. Sample daily output to client

The full potential of this system becomes clearer when allocating water among multiple fields. Figure 6 shows monthly crop water demand for each of four crops on seven fields during the 2002 crop year and aggregate demand for all fields on a cooperating farm in eastern Oregon. The horizontal line indicates the farm water supply.

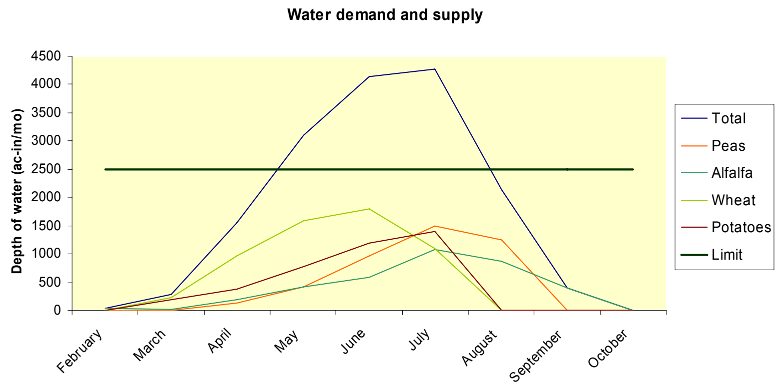


Figure 6. Nominal Crop Water Demand for four crops on Seven Fields

At peak of season, the water demand for full irrigation is about 80% greater than the supply. Clearly it is not possible to fully irrigate all seven fields, but strategic timing and deficit irrigation strategies have enabled this farm to manage these fields profitably in water short years. The present program is designed to deal with the unconventional strategies that farms such as this have chosen to use over the years. Since different managers have different objectives and tolerance for risk and face different local circumstances their irrigation strategies will differ. The procedure is as follows:

(i) propose a water management plan (cropping pattern, irrigation system configuration and irrigation management strategies) for each field
(ii) estimate daily water demand and resulting crop yields for each field for weather years of low, average and high water demand.
(iii) compare total demand with water supply and delivery system capacity
(iv) if the water demand exceeds available supply or system capacity, adjust the water-use plan and repeat the analysis until a feasible strategy is found such that the total demand is in-line with available water.

An example seasonal water use plan from the same cooperating farm[2] is shown in Figure 7. The color coded lines show projected irrigation dates and delivery rates (gallons per minute) for irrigation of five crops on seven fields of various sizes with a variety of irrigation systems. The resulting aggregate farm water demand, summed for all fields, is also shown (black line). Total farm water delivery capacity, about 2400 gpm, is shown as a horizontal line. As in the earlier example, the water demand would exceed supply for much of the season, particularly in May and June, so the initial water use plan shown here is not feasible. Several changes might then be proposed to deal with this water shortage; (i) a small field of alfalfa in its last year of production could be fallowed, (ii) a second field of alfalfa could be deficit irrigated, (iii) alfalfa cutting dates could be shifted slightly, and (iv) a circle of winter wheat could be deficit irrigated

[2] This plan is for a different crop mix than was in place in 2002.

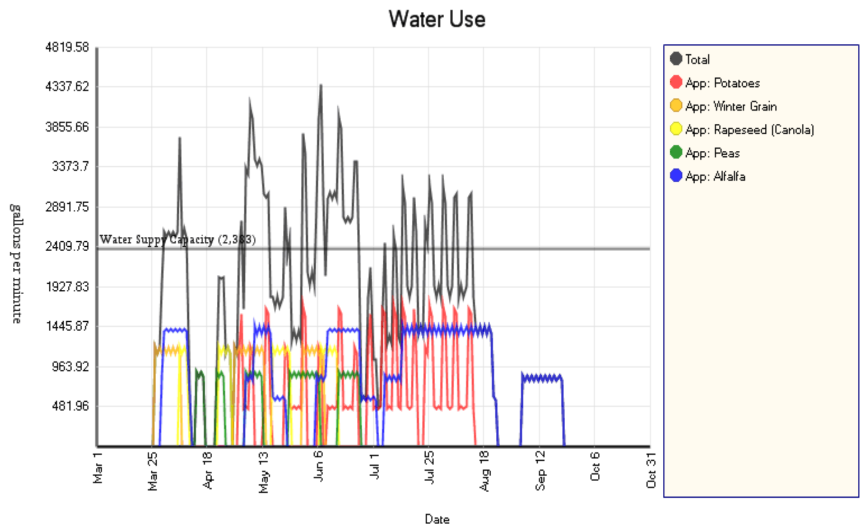


Figure 7. Seasonal Water Demand on a Cooperating Eastern Oregon Farm

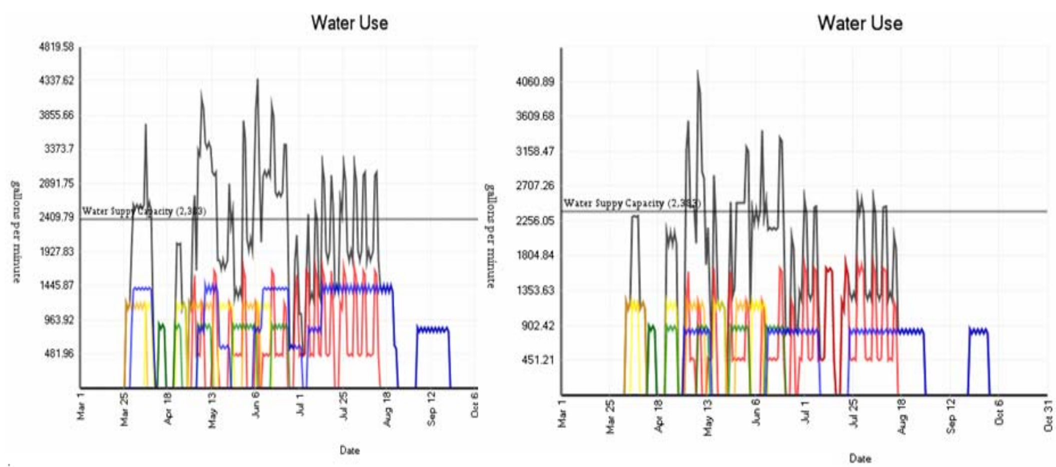


Figure 8. Original & Revised Water Demand Plots

Figure 8 compares the first water demand graph (left) with the resulting revised graph (right). The proposed changes would substantially reduce overall demand, and shorten most periods of excess demand which would make the water shortages more manageable. The next step would be to further refine the irrigation schedules on a day-by-day basis, shifting irrigations from specific high demand days to days when capacity is under-utilized.

Recall that the bottom row of the irrigation calendar shown in Figure 5 represents total water demand (gpm) for a set of fields that share a water source. When irrigation system capacities are not sufficient to meet total demand the total will be flagged by red highlighting. To facilitate allocation of limited capacity, the program will allow direct editing of this scheduling calendar, deleting or adding entries for specific dates or clicking and dragging strings of entries, until the total demand for each date is brought in line with supply. The concept is illustrated in Table 1 which shows two minor changes in a recommended schedule. Starting canola irrigation one day earlier and eliminating the last day of a scheduled irrigation of wheat would avoid the two days of excess demand.

Table 1. Calendar of Irrigation Dates & Rates

	Jun/4	Jun/5	Jun/6	Jun/7	Jun/8	Jun/9	Jun/10	Jun/11	Jun/12	Jun/13	Jun/14	Jun/15	Jun/16
43 potatoes									480	480	480	480	480
44 alfalfa										850	850	850	850
45 peas									900	900	900	900	900
46 alfalfa													
47 wheat	1200	1200	1200	1200	1200	1200	X 1200						
48A potatoes							~~1200~~	~~1200~~					
48B canola	←	1200	1200	1200	1200	1200	1200	1200	1200				
Total	1200	2400	2400	2400	2400	2400	**3600**	2400	**2580**	2230	2230	2230	2230

The procedures described above represent two different approaches for managing water use. The first involves preseason planning by way of an irrigation strategy. The second represents management of day-to-day operations. In both procedures the irrigation manager is a critical component of the system. The manager decides if a strategy is feasible and the manager decides which irrigation events can be changed. By relying on the irrigator as the primary decision maker OISO is a tool that supports –rather than supplants– irrigation scheduling. This pair of techniques, pre-season strategy and day-to-day operations management provides first part of a toolset for irrigation optimization.

Phase II: Optimum Irrigation Scheduling

Yield modeling

Initially, yield modeling has been based on FAO Irrigation and Drainage Paper No. 33. That model estimates relative yield as a function of relative evapotranspiration or relative crop water use by the yield response factor (K_y) (Doorenbos and Kassam, 1979):

$$\left(1-\frac{Y_a}{Y_m}\right)=ky\left(1-\frac{ET_a}{ET_m}\right)$$

Where: Y_a = actual harvested yield
Y_m = maximum harvested yield with no water deficit
K_y = yield response factor
ET_a = actual evapotranspiration
ET_m = maximum evapotranspiration

Though FAO 33 is perhaps the most widely used of all FAO Irrigation and Drainage papers, our experience and the experience of many others with the use of this model under ordinary field conditions has been unsatisfactory. During the last few years, a team of climate, crop, soil, irrigation and water scientists from various countries have been working under the auspices of FAO to develop a new crop-water production model to replace the FAO 33 model. The new FAO model, known as "AquaCrop", is a simple, accurate, robust, menu-driven and user friendly program that is designed for a wide range of users. It is expected that this new general yield model will be ready for distribution and available on the FAO website later this year. The model is still being calibrated for a variety of crops based on experiments done in different countries (Raes et al., 2006).

The AquaCrop development has been led by people of deep knowledge and broad experience, including Pasquale Steduto, Chief of FAO's Water, Development and Management Unit in Rome; Dirk Raes from the Department of Land Management and Economics at Katholieke Universiteit, Leuven, Belgium; Elias Fereres, Director of the Institute for Sustainable Agriculture, University of Cordoba, Spain; and Theodore Hsiao of the Department of Land, Air and Water Resources at the University of California in Davis. Given the credentials and experience of this team the new yield model should be a substantial improvement over FAO 33, and we are looking into the possibility of using it in conjunction with the irrigation advisory service outlined in this paper. At this point it appears likely that the existing IEM model described above will need to be modified in some respects to provide the input parameters and field data needed to support AquaCrop.

AquaCrop is composed of 3 submodels describing soil water balance, canopy development under water stress and yield response to water. The model requires minimal input and will be used to predict yield under water deficit conditions in different environments and regions where the other developed yield models require a lot of data that can be provided only by research stations and they need to be calibrated when they are used in new regions. AquaCrop describes the effect of irrigation amount and timing on crop yield. The model will include the crop response to saline water and different levels of fertilizers in addition to the effect of different irrigation methods (surface, sprinkler and trickle) and management types (supplementary and deficit irrigation) on the crop.

The model needs specific calibration for additional crops, including alfalfa. Work will be done at Oregon State University in collaboration with FAO to test the model for wheat and contribute to calibration for alfalfa. The alfalfa calibration procedure will be done using a combination of new field data from the Hermiston Branch Experiment Station in the Columbia Basin and existing data sets from other western states that link lysimeter-based measurements of ET with observed crop development.

Reconciling estimates of soil water depletion

Irrigation management depends upon continuous estimation of the amount of crop-available water stored in the active root zone. When the management objective is to avoid crop stress altogether, it is common practice to keep soil moisture relatively high, maintaining a certain amount of soil moisture in reserve to minimize risk. Given the margin for error in that approach, precise determination of soil moisture content is not critical. On the other hand, accurate estimation of crop-available soil moisture will become critical when the objective is to maximize net economic returns with limited water. The fourth element of the advisory service is therefore exploring algorithms to derive better real-time estimates of soil moisture. We are focusing on more effective tools for combining the information provided by two commonly used estimators of soil moisture depletion to minimize uncertainty of soil moisture determinations. The two estimators are cumulative calculated ET (as a proxy for cumulative depletion), and direct measurement of changes in soil moisture.

While it is common practice to regard soil moisture measurements as the final determinant of 'true' soil water content, the reality is that both of these estimators provide useful information and neither is perfectly accurate. The advisory service is therefore developing algorithms based on decision theory to combine these two estimators, extracting the maximum usable information from both in a hybrid estimator. Details of this work are to be presented at an EWRI Annual Conference in May, 2008, and will be incorporated into the advisory service during the coming year.

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Irrigation Scheduling of a Water Stress Sensitive Crop, Lessons from Potato

C. Shock, R. Flock, E. Eldredge, A. Pereira, and L. Jensen

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Malheur County Extension, Oregon State University: *Lynn Jensen, staff chair and potato and onion specialist.*

Abstract

Potato (*Solanum tuberosum*) is known to be very sensitive to under- and over-irrigation. Economic expressions of under-irrigation include loss of tuber yield, tuber market grade, and internal quality. The direct economic consequences of over-irrigation include tuber decomposition, increased fungicide and pumping costs, and inefficient use of water and nutrients. The economic consequences of potato irrigation errors have stimulated numerous irrigation scheduling studies. The state of the art of potato irrigation scheduling by evapotranspiration, soil water content, and soil water tension is well developed and often utilized while irrigation scheduling by plant responses has not been adopted. The application of these irrigation scheduling methods will be described and the factors that contribute to their usefulness will be discussed. Irrigation scheduling choices vary based on the climate, soil texture and uniformity, and the scale of operations.

Introduction*

In the late 1980s, the U.S. Pacific Northwest potato industry faced a crisis. Potato tuber quality was inadequate to meet the needs of potato processing companies due to a condition called “sugar ends” or “dark ends” in fried tuber slices. This defect was common in tubers grown on stressed Russet Burbank plants, but the stresses aggravating the condition were poorly defined. Growers lost contracted acres.

In 1989, northern Malheur County was declared a groundwater management area due to groundwater nitrate contamination. The groundwater contamination was linked, at least in part, to furrow irrigation of potato. All irrigation systems in arid regions require some leaching fraction to avoid salt accumulation. However, with the high nitrogen fertilizer rates used through the 1980s, and heavy water applications on furrow-irrigated potato, nitrogen and other mobile nutrients were readily lost to deep percolation and in runoff.

In response to these problems, Malheur Experiment Station began research to determine the soil water requirements for potato production in the Treasure Valley by carefully monitoring soil water status using soil moisture sensors. As growers modified irrigation and other practices to **minimize water stress** on potato plants during tuber development, sugar ends became less prevalent.

At the same time, Experiment Station research and grower experience found that **sprinkler irrigation** could reduce sugar ends and improve tuber grade. Some growers purchased or leased sprinkler irrigation systems. Growers regained contracted acreage by learning to schedule irrigation, shifting to the Shepody variety, and converting from furrow to sprinkler irrigation.

Other growers, however, were unwilling to plant potatoes again. If potatoes were so unpredictable, they wondered, how could they consistently produce a quality crop? However, new understanding of potato development and new information resources have largely taken the mystery out of irrigated potato production in the Treasure Valley.

Irrigation methods

Irrigation method is an important consideration in irrigation scheduling. For potatoes, the leading irrigation method is sprinkler irrigation of hilled rows. Furrow irrigation is still widely used worldwide. Drip irrigation has grown in popularity as the agricultural community has gained familiarity with the system. Drip irrigation advantages, disadvantages, and methods are discussed in *Drip Irrigation Guide for Potatoes in the Treasure Valley*, EM 8912-E (Shock et al., 2006).

Irrigation scheduling

Potatoes have little tolerance for water stress. Tuber market grade, tuber specific gravity, and tuber processing quality for French fries are all critically influenced by water stress during tuber bulking. The incentives for a grower to maintain a precise irrigation schedule to keep the soil water potential within a narrow range of values are significant.

- Under-irrigation leads to losses in tuber quality, market grade, total yield, and contract price.
- Over-irrigation leads to erosion, disease susceptibility, water loss, extra energy costs for pumping, nitrogen leaching, and increased crop N needs.

Scheduling methods

In order for an irrigation schedule to be effective, it has to tell us **when** to water and **how much** to apply. Scheduling methods that are successfully used in the Treasure Valley of Oregon and Idaho are:

- Crop evapotranspiration using the checkbook method
- Soil water tension using a graph of soil moisture
- A combination of these two methods

Crop evapotranspiration (ET)

Crop evapotranspiration (ET) is the combined evaporation of water from the soil surface and crop water use (transpiration of water through plant tissue). Crop evapotranspiration values are calculated using weather stations in a production region. In the Treasure Valley, ET data are available online through AgriMet, a U.S. Bureau of Reclamation cooperative agricultural meteorological network for the Pacific Northwest. Other areas are served by public meteorological networks. Weather stations that estimate evapotranspiration are also sold for farm use.

To illustrate how ET works, think of the soil as a checking account and the water in it as the money in the account. You keep a record (ET log) of all the charges and deposits made to the account. You can run up your charges only to a certain point; after that you must make a deposit, or get "zapped."

To use this method of irrigation scheduling, you must have access to the following:

- AgriMet or other local weather station information to estimate potato crop water use (ET) based on the crop coefficient and crop development data (Table 1, page 3).
- A rain gauge placed in each production field or group of adjacent fields.
- A good estimate for the allowable depletion of water for each soil. The allowable soil water depletion for potatoes can be calculated if you know the following:
  (1) potato plants' effective rooting depth in a given soil and (2) the soil's water retention characteristics in the range where the potato plant does not suffer water stress. Be careful not to overestimate either the root zone depth or the soil's capacity to hold water.

When using this checkbook method, keep the following in mind:

- **Spending depletes your account.** Water use by the plant plus losses from evaporation make up the ET estimated by AgriMet.
- **Deposits refill the account.** Applied irrigations plus rainfall (measured at the field) are considered deposits.
- **You can get "zapped."** Overcharging your bank account or paying a bill late results in a penalty. The same is true here. Letting the field get too dry will result in tuber yield and grade penalties. Keep in mind that **water stress can occur by watering only 1 day late.**
- **The soil water account for potato has a limited size.** If there is more rain or irrigation than the soil can hold, the excess is lost.

Table 1. This sample of an AgriMet table gives ET for Shepody potato (POTS) with an emergence date of May 5 (Start Date 505), and for Russet Burbank potato (POTA) with emergence dates of May 15 and May 23. Columns entitled Daily Crop Water Use display the calculated value as inches per acre for the past 4 days, while the Daily Forecast predicts water use for the current day. The last two columns provide the 7- and 14-day accumulated ET.

ESTIMATED CROP WATER USE - AUG 15, 2005 ONTO

CROP	START DATE	DAILY CROP WATER USE-(IN) PENMAN ET - AUG 11	12	13	14	DAILY FORE CAST	COVER DATE	TERM DATE	SUM ET	7 DAY USE	14 DAY USE
POTS	505	0.29	0.27	0.26	0.20	0.24	610	901	25.9	1.8	3.6
POTA	515	0.39	0.36	0.35	0.28	0.33	710	920	22.7	2.4	4.6
POTA	523	0.40	0.37	0.36	0.28	0.33	710	925	21.7	2.4	4.6

How much water to apply?

Table 2 shows an example of the checkbook method of irrigation scheduling by crop evapotranspiration. In this example, ET is tallied for a potato root zone with an allowable depletion of 1.2 inches of water. The soil is Owyhee silt loam, a common soil around Ontario, Oregon. The daily potato evapotranspiration amounts are the August 2005 AgriMet estimates at this arid location, but the rainfall events are hypothetical, for instructional purposes. Let's suppose that each irrigation supplies 1.2 inches of water, thus replenishing the allowable depletion.

The checkbook method consists of keeping a record of rainfall, estimated daily ET, and the accumulated net ET from one irrigation to the next. Estimated daily ET for locations served by AgriMet is available online at www.usbr.gov/pn/agrimet/h2ouse.html.

Rainfall is subtracted from the net ET. If rainfall makes the net ET account negative, the negative balance is dropped, and net ET is set to zero for that day. The negative balance is dropped because it represents water applied in excess of the root-zone water-holding capacity; this water is lost to runoff or leaching, typically within 24 hours.

Note that the ET for the day of irrigation is also added; thus, net ET accumulated up to the day of irrigation includes the ET for that day. Irrigation never exceeds 1.2 inches because the extra water would be quickly lost to runoff or leaching.

Table 2. The checkbook method of irrigation scheduling where a silt loam soil has 1.2 inches of allowable depletion for potatoes.

Action	Date August	Daily ET (inches)	Rain (inches)	Accumulated ET (inches)
	1	0.35		0.35
	2	0.34		0.69
	3	0.34		1.03
Irrigate	4	0.32		0.15
	5	0.31		0.46
	6	0.29	0.08	0.67
	7	0.27	1.45	---0---
	8	0.29		0.29
	9	0.31		0.60
	10	0.40		1.00
Irrigate	11	0.40		0.20
	12	0.37		0.57
	13	0.36		0.93
	14	0.28		1.21
Irrigate	15	0.26		0.27
	16	0.25		0.52
	17	0.24		0.76
	18	0.26		1.02
Irrigate	19	0.25		0.07
	20	0.23		0.30
	21	0.25		0.55
	22	0.27		0.82

When should I irrigate?

The grower decides when to irrigate by not allowing net ET to exceed the allowable depletion. To avoid getting zapped, he must begin irrigation on the day the balance would have exceeded 1.2 inches.

The grower knows how much to irrigate by replacing only the soil's allowable depletion (1.2 inches). There is no mystery here. We have made clear decisions about when to irrigate and how much water to apply: the result is successful potato irrigation.

Does the checkbook method work on sandy soil?

The checkbook method operates in the same way on a sandy soil, but the irrigation frequency is much higher and irrigations typically are much smaller. Assume irrigations of 0.33 inch and a 0.5-inch allowable water depletion for potatoes on this sandy soil (Table 3).

Table 3. The checkbook method of irrigation scheduling where a sandy soil has 0.5 inch of allowable depletion for potatoes.

Action	Date August	Daily ET (inches)	Rain (inches)	Accumulated ET (inches)
	1	0.35		0.35
Irrigate	2	0.34		0.36
Irrigate	3	0.34		0.37
Irrigate	4	0.32		0.36
Irrigate	5	0.31		0.34
Irrigate	6	0.29	0.08	0.22
	7	0.27	1.45	---0---
	8	0.29		0.29
Irrigate	9	0.31		0.27
Irrigate	10	0.40		0.34

Irrigation scheduling by soil water content

On sandy soils, irrigation scheduling by the checkbook method alone has a narrow margin of error. Measuring the trend in soil water content in conjunction with the checkbook method can help assure that the field is not getting too dry or too wet. Regular measurements are made by neutron probe or by other equipment and are plotted over time.

Irrigation scheduling by Soil Water Tension (SWT)

Another effective method for irrigation scheduling is based on soil water tension. SWT is a measure of how strongly water is held by the soil. Potato plant performance is closely related to the amount of tension the plant has to exert to move water from the soil into the plant roots. That force can be measured using either tensiometers or Granular Matrix Sensors (GMS).

GMS (manufactured as Watermark soil moisture sensors by Irrometer Co., Riverside, CA) measure SWT using a battery-powered meter. These measurements are recorded, and they provide information about **when** to irrigate. Since 1988, SWT readings from GMS have been used to schedule irrigations in Malheur County growers' fields.

Six or more GMS can characterize the soil water tension in a field, provided they are installed in representative areas and are responsive to ET and irrigations. The six GMS may be distributed widely across an area with similar irrigation needs. Sensors are installed 8 inches deep in the potato row between two healthy plants. Wires from sensors in a given area are brought to a single easily accessible location, such as a field edge, for rapid reading.

Irrigation onset criteria must be developed for each production environment. Criteria for irrigation onset by SWT depend on the climate, soil, and irrigation system in use (Shock et al. 2007). Studies have determined criteria from 20 to 60 centibars (cb). The SWT irrigation criteria that optimize potato yield and grade vary by production area. Based on potato yield and grade responses to irrigation, ideal potato SWT irrigation criteria are as follows:

- 50 to 60 cb for sprinklers on silt loam in Oregon (Figure 1)
- 60 cb and 30 cb for furrow and drip irrigation, respectively, on silt loam in Oregon (Figure 2)
- 50 cb for furrow irrigation on loam in California
- 25 cb for sprinklers on silt loam in Maine
- 20 cb for sprinklers on sandy loam in western Australia

An SWT scale for potato

- > 80 cb indicates dry soil and water stress for potato plants.
- 20 to 60 cb is the range that indicates it's time to irrigate, depending on location, soil type, and irrigation system.
- 10 cb is close to field capacity.
- 0 to 10 cb indicates the soil is saturated with water.

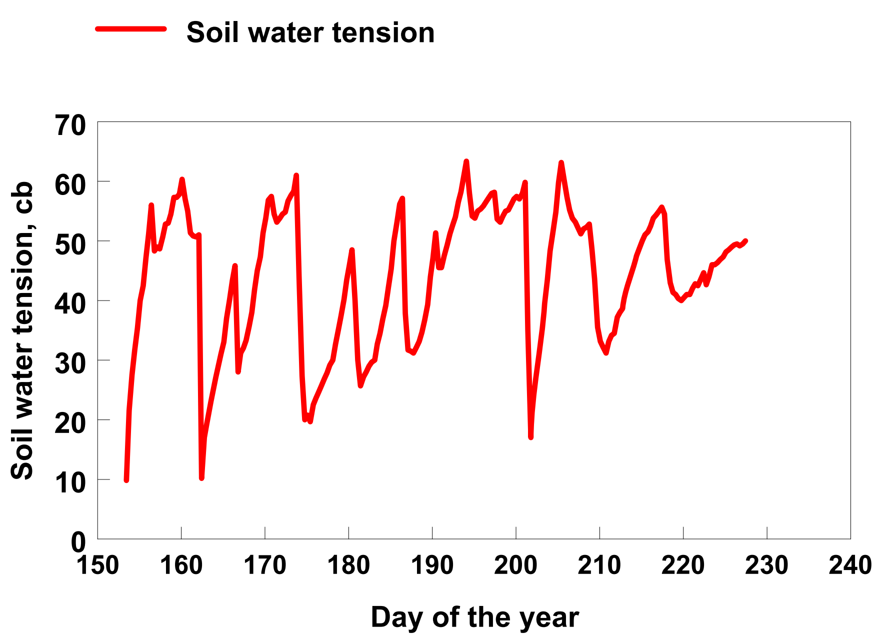

Figure 1. Sprinkler-irrigated potato with irrigation criteria of 60 cb on silt loam at Ontario, OR. Soil water tension drops following each irrigation. The irrigations between days 191 and 200 (July 10 and 19) while replacing ET, did not get the soil wet around the GMS because the irrigations did not refill the root zone.

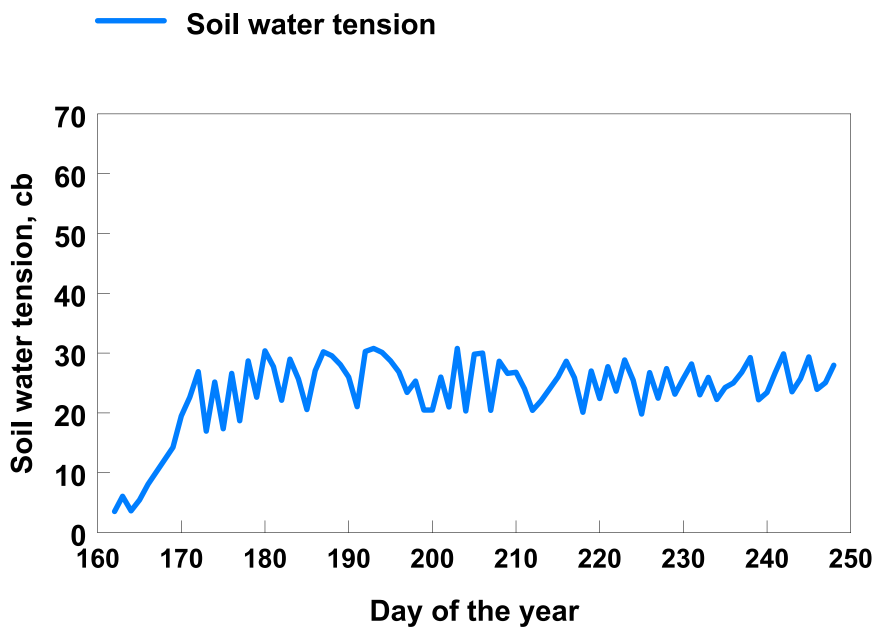

Figure 2. Drip-irrigated potato with small drops in soil water tension following irrigations on silt loam at Ontario, OR. Irrigations are much more frequent. They maintain an average SWT wetter than 30 cb and do not saturate the soil.

When to irrigate on silt loam in the Treasure Valley?

Read sensors daily and plot the data on a graph for immediate interpretation. On silt loam, tuber growth and grade are maximized when irrigation occurs before the average readings at the 8-inch depth reach 60 cb for sprinkler and furrow irrigation systems or 30 cb for drip systems (Figures 1 and 2).

Moderate water stress causes little damage to potatoes before tuber initiation, but during tuber development even small amounts of water stress (higher than 50 cb) can result in decreased tuber grade. On silt loam, water stress beyond 60 cb results in decreased specific gravity and increased incidence of dark-end fry colors in susceptible cultivars such as Russet Burbank.

A single, short-duration incident of water stress (SWT drier than 60 cb, zap!) can lead to reduced tuber grade and increased dark fry colors (Eldredge et al., 1996). In one experiment, a single episode of water stress, with GMS readings reaching an SWT of 75 cb or more, resulted in a loss of USDA No. 1 grade tubers, correspondingly more USDA No. 2 grade tubers, and losses in tuber solids. A single stress episode with GMS readings of 75 cb or drier was associated with increased incidence of the darkest fry colors: USDA No. 3 and No. 4 (Eldredge et al., 1996).

Total yield generally is unaffected by one brief episode of stress, but reduced tuber quality can render the crop unprofitable (Eldredge et al., 1992). Thus, it is critical to maintain SWT at adequate levels. However, it is very difficult to gauge water stress without a quick, reliable field determination of soil water tension. GMS provides this capability. When viewed in graphical form, SWT clearly indicates the current condition of the crop root zone and how rapidly water is being depleted. Methods for determining crop water needs and installing and managing granular matrix sensors and tensiometers are discussed more thoroughly in *Irrigation Monitoring Using Soil Water Tension*, EM 8900 (Shock et al., 2005).

Combining SWT with ET

A powerful way to schedule irrigation is to combine the ET and SWT methods. The strong point of SWT is its ability to predict stress before it occurs, while the strong point of ET is its ability to prevent over-irrigation. Combine the two methods by irrigating when the average tensiometer or GMS reading reaches the SWT criterion and applying enough water to replenish ET but not more than needed to refill the root zone.

Automated SWT readings

Dataloggers that automatically read GMS and record SWT can facilitate irrigation management. The data can be viewed with the push of a button and can be downloaded to a laptop computer or PDA. Downloaded data can be imported into a spreadsheet and graphed. The SWT graphs constructed from the stored data make it possible to determine soil moisture trends and to predict or modify irrigation schedules at each GMS location. The dataloggers also can include soil temperature sensors to correct the SWT data.

Irrometer Co. Inc. (Riverside, CA) makes the Watermark Monitor, which automatically stores readings from up to eight sensors, including a temperature sensor and pressure switches for recording irrigation events. Data intervals can be set from once a minute to once every 24 hours. Data can be downloaded from the Watermark Monitor to a laptop or PDA in the field, or can be transmitted by radio or cellular modem to a remote computer.

The AM400, by M.K. Hansen Co. (East Wenatchee, WA), automatically records readings every 8 hours from six GMS and a temperature sensor. By pushing a button, the grower can view soil moisture graphs of the recorded data.

Stress-resistant varieties

Potato varieties that express fewer negative characteristics when subjected to stress have been identified. One of these varieties, Shepody, has become more popular with growers and processors in the past decade. Other varieties, including Ranger Russet, Umatilla Russet, and other experimental varieties, are discussed in Malheur Experiment Station annual reports and in Shock et al. (2003b).

Irrigation and disease

Excessively wet soil is conducive to many tuber-rotting pathogens, encouraging the incidence of blights, rots, and wilts that can limit yield, tuber quality, tuber size, tuber dry matter content, and crop marketability at harvest or from storage. Together dense canopy growth, long periods of leaf wetness, and high relative humidity create microenvironments that favor infection. Improperly managed irrigation often keeps the vines wet for long periods of time, exacerbating the risk of infection.

Diseases promoted by over-irrigation include:

- Late blight (*Phytophthora infestans*)
- Early blight (*Alternaria solani*)
- Soft rot (*Erwinia* spp.)
- White mold (*Sclerotinia sclerotiorum*)
- Black leg (*Erwinia carotovora atroseptica*)
- Potato leak (*Pythium* spp.)
- Pink rot (*Phytophthora erythroseptica*)
- Rhizoctonia canker (*Rhizoctonia solani*)
- Powdery scab (*Spongospora subterranea*)
- Verticillium wilt (*Verticillium dahliae*)

Prolonged periods of saturation following planting can promote seed piece decay as well as poor and erratic tuber emergence.

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Quick Facts

- Potato is a water-stress-sensitive crop. Potato plants are more productive and produce higher quality tubers when watered precisely using soil water tension (SWT) than if they are under- or over-irrigated.
- Potatoes are more sensitive to water stress than are most other crops.
- Potatoes have a relatively shallow root system that provides very little margin for irrigation errors.

- Yield reductions due to over-irrigation can be attributed to poor soil aeration, increased disease problems, and leaching of nutrients from the shallow crop-root zone.
- Granular Matrix Sensors provide good estimates of SWT for many soils.
- SWT provides useful guidelines to avoid water stress by projecting **when** to irrigate.
- A soil water potential of -30 cb is the same as a soil water tension of +30 cb. Also, cb (centibars) is the same as kPa (kiloPascals).
- In the Treasure Valley, sprinkler- and furrow-irrigated potatoes on silt loam are irrigated at an SWT of 60 cb. With drip systems, potatoes are irrigated at an SWT of 30 cb.
- Irrigation to replace estimated crop water use (estimated accumulated crop evapotranspiration) can be an effective way to irrigate potatoes with a sprinkler or drip system.
- AgriMet provides an online estimate of daily crop water use for the Ontario, Oregon area at http://www.usbr.gov/pn/agrimet/chart/ontoch.txt and for other locations served by AgriMet at http://www.usbr.gov/pn/agrimet/h2ouse.html

Micro Sprinkler Irrigation using SCADA and sensor network for freeze protection.

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Abstract

Freeze damage to crops occur when water within the crop freezes and ruptures the cell membranes, which is not limited to only the fruit but also the leaves, twigs and wood. Citrus and some vegetable crops unlike deciduous trees cannot protect it self by shedding their leaves in the fall, but continue to grow year around. The overall objective of this research is to investigate the potential of Supervisory Control and Data Acquisition (SCADA) systems with a combination of soil moisture sensors and micro sprinklers as an efficient irrigation system during freeze condition. As 1 gram of water is applied using micro sprinklers and controlled by a SCADA system and monitored via soil moisture, temperature and wind speed sensors, it will freeze releasing 80 calories of heat energy to protect the plant. If not properly managed/controlled water being applied to freeze will rather evaporate, thereby 600 calories will be absorbed and further lower the temperature around the plant canopy.

Introduction

Freeze damage occurs in crops occur when water within the crop freezes and ruptures the cell membranes, this is not limited to only the fruit but also the leaves, twigs and wood (Boorse et. al 1998). The damage at times is limited not only to the leaves and fruits but can be so severe as to destroy the whole orchard.

California's San Joaquin Valley which is situated in the heart of the state is the top agricultural production region, also sometimes referred as "the nation's salad bowl" for the range of fruits and vegetables grown in its fertile soil. But this region is plagued with the problem of salinity (approximately 1.82 million hectares)(Jacobsen and Basinal 2004;Ayars 2005) and now this year we have the added burden of "freeze damage" to the crops. The freeze damage to citrus alone in this region has been estimated at $ 1 billion (Mercury News 2007). Freeze damage to crops occur when water within the crop freezes and ruptures the cell membranes, which is not limited to only the fruit but also the leaves, twigs and wood. Unlike deciduous trees, that protect it by shedding their leaves in fall, Citrus and some vegetable crops continue to grow year and are prone to freeze damage due to the presence of heavy vegetative mass like leaves. This year's sudden drop in temperature has affected citrus, avocado, strawberry, winter vegetables, spring vegetables, artichokes, olives and flowers. Damage has been reported from as far as Imperial Valley and San Diego among others and has turned this into a Federal disaster.

Traditionally *radiation and advection freeze* are encountered in California orchards. Both of these freeze events vary greatly from one another in terms of meteorological conditions and frequency of occurrence associated with them. Advection or horizontal movement of a cold air mass over land creates widespread cooling as cold air moves into a region or from the loss of heat due to radiation. If radiation heat loss becomes predominant form of cooling then it is called radiation freeze whereas advection freeze happens when cooling by advection is the predominant factor.

When a large mass of Arctic air moves in and covers the region resulting in drop of day and night temperature an advection freeze is said to have occurred. During advection freeze the weather condition may be clear or cloudy with strong winds that continue into the night. We may also see a lot of mixing and interaction at the lower layers of the atmosphere.

Unlike advection freeze, radiation freezes occur mostly on clear, calm nights after cold air has moved into the region, which results in heat being lost to the atmosphere throughout the night. The rate of heat loss by radiation into space is partly dictated by the amount of moisture present in the atmosphere. The heat loss is greater in dry air compared to moist air. During such freeze condition the coldest layer of air is normally found near the radiating surface as the air layers into various regions of air with varying temperature with relatively hotter air at the top. Normally, temperature decreases as height in the atmosphere increases. Thus, this meteorological condition is known as a temperature inversion (warm air layers over cool air layers).

Almost all spring freeze events in California vineyards are radiation freezes. Fortunately, a wide range of frost protection methods can be employed against radiation freezes. Advection freezes are relatively rare and normally occur only during the dormant season. The 1990, 1998 and 2007 freeze are examples of an advection freeze. Very little or no protection mechanism are available to protect the orchards from severe advection freeze. Therefore, the remainder of the paper will deal with the some concepts to deal with advection freeze.

In order to meet the food and fiber needs of existing population and also meet the demands of the future populations, the world's food supply must be made sustainable and renewable without putting undue pressure on the ecosystem. Therefore, sound resource management which emphasizes careful and efficient use of our agricultural production and our ecosystem is the key to achieving these objectives. The overall objective of this research is to investigate the potential of SCADA systems for the irrigation management during freeze condition, such that application of irrigation water as a means of protection will elevate the temperature around the crop canopy. By optimizing the irrigation delivery system with a SCADA system the irrigation age old technique of applying water during freeze can be perfected and made efficient.

Purpose

A more deliberate and scientific approach to the frost/freeze protection mechanism is needed in order to prevent frost/freeze damage. A currently available technology that could be utilized for this purpose is SCADA (Supervisory Control and Data Acquisition) systems. SCADA consist of a complex central computer system that can monitor and control an irrigation system spread out over a long distance. SCADA systems are capable of monitoring and controlling many parameters with the help of various sensors and feedback mechanisms. By properly monitoring the wind speed, evaporation rate, soil heat flux and rate of irrigation, *adequate irrigation* can be used as protection mechanism (NC Coop. Extension 2007). Additionally a combination of irrigation, wind machine and gas heaters can be deployed for best result under varying condition.

Significance

Historically over the last decade or so, freeze damage to crops in California in particular occurs every 8 years. The freeze damage that occurred in 1990 devastated most of the citrus crops and many orchards had to be replanted, leading to heavy financial losses to the grower and the economy. The crop damage during 1998 freeze was comparatively less, and this can be partially attributed to some of the advances in freeze prevention methods gained since 1990. In the wake of the recent (2007) crop damage all over California and other parts of the United States, unless drastic remedial measures are researched and implemented this might turn in to an epidemic in the years to come. This will not only affect the local economy but also the constant supply of fruits and vegetables for the masses.

Project Statement

***Hypothesis**:* Irrigation via micro-drips or spray heads in an efficient and scientific manner can reduce freeze damage. As 1 gram of water applied through irrigation freezes, 80 calories of heat energy is released, thereby providing latent heat as long as ice is formed. This method fails if the irrigation rate is not adequate, thereby resulting in more damage then cure. Insufficient irrigation rate results in inadequate water being applied to freeze, as 1 gram of water evaporates rather then freeze, 600 calories of heat energy are absorbed from the environment, which will take heat from the crop. The crop will freeze faster compared to no irrigation protection as evaporation is being promoted by wind speeds of 5 mph or higher in a typical frost/freeze condition there by limiting the success of this protection method (NC Coop. Extension 2007).

The overall objective of this research is to investigate the potential of SCADA systems as an efficient irrigation management system and also to investigate the potential of this system to deliver irrigation water via micro-sprinklers during freeze condition. This will not only result in comprehensive water management but also contribute to the reduction in fossil fuel wastage, as otherwise heaters and wind machines are used during freeze conditions.

With the goal of improved water efficiency and fuel management, we propose to refine the irrigation management techniques round the year using the SCADA system and also use this multi purpose system to prevent freeze damage via application of irrigation water during freeze condition. The usage will be electronically documented and compared with the net freeze damage if any. In order to achieve these objectives and quantify the positive attributes of this system, we take into account the following assumptions and limitations:

Assumptions:

- Water can prevent freeze damage
- Water is affordable and readily available
- Realtime feedback and sensor technology for the proposed measurements are available

Limitations:

- Climatic conditions
- Time period of the study
- Site selection
- Equipments
- Finance/Funding opportunity
- Available personal to carry out the technical and field work

Scope of research:

In order to achieve the project objectives rigorous lab testing in simulated environment will have to be performed, followed by site selection at a freeze prone location. With proper data acquisition and system fine tuning this model can be developed into an irrigation controller chip and added to the existing irrigation system. We understand that we will have to add minor adjustments to the current irrigation system, but if successful this research has endless benefits for areas prone to freeze.

Proposed Work and Statement of Methodology

With the goal of improved water efficiency and freeze management, we propose to refine the irrigation techniques used during frost/freeze condition, as well as electronic documentation of the characteristics of the applied water. In order to achieve these objectives we have identified three major components for the proposed work:

Component 1: Incorporation of a SCADA system in a farm during frost/freeze season

During this phase of the research, the focus will mainly be on adapting and incorporating the SCADA into the regular irrigation system which will also act as frost/freeze irrigation protection method during winter months.

Component 2: *Monitoring changes in the micro climate*

The proposed SCADA system will schedule irrigation water in a manner that leads to improved water usage during normal operation and deliver irrigation water in a manner so as to prevent freeze damage during frost/freeze condition. We will allocate a control area with traditional farmers practice and another area treated with our system and compare both micro climate.

Component 3: Design the SCADA System

The proposed SCADA system will have soil moisture sensors, pH sensors, wind speed sensors, soil heat flux plates, soil salinity sensors, pressure transducers for line pressure, flow-meters for monitoring the usage of Irrigation District water , flumes to check for flow and host of other sensors and controller. In addition to the sensors, the SCADA system will have its own hardware for the central processing unit, which is a low power usage embedded computer capable of withstanding harsh field conditions of heat, dust and humidity. Communication and monitoring with the SCADA system will be done remotely at times using wireless technology (WiFi). Specific attention will be paid while choosing the hardware to prevent conflict interfacing among different hardware's.
The SCADA system once built, will be designed or programmed according to the system variables and information collected during field study. The system will also be tested with ***supervisory*** controls to check the system performance to match user changing demands.

The final SCADA system will be tested under laboratory conditions using predetermined circumstances .Discrepancy of the system, if any, will be rectified by modifying the program.

Once the system is tested and corrected in the lab, the SCADA system will be made mobile and stationed at the field site and instrumented with all the sensors and the feedback system. The system will be programmed to run in an automatic mode and monitored for effective freeze protection. The system will be run at various freeze susceptible regions for 2secutive years.

Data collected during the field testing will be compared with the data obtained in the laboratory. Calibration curves, system performance and efficiency will be modeled using a computer generated simulation program. Salinity and hydraulic loading of the soil will be studied and curves will also be generated. Response curves and system performance will be generated on a weekly basis so that appropriate changes, if any, can be made in a timely fashion.

Definition of results and evaluation of the calibration curve with confidence limit will be made. If the range of the values defined by the confidence limits at a given reading is so great as to leave the blending decision unsupported, the system performance for those testing conditions will have to be revisited and re-programmed.

Summary and Conclusion

Nearly all orchards and vineyard regions of the world are subject to spring frost damage and finding an efficient frost protection mechanism especially for advection freeze is of paramount importance and a challenge for most commercial orchards. Avoidance of frost damage can be achieved through a combination of passive or active methods in a way, such that minimal damage occurs to the plant especially if the active method like application of irrigation water can be further automated and controlled. Active methods like wind machines, heaters combinations or sprinklers are more expensive but can provide 5-6°F of protection under ideal freeze conditions. Further work is underway to test our system and improve upon it as we move it out of the laboratory to the real field condition

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Tuesday, December 11, 2007
IA07-1065

Decision Support Model for Irrigation and Drainage Management of Paddy Fields in Uganda

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A decision support model - IDRAMAP - has been developed as planning and operational tool for the main irrigation system. Within each block responsibility for water allocation and distribution lies in the hands of the Water Users Association. The model is based on the water balance for paddy fields. The irrigation and drainage requirements are determined considering the amount of expected daily average rainfall and reference evapotranspiration, the current field conditions of water depth and the stage of growth of the crop. The model provides a flexible database linked to a weather station in which the user enters the design, the meteorological, and the agronomical information. In case the scheme water demand exceeds the available water at the headworks, an equal reduction factor is applied to all the blocks. The results of the model are displayed in the form of tables and graphs.

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Tuesday, December 11, 2007
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Irrigation Scheduling in Cassava based Forage Intercropping systems

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Field experiments were conducted to find out the level of irrigation and the effect of intercropping on the growth and yield Cassava at Veterinary College and Research Institute, Namakkal, Tamil Nadu during 2001 and 2002. The popular hybrid of cassava H 226 was tried as test crop. The soil of the experimental site was moderately drained, loamy sand. The soils were low in available N, medium in available P and low in available K. The experiments were laid out in a split plot design with three replications. In the main plot, four levels of surface irrigation at 1.0, 0.80, 0.60 and 0.40 IW / CPE ratio to 5 cm depth were compared. Three intercropping systems viz., sole cassava, cassava + maize (var. African tall) and cassava + cowpea (var. CO 5) were assigned to sub plot. Disease free setts of cassava were planted at a spacing of 90 x 90 cm. Two rows of intercrops were sown in between the rows of main crop as additive intercropping series. Seeds of fodder maize and cowpea were dibbled in lines at a spacing of 30 x 20 cm accommodating two rows of intercrops between the rows of cassava. The results revealed that irrigation at 0.80 IW / CPE ratio registered the highest tuber yield. However this yield was comparable with the tuber yield obtained with irrigation scheduled at 0.60 IW / CPE ratio. The economic evaluation revealed that the BC ratio was higher surface irrigation scheduled at 0.80 IW / CPE ratio followed by irrigation scheduled at 0.60 IW / CPE ratio and were comparable. Among the intercropping systems, sole cassava recorded the highest tuber yield and BC ratio followed by cassava intercropped with cowpea and both were comparable. Cassava intercropped with maize recorded the least tuber yield and BC ratio.

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Evaluating Three Evapotranspiration Mapping Algorithms with Lysimetric Data in the Semi-arid Texas High Plains

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Abstract

Ground water levels are declining at unsustainable rates in the Texas High Plains. Accurate evapotranspiration (ET) maps would provide valuable information on regional crop water use and hydrology. This study evaluated three remote sensing based algorithms for estimating ET rates for the Texas High Plains. Data from four large-scale weighing lysimeters (two each irrigated and dryland crops) at the Conservation Production Research Laboratory, USDA-ARS at Bushland, TX, were used to evaluate the remote sensing methods. ET algorithms evaluated include Mapping Evapotranspiration at High Resolution using Internalized Calibration model (METRIC), Two-Source Energy Balance model (TSM), and an Aerodynamic Temperature based Energy Balance model (ATEB). A Landsat 5 TM image acquired on July 23, 2006 was used for estimating ET. Predicted ET values were compared with lysimetric data to determine how well the different ET models worked. A discussion of each model's strength and weaknesses, under the climatic conditions encountered in the Texas High Plains, is provided.

Keywords: Texas Panhandle, semi-arid environment, remote sensing, irrigation scheduling, surface energy balance.

Introduction

The Ogallala Aquifer is the main source of water supply for the Texas High Plains (THP) and is being depleted at an unsustainable rate (Axtell, 2006). In the THP, irrigation alone uses approximately 89% of the water pumped from the Ogallala Aquifer (Dennehy, 2000). McGuire (2004) indicated that the change in water storage in the aquifer beneath the THP, from predevelopment to 2003, was about 164.1 km^3 (5.2 km^3 from 2002 to 2003) with an average area-weighted predevelopment water-level decline of 10.6 m

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(0.37 m from 2002 to 2003). For this reason and considering the positive trends in population growth in the THP, there is a need for greater efficiency in irrigation water management for agriculture.

Improvement in irrigation water management is achieved when the beneficial crop water use is accurately quantified in time and space. Remote sensing (RS) based evapotranspiration (ET) methods are found to be useful for deriving such information. Numerous RS algorithms, such as METRIC (Mapping Evapotranspiration at high Resolution with Internal Calibration; Allen et al., 2007, 2005a), SEBAL (Surface Energy Balance for Land; Bastiaanssen et al., 1998), a Two-Source energy balance Model (TSM; Norman et al., 1995), Aerodynamic Temperature based energy balance models [Chávez et al., 2005; Crago et al. (1999), Crago (1998), and Chehbouni et al. (1996, 1997)], a dimensionless temperature method (Δ_T, Suleiman and Crago, 2004), and an Analytical Land Atmosphere Radiometer Model (ALARM; Suleiman and Crago, 2002), among others, have been developed to spatially estimate crop water consumption or ET and are being evaluated around the world. These algorithms mainly solve the energy balance of the land surface for latent heat flux (LE) at the time of satellite or airborne RS system overpass and extrapolate instantaneous LE (ET_i) to daily ET values.

Gowda et al. (2007a) discussed the pros and cons of numerous RS algorithms for ET estimation. For instance, they indicated that the TSM model yielded surface heat fluxes with errors within 10-12%, although this model demands several crop and micro-meteorological data that, in many circumstances, are very difficult to obtain. They summarized that SEBAL had a typical accuracy at the field scale of 85 % or errors ranging from 2.7 to 35.0 % with an overall average of 18.2 %, under a variety of climatic/environmental conditions. However, METRIC appeared to have an advantage over SEBAL under advective conditions. METRIC's ET estimation errors were reported to be approximately 10 to 20 % for daily estimates and as low as 1 to 4 % for seasonal ET estimates, requiring only vapor pressure (or relative humidity) and wind speed measurements from weather stations (WS) within the satellite scene. METRIC, as in SEBAL, needs to be applied by individuals with background knowledge in hydrology, engineering, and environmental physics, and demands experience in the selection process of the cold/wet and hot/dry pixels in the remote sensing scene in order to properly determine a relationship between surface radiometric temperature and dT (aerodynamic temperature – air temperature) for estimating sensible heat fluxes. The need of extreme pixel selection does not apply for aerodynamic temperature based land surface energy balance algorithms. Therefore, in this study, three distinct methods have been selected to assess their ability to accurately predict spatial ET in the THP: METRIC (based on extreme pixels); TSM (based on the discrimination of canopy and soil temperature); and the Aerodynamic Temperature based Energy Balance method by Chávez et al. (2005), herein denominated ATEB, which is a function of radiometric surface temperature, air temperature, leaf area index, and wind speed.

Materials and Methods

Study Area

This study was conducted at the USDA-ARS, Conservation and Production Research Laboratory (CPRL), located in Bushland, Texas, USA (Fig. 1). The geographic coordinates of the CPRL are 35° 11' N, 102° 06' W, and its elevation is 1,170 m above mean sea level. For this study, a 30-m resolution Landsat 5 Thematic Mapper (TM) scene was used to derive energy fluxes at the land surface. The scene path/row was 31/36 and was acquired at 11:20 CST (17:20 GMT) on July 23, 2006. Thermal band (TM band 6) image was captured at a coarser resolution of 120-m, and was resampled to 30–m by the image supplier. Soils around Bushland are classified as slowly permeable Pullman clay loam soils. The major crops in the region are corn, sorghum, winter wheat and cotton.

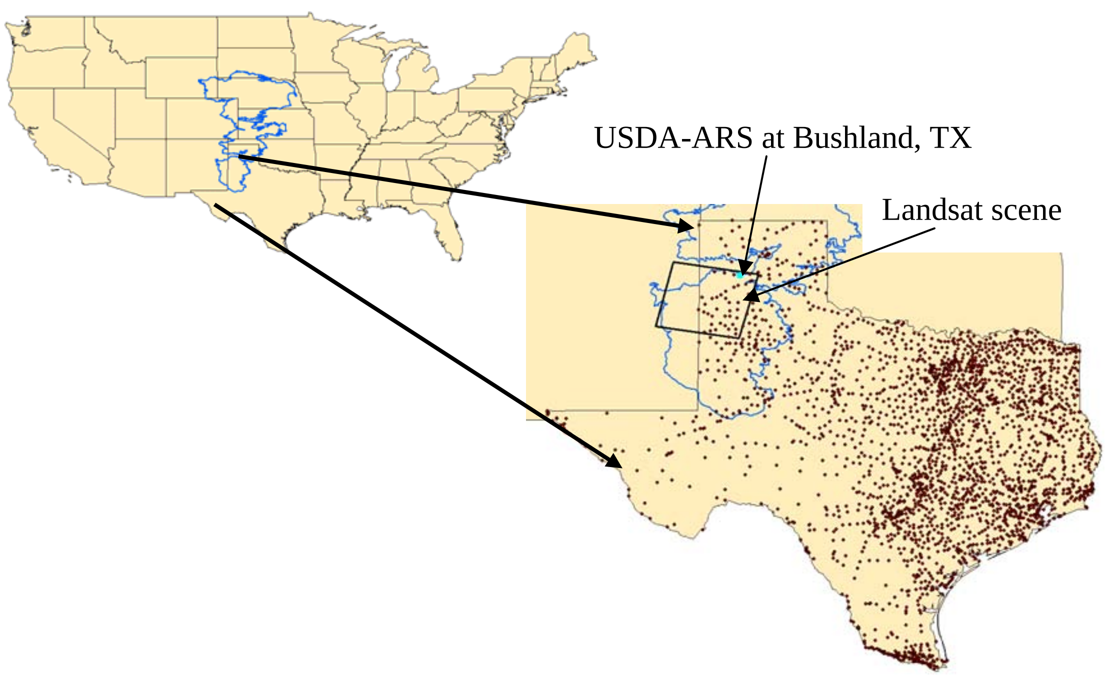


Figure 1. Landsat 5 TM path/row 31/36 scene (rectangle) covering an area underlaid by the Ogallala Aquifer (irregular polygon) in the Texas High Plains (Panhandle). The USDA-ARS-CPRL laboratory location is indicated by a dot.

Estimated ET values were verified by comparing them with soil water mass change-based daily ET values from five monolithic weighing lysimeters located at the CPRL (Fig. 2). Four large lysimeters (3 m length x 3 m width x 2.5 m depth) were located in the middle of 4.7-ha fields. In 2006, the SW and NW lysimeters were planted to dryland grain sorghum with NW field planted in clumps as part of another study. The irrigated SE and NE lysimeter fields were planted to forage sorghum and corn, respectively. The grass lysimeter was 1.5 m by 1.5 m by 2.5 m deep and was located in the reference ET weather station field (0.31 ha) which is a part of the Texas High Plains ET Network (TXHPET, 2006). Each lysimeter field is equipped with one net radiometer [Q*7.1, Radiation and Energy Balance Systems (REBS) [3/], Seattle, WA] and one infra-red thermometer (IRT) (2G-T-80F/27C, Exergen, Watertown, MA) for measuring net radiation and surface temperature, respectively.

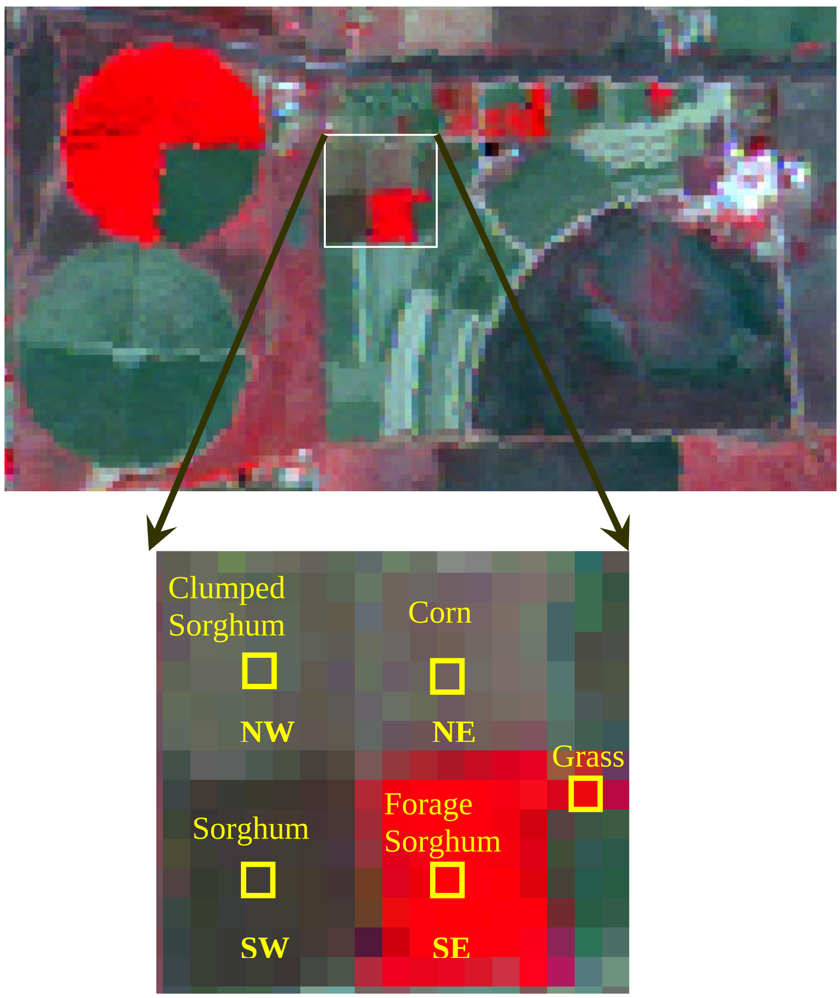


Figure 2. Landsat 5 TM false color image showing lysimeter locations at USDA-ARS-CPRL facility in Bushland, TX.

[3/] Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the United States Department of Agriculture.

Lysimeter Setup

Each of the four large lysimeters at Bushland contains monolithic Pullman clay loam soil core. Change in the soil water mass is used for determining ET values. Changes in lysimeters mass were determined using a data logger (model CR7-X, Campbell Scientific, Inc., Logan, UT) to measure and record the lysimeter load cell (model SM-50, Interface, Scottsdale, AZ) with the signal sampled at 0.17-Hz (every 6 s) frequency. The lysimeters calibration can be found in Howell et al. (1995). The lysimeter mass measurement accuracy in water depth equivalent was 0.01 mm, as indicated by the root mean squared error of calibration. The load cell signal was averaged for 5 min and composited to 60-min means. The lysimeter mass data were reported on the midpoint of the 60 min, that is, data were averaged from 0 to 60 min and reported at the midpoint of the averaging period. Daily ET was calculated as the difference between lysimeters mass recorded at 2330 h CST of one day and 2330 h CST of the next day to determine mass losses (from evaporation and transpiration) to which lysimeter mass gains (from irrigation or precipitation) were added. A vacuum pump regulated to -10 kPa provided drainage, and the drainage effluent was held in two tanks suspended from the lysimeters and weighed with lever-load cells.

Radiometric and atmospheric calibration of Satellite data

Landsat 5 TM imagery was obtained as digital numbers (DN) which were first converted into radiance (L_b), for each band as L_b= (gain x DN) + bias), then ‘at sensor’ or ‘Top-of-the-Atmosphere’ (TOA; exoatmospheric) reflectance values for the shortwave bands were estimated. Reflectance values were calculated by dividing the detected radiance at the satellite (for each band) by the incoming energy (radiance) in the same shortwave band. The incoming radiance is a function of mean solar exoatmospheric irradiance, solar incidence angle, and the inverse square of the relative earth-to-sun distance. In the case of the thermal band, the spectral radiance values were converted into effective at-satellite temperatures of the viewed earth-atmosphere system under an assumption of unity for surface emissivity and using pre-launch calibration constants by means of an inverted logarithmic formula. Detailed steps on the Landsat 5 TM radiometric calibration procedures can be found in Chander and Markham (2003). Subsequently, surface reflectance values were computed after applying atmospheric interference corrections, on the TOA reflectance image, for shortwave absorption and scattering using narrowband transmittance values for each band as calibrated by Tasumi et al. (2005) for METRIC; which obtains surface temperature after correcting the at-satellite effective ‘brightness’ temperatures for surface emissivity only. However, images were calibrated using MODTRAN v4 (Berk et al., 2000) for TSM and ATEB. With the MODTRAN procedure, thermal surface emissivity and atmospheric interference were accounted.

Remote Sensing based ET Algorithms

In this section, TSM, METRIC, and ATEB are described. Several sub-models are common in all and are described without specifying the name of the EB algorithm. However, we indicate model denomination where the EB sub-models are different.

In all three algorithms, ET is computed as a residual from the surface energy balance equation as an instantaneous ET or latent heat flux (LE) [Note: ET = LE ρ_w^{-1} λ_{LE}^{-1}, where ET is in mm d^{-1}, LE is in MJ m^{-2} d^{-1}, ρ_w is water density in Mg m^{-3} (~1.0 Mg m^{-3}), and λ_{LE} is the latent heat of vaporization in MJ kg^{-1} (~2.45 MJ kg^{-1})] for the time of the satellite overpass, as shown in Eqn. (1).

$$LE = R_n - G - H \quad (1)$$

where, R_n is net radiation (W m^{-2}), G is the soil heat flux (W m^{-2}) and H is the sensible heat flux (W m^{-2}). LE is converted to ET (mm h^{-1} or mm d^{-1}) by dividing it by the latent heat of vaporization (λ_{LE}; ~2.45 MJ kg^{-1}), density of water (ρ_w; ~1.0 Mg m^{-3}), and an appropriate time constant [Note: 1 W = 1 J s^{-1}]. The sign convention for the different flux terms in Eqn. (1) is positive from the land surface to the atmosphere (up) for LE and H, and positive towards the surface for R_n and into the ground (down) for G. R_n is calculated using surface reflectance and surface radiometric temperature (T_s) derived from satellite imagery, near surface vapor pressure from a near-by weather station (WS), and R_s as explained below. R_n is the result of the surface energy budget between short and long wave radiation terms [Eqn. (2) for METRIC, and Eqn. (3) for TSM and ATEB].

$$R_n = R_s \downarrow - \alpha R_s \downarrow + R_L \downarrow - R_L \uparrow - (1 - \varepsilon_o) R_L \downarrow \quad (2)$$

$$R_n = (1 - \alpha) R_s \downarrow + R_L \downarrow - R_L \uparrow \quad (3)$$

where, $R_s\downarrow$ is incoming shortwave radiation (W m^{-2}). $R_s\downarrow$ was measured with a pyranometer (model CMP 6, Kipp and Zonen, Bohemia, NY) installed at the ARS-Bushland weather station (TXHPET, 2006). Surface albedo (α) is a function of surface reflectance values in the shortwave portion of the electro-magnetic spectrum (a weighted average of reflectance in TM bands 1, 2, 3, 4, 5 and 7 for METRIC, and of bands 3 and 4 for TSM and ATEB; Brest and Goward, 1987), dimensionless; $R_L\downarrow$ is incoming long wave radiation (W m^{-2}) or downward thermal radiation flux originated from the atmosphere which was estimated using the Stefan-Boltzmann equation and near surface air temperature as well as vapor pressure for sky emissivity in TSM and ATEB. In METRIC, $R_L\downarrow$ is estimated using T_s and atmospheric (sky) thermal emissivity (which is a function of atmospheric transmissivity for shortwave radiation). $R_L\uparrow$ is outgoing long wave radiation (W m^{-2}), and ε_o is broad-band surface thermal emissivity (dimensionless). The ε_o term was calculated using empirical equations developed by Tasumi et al. (2005) based on remote sensing LAI estimates [Eqn. (4)] and based on soil and vegetation thermal spectral emissivities. The $(1-\varepsilon_o)R_L\downarrow$ term represents the fraction of incoming long wave radiation reflected from the surface, and $R_L\uparrow$ is the term that depends on broad band surface emissivity (function of biomass or leaf area index, LAI, presence) and T_s.

$$LAI = -\ln((0.69 - SAVI_{ID}) / 0.59) / 0.91 \quad (4)$$

where, $SAVI_{ID}$ is the Soil Adjusted Vegetation Index [(1 + L) (R-NIR) / (L + R+NIR)] calibrated for the soils of southern Idaho. It is an index that tries to remove soil background effects on vegetation indices. R is reflectance in the red band and NIR is reflectance in the near infrared band. L is a constant, equal to 1 for the soils of southern Idaho.

Soil heat flux (G) was modeled as a function of R_n, vegetation index, surface temperature, and surface albedo for near midday values (Bastiaanssen, 2000):

$$G = ((T_s - 273.15)\,(0.0038+0.0074\,\alpha)\,(1-0.98\,NDVI^4))\,R_n \quad (5)$$

where, NDVI is the Normalized Difference Vegetation Index [(R-NIR)/(R+NIR)].

Sensible heat flux (H) is defined by the bulk aerodynamic resistance equation, which uses aerodynamic temperature (T_{aero}) and aerodynamic resistance to heat transfer (r_{ah}):

$$H = \rho_a\,Cp_a\,(T_{aero} - T_a) / r_{ah} \quad (6)$$

where, ρ_a is air density (kg m^{-3}), Cp_a is specific heat of dry air (1,004 J kg^{-1} K^{-1}), T_a is average air temperature, (K), T_{aero} is average aerodynamic temperature (K), which is defined for a uniform surface as the temperature at the height of the zero plane displacement (d, m) plus the roughness length (Z_{oh}, m) for sensible heat transfer, and r_{ah} is aerodynamic resistance (s m^{-1}) to heat transfer from Z_{oh} to Z_m [height of wind speed measurement (m)].

In the case of ATEB model, Chávez et al. (2005) linearly correlated inverted T_{aero} from measured H values by a network of eddy covariance (EC) systems to T_s (ºC) and LAI (m^2 m^{-2}) derived from airborne remote sensing data, and measured T_a (ºC) and horizontal wind speed (U, m s^{-1}) on corn and soybean fields in central Iowa.

$$T_{aero} = 0.534\,T_s + 0.39\,T_a + 0.224\,LAI - 0.192\,U + 1.67 \quad (7)$$

Eqn. (7) resulted with a coefficient of determination of 0.77. LAI was spatially estimated using the THP-specific LAI model (Gowda et al., 2007b). Equation (8) shows the LAI model.

$$LAI = 8.768\,(NDVI)^{3.616} \quad (8)$$

In METRIC, H is estimated without needing to know T_a or T_{aero}, instead a temperature difference (dT), a function of T_s, was used as:

$$H = \rho_a Cp_a \frac{dT}{r_{ah}} \tag{9}$$

where, r_{ah} is calculated between two near surface heights, z_1 and z_2 (generally 0.1 and 2.0 m) using a wind speed extrapolated from some blending height above the ground surface (typically 100 to 200 m) and an iterative stability correction scheme for atmospheric heat transfer based on the Monin-Obhukov stability length scale ($L_{\_MO}$, similarity theory; Foken, 2006). In this study, a height of 200 m was used in the calculation of distributed friction velocity (u_*), a term utilized in the estimation of H.

Allen et al. (2007a) explained that dT (K) is a parameter that represents the near surface temperature difference between z_1 and z_2, and that the indexing of dT to T_s does not rely on absolute values of T_s, which allegedly reduces the error in calculating H substantially. Eqn. (10) characterizes the relationship of dT to T_s (Bastiaanssen, 1995).

$$dT = a + b\, T_s \tag{10}$$

where, *a* and *b* are empirically determined constants. The determination of *a* and *b* in Eqn. (10) involves locating a hot (dry) pixel in an agricultural field with large T_s and a cold (wet) pixel with a small T_s (typically one in an irrigated agricultural setting) in the remote sensing image. Once these pixels have been identified, the energy balance of Eqn. (1) can be solved for H_{cold} and H_{hot} as:

$$H_{cold} = (R_n - G)_{cold} - LE_{cold} \tag{11}$$

$$H_{hot} = (R_n - G)_{hot} - LE_{hot} \tag{12}$$

where, H_{hot} and H_{cold} are the sensible heat fluxes for the hot and cold pixels, respectively. The hot pixel is defined as having $LE_{hot} = 0$, i.e. no latent heat flux, which means that all available energy is partitioned to H. However, LE_{hot} may be non-zero and calculated according to a soil water budget if rainfall has occurred shortly before the image acquisition date. The cold pixel is assumed to have an LE value equal to 1.05 times that expected for a tall reference crop (i.e., alfalfa), thus LE_{cold} is set equal to 1.05 $ET_r\ \lambda_{LE}$, where ET_r is the hourly (or shorter time interval) tall reference (like alfalfa) ET calculated using the standardized ASCE Penman-Monteith equation. A 1.05 coefficient was used to estimate LE_{cold} as the cold pixels typically have an ET rate of 5% larger than that for the reference ET (ET_r) due to wet soil surface beneath a full vegetation canopy that will tend to increase the total ET rate (Allen et al., 2007a).

The hot pixel was chosen after careful screening of fallow/bare agricultural fields displaying high temperatures, high albedo, and low biomass (LAI). With the calculation of H_{hot} and $H_{cold,}$ Eqn. (9) was inverted to compute dT_{hot} and dT_{cold}. The '*a* and *b*' coefficients were then determined by fitting a line through the two pairs of values for dT and T_s from the hot and cold pixels. These *a* and *b* values were initial estimates that were used in an Iterative stability Correction (ISC) scheme programmed in a spreadsheet. After some iterations, the ISC shows numerical convergence and the *a* and *b* coefficient, for each iteration, were then exported to a model in ERDAS Imagine to obtain the final stability corrected H image.

Instantaneous LE raster image values were obtained using Eqn. (1) and were converted in METRIC to an hourly evapotranspiration rate, ET_i in mm h^{-1}, by division by λ_{LE} and ρ_w as:

$$ET_i = 3600\ LE / \{[2.501 - 0.00236\ (T_s - 273.15)]\ (10^6)\ (1.0) \qquad (13)$$

Reference ET fraction (ET_rF) is the ratio of ET_i to the reference ET_r that is computed from WS data at overpass time (hourly average). The WS information is explained in a subsequent section. Finally, the computation of daily or 24-h ET (ET_d), for each pixel, is performed as:

$$ET_d = ET_rF\ \ ET_r24 \qquad (14)$$

where, ET_r24 is the cumulative 24-h ET_r for the day (mm d^{-1}).

For the calculation of ET_r and ET_r24 for alfalfa, weather data recorded by the USDA-ARS (Bushland) reference WS located on a grass field was used (TXHPET, 2006). The TXHPET reported hourly and daily weather data for the calculation of the grass (ET_o) and alfalfa (ET_r) reference ET by means of the standardized ASCE Penman-Monteith method (Allen et al., 2005b).

In the TSM, H is estimated by adding the H values of the soil background (H_{so}) and the crop canopy (H_c) that were estimated separately considering a vegetation-soil parallel resistance network, Norman et al. (1995).

$$H = H_c + H_{so} \qquad (15)$$

$$H_c = \rho_a\ Cp_a\ (T_c - T_a) / r_{ah} \qquad (16)$$

$$H_{so} = \rho_a\ Cp_a\ (T_{so} - T_a) / (r_{ah}\ r_{so}) \qquad (17)$$

$$T_s = [f_c\ (T_c)^4 + (1 - f_c)\ (T_{so})^4]^{1/4} \qquad (18)$$

where, T_c is canopy temperature, T_{so} is soil temperature, r_{so} is the resistance to heat flow above the soil (s m^{-1}), and f_c is fractional vegetation cover (function of LAI). An initial estimation of H_c applying Priestly and Taylor (1972) is found. Then, this H_c value is used to derive an initial T_c inverting Eqn. (16) assuming neutral atmospheric condition. Subsequently, Eqn. (18) is inverted and solved for T_{so} and updated values of H_c and H_{so} are computed correcting r_{ah} for atmospheric stability. T_c and T_{so} are verified by testing the estimated LE for a negative value, in which case temperatures are not correct, and the soil is assumed to have a dry surface. A new iteration cycle is needed, in which LE is set to zero for the soil component, and H_{so} is re-calculated ignoring LE. A new T_{so} and T_c values are found and sensible heat flux components are again estimated.

TSM and ATEB models estimate ET_d (mm d^{-1}) as follows:

$$ET_d = 86{,}400\ [EF\ (R_n - G)_d] / (\lambda_{LE}\ \ \rho_w) \tag{19}$$

$$EF = [LE / (R_n - G)]_i \tag{20}$$

where, 86,400 is the number of seconds in one day, EF is the evaporative fraction (dimensionless). λ_{LE} was calculated to be 2.45 MJ kg^{-1} (function of T_a), ρ_w as1.0 Mg m^{-3}. The subscripts "i" in Eqn. (20) and "d" in Eqn. (19) denote instantaneous and daily fluxes respectively.

ET Estimation Evaluation

Three different EB algorithms were evaluated by comparing their estimated ET values to lysimeter data. In addition, RS estimated R_n was compared with measured values on five lysimeters.

Results stemming from the comparison of spatially estimated ET and ET with lysimeters data were reported as absolute differences and in percent errors:

$$\text{Difference (\%)} = (ET\_p - ET\_L) \times 100 / ET_r \tag{21}$$

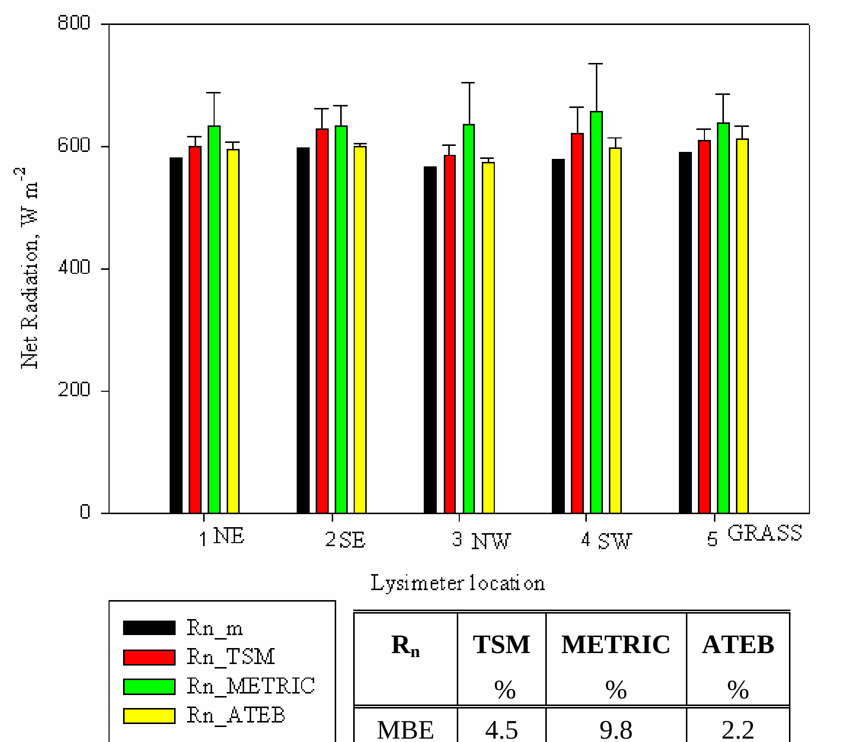
where, ET_p is the ET predicted and ET_L is the ET derived from water mass loss/gain data from lysimeters. ET_r is the alfalfa reference daily ET value acquired from the local Bushland-ARS weather station (TXHPET, 2006). A more comprehensive evaluation of ET estimation errors (comparison of estimated/measured ET) was carried out comparing 'mean bias error' (MBE) and 'root mean square error' (RMSE). These are the mean and standard deviation errors respectively.

Results and Discussion

Net Radiation Estimation

Remote sensing based R_n estimates resulted in larger bias for METRIC method. Its corresponding error was 56.8 ± 17.2 W m^{-2} (MBE ± RMSE) compared with 26.1 ± 10.9 W m^{-2} for the TSM, and 12.8 ± 7.4 W m^{-2} for the ATEB model. Figure 3 illustrates the comparison of three R_n estimates with measured values (Rn_m) in percent errors.

MBE for ATEB was 2.2% and was 7.6 % and 2.3 % lower than that for METRIC and TSM models. Standard deviation values of ATEB-estimated R_n were also small (1.3 %) compared to METRIC (3.1 %) and TSM (1.9 %). These results are an indication that using MODTRAN calibrated T_s and measured T_a and e, that it is possible to obtain more accurate spatially distributed R_n estimates.



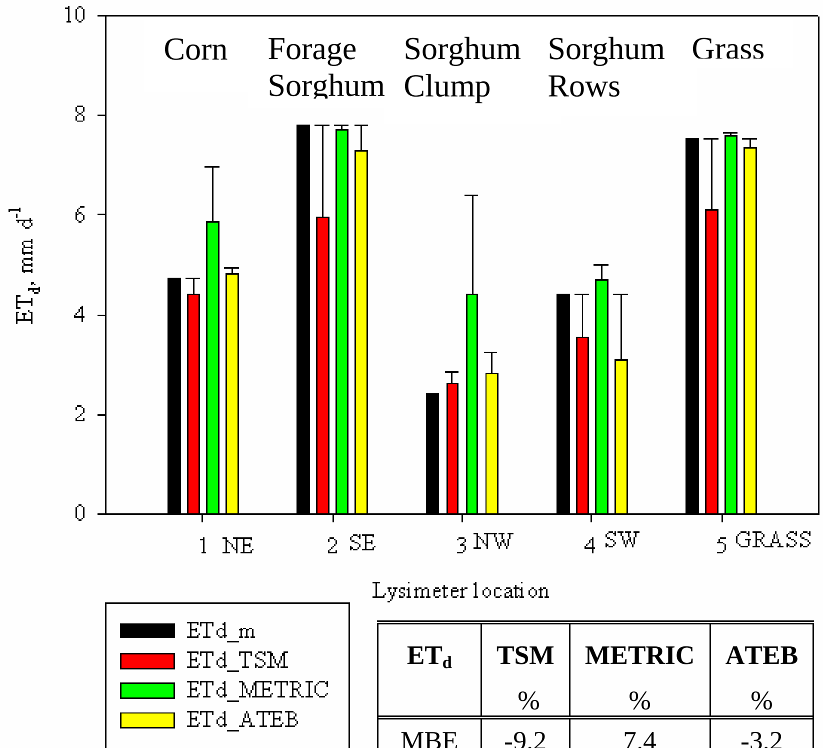
R_n	TSM %	METRIC %	ATEB %
MBE	4.5	9.8	2.2
RMSE	1.9	3.1	1.3

Figure 3. Net radiation estimates versus measured values showing error bars plus MBE and RMSE.

Overestimation of METRIC-based R_n compared to TSM or ATEB may be due to errors introduced in the computation of $R_{lw}\downarrow$ and $R_{lw}\uparrow$. In $R_{lw}\downarrow$ calculation, METRIC replaces T_a by T_s and estimates atmospheric (air) emissivity (ε_a) based on an estimation of atmospheric transmissivity that only uses ground elevation (respect to mean sea level) instead of T_a and actual vapor pressure, as in the Brutsaert (1975) model. In the Stefan-Boltzmann equation [$\varepsilon_a\ \sigma\ (T_a)^4$] used in the computation of $R_{lw}\downarrow$ if T_s is used instead of T_a ($T_s > T_a$ in our case), then a higher temperature will be raised to the power of 4 thus overestimating $R_{lw}\downarrow$ beyond the value that would have been estimated had T_a been used. The result is that adding $R_{lw}\downarrow$ to the shortwave net radiation [$(1- \alpha)\ R_s$] yields a higher sum had the proper temperature been used.

Daily ET Estimation

Comparison of estimated ET_d values with lysimeter data indicated that ET estimated using ATEB gave smaller errors (-0.3 ± 0.7 mm d^{-1} or -3.2 ± 7.2 %) followed by that estimated using TSM (-0.8 ± 0.8 mm d^{-1} or -9.2 ± 9.0%) and METRIC (0.7 ± 0.9 mm d^{-1} or 7.4 ± 9.5 %). Graphical comparison to measured values (ETd_m) can be found in Fig. 4. ET prediction bias was larger for the NW Lysimeter irrespective of the method used for deriving surface temperature. It may be partly due to errors in the estimation of aerodynamic resistance and surface roughness length for the clumped grain sorghum in NW lysimeter field as none of these methods have been calibrated for clumped crops.



ET_d	TSM %	METRIC %	ATEB %
MBE	-9.2	7.4	-3.2
RMSE	9.1	9.5	7.2

Figure 4. ET_d estimates versus measured values showing error bars plus MBE and RMSE.

TSM estimated ET_d with absolute error of -20 and 16 % for SE and grass lysimeters fields, respectively. Higher absolute errors were partly due to the fact that both sorghum and grass fields were irrigated and had larger LAI values (4.2 and 3.0 m^2 m^{-2} respectively). It is possible that the TSM under predicted LE from the soil layer under closed canopy conditions (full cover). In addition, the grass lysimeter field is smaller than the thermal pixel size on the Landsat image and was contaminated by surrounded dry and irrigated fields. METRIC, on the other hand, showed overestimation errors of 12 to 22 % for NE and NW lysimeters fields. The NE lysimeter field was late planted to corn and showed a low LAI value of 0.4 m^2 m^{-2} while NW lysimeter field planted to clumped grain sorghum had an LAI value of 0.3 m^2 m^{-2}. It seems that the dT function may have not scaled H properly for high T_s areas, i.e. drier and sparse vegetation areas, due to lack of atmospheric corrections on the at sensor (satellite) surface brightness temperatures. In the case of ATEB, the only ET_d estimation error larger than 10 % occurred on the SW lysimeters field (-14.1 %). This field was planted to grain sorghum and had an LAI value of approximately 0.5 m^2 m^{-2}. Considering that the SW field was bound by fallow fields to the south and west and by natural vegetation (dryland) to the south-west, it is likely that local advection occurred in larger proportions to the SW lysimeters field, thus causing a larger error in ET_d estimation using ATEB. This model performance exceeded expectations since it was calibrated for a different region and under different environmental conditions.

Evidence of heat advection was proved by METRIC at the cold pixel heat flux estimation. H at the cold pixel was estimated as being -65.7 W m^{-2}; for an average wind speed of 3.0 m s^{-1} at overpass time. This negative H value represents an 11.2 % greater heat energy (on top of the available energy (R_n – G)) that was added from local/regional advected heat; thus resulting in an enhancement of ET in the same magnitude.

Figure 5 illustrates the spatial variability of daily ET in and around the lysimeter fields, where the difference between irrigated and dryland regimes for sorghum and corn crops is evident within the lysimeters fields (rectangle). Estimated ET_d values were varied from 7.8 mm d^{-1} for the irrigated silage sorghum field (SE lysimeters area) to 4.3 mm d^{-1} for grain sorghum (SW lysimeter area). Estimated ET_d for the grass lysimeter field was 7.6 mm d^{-1}. Greater ET_d rates, up to 9.9 mm d^{-1}, can be observed on the centre pivot-irrigated silage sorghum (field survey) belonging to the commercial Johnson Farm located on the west of the lysimeters fields. In addition, ET_d was 7.2 – 7.8 mm d^{-1} for the sub-surface drip irrigation (SDI) irrigated corn plots to the east of the lysimeters fields.

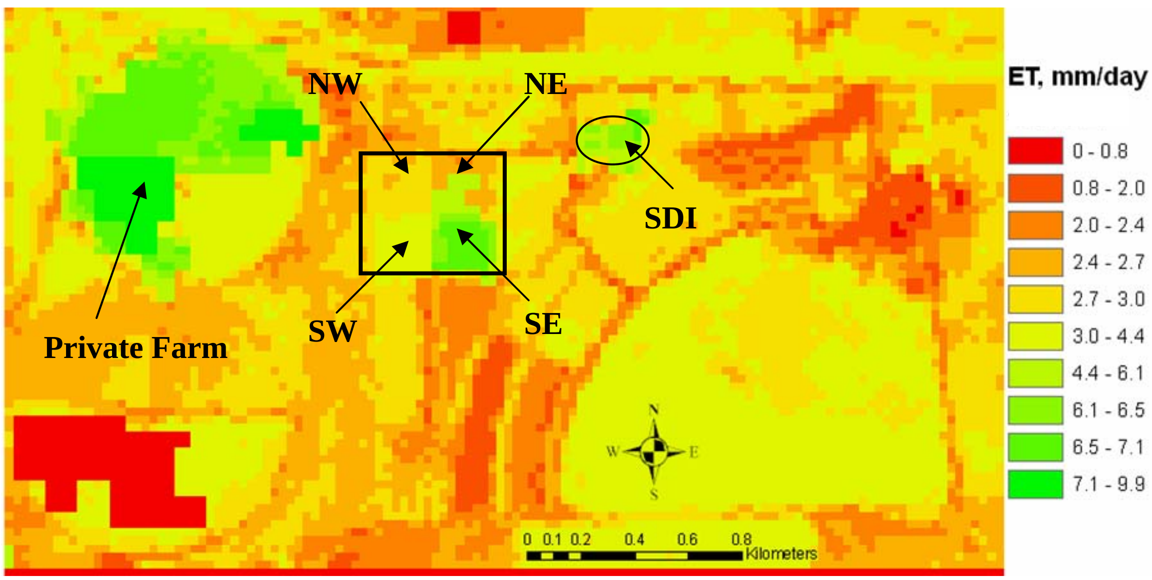


Figure 5. Spatially distributed daily ET on July 23, 2006 covering part of the USDA-ARS- CPRL and an adjoining private farm (centre pivots) to the west. SDI corn field shown by the oval polygon.

Conclusions

TSM, METRIC and ATEB algorithms were applied to the THP using a Landsat 5 TM image acquired on July 23, 2006 at 11:20 CST hours. Net radiation estimates using model ATEB more closely matched with measured values at lysimeters locations with MBE and RMSE values of 12.8 ± 7.4 W m^{-2} or 2.2 ± 1.3 % followed by the TSM (26.1 ± 10.9 W m^{-2} or 4.5 ± 1.9 %). METRIC showed a larger error of 56.8 ± 17.2 W m^{-2} (9.8 ± 3.1). METRIC's performance was most probably due to lack of atmospheric correction on the thermal imagery and use of T_s in place of T_a in the estimation of the incoming long wave component of R_n.

Estimated ET_d compared well with lysimeter data. ET estimated using ATEB yielded the smallest estimation error (-0.3 ± 0.7 mm d^{-1} or -3.2 ± 7.2 %) followed by TSM (-0.8 ± 0.8 mm d^{-1} or -9.2 ± 9.0 %), while METRIC prediction error was 0.7 ± 0.9 mm d^{-1} (7.4 ± 9.5 %). TSM showed larger errors on lysimeter fields with LAI values larger than 3.0 m^2 m^{-2} indicating that it works better for sparse vegetation conditions where some soil background is detected by the remote sensing system, since this model partitions T_s into canopy and soil surface temperatures. Full canopy covers may prevent TSM from discriminating between canopy and soil surface conditions. METRIC showed larger prediction errors on low/dry biomass conditions, most likely due to lack of atmospheric correction for the thermal imagery which corrects hotter pixels in greater proportion than cooler pixels. Finally, ATEB underestimated ET by 14 % on the SW field perhaps due to local advection since this field was bounded by dry and fallow land.

In conclusion, all three tested models performed satisfactorily although, TSM and METRIC algorithms are more computational intense and require skilled users. The ATEB exceeded expectations since it was developed and tested for humid regions. However, a thorough evaluation and perhaps a local calibration of this type of model is needed for the THP.

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Is Irrigation Real or Am I Imagining It?[*]

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Abstract

Irrigation is an ancient practice of applying water to crops and/or plants to sustain their life so they can be productive for their intended purpose. Through the years and into today's literature there are many terms such as "artificial irrigation" and "supplemental irrigation." We know irrigation is real, not artificial! We know ALL irrigation supplements either precipitation (or just rainfall) resources, ground water uptake by crops, or existing soil water resources. Other terms such as "limited irrigation" and "deficit irrigation" emerged in the 1960s to 1970s, while more recently newer terms like "partial root zone drying (PRZD)" and "regulated deficit irrigation (RDI)" have emerged. We propose that "artificial" not be used to describe irrigation. We recommend that "deficit irrigation" should be the preferred term rather than "limited irrigation." We describe "regulated deficit irrigation" and illustrated clearly its difference from "deficit irrigation." We describe "partial root zone drying" as an irrigation management strategy, but we believe PRZD will be effective mainly in improving crop quality of tree or vine crops. It is important that irrigation literature utilize "correct" terminology to describe current technologies.

Keywords: terminology, deficits, water potential, irrigation scheduling

Introduction

Irrigation is an ancient practice mentioned in the Bible, early Egyptian writings, and likely predates the birth of Christ as practiced in Mexico and Central America. Several terms are ingrained into irrigation literature that are ambiguous or unnecessary while other newer terms are often misused or misunderstood. This brief article discusses several of these terms in the current irrigation technology context.

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Artificial Irrigation
The term “artificial irrigation” permeates irrigation literature (e.g., Eternal Egypt, 2005; DeJonge and Kaleita, 2006; Zelles et al., 1987). For anyone that has donned irrigation boots, worked a shovel, set siphon tubes, moved pipelines, etc., there is little about irrigation, especially the labor, that is “artificial.” Yet, the term remains in relatively wide use today. It likely implies that sprinkler irrigation is like “artificial rain” instead of the term artificial irrigation used in most cases today. Nevertheless, it is a term that is unclear and confusing.

“Artificial” irrigation is in the language of the U.S. Statutes (U.S. Statute, 1877) that formed the basis for westward expansion of the U.S. to populate the land in 65 ha (160 ac) parcels in the western U.S. territories (that eventually became states) and thus rendered the land more productive and habitable. Even more recently, the U.S. EPA (Greening REPA, 2007) used the language “**Extensive Garden:** Extensive gardens have thinner soil depths and require less management and less structural support than intensive gardens. They do not require *artificial irrigation* {emphasis added}. Plants chosen for these gardens are low-maintenance, hardy species that do not have demanding habitat requirements. The goal of an extensive planting design is to have a self-sustaining plant community.” It was used before the U.S. Supreme Court (1905) in Lee et al. v. Nash “That said land of plaintiff above described is arid land and will not produce without *artificial irrigation* {emphasis added}, but that, with artificial irrigation, the same will produce abundantly of grain, vegetables, fruits, and hay.”

A Google (internet) search of the term “artificial irrigation” produced 38,000 hits. Clearly, “artificial irrigation” is simply irrigation. The Webster’s New Collegiate Dictionary (Webster’s NCD, 1980) defines “artificial” as “1, humanly contrived often on a natural model: man-made; 2, having existence in legal, economic, or political theory; 3, artful, cunning; 4a, feigned, assumed; 4b, lacking in natural quality; 4c, imitation, sham; 5, based on differential morphological characters not necessarily indicative of natural relationships.” One could argue that 1, 2, and 5 might fit appropriately as irrigation is designed, constructed, and operated by humans, at least the hardware/software; but irrigation is certainly genuine and not an imitation in terms of 3 or 4, although in some eyes irrigation is certainly artful! We argue that the adjective, “artificial”, adds marginally in describing irrigation. In fact, it likely detracts from the term “irrigation.”

Supplemental Irrigation
Equally permeating irrigation literature is the term “supplemental irrigation.” A Google (internet) search on this term reported 117,000 hits. The very nature of irrigation is to “supplement” the crop/plant water supply to achieve economic production. Clearly, in arid regions, little growing season rainfall occurs so irrigation supplies almost all crops water requirement with some additional water sources coming from ground water or harvested runoff (Oweis et al., 1999; Oweis and Hachum, 2006) or residual soil water. In more semi-arid regions, Oweis (1997) proposed adding small, but varying amounts of irrigation to traditionally dryland crops growing mainly on winter or pre-season stored soil water to improve crop yields and water productivity. Although the concept certainly has merit, we question its economic feasibility in regions to “spread” relatively small

amounts of water. In addition, the on-farm or infrastructure costs must be recaptured leading one to favor a more fully irrigated system that might be more sustainable. It is widely known that supplying even rather small irrigation amounts (~80-150 mm) at critical crop growth stages can dramatically improve crop yields and thus water productivity, yet the logistical protocols to perform this task may be impractical. Hence, we offer that all irrigation is "supplemental" in its basic sense although there are wide variations in the need, amount, and timing for the "supplemental" irrigation. We prefer to simply describe all irrigation as just "irrigation" without the adjective "supplemental".

Limited and Deficit Irrigation

The term "limited irrigation" is widely used but ambiguous. We don't know its exact origin. We both attribute it largely to the pioneering research on irrigation by the late Jack Musick at the Bushland USDA-ARS laboratory. He used it to imply a single or perhaps two seasonal irrigations timed at critical crop development growth stages using predominately furrow irrigation (Musick and Dusek, 1971). Basically, it was aimed at ground water irrigation where the producer knew that a farm or field had inadequate water to meet the crop demand. The literature on "limited irrigation" is quite jumbled from constraints on irrigation amount (volume per unit area) to constraints on irrigation capacity (flow rate per unit area). Although not specifically intended to augment dryland water availability (like with "supplemental irrigation"), "limited irrigation" assumes an irrigation infrastructure and water availability, albeit inadequate, and aims to pinpoint applications at the crop development stage known to be the most sensitive to soil water deficits. A Google (internet) search on the term "limited irrigation" returned 50,500 hits.

The term "limited irrigation" was basically analogous to the term "deficit irrigation" that Miller (Miller and Aarstad, 1976; Miller, 1977) used in the northwestern U.S. English (English and Nakamura, 1989; English, 1990) further characterized the term deficit irrigation. Deficit irrigation as characterized by English et al. (1990) has the fundamental goal to increase water use efficiency (WUE; another term we'll discuss later). They stated that the fundamental goal of "deficit irrigation" was to increase water use efficiency, either by reducing irrigation adequacy {i.e., not fully meeting the crop water requirement evenly} or by eliminating the least productive irrigations." Fereres and Soriano (2006) recently reviewed deficit irrigation and concluded that the level of irrigation supply should be 60-100% of full evapotranspiration (ET) needs in most cases to improve water productivity. They indicated "regulated deficit irrigation" (RDI; another term we'll discuss later) was successful in several cases, especially with fruit trees and vines, to not only increase water productivity but also farm profit. We conclude for many reasons that the term "deficit irrigation" should be preferred over the term "limited irrigation" in future literature.

In using "deficit irrigation", it is important to distinguish irrigation amount (volume per unit area) from irrigation capacity (flow rate per unit area) or both. These constraints might be physical (e.g., well flow rate for the later) or regulatory (e.g., a water right for the former). One inherent characteristic with "deficit irrigation" is that dependence on precipitation and/or soil water reserves to meet a significant proportion of the crop requirement. During the course of the irrigation season, soil water reserves may become nearly depleted. Thus, deficit irrigation usually has less applicability in arid regions where there is little precipitation for replenishment of soil water reserves. Additionally, rainfall is difficult to predict, non-uniform, and perhaps occurs at a rate that exceeds the soil infiltration, and can occur at a non-critical crop development growth stage. Hence, the need for irrigation is enhanced to reduce risk, increase yield, stabilize profits, and improve water productivity (Lamm et al., 1994).

Water Use Efficiency

The term "water use efficiency" (WUE) is likely one of the most widely used irrigation terms, but it also is largely misused as often, too. A Google (internet) search on this term returned 795,000 hits. The term was popularized by Viets (1966), but it is the inverse of the early transpiration ratio used in the late 19th and early 20th century. One problem with WUE is that it encompasses scales from cellular, leaf, plant to field and time scales from instantaneous to a season (Sinclair et al., 1984). Typically, WUE is the yield per unit evapotranspiration (Bos, 1979), and as such it really isn't an "efficiency" at all.

A better term for WUE gaining popularity is water productivity (Zwart and Bastiaanssen, 2004). "Water productivity" is basically the same definition as WUE and has the same spatial-, time-scale shortcomings but without the confusing "efficiency" terminology for basically a bio-physical term. Water productivity places the emphasis properly on the productivity from a unit of water without implying an incorrect efficiency concept.

Regulated Deficit Irrigation

"Regulated deficit irrigation" (RDI) has been successful in tree and vine crops to enhance yield and, especially, crop quality (Kreidemann and Goodwin, 1995). Jim Hardie (Cooperative Research Centre for Viticulture, Adelaide SA) defined RDI as "the practice of using irrigation to maintain plant water status within prescribed limits of deficit with respect to maximum water potential for a prescribed part or parts of the seasonal cycle of plant development. The aim in doing this is to control reproductive growth and development, vegetative growth and/or improve water use efficiency {water productivity}." RDI is similar to deficit irrigation, but RDI varies the deficit level by crop development growth stage to either enhance yield or quality. Implicit with RDI is an irrigation capacity sufficient to increase irrigation rate or volume, if required, to reduce the soil water deficit (greater plant water potential) at a specific crop development growth stage.

With RDI re-wetting frequency should be determined by detection or prediction of a decrease in plant water potential (or some plant water status measurement) below a prescribed set-point. For convenience and cost saving, this set-point could be inferred from soil water depletion or estimates of evapotranspiration based on weather conditions or direct measurement of stem/sap flow.

Often RDI is utilized with "partial root zone drying" (PRZD). Jim Hardie (Cooperative Research Centre for Viticulture, Adelaide SA) defined RRZD as "the practice of using irrigation to alternately wet and dry (at least) two spatially prescribed parts of the plant root system to simultaneously maintain plant water status at maximum water potential and control vegetative growth for specific crop development growth stages." These alternating wetting zones have controlled vegetative growth or improved water productivity or both while maintaining reproductive growth and development. The re-wetting frequency under PRZD should be based on the measurement or prediction of soil water uptake from the drying side. In practice, this can be accomplished by soil water measurements or estimates of evapotranspiration based on weather data or direct measurement of stem/sap flow. PRZD is impractical for center pivot sprinklers, unless LEPA (low-energy, precision application) drops are in every furrow and alternated. PRZD might be accomplished by alternating furrows in surface irrigation, but PRZD seems more practical with microirrigation. But even with microirrigation, PRZD would require almost double the lateral line installations (with the increased costs).

Both RDI and PRZD depend on measurement of actual plant water potential compared with a known or controlled site having a full-irrigation regime. In practice, PRZD success should not be based on whether or not reproductive growth, berry or fruit size or mass has been decreased because this seems unlikely if maximum plant turgor has been maintained. PRZD will result in a plant/crop deficit (i.e., sub-maximal plant water potential), however, because the irrigation applications to maintain maximum plant water potential throughout the wetting cycle will have insufficient re-watering frequency, insufficient irrigation application, insufficient infiltration, and insufficient size of the wetted zone relative to canopy size and evaporative demand (Kreidemann and Goodwin, 1995).

Several issues that impact PRZD applications are:

- Determination of the allowable or desirable set-point in plant water potential (or soil water depletion) for any departure from the fully irrigated site?
- Determination of the consequences of regional/site differences in vapor pressure deficit or evaporative demand, crop rooting characteristics, or soil water redistribution as they impact the daily range of plant water potential of plants under PRZD regimes?

(Kreidemann and Goodwin, 1995) summarized that "relation to water deficit strategies in general, a barrier to implementation, apart from lack of convenient plant based measures of water potential, appears to be the lack of broad recognition that plant stress is a quantifiable continuum and that any attempt to regulate the deficit to achieve plant responses must involve defining, measuring and controlling the stress within prescribed limits. Satisfactory implementation of deficit strategies in warm areas i.e. high vapor pressure deficit, generally requires responsive watering systems and soils with high infiltration rates." In general, in the U.S., few experiments have verified the success of PRZD, but RDI has had success in tree and vine crops to improve yield and especially quality while enhancing water productivity (Castel and Fereres, 1982; Goldhamer et al., 2006; Teviotdale et al., 2001).

Summary

We reviewed widely used historical irrigation terms like “artificial irrigation,” supplemental irrigation,” and “limited irrigation. We suggest the first two are not descriptive and add little to just “irrigation.” The third term has been largely replaced by the more descriptive term, “deficit irrigation;” however, it requires some clarification to the constraints (i.e., volumetric or capacity).

We believe the term “water use efficiency” (WUE) although still widely used should be replaced by the term “water productivity” as it doesn’t perpetuate the incorrect use of an “efficiency” name and emphasizes the positive aspects of crop yield per unit water.

Newer terms like “regulated deficit irrigation” (RDI) and “partial root zone drying” (PRZD) were discussed, and they each require a measure of direct plant/crop water potential (or at least soil water depletion and/or estimated crop evapotranspiration). PRZD requires knowing or estimating the state of a “fully irrigated” crop, as well. In our opinion, RDI is a specialized case of “deficit irrigation” with a crop development stage set point for irrigation management.

Acknowledgements

We recognize the literature cited is just a selected subset of the vast information resource on this topic. We did not intend the cited literature within to be exhaustive, or even representative, but it is simply a limited sampling that can lead readers to a much greater and extensive literature body on this topic.

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Drip and Furrow on Processing Tomato - Field Performance

Charles M. Burt[1] and Brian P. O'Neill[2]

Abstract: Data were collected from 187 conventional furrow-irrigated fields, as well as from 164 drip tape-irrigated fields in Westlands Water District. The study found that there is a significantly lower deep percolation with drip irrigated than with furrow irrigated fields. However, there was no significant difference in tomato yields between furrow and drip irrigated fields. This was not a before/after comparison of individual fields, but rather a comparison of data from distinct fields.

Introduction

In the spring of 2005, the Irrigation Training and Research Center (ITRC) of California Polytechnic State University, San Luis Obispo (Cal Poly) began a study into reducing drainage problems by using drip irrigation on tomatoes rather than using conventional sprinkler/furrow, or furrow irrigation.

The study was prompted by the environmental and economic concerns that arise from drainage disposal challenges. There is currently no known economical, technically feasible, and environmentally friendly drain water disposal method available for the west side of the San Joaquin Valley (Hanson and Ayars, 2002), although searches for solutions have been on-going for several decades. In Westlands Water District alone, more than

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200,000 acres have saline groundwater within 10 feet of the soil surface (WWD, 2004). Westlands Water District and other neighboring areas have recently seen a large movement by farmers towards subsurface drip irrigation (SDI) on processing tomatoes. SDI is expensive to install and maintain, but farmers have been convinced by considerable anecdotal evidence that using drip irrigation might improve yields and reduce applied water – thereby providing more "crop per drop" while simultaneously reducing drainage volumes.

Processing tomatoes grown in areas with a high water table, under high soil salinity, have yields that can be considerably higher than expected using conventional salt tolerance tables (Hanson, et al, 2006). Previous research in the San Joaquin Valley has found that drip systems can increase yields and reduce percolation below the root zone (Hanson and May, 2003a; Hanson et al 2006). Hanson and May (2003b) found that drip irrigation could significantly increase yield and profit on processing tomatoes. Internationally, similar results have been found in research comparing drip irrigation and other methods on tomatoes in the North China Plain (Wang et al, 2007), Ethiopia (Yohannes and Tadesse, 1998), and the Ebro Valley, Spain (Vasquez et al, 2006).

Prior to beginning the study, it was recognized that although one field under hypothetical irrigation treatment "A" might have better yield than another field under hypothetical treatment "B", the yield differences may have nothing to do with the treatments, themselves. Rather, yield differences may be due to soil variability, water table fluctuation, salinity, irrigation management, tomato variety, tomato planting date, etc.

differences. However, the budget and time did not allow for a standard research design with all variables controlled except irrigation treatment. Even if a standard replicated research design were to be used, the data would be limited to one or two fields.

In general, farmers have reported to us that when they convert to drip on processing tomatoes and have worked out the problems, yields under drip will outperform historical yields – in particular on problematic fields. But this study does not have the data to make that comparison of one field before (with conventional irrigation) and then afterward (with SDI). We definitely attempted to find fields with such data, but because there are so many different tomato varieties with such different harvesting/planting dates and such different yields (see **Table 1**), we found that we were not able to make that comparison.

Table 1. Processing tomato yields in 2004 with SDI from one grower.

Field	Variety	Reported Paid Tons/Acre
A	1	53.6
	1	54.4
B	2	57.4
	3	57.9
	4	49.5
C	5	57.5
D	6	60.3
	2	52.6
E	7	61.9
	3	58.3
F	8	53.9

However, we did obtain data from several hundred fields with a wide range of conditions, over multiple years. Those data do provide some interesting insights into drainage volume, water applications, and yields.

Data Collection/Organization

Fields

The sites selected for this study were all commercial processing tomato fields, located within the boundaries of Westlands Water District.

Typically, fields were treated with a sprinkler pre-irrigation, and sprinklers were used as the first irrigation after direct seeding or transplanting. After the initial irrigation, the fields were irrigated with the following irrigation methods:

- Furrow (gated pipe)
- Drip
    - Permanent Subsurface Drip (SDI)
    - Surface Drip (every row)
    - Surface Drip (every other row)

Data were collected from 187 conventionally-irrigated (furrow) fields, as well as 164 drip-irrigated fields. **Table 2** shows the number of fields examined, by year.

Table 2. Numbers of fields analyzed by irrigation method

			Drip					
	Furrow		Surface – Every Row		Surface – Every Other Row		SDI	
Year	Direct Seed	Transplant	Direct Seed	Transplant	Direct Seed	Transplant	Direct Seed	Transplant
2000	18							
2001	17							
2002	28						5	
2003	36						7	3
2004	62	5	8	0	31	5	24	3
2005	17	4	0	0	14	18	30	16
Totals	178	9	8	0	45	23	66	22

Estimating Deep Percolation

A water balance was developed for each field using the soil moisture depletion data collected in the field, the soil and water table maps, CIMIS data, crop coefficients developed at ITRC that account for soil evaporation as well as crop transpiration, etc. The water balance was only considered to be valid on fields that had a water table of more than five feet deep on sandy loam, and more than seven feet on clay loams, because the ET contribution of water from a high water table was deemed too difficult to quantify accurately.

Final Results

Deep Percolation

Table 3 provides the summarized values of deep percolation for various irrigation methods. There is a **highly significant** difference in the average Deep Percolation across the four methods. A one-way ANOVA rejects equality of means (F=4.344, df1=3, df2=349, p=.005) in favor of differing means.

Table 3. Deep percolation (DP) for different irrigation methods in Westlands WD.

Irrigation Method	Sub-category	# of Fields	Average D.P. (in)	Std. Error
Furrow	Furrow	187	8.1	.45
Drip	Surface Every Row**	8	3.9	.95
	Surface Every Other Row	68	6.4	.46
	Sub-Surface (SDI)	88	6.3	.53

**One grower with this method

Yields

An argument might be made that if drip yields are higher than furrow yields, then even if both irrigation methods use the same amount of water, there is true water conservation in the sense that more product is produced per unit of water consumed – i.e., "more crop per drop". However, there was not a **significant** difference in the average yield across the four methods. **Table 4** provides the summarized values of processing tomato yields. A one-way ANOVA cannot reject equality of means (F=1.493, df1=3, df2=349, p=.216) in favor of differing means. Again, one must realize that this was not the type of research design that compares identical fields and only changes one variable.

Table 4. Processing tomato yields.

Irrigation Method	Sub-Category	Number of Fields	Average Paid tons/acre	Std. Error
Furrow	Furrow	187	40.0	.58
Drip	Surface Every Row	8	45.2	2.60
	Surface Every Other Row	68	38.7	.26
	Sub-Surface	88	40.5	1.25

Yield vs. Water Applied

Figure 1 illustrates how Yield varied with Water Applied on the fields, comparing Furrow vs. Drip. The figure indicates that extreme cases of high irrigation water application tend to be more prevalent among Furrow fields than Drip-irrigated fields.

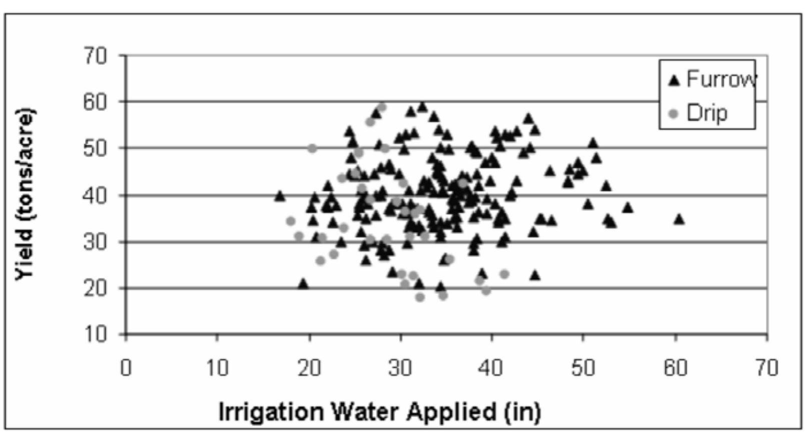

Figure 1. Tomato Yield vs. Irrigation Water Applied.

Conclusions

Data from a large number of commercial processing tomato fields in Westlands Water District in California showed that for these fields:

1. There was no significant difference in tomato yields, between furrow and drip.
2. There was less deep percolation with drip irrigation than with furrow irrigation.
3. Less grossly over-irrigated fields were found with drip than with furrow.
4. There is a large difference in yield between different tomato varieties, which indicates the importance of not extrapolating tomato yield data from a small number of fields.

Discussion

The second and third conclusions match common perceptions among farmers and the irrigation industry. Nevertheless, there is a relatively small difference in average water applied between the furrow and drip fields, and many furrow fields had excellent yields with low water applications.

The first conclusion will be troublesome to some farmers (who invest approximately $1000 - $1400/acre for drip systems on processing tomatoes) and many irrigation industry folks. There are several points to be made:

1. As mentioned several times, this data set is not equivalent to a data set that would be obtained from research that could eliminate all variability except the irrigation method. The data contained a wide range of farming techniques, tomato varieties, dates of planting and harvest, soils, water table depths, salinities, etc.

2. It is popular belief among farmers (and the senior author agrees without having good research data to back this up) that if one takes a field on poor soils and with a high water table, and shifts from furrow to drip, the yields tend to increase. The senior author knows several farmers who have consistently increased their average tomato yields from about 35-40 tons/acre to 50-60 tons/acre by shifting to drip on such fields.
3. One can conclusively state that:
    a. Having drip irrigation does not guarantee high yields or water savings.
    b. Some farmers have excellent yields with furrow irrigation, with excellent irrigation efficiencies.
    c. Some farmers have excellent yields with drip irrigation, with excellent irrigation efficiencies.
    d. Many farmers are convinced that drip irrigation has substantially increased their processing tomato yields on problem fields that were previously irrigated with furrow irrigation.

Acknowledgements

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Measuring water use and root distribution of drip irrigated watermelon in a humid climate using multi-sensor capacitance probes.

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Abstract.

Water for use by drip irrigated crops in a humid climate can come from both irrigation and rainfall. Scheduling irrigation using daily reference ET (ET_0) requires the use of rainfall data along with estimates of how much of the rain the crop can actually use. In mulched drip irrigation the contribution of rainfall to crop water uptake depends upon how much rainfall infiltrates into the volume of soil accessed by the roots. Multi-sensor capacitance probes (MCPs) measure near-continuous soil water content simultaneously at discrete depths. Replicated field studies on drip irrigated watermelon were conducted in Delaware using MCPs to measure water uptake under different irrigation amounts from different vertical and horizontal locations relative to the drip tape and the plastic mulch. Results indicate that the watermelon root system allows the crop to use significant amounts of rainfall, resulting in lower irrigation requirements than growers commonly apply.

Introduction

Drip irrigation in humid areas is difficult to manage because, unlike in arid areas, there are two potential sources of water. The first is irrigation, over which the grower has full control over timing and amount. The second water source is rainfall over which the grower has no control. In arid areas the rootzone of the crop is primarily limited to the volume of soil that is wetted by the irrigation, while in humid areas rainfall can wet the soil outside the volume wetted by irrigation. Rainfall can infiltrate the soil directly, but also runs off the plastic mulch to the edge where it is concentrated before it infiltrates. This infiltrated rainfall can contribute to crop water use if roots are present to use it. Rain can also enter the soil under the mulch through the planting holes (perhaps also channeled by stem flow) and through cuts and tears that may develop in the mulch. The lateral and vertical root distribution relative to the drip tape may therefore be affected by both irrigation management and rainfall patterns.

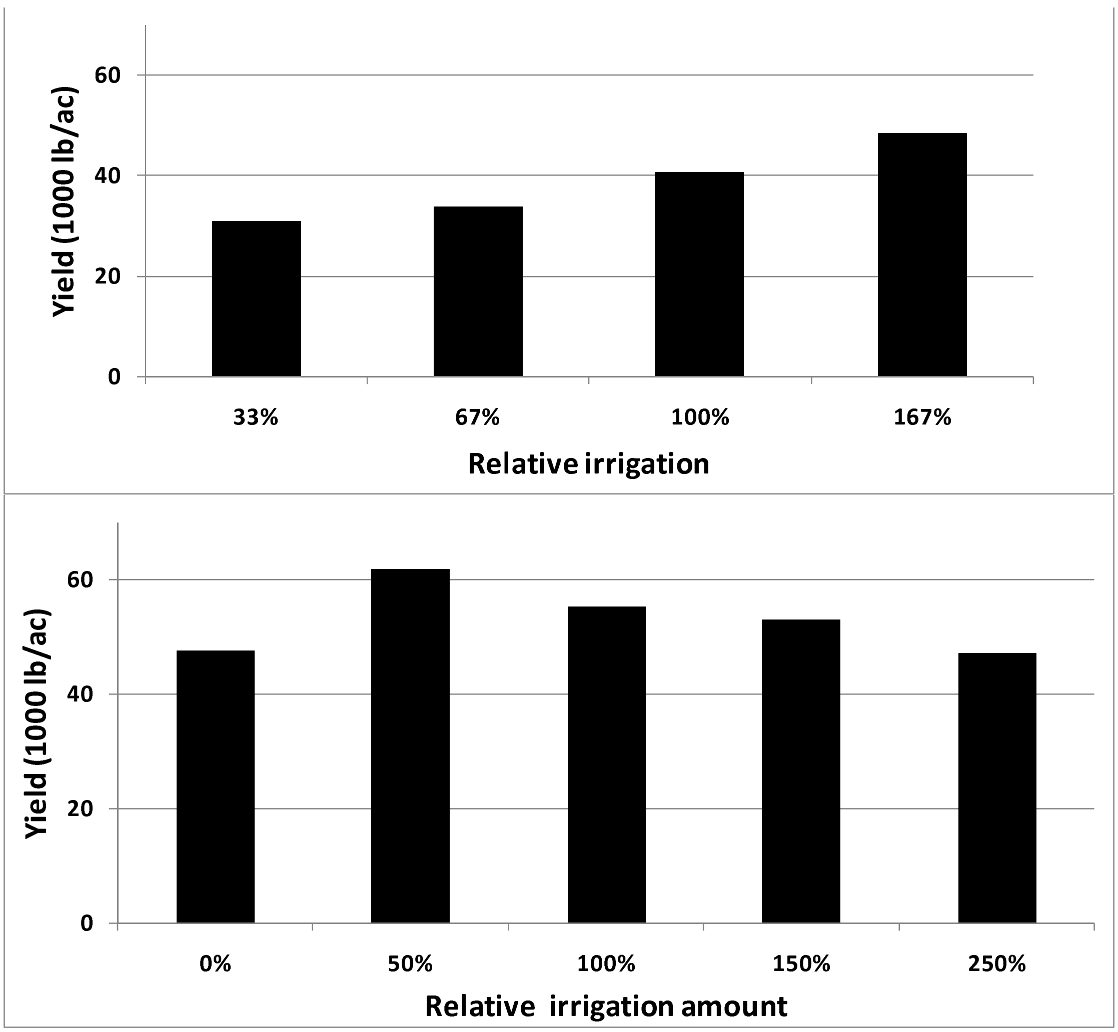

Figure 1. Yield of seedless watermelon as a function of relative irrigation amount in 2007 (top) and 2006 (bottom).

Figure 1 shows yield of seedless watermelon in 2006 and 2007 in experiments at the University of Delaware Research and Education Center in Georgetown, Delaware. Different relative irrigation amounts were used to try and determine the response of watermelon to irrigation. In both years the irrigation amount varied from deficient to excess. The 100% relative rate was determined using reference ET from a nearby weather station, and by continuous measurements of soil water content (SWC) to determine trends over time, with the purpose of maintaining soil water content within an optimal range. The other relative rates received irrigation amounts in proportion. In 2006 the deficient irrigation treatments included relative rates of 0% (no irrigation) and 50%, while in 2007 the deficient rates were 33% and 67%. The difference between 2006 and 2007 was in the rainfall during the season. In June 2006 rainfall totaled 13.4 inches, while in June 2007 the total was 2.6 inches. In July 2006 the total was 4.4 inches while in July 2007 there was 1.7 inches of rainfall. Thus, 2007 was much drier than 2006.

In 2006 the 50% irrigation rate had the highest yield (although the yields under all except 0% were not statistically different). The yield under 0% irrigation was still good, at 77% of the highest irrigated yield, and this yield was due entirely to rainfall. In 2007, the highest irrigation rate (167%) had the highest yield. There was no 0% treatment, but the lowest rate (33%) had the lowest yield (64% of the yield at the highest rate). Yields in 2007 were generally lower than in 2006.

Obtaining significant yield with reduced or no irrigation prompted this study. The relative yields as a function of relative irrigation indicate that rainfall can make a substantial contribution to crop water requirements, and this has implications for the development of improved irrigation management guidelines.

Methods

To attempt to quantify SWC and root distribution of mulched drip irrigated watermelon, we used multi-sensor capacitance probes (MCPs) located at three positions relative to the drip tape. The probes were located in the “center”, “fringe” and “edge” positions, as shown in figure 2. The fringe position was halfway from the center to the edge of the mulch, while the edge position was outside the mulch. The sensors were located at depth of 4, 8, 12, 20 and 28 inches relative to the surface, and automatically read every 10 minutes in 2006 and every 30 minutes in 2007. In 2006 we measured SWC under the 50%, 100% and 150% irrigation rates in three replications, while in 2007 we made measurements under the 33%, 67%, 100% and 167% treatments in two replications. Further details of the experimental setup can be found in McCann and Starr, 2006.

MCPs can be used to show daily water uptake patterns (eg. McCann and Starr, 2007; Townsend, 2007; and Thompson et al, 2007). On days when the only change in soil water content is from crop water uptake, there is a characteristic “stair stepping” pattern in which SWC decreases during the daytime and levels off during the nighttime.

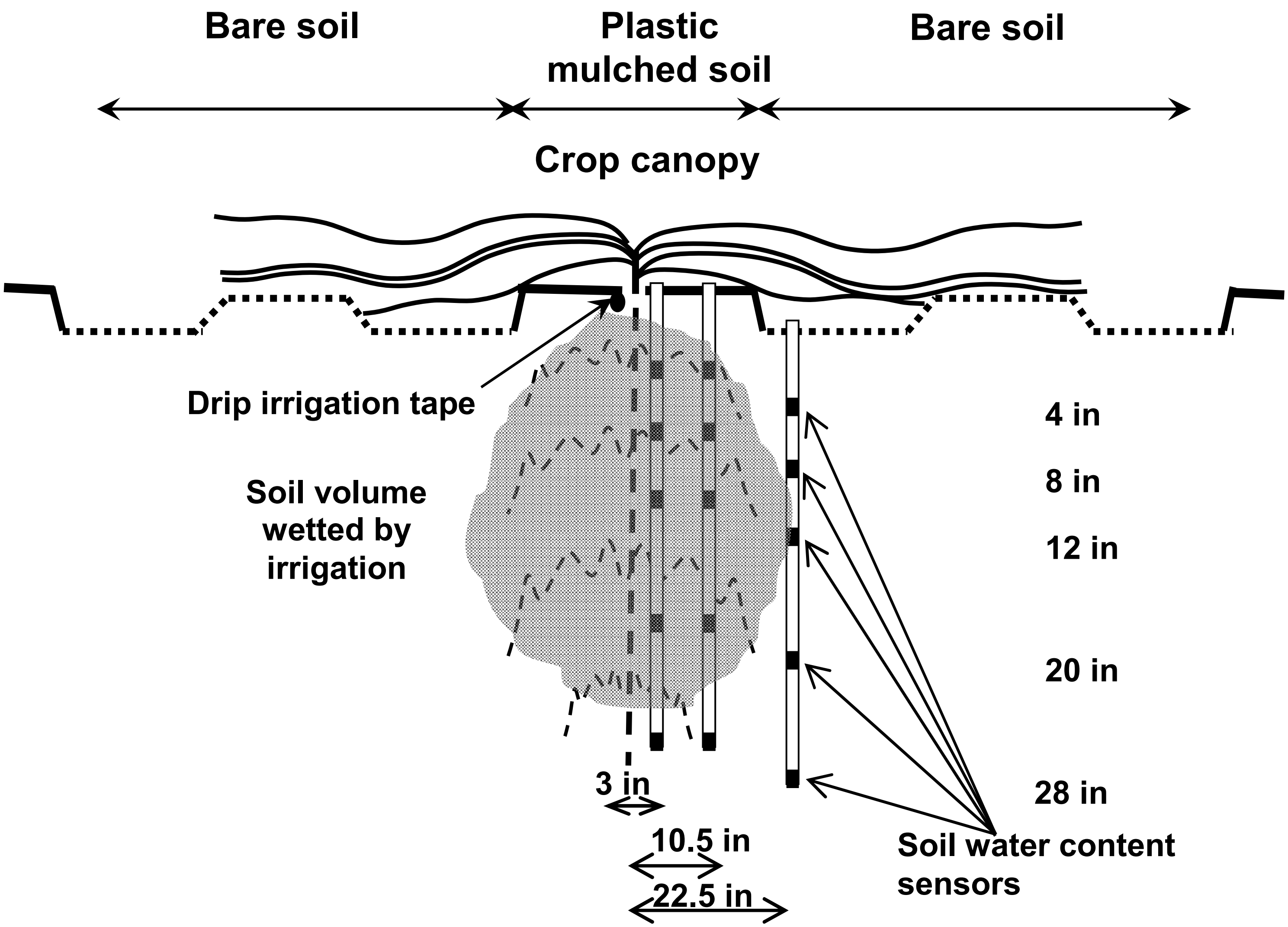

Figure 2. Plastic mulched drip irrigation of watermelon and layout of MCPs in 2006 and 2007. The center position and fringe position are in the mulched area, while the edge position is in the bare soil outside the mulch.

Results and discussion.

Figure 3 shows an example from 2006 that illustrates the “stair stepping” following an irrigation. The measured values of SWC are shown as a “stacked” graph in which the readings from the sensors are arranged from top (4 inches) to bottom (28 inches), each with a different scale so that they can be easily seen.

If stair stepping is evident, there must be active roots present. In figure 3, it can be seen that there are roots at the depth of the deepest sensor.

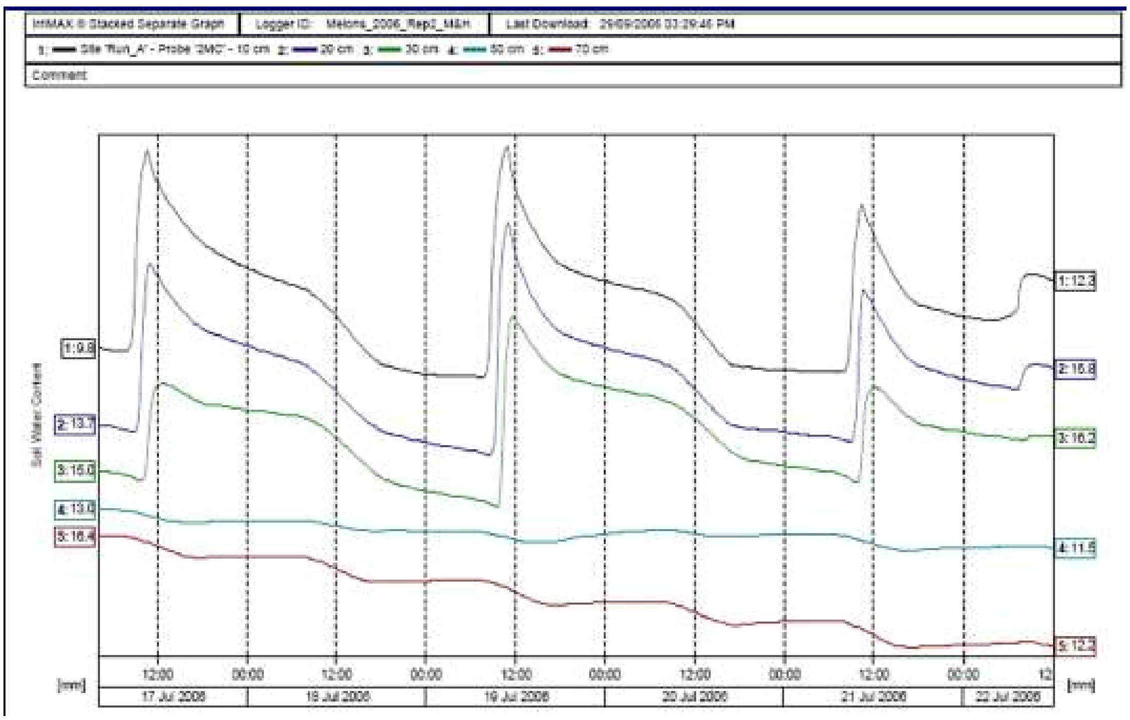

Figure 3. Example from 2006 of the “stair stepping” pattern of soil water depletion caused by crop water uptake during the daytime. The sensors are arranged from top (4 inches), through 8, 12 and 20 inches, to the bottom at 28 inches.

The magnitude of the decrease in SWC reflects the amount of water extracted from the soil surrounding the sensor. Each sensor represents a vertical cylinder of height from 5 cm below to 5 cm above the nominal depth of the measurement. Thus the 10 cm (4 inch) sensor represents a cylinder 10 cm in height extending from 5 to 15 cm depth. The sensors give measurements in units of % by volume, which corresponds to mm of water in the 10 cm cylinder.

If the decrease in SWC is summed in depth increments over the measured profile, (interpolating where necessary), the total decrease should be a function of the root density within the measured profile, and ET_0. Figure 4 shows such a sum for a probe at the center (top) and fringe position (bottom), for the 50%, 100% and 150% relative irrigation rates.

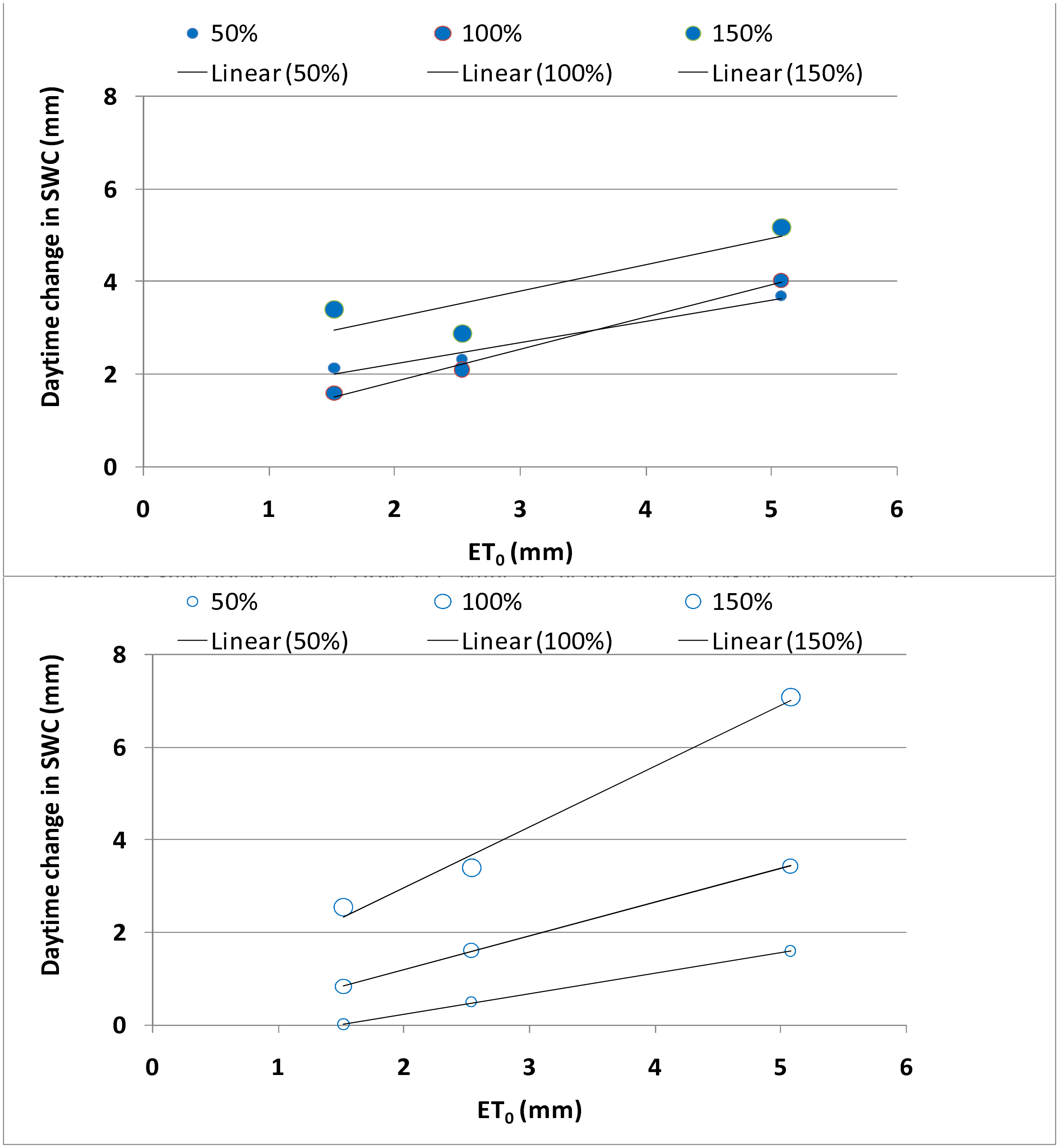

Figure 4. Change in SWC summed over the measured profile for the center position (top) and fringe position (bottom), for relative irrigation rates of 50%, 100% and 150%. The data are for 3 consecutive days following an irrigation and are plotted as a function of ET_0 on those days as estimated from weather data.

In this example, the decrease in SWC was greater at the center position under the 50% irrigation rate than at the fringe position. At the 100% rate the decrease in SWC was about the same at the center and fringe positions, whereas at the 150% rate the SWC decrease was greatest at the fringe position.   There is an approximately linear relationship between ET_0 and the decrease in SWC under all irrigation rates and at both positions.

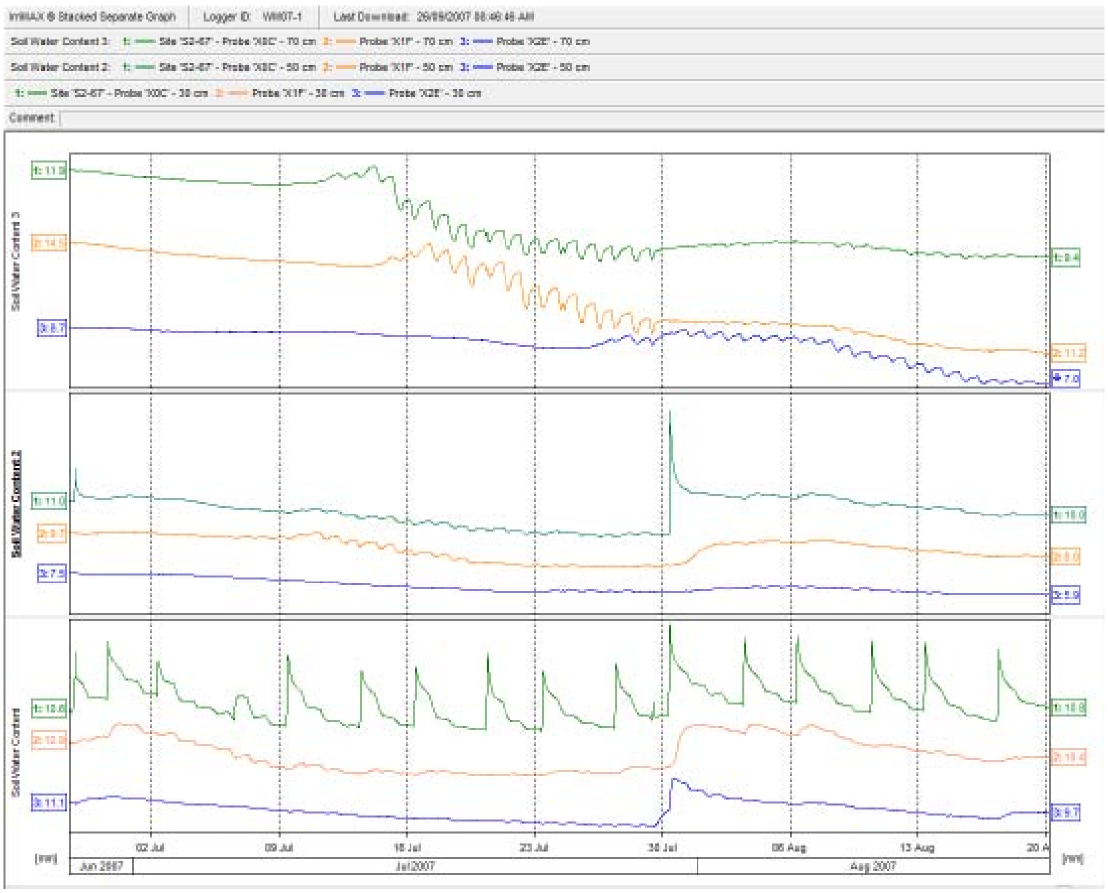

Figure 5. SWC measured at 70 cm (top), 50 cm (middle) and 30 cm (bottom) in 2007 under the 67% irrigation rate. Within each graph, the data are stacked with the center position at the top (green), the fringe position in the middle (red) and the edge position at the bottom (blue).

In figure 5, the fluctuations in SWC due to irrigations can be seen in the center position at 30 cm. A rainfall event at the end of July can also be seen that increased SWC at the edge position at 30 cm. There is some stair stepping at the edge position at all three depths, indicating that there is some root water uptake. At 70 cm, the stair stepping pattern begins first at the center position, but can be detected later at the fringe position and then at the edge position.

Figure 6 shows SWC at all five sensors at the edge position for the 33%, 67% and 100% irrigation rates in 2007. It can be seen that the rainfall event at the end of July penetrates

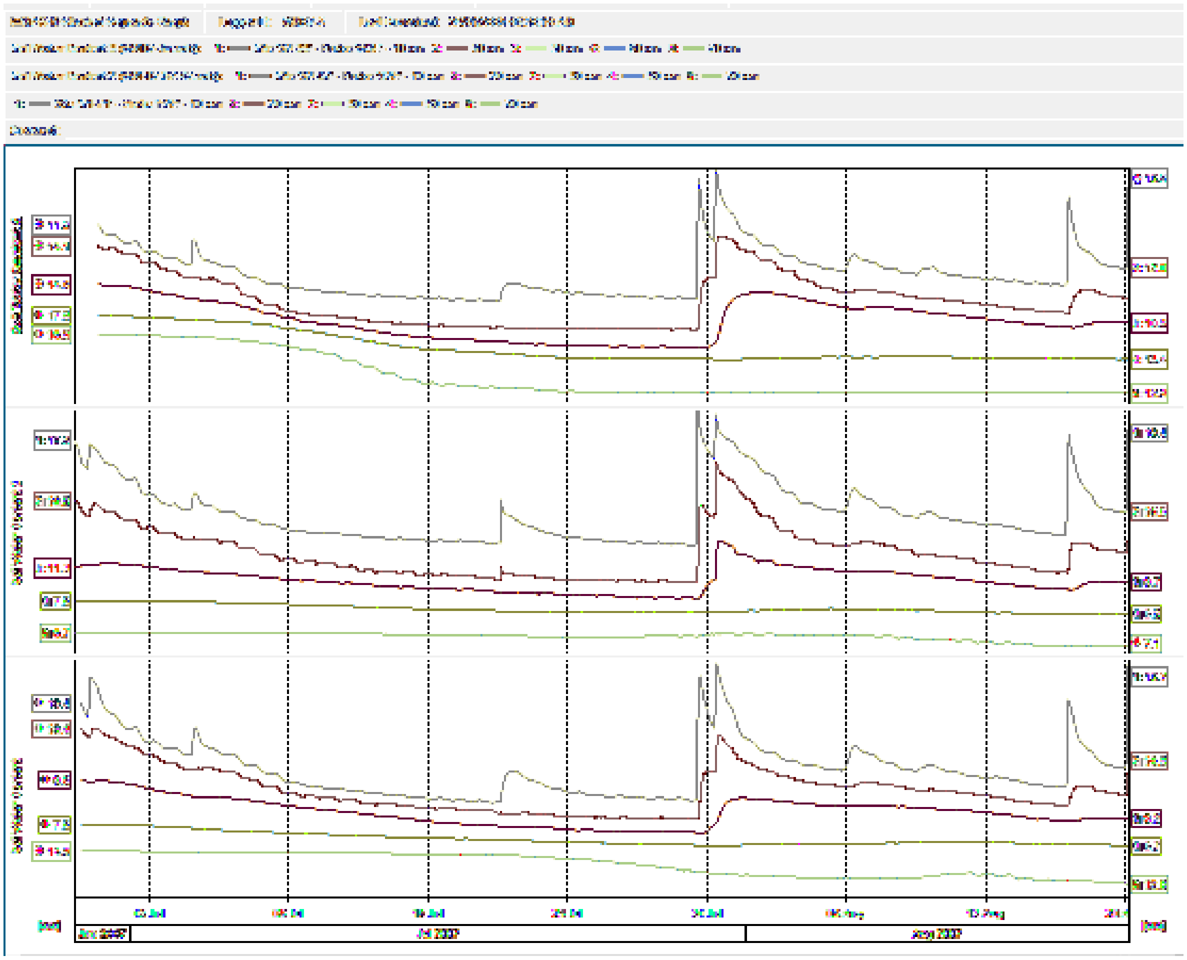

Figure 6. SWC measured at the edge position in 2007 for the 33% irrigation rate (top), the 67% rate (middle) and 100% rate (bottom). Within each graph, the data are stacked according to sensor depth with 10 cm at the top (blue), 20 cm (green), 30 cm (orange), 50 cm (purple) and 70 cm (red) at the bottom.the center position at the top (green), the fringe position in the middle (red) and the edge position at the bottom (blue).

to 30 cm in all cases. There is stair stepping evident at 10 cm, but this could be due to evaporation from the soil as well as root uptake. At deeper depths, evaporation would likely not be a significant cause of stair stepping. Under the 33% irrigation rate, root water uptake at 70 cm is more evident earlier in the season than it is under higher irrigation rates. Where there is some water stress, the crop may more actively develop a rooting system that is more extensive or deeper.

Conclusions

MCPs can detect root water uptake and may also be able to quantify crop water use, but further studies are necessary to investigate the complex dynamics of SWC under mulched drip irrigation.

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In-field evaluation of subsurface drip irrigation (SDI) systems in Kansas

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Kansas State University research on suitability of using subsurface drip irrigation (SDI) has shown it to be a feasible technology for field crops like corn. Present SDI acreage is estimated at 20,000 acres, most of which is in western Kansas. A recent survey indicated that most of the producers were either satisfied or very satisfied with their systems. Producers were asked if they would like an in-field evaluation of their systems. Many responded indicating willingness. Several systems were selected based on SDI system age and location. A few systems have been evaluated and more are underway. Results or findings will be presented in this paper.

Web Page: www.oznet.ksu.edu/sdi/Reports/2005/IA05-1209.pdf

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Use of Gravity Drip on the Navajo Nation

E. C. Martin[*] **D. M. Livingston**

ABSTRACT

Water supply and conveyance on the Navajo Nation is limited and many people are required to haul water for daily use from collection points. There are also large areas where electricity is not available. Simple drip irrigation systems offer an efficient water use solution for the cultivation of limited amounts of crops in rural areas without the need for a mainline water or electrical power supply. In this research, a two-year study was initiated in 2005 at the Hubbell Trading Post, a National Park Historic Site, located in Ganado, Arizona on the Navajo Nation. Drums filled with water supplied from a newly installed irrigation pipeline were used to feed low-pressure drip tape by gravity flow, in order to cultivate native corn. Gravity-fed drip irrigation systems were also set up in Tucson, AZ and Maricopa, AZ. Results from the Tucson and Maricopa sites showed that the systems could reliably provide irrigation water. By comparing three gravity-fed drip systems with a conventional surface irrigated plot at the Ganado, AZ site, yields of 3,675 kilograms per hectare (kg/ha) (average) and 4,011 kg/ha of dry grain were obtained with 663 mm (average) and 991 mm of water respectively in 2005. In 2005, surface water applied could only be estimated due to staff inexperience with the newly installed supply system. In 2006, using improved measurement techniques for the surface plot, yields of 3434 kg/ha (average) and 3301 kg/ha of dry grain were obtained with 704 mm (average) and 533 mm of water respectively for the drip and surface systems. Overall test results showed that acceptable corn yields could be achieved using inexpensive irrigation systems, very little labor, and a modest daily supply of water. Furthermore, results showed that the drip irrigation systems performed equally well compared to the surface plot.

BACKGROUND

The Hubbell Trading Post National Historic Site is located near Ganado on the Navajo Nation in Northeast Arizona. It is the oldest, continuously operated trading post on the Navajo Nation. The trading post was purchased by John Lorenzo Hubbell in 1878 and remained in the family until it was sold to the National Park Service (NPS) in 1967. The Trading Post site is located on 160 acres, one mile west of the small town of Ganado. In addition to the Trading post, there is a Visitor Center and the Hubbell home, all open to the public. The Trading post and historic site has become a key location within the Western Navajo Nation for both tourist and Navajo's alike.

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The irrigation system within the city of Ganado has recently been repaired and improved through the Ganado Irrigation and Water Conservation Project (GICP). The GICP was initiated and funded by several sources in the Federal Government and the Navajo Nation. Groups involved in a Memorandum of Understanding to collaborate in the development of agriculture in the Ganado valley included the Ganado Water Users Association, the Navajo Nation Department of Water Resources, the Navajo Nation Department of Agriculture, the Bureau of Indian Affairs (BIA), the Bureau of Reclamation (BOR), the Natural Resource Conservation Service (NRCS) and the National Park Service (NPS). Working through contracts with the BIA and Navajo Nation Department of Water Resources, the BOR began reconstruction and repair of the Ganado system. A total of $1.5 million was spent to upgrade the Ganado dam and the irrigation water delivery system. The goal is to re-establish agriculture in the Ganado area to a profitable enterprise.

METHODOLOGY

Experimental Site

The demonstration was conducted in 2005 and 2006 for a two-year period. Three sites were used to conduct the study. The irrigation systems used at all sites employed materials supplied by Chapin Watermatics, Inc. and Chapin Living Waters Foundation's Super Bucket Kit (Chapin Living Waters Foundation, 2007)[†].

Hubbell Trading Post Site

The main research site was located at the Hubbell Trading Post National Historic Site, located near Ganado, Arizona, on the Navajo Nation. The National Historic Site has a total area of 65 hectares and an elevation of 1932 m. The geographical location is at latitude 35° 42' 31" N and longitude 109° 33' 14" W. Two sets of soil samples from six depth increments (0-0.15, 0.15-0.30, 0.30-0.45, 0.45-0.60, 0.60-0.9, 0.9-1.2 m) were obtained by soil auger. The soil texture was classified using the Bouyoucos Method and Calgon Hydrometer (Bouyoucos, 1936), which determined the percentage of sand (2.0 to 0.050 mm), silt (0.050 to 0.002 mm) and clay (<0.002 mm) in each soil sample. The soil samples were first dispersed to separate aggregates into individual granules. The different particle size fractions were then determined by sedimentation. Sand sized particles settled out within 40 seconds, clay sized particles settled out within two hours, and after two hours only the silt fraction remained in suspension. For additional details see Bouyoucos (1936). The electroconductivity (EC) of the soil samples was measured by electrode. De-ionized water was added to a weighed amount of each soil sample. These were placed on a stirring rack at high speed for one hour, and then centrifuged for half an hour. The supernatant was decanted and the EC was measured in μS/cm using an Accumet EC cell 13-620-155 containing two coiled

[†] *Any products, services, or organizations that are mentioned, shown, or indirectly implied in this publication do not imply endorsement by The University of Arizona.*

contacts wrapped around a glass case separated by 1 cm. The conductivity was displayed on the Accumet Model 50 pH/Ion/Conductivity Meter. The EC of the irrigation water was measured using the same probe.

The layout of the National Historic Site and location of the research plots are indicated in Figure 1. The letter A shows the location of the Hubbell Trading Post buildings and the letter B shows the location of the agricultural field. Three replications of the drip-irrigated plots were used, each with dimensions of 6 m long and 4.5 m wide. The 6-meter long rows were oriented in a north-south direction and five lines of drip tape were laid out with a row spacing of 0.9 m, as shown in figure 2. The supply drum was located at the south end of the plot and was elevated 1.2 m above the ground. This layout was typical of all drip irrigation plots and research sites. The adjacent surface irrigated plot for comparison was laid out in an east west orientation with dimensions of 15 m long and 6 m wide. Figure 3 shows the layout of the three drip irrigated

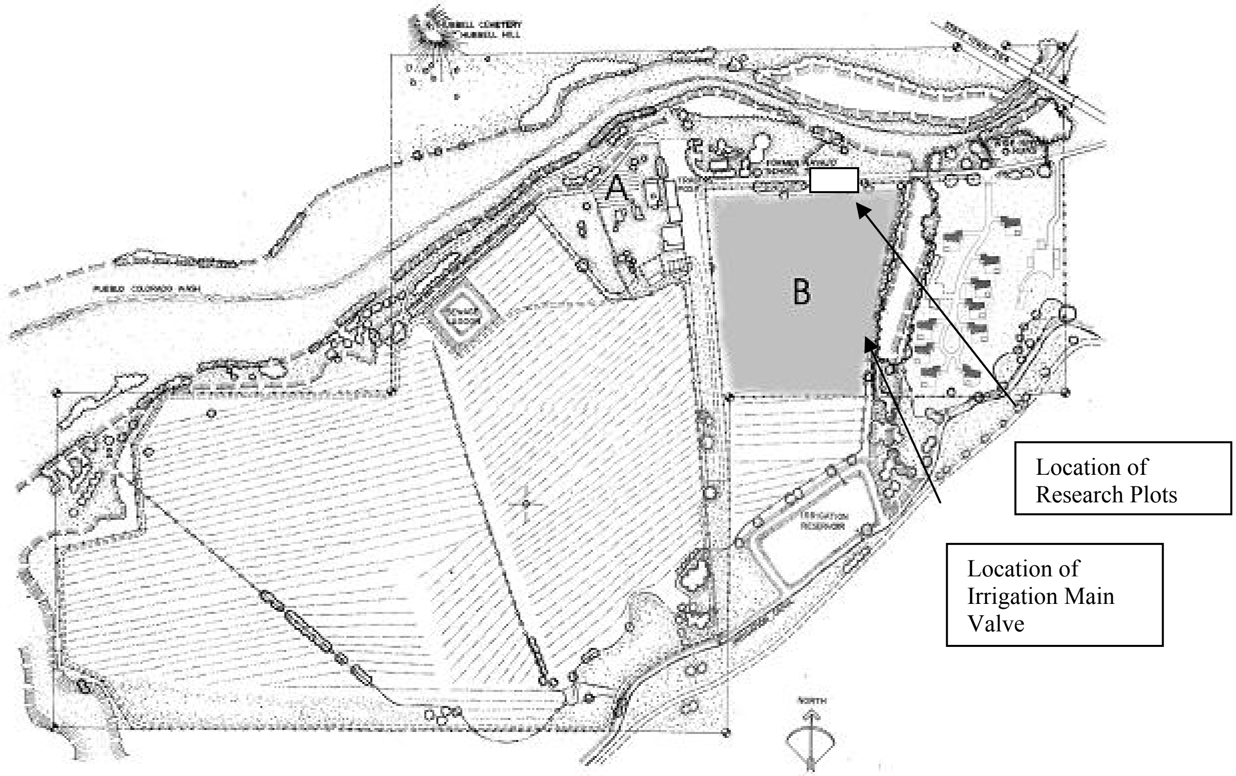


Figure 1. Layout of the Hubbell Trading Post National Historic Site with location of Hubbell Trading Post (A), Agricultural field (B) and location of research plots and irrigation main valve.

plots relative to the adjacent surface irrigated plot. In the first year, the surface plot was irrigated using a new gated pipe irrigation system installed by the Hubbell Trading Post. The surface plot was oriented to allow for direct irrigation from this system. Due to difficulties in measuring and controlling the water from the new irrigation system in 2005, a series of pipes and valves were connected downstream of a water meter in 2006 which allowed workers to irrigate parts of the plot as needed, and provided an accurate means of measuring water use.

Navajo White corn was planted on June 14th in 2005 and Navajo Yellow corn was planted on May 23rd in 2006. In both years, forage crops were grown on adjacent plots within the agricultural field on the Hubbell Trading Post property, which were grazed by sheep.

The field had not been cultivated for many years. The entire field was plowed, leveled and terraced prior to the 2005 season. Fertilizer in the form of horse manure was applied during the field preparation period. One east-west terrace was used to accommodate the three drip irrigated plots as well as the surface irrigated plot. Berms were constructed to prevent any water migrating from the other terraces onto the research plots. The irrigation water source was the Ganado reservoir, supplied to the Hubbell Trading Post site by the Ganado irrigation pipeline and Hubbell Trading Post irrigation lateral.

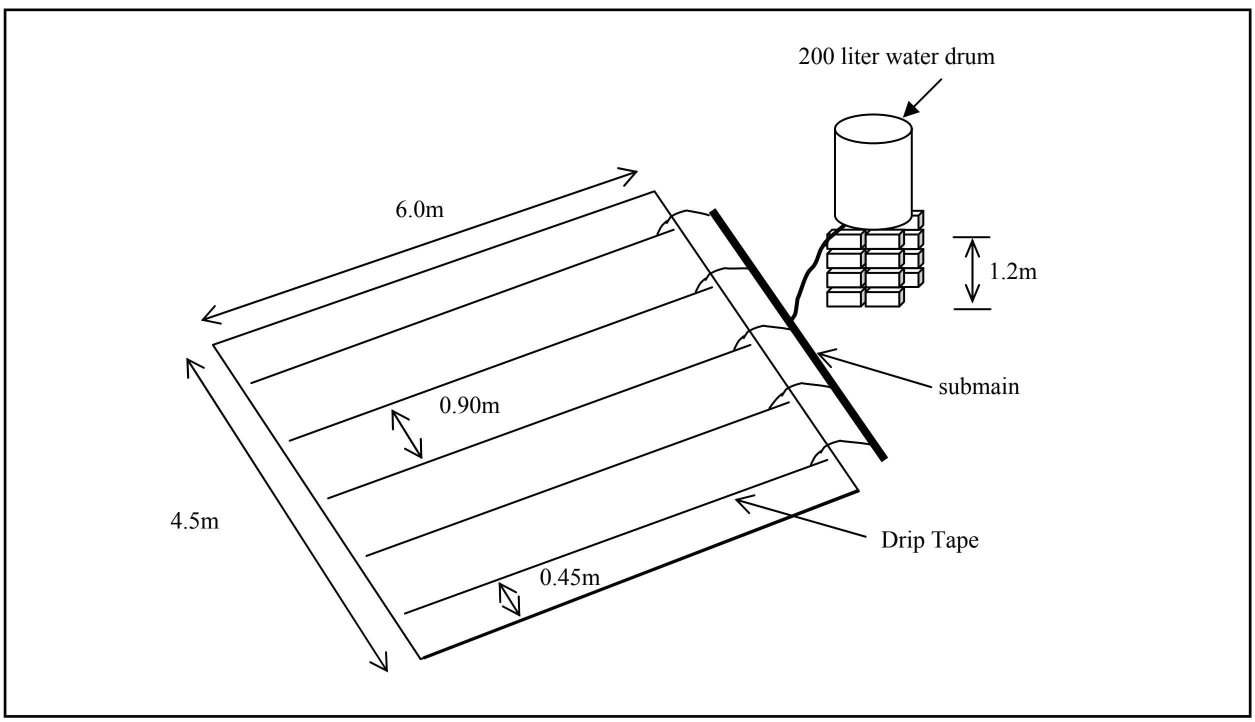


Figure 2: Layout of drip irrigation plots, typical for all plots and research sites.

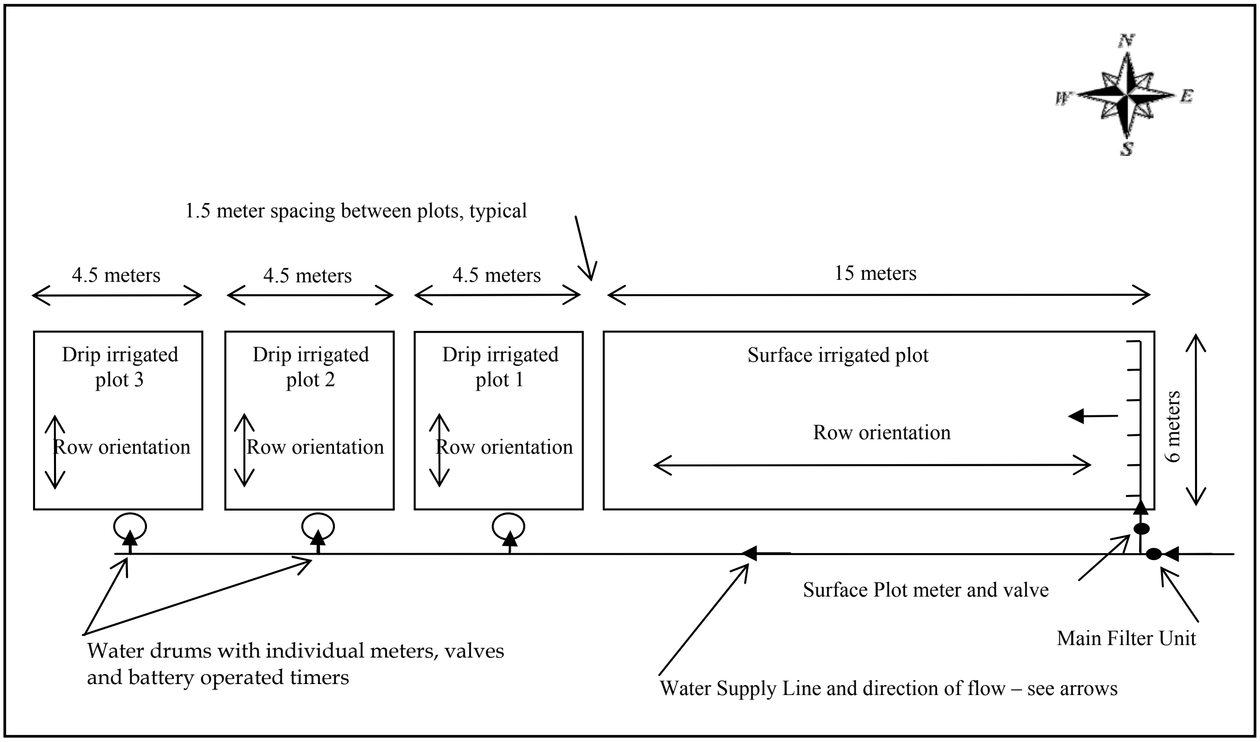


Figure 3: Layout of the drip irrigation plots relative to the surface irrigated plot, with row orientation. The surface plot water meter and valves were added in 2006. In 2005, the surface plot was irrigated by gated pipe, which ran along the eastern edge of the surface plot.

Water for the drip irrigation plots was taken from a connection point on the supply line located on the south-east corner of the agricultural field, immediately upstream of the main irrigation valve (Fig. 1) and was conveyed to the plots through approximately 275 m of 2.54 cm Schedule 40 Polyvinyl Chloride (PVC) pipe constructed for this project. Rainfall data were taken from the Ganado cooperative weather station data (NOAA, 2006). No rain monitoring equipment was set up at the site due to the periodic nature of field visits. Harvest dates were October 1st, 2005 and September 10th, 2006.

Equipment

All three of the drum irrigation systems were constructed of identical materials, with identical controls. Instrumentation was necessary in order to control daily watering intervals, avoid overflows, and monitor water use throughout the season.

Irrigation Drum

Recycled plastic drums were purchased from Sun West Container Company in Tucson, Arizona, a supplier of new and recycled drums. These drums were chosen on the basis of low cost, appropriate size for a daily watering volume, and durability to withstand transportation and handling stresses, as well as extreme heat and intense solar radiation experienced in Arizona.

The drums had previously been used for transporting food industry concentrates, and were equipped with two screw-in tops which had a molded 19 mm threaded outlet able to accept SCH 40 PVC fittings which made for easy attachment of valves as well as a leak-proof seal. The drums were used base-up in order to utilize these threaded connections as gravity fed outlets on the underside. A double outlet manifold was constructed from PVC fittings and was closed with two 13 mm PVC valves. A hole was cut in the base of the drum for access and an aluminum bracket was fabricated to hold a standard toilet cistern float valve assembly. The float valve was used as a failsafe check valve to prevent the drum overflowing in the event of timer failure. The aluminum bracket and float valve were bolted to the underside of the drum base adjacent to the access hole, and was adjusted using U-bolts for optimum float height.

Standard hoses and fittings were used to connect the stem of the float valve to a canister type filter unit and an automatic battery operated irrigation timer on the water inlet line which were fastened securely to the outside surface of the drum using U-bolts. The access hole was covered with a heavy rubber flap bolted in place on one side to allow flap access, and was designed to exclude insects, dust and other wind-borne debris. The drum was elevated to a height of 1.2m above the ground by fixing it on top of three columns of concrete blocks (each block sized 0.2 x 0.2 x 0.4 m), piled six high. The blocks were wired together for stability and the drums were held on top of the blocks with rubber ties stretched over the top of the drums. A view of the assembled drum is shown in figure 4, and the drums are shown in the installed position at the Hubbell Trading Post in figure 5. Figures 6 and 7 show the bracket holding the overflow prevention valve inside the drum, and the operation of the float valve respectively. Figure 8 shows the outlet valves which were used to connect the drum to the drip tape header using 8 mm tubing via slip-on connections.

Figure 4: View of the assembled irrigation drum.

Figure 5: View of the drums as installed at the Hubbell Trading Post research site.

Figure 6: Inside view of the irrigation drum showing the bracket holding the overflow prevention valve.

Figure 7: Overflow prevention valve operation: left picture shows float up (off) position, right picture shows float down (on) position.

Figure 8: Base of the irrigation drum showing PVC outlet valves and connections.

Irrigation Controller

A battery operated irrigation controller, inline spigot mounted type 62015 from Orbit, was used to control irrigation water applications (Fig. 9). The controls could be set to allow watering intervals of 2, 5, 10, 15, 30, 60, 90 and 120 minutes at set intervals between irrigation events of 2, 4, 8, or 12 hours, or daily, every second, third or fourth day, or once weekly. Initial tests showed that a drum would fill in less than 15 minutes at typical city water supply pressure and in approximately 25 minutes at pressure on the irrigation pipeline at the Hubbell Trading post. Being limited to the set times on the device a fill interval of 30 minutes was used (greater than the fill time of the drum), and the float valve was used to prevent overflow. At the end of the 30-minute interval the timer closed the main valve mechanically. As the outlet valves to the drip tubing were typically left in the open position, irrigation would begin as soon as the drum started to fill and the plots typically received more than a full drum of water on each irrigation event, being fed from the start of filling until the drums emptied.

Figure 9: Spigot Mounted Inline Irrigation Water Controller, model 62015 by Orbit.

Water Meter

In order to measure daily water use and cumulative water use for the season DLJ Hose Bibb Water Meters were installed on each system (Fig. 10). The water meters are accurate to standards specified by the American Water Works Association (AWWA). The water meters contain course mesh filters to exclude large debris from the unit and had to be checked at intervals. Standard 13 mm threaded male and female connections on the water meters allowed easy connection to hose fittings and automatic irrigation timers.

Figure 10: DLJ Hose Bibb (Sill Cock) Water Meter with 13 mm Garden Hose Thread inlet and Outlet.

Inline Filter

In 2005 small inline canister type filter units with removable screen filter tubes were used on each system (Fig. 11). In 2006 a much larger screen filter unit was used in the supply line upstream of all three systems at the Hubbell Trading Post (Fig. 12). This was done to reduce filter cleaning to one filter instead of three and provide a larger filter mesh area.

Figure 11: Thirteen mm MIPT 'Y' Irrigation Filter with threaded Cap.

Figure 12: Aquarius Brands Incorporated 5.1 cm T-type screen filter with bottom outlet for quick flushing.

Drip Tape

The Chapin drip tape used is sold as a kit specifically for use on small plots and is part of the Super Bucket Kit (Chapin Living Water Foundation, 2007). The drip tape is constructed from durable 15 mil plastic and is sold as a 90-meter roll of flat tape with precision laser-cut emitter slits every 30 cm. Inside the twin walled drip tape is a strip containing 10,000 filters per 30-meter length, which keeps water flowing in a turbulent flow regime and provides a self-cleaning function. The zig-zag pattern of this filter mechanism also helps to maintain a uniform pressure throughout the drip tape length (Fig. 13).

Figure 13: Section of Chapin Drip tape showing a slit emitter and the zig-zag pattern of filter within the twin-walled drip tape. Source: Chapin Watermatics Inc., 2007.

The kit includes 8 mm tubing for making the connection between the drum and the header tubing, as well as smaller diameter 5 mm tubing, which connects the header tubing to the drip tape. A larger 40 mm diameter section of tubing is used as a header for connecting a number of rows of drip tape to the irrigation source. All connections are made by inserting the small diameter tubing into holes in the drip tape and header tubing made with a sharpened nail of appropriate size (Fig. 14) which forms a watertight seal without the need for special fittings or connections.

Figure 14: Holes for inserting tubing are made by inserting a nail at 45 degrees through one side of the tubing and twisting. Source: Chapin Watermatics Inc., 2007.

The ends of the drip tape and header tubing are terminated by folding the tubing over itself and inserting the folded end into a short sleeve piece of the same tubing (Fig. 15).

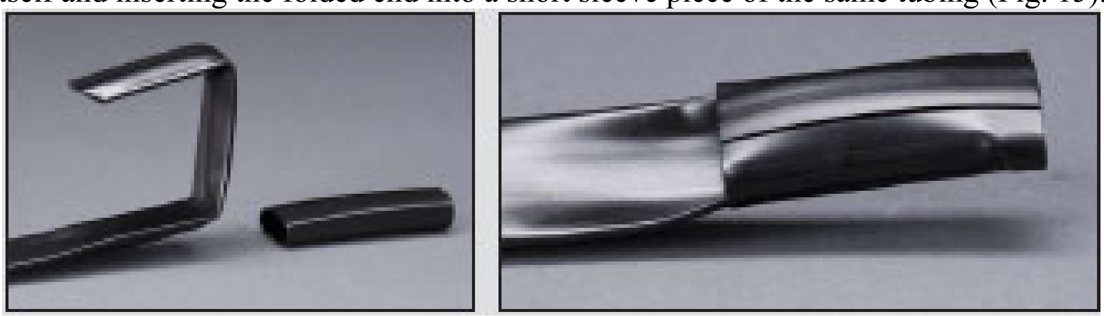


Figure 15: Ends of drip tape are terminated by folding the drip tape twice and inserting into a sleeve made of a short piece of the same drip tape. Source: Chapin Watermatics Inc, 2007.

These connections were found to be watertight and reliable. The drip tape was installed on the top of the ground with the emitters upward which help to prevent clogging by reducing the risk of suspended material in the water settling out and clogging the emitters.

Field Work

Installation of Supply Line

The 2.54 cm PVC supply line for the Hubbell research plots was laid along the historical surface irrigation ditch, which ran due north on the eastern side of the property. This amounted to approximately 275 m of piping. Individual control valves were installed for each system, and a main shut-off valve was installed at the tie-in point to the Hubbell Trading Post irrigation main valve at the south-east corner of the field (Fig. 1).

System Set-up and planting

The plots were leveled and measured out. Drip tape was cut and terminated, aligned north/south and connections were made to the submain. The drums were elevated (1.2m) on blocks and securely fastened. Meters, filters and automatic timers were connected together and tied into the supply line. Connections were made between the drum valves and the submain and all connections were tested for leaks. In 2005 the surface plots were irrigated using the newly installed gated pipe system. Unfortunately, problems with flow measurements made it difficult to determine accurately the amount of water applied to the surface plots. In 2006, the surface irrigation system for the surface plot was replaced with a furrow planting configuration with individual control valves at the head of each furrow as shown in Figure 16.

Planting in the drip irrigated plots was done by placing two seeds every 15 cm along the drip tape at a depth of 2.5 cm. Seeds were planted adjacent to each emitter and halfway between each emitter. Planting in the surface irrigated plot was done according to traditional Navajo methods of placing about 5-10 seeds in holes at intervals of approximately 0.6 m along the row. This traditional method of clumping the seeds together is thought to provide redundancy in case of plant death in the early stages, as well as protection for individual plants and less competition for soil moisture due to the greater spacing than used in conventional irrigated agriculture. Six rows of corn were planted in this way.

In 2005 and 2006, the drip irrigation systems were set up to water daily for 30 minutes each morning in order to provide 0.71 cm of water (maximum daily irrigation requirement at peak season) calculated for the entire plot area. This irrigation scheduling was increased in mid season by applying two drums of water per day (approximately 1.4 cm per day) due to plant requirements. In 2006, in an attempt to make more efficient use of water, a stepped approach to irrigation was used. One drum of water was applied daily in the initial growth period and two drums were applied daily from mid season until harvest. In both seasons, the surface irrigated plot was controlled by the agricultural crew at the Hubbell Trading Post and water was applied as needed.

The drums were washed out between the two growing seasons, and new drip tape was used in the second season. For research purposes it was thought best to use new drip tape in each season in order to more accurately compare results.

System Maintenance and Checking

System maintenance and data verification was done at approximately two-week intervals during the growing season. System maintenance included: observation of system operation, cleaning of filters, checking drip tape for leaks or blockages, timer maintenance, verification of data sheets, checking plant growth and monitoring for pests and disease, and discussion of any problems encountered by the Hubbell Trading

Post staff. The decision to increase the amount of water applied to the plots was based on field observations of plant conditions and soil moisture content.

Figure 16: Individual control valves at the head of each furrow, Hubbell surface plot, 2006.

Harvesting

Entire plants were harvested for analysis of dry plant biomass and dry kernel weight produced. Three separate samples of two-meter row length each were harvested from the surface irrigated plot according to a random sampling procedure which dictated the starting point for sampling. The outer rows were not sampled in order to avoid edge effect and samples were not taken from the first or last meter in any row for the same reason.

The drip irrigated plots were sampled in a similar way with the outer rows being excluded. A random row number was generated from the inner three rows and plants were harvested from a two-meter length in the center of the randomly chosen row. Once again this was done to avoid edge effect from the ends of the rows as well as from the two outside rows.

The full wet weight of plants (leaves and stalks) was measured, as well the weight of ears produced within the sample. The plant matter was sub-sampled and dried in ovens at 65 degrees Celsius. The ratio of wet to dry weight of the sub-sample allowed calculation of total dry biomass produced from each two-meter sample. The total number of ears in each sample were dried and shucked and the resulting kernels were weighed after being removed from the cob. A calculation was made for grain produced per m^2 and subsequent extrapolation for grain produced per hectare. As row spacing was 0.9 m, a two-meter long row sample was calculated as using 1.8 m^2 of field surface. The grain weight produced from each sample was converted to a kg/ha yield for general comparison.

Data Collection

The staff of the Hubbell Trading Post used bi-weekly record sheets to monitor daily water applied for the three drip irrigation systems and the surface irrigated plot by taking readings directly from the water meters. These data sheets were normally faxed once a week for checking in Tucson. The flow trends allowed monitoring of the daily operation of each system and frequency of irrigation events on the surface plot. This method of data collection was used to ensure daily monitoring of the systems for leaks or other damage, as well as for monitoring of effective operation of the irrigation controllers. Data was checked and verified at approximately two-week intervals by site visits throughout the growing seasons.

RESULTS AND DISCUSSION

Collection of data was done manually by regular visits to each site and by tabulating the water meter readings. The corn was sampled prior to general harvesting at the end of each growing season and each sample was dried and weighed to determine total dry plant matter produced and total dry kernel weight.

Results

One of the objectives of the study was to identify a simple gravity-fed drip system that could operate reliably, effectively and efficiently on the Navajo Nation. Observation of the working systems allowed appraisal of reliability and effectiveness of the systems in producing a corn crop. Comparison of harvest data with a surface irrigated plot at the Hubbell Trading Post location was done to determine if drip irrigation was an efficient means of irrigation in corn production. To accomplish this, harvest weights from the drip irrigated plots were compared to harvest weights from the surface irrigated plot.

Soil and Water Analysis

Soil samples from the Hubbell Trading Post were analyzed for soil texture using the Bouyoucos Method (Calgon Hydrometer). Two sets of samples were taken to an augured depth of 150 cm in the center of both the surface irrigated plot and the drip irrigated plots. Analysis of the soil samples yielded the results shown in table 1.

Table 1: Results of Hubbell Trading Post soil analysis using the Calgon Hydrometer

Plot	Sample Depth	% Sand	% Clay	% Silt	Soil Texture (Bouyoucos Method)
Drip Plot	0-15 cm	41	45	15	Clay
	15-30 cm	41	43	17	Clay
	30-60 cm	26	50	25	Clay
	60-90 cm	0	76	25	Clay
	90 –120 cm	28	58	15	Clay
	120-150 cm	33	50	17	Clay
Surface Plot	0-15 cm	46	43	12	Sandy Clay
	15-30 cm	44	45	12	Clay
	30-60 cm	44	43	14	Clay
	60-90 cm	0	68	32	Clay
	90 –120 cm	0	76	24	Clay
	120-150 cm	49	38	14	Sandy Clay

These results, when plotted on a standard USDA soil texture classification triangle determined the soil type to be mainly clay textured with some sandy-clay soil texture evident from surface to a depth of 15 cm and from 120 cm to 150 cm. The same soil samples were analyzed for soil EC and results are shown in table 2.

Table 2: Results of Hubbell Trading Post soil analysis for soil EC.

Sample	Depth (cm)	Soil EC (dS/m)
Surface Plot	10 – 15	0.40
	15 – 30	0.28
	30 – 60	0.29
	60 – 90	0.58
	90 – 120	0.32
	120 – 150	0.59
Drip Plots	10 – 15	0.34
	15 – 30	0.28
	30 – 60	0.29
	60 – 90	0.39
	90 – 120	0.69
	120 – 150	0.66

The results of the soil EC data show that the soil does not represent a significant concern with respect to salt content for corn production. According to Ayers and Westcot (1994), corn can be grown in soil with an EC of 1.7 dS/m without any reduction in yield. Table 3 shows the EC data recorded for the irrigation water used at Hubbell.

Table 3: Electrical Conductivity (EC) measurements on water samples.

Site	Hubbell Drip Irrigation	Hubbell Surface Irrigation
Water Source	Ganado Reservoir	Ganado Reservoir
2005 EC (dS/m)	0.37	NA
2006 EC (dS/m)	0.24	0.33

NA = Not available

Irrigation Water Applications

The daily water applications for the drip plots were calculated according to a maximum daily requirement for hybrid corn of 0.71 cm per day for the month of July (NMSU, 2005). Irrigation data from the New Mexico State University Plant Science Extension service was used, which is based on cultivation of hybrid varieties at Farmington, NM. This was the closest comparable site growing corn for which published data were available.

The 200-L drum was used in order to supply the daily irrigation requirement of 0.71 cm to the drip irrigated plots with one fill of the drum per day. After planting, the automatic timers were set to fill the drums once each day. In 2005 it became evident from wilting that plants were not receiving adequate water and the timers were reset on July 20th to supply two drums per day (Day 36 after planting). On scouting the field, morphological symptoms such as leaf rolling, limp leaves and dry soil in the top five centimeters were taken as indicators of moisture stress. In order to maintain similar conditions on all three drip plots, it was easier to control water applications by complete drum fills rather than by a timed interval, as the three systems operated at different rates of fill. Irrigating with two drum fills per day amounted to a daily irrigation depth of 1.42 cm.

Due to plugging of the drip tape in the second half of the season which caused the drums to drain more slowly through the drip tape, as well as blockages in the filter systems and supply, the practice of using two drums per day was continued to harvest in order to supply sufficient water to the crop. Figure 17 shows the cumulative water applied for the three Hubbell drip irrigated sites in 2005. Irrigation of the Hubbell surface irrigated plot could only be estimated from the number of irrigation events and the estimated depth irrigated on each event as no water metering device was used and staff were unfamiliar with the gated pipe system which caused some flooding in early season, as well as making it difficult to calculate precise delivery rates. A total 991 mm irrigation water (estimated) was applied during the season.

In 2006, an attempt was made to be more efficient with irrigation scheduling. The timers were initially set to supply one drum per day after planting. It was thought that this would be increased to two drums per day in mid season and back to one drum per day in late season. Research was done into daily water use by corn by stage of development. Figure 18 shows a daily consumptive water use curve for corn (Evans et al, 1996). On this curve, a sharp increase in water use is noted when the corn reaches knee height. There is a higher consumptive water use throughout the vegetative growth phase, tasseling, silking and production of the corn ear. Following this curve, irrigation frequency was increased from one drum per day to two per day on August 7th 2006 (Day 47 after planting). Due to plugging of the drip emitters the daily water applied to the plots was restricted and the irrigation frequency was maintained at two drums per day in order to supply sufficient water to the plants.

Figure 19a and 19b show the cumulative water applied for the three drip irrigated sites in 2006. On day 46 the water meter for Drip System 1 was installed backwards by mistake after cleaning and the meter counted backwards until day 62 at which point it was installed correctly again. The meter appeared to then count higher flow than normal. The numbers reported for Drip System 1 between day 46 and day 76 are estimated based on meter readings prior to day 46. Figure 19a shows the actual readings for the drip systems and Figure 19b shows the actual readings for drip systems 2 and 3 and the estimated readings for drip system 1.

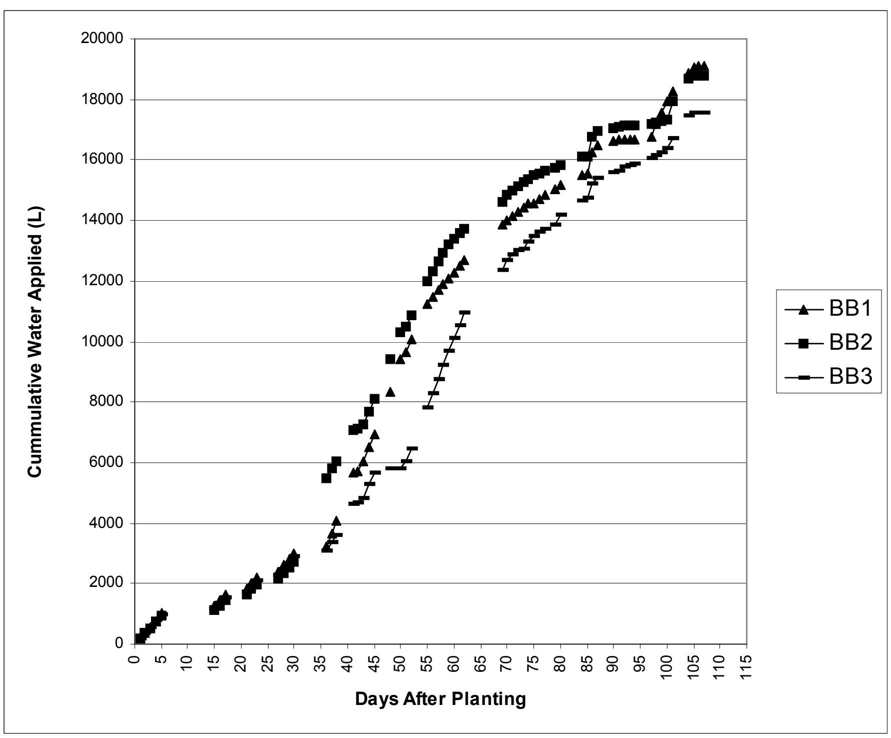


Figure 17: Cumulative water applied for Hubbell Drip Systems 1 through 3 in 2005. BB1= Hubbell Drip Plot 1, BB2=Hubbell Drip plot 2, BB3=Hubbell Drip plot 3.

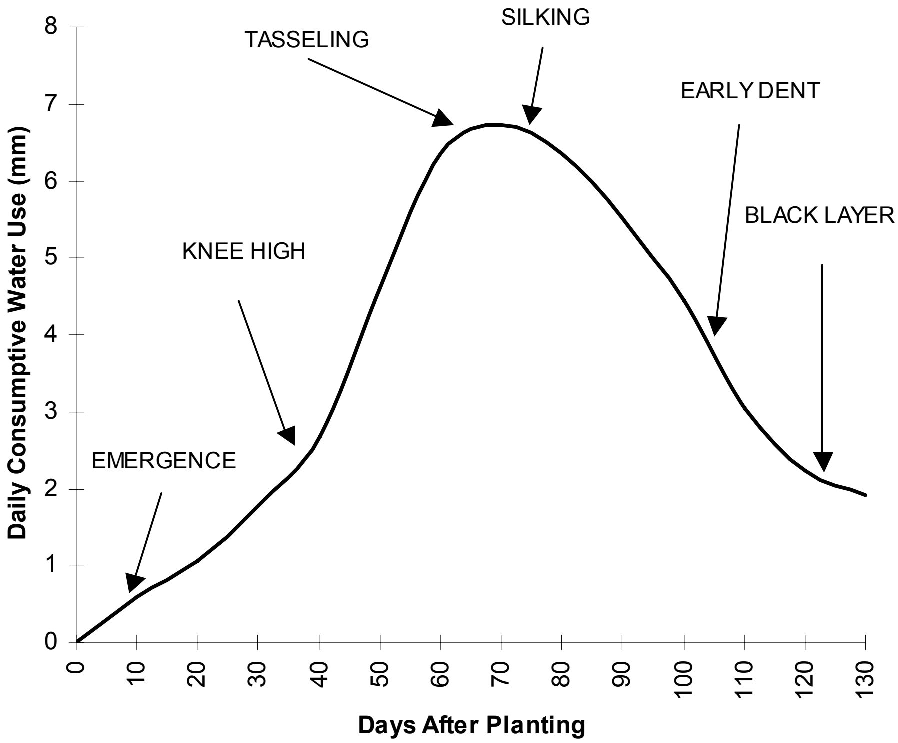


Figure 18: Daily consumptive water use for corn (Modified from Evans et al, 1996).

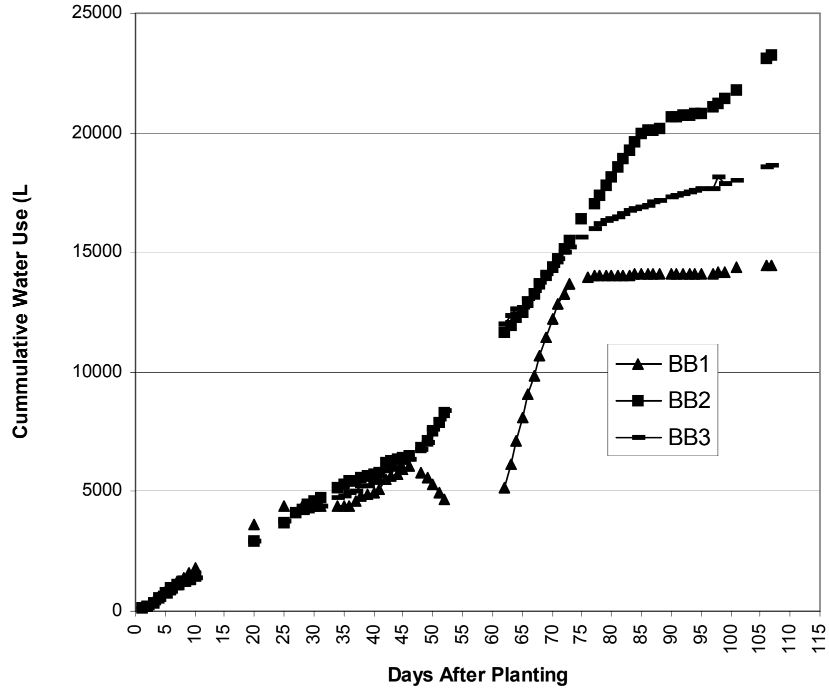
Irrigation scheduling for the Hubbell surface irrigated field was carried out according to the needs of the crop. In 2005 the field was flood irrigated. As this was the first season of cultivation for many decades, the newly formed terraces were not perfectly level and it was difficult to irrigate evenly and with complete control. Some flooding occurred from adjacent terraces. An estimated 991 mm was applied to the field over 6 irrigation events throughout the season. In 2006 a more accurate system of measurement was installed which used a single inlet to the field through a water meter. In this way, PVC piping was used to supply individual furrows with water through individual valves. The total water applied to the plots is given in Table 4.

Table 4: Irrigation water applied for all plots during 2005 and 2006.

Site	Water applied 2005 (mm)	Water applied 2006 (mm)
Hubbell drip plot 1	686	591*
Hubbell drip plot 2	674	844
Hubbell drip plot 3	630	677
Hubbell surface plot	990	533

*Estimated

(a)



(b)

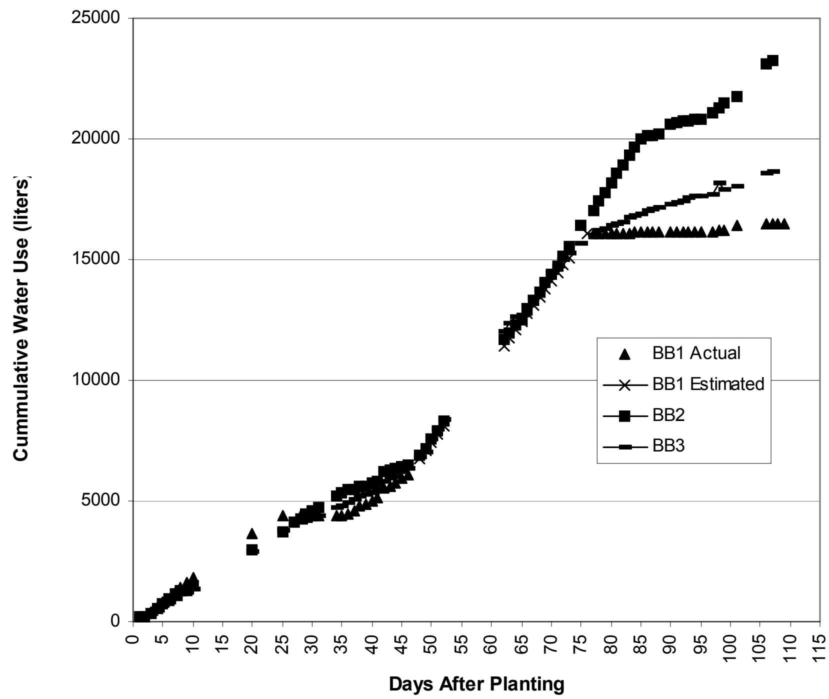


Figure 19: (a) Cumulative water applied for Hubbell Drip Systems 1 through 3 in 2006 based on actual meter readings. BB1= Hubbell Drip Plot 1, BB2=Hubbell Drip plot 2, BB3=Hubbell Drip plot 3; (b) Cumulative water applied for Hubbell drip systems 1 through 3 in 2006 based on actual meter readings (BB2 and BB3), and estimated readings for BB1. BB1= Hubbell Drip Plot 1, BB2=Hubbell Drip plot 2, BB3=Hubbell Drip plot 3.

A measured total of 533 mm was applied evenly to the field throughout the season using this method. Although this system allowed for more accurate measurement of water applied, it may not have represented a traditional surface irrigated system.

Harvest Data Analysis

Harvest yield data for both seasons is presented in table 5. The grain weight per hectare was obtained by multiplying the grain weight obtained from the two-meter sample of crop row to give a proportional yield per hectare. The area associated with a two-meter sample of a crop row was calculated as a two-meter length of row multiplied by a row width of 0.90m to give 1.8 m² for each sample. All five rows of each plot were sampled in entirety. The yield from the entire 27 m² of plot was totaled for the five rows and this total yield was converted to a yield per hectare.

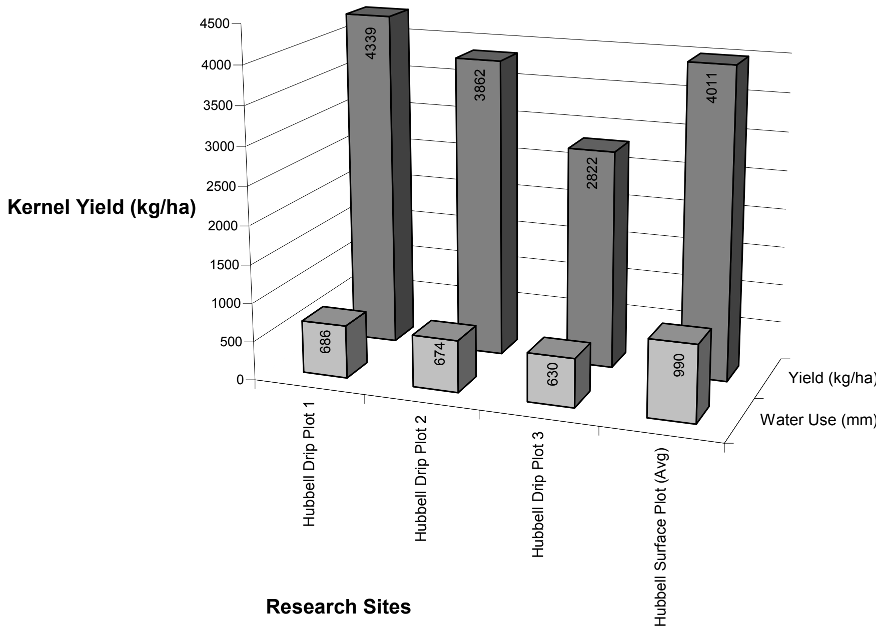
A combination plot showing water applied data with yield data for 2005 and 2006 for each plot is shown in figure 20a and b. In 2005, average yields of grain per hectare, per mm of water applied (including rainfall) of 3.70 kg/ha/mm and 4.86 kg/ha/mm were achieved for the surface and drip plots respectively. In 2006, yields of 4.90 kg/ha/mm and 4.07 kg/ha/mm (including rainfall) were achieved for the surface and drip irrigated plots respectively. Average yields per mm applied (including rainfall) over both years were 4.30 kg/ha/mm for the surface irrigated plot and 4.47 kg/ha/mm for the drip irrigated plot. Ganado rainfall data shows 93 mm of precipitation during the 2005 season and 140 mm during the 2006 season.

Table 5: Harvest yields of grain in kilograms per hectare for 2005 and 2006, Hubbell site.

Site	2005 Yield (kg/ha)	2006 Yield (kg/ha)
Hubbell Drip 1 plot	4339	2891
Hubbell Drip 2 plot	3862	3301
Hubbell Drip 3 plot	2822	4109
Hubbell Surface plot – sample 1	3767	3071
Hubbell Surface plot – sample 2	3337	3776
Hubbell Surface plot – sample 3	4930	3055

CONCLUSIONS AND RECOMMENDATIONS

The objectives of the research project were achieved firstly by designing a water supply system using simple methods and low cost components for growing corn using gravity-fed drip irrigation tape. Secondly, the implementation was successful at the Hubbell Trading Post where three research systems were operated alongside a conventional surface irrigated plot over two seasons using the upgraded Ganado reservoir and irrigation supply pipeline. Finally, the demonstration aspect of the project was achieved by stimulating local interest through operating the research plots in a highly



(b)

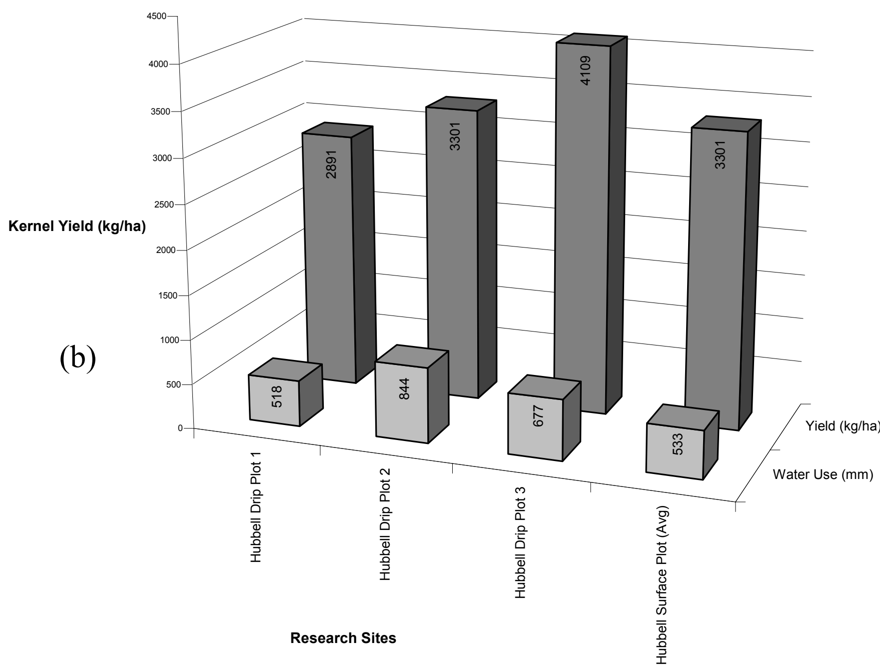


Figure 20: (a) Water applied (mm) vs. yield (kg/ha) for all plots 2005; (b) 2006.

visible location and by involving Hubbell Trading Post staff in the setup and planting as well as in the operation, maintenance and data collection.

Operation of System

The watering systems and drip tape operated reliably over two seasons with very little maintenance and very low labor input. However, water quality was seen to have a major effect on the operation of the system. In particular, blockages caused by plastic film and algae in the many flow orifices associated with the water meter, filters and timer devices on each drip system caused the greatest problems. The drip tape experienced emitter blockage by salt accumulations when used with lower quality irrigation water and by algae when using chemically untreated source water. The manufacturers claims of good self cleaning properties resulting from the turbulent flow regimes generated in the drip tape emitters are designed to remove particulate matter. Algae and salt accumulations cannot be controlled in this way.

All the drum systems operated reliably and effectively throughout each season. The systems stood up well to the natural elements, and no mechanical failures were seen. Minor leaks in the drip tape associated with rodent damage were easy to repair and did not cause problems to the overall operation. All connections and valves, including the battery operated timers operated flawlessly throughout each season. In addition, the systems were easy to build and all parts were easy to source. As a maximum of two drum-fills were used per day it would be possible to operate the system in the absence of a piped water supply by hauling water to the plot.

Corn was chosen solely for the importance of this crop to the Navajo way of life. However, corn is a relatively high water-use crop. The development of such a large plant, with a high amount of leaf mass demands more water than a smaller vegetable plant. For this reason the daily watering requirements were relatively high for such a small plot. Acceptable yields of corn were produced which was one of the aims of the study.

Comparison of Yields

In general, yields for the Hubbell drip plots and the Hubbell surface irrigated plots were similar. Irrespective of irrigation method used, higher water use showed a higher yield. Comparing the grain produced per mm of irrigation water applied in both years, the drip plots were seen to have effectively the same production per mm as the surface plot. This showed that corn could be produced with similar efficiency to surface irrigation using drip irrigation methods.

Demonstration

The bucket drip irrigation project intended to show interested people that possibilities exist for small farms and gardens to produce crops even without a piped water supply. The potential for information transfer was excellent given the location of the study. The site was visible to visitors to the National Park and the public, both of who are free to walk the grounds of the historic site. The Hubbell Trading Post staff was trained in operating and maintaining the system on a daily basis. The irrigation systems were demonstrated as part of the regular interpretive tours given during the summer months and field days were held during the growing season when local residents were allowed to collect pollen from the plants for ceremonial use. At harvest time, Hubbell Trading Post staff shared the ears of corn with local residents.

In connection with this project, numerous presentations and talks on the simple drip irrigation systems have been made throughout the Navajo Nation: at local Ganado Schools, the Navajo National Farm Board Meetings and other Navajo local events. Additional exposure was received by a presentation made at a sustainability workshop, attended by a number of Navajo smallholders and other interested parties. Other interest has been stimulated at Diné College located in Tsaile, AZ, the first tribally controlled college in the United States, where College students collaborated to play different roles in their own simple drip irrigation project, using one of the same systems that were used at the Hubbell Trading Post.

Working at the Hubbell Trading Post allowed us to easily attain temporary use of a plot of land for research and demonstration purposes, and provided much help with field preparation, planting, harvesting and regular data recording. It would have been difficult to establish the same infrastructure in a short time without the help of the Hubbell Trading Post staff.

Furthermore, in addition to the research plots a demonstration plot was established using a small scale version of the bucket drip system to grow corn over three seasons (2004-2006) on the site of the original Hubbell Trading Post kitchen garden. In this demonstration, three 20 L buckets were each connected to a 24 m length of drip emitter tubing, which served as an example of a simpler alternative to the larger system installed for research purposes in 2005 and 2006. The study played a small role in the overall picture of bringing agriculture back to the Hubbell Trading Post after an absence of many years, and stimulating a general interest in agriculture in the Ganado area.

In 2007, bucket drip or variations of that system, can be seen throughout the western Navajo Nation. At the Hubbell Trading Post, the drip systems are being used in the kitchen garden. At Tsaile, three large drip plots are being used at Dine College. In Chinle, just North of Ganado, there are three drip demonstration gardens at the Regional hospital, promoting water conservation and healthy eating. A large 500 m^2 drip plot is being used within Canyon de Chelly, along with a traditional big bucket system. Finally, a local group called the Canyon Farmers (growers who cultivate inside Canyon de Chelly) requested 50 small bucket drip kits from Chapin. The kits were donated by Dick Chapin and have been distributed to interested people throughout Chinle and Canyon de Chelly.

Recommendations

The use of an adequate filtration system was found to be crucial in maintaining a steady flow of water through the system. A single large filter provided much easier maintenance than single filters located on each separate system. This limited the number of connections to be broken for cleaning purposes and controlled the build-up of debris on the individual filters in the meter and timer. As well as reducing the general maintenance requirement there is also less chance of components being incorrectly reinserted or badly connected.

Means of reducing algal growth could include painting the drums to make them opaque and periodic treatment with a disinfectant such as chlorine. In order to actively attack the problem the drums could be filled with a disinfectant solution and allowed to soak before being carefully flushed out. This was not possible during the study due to time constraints as well as the absence of a disposal point for the disinfectant solution and it was not thought advisable to have disinfectant solution draining to the plot.

Daily observation of the system proved to be an important factor in ensuring reliable operation, which was not always possible during the study. In this way, problems such as having valves closed by outside parties, or valves closed for maintenance and not re-opened are easily caught before the plants begin to suffer a lack of water. Other problems such as timer mechanisms not operating due to low battery power, plugging of components with debris or algae, and wrongly inserted components could be identified quickly. The simplest check is to observe the drum filling, as well as emptying to the drip tape. This would ensure that both the water supply and the flow to the drip tape were operating correctly.

Typically drip tape should last for a few years with a little maintenance after each season. At all sites minor damage occurred as a result of rodents. This damage was easily repaired using waterproof tape. Algae only seemed to cause emitter plugging in the drip tape towards the end of the growth season. Flushing the drip tape could reduce plugging problems. This is achieved by opening the ends of the drip tape lengths and flushing through either with water or a disinfecting solution to remove biological growth. In addition an acidic solution can be used to dissolve accumulated calcium deposits. A dilute acid flush was attempted in the first season at Maricopa when calcium deposits were observed around the emitters with little effect, and it was found easier to replace the drip tape. The drip tape used is low cost and the fact that it is used in a surface application makes replacing it a simple operation. Commercial growers use regular acid flushes to avoid problems of salt accumulations in emitters. This requires a regular supply of chemicals and the correct handling and control of these. As this study was aimed at simplicity and rural applications, these methods were not considered further in this study. Use of subsurface drip irrigation may also reduce plugging problems due to lower ambient temperatures around the drip tape, as well as lower evaporation rates than those seen at the soil surface.

A certain amount of site preparation is required. To ensure uniformity of emitter flow it is recommended that the growing area be leveled as well as possible prior to planting. Other agricultural considerations such as tillage of the soil and application of fertilizer are not discussed in detail here but may be of importance depending on soil type and condition. Protection of the plot from animals, which may damage both the crop and the equipment, may be necessary. In particular, rodent damage was seen on plastic components and drip tape.

Growing a high water use crop such as corn on a simple system such as used in this study meant that a relatively high amount of water was applied to a small plot. If a low water-use crop was chosen, the plot could either be expanded for the same daily use of water, or alternatively, less water could be applied to the same size of plot. Depending on the available water supply method either of these alternatives may be worthy of consideration.

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Irrigating Onions with Subsurface Drip Irrigation under Different Stress Levels

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Abstract

Irrigation technologies that conserve water are necessary to assure the economic and environmental sustainability of commercial agriculture. This study was conducted in the lower Rio Grande Valley in Texas to evaluate yield and quality of subsurface drip irrigated onions using different scheduling strategies and water stress levels. One strategy consisted on initiating irrigation when the reading of a watermark sensor reached 20 kPa (optimum), 30 kPa and 50kPa. The second strategy was to replace 100%, 75%, and 50% of crop evapotranspiration (ETc) weekly. Even though yields were very similar for the 100% and 75% ET treatments, about 85 mm of water could be conserved by slightly stressing the crop. The soil moisture based method permitted better control of the irrigation because onion yields for the 20 and 30 kPa soil moisture treatments were very similar to the 100% ET based treatment, and 104 and 132 mm of water could be conserved with these treatments without sacrificing yields. This suggests that crop coefficients may over estimated ET requirements. Onions in the large size class were increased for the 20 kPa, 30 kPa, and 100% ET treatments. There was no effect of irrigation scheduling treatment or irrigation level on the small, medium and colossal size classes. There was no difference between the irrigation scheduling treatments on pungency levels. Although soluble solids concentrations were different between treatments, there was not a clear trend that indicated higher soluble solids for any irrigation method

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treatment or water level. Productivity based on the amount of water applied ranged from 10.7 to 12.9 kg/m^3, and highest water use efficiencies were observed for the soil moisture based methods and for the 50% ET method. The 50% ET method also resulted in the lower onion yields.

Introduction

Significant water savings can be achieved for a variety of crops by deliberately stressing the crop to a certain profitable level. This management technique is generally known as deficit irrigation. To manage plant water stress it is necessary to carefully schedule irrigation which consists of determining the amount and timing of irrigation applications (Martin et al., 1990). There are two main methods to schedule irrigation: 1) by replacing crop evapotranspiration (ETc) fractions according to a soil water balance, or 2) by triggering irrigation according to water content status of the soil, storage capacity, rooting depth and allowable depletion (Hanson et al., 2000). The first method requires the use of a weather station and a computer program to follow the soil water balance and the second method consists of monitoring soil water status either by direct sampling or using soil moisture sensors. One of the difficulties of irrigation scheduling using ETc is that local crop coefficients are needed, and these vary according to crop varieties, plant densities, row configurations and planting dates (Enciso et al., 2007). Another problem is that soil variability may influence water retention and consequently the allowable depletion to trigger irrigation. Soil water status can be monitored and measured directly with sensors such as watermark sensors, tensiometers, and capacitance probes (Enciso, 2006). The choice of sensor will depend on soil water range to be measured, cost effectiveness, easiness to maintain, and the sensor’s performance reliability. According to Muñoz-Carpena et al., (2005) granular matrix (GM) sensors and dielectric sensors like time domain reflectometry (TDR) require less field maintenance than tensiometers and have a greater potential for commercial adoption. The use of soil moisture data from GM sensors as a decision making tool for irrigation is convenient and inexpensive. However, the sensor reading is highly dependent on type of soil, climate, plant root zone depth, soil salinity, and soil temperature. Sensor calibration, installation and placement must also be taken into consideration.

Irrigation scheduling with watermark sensors using different ranges of water potentials have been studied for onions by Shock et al. 2000. They studied the yield response to five soil water potentials (-10, -20, -30, -50 and -70 KPa) when the sensors were installed at 200 mm soil depth. Onion profits and yields were highest with higher water application levels. Bekele and Tilahun (2007) found no differences between irrigation replacing of 25%, 50%, 75% ET, and optimal irrigation defined as 100% ET when stresses were applied in the first and last part of the onion growing season. They also reported that if the deficits persist during all the onion growing season or during the second and third of four growing stages, the yields were significantly different between the stress and optimal treatments. The water-saving strategy of reducing irrigation rates at predetermined developmental stages where deficits would not severely impact productivity is called regulated deficit irrigation (RDI) (Kirda, 2002). The net effect is an increase in crop water use efficiency especially when the impact on yield is not significant. Considering farmer's preference to use pan evaporation, Kumar et. al., (2007) studied the influence of four ratios (0.6, 0.8, 1.0 and 1.2) between irrigation water and cumulative evaporation on onion yield. The best yields were observed for the 1.0 and 1.2 ratios but the highest irrigation water use efficiency at the 0.8 ratio and declined at higher irrigation levels. Although the possibility of achieving optimum yields under RDI practices has been demonstrated for many crops (Bekele and Tilahun, 2007; Kirda, 2002; Thompson et al., 2007), the potential water savings from scheduling RDI using ET-based data versus soil moisture monitoring has not been evaluated.

The objective of this study was to evaluate the water-saving potential of ET-based versus soil moisture monitoring approaches of managing RDI in onion production.

Material and Methods

This study was conducted during the fall-spring onion growing seasons (2005-2006 and 2006-2007) in a commercial-type field in Weslaco, S. Texas (longitude 26" 9' N, latitude 97" 57' W; Hidalgo sandy clay loam soil). This region has a semiarid climate and the average annual rainfall is 558 mm. The onion variety, 'Cougar' (hybrid, yellow short day sweet onion) was direct-seeded on 11 Nov 2005, and on 30 Oct 2006 (Table 1) on 1.02 m (40 inch) wide raised beds in double rows and onion plants were spaced along each row at 254 mm (10 inches) apart. Standard commercial practices for spring onion production were followed (Danielo and Anciso, 2004). Treatments consisted of two irrigation scheduling approaches (ET-based or direct soil moisture monitoring based) and three irrigation levels within each approach. The ET-based irrigation levels were (100% ET or optimum, 75% and 50% ET) whereas the soil moisture monitoring irrigation levels were 20 kPa (or optimum), 30 kPa and 50 kPa. These treatments were randomly assigned to three-row plots replicated tree times. Data were collected only from the center experimental row. The treatments were set up to replace ET fractions (100, 75 and 50%) or by initiating irrigation based on the pre-determined soil water status (20, 30 or 50 kPa). All treatments were irrigated with a subsurface drip irrigation system with the drip tape (model Typhoon 875-10 mil-F; 0.908 L/h flow rate; Netafim) installed at 150 mm below the soil surface and emitters spaced every 300 mm. The irrigation water source was the Rio Grande river, which was filtered with a sand media filter.

Granular matrix sensors (Watermark soil moisture sensor, Irrometer, Co., Riverside, CA) were installed at 300 mm below the soil surface to monitor soil moisture changes. One watermark sensor was installed per treatment. For the ET-based treatments, irrigations were applied approximately twice per week depending on rainfall inputs and the ETc fraction treatments; for the soil moisture monitoring treatments, irrigation was triggered whenever the soil moisture readings reached the set points (20, 30 or 50 kPa) for each treatment. The amount of water applied to each plot was recorded with totalizing water meters connected to the irrigation system with one flow meter installed plot. Crop water use was estimated as ETc using weather data and the Penman-Monteith method (Walter et al., 2000) with FAO crop coefficients for seed onions (0.7 for initial, 1.05 for mid, and 0.8 for end season) as suggested by Allen et al. (1998). The lengths of the four growth stages were 20 d for initial, 35 d for development, 80 d for mid and 23 d for the end stage in 2006 and 21 d in 2007. These durations were adjusted based on visible developmental changes. Onion were harvested on 19 Apr 2006 and on 4 Apr 2007 and classified by size as small (<50 mm diameter), medium (50 - 75 mm), large (75 - 100 mm), or colossal (>100 mm). The weight for each size class was recorded and total yields computed. Onion bulb quality parameters included pungency which was measured as the pyruvic acid concentration, and soluble solids concentration (brix) were determined using the method of Randle and Bussard (1993). Data were analyzed with a general linear model (GLM) procedure of SAS (Cary, NC). Least square differences test (P = 0.05) was used to for mean comparisons within each season.

Results and Discussion

Total rainfall amounts for the two growing seasons were 81 mm and 133 mm in 2006 and 2007 respectively. In both years, more than 70% of the total rainfall was received within the first 12 weeks of the study, between October and March. Hence, it was difficult to sustain the desired dry soil conditions in 50 kPa and 50% ET treatments (Fig 1). Despite these inputs, the top soil tended to dry out faster than the lower soil profile thanks to high air temperatures and vapor pressure deficits, thus requiring additional small irrigation inputs to ensure adequate stand establishment. Cumulative crop evapotranspiration amounts for 2006 and 2007 were 470 mm and 340 mm respectively. Less rainfall received and higher crop water demand during 2006, resulted in bigger irrigation amounts applied than in 2007.

The amount of water applied in each scheduling approach was significantly different in each of the study years (P = 0.05). In 2006, the total irrigation amounts were 430 mm, 350 mm and 270 mm for the 100%, 75% and 50% ET treatments respectively. Over 80% of these amounts were applied late in the crop during the bulb development and maturing stages of growth (Feb-May). Compared to the 100% ET treatment, 80 mm of water was saved by scheduling irrigation at 75%ET. Similarly, the water savings from the 50% ET approach was 160 mm compared to the 100% ET. In 2007, the corresponding water savings were 40 mm for the 75% ET, and 80 mm for the 50% ET treatments.

In 2006, the total irrigation amounts were 330 mm, 300 mm and 190 mm for the 20 kPa, 30 kPa and 50 kPa treatments respectively. Over 80% of these amounts were applied during the bulb development and maturing stages of growth (Feb-May). Compared to the well-watered 20 kPa treatment, 30 mm and 140 mm of water were saved by scheduling irrigation at 30 kPa and 50 kPa respectively. In 2007, the savings were 50 mm for the 20 kPa and 90 mm for the 50 kPa treatments.

Yield and irrigation water use.

There was no interaction between treatment and year, therefore onion yields from the two years of the experiment were combined (Table 3). There was no significant difference in total yield between the 20 kPa, 30 kPa, 100% ET and 75% ET treatments. Lower yields were observed for the 50 kPa and 50% ET treatments. Even though more irrigation water was applied with the 100% ET treatment (434 mm) than with the 75% ET treatment (349 mm), there were no significant differences in yield between these treatments, indicating that 85 mm of water can be conserved by slightly stressing the crop (Table 3). When scheduling irrigating with soil water sensors about 28 mm can be conserved by slightly increasing the stress from 20 to 30 kPa without sacrificing onions yields. If the soil water deficit is increased further to 50 kPa onion yields are decreased significantly. More water was applied while scheduling irrigation based on ET than when using soil water sensors. The reason that although more water was applied with the ET method and that yields were not different between ET and soil moisture based, could be that the crop coefficients could be overestimating ET, and the soil moisture sensors may be more accurately matching water demand with water supply.

Large and colossal size onions are easy to market according to farmers' perceptions. When onion yields were sorted by size into small, medium, large, and colossal size classes, irrigation method and water level did not significantly affect the small, medium and colossal onion sizes. In the large size class, higher yields were observed for the 20 kPa, 30 kPa and 100% ET treatments, and lower yields were observed for the 50 kPa and 50% ET treatments. This is an indication that larger onion sizes can be produced when more water is applied, and the water stress affects the size of the onions.

Onion bulb pungency (pyruvic acid content), an indicator of the hotness of the onions, ranged from 3.9 to 4.4. There was no distinctive trend due to the treatments applied in this experiment indicating a relationship between pungency level and water stress (Table 4). The soluble solids concentration (brix), an indicator of the sweetness of the onion, in this experiment ranged from 7.1 to 7.8. Higher brix was observed with the 20 kPa treatment, and there was no significant difference between this treatment and the ET based treatments. Although higher brix values were observed with the 20 kPa treatments there is no a clear indication to relate brix to water levels or irrigation scheduling method. There are not any reported values on the literature that indicated a relation between onion quality parameters such as pungency or brix content and water stress.

Highest was use efficiencies were observed for the soil moisture based scheduling method and for the 50% ET method. The lower water use efficiency was observed for the 100% ET treatment. The lower productivity of the 100% ET treatment compared to the 20 and 30 kPa soil moisture based treatments, even though similar yields were obtained, is an indication that water was over-applied by the ET scheduling method.

Onion Yield and Quality

Productivity per unit of water applied

Productivity per unit of water applied estimated as the ratio between onion yield and irrigation plus rainfall received ranged from 10.7 to 12.9 kg/m^3 (Table 2). The highest water use efficiencies were observed for the soil moisture based methods and for the 50% ET method. The 50% ET method also resulted in the lower onion yields. Some other studies have reported water use efficiency for SDI onions from 11.7 to 13.7 kg/m^3 in the Lower Rio Grande Valley of Texas (Enciso et al., 2007). Bekele and Tilahun (2007) obtained water use efficiencies that ranged from 9 to 9.7 kg/m^3 in well water onions that received 100% ET or onions that received 75% of ET only in the initial or final stage of onion growth, but 100% in the rest of the growing season.

Summary and Conclusions

Slightly stressing the crop can be used as a water conservation strategy for onions. About 85 mm of water could be conserved by slightly stressing the crop from 100% to 75% ET without affecting yield or onion quality indicators such as pungency and brix content. The soil moisture based methods at the 20 and 30 kPa permitted a better control of irrigation than the 100% ET based treatments, because 104 and 132 mm more water could be conserved with this method without sacrificing onion yield or quality. This suggest than that onion crop coefficients may over estimated ET requirements.

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Table 1. Agronomic and irrigation data for two irrigation seasons.

Variable	2005-06	2006-07
Planting date	11-Nov-05	30-Oct-06
Last irrigation	17-Apr-06	25-Mar-06
Harvest date	19-Apr 06	04-Apr 07
First fertilizer application	12-Dec-05	04-Dec-06
Amount applied during first application	33 kg/ha N	28 kg/ha N
Second fertilizer application	02-Jan-05	31-Jan-07
Amount applied during second application	33 kg/ha N	117 kg/ha N 26 kg of P_2O_5 34 kg of K_2O
Third fertilizer application	March 13-06	-----------
Amount applied during third application	33 kg/ha N	------------
Length of growing season (days)	158	156
Estimated Onion ETc (mm)		
Irrigation applied after planting to germinate the seed (mm)	100	84
In-season irrigation (mm)	434	260
Growing season precipitation (mm)	81	133

Table 2. Rainfall, irrigated applied and water use efficiencies for two irrigation scheduling methods and 6 irrigation water levels.

Irrigation Method	Irrigation Level	Irrigation applied 2006 (mm)	Irrigation applied 2007 (mm)	Average Water Use Efficiency (kg/m^3)
ET	50%	270	180	12.6 ab
	75%	350	220	11.3 bc
	100%	430	260	10.7 c
CB	20cb	330	280	11.6 abc
	30cb	300	230	12.8 ab
	50cb	190	190	12.9 a
P > F				0.0023
LSD				1.5

Means in each column followed by the same letter are not significantly different according to least significant difference (P = 0.05). Where no letters follow means, no significant differences were found.

Table 3. Effect of two irrigation scheduling methods and 6 irrigation levels on sweet onion (var. Cougar) yield parameters as classified by size classes during two years of the study (2006-2007).

		Size Class				
Irrigation Method	Irrigation Level	Small	Med	Large	Collosal s	Total Yld
		---------------------------- T/ha ---------------------------				
ET	50%	1.2	27.7	7.5 c	0.0	36.4 b
	75%	1.7	27.0	9.9 bc	0.5	39.2 ab
	100%	1.0	25.9	15.3 ab	0.3	42.5 a
Soil moisture	20kPa	0.6	23.5	18.8 a	0.7	43.6 a
	30kPa	0.8	24.6	16.4 a	0.3	42.2 a
	50kPa	1.2	26.5	6.6 c	0.0	34.4 b
P > F		ns	ns	0.0002	ns	0.0018
LSD				5.7		4.8

Means in each column followed by the same letter are not significantly different according to least significant difference (P = 0.05). Where no letters follow means, no significant differences were found.

1

Table 4. Effect of two irrigation scheduling methods and 6 irrigation levels on sweet onion (var. Cougar) quality parameters during two years of the study.

Irrigation Method	Irrigation Level	Pungency	SSC
ET	50%	4.1	7.2 ab
	75%	3.9	7.3 ab
	100%	4.2	7.2 ab
Soil moisture	20kPa	4.1	7.8 a
	30kPa	4.1	7.1 b
	50kPa	4.4	7.1 b
P > F		ns	0.0438
LSD			0.6

Means in each column followed by the same letter are not significantly different according to least significant difference (P = 0.05). Where no letters follow means, no significant differences were found.

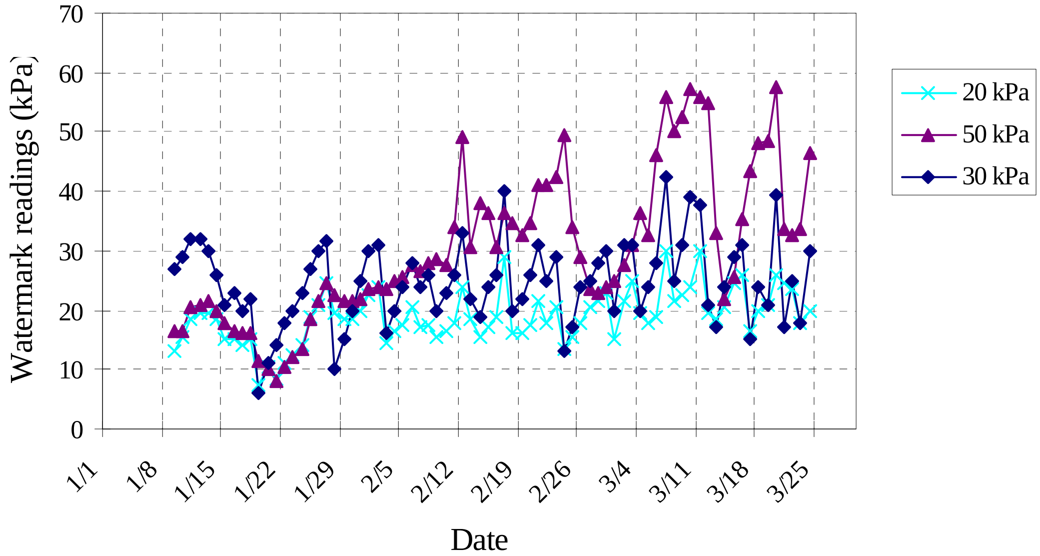

Fig. 1 Average soil moisture readings on the 20, 30 and 50kPa treatments on SDI onions, Weslaco,TX. 2006

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Integration of Micro Irrigation Systems with Minor Irrigation Projects – A Case Study

Sharad Dugad, Jain Irrigation Systems Ltd,Jalgaon, Plastic Park, Bambhori,, Jalgaon, India and Somnath Jadhav, Jain Irrigation Systems Ltd, Plastic Park,, Bambhori, Jalgaon, 425001.

Maharashtra is one of the major states of India and it occupies about 9.4 % of the total geographical area of the country. Agriculture has been the prominent occupation of the people. The Govt. of Maharashtra in the last 43 years (till 2003) has spent around Rs. 30000 Crores (approximately US$ 6 Billion) for development of irrigation facilities in the state. However, in spite of such a huge capital investment, the Gross Irrigated Area of the state remains at meager 17 % as against the national average gross irrigated area of 41%. This is so because the efforts were concentrated only in creating the storage rather than efficient water distribution and application methods in the schemes in the past.

To bring more area under irrigation, to increase the crop production and productivity per unit volume of water vis-à-vis making the scheme economically viable, the minor irrigation projects must be integrated with micro irrigation systems. The integration of micro irrigation systems with minor irrigation schemes have been done in few projects executed by Jain Irrigation Systems Ltd, Jalgaon. In such schemes, the water stored in the minor irrigation projects is distributed through piped network and is applied to the crops using micro irrigation systems. This has lead to huge water savings, increase in irrigated area, increase in agricultural produce and productivity, considerable savings in various inputs, social justice through equitable distribution of water and many other benefits. The case study of one such project would be presented in this paper.

In the wake of the ensuing second green revolution in India, more intensified efforts will have to be made for promoting integration of Micro Irrigation Systems (MIS) with Minor Irrigation Projects (MIP) with active participation of Indian farmers for sustainable water management, food and water security of the nation.

See more of Agriculture: Microirrigation
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A Study of Emitter Clogging and Development of the Mathematical Relationship between Emitter Clogging and Water Quality

Ahmad Asgari[1], Farid Ejlali[2], Jamshid Khairabi[3], Mohaamd Ali Hajjari[4]

Abstract: The performance of the drip irrigation system and its water application could be degrading at a high level by the clogging. Emitter clogging a function of the water quality, included: suspended solids, chemical component and biological activities.
In the current study, causes of emitter clogging in the some different systems were investigated. To achieve this aim water quality testing was performed and the results were compared with the standard criteria to evaluate the clogging potential. Also effects of emitter performance variation on the water application uniformity evaluated involved the ASAE EP458 standards. Finally, for the drip irrigation systems which were studied, the mathematical regression equation between emitter clogging and water quality was developed.

Keywords: emitter clogging, field evaluation, water quality, regression equation.

Introduction

Drip irrigation systems are methods of water distribution which delivers water and nutrients to precise amounts and controlled frequencies directly to the plants root one via pressurized network.
Micro irrigation systems have many potential advantages when compared with other irrigation methods. Most of them are related to the low rates of water application. It can be argued that some of these benefits are not unique to a micro irrigation system. However, certain combinations of these advantages are responsible for uniqueness of micro irrigation in contrast to other systems (Haman, Izuno 1989).
Micro irrigation, properly managed, offers several potential advantages over other methods of irrigation. The clogging of emitters is one of the most serious problems associated with micro irrigation use. Emitter clogging can severely hamper water application uniformity (Pitts, et al 2003).
Information concerning emitter discharge rates and uniformity has been presented by several researchers. Bralts et al (1981) an attempt to statistically include manufacturing variation in calculations for uniformity and emitter flow variation of single chamber and emitter clogging in the calculations for uniformity of single and dual chamber drip irrigation lateral lines. A simulation model was developed by Nakayama and Bucks (1981) to evaluate the uniformity and average water discharge rate of a trickle system with different degrees of clogging. Bralts and Kesner (1983) presented a statistical

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method for field uniformity estimation of drip irrigation sub main units based upon the coefficient of variation and statistical uniformity coefficient. Solomon (1985) was developed a simulation model which treats the various equipment, system and other factors known to influence emitter flow rate variation. Talozi and Hills (2001) was developed a mathematical model to simulate the effects of emitter clogging on subunits hydraulics.

Gilbert et al (1979) experiments using Colorado River irrigation water on citrus trees in south western Arizona were conducted to evaluate clogging of emitters and to investigate methods for controlling clogging. Bucks et al. (1979) compiled a water quality classification relative to its potential for drip emitter clogging.

Clogging hazards for drip irrigation systems fall into three general categories: physical (sediment), biological or organic (bacteria and algae), and chemical (scale). Frequently, clogging is caused by a combination of these factors. The type of emitter clogging problems will vary with the source of the irrigation water. Water sources can be grouped into two categories: surface and ground water. Each of these water sources is likely to present specific clogging hazards (Benham and Blake Ross, 2002).

Irrigation water testing is performed to evaluate the suitability of a water source for use with drip irrigation systems. Testing can also be used after emitter clogging problems arise to determine the source of clogging and to devise a plan to correct the problem (Storlie, 1995).

The review of selected studied on uniformity and emitter clogging shows no study addresses mathematical relationship between emitter clogging and water quality. The objectives of the present work are: (a) to introduce the notion of ASAE EP458 capability to emitter clogging evaluation; (b) the effect of the most chemical composition on water application uniformity (c) developed mathematical relationship between emitter clogging and water quality.

Methodology

1- Drip irrigation water Test

Fourteen systems were visited. Seven systems with chemical clogging and suitable data are used. Table (1) shows the characteristic these systems.

Table 1. General characteristic of seven suitable systems

System No.	Namely discharge (lit/hr)	Emitter type	Tree crop	Number of emitter per tree
1	4	In-line	Citrus	6
2	4	In-line	Peach & Plum	4
3	4	In-line	Peach & Plum	4
4	4	In-line	Olive	1
5	4	In-line	Pomegranate	3
6	4	In-line	Olive	1
7	4	In-line	Pistachio	1

The water for the experiment was taken from the emitter emission water and delivered the samples to a testing lab, and interpreting the water analysis. Since chemical properties of the irrigation water (pH) and chemical constituents (iron, manganese, hardness) can cause chemical reactions and result in the precipitation of certain water and fertilizer constituents, we performed these tests in a capable water testing laboratory. The results are shown in Table (2).

Table 2 Irrigation water test in visited system

System No.	SAR	concentration (ppm)				concentration (meq/l)						PH	EC 10^6
		hardness	TDS	Mn	Fe	Na	Mg	Ca	Cl	HCO_3	CO_3		
1	0.5	268	312	0.02	0	0.9	2.5	2.9	0.3	5.2	0	7.4	488
2	1.5	313	492	0.02	0.04	2.5	2.4	3.9	7.6	4.8	0	7.3	769
3	0.3	308	326	0	0.04	0.5	2.5	3.7	2.5	4.6	0	7.3	510
4	0.4	407	451	0.01	0	0.7	4.3	3.9	1.4	5.4	0	6.7	705
5	4.6	2040	2923	0.02	0	21	12	29	17	2.8	0	6.3	4568
6	4.9	1940	3029	0.02	0	21.5	13	26	19	3.2	0	7.8	4734
7	10.1	1990	4970	0.02	0.03	45	12	28	53	2.4	0	6.5	7766

2- Field evaluation of drip irrigation systems

Using the Field Uniformity Estimator, as few as 18 flow measurements per zone can provide a reasonable estimate of actual water flow uniformity in a good drip irrigation system. Measurements were taken only after the system has reached its normal operating pressure and flow rate. These measurements were scattered uniformly over the zone to be tested to accurately represent conditions throughout the entire zone. Individual emitters were randomly selected. For accuracy, the water caught measured in milliliters. A graduated cylinder marked in milliliters used to measure volume caught. For each selected emitter 200 milliliters water caught. A wrist watch with a seconds indicator did the timing. Therefore ASAE EP458 methods used to evaluate drip irrigation systems as follows:

2-1- Flow Rate Variation and Uniformity

The uniformity of water application can be calculated from the statistical distribution of emitter flow rates that are measured in the field.

$$U_s = 100\,\%(1-V_{qs}) \qquad (1)$$

Where

U_s = statistical uniformity of the emitter discharge rates, and V qs = statistical coefficient of variation of emitter discharge rates.

In Equation (1), the coefficient of variation is the standard statistical definition of the sample standard deviation divided by the mean.

2-2- Pressure Variation and Uniformity

Hydraulic uniformity refers to the effects of pressure variation on the uniformity of water application from a drip irrigation system. Hydraulic uniformity, Ush , is defined similar to water application uniformity in Equation (1) , except that the emitter discharge exponent, x, must also be considered. This exponent shows the relationship between emitter operating pressure and flow rate. Because x is different for different types of emitters, the allowable pressure variation is also different for each emitter type.

$$Ush = 100\,\%(1-xVhs) \qquad (2)$$

Where

U sh = hydraulic uniformity based on pressure distributions,

x= emission exponent, and

Vhs= hydraulic variation, which is the statistical coefficient of variation of pressures.

In this study pressures easily measured using a portable pressure gauge at the same emitters where flows were measured.

-Emitter flow equation determination

The relationship between emitter operating pressure and flow rate given by:

$$q_e=KH^X \qquad (3)$$

Where:

q_e= emitter flow rate, K= emitter discharge coefficient, H= operating pressure and x emission exponent.

In this study, the coefficient (K) and exponent (X) for this equation from testing laboratory obtained is as below:

In different pressure condition at 0.2, 0.4, 0.6, 0.8, 1 bar, the average of 4 emitter flow rate in lit/hr measured. Then by power regression type between q and H emitter flow rate equation with R^2=0.98 is obtained as below:

$$q=1.61H^{0.44}$$

The above equation shows that the exponent X=0.44, in in-line emitter which is under study is a turbulent flow emitter.

2-3- Emitter Performance Variation and Uniformity

Emitter performance variation, V_{pf} refers to non-uniformity in water application that is caused by the emitters. If the emitter performance variation is high, this is normally due to emitter clogging or to manufacturing variation among emitters. It may also be due to other factors which affect emitter flow rates, such as temperature. The emitter performance coefficient of variation, V_{pf}, shall be determined using the equation as follows:

$$V_{pf} = (V_{qs}^2-V_{qh}^2)^{1/2} \qquad (4)$$

Where

V_{qs} = emitter discharge coefficient of variation

V_{qh} = emitter discharge coefficient of variation due to hydraulic

The statistical uniformity of the emitter performance, U_{pf}, is determined as follows:

$$U_{pf} = 100(1-V_{pf}) \qquad (5)$$

3- Mathematical relationship development

To develop the mathematical relationship, various water quality parameters were studied. Finally, the PH, temporary hardness and dissolved solids as independent variables were considered. Therefore Emitter Performance Variation was used as a dependent Variable. The multi variable of nonlinear regression can be performed, using suitable software such as Data Fit by which 90 different models were run.

Result and Discussion

Water Quality evaluation

Fourteen visited systems were mainly wells and all of the systems were equipped with filtration units. In the most of visited systems the filters especially screen filters was frequently flushed. This flushing was down on a set time interval or at a specific pressure drop. Therefore the main of causes of emitter clogging were chemical agents. Table 3 shows chemical water quality testing was compared with the standard criteria to evaluate to evaluate the clogging potential.

Table 3. Chemical water quality testing evaluation

System no.	hardness	clogging potential	TDS	clogging potential	Mn	clogging potential	Fe	clogging potential	PH	clogging potential
1	268	moderate	312	Slight	0.02	Slight	0	Slight	7.4	moderate
2	313	severe	492	Slight	0.02	Slight	0.04	Slight	7.3	moderate
3	308	severe	326	Slight	0	Slight	0.04	Slight	7.3	moderate
4	407	severe	451	Slight	0.01	Slight	0	Slight	6.7	Slight
5	2040	severe	2923	severe	0.02	Slight	0	Slight	6.3	Slight
6	1940	severe	3029	severe	0.02	Slight	0	Slight	7.8	Severe
7	1990	severe	4970	severe	0.02	Slight	0.03	Slight	6.5	Slight

Physical and biological clogging in some system occurs and the there was because:

1- lake of adequate management
2- Ignorance of farmers from operation functions of filtration and flushing.
3- Biological (bacterial and algae) in sedimentary basin
4- Lake of sediment basin installation
5- Sedimentation of suspended particle in systems due to low pressure

In some systems, water quality test shows that amount of suspended solid in water is very low and can be ignored. The result shows that the main cause of clogging was temporary hardness.

In some systems, the white and tiny layers of calcium carbonate on the emitters and soil were appeared. In these systems the ignorance of chemical treatment causes to clogging accumulation and only in one system acid treating causes to improve emitter performance. In most system, there was fertilizer tank with filtration system. But it was rarely used for fertigation and chemical injection. Systems assessment indicated that many of them with problem such as low quality components, low designing and low management that cause decline in system efficiency and performance.

Water Application uniformity evaluation

In the visited system statistical uniformity (U_s) based on emitter discharge rates, hydraulic uniformity (U_{sh}) based on pressure distributions and statistical uniformity of the emitter performance (U_{pf}) is classified as shown in Table 4, and 6.

Table 4 U_s evaluation

System No.	V_{qs}	U_s	**classification**
1	0.08	92	Excellent
2	0.16	84	Very good
3	0.25	75	Fair
4	0.07	93	Excellent
5	0.28	72	Fair
6	0.20	80	Very good
7	0.12	88	Very good

Table 5 V_{hs} evaluation

System No.	V_{hs}	V_{qh}	U_{sh}	**classification**
1	0.09	0.04	96	Excellent
2	0.22	0.1	90	Fair
3	0.28	0.12	88	Fair
4	0.14	0.06	94	Very good
5	0.28	0.12	88	Fair
6	0.07	0.03	97	Excellent
7	0.06	0.03	97	Excellent

Table 6 V_{pf} evaluation

System No.	V_{pf}	U_s	**classification**
1	0.07	93	Excellent
2	0.12	88	Very good
3	0.21	79	Fair
4	0.04	96	Excellent
5	0.25	75	Fair
6	0.20	80	Fair
7	0.12	88	Very good

According to Table 4 to 6 the following result:

- Whenever U_s is excellent, U_{sh} and V_{pf} is excellent.
- Whenever U_s is very good, V_{pf} is very good or fair.
- Whenever U_s is fair, U_{sh} and V_{pf} is fair.

Therefore we can say Vpf more effective than Ush in declining of Us. Figure (1) indicate that descending of clogging or Vpf.

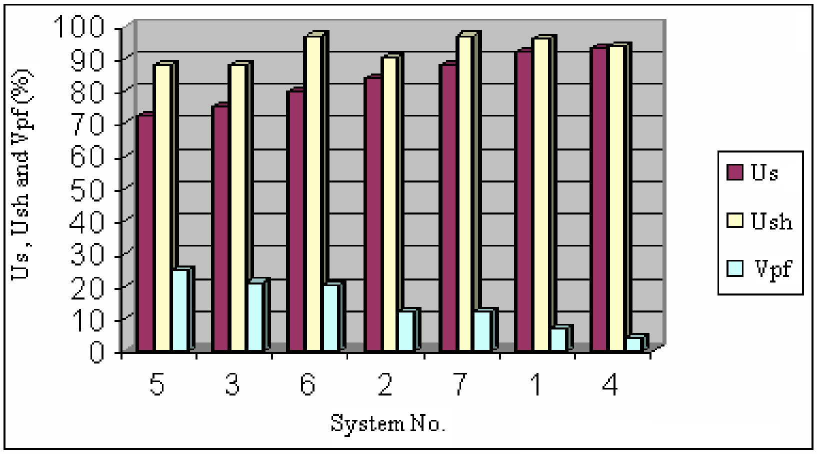

Figure (1) shows that V_{pf} have inverse relationship to U_s but is not effective to U_{sh}.

Mathematical relationship evaluation

One of the advantages of development of mathematical relationship in comparison to "criteria for plugging potential of micro irrigation water sources (Bucks and Nakayama Table)" is assessment of effects of Interactive water quality factors. For example, there may be a kind of water which is with pH or hardness near to "Slight" or between "moderate" and "Severe" in Table will not cause emitter clogging (but in fact, there are much probability for this water to create severe problem for the system).

Instead of water which have very high acidity and have little hardness, as it has shown in the Table causes "severe" emitter clogging (it has much probability this water has less problems for the system).

To develop a mathematical relationship in first stage, acidity, total hardness and dissolved solids as independent variable were considered. Due to, low concentration of Fe and Mn, these elements were not considered. In this stage regression coefficient between these factors and V_{pf} (dependent variable) was low.

In second stage, acidity, permanent hardness and dissolved solids were considered as independent variable. But still regression coefficient was low.

In the third stage, acidity, temporary hardness and dissolved solids were considered as independent variable. In this stage regression coefficient was good and it was equal to 0.985. There fore non-linear multi regression was obtained as follow:

$$Y= \exp (ax_1+bx_2+cx_3+d)$$

Where:
Y= emitter performance variation
x_1= acidity
x_2= temporary hardness
x_3=dissolved solids.
a, b, c and equals 0.281,-0.028,-0.008 and 7.650 respectively.

In the above a, b, c and d equation coefficients and may be alter in other systems with different water quality and emitters.

In fact, temporary hardness indicator of precipitation of calcium carbonate in the water. We can say the factors in the above equation the highest effects in emitter clogging and from this view point above equation complies with national condition.

Table (7) and figure (2) show calculated clogging error in above equation in different visited system.

Table (7) error for mathematical relationship between emitter clogging and water quality

X_1 (pH)	X_2 (temporary hardness)	X_3 (dissolved solids)	Y (visited clogging)	Y (calculated clogging)	Residual	Error%	Absolute residual
7.4	260	312	7	8.491	-1.491	-20.988	1.491
7.3	240	492	12	12.655	-0.655	-5.458	0.655
7.3	230	326	21	19.036	1.964	9.353	1.964
6.7	270	451	4	4.722	-0.722	-18.043	0.722
6.3	140	2923	25	25.764	-0.764	-3.055	0.764
7.8	160	3029	20	20.574	-0.574	-2.868	0.574
6.5	120	4970	12	10.216	1.784	14.865	1.784

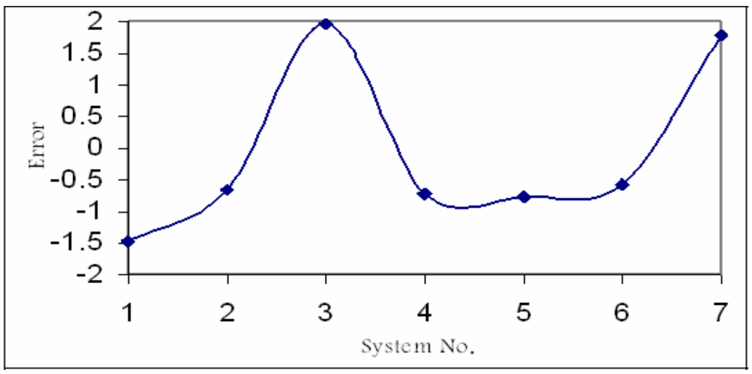

Figure 2 calculated clogging error in mathematical relationship between emitter clogging and water quality

Conclusion

One of the most important factors of proper performance in drip irrigation is good maintenance and management. In visited systems when ever clogging problem was low, it was due to lake of awareness of the user from technical information of filtration operation and flushing procedure. It is necessary for farmers to have a manual which provide information about irrigation time and interval, flushing of system network and filters and number of sub main to be simultaneously irrigated.

It is advisable to use emitter with high emitter operating pressure in the area which has water hardness and high concentration of substances. We should consider choose emitter not only match crop water requirement but also it should survey clogging potential.

It is proposed that water application uniformity tests as a guarantee of performance for the companies which undertake to install drip irrigation systems. Also, we can consider by frequent these tests to study system performance in consecution years. By execution of this procedure we can remove the shortcoming and defects of the system. Moreover we can study special emitter performance related to water quality in specific area over a period of time.

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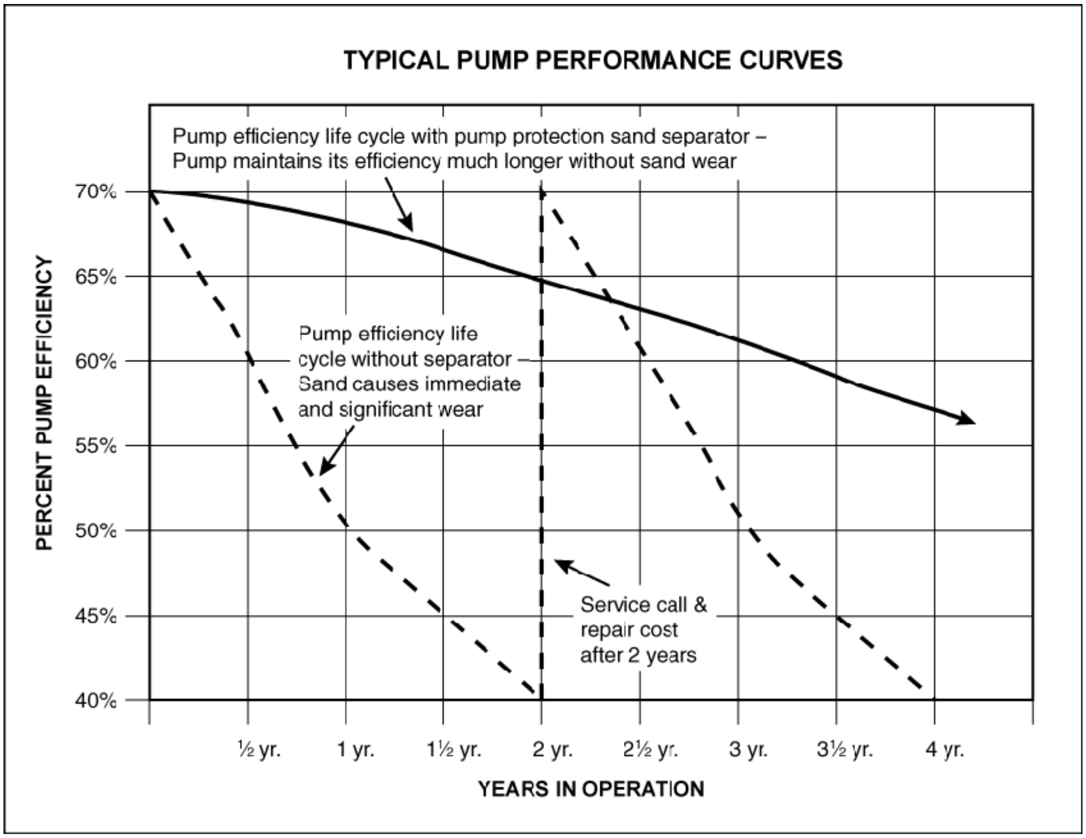
Technologies For Longer Pump Life

Pump manufacturers continue to design and develop impellers, bowls, wear rings and other innovations to curb the abrasive & damaging effects of sand in a water well. The challenge is that these same pump manufacturers are also pressed to design and develop more and more efficient pumps for moving more water from greater depths with less energy draw. It is not realistic to expect the solution to lie solely with the design of the pump … and it is not possible to expect a water well to forever be sand-free.

To be sure, a properly drilled, cased, gravel-packed and developed water well faces many circumstances that can defeat its best designs for keeping out unwanted sand. Pumping in excess of a water well's designed flow increases flow velocity to draw sand into a well. Overpumping an aquifer within a specific region by multiple water wells can also combine to draw more flow and sand into the well. Periodic droughts will lower the water table, and subsequent depth restoration can flush sand into a well. Deteriorating well casings, for sure, allow more sand to infiltrate a well. Earthquakes and major construction also have their affect to damage casings and upset the aquifer conditions, encouraging sand movement into a well. These and other circumstances threaten the best practices for commissioning a water well to long-term, sand-free service.

So, even a good well can become a sandy well. And it is the effects of that sand that signify the value of protecting the pump from the abrasive damage that sand causes. Clearly understood is the cost of repairing and replacing a pump versus protecting the pump for longer service life. Added value comes from prolonging the efficiency of a pump so that the cost of operating the pump to deliver the required water does not become an excessive energy cost. In essence, if a pump must work longer or harder to deliver water, the power cost also becomes a factor in its effective longevity. Worn early by sand, a pump can often operate at its lower efficiency for a long period of time before dropping to a low efficiency point that demands repairs or replacements. In that time, the energy cost can be significant, suggesting that repairs or replacement should have been considered much sooner.

Note the chart, depicting "Typical Pump Performance Curves", plotting a pump's typical loss of efficiency due to sand abrasion, suggests that pump wear does not occur evenly over time, but rather immediately, dropping a pump's efficiency quickly and causing the pump to operate longer at lower efficiency. Alternatively, keeping a pump's efficiency at higher levels over that same time will logically result in both energy and cost savings.

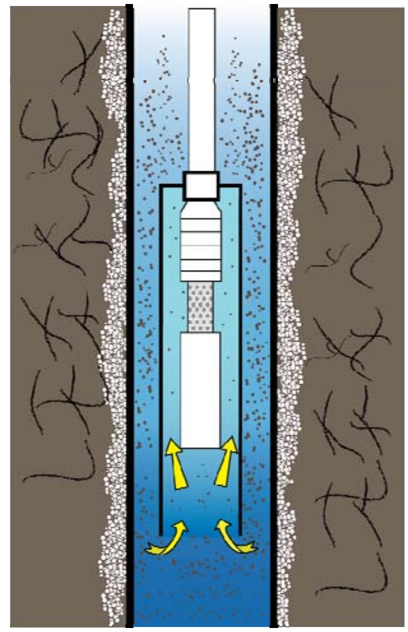


There is obvious and distinct value in protecting pumps from sand. The challenge is to apply an effective solution without the time, costs and restrictions of drilling a new well. Such solutions must take into consideration not only their relative cost, but also their suitability within the well's environment, their lifespan and, most importantly, their ability to effectively remove the sand that could damage the pump and reduce its potential longevity.

Pump Shrouds

Essentially recognized as a shield around a pump's intake, the pump shroud directs flow to the pump intake only via an upward movement past the pump's motor. Initially designed as a pump motor cooling technique, the pump shroud also serves to keep large, unwanted particle matter from getting into the pump. It is widely known and easily applied in many well environments, requiring only that the shroud provides adequate clearance between the shroud and the pump to allow design flow to pass with little or no restriction … and that the shroud fits easily down into the well.

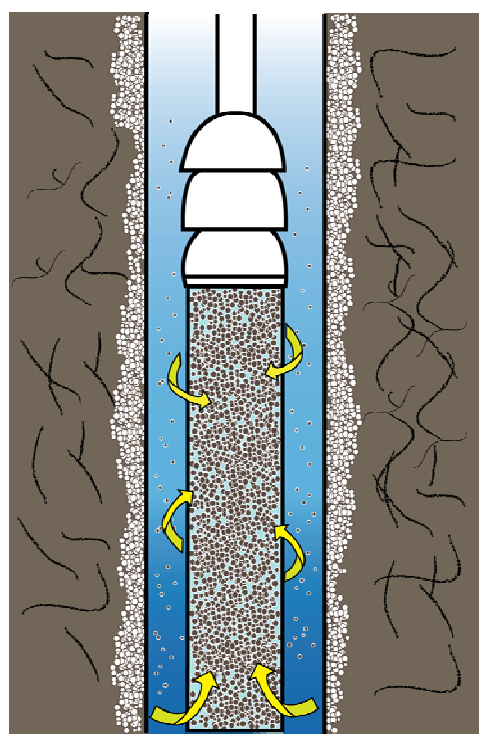
The performance of a pump shroud relies on particle matter in the well to be heavy enough that it will not follow the upward flow of water into a pump's intake, but will instead fall down deep into the well. Consider, however, that today's pumps, with the capability for effecting higher flow velocity, can draw such larger particle matter upward and potentially limit this technique's actual performance results.



There is little or no potential for increased flow restriction beyond any sizing and/or spacing issues imposed by the shroud itself. No maintenance routines are required. The pump shroud can operate with both steady and variable flow pumps, working best at lower flows & velocities.

Suction Flow Control Devices

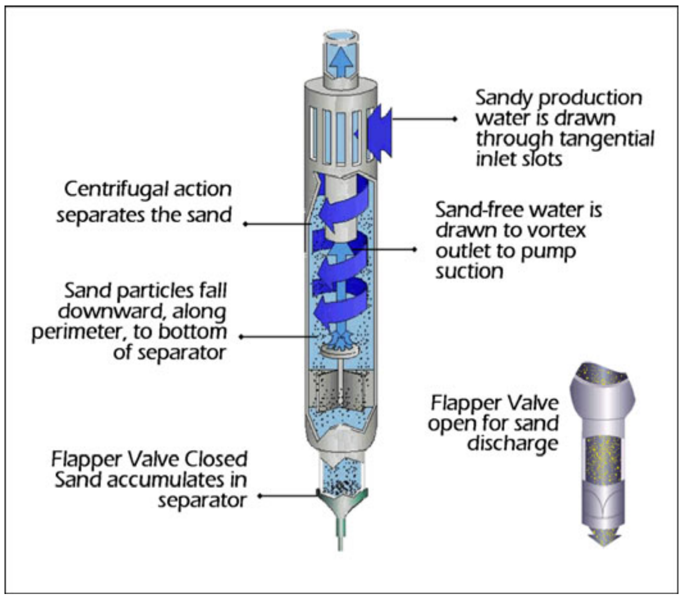
This technology employs an epoxy-coated sand/gravel pack that is layered around a length of casing/screen. The overall device is connected to a pump's intake. The size and diameter of the suction flow control device is determined by the pump's actual flow rate and the inside diameter of the well. The design is meant to diffuse incoming flow over a greater area in order to reduce intake velocity to the pump over a larger area of the suction flow control device. Wells smaller in diameter are accommodated with longer suction flow control devices where possible. Flow simply passes through the epoxy/sand/screen into the pump intake.



The design premise is that flow enters the well via a larger percentage of the water-producing area at an overall lower velocity, thus reducing particle matter from coming into the well. Performance is ultimately achieved by straining out any incoming particle matter that is larger than the openings of the epoxy/sand/screen assembly. It is intended that when the pump shuts off and releases its drawing effect on the particle matter trapped on the epoxy/sand/screen, the particle matter will drop off and fall down into the well. One must consider and expect, however, that at least some particle matter will lodge within the epoxy/sand/screen assembly and not release from the device, at least somewhat restricting the flow through the device over time. If that continues, the pass-through velocity increase will further draw more particle matter to lodge upon its surface and may ultimately restrict flow.

Best results are obtained when flow and velocity are low. There are no maintenance routines while in service. Periodic removal of the suction flow devlce from the well and cleaning of the epoxy/sand/screen may be necessary.

Pump Protection Separators



Employing centrifugal action to remove settleable particle matter from pumped water, the pump protection separator can be installed with either a submersible or turbine pump. It is attached to the pump prior to the intake, either onto the suction casing of a turbine pump or in conjunction with a pump enclosure shell to direct water first through the separator before going to the intake of a submersible pump. As the pump pushes water to the surface, the pump protection separator is fed by head pressure created by submergence. A minimum of 25-30 feet of drawdown head is required to feed proper flow through this technology. Each pump protection separator has a specific flow range that it best operates within.

The pump protection separator's centrifugal action spins unwanted sand from the flow of water, which then follows a vortex action up to the pump intake. Separated sand drops to the bottom of the separator, collected until either the pump shuts off to allow sand to pass through a flapper-type valve and discharge deep into the well, or until the accumulation of sand pushes its way through the flapper valve for discharge deep into the well.

Sizing of the pump protection separator begins with the actual flow rate of the pump. A widely-variable flow range cannot be accommodated. The well's inside diameter must also be able to accommodate the separator (and pump enclosure shell, if applicable). In addition to the required submergence, a clearance of about 25 feet below the separator is required to allow for separated sand to discharge deep into the well.

Performance is reliable and predictable when operating within the specified flow range for any given model. Pump life increases of four to five times longer are to be expected. There is a head loss attributable to this technology (about 9-14 feet), but no maintenance routines are necessary.

Where does the sand go?

Each of the above techniques for protecting pumps from sand results in the ultimate discharging of sand back into the well. It is the trade-off for not pumping sand and damaging the pump. While it is common to be concerned about filling the well with this sand, it is equally common that the sand does not accumulate to such troublesome levels. In essence, one must remember that underground aquifers are not static bodies of water, but rather moving flows. That movement not only allows sand to flow into a well, but also out of a well. There are also other theories on this subject. Use your own judgment, but know that these technologies have all been successfully employed and that sand accumulation is clearly not a routinely significant issue.

It is, in fact, possible for sand to accumulate and require mechanical removal techniques. Such occurrences are typically the result of only significant sand problems … and the cost of periodically bailing a well is then considered acceptable when compared to pump damage, sand-locked pumps and similarly costly alternatives.

Sand does present a challenge to pumping technology. Sand cannot be completely avoided, even when employing the best equipment and trade practices. Sand, however, can be controlled to reduce operating costs and prolong pumps at greater efficiencies. In this age of information availability, your customers know, are aware, or will come to learn of these technologies … be prepared to professionally apply the solutions that best serve your customers.

Increasing Crop Productivity and Water-Use Efficiency by Utilizing Ethanol CO_2 Emissions

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Abstract:
Ethanol production is growing in the San Joaquin Valley (SJV), which is one of the most productive agricultural areas of California. About ten new ethanol plants are expected to be built in the near future in the SJV. These production facilities are expected to produce more than one million tons of CO2 annually, which will be vented directly into the atmosphere if not captured and sequestered or used for beneficial purposes. In this presentation we outline the technology used to deliver the CO2 and summarize the research conducted to date. Our findings to date imply utilizing CO2 emissions from ethanol production facilities has good potential to enhance crop yield, water use efficiency, and farm income, while at the same time mitigate global warming by recycling CO2 emissions in agricultural fields.

Attached is the PowerPoint Presentation to be presented at the IA conference.

Increasing Crop Productivity and Water-Use Efficiency by Utilizing Ethanol CO_2 Emissions

By

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CATI
CENTER FOR IRRIGATION TECHNOLOGY

Topics

- CO_2 Emissions
- CO_2 and Plants
- Ethanol Production / CO_2 Emissions
- CIT CO_2 Research

CO_2 Emissions

Annual rate of CO_2 emissions increases:

- U.S. = 1.2% per year (1990-2005)
- Global = 2.1% per year

Global CO_2 Emissions:

- Year 2003: ~ 26,000 MMT
- Year 2030: ~ 44,000 MMT--- ~70% rise in less than 30 years

CO_2 and Plants

Available CO_2/Plant Data:

- Thousands of scientific CO_2 studies available from greenhouses and growth chambers over the past 50 years
- Hundreds of experiments available from Free Air CO_2 Enrichment (FACE) projects in open fields over the past 15 years

CO_2 and Plants- Cont'd

Available Data Shows Elevated CO_2:

- Enhanced crop growth and yield
- Increased water use efficiency
- Reduced growth-limiting environmental stress
- Increased soil carbon sequestration

But CO_2 benefits are site specific ---

depend on crop and growth conditions

CO_2 and Plants- Cont'd

Tomatoes Open Field CO_2 Enrichment (CIT)

CO_2 and Plants- Cont'd

CO_2 enriched tomatoes

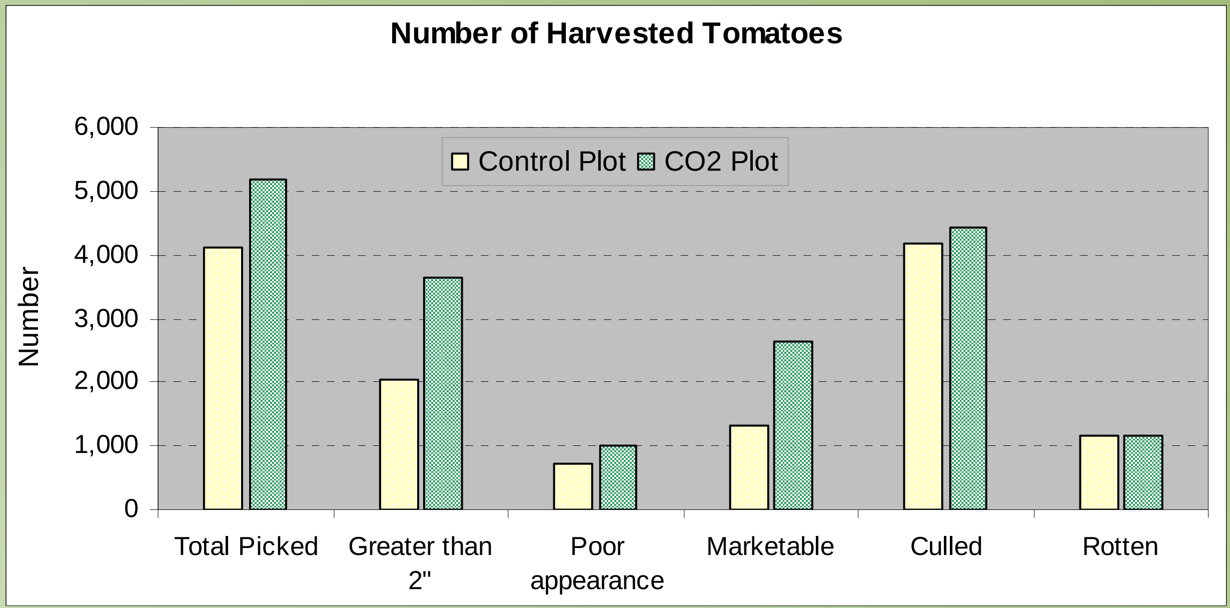
Control (non-CO_2) tomatoes

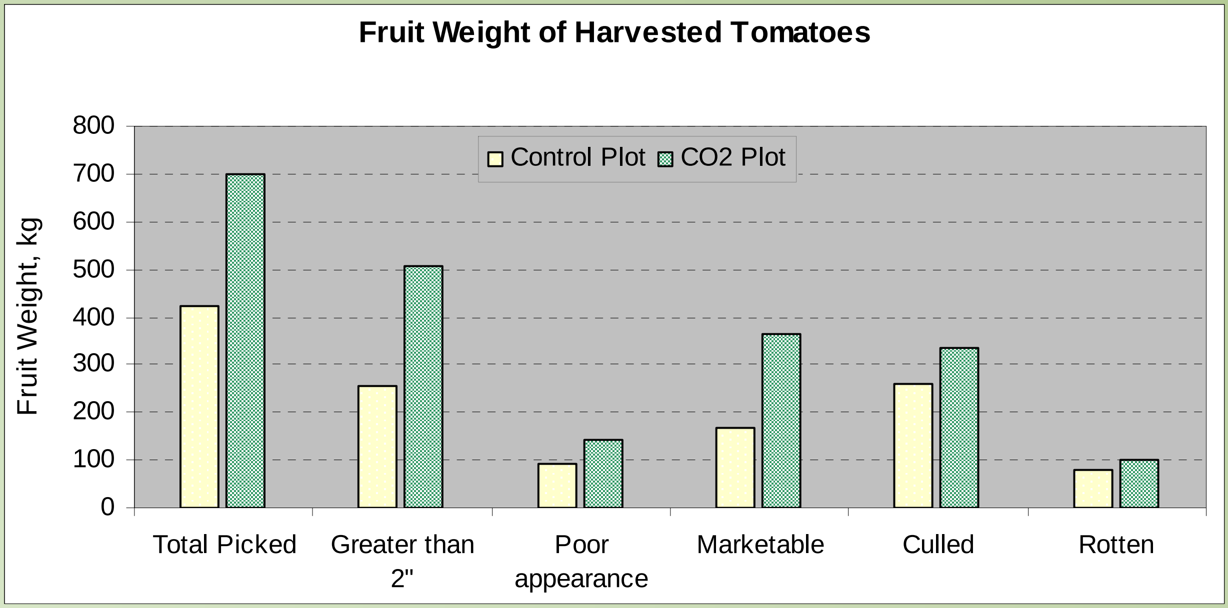
CO_2 and Plants- Cont'd

CO_2 enriched tomatoes

Control (non-CO_2) tomatoes

CO_2 and Plants- Cont'd





Ethanol Production / CO_2 Emission

U.S. Annual Ethanol Production/Projection:

- Now: ~5 billion gallons
- 2012: ≥ 7.5 billion gallons (2005 Energy Bill)
- 2030: Displacing 30% of 2004 gasoline demand with biofuels (DOE goal)- 60 billion gallons/year required to achieve the goal

Now: Ethanol production in U.S. is corn based

Future: Ethanol will be based on cellulose too

- CO_2 is a natural by-product of ethanol --- One-third of a bushel ends up as CO_2

Ethanol Production / CO_2 Emissions

California:

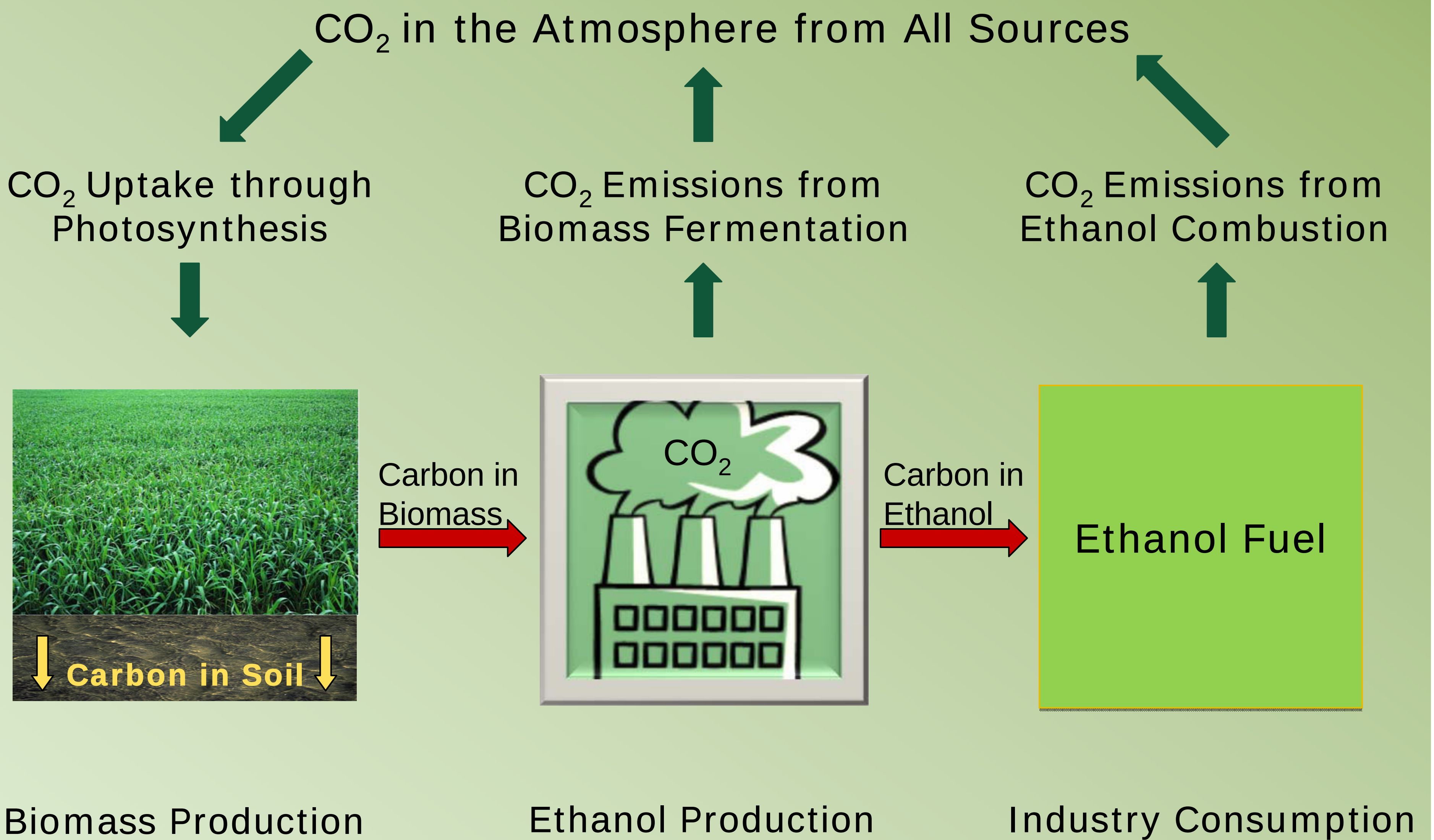
- Is the largest consumer of ethanol in the U.S.
- Currently has a small national production share
- Should produce 20% of its own biofuels by 2010, 40% by 2020, and 75% by 2050 (Executive Order S-06-06)

Businesses to build new plants in California

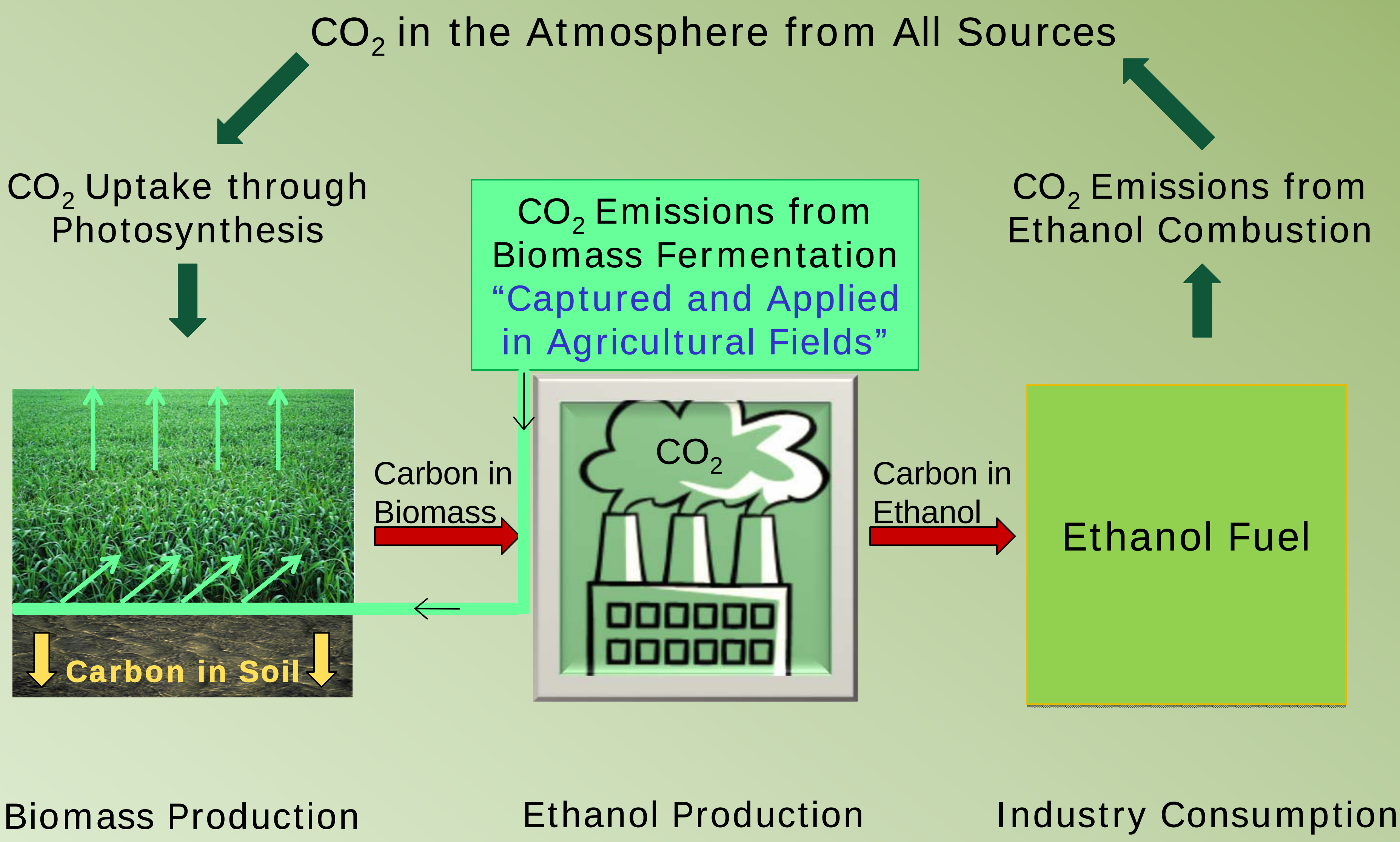
Most plants will be in the San Joaquin Valley

Opportunity to capture/utilize waste CO_2 from ethanol for agriculture?

CO_2 Cycle in Ethanol Fuel Production *Without* Capture



CO_2 Cycle in Ethanol Fuel Production *With* Capture



CIT CO_2 Research

Objectives:

Utilizing CO_2 wastes from ethanol production facilities in agriculture to:

- Increase crop yield per unit land
- Increase crop yield per unit water
- Recycle/sequester carbon in plant/soil

CIT CO_2 Research- Cont'd

Objectives address three important agricultural/environmental/political issues:

- Increasing food demands
- Increasing freshwater shortages
- Increasing CO_2 emissions

CIT CO_2 Research- Cont'd

CIT research is focused to:

- Evaluate technical and economic feasibility of utilizing ethanol CO_2 wastes in agriculture
- Evaluate potential environmental benefits as related to climate change

CIT CO_2 Research- Cont'd

Many (technical/economic/environmental) testing/measuring/monitoring/verification to do:

Technical Issues:

- Proof of concept of new technology
- Development of new technology

  "e.g., methods to transport, deliver, control and apply CO_2 to commercial farms efficiently and cost-effectively"

CIT CO_2 Research- Cont'd

Economic Issues:

- Does CO_2 enrichment offer a profitable business for commercial growers?
- Does investment in a CO_2 recovery system provide an attractive return for ethanol industry?

Environmental Issues:

- Total greenhouse gas emissions from agricultural operations without and with CO_2 capture?

  "e.g., energy and fertilizer use efficiencies, land and water use efficiencies"

CIT CO_2 Research- Cont'd

CIT Work Plan:

- Research will be conducted over at least three growing seasons in the San Joaquin Valley
- Major crops will be selected for field testing
- All necessary field equipment will be installed/software and hardware developed
- Necessary soil, plant, air, and engineering measurements will be taken
- Technical, economic, and environmental studies will be conducted

Risk in Income Return from Limited Irrigation using the Crop Water Allocator

N. L. Klocke, L. R. Stone, T. J. Dumler, S. Briggeman

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Abstract

The Crop Water Allocator (CWA) has been developed for irrigators to allocate limited water among selected crops. Irrigators are under pressure to develop cropping strategies as pumping capacities dwindle and water allocations become more restrictive. Pumping costs, crop production costs, and fluctuating commodity prices are also forcing producers to examine crop selections and water allocations. CWA calculates net economic returns from all possible combinations of crops, irrigation patterns, and land allocations, proposed by a user's inputs and ranks the net returns from maximum to minimum values. Income risk analysis was added to the existing CWA software. Users can account for net income shifts in response to a range for input variables--rainfall, production costs, commodity prices, irrigation costs, irrigation efficiency, and maximum yields. Output shows net returns for each range of selected inputs. CWA is available to download to an individual's computer at: www.oznet.ksu.edu/mil

CWA Features

Water supplies for irrigation are declining in many irrigated regions due to lower pumping capacities, smaller surface water supplies, and regulated restrictions of water applications. To reduce irrigation, irrigators can consider shifts in crop rotations. Irrigators with shrinking water supplies who are considering different crops and rotations need to know the potential net economic returns from each combination of crops and water applications to each crop that suit their management system

The Crop water Allocator (CWA) has been developed to assist irrigators in evaluating an array crop rotations and water allocations to each crop (Kansas State University, 2006 and Klocke et al., 2006). It is an agronomic/economic model that predicts the net economic returns from all possible crop and irrigation combination. Net return to land, management, and irrigation equipment is:

(Crop price X Crop Yield) – (Production Costs) – (Irrigation Costs)

Gross return is calculated from the multiplication of crop yield and crop price. Net return is gross return minus crop production costs and irrigation costs. Crop production costs can come from the CWA user's information that is entered in production cost screens for each crop or from default production costs, internal to the program, as entered by extension agricultural economists (Dumler and Thompson, 2006).

The CWA determines crop yields from irrigation and precipitation available to the crop. Tables of yield versus irrigation over the range of annual precipitation, from 11 to 21 inches, for alfalfa, corn, soybeans, grain sorghum, wheat, and sunflowers are in the CWA (Khan et al., 1996; Stone et al., 2006). Figure 1 is the graphical representation of the table for corn. The data for the yield versus irrigation and precipitation were developed from field research plots, using conventionally tilled management in western Kansas on silt loam soils. CWA users also can add crop and yield versus irrigation and precipitation data through the "custom crop" screen, accessed by the "tools" menu on the main input screen. The "custom crop" option allows users add grain or forage crops with their own irrigation versus irrigation and precipitation data or add custom data to the default crops by adding a crop name like corn2 or forage sorghum.

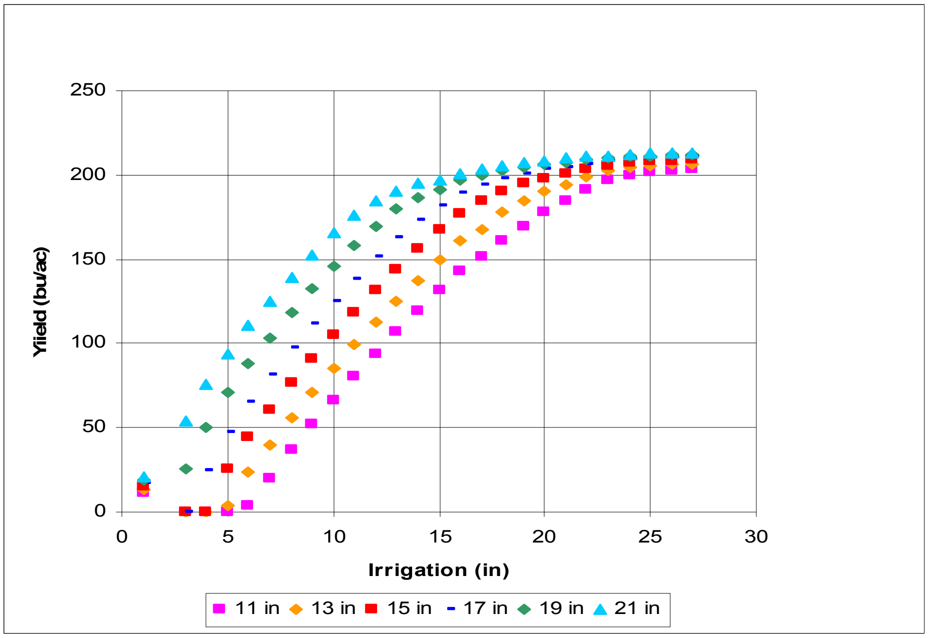

Figure 1.Grain yield for corn versus irrigation over a range in precipitation, derived from research data in western Kansas for silt loam soils.

CWA assumes that farming practices are carried out with good crop management in dryland, limited irrigation, and full irrigation situations. The yield relationships with irrigation that are the foundation for the model are based on research and management practices in "best management" crop production. Crop management that does not meet "best management practices" will not achieve the predicted results of CWA.

The user of CWA can choose a rotation scheme five possible "land splits": 50%-50%; 75%-25%; 33%-33%-33%; 50%-25%-25%; or 25%-25%-25%-25%. These land splits were chosen as predominate divisions fields or farms for crop rotations. The user can choose one land split for each execution of CWA or hold "land split" constant as other inputs are changed. The program will assign every combination of every selected crop to each part of the land split. More crops than land splits can be selected for CWA analysis. One crop may be in more than one part to all parts of the rotation.

Irrigation is then allocated to each crop in each combination of selected crops for the rotation. The irrigation allocation is an iterative process. The "irrigation iteration factor", accessed by edit/options menu on the main input screen, sets the number of irrigation allocation calculations executed by CWA. The default "irrigation allocation iteration factor" is 10. If the user decreases the "irrigation allocation iteration factor", CWA calculates more net returns and results are "coarser" iterations of water allocations to each crop. For example, an "irrigation allocation iteration factor" with a value of 10, tells CWA to calculate net returns for each of 10% increment of the input water allocation (e.g. 12 inches of water is divided into equal units of 1.2 inches). An "irrigation allocation iteration factor" with a value of 5 tells CWA to calculate net returns for each increment 20% of input water allocation (e.g. 12 inches of water is divided into equal units of 2.4 inches). If more crops are selected for more land splits and irrigation iterations, CWA execution time will increase dramatically.

Net return results from all combinations of crops in each part of the rotation and irrigation iterations are "stacked" from maximum to minimum. The user can scroll through approximately 20 of the largest net return results displayed on the output screen. Some of the crop combinations in the rotation may not be feasible for the user even though they have more net return than others. For example, soybeans in all parts of the rotation would not be feasible because continuous soybeans are not recommended.

If a CWA user chooses to evaluate the net returns from a range of an input variable(commodity prices, production costs, irrigation costs, maximum crop yields, precipitation, or irrigation system efficiency), multiple executions of CWA will produce the range of net returns over the range of that input variable. The output of multiple executions will indicate the income risk when an input varies. The "trend processing" feature of CWA, accessed through the "tools" menu on the main input screen, automates multiple executions to obtain ranges of net returns from user chosen ranges of these input variables. For example, the program user may be interested in the net returns if irrigation costs are from $5 to $15 per acre-inch. CWA executes a series of calculation over the range of irrigation costs, producing the corresponding range of net returns. Another example, annual precipitation may have 80%, 50%, and 20% probability for occurrence which corresponds to 15, 18, and 21 inches.

Fixed and variable trend processing are the two options of trend processing. Fixed trend processing is executed after a user has chosen one of the options of crop rotation and water allocation for each of the crops in the rotation from the output screen of CWA. Fixed trend processing allows the user to evaluate income risks of this particular scenario if any two of the input variables change. The "generate output" key on the main input screen will initiate calculations of net returns for the chosen scenario, as normally executed by CWA. An example set of inputs are in table 1. Activating the "Run Fixed Trend on selected option" button on the output screen will take the user to a screen to designate ranges for one or two variables. For example, clicking on "annual rainfall" allows the user to enter a range of rainfall expected for the location. The "add a trend variable" button switches for entry of a second variable such as irrigation cost. CWA executes multiple calculations of net return for all combinations of annual rainfall and irrigation costs over their designated ranges. The results can be exported to EXCEL in the form of a two way table. See table 2 for the example's output.

Table 1. Input values for determining net return with Crop Water Allocator (CWA).

Item	Value	Units	Comment
Irrigation efficiency	100	%	Net irrigation values were used.
Annual precipitation	15, 18, 21	inches	80%, 50%, 20% precipitation probability--semi-arid climate
Annual Irrigation allocation*	8	inches	
Maximum expected grain yield	210, 150	bu ac^{-1}	For corn, grain sorghum
Commodity prices	4.00, 3.50	\$ bu^{-1}	For corn, grain sorghum
Irrigation operating cost	7-15	\$ ac^{-1} in^{-1}	

Table 2. Net return ($/ac) from fixed trend processing for 15, 18, 21 inches of annual precipitation and irrigation operating cost of $7-15 ac^{-1} in^{-1}.

	Annual Rainfall (inches)		
Irrigation Costs ($/ ac-in)	15	18	21
7	173	238	285
9	158	222	269
11	142	206	253
13	125	190	237
15	110	174	221

Variable trend processing is the second option for trend processing in CWA. In variable trend processing net returns are calculated for optimum combinations of crops, water allocations to each crop, and land allocations for each selected crop are free to change to find optimum solutions over the range of one input variable. Variable trend analysis is activated through the "tools" menu selection on the main input page. All inputs, including crop selections, land area, irrigation costs, land split, irrigation efficiency, seasonal irrigation, rainfall, production costs, commodity prices, and maximum yields, must be entered before executing variable processing. After initiating variable trend processing through the "tools" menu, CWA will go to a screen to designate the range of one variable. Only one input variable can be used with variable trend processing. CWA then executes multiple runs to find net returns over the range of the designated variable. The results from CWA's of variable trend processing can be exported to an EXCEL file (see table 3). Corn and grain sorghum were chosen by the user. Annual water allocation was 800 ac-inches for the 100 ac field. Net returns were calculated for a range of annual precipitation, 15, 18 and 21 inches. For 15 inches of annual precipitation, corn and sorghum would be rotated with 3.2 inches of irrigation applied to the sorghum and 12.8 inches to the corn. As rainfall increased to 18 and 21 inches, continuous corn would grown with the uniform application of the 8 inch irrigation allocation.

Table 3. Variable trend output for inputs in table 1.

Annual Rainfall (in)	Crop	Acres	Net Irr (in)	Price ($/bu	Max Yield (bu/ac)	Irr Cost ($/ac)	Total Prod Costs ($/ac)	Net Return ($/ac)
15	Sorghum	50	3.2	3.5	150	40	181	146
	Corn	50	12.8	4	210	144	456	
18	Corn	100	8	4	210	92	372	218
21	Corn	100	8	4	210	92	393	200

Summary

The CWA model allows irrigators, Extension personnel, consultants, or water planners to calculate net economic returns for combinations of selected crops for a rotation, land allocations to each crop, and water allocations to each crop. The CWA is user friendly and can be executed with inputs crop selection, land area, irrigation and production costs, commodity prices, irrigation system efficiency, and irrigation amount. As water resources become more limited, programs such as the CWA can be used to assist in planning for future farming operations or to assess potential impacts of changes in water policy.

The trend analysis feature of CWA gives producers the ability to find income risks from net returns when input values vary over a specified range. Producers and policy makers can project micro and macro economic effects of volatile commodity prices, escalating production and irrigation costs, uncertain rainfall, and possible water allocations.

Acknowledgements:

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LIMITED IRRIGATION OF ALFALFA

Mark A. Crookston[1]
Dr. Neil C. Hansen[2]

ABSTRACT

Northern Water (Northern Colorado Water Conservancy District) conducted a study of limited irrigation of alfalfa on a 4.7-acre field near Berthoud, Colorado, during the 2006-2007 seasons. The study was a collaborative effort between Northern Water and Colorado State University's Soil and Crop Sciences Department.

Irrigation was supplied via a linear sprinkler with independently controlled drops: 2-wire encoder, valve/solenoid, pressure regulator, and sprinkler nozzle. A programmable controller/logger, base station controller for the sprinkler valves, and a GPS receiver were all on-board the sprinkler cart. Unscreened irrigation water was supplied by a variable frequency pumping unit to maintain constant line pressure over the variable flow range required.

The alfalfa field was divided into 12 plots to accommodate three replicates of four different irrigation treatments:

1. Full irrigation to meet well-watered crop ET.
2. Stop irrigation following one irrigation after first cutting, then resume irrigation after third cutting.
3. Stop irrigation after second cutting.
4. Stop irrigation after first cutting.

Crop water use was estimated using meteorological data from an adjacent weather station. Soil moisture sensors tracked volumetric moisture in the top 4 feet of the alfalfa root zone. Yields for each cutting from each plot were estimated from hand samples (20-foot length of windrow by 16-foot wide swath). Results were summarized by inches of alfalfa water use per ton of harvested yield at 0 percent moisture.

INTRODUCTION

Field Layout

The alfalfa field was 260 feet (east-west) by 890 feet (north-south) and included along the west edge a 30-foot wide, grassed hose drag lane for the linear sprinkler. The soil was a silty clay

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loam. Field capacity was taken to be 0.35 inches of water per inch of soil, and the permanent wilting point was assumed to be 0.16 inches of water per inch of soil. With an allowable depletion of 60 percent, this provided 5.5 inches of useable moisture in the top 4 feet of the alfalfa root zone. The water table was typically 20 feet below the soil surface as monitored via adjacent observation wells. Because of this depth, capillary rise of groundwater has to date been neglected for potential contributions towards crop water use.

Crop Establishment and Harvest

Following harvest of a barley crop, the field was planted to Dairyland Magna Graze alfalfa from Agland on August 26, 2004. Because of intense competition with volunteer barley, it was over-seeded the following year on June 16, 2005, to achieve 92 percent of stand. The study of limited irrigation began in 2006, which was the second full season of the alfalfa crop. The alfalfa crop was harvested by swathing and green-chopping, thereby minimizing the time between cutting and green-up of the next stand. Alfalfa was often left in windrows as little as 24 hours.

Irrigation System

Irrigation was provided through a 2-span linear sprinkler utilizing a guidance furrow for the end cart. Sprinkler drops were 5 feet on center with LDN heads 3 feet above the ground. Two hydrants along the west edge of the field supplied water to the linear sprinkler through a 4-inch diameter drag hose. Electrical power was supplied via an on-board 480 VAC gas-powered generator. The travel speed of the linear sprinkler was adjusted so the nozzles applied 0.75 inches of water across the field in 9 hours of run-time.

AUTOMATION OF IRRIGATION TREATMENTS

Study Layout

The field was divided into 12 plots, 4-wide by 3-long grid, to provide three replicates of each of four irrigation treatments. Along the direction of travel for the linear sprinkler, a 15-foot wide buffer was provided between plots. The valves on each drop were turned on or off within these buffers, usually within the center 7- to 10-feet of the buffer.

Pump House

Irrigation water was delivered from the Handy Ditch to an on-site, 9 acre-foot capacity fully-lined pond. Water from the pond was supplied to the linear sprinkler via a pumping unit with a variable frequency drive electric motor and controls. The system maintained near constant line pressure from 25 percent up to 100 percent of the designed flow rate. The supply water was not filtered or screened in 2006-2007, but screens are planned to be installed before the 2008 season to reduce clogging of control orifices in the sprinkler valves.

Sprinkler Drops

Each of the 44 sprinkler drops were equipped with a 2-wire encoder, 9 VDC latching solenoid on a ¾-inch plastic sprinkler valve, pressure regulator, manual ball valve, and LDN spray head.

The 9 VDC latching solenoids were selected because of the lower power requirements. A typical 24 VAC solenoid needs 0.4 amps in-rush current and 0.2 amps current to hold, thus requiring 211 to 422 watts of power to energize 44 solenoids. In contrast, the 9 VDC latching solenoids only need a brief voltage pulse to turn the valve on or off, with no holding power requirement. A positive voltage pulse turned a valve on, and a negative pulse turned it off as provided by the on-board base station controller.

The 2-wire encoders were selected over direct wiring of each solenoid to the base station controller in order to reduce the number of conductors running from the base station controller on the cart and starting down the linear pipe. Direct wiring of 44 solenoids would have required a total of 45 conductors: 1 power/active for each of the 44 valves plus one common. In contrast, the 2-wire encoders required only two conductors, connected in turn to each of the 44 encoders. Power to, and control of, each solenoid was provided through its 2-wire encoder.

Programmable Controller / Data Logger

An on-board programmable controller/logger interfaced with the base station controller for the sprinkler valves on the linear cart to automatically control irrigation to each plot in the alfalfa field. Utilizing a GPS receiver, the controller was able to determine the position of the linear cart within 3.5 to 5 feet and control which plots were turned on or off at any given time. Data was logged by the controller every 15 minutes with communication to the headquarters office via a license-free, 100 milli-Watt spread-spectrum radio.

The programmable controller/logger, coupled with individual solenoid valves on each sprinkler drop, provides flexibility to redesign plot treatments in the future. A new program written in Basic would simply be downloaded to the controller with no hardware changes required. In addition, variable rate irrigation treatments are possible by pulsing sprinklers or by toggling every other sprinkler on/off in sequence rather than running each sprinkler constantly.

SOIL MOISTURE MONITORING

Four soil moisture monitoring stations were installed in the alfalfa field, one in each irrigation treatment. Each station employed a programmable data logger with a 100 milli-Watt spread-spectrum radio for communication to the headquarters office. A total of four soil moisture sensors were connected to each data logger, measuring the dielectric constant of the soil to determine volumetric soil moisture. Moisture sensors were installed vertically at depths of 6, 18, 30, and 42 inches below the surface. A gas-powered auger was utilized to bore a separate hole to the appropriate depth for each sensor, which was then bedded in place with soil slurry.

Each station included a tipping bucket rain gauge, an18 amp-hour rechargeable battery, and 5-watt solar panel. Additional/deeper soil moisture sensors are anticipated for the 2008 growing season.

YIELD MEASUREMENTS

All yield estimates for each plot were provided by personnel from the Soil and Crop Sciences Department of Colorado State University. Usually on the same day as the alfalfa was swathed, Colorado State University staff would sample the yield from each of the 12 plots in the field. They would typically collect and weigh a 20-foot length of windrow (16-foot wide swath) from the center of each plot. Sub-samples were weighed and placed in paper bags for oven-drying and determining moisture content. Harvest of the alfalfa occurred on the dates indicated in Table 1 with the estimated yield data provided in Table 2.

Table 1. Alfalfa Cutting Dates.

	2006 season	2007 season
1st cutting	May 30th	May 29th
2nd cutting	July 17th	July 9th
3rd cutting	August 15th	August 8th
4th cutting	September 25th	September 21st

Table 2. Estimated Alfalfa Yields in tons per acre at 0 percent moisture.

Season	Irrigation Treatment	1st cutting	2nd cutting	3rd cutting	4th cutting	Total
2006	Full irrigation to meet crop ET	2.1	2.6	1.8	1.1	7.6
2006	Stop after 2nd cutting	1.8	2.6	1.5	0.5	6.4
2006	One irrigation after 1st cutting, resume irrigation after 3rd cutting	1.9	1.9	1.0	1.2	6.0
2006	Stop irrigation after 1st cutting	1.9	1.3	0.6	0.2	4.0
2007	Full irrigation to meet crop ET	3.1	2.3	1.8	1.3	8.5
2007	Stop after 2nd cutting	3.5	2.4	1.5	1.1	8.5
2007	One irrigation after 1st cutting, resume irrigation after 3rd cutting	3.5	1.9	1.3	1.3	8.0
2007	Stop irrigation after 1st cutting	3.1	1.9	1.2	1.0	7.2
Average		2.6	2.1	1.3	1.0	7.0

CROP WATER USE

The measured precipitation for all treatments is provided in Table 3. Precipitation during the 2007 growing season was more than double the precipitation in 2006 and may have contributed to the higher alfalfa yields in 2007.

Table 3. Measured Precipitation in inches.

	1st cutting	2nd cutting	3rd cutting	4th cutting	Total
2006	1.73	1.90	1.23	1.15	6.01
2007	7.53	0.27	4.19	0.92	12.91

The gross applied irrigation for each plot is provided in Table 4 as measured with an electronic flow sensor on the pump discharge line.

Table 4. Gross Applied Irrigation in acre-inches per acre.

Season	Irrigation Treatment	1st cutting	2nd cutting	3rd cutting	4th cutting	Total
2006	Full irrigation to meet crop ET	5.62	10.82	6.06	5.20	27.70
2006	Stop after 2nd cutting	5.62	10.82	0	0	16.44
2006	One irrigation after 1st cutting, resume irrigation after 3rd cutting	5.62	4.24	0	5.20	15.06
2006	Stop irrigation after 1st cutting	5.62	0	0	0	5.62
2007	Full irrigation to meet crop ET	2.85	7.14	7.25	5.17	22.41
2007	Stop after 2nd cutting	2.85	7.14	0	0	9.99
2007	One irrigation after 1st cutting, resume irrigation after 3rd cutting	2.85	2.89	0	5.17	10.91
2007	Stop irrigation after 1st cutting	2.85	0	0	0	2.85
Average		4.24	5.38	1.66	2.59	13.87

The crop water use in acre-inch per acre for each treatment is shown in Table 5 and was estimated as the sum of gross applied irrigation, measured precipitation, and change in soil moisture in the top four feet of the root zone. Losses to surface runoff (both rain and irrigation) were assumed to be negligible, as was deep percolation. To date, upward migration of deeper soil moisture was not quantified as contributing to crop water use. Further evaluation is needed in this regard.

Table 5. Estimated Alfalfa Water Use in acre-inches per acre.

Season	Irrigation Treatment	1st cutting	2nd cutting	3rd cutting	4th cutting	Total
2006	Full irrigation to meet crop ET	13.4	12.5	6.4	6.4	38.7
2006	Stop after 2nd cutting	13.4 est	12.0	4.0	1.8	31.2
2006	One irrigation after 1st cutting, resume irrigation after 3rd cutting	12.6 est	7.7	1.8	5.0	27.1
2006	Stop irrigation after 1st cutting	12.2 est	4.7	1.5	1.7	20.1
2007	Full irrigation to meet crop ET	10.7	7.6	6.2	9.0	33.5
2007	Stop after 2nd cutting	11.7	7.4	2.6	5.5	27.2
2007	One irrigation after 1st cutting, resume irrigation after 3rd cutting	11.1	6.8	2.7	7.0	27.6
2007	Stop irrigation after 1st cutting	10.8	4.3	1.0	4.4	20.5
Average		12.0	7.9	3.3	5.1	28.3

Table 6 provides the crop water use in acre-inches per ton of yield for each treatment. Values were calculated as the crop water use in acre-inch per acre divided by the yield in tons per acre at 0 percent moisture.

The season average for estimated alfalfa water use provided in Table 6 was calculated as the total season water use divided by the total season yield.

Table 6. Estimated Alfalfa Water Use in acre-inches per ton at 0 percent moisture.

Season	Irrigation Treatment	1st cutting	2nd cutting	3rd cutting	4th cutting	Season average
2006	Full irrigation to meet crop ET	6.4	4.8	3.4	5.7	5.0
2006	Stop after 2nd cutting	7.4	4.7	2.7	3.3	4.9
2006	One irrigation after 1st cutting, resume irrigation after 3rd cutting	6.6	4.2	1.9	4.1	4.6
2006	Stop irrigation after 1st cutting	6.4	3.7	2.3	8.5	5.0
2007	Full irrigation to meet crop ET	3.4	3.3	3.3	6.8	3.9
2007	Stop after 2nd cutting	3.4	3.1	1.7	5.2	3.2
2007	One irrigation after 1st cutting, resume irrigation after 3rd cutting	3.2	3.7	2.1	5.3	3.5
2007	Stop irrigation after 1st cutting	3.5	2.3	0.9	4.5	2.9
Average		5.0	3.7	2.3	5.4	4.0

SUMMARY

The 2007 season differed from conditions experienced during the 2006 season. Overall, the 2007 season had roughly double the precipitation. With more cloudy skies and cooler weather, crop water use was 13 percent lower in 2007. As a consequence, the required irrigation for well-watered alfalfa was 19 percent lower in 2007. These combined differences contributed toward 2006 season yields being 25 percent lower overall than yields from the 2007 season.

The study results to date indicate greater water use efficiency during periods of peak seasonal crop water use (2nd and 3rd cuttings). For all irrigation treatments, typically less water was required per ton of yield for the third cutting than earlier or later cuttings. Additionally, those treatments where irrigation was withheld during some period of the growing season averaged lower crop water use per ton of yield than the treatment that was fully irrigated to meet well-watered crop ET.

The authors acknowledge that a deep rooted crop such as alfalfa growing on a silty clay loam soil without rooting limitations will extract moisture from below the 4-foot depth monitored by the installed soil moisture sensors during 2006 and 2007. Increased/deeper soil moisture monitoring is anticipated for the 2008 growing season. It is likely this will increase the crop water use calculations in this study.

To date, capillary rise of groundwater and upward migration of deeper soil moisture has been neglected as contributing towards crop water use estimates. Further evaluation is needed in this regard and is anticipated for inclusion in future reports.

DISCLAIMERS

Northern Water does not in any way endorse or recommend equipment from any particular manufacturer or distributor. Mention of a specific make or model of equipment is provided for informational purposes only and is not intended to imply any preference, higher quality, better value, etc. The authors recognize that numerous other manufacturers market comparable equipment well-suited for irrigation. No comprehensive review of available equipment or any formalized screening process for selection of equipment was attempted.

ACKNOWLEDGEMENTS

Northern Water expresses appreciation for the collaboration of Dr. Neil Hansen and his colleagues from the Soil and Crop Sciences Department at Colorado State University. Their cooperation was essential to the success of this study.

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Irrigation water stress management study of vineyard transpiration with a sap flow meter

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ABSTRACT

Water balance models on non-irrigated vineyards are commonplace. Those models rely upon a correct estimate of plant transpiration rate. However, the transfer of existing models to irrigated vineyards under high evaporative demand is difficult. Irrigation practices during high vapor pressure deficit (VPD) have contrary and complex effects on vine transpiration. Monitoring vine sap-flow allows a direct assessment of vine transpiration rate and offers improved understanding of the effects that soil moisture gradients and VPD have on the plant's water deficit. Current vine-water status assessments are based on discontinuous, difficult, and time-consuming leaf-water potential measurements. Sap-flow measurements available now provide the vineyard manager with a continuous estimate of vine transpiration throughout the season. Assessing sap flow variations can indicate plant water status and provide a tool to optimize irrigation. We compare vine transpiration with stem water potential and soil moisture while explaining the advantages and inconveniences of this new method.

INTRODUCTION

Initial transpiration stress measurement was proposed in the 1992 National Irrigation Convention Proceedings (**Van Bavel, Michael G.** 1992, Stem Flow Gauges for Measurement of Crop Water Use, National Irrigation Convention Proceedings, (pg 59-72) and published in International Water & Irrigation Review (**Van Bavel, Michael G.,** 1993, System Solution for Real-Time Sap Flow Monitoring. International Water & Irrigation Review, Vol. 13, No. 1, 1993, pp.25-29.) In 1992 **Lascano** (Am. J. Enol. Vitic. Vol 43: (2)) published water use records on grapevines and confirmed the accuracy of the stem heat balance method.

In 1995 a closed loop method of controlling irrigation by a sap-flow monitoring system was proposed (**Van Bavel, M.G., 1995 -** Advances in micro irrigation control by sap-flow monitoring systems. Proceedings of the Fifth International Microirrigation Congress., ASAE., April 2-6, 1995, Orlando, Florida: 234-238). An integrated sap flow, ET weather station network, and transpiration modeling approach was described in 1996 by a Texas A&M study by Dr. Robert Lascano (**van Bavel, Cornelius, H.M., van Bavel, Michael G., Lascano, Robert, J., 1996 -** Automatic Irrigation Based on Monitoring Plant Transpiration. American Society of Ag Engineers, Proceeding of the International Conference Nov 3-6, 1996, pp 1088-1092.)

In 2002 the closed loop method was implemented by Dynamax Inc with the announcement of the FLOW4-IS Irrigation Scheduling system (US Pat No.).

There are two approaches possible for sap flow transpiration stress measurement. One approach would be to compare sap flow by set of well-watered plants with a set of plants in stressed conditions. This method requires two sets of plants and two independent records of sap flow, but could be performed without a weather station reference ETo.

The alternative explored in this study is to measure sap flow after irrigation when well watered, and then compare the sap flow on the same set of plants during stressed conditions. A benchmark crop coefficient (Kc) is then established in actual field conditions. The maximum transpiration can be calculated and compared to the actual transpiration for subsequent conditions of stress. This approach requires a weather station reference ETo, but only one set of sap flow readings.

The purpose of this study was to show the relationship between sap flow stress management and the more traditional water status derived from stem water potential measurements.

By comparing the effective transpiration by direct measurement with stem water potential, we show the utility of water stress measurement by packaged sap flow systems. A positive and strong correlation of the two methods will allow us to implement an effective vine stress water management method with an automated sap flow system, and thereby save labor, cost, and time required for more traditional alternatives.

MATERIAL AND METHODS:

Experimental sites and management practices: The study was conducted in 2006 in one California vineyard (Napa Valley, CA, USA). A follow up study was performed in 2007 in five vineyards in Napa Valley. Vineyard elevation is 80 m above sea level. Rows are oriented parallel to a downgrading slope oriented towards the Northeast. Vines (*Vitis vinifera* cv. Cabernet-Sauvignon) were planted in 1989, grafted over the rootstock 101-14 Mgt, in North East-South West rows, 1.8 m apart with a 1.5 meter within row spacing. Canopy hedging after growth stopped was performed on July 19th. Cluster thinning was performed on July 27th. Water volume per irrigation ranged from 0.9 to 8.8 mm per vine across the vineyard. There were 24 water applications events until harvest. Our plot consisted of 18 vines planted next to each other over 3 adjacent rows.

Soil Water Status: we determined available soil moisture for the plant along the soil profile explored by the sensors. We weighed the soil moisture measurements (volumetric content) by the thickness of each soil horizon where a sensor had been installed.

$$SM(t) = \sum_{i=1}^{i=5} f_i \bullet SM_i(t) \qquad \text{(Equation 1)}$$

where f_i is thickness of soil layer *i*, and $SM_i(t)$ is daily average soil moisture reading at soil layer *i.*

Plant Water Status: Stem Water Potential (SWP) was measured with a pressure chamber (model 600, PMS Instrument Co, OR. USA)., SWP was measured 30 times between May 15th and October 11th. Leaves were bagged with a plastic sheet and an aluminum foil at least 40 minutes before measurements following the methodology of Chone (2001). SWP was measured at solar noon on 3 leaves per vine and each leaf was located at the bottom part of the canopy (lower third), on the shaded side of the vine. Pre dawn leaf water potential were measured throughout the season on the same vine, just before the sunrise.

Sap Flow Transpiration Measurements

Sap flow was measured on two vines using the FLOW-4 DL logger (Dynamax, Inc., Houston, TX, USA). Sap flow measurements were scaled at the plant level according to the leaf area estimates on a per plant basis. The ratio of leaf area for measured vines over the total leaf area for the test area provided the conversion of sap flow to actual evapotranspiration (ETa) in mm.

Sap Flow Gages produced by Dynamax provided measurement of transpiration in selected vine cordons, avoiding irregular basal trunks or ground temperature gradient effects. The basis of the sap flow sensor is the energy balance method derived from a constant heat source applied to the plant stem (SHB method). The sensors are precision instruments that measure power transfer from a heater strip to the stem, the ambient and into the sap flow. Sap cools off the heater in varying amounts corresponding to the flow rate. The sap flow (F) was computed and saved in grams per hour and accumulated grams per day by a formula using the heat applied to the stem (Pin), the radial energy from the stem (Qr), the vertical conducted heat loss (Qv) and temperature differences (dT) of sap above and below the strip heater. The Flow4 system provided for this experiment recorded the signals and calculated the sap flow (F) with a well accepted energy balance formula (Van Bavel 1987):

$$F = (Pin - Qv - Qr) / Cp * dT \text{ (g/s)} \qquad \text{(equation 2)}$$

Various expert methods to filter out nighttime, weak or erroneous signals were applied so that calculated data values were consistent with generally accepted sap flow methods (Lascano, R.J., Baumhhardt, R.L., Lipe, W.N., 1992).

Meteorology and Phenology : A meteorological station provided data, less than 20 m from the experimental vines (Adcon weather station, Adcon International Inc., CA, USA). Air temperature, relative humidity (RH), photosynthetic active radiation (PAR) and wind speed measurements were recorded every 60 seconds and averaged every 15 minutes by a data logger. No precipitation was recorded between June 16th and October 2nd. During that period, daily temperatures showed an average value of 20 ^{0}C ranging between 13.9 ^{0}C and 26.8 ^{0}C for minimum and maximum respectively. The daily vapor pressure deficit was on average 1.18 kPa. Peak values for vapor pressure deficit reached 6.6 kPa and were recorded on July 17th and August 6th. Main phenological phases were recorded at all sites.

Leaf area index and fruit weight estimates: We estimated LAI in August when all the leaves were still green by using a direct method of measurement. First, to determine the leaf area per vine, we sampled 3 vines at each plot. We counted the number of shoots per vine and the total number of leaves per shoot on 6 shoots per vine. We randomly sampled 6 leaves per shoot along 6 shoots per vine. Leaf area was determined using a leaf area meter (model LI-3100, Lincoln, Nebraska USA). Leaf area index was calculated as follows:

$$LAI = Nsh \bullet Nlv \bullet LA \bullet d \qquad \text{(Equation 3)}$$

Where Nsh = number of shoots per vine; Nlv = average number of leaves per vine; LA = average leaf area/leaf; d =number of vines/m^2. Fruit weight per vine was estimated on harvest day for each plot. In both vineyards clusters were harvested and weighed from a number of vines per plots. Fruit weight was divided by the number of vines to get an estimate of the fruit weight per vine in each plot.

Soil and root: soil samples were extracted with an auger, 10 cm away from the vine row. We measured bulk density ($g.cm^{-3}$) and soil texture (% of clay, loam and sand) at 3 different depths ranging from 0.10 to 0.75 m. Bulk densities were between 1.19 and 1.34 g cm^{-3}. Sand content was between 29% to 48%. Root density along the soil profile was estimated from a 150 cm deep backhoe pit at each site. We counted the number of roots present in 5 different soil layers (0-20 cm, 20-40 cm, 40-55 cm, 55-70 cm, 70-90 cm). Soil moisture was measured using capacitance probe (C-Probe™ Agrilink Int. Inc., CA, USA). Soil moisture probes were placed under the vine row, 30 cm away from the trunk, at depths of 10 cm, 30 cm, 50 cm, 60 cm and 80 cm below ground. The data logger recorded one measurement every 5 minutes. We averaged to determine daily soil moisture content over the first 90 cm.

Additional data was taken in 2007 from three vineyards with the same variety, Cabernet Sauvignon, and included the same information as previously cited in 2006.

RESULTS

The problem with scheduling irrigation by only soil moisture or only by a water balance is the fine detail, and narrow moisture ranges needed to determine a site specifiic irrigation strategy. Furthermore the actual transpiration deficit varies widely due tho the plant response over a very narrow range of soil moisture found in realistic field conditions. The soil characteristics will also vary widely from one irrigation block to another, and the results may not be translated from one area to another. In Figure 1 the transpiration for a typical plant is shown varying over the season as the soil moisture changes. The soil water content through the root depth was measured as an average over 900 mm. Soil water content varied from .13 to .17 m3.m-3, yet the transpiration shows a variability of 175 to 400 g.d-1. End of the season tanspiration decreases as the vine senesces after harvest, and VPD and Eto decline. Eto for the season is shown in Figure 2. We found that Eto peaks at 5 mm . d –1 declined to 2 mm . d –1 as the season ended. Early and laste season stress and transpiration would not neccesarily correlate or depend on soil mositure.

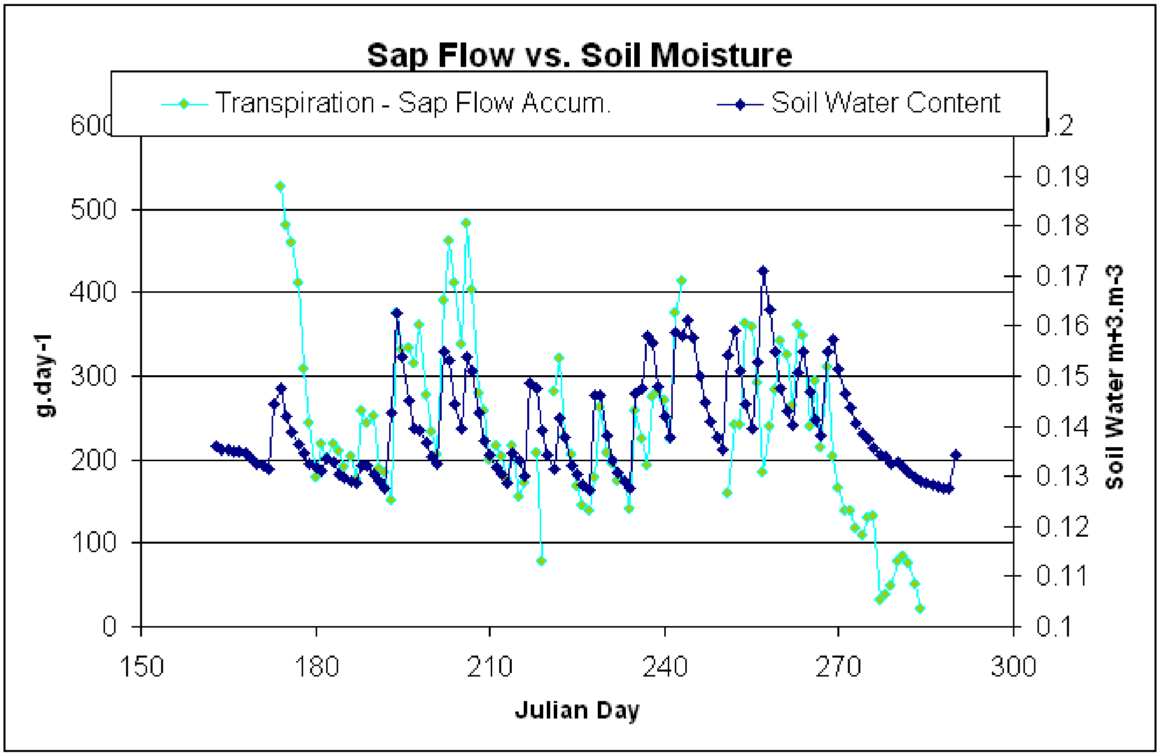

Figure 1. Relationship between Transpiration and soil moisture.

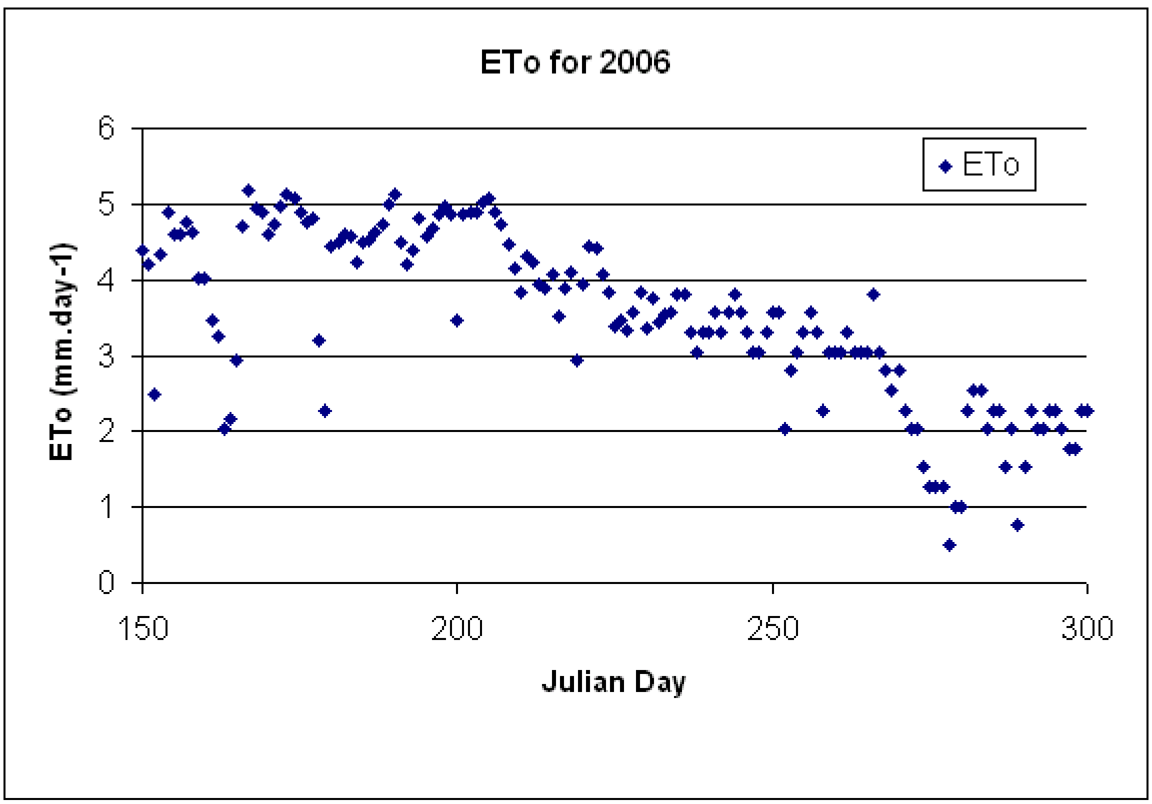

Figure 2. Eto, reference evapotranspiration during the growing season in 2006.

In Figure 3 the crop coefficient Kc is shown as the season progressed. The values represent a Kc from early season through a wide variation with respect to soil moisture. In the literature and in the FAO guidelines (Publ 56) there is no term for the real time crop coefficient, however we may borrow the term for Kc adj, the Kc determined from the ET c adj, which is defined as the evapotranspiration determined during non-standard conditions such as vines under water stress.

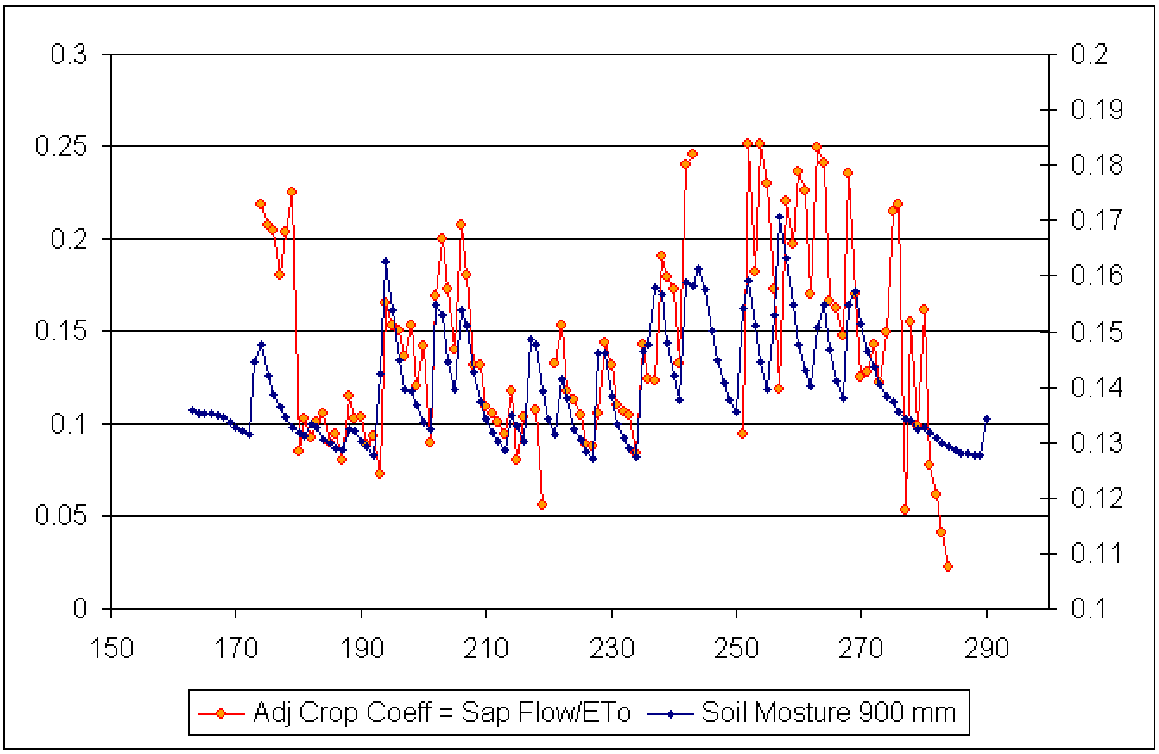

Figure 3 – Crop Coefficient Kc adj varying throughout the season, and under varying soil moisture conditions.

The irrigation events for 2006 are shown in Figure 4. The typical irrigation management method was used to induce stress, and to provide for a high quality wine grape product.

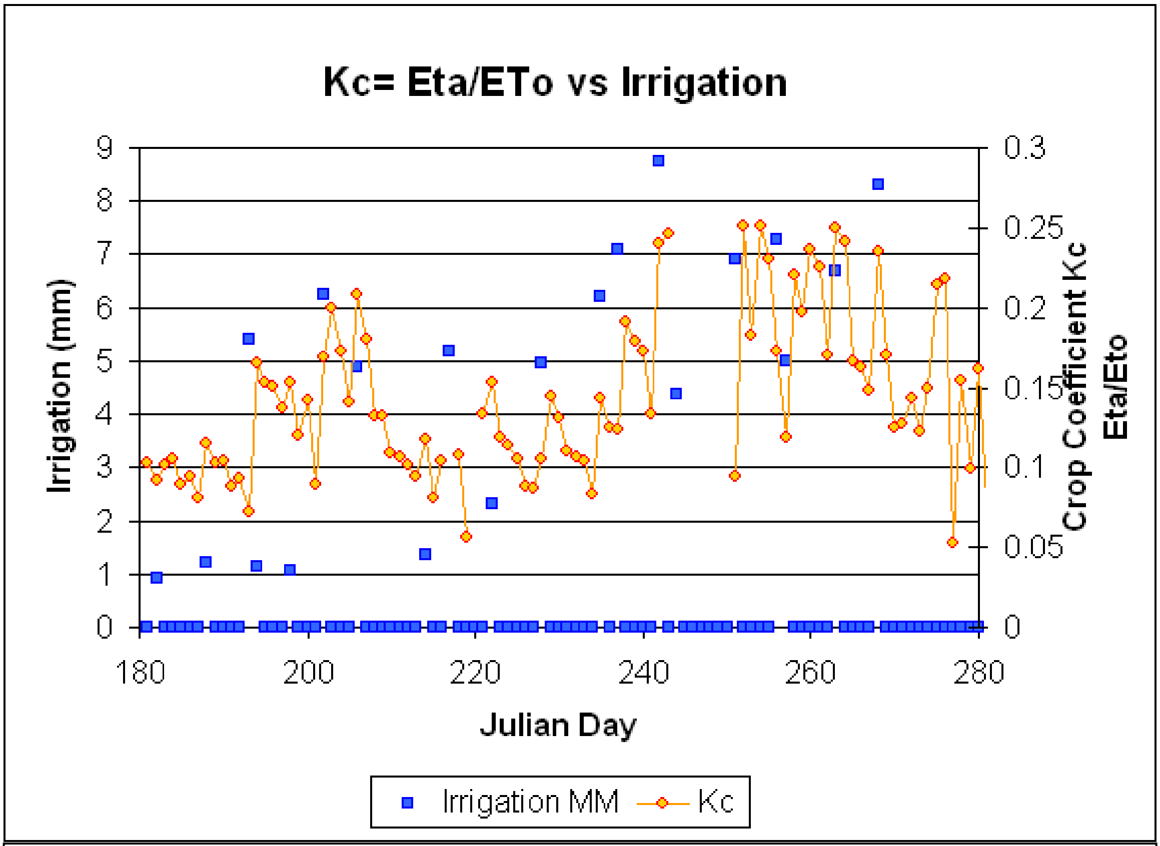

Figure 4 Relationship between Transpiration peaks and Irrigation events

Irrigation varied from 1 to 9 mm over the season to maintain a reletively high stress level, and no less than a -15 bar stem water potential. Note that the effects of water stress decreased rapidly after the large irrigation events, and daily transpiration increased Kc over 1.7 rapidly after almost all irrigations exceeding 5 mm in one day.

The 2006 stem water potential reeadings were made mid-day periodically, and irrigation adjusted, possibly scheduled on the same day, or on the following evening. As a result there was limited stem water potential data during well watered conditions. Figure 5 does show that there is a positive correlation to the SWP and the Kc adj. The Kc in this case was determined with transpiration readings from only two sensors, and adjusted by leaf area estimates. Thus we expected that with more sap flow sensors per plot, and more SWP readings before and after irrigation, a much clearer relationship will be determined and with improved correlation.

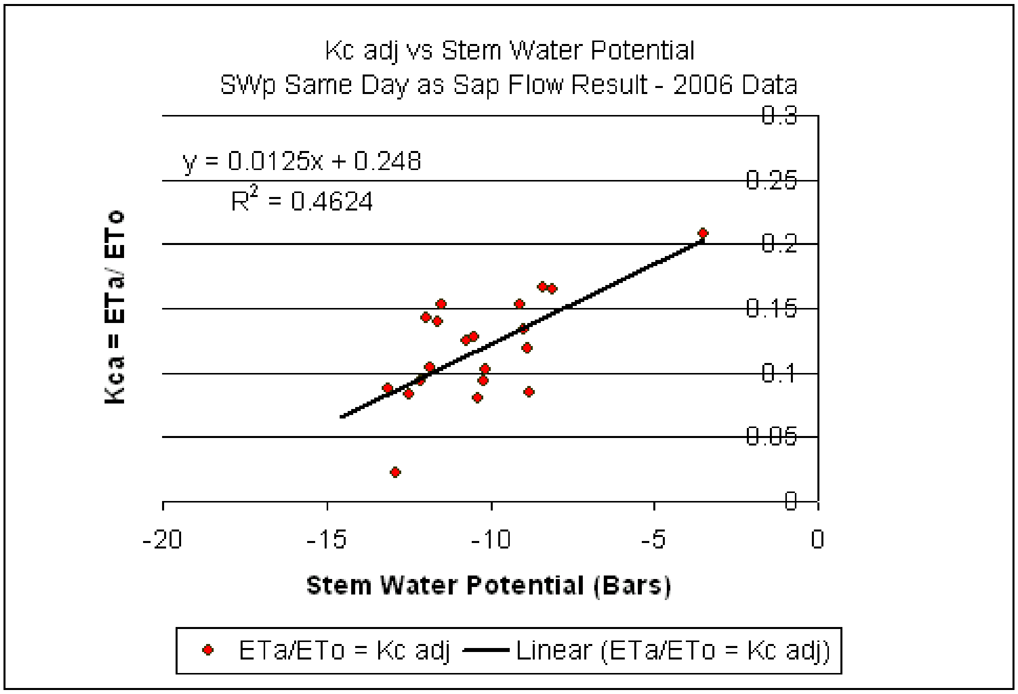

Figure 5 - Relationship between Kc adj and Stem water Potential

In 2007 we made an adjustment to the procedure by reading SWP much more frequently to determine a fixed relationssship between sap flow derived Ks, the stress coefficient and the stem water potential. In figure 6 there is consistent data showing that relationship between stem water potential and the varying crop stress factor Kc. The crop stress factor is provided in the FAO guidlines publication 56. (FAO Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56). After setting the leaf area parameters, the Flow 4 sap flow system automatically indexed sap flow to the irrigation block area. The ratio of the indexed sap flow on well watered days provided the Kc max, maximum ET over ETo. By calculating the reference ETo multiplied by the Kc max, we determined a maximum Etm for all days.

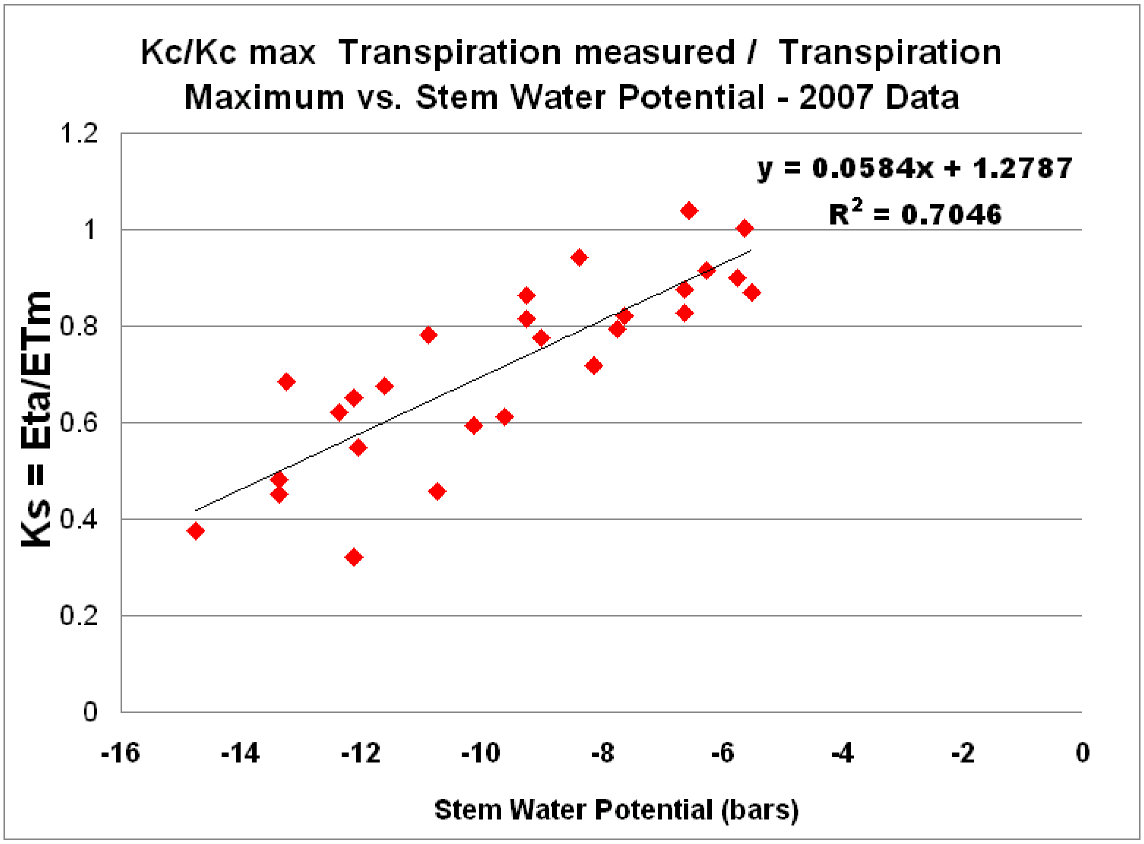

Figure 6 – Ks stress coefficient, with respect to stem water potential.

The Ks, stress coefficient with the sap flow method, is simply

ETa / ETm = Kc adj/ Kc max

on the day of concern, where Kc Max is determined under the well watered conditions (however see discussion on conditions). In 2007 we included a data set from three vineyards, on the same variety but with a great variation in spacing and plant leaf density, and thus the results are representative of several vineyards pooled together. By indexing the Ks with individually determined Kc adj, and Kc max, all the results are normalized in Fig 6. Each of the days with a SWP measurement, and a confirmed sap flow result are displayed in Figure 6.

Conclusions

Though the application of sap flow information we have concluded there is a direct relationship between the actual stress coefficient, Ks, and the stem water potential. By observing ETo, soil moisture, irrigation and resulting water balance before and after irrigation, we noted the trends that caused transpiration deficit. However the integration of all the factors appear in the final correlation of SWP to the transpiration devrived from crop stress. In Figure 6, the stress index was 1 (no stress) at a SWP of about 5 Bars. Since a deficit irrigation is in effect, the ususal crop coefficients commonly used by agricultural commmodities growers and irrigators are not confirmed here. Stress index at a SWP of -12 to –14 Bars indicate a transpiration drop of 50 % (Ks=.50) below the normal (deficit) irrigated transpiration.

The relationships showing a real time, daily, Kc adj, can be determined for a specific vinyard and variety. In fact this is needed if one intends to compare the Kc from one block to another. In the limited data set from 2006, there is a indication of the Ks (and Kc) to the SWP, however we conclude that at a minimum four sap flow sensor readings should represent a Eta measurement, and we conclude that at least SWP readings relationships should be observed from one to two days after an irrigation.

The next steps are to provide Kc relations and Ks factors to growers with a wider variety of wine grape vines, and under specif field arrangements. This study shows that is is possible to increase future improvements in projecting plant transpiration stress, and a yield and quality improvement production methodology based on sap flow stress measurment methods.

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Definitions:

(FAO Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56)

ET	evapotranspiration [mm day^{-1}]
ET_o	reference crop evapotranspiration [mm day^{-1}]
ET_c	crop evapotranspiration under standard conditions [mm day^{-1}]
$ET_{c\ adj}$	crop evapotranspiration under non-standard conditions [mm day^{-1}]
$K_{c\ ini}$	crop coefficient during the initial growth stage [-]
$K_{c\ mid}$	crop coefficient during the mid-season growth stage [-]
$K_{c\ end}$	crop coefficient at end of the late season growth stage [-]
$K_{c\ max}$	maximum value of crop coefficient (following rain or irrigation) [-]
K_s	water stress coefficient [-]
$ET_{c\ adj} = K_s\ K_c\ ET_o$	Formula defining Ks relative to ET adjusted for stressed conditions, ETC adj

Crop Growth and Soil Water Spatial Variability under a Variable Rate Center Pivot

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Abstract

Managing irrigation spatially can enhance water conservation and optimize water applications. Information and guidelines are needed on how to spatially precision-apply irrigation water with these systems. In this research, we investigated using soil electrical conductivity (EC) to delineate management zones for spatial water applications using variable rate irrigation systems. Our preliminary results indicated potential correlations between soil EC, spatial plant growth, and stomatal resistance.

Introduction

The reasoning for spatial water application is based on local site-specific problems that included spatial variability in topography, soil type, soil water availability, landscape features, cropping systems, and more recently for water conservation. Three examples of this include: 1) rocked outcrops in the Pacific Northwest, where water application to is discouraged because these areas are not suitable for crop production. 2) Rolling terrain, where water applications upslope can produce runoff resulting in dry soils upslope and ponded soils at nearby lower elevations under the same irrigation system. 3) Retrofit of existing pivots in Georgia and South Carolina under the USDA- Natural Resources Service Environmental Quality Incentives Program (EQIP) program using site-specific controls to enhance water conservation. These variable rate irrigation systems have recently been approved by as a best management practice for conserving water by the USDA-Natural Resources Service.

Although the technology for spatially applying water is available and has high grower interest, science-based information is needed on how to precision-apply water with these systems. Commonly, farmers with retrofitted systems are making educated guesses about spatial water application rates, based on past experience in their fields. Some researchers are working with growers to use soil electrical conductivity (EC) maps of fields together with historic yield maps to develop management zones (Lund, et al. 2001). Soil EC measurements in non-saline soils are driven primarily by soil texture and soil moisture. Those same factors correlate highly to the soil's water-holding capacity. Thus, an EC map can serve as a proxy for soil water-holding capacity, resulting in soil EC and yield maps that frequently exhibit similar spatial patterns. Sadler et al. (2005) identified critical needs for site-specific irrigation research that included decision support systems for spatial water application and improved real time monitoring of field conditions with feedback to irrigation systems.

To address these needs for determining an optimum method for prescribing spatial water application using variable rate irrigation systems, we initiated a study to evaluate soil based measurements (EC and soil water content) and their impact on plants. The objective of this paper was to evaluate the spatial plant response to water and soil properties on a highly variable coastal plain field.

Materials and Methods

In 2006, an experiment was initiated in a producer's field that has a center pivot retrofitted for site-specific irrigation. The field is approximately 40 ha in size, with half planted with corn and half planted with cotton. The farmer rotates these crops between sides annually. The grower's initial plan was to use the site-specific center pivot system to irrigate the corn and cotton separately, but not to vary water application rates within each crop. Soil electrical conductivity was measured with a Veris 3100 EC Soil Mapping System in April 2006. An EC map of the field is shown in Figure 1.

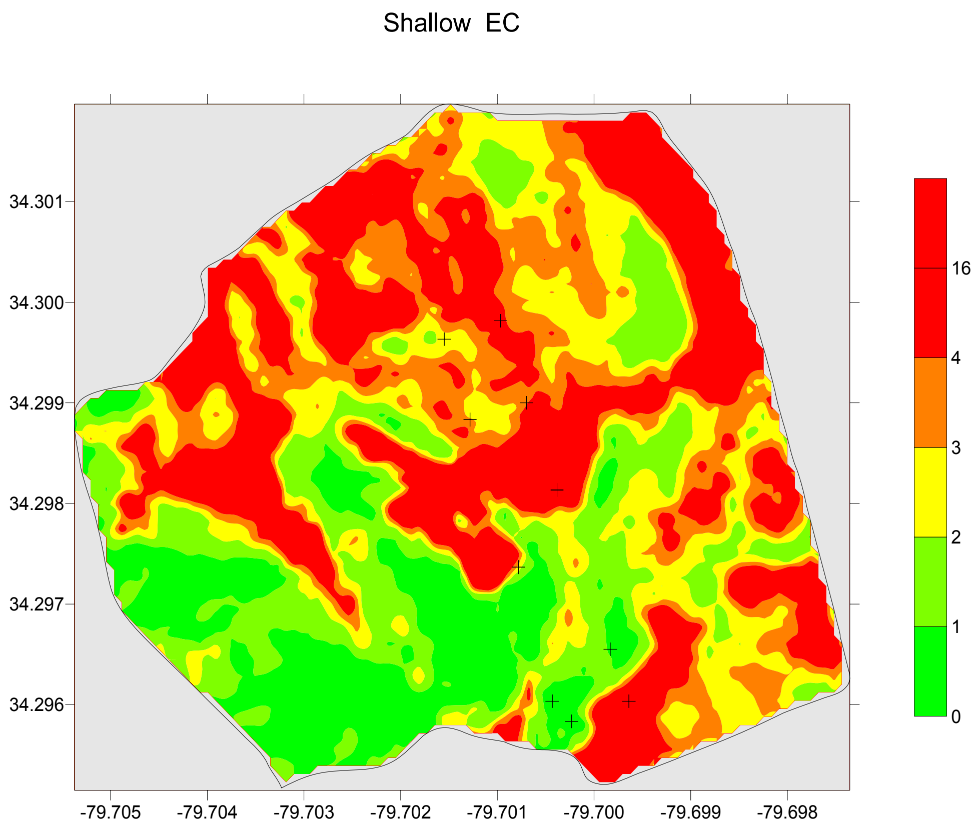

Figure 1. Soil EC map of the entire field. Crosses show approximate location of the 10 sampling points where data on cotton growth and water status were collected through the growing season.

To assess variability within this field and to provide guidance for spatially irrigating within the cotton crop, ten 0.1-ha areas on each side under the center pivot were monitored. Selection of sites was based on EC, slope, and surface soil texture. At each of these ten sites, an access tube was installed for a Delta-T PR2/6 Profile Capacitance Probe measuring water content at six depths (10, 20, 30, 40, 60, and 100 cm). Soil water content was determined regularly through the growing season.

Leaf stomatal resistance was monitored on the uppermost fully expanded leaf with a Decagon Leaf Porometer (Decagon Devices, Pullman, WA). Cotton plant height was measured on 10 plants at each site from June through mid-August.

At the end of the season, a two-row cotton picker with a yield monitor was used to collect yield data at six of the ten sites. Wet soil conditions at harvest prevented sampling for yield at four of the sampling sites.

Results

The rainfall plus irrigation for 2006 growing season had several periods of 5-10 days with little to no water application (Figure 2). These short periods without rainfall (5-10 days) are common through the growing season in the southeastern US. The rainfall from late June though July had 20-25 days with no rainfall or irrigation which allowed for the measurement of crop stress parameters.

During the period from June 29, 2006 to July 18, 2006 with no rainfall, leaf stomatal resistance was measured on three dates (6/29, 7/7, and 7/18). During this period, the stomatal resistance increased for the 10 sites as water stress intensified. The stomatal resistance increased faster at sites with low and with high soil EC than at sites with intermediate EC.

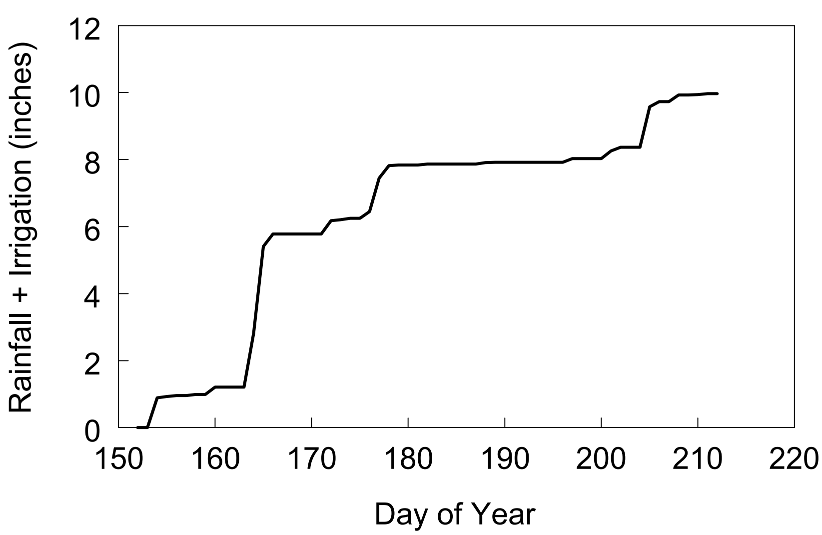

Figure 2. Cumulative irrigation and rainfall for the 2006 cotton crop.

Cotton plant height varied substantially among the different sites. Plants grown on high EC soils were larger early in the season. When stress occurred around day 190, height did not change much for the cotton on the lowest and the highest EC soils. Meanwhile, cotton on soils with intermediate EC levels continued to grow during this time. Yields for the six sites sampled ranged from about 1350 kg seed cotton per ha to 2450 kg seed cotton per ha.

Conclusions

These preliminary data suggest there is potential for using soil EC for spatial irrigation management on southeastern US coastal plain soils. Plant growth responses and stomatal responses to water deficit stress varied for the different soil EC levels. Initial spatial irrigation applications could potentially be delineated using soil EC. Additional studies are planned with more in-depth evaluations on additional study sites.

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MANAGING SPRINKLER IRRIGATION USING IN SITU INFILTRATION DATA

Robert W. Molacek, P.E., Randy Kramer, Dave Dearstyne[1]

ABSTRACT: The Lower Gunnison River Basin, located in Western Colorado, historically has had adequate water to support flood irrigation of over 135,000 acres. However, with six years of drought and water in the region declared over appropriated, farmers and ranchers are beginning to recognize the advantages of sprinkler irrigation. Over the last four years, the number of installed sprinkler irrigation systems has increased dramatically within the basin. In response, the local Natural Resource Conservation Service (NRCS) field office and Delta Conservation District began gathering soil infiltration data in March 2007 to help with sprinkler design and to support management recommendations given to producers switching to sprinkler irrigation. Soil infiltration data were gathered to correlate with soil textures, management practices and permeability data. These data are currently being used to determine design flows, sprinkler application rates and best management techniques for areas converted to sprinkler irrigation. Preliminary results show higher soil infiltration rates than previously documented by NRCS. In addition, data reveals that management practices play a larger role in increasing infiltration rates than soil textures.

INTRODUCTION

Delta Conservation District is located in west-central Colorado and includes Delta County and portions of Montrose and Gunnison counties (Figure 1). In Delta County alone, approximately 71,000 acres are irrigated and over 75,000 acres are considered prime or unique farmland (USDA 1979). Primary agricultural products include livestock, fruits, vegetables, sweet corn, and melons. Alfalfa hay, grass hay and corn for grain account for the largest acreage of harvested field crops. Surface flood irrigation has been the preferred irrigation method.

After several years of drought (2001-2006), farmers and ranchers began exploring more efficient irrigation systems. As the benefits of sprinkler irrigation systems began to emerge: increased production, reduced water use and decreased labor costs; demand also increased.

To better manage the increased use of sprinkler irrigation, NRCS and the Delta Conservation District began gathering soil infiltration data to help with sprinkler design and to support management recommendations given to producers switching to sprinkler irrigation. The program objective was to identify the expected soil infiltration rate for different soil surface textures under various management techniques. The specificity of this information will allow a better match between sprinkler design flows and soil and management conditions. In addition, irrigation professionals will be better prepared to problem solve with landowners who are experiencing irrigation difficulties.

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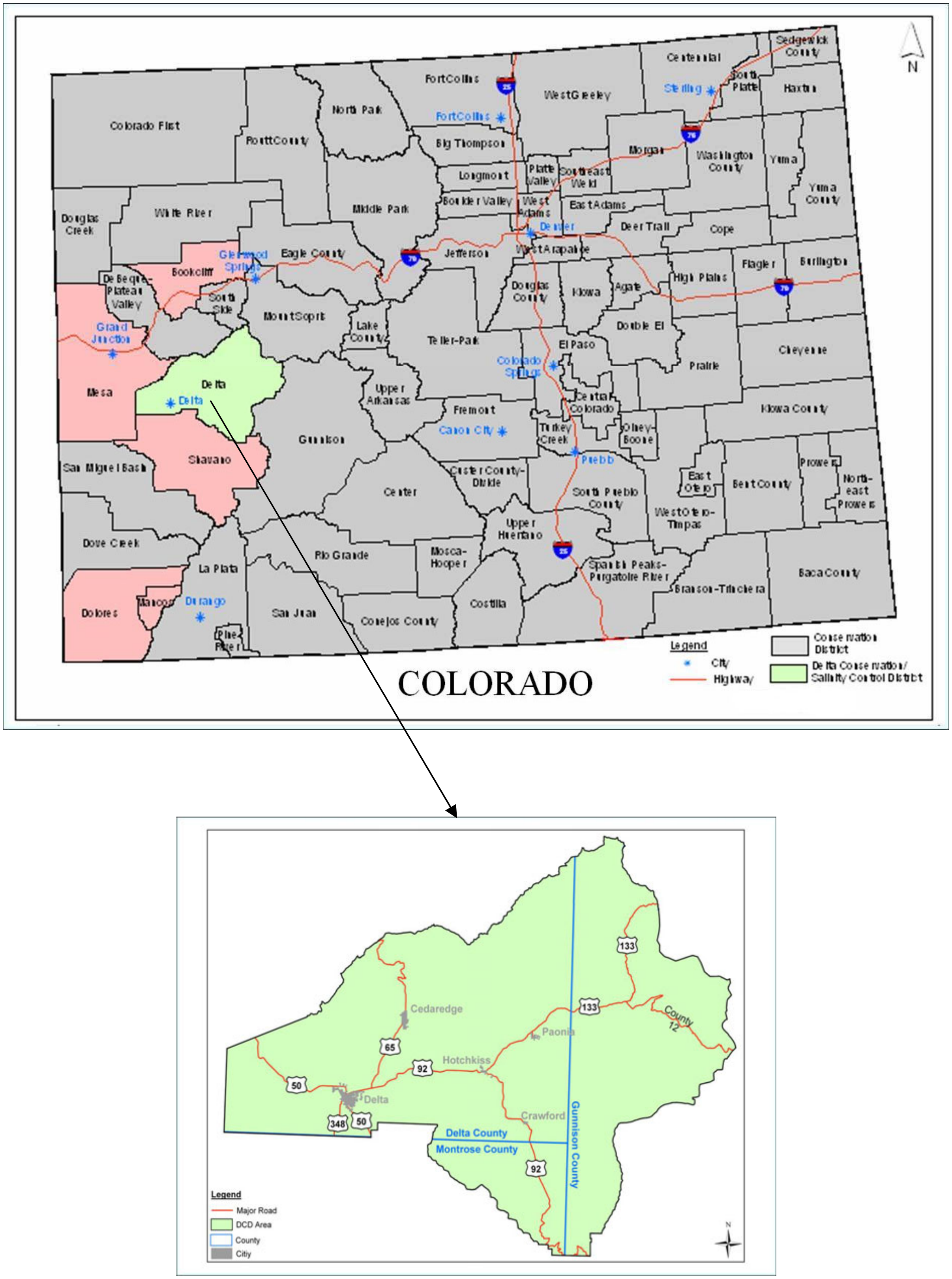

FIGURE 1: Study Area

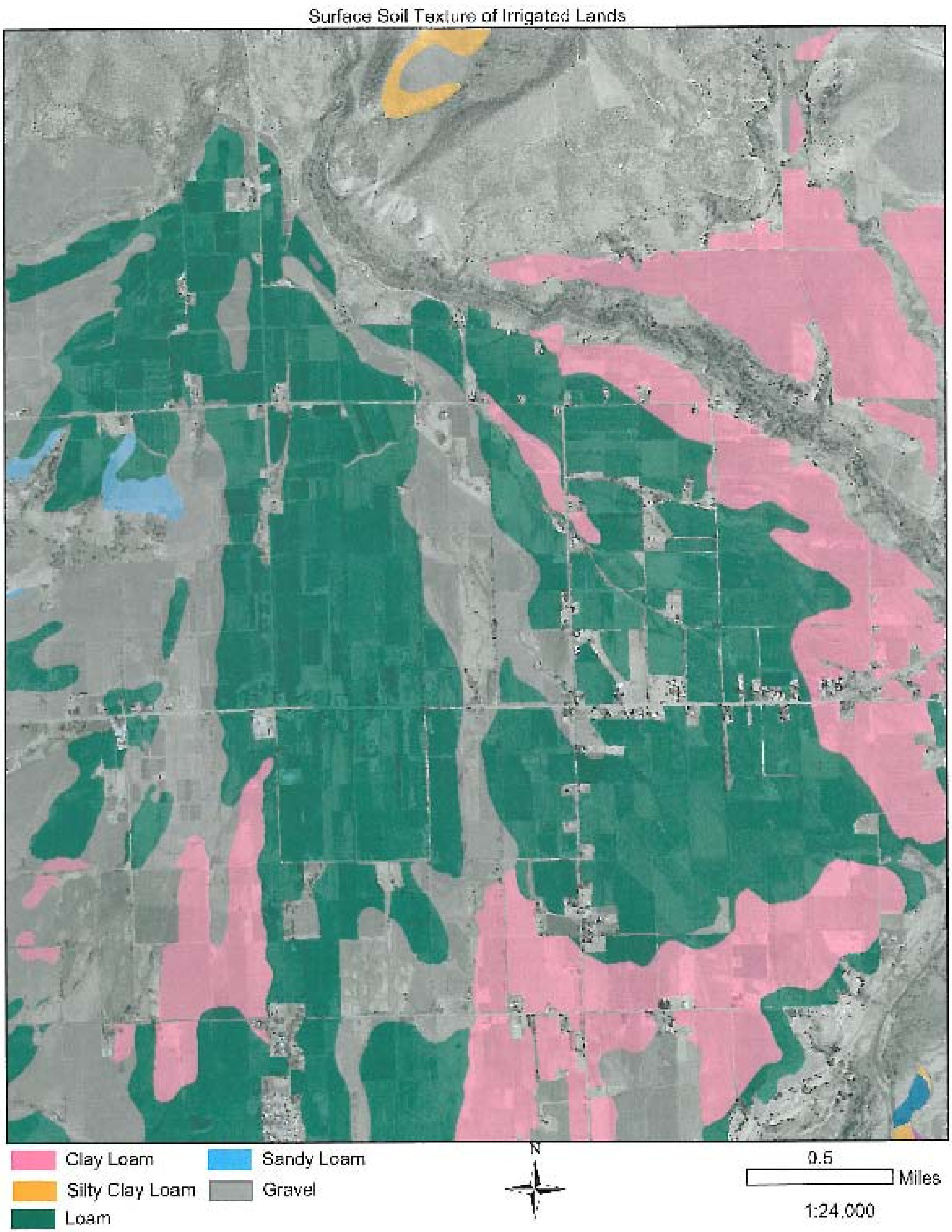

FIGURE 2: Example of Mapped Surface Soil Textures

METHODS

Surface soil textures were mapped using Geographical Information System (GIS) soil data obtained from soil surveys to identify soil infiltration testing locations (Figure 2). Initially, testing locations were selected where new sprinkler systems were planned in areas with finer textured soils. Subsequent testing was preformed on most dominant surface soil textures located in the area.

In the study area, the dominant surface soil textures on irrigated soils are clay loam, silty clay loam and loam. Prior to the collection of infiltration data, the limited available permeability data from the soil survey information showed maximum sprinkler application rates ranging from 0.2 to 1.0 in./hr. for these soils. This raised concerns about the effectiveness of sprinkler irrigation, since most sprinklers are not well adapted to soils with low infiltration rates.

Infiltration data were collected using a Cornell Infiltrometer (Figure 3; Ogden 1997). This rainfall simulator was simple to operate and convenient to use in the field. Operation required only minimal training. Rapid and replicated measurements were obtained in minimal time.

FIGURE 3: Infiltration testing with Cornell infiltrometer

For each testing site, the following information was also collected:

- Available soil data (soil mapping unit, soil description, mapped surface texture, parent material and permeability and maximum sprinkler application rate (if available);
- Soil sample data (observed soil texture, structure, moisture and root structure);
- Management practices (type of irrigation, current crop, estimated ground cover, surface residue, type of tillage, date of last tillage, and # of irrigations since last tillage).

Soil samples were also taken from each site for hydrometer and calcium carbonate laboratory tests. Hydrometer testing was conducted to determine the proportion of sand, silt and clay in the soil. This method quantitatively determines the physical proportions of three sizes of primary soil particles as determined by their settling rates in an aqueous solution. The amount of calcium carbonate in the soil was determined to better understand how its silt/clay particle size and cementation characteristics influence infiltration.

Management practices were documented based on site observations and discussions with the landowner. Management practices were placed into several categories based on tillage techniques, crop residue and grazing practices. Management categories included:

1. Row crop:
    a. Minimum till to minimum till (>75% residue),
    b. Conventional till to minimum till (>75% residue),
    c. Conventional till to minimum till (<75% residue),
    d. Conventional till to conventional till (<15% residue).

2. Hay crop:
    a. No grazing
    b. Grazing at appropriate time and intensity,
    c. Grazing at appropriate time, low intensity,
    d. Grazing at appropriate time, high intensity,
    e. Grazing with poor timing, appropriate intensity,
    f. Grazing with poor timing, low intensity,
    g. Grazing with poor timing, high intensity.

Minimum till represents soil that is left undisturbed from harvest to planting except for nutrient injection and the soil surface is covered with over 75% crop residue. Conventional till leaves less than 15 percent residue cover after planting (CTIC 2006). Hay crop management categories are based on grazing practices. Grazing practices are based on an evaluation of how well forage quality matches animal units and the grazing schedule (USDA 2003).

Soil infiltration data were plotted to obtain steady-state infiltration rates. Soil infiltration rates were categorized by soil texture and management technique. Data were reviewed to determine if correlations exist between soil infiltration rates and surface soil textures for the various management practices. Graphical trends were examined to evaluate preliminary results. Statistical analysis will be performed as additional data are collected.

Future analysis will evaluate if the amount of calcium carbonate in the soil correlates with infiltration rates. In addition, infiltration rates will be compared to available soil permeability data to see if permeability can be used to accurately predict soil infiltration rates.

PRELIMINARY RESULTS

Figure 4 displays the typical infiltration curve that resulted from the Cornell infiltrometer test. The infiltration rate increases as the dry soil is wetted and decreases over time until it reaches a steady-state condition. Table 1 and Figure 5 show the average infiltration rates recorded for a specific soil texture with various management techniques. Similar figures will be developed for other soil textures as additional data are collected.

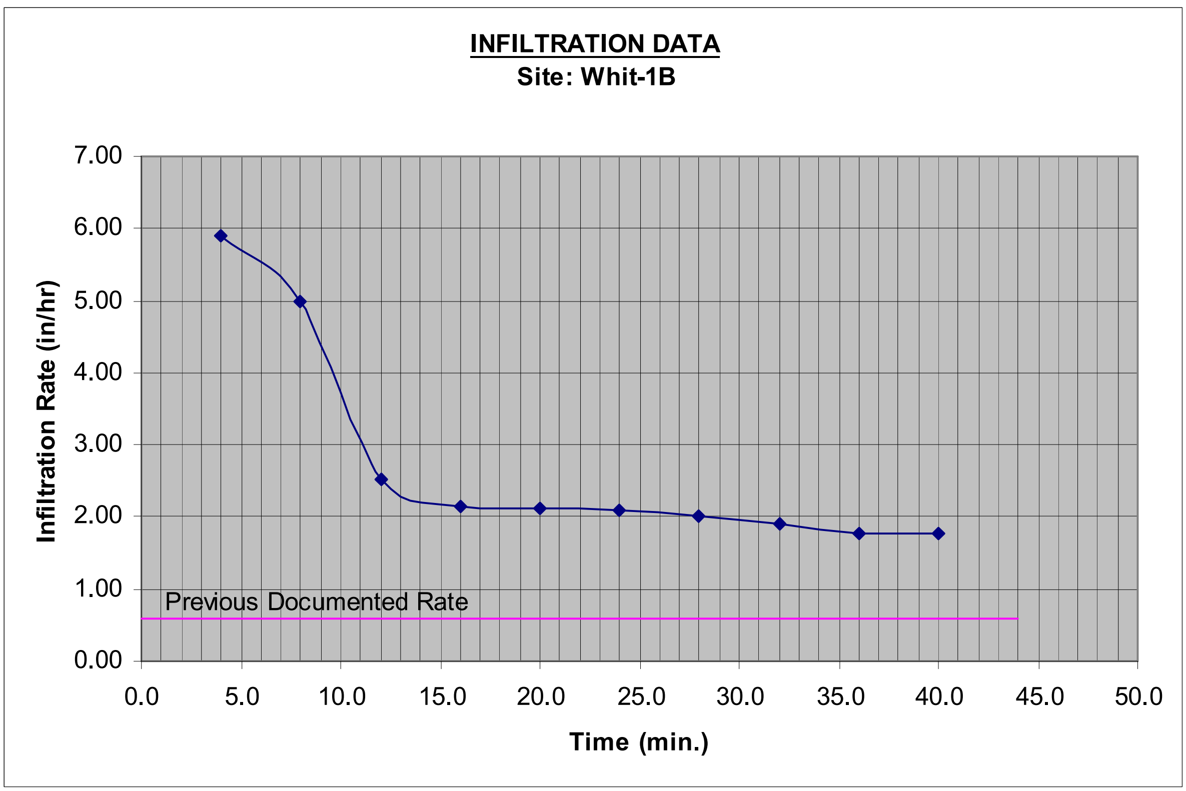

FIGURE 4: Typical Infiltration Curve

	Average Infiltration Rates (in./hr.)					
	ROW CROP		HAY CROP			
	Surface Soil Textures					
Management	**Silty Clay Loam**	**Clay Loam**	**Loam**	**Silty Clay Loam**	**Clay Loam**	**# of Samples**
Minimum till to minimum till (>75% residue)	7.1					4
Convention till (<15% residue) to minimum till	5.5					1
Conventional till to minimum till (<75% residue)	4.3	4.2				2, 2
Conventional till to conventional till (<15% residue)						0
No grazing			6.6		6.2	1, 2
Appropriate timing and intensity			5.0	5.0		2, 1
Appropriate timing, low intensity						0
Appropriate timing, high intensity						0
Poor timing, appropriate intensity				1.8		1
Poor timing, low intensity						0
Poor timing, high intensity					1.6	1

TABLE 1: Preliminary Results

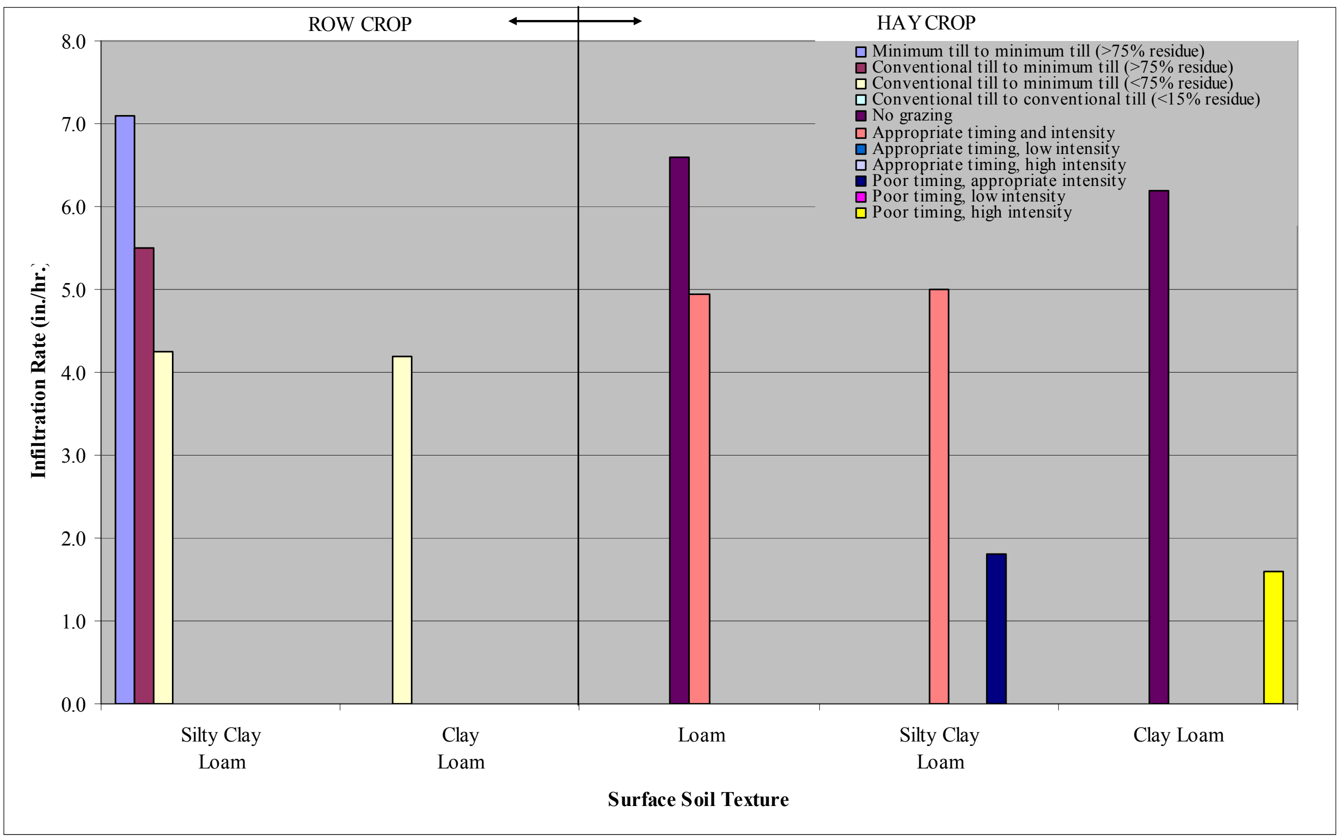

FIGURE 5: Preliminary Results

CONCLUSIONS

Preliminary results suggest that management techniques play a larger role in increasing/decreasing infiltration rates than soil textures. Management techniques greatly impact factors that influence infiltration, such as surface soil structure, soil pore space, compaction and amount of organic matter present in the soil. Soils that maintain blocky structure, high organic content, continuous pore spaces and limited compaction result in higher infiltration rates and more effective sprinkler irrigation.

Infiltration rate were also higher than previous documented by NRCS. This is a result of how previous data were collected. The previous data were based on constant-head permeability tests performed in the laboratory without consideration of existing management conditions.

Additional data are required for statistical analysis. Additional data will better define confidence intervals for mean infiltration rates for various soil textures. In addition, infiltration rates should be tested to see if they are statistically different for various management techniques.

These data are currently being used to select design flows and application rates for sprinklers being installed, to support management recommendations and trouble shoot previously installed sprinkler irrigation systems that may not be working effectively. As additional data are collected and correlations are statistically tested, sprinkler designs will continue to improve across the wide variety of soil conditions in our region.

ACKNOWLEDGEMENTS

We would like to extend our thanks to the Delta Conservation District Board of Supervisors and Colorado NRCS Soil Survey Team for dedicating staff to this effort as well as the State NRCS Office for supplying the testing materials.

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2007 Technical Conference of the IA

Selection of Pressure Reducing Pilots for Low Volume Irrigation Systems

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Abstract

Hydraulic pilots are used for pressure regulation of hydraulic valves. Typically, a combination of normally- closed pressure-reducing pilot is used in low volume irrigation systems. This configuration is presented in the following study as an example.

As all irrigation devices, hydraulic pilots are made to conform to the industry requirements and quality standards. Yet, there is no standard for the hydraulic performance. The specs are set by makers, and obviously, the products are varied in some important features. Thus, selection of an appropriate pilot requires relevant data, especially for applications that include thin-walled pipes or brackish water supply,

Typical requirements are precision, repeatability, smoothing of pressure surges and high clogging resistance.

The study analyzes differences between 2-way and 3-way modes, regarding the in-field conditions.

Some quantitative hydraulic tests were devised and applied to define different pressure pilots. These tests include: flow characteristic, hysteresis, rebound, precision and repeatability. Consequently, we developed a methodical approach for selection or definition of hydraulic pilot.

Typical Conditions of Low-Volume Irrigation

Application of low-volume irrigation systems requires a typical set of specs. High precision and minimal headloss in a low working pressures in one hand. High resistance for clogging, corrosion, wear and outdoor conditions at low overall cost on the other hand. Hydraulic pilots are no exception to that.

High chemical resistance is critical because low volume irrigation combines fertigation, chlorination and acid flushing as routine practices. That means, that the devices materials should withstand low and high pH, high chlorine content and other chemical deteriorating agents.

Using reinforced plastics for hydraulic designs is a very good solution. Plastics feature low weight, low cost and robust material. Plastic materials withstand chemical and outdoor conditions.

In many cases low volume irrigation systems use brackish water. Consequently, the suspended solid content is relatively high. The suspended solids are widely variable in size and source. Soil particles as clay, silt and sand, are always found in water. Micro-fauna and micro-flora dead and alive are abundant and proliferating, looking for a chance to settle down. All this population is a constant risk of clogging water passages, small orifices or sharp corners. The flow of suspended solids continuously grinds passages and orifices. The design and materials should withstand that as well.

Last but not least are the cost considerations. Low volume irrigation systems are cost effective. New designs and material selection should comply with it. For example, needle valve is replaced with simple orifice; stainless steel screen is replaced with fixed plastic grid. These replacements are cost

Hydraulic Valves

By definition, hydraulic valves are operated by the water line pressure by means of membrane or piston. There are many designs of hydraulic valves in irrigation applications. The valves designs are different from each other by construction, hydraulic characteristics, materials, endurance and cost. According to the requirements of low volume irrigation systems, a typical valve is made of reinforced plastics or cast iron and has one-chamber over an EPDM membrane.

The valve is operated by controlling the volume of the water at its chamber. The headloss of the through flow is depending on the membrane geometry. When the chamber is empty of water, the membrane conform to the walls of the chamber, the water passage through the valve is fully open. In this case, pressure headloss across the valve is minimal. The specific headloss of fully opened valves are defined by the flow factor **Kv** as cited by most makers.

$Kv = \mathbf{Q} / (\sqrt{\mathbf{\Delta P}})$ Where,

Q- Flow rate [m3/hr)

ΔP- Head loss [Kg/cm2]

When the chamber is partially full by water, the membrane swell and decrease the water passage inside the valve and increase the local headloss across the valve. When the chamber is full, the membrane closes the water passage and valve is closed.

The principle of operation is illustrated in fig 1 below. Another single chamber design is shown in fig 2 below.

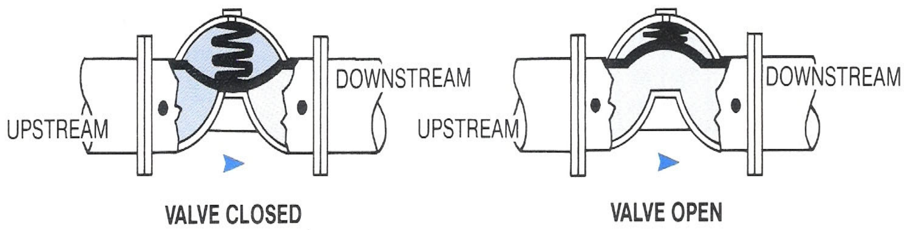

Fig 1: Hydraulic Valves: Principle of Operation

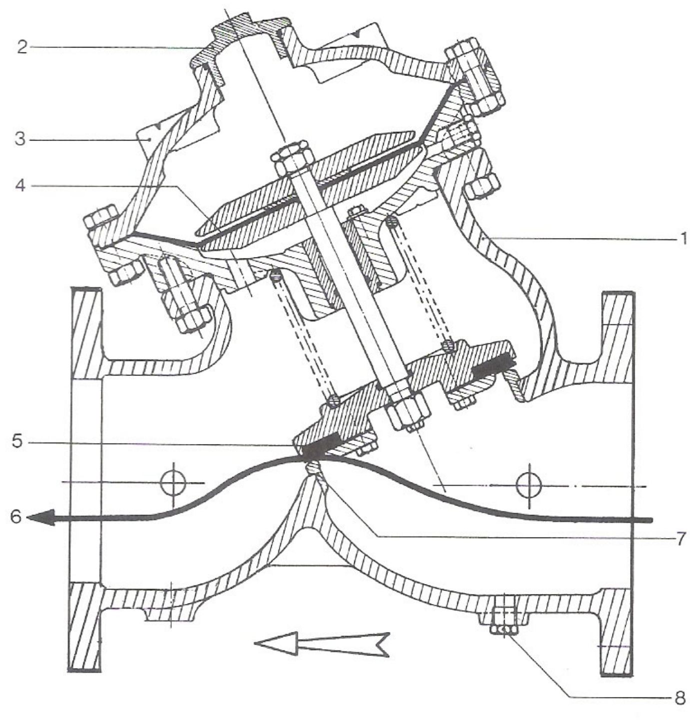

Fig 2: Globe Type Hydraulic Valve with one-chamber

Pilot Valves

Pilot valves are devices that control hydraulic valve according to external signal.

As explained above, the control of a hydraulic valve is done by changing the water volume inside its chamber. Possibly, the drained (to open the valve wider), filled (to close it) or maintained (to hold).

The signals are communicate through few media: electrical, hydraulic or pneumatic. Practically, in low volume irrigation, only solenoids (electric) and hydraulic pressure sensors are used.
This paper deals with one pilot application namely, Pressure Reducing. PR pilots are divided to 2-way and 3-way as explained here below. Selection of either configuration depends on the application and field condition. The two configurations are shown schematically in fig.3.

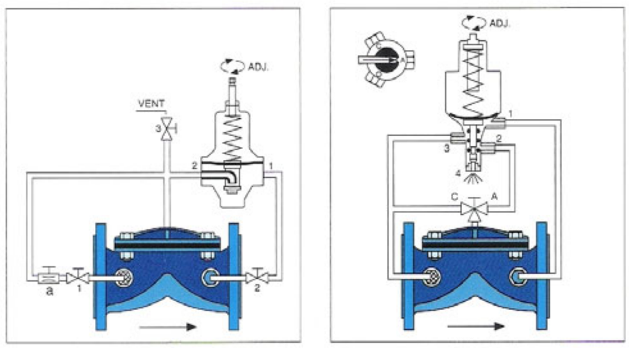

Fig 3: Schematic 2-way & 3-way configurations

Two-Way Pressure Reducing Pilot
2-way PR pilot is illustrated schematically in fig 4 below. The ports are connections are as follow:
In- is connected to the chamber which has a continuous supply of upstream flow.
Out- drains the chamber to the downstream.
Thus, when downstream pressure is too high, the pilot is closed as shown below. The chamber is filled with upstream water and consequently the membrane suffocates the through flow of the valve.
When downstream pressure is lower the pilot opens as shown to allow draining of the chamber and consequently increasing the water passage through the valve.
Note that draining of the chamber is possible only if the inflow to the chamber (not shown) is much less than the outflow. This feature is represented by the needle valve **(a)** in the illustration above. In all new designs the needle valve is replaced by a small orifice and screen filter.

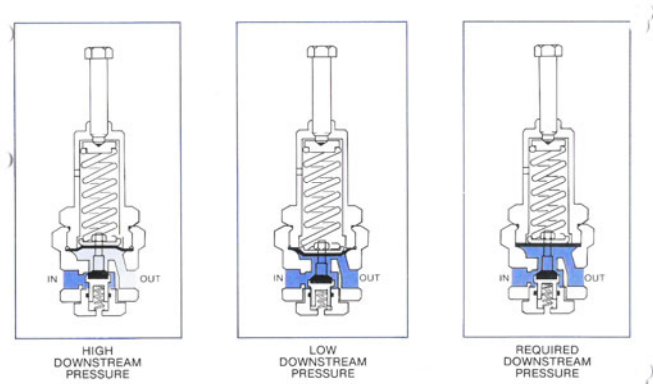

Fig 4: Schematic Operation of PR 2-way Pilot Valve

The pros of the 2-way pilot valve are:

- Fast response to pressure modulations
- Relatively high precision: ±0.2 bar.
- Integral design (that combines valve body and PR pilot into one unit) is possible, i.e. Aquanet valve.
- No spill of water.
- Excellent for modulating upstream pressure and alternating flow conditions.

The cons are found as well:

- The operational head loss in 2-way pilots is 0.5-1.0 bar.
- The valve passage is never fully open, thus the head loss is always above the flow factor.
- Considerable amounts of water flow through the pilot body and the tiny orifice (or needle valve). Clogging of that orifice eliminate the pilot! Thus, continuous maintenance is crucial.

Three-Way Pilots

A schematic 3-way PR pilot is shown in fig 5 below. Port 1 is connected to the downstream pressure (sensing pressure). Port 2 is connected to the chamber, port 3 is a vent to the atmosphere and port 4 is connected to the upstream pressure (operational pressure).
When the downstream pressure is low, the spring overcome the membrane, pushes the plunger down and allow connection between ports 2&3. The chamber drains to the air (by spilling water), the membrane let the valve open. Possibly, valve may remain fully open.
In case of high downstream pressure the membrane is pushed back, and the plunger moves upwards, connecting the chamber to the upstream pressure. Thus the valve is closed.

If the downstream pressure is within the "neutral zone" (see fig. 6) the plungers stay still, without water flow.

Thus, 3-way pilot has three downstream pressure zones : low, high and neutral. In normal conditions, low volume systems work constantly without considerable pressure modulations. Most of the time, the pressure is within the neutral zone keeping the pilot unchanged. In this case, there is no water flow, no risk of clogging and no water spill. 3-way pilots are excellent for low volume applications.

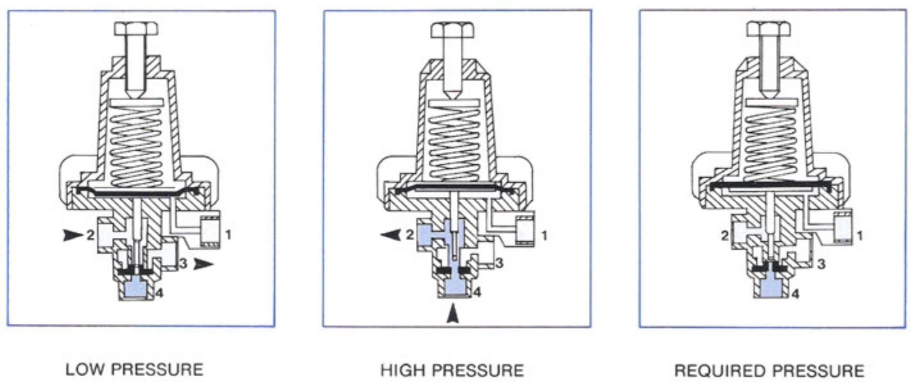

Fig 5: Schematic Operation of PR 3-way Pilot Valve

3-way pilot of any design has a built-in hysteresis. Hysteresis is a friction phenomenon that causes a different behavior of the system for increasing and decreasing branches. A typical hysteresis is shown in figure 6. **P1** and **P3** are the switching points. That means, that if the sensing pressure is less than **P1** the chamber drains to the atmosphere, and if it greater than **P3** the chamber is connected to the upstream pressure. If the downstream pressure is in the neutral zone between these values the chamber is disconnected from the other ports.

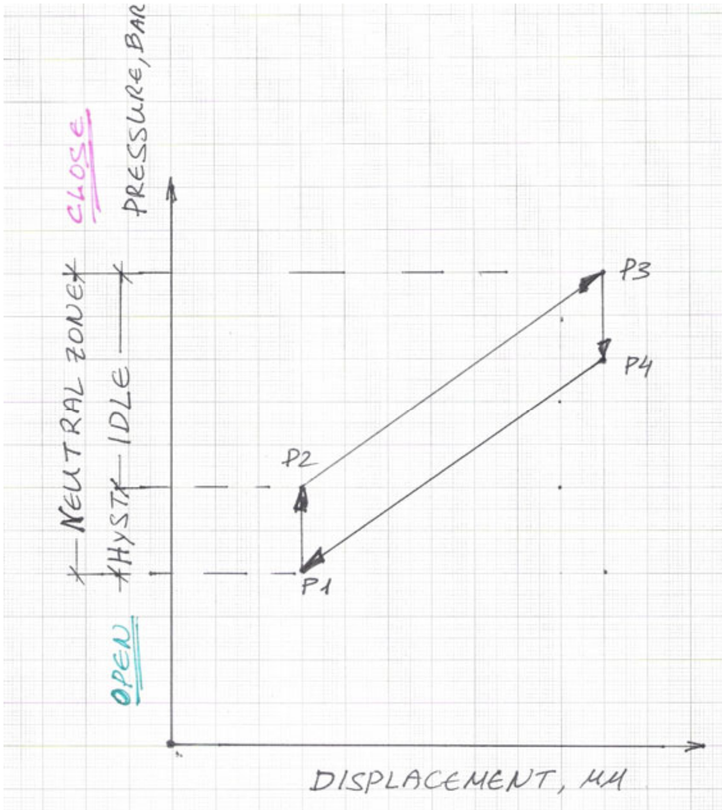

Fig 6: Characteristic diagram of a Pilot Valve

The data was collected using a 3-way pilot, as shown in fig 5. Port 1 (sensing port) was connected to a regulated pressure source. Port 2 was connected to an operation pressure source. When the sensing pressure was gradually increased the pilot valve switches from one port to the other- due to the movement of the plunger- at certain pressures. Same process was repeated while the sensing pressure was gradually decreased. The data is shown in table 1. This procedure was repeated for different set pressures.

Rep.1

Pressures:	[bars]		
Set Pressure	**1.2 bar**		
	Switch	***Switch***	**Idle**
Up►	1	1.45	**0.45**
Up►	1.1	1.5	**0.4**
Down◄	0.85	1.25	**0.4**
Down◄	0.9	1.3	**0.4**
Hysteresis	**0.175**	**0.2**	

Rep.2

Pressures:	[bars]		
Set Pressure	**2.35 bar**		
	Switch	***Switch***	**Idle**
Up►	2.15	2.65	**0.5**
Up►	2.2	2.65	**0.45**

Down◀	2	2.45	**0.45**
Down◀	2.1	2.6	**0.5**
Hysteresis	**0.125**	**0.125**	

Rep.3

Pressures:	[bars]		
Set Pressure	**3.3 bar**		
	Switch	***Switch***	**Idle**
Up▶	3.1	3.6	**0.5**
Up▶	3.15	3.65	**0.5**
Down◀	2.95	3.4	**0.45**
Down◀	2.95	3.45	**0.5**
Hysteresis	**0.175**	**0.2**	

Table 1: Measurements of idle and hysteresis Δp in different set points of the same pilot

A 3-way pilot closes and opens flow by means of rubber seal. Fig 7 shows a different design of 3-way pilot. The whole operation is done by small displacement of the plunger and its o-rings. Fig 8 shows a blow-up of the plunger in the neutral position. When it goes up or down it connects the passage to atmosphere/operating pressure.

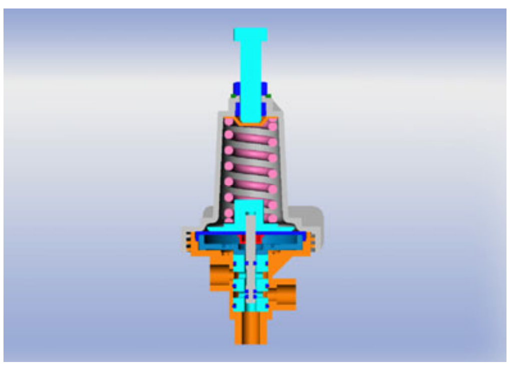

Fig 7: Crossection of a 3-way PR pilot valve

The idle pressure increment (fig 6) derived out of a predetermined displacement of the plunger against a loaded spring. The displacement is linear with the pressure increments in both directions.
The hystersis resulted from the irreversible distortion energy that wasted as heat. The distortion of the rubber seal, o-ring in this case, is shown in fig 9. The "sluggish" distortion reversed when the plunger move to the opposite direction.
The hysteresis value can be controlled up to point. As many friction problems, it has few factors, part of them non-linear or chaotic. Thus, the "neutral zone" is not fixed, and may increase as things getting tough, materials age and surfaces deteriorate. Pilots with initial low hysteresis are superior, as they are more responsive and operate more smoothly.

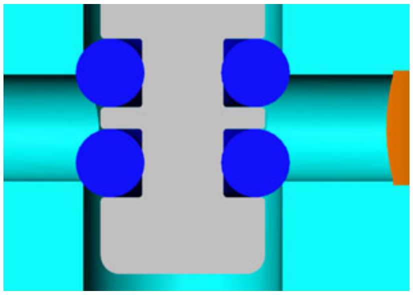

Fig 8: Blowup of the above crossection shows: plunger, O-rings and water passages

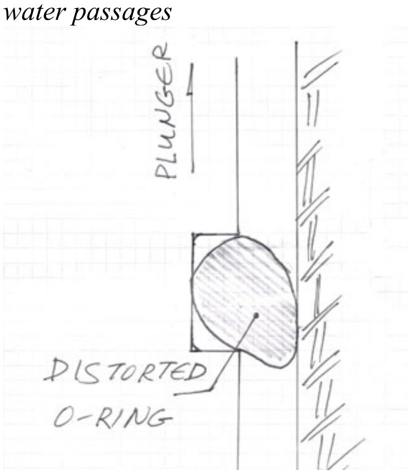

Fig 9: Explain of the Hysteresis Phenomenon in Pilot valves

The pros of the 3-way pilot valve are:

- The valve-chamber drains completely, enables minimum head loss in full flow.
- Operation use small water quantity.
- Relatively large water passages assure high clogging resistance.
- Good response to pressure modulations.
- In normal conditions acceptable precision: ±0.3 bar.
- Excellent for steady flow and constant upstream pressure conditions.

The cons are:

- Spill of water.
- Minimum response range is ±0.7 bar.
- Inherent hysteresis may increase response range up to ±1.1 bar.

Comparison Table

	2-Way	3-Way
Use & Applications		

Upstream Pressure	Modulating	Constant
Applications	All	Especially PR,PS
Typical Market	Water supply, Industry, landscape	Ag, turf and crops Irrigation.
Precision & Repeatability		
Responding Speed	Fast	Medium
Friction	low	Medium
Hysteresis	Very low	medium
Overall	±0.2 atm	±0.3 atm
Head loss across Valve		
At low downstream pressure	Valve is Never Fully Open	Valve is Fully- Open
Operational headloss	0.5-1.0 atm	Null
Maintenance		
Passage	Ø1-2 mm	Equivalent Ø2.5mm
Filter	Necessary 120#-200#	Optional 40#-80#
Water throuflow	Constant	Small
Water Spill	None	Some

Practical Hints

- Use 3-way pilot if you doubt the water quality.
- Use 3-way for irrigation applications, especially low-volume systems.
- While using 2-way pilot- keep the inner filter clean at all time.
- Use 2-way pilot where the water quality is good (potable water, suburban supply systems).
- Use 2-way pilot where the pressure is modulating (urbane or suburban supply systems).
- When you consider using a 3-way pilot, check the range of sensitivity. Ask your dealer for data.
- Avoid using under size hydraulic valves. Consult your dealer.
- Always perform fine tuning of the pilot in extreme field conditions: maximum expected flow rate and lowest probable upstream pressure.

SURFACE IRRIGATION EVALUATION BASED ON ANALYTICAL INTERRELATION AMONG WATER INFILTRATION, ADVANCE, AND RECESSION

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Abstract.

Surface irrigation systems can be evaluated by measuring water infiltration rate, advance, and recession along irrigated field. The infiltrated water distribution depth was mathematically derived based on the three noted parameters to calculate the coefficient of variation. Evaluation of surface irrigation was done by using both mathematical and statistical analyses for water distribution depth and compared to field data. The field study was conducted at Shibin El-Kom agriculture farm in a grape field. The field is a clay loam soil with 1.28 gm/cm^3 bulk density and 32 mm/h saturated hydraulic conductivity and irrigated using border irrigation with strips that were 54 m long and 2.5 m wide with 0.148% slope. Inlet discharge rates of 23, 38, and 60.6 m^3/h were applied. Power empirical relationships were found among advance time and strip length, horizontal recession time and strip length, and infiltrated water depth and opportunity time in field situations. The infiltrated water depth was found for each inlet discharge and averaged 65.6, 70.4, and 74.5 mm at 23, 38, and 60.6 m^3/h, respectively. The coefficient of variation was 16.0, 12.6, and 10.3%, respectively. Excellent values uniformity coefficient (91.1%) and distribution uniformity (86.3%) were obtained, for 60.6 m^3/h discharge. An application efficiency of 98.3% for 23 m^3/h discharge due to maximal of water deficit. The highest storage efficiency (96.3%) for 60 m^3/h due to slight uncertain water depth. Mathematical and statistical analyses were almost exact matches of field observations. Statistical analysis could be simply used than mathematical for water profiles where maximum depth occurred in either the upstream end or the downstream.

Keywords. surface irrigation, scheduling, evaluation, water distribution and efficiency.

INTRODUCTION

In surface irrigation, irrigation water is infiltrated into root zone during conveyance and recession of water at the soil surface. The inlet irrigating stream size should be adjusted to meet the intake characteristics of the soil, the slope, and the entire area to provide a nearly uniform time for water to be infiltrated at all points along the length of the furrow, border, or basin. Three phenomena should be considered in surface irrigation design: (1) the intake characteristics of the soil; (2) the rate of advance of water front moving along the furrow or strip; (3) the rate of recession of water along the furrow or strip after water has been cutoff. The shape of water infiltrated depth depends on numerous factors, such as the variability of the soil, flow channel shape, type of irrigation (furrow versus border strip), inflow rate, irrigation hydraulics, duration of the irrigation, and slope of the field as defined by Vaziri and Wu (1972), Holzapfel et al. (1984), and Bliar and Smerdon (1988).

The general surface irrigation process may thus be considered to include three phases (advance, vertical recession, and horizontal recession). Water advances can be defined as water traveling down slope toward the downstream end when the inflow stream is introduced at the upstream end of the plane. This phase is characterized by downfield movement of the advancing water front and continues until the water reaches the lower end of the field. After the water has advanced to the downstream end, water will continue to accumulate in the field in the vertical recession stage which is considered the storage and depletion phases in blocked-end furrow or border strip. The vertical recession continues until the depth of the surface water at the upstream end is reduced to zero. The horizontal recession phase begins when the depth of surface water at the upstream decreases to zero. This marks the initiation of the water drying or recession front. This phase continues until no water remains in the field and the irrigation is complete. The time interval during which infiltration of water into the soil can occur is bounded by the advance and recession functions and is often referred to as the infiltration opportunity time as described by Holzapfel et al. (1984) and Foroud et al. (1996). The flow pattern into root zone along furrow of surface irrigation is generally nonuniform and unsteady due to variation factors as water inflow, soil surface roughness, and infiltration rate. The water inflow is expressed in a continuity equation and an equation of motion. The equations may be solved using boundary conditions represented in infiltration and friction roughness as defined by Michael and Pandya (1971) and Cahon et al. (1995). Due to complexity of solving equations, most of cases are aimed to study individual inflow as water advance or recession as an effect on water outflow as studied by Bishop (1962) and Wu (1971). Analytical methods that used to solve continuity equation were aimed to determine approximately infiltration function, expressed in water distance run related to time, and irrigation efficiencies of surface irrigation. The derivations of infiltrated water into soil along furrow were only for two functions of surface irrigation which are advance and infiltration functions.

Warrick (1983) examined six statistical distributions of depth of water infiltrated for surface irrigation. He found uniformity coefficient (UC) as well as lower quarter distribution uniformity (DU) is related analytically to the coefficient of variation (CV) in each case. The distributions were the normal, log normal, uniform, a specialized power, beta and gamma distributions. He demonstrated that the specialized power function is exact for basin irrigation provided the surface water advance is proportional to a power of time and the intake everywhere has approached a constant value before recession. The results lend credibility to the general approximations as: (UC = 1-0.8 CV) and (DU = 1- 1.3 CV).

This research aims to study the infiltrated water distribution along border or furrow from water advance, recession, and infiltration. In this work, three functions are considered to determine the infiltrated water depth and coefficient of variation. Mathematical analysis is applied to evaluate and schedule surface irrigation. Simplicity method using statistical analysis is developed to be used for different water distribution shapes.

THEORETICAL DEVELOPMENT

Furrow infiltration rate is an empirical power function describing the infiltration intensity as a function of opportunity time and can be expressed as:

$$I = k\ t_o^{\ n} \qquad -------- \quad (1)$$

where *I* is infiltration intensity in mm/min, *t* is an opportunity time in minute, k and n are empirical coefficients.

The cumulative infiltrated depth as a function of opportunity time can be derived by integrating the right side of

Eq. (1) respect to time and expressed as follows:

$$Z = \frac{k}{n+1} \; t_o^{\,n+1} \qquad --------- \quad (2)$$

where Z is infiltrated depth in mm, t is time in minute, and n is infiltration power coefficient which ranges from -0.2 to -0.8 for most soil types.

Water advance and recession functions together define the infiltration opportunity time along furrow length as shown in Fig. 1. The two functions can be defined as advance or recession time versus distance along the furrow and formulated in empirical equations as follows:

$$t_\ell = a \;\ell^m \qquad --------- \quad (3)$$

$$t_r = c \;\ell^x \qquad --------- \quad (4)$$

where t_ℓ is advance time in min, t_r is recession time in min, and ℓ is furrow length in m, and a, c, m, and x are empirical coefficients into equations.

The infiltrated opportunity time at each furrow length point is the difference between the last time when water disappeared to the first time when water started at the same point along furrow and can be determined as follows:

$$t_o = T + t_r - t_\ell \quad ---- \quad (5)$$

where t_o is infiltration opportunity time in min, T is duration time that started from water turn on and ended when the water at the upstream end disappeared in min as shown in Fig. 1. In case of vertical recession is not occurred, total time, T, is taken from water turn on to cutoff.

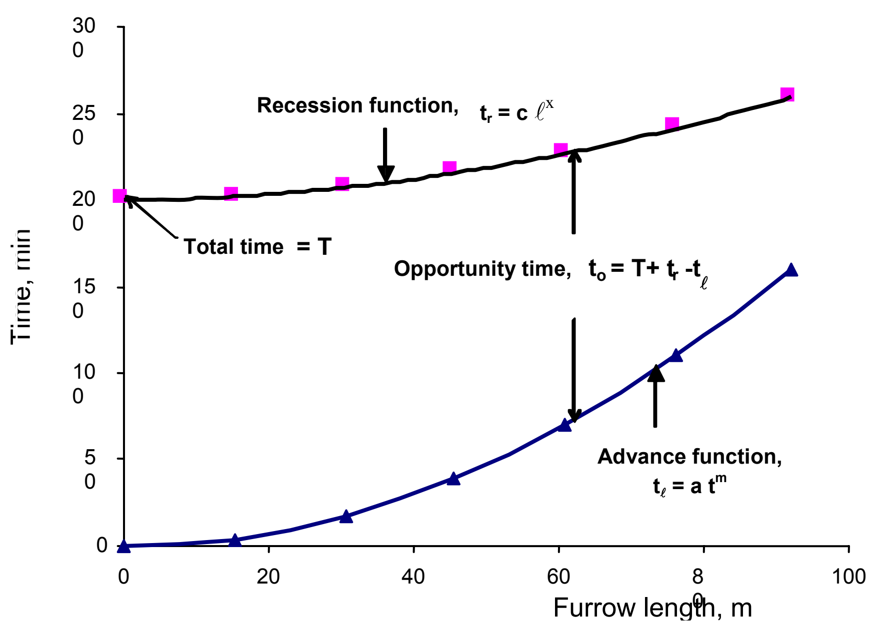

Fig. 1: Advance and recession furrow length versus time.

The infiltrated water depth along furrow can be formulated as follows:

$$Z = \frac{k}{n+1}(T + t_r - t_\ell)^{n+1} \quad ---- \quad (6)$$

The most preceding parameters can be employed to find the variation of infiltrated water depth (Z) from the variation of opportunity time (t_o) using the following statistical equation as used by Anyoji and Wu (1987) and Valiantzas (1998):

$$\frac{\sum(Z-\bar{Z})}{\bar{Z}} = (n+1)\,\frac{\sum(t_o-\bar{t}_o)}{\bar{t}_o} \quad ------ \quad (7)$$

where $\bar{Z}$ and $\bar{t}_o$ are averages of infiltrated water depth and opportunity time, respectively, and can be formulated by integrating the right sides of Eqs. (5) and (6) respect to the furrow length after setting ℓ instead of t and dividing all integration by total length (L) as follows:

$$\bar{Z} = \frac{k}{n+1}\left(T+\frac{t_R}{x+1}-\frac{t_L}{m+1}\right)^{n+1} \quad ---- \quad (8)$$

$$\bar{t}_o = \left(T+\frac{t_R}{x+1}-\frac{t_L}{m+1}\right) \quad ------ \quad (9)$$

where t_L and t_R are total time of water advance and recession, respectively.

By applying Eq. (7) using Eqs. (5), (6), (8), and (9), the left part of Eq. (7) can be formulated after squaring and dividing both sides by total furrow length (L) as follows:

$$\frac{1}{L}\int_0^L\left(\frac{Z-\bar{Z}}{\bar{Z}}\right)^2 d\ell = \left(\frac{n+1}{\bar{t}_o}\right)^2 \frac{1}{L}\int_0^L\left((t_r-\frac{t_R}{x+1})+(\frac{t_L}{m+1}-t_\ell)\right)^2 d\ell \quad --(10)$$

or using the following term: $CV^2 = \frac{(n+1)^2}{L}\int_0^L\left(\frac{t_o-\bar{t}_o}{\bar{t}_o}\right)^2\cdot d\ell$

solving Eq. (10) as follows:

$$CV^2 = \left(\frac{n+1}{\bar{t}_o}\right)^2 \frac{1}{L}\int_0^L\left((t_r-\frac{t_R}{x+1})^2+(\frac{t_L}{m+1}-t_\ell)^2+2\,(t_r-\frac{t_R}{x+1})(\frac{t_L}{m+1}-t_\ell)\right)d\ell$$

$$\frac{1}{L}\int_0^L\left((t_r-\frac{t_R}{x+1})^2\right)d\ell = \frac{t_R^2}{2x+1}-\frac{t_R^2}{(x+1)^2} \qquad \text{hence } t_R = c\,L^x$$

$$\frac{1}{L}\int_0^L\left(((\frac{t_L}{m+1}-t_\ell)^2\right)d\ell = \frac{t_L^2}{2m+1}-\frac{t_L^2}{(m+1)^2} \qquad \text{hence } t_L = a\,L^m$$

$$\frac{2}{L}\int_0^L\left((\frac{t_L}{m+1}-t_\ell)\,(t_r-\frac{t_R}{x+1})\right)d\ell = \frac{2\,t_L\,t_R}{(m+1)(x+1)}-\frac{2\,t_L\,t_R}{m+x+1}$$

By setting t_ℓ in Eq. (3) and t_r in Eq. (4) in Eq. (10), integrating both sides, and taking the square root of both sides, the coefficient of variation can be formulated as:

$$CV = \frac{(n+1)\cdot\sqrt{\frac{t_L^{\,2}}{2m+1}+\frac{t_R^{\,2}}{2x+1}-\frac{2\,t_L\,t_R}{x+m+1}-\left(\frac{t_L}{m+1}-\frac{t_R}{x+1}\right)^2}}{T+\frac{t_R}{x+1}-\frac{t_L}{m+1}} \quad --(11)$$

where CV is the coefficient of variation for water infiltrated along strip.

MATHEMATICAL ANALYSIS OF INFILTRATED WATER DISTRIBUTION

Infiltrated water depth along furrow or strip can be profiled using Eq. (6) as shown in Fig. (2). The desired water depth, d, which soil can keep it in root zone divide the area under irrigated into three divisions which are A_1 represents the water stored into root zone, A_2 represents the water of deep seepage, and A_3 represents the deficit area. The infiltrated water depth, Z, can be formulated from Eq. (6) in a simple form by using binomial expansion and keeping only first two terms without significant deference as follows:

$$Z = k\sum_{r=0}^{\infty} C_r^{n+1}\, T^{n+1-r}\,(t_r - t_\ell) = k\,T^n\left(\frac{T}{n+1} + t_r - t_\ell\right) + \cdots \quad --- \quad (12)$$

where C represents the combination and r is integral number.

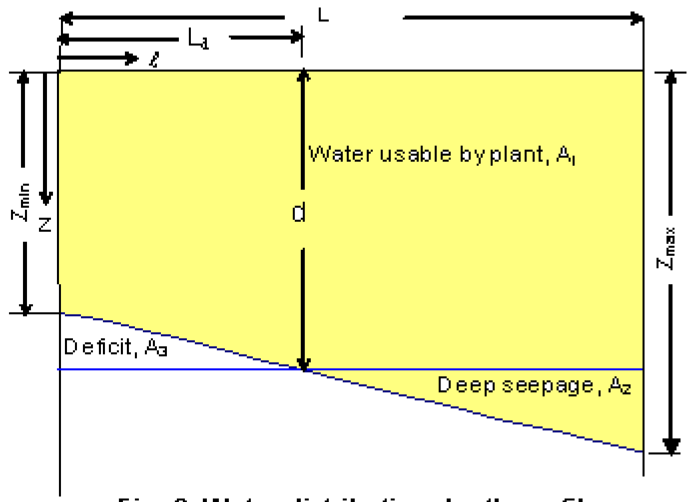

Fig. 2: Water distribution depth profile.

The available water depth for plant (d) is expressed as ≥ 50% soil water available in millimeters. The schedule water depth can be determined by multiply the soil root zone depth by the deference between soil volumetric water content before irrigation and after irrigation. The schedule water depth (d) segregate the irrigated area into deep seepage and deficit areas as shown in Fig. 2. Deficit area (A_3) which occurred at inlet furrow or strip as matched to the experimental work can be formulated as follows:

$$A_3 = d \cdot L_d - k\,T^n \int_0^{L_d}\left(\frac{T}{n+1} + t_r - t_\ell\right) \cdot d\ell \; - \quad --- \quad (13)$$

where L_d is furrow or strip length which d is occurred.

Water usable by plant area (A_1) can be formulated as follows:

$$A_1 = d \cdot L - A_3 \quad ----- \quad (14)$$

Deep seepage area (A_2) can be formulated as follows:

$$A_2 = L \cdot \bar{Z} - A_1 \quad ----- \quad (15)$$

The percentage of water deep seepage (P_{DS}) defined as the ratio of irrigation water drained beyond the root zone to the total water applied, the ratio of amount of water can be formulated as follows:

$$P_{DS} = \frac{A_2}{A_1 + A_2} \quad ------- \quad (16)$$

The percentage of water deficit (P_D) defined as the ratio of water deficit to the water needed into the root zone, can be formulated as follows:

$$P_D = \frac{A_3}{A_1 + A_3} \quad ------- \quad (17)$$

The average infiltrated depth of low quarter ($\bar{Z}_{LQ}$) that occurred at the beginning of furrow or strip water distribution can be derived as follows:

$$\bar{Z}_{LQ} = \frac{4\,k\,T^n}{L}\int_0^{L/4}\left(\frac{T}{n+1} + t_r - t_\ell\right) \cdot d\ell$$

$$\overline{Z}_{LQ} = k\,T^{n}\left(\frac{T}{n+1} + \frac{4\,t_R}{x+1}\;(0.25)^{x+1} - \frac{4\,t_L}{m+1}\;(0.25)^{m+1}\right) -- (18)$$

Water uniformity for surface irrigation profile can be determined by measuring infiltrated water along furrow or strip in systematical stations. Uniformity coefficient (UC) as a parameter that shows how water uniformly distributed along furrow can be defined as follows:

$$UC = 1 - \frac{\sum_{i=1}^{N}\left|Z - \overline{Z}\right|}{N\;\overline{Z}} \qquad -------- \quad (19)$$

where Z_i is water depth measured at each station in mm, $\overline{Z}$ is mean water depth measured in all stations in mm, and N is total number of stations.

The distribution uniformity (DU) defined as the ratio of average low quarter depth of water infiltrated to the average depth of total water applied can be expressed as:

$$DU = \frac{\overline{Z}_{LQ}}{\overline{Z}} \quad ---- \; (20)$$

The application efficiency (E_a) defined as the ratio of amount of irrigation stored in the root zone to the total water applied, can be expressed as:

$$E_a = \frac{A_1}{A_1 + A_2} \qquad ---- \; (21)$$

The storage efficiency (E_S) defined as the ratio of amount of water stored to the water needed into root zone, can be expressed as:

$$E_s = \frac{A_1}{A_1 + A_3} \quad ---- \; (22)$$

STATISTICAL ANALYSIS OF INFILTRATED WATER DISTRIBUTION

The power distribution function as developed to suit water distribution profile of surface flood irrigation can be used in statistical analysis. The infiltrated water depth (Z) along furrow or strip in dimensionless value can be expressed as (1+ α CV) where α specifies the deviation in terms of the coefficient of variation CV as shown in Fig. 3. The α-value varies from -2 to 2. The statistical analysis can be used as a standard analysis in all water distribution situations. The maximum and minimum water depth is defined as $Z_{max} = \overline{Z}$ (1+2 CV) and $Z_{min} = \overline{Z}$ (1-2 CV).

The power density function, f(α), as shown in Fig. 3 for α -value can be expressed as follows:

$$f(\alpha) = 0.375 - 0.094\,\alpha^2 \qquad ---- \; (23)$$

where, α is a number ranges from -2 to 2 specifies the deviation of relative infiltrated water depth of terms of CV in the distribution.

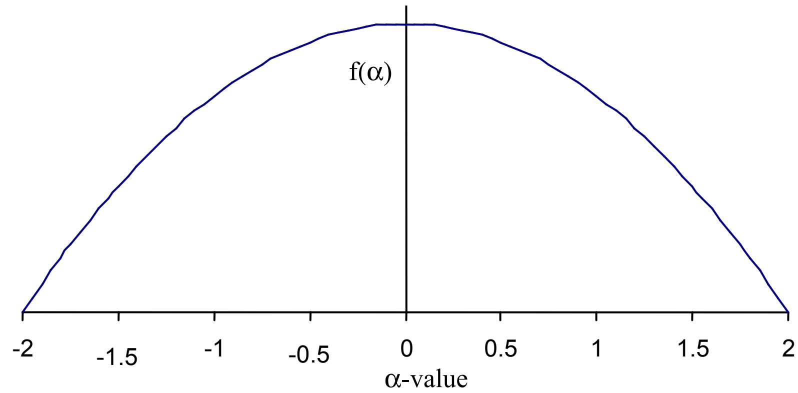

Fig. 3: Standard power distribution density function

The cumulative density function (P) of the power distribution can be expressed as:

$$P = \int_{\alpha}^{2} f(\alpha) \cdot d\alpha = 0.5 + 0.0314\,\alpha^{3} - 0.375\,\alpha \qquad ---- (24)$$

The relative schedule irrigation depth in root zone ($d/\overline{Z}$) can be expressed as equals to (1+α CV) as shown in Fig. 4, the area under the frequency curve can be integrated as follows:

$$\int_{\alpha}^{2} (1+\alpha\,CV) f(\alpha) \cdot d\alpha = P + CV\,(0.6124 - 0.1535\,\alpha^{2})^{2} \quad ---- (25)$$

The percentage of deep seepage (P_{DS}) defined as the ratio of irrigation water drained beyond the root zone to the water applied can be expressed in underirrigation situation as follows:

$$P_{DS} = CV\,(0.6124 - 0.1535\,\alpha^{2})^{2} - \alpha\,P\,CV \quad ---- (26)$$

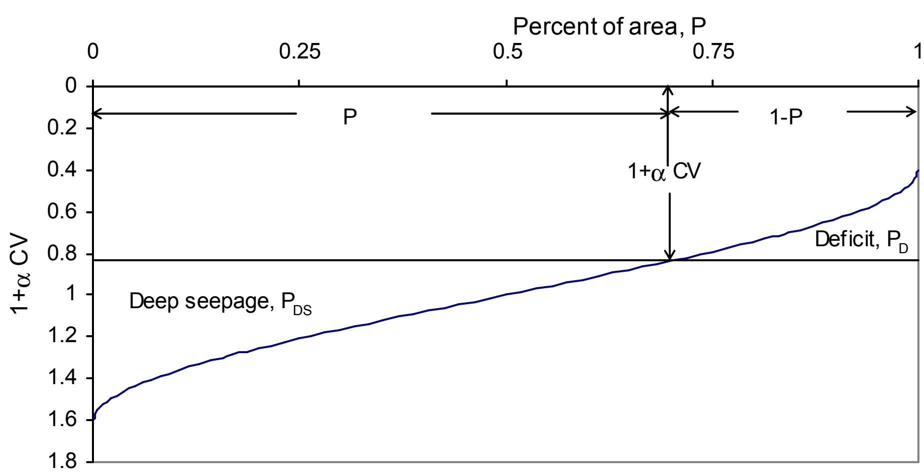

Fig. 4: Accumulative power frequency water distribution for CV=0.3 .

The percent of deficit (P_D) defined as the ratio of water deficit to the required water into the root zone can be expressed in underirrigation situation as follows:

$$P_D = \frac{CV\,(0.6124 - 0.1535\,\alpha^{2})^{2} + \alpha\,CV(1-P)}{1+\alpha\,CV} \quad --- (27)$$

The application efficiency (E_a) can be expressed in power distribution as follows:

$$E_a = 1 - P_{DS} \qquad ---- (28)$$

The storage efficiency (E_S) can be expressed in the distribution as follows:

$$E_s = 1 - P_D \quad ---- (29)$$

The uniformity coefficient (UC) can be expressed in power distribution for water infiltrated depth which determined from Eq. 6 as follows:

$$UC = 1 - 0.86\ CV \quad ---- (30)$$

The distribution uniformity (DU) can be expressed for 100% data determined from three empirical foregoing functions as follows:

$$DU = 1 - 1.33\,CV \quad ---- (31)$$

MATERIALS AND METHODS

Border irrigation system was used to apply water to grape farm at the Faculty of Agriculture, Menoufiya University in shibin El-Kom area. Three inlet discharges (23, 38, 60.6 m^3/h) were used and had two replicates. The border strips were 54 m in length and 2.5 m in width. The shape of border strip was shown in Fig. 5. Discharge rate was adjusted using 5, and 4, and 3 inch inside diameter of PVC tube under constant head from an open channel. The water advance time was recorded for each 4.5 m strip length during irrigation time. Water was cutoff after 2 minutes from water reached the field end. The time of water cutoff (T_{off}) was 23, 15, and 10 min. Water recession time as a function of strip length was recorded in an empirical equation. The total flow time (T) which including the time of water advance and storage (vertical recession) was recorded from turn water on to the end of vertical recession. The infiltration rate of the classified soil was measured using double ring method before irrigation. The field slope was measured using water level tube and recorded as 0.148% down slope.

Soil in the study area was classified as clay loam with 1.28 g /cm^3 soil bulk density. Soil particle sizes for 0.3 m of soil profile were distributed as 2% coarse sand, 23.5% fine sand, 37.7% silt, and 36.80% clay. Soil particle sizes for 0.3-0.6 m of soil profile were distributed as 1.7% coarse sand, 26.3% fine sand, 32.6% silt, and 39.4% clay. The volumetric water content values were 58, 47.5, and 21.1% at saturated, field capacity, and wilting points, respectively. The Irrigation water was applied when soil water by volume was reduced to 35.3% by taken soil sample before irrigation. Soil samples were taken to 0.9 m depth along the strips in systematical stations each 4.5 m before and after irrigation. The water table at farm was more than 2.5 m.

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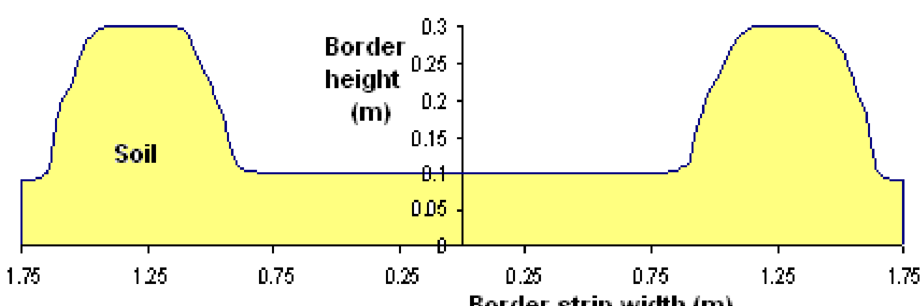

Fig. 5: Border strip profile.

The irrigation schedule in grape farm was to refill water to reach the reduced water content in 0.6 m of soil depth to field capacity so irrigation interval could be determined. The schedule water depth (d) was determined as 73.2 mm for 0.6 m soil depth when soil water content by volume was averaged 35.3% as recorded before irrigation.

RESULTS AND DISCUSSION

An empirical equation was found in experimental site for clay loam soil to express the infiltration rate (I) in mm/min as a function of opportunity time (t_o) in minute as found: $I = 3.95\ t_o^{-0.423}$. The cumulative infiltrated depth (Z) in mm was integrated as: $Z = 6.846\ t_o^{0.577}$. Water advance time in minute was found as a function of strip length in meter each inlet discharge as: $t_\ell = 0.018\ \ell^{1.76}$, $t_\ell = 0.018\ \ell^{1.65}$, and $t_\ell = 0.018\ \ell^{1.53}$ for 23, 38, and 60.6 m^3/h inlet discharge, respectively as shown in Fig. 5. While the horizontal water recession time was functioned as: $t_r = 0.72\ \ell^{1.13}$, $t_\ell = 0.67\ \ell^{1.1}$, and $t_\ell = 0.52\ \ell^{1.12}$ for 23, 38, and 60.6 m^3/h, respectively. The total flow time, T, was 27, 36, 44.5 minute, respectively. The total advance time (t_L) was recorded as 20.2, 15, 10 min, respectively. The total horizontal recession time (t_R) was recorded as 65, 54, and 45.3 min, respectively. The curves in Fig. 6 showed that the greater the inlet discharge, the smaller the advance time. In the same trend, the larger the discharge the smaller the horizontal recession time. On the contrary, the smaller the inlet discharge, the larger the vertical recession time. The similar trend was earlier found by Smedema (1984) for Vertisols which referred to black cotton soils.

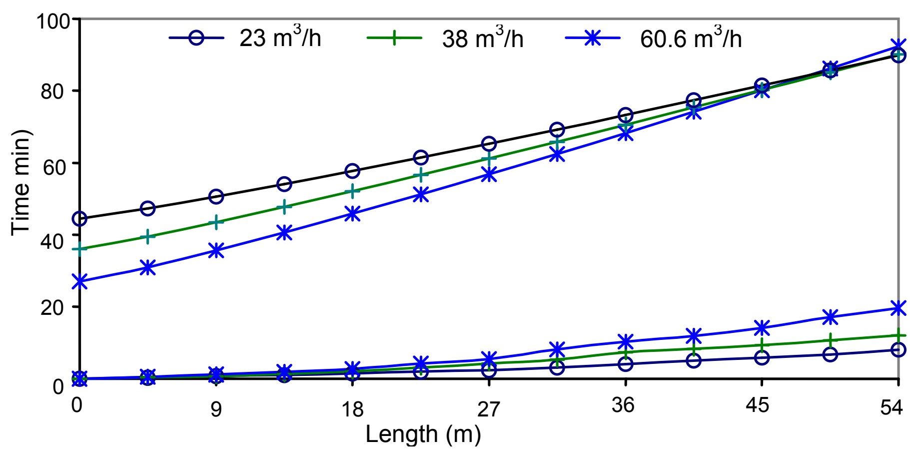

Fig. 6: Water advance and recession versus strip length.

Water distribution depth (Z) was determined and measured along strip for 23, 38, and 60.6 m^3/h as illustrated in Fig. 7. Linear regression analysis showed that highly correlation between measured and determined data, the correlation coefficient (r^2) was more than 0.9295 and the slope was around unity with no intercept. Measured infiltrated water depth was higher than the determined depth at the beginning of strip due to some water infiltrated from open channel and the strip end due to 0.148 % downslope. The trend of increased infiltrated depth was to increase both of strip length and inlet discharge. These results occurred due to the minimal advance time compared to recession time. As a result of the big border strip slope, the maximum irrigation depth was accumulated the end of the field. For this reason, the deviations among maximum infiltrated depths were lesser than that those among minimum infiltrated depths. The actual amount of water each irrigation was 650, 700, and 743 m^3/ha at 23, 38, and 60.8 m^3/h, respectively. The results concluded that the irrigation interval in spring time with 4 mm/day crop evapotranspiration in experimental area was 18.3 days for all inlet border strip discharge, respectively. It was 12 days in summer with 6 mm of ET.

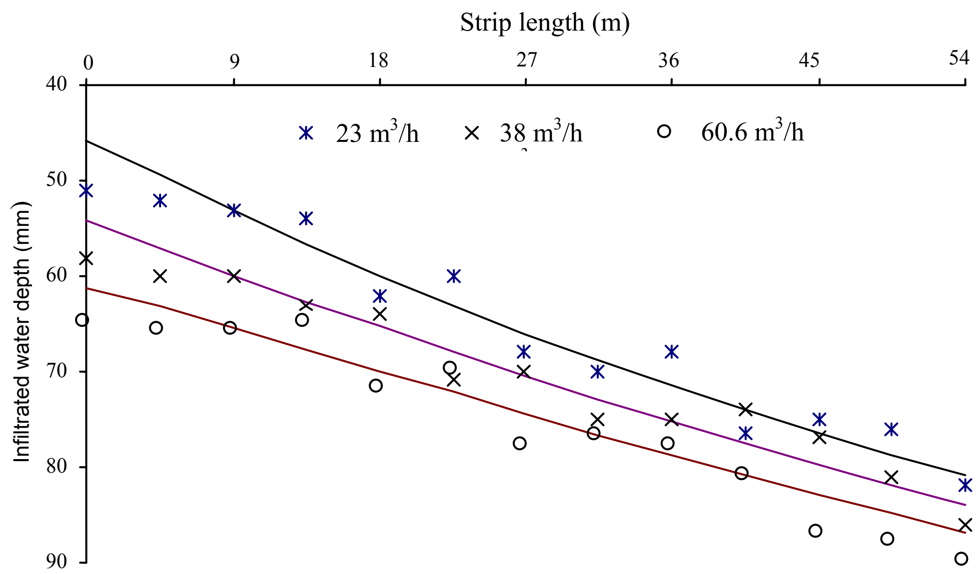

Fig. 7: Determined and field infiltrated water depth for different discharges.

Evaluation and scheduling of surface flood irrigation from the three functions of infiltration, advance rate, and recession rate were analyzed by two ways: Mathematical and Statistical Analyses. Input parameters were for 23, 38, and 60.6 m^3/h inlet discharge (Q) illustrated in Table 1. Advance and recession coefficients were used to determine infiltrated water depth along border strip with infiltration coefficients as k = 3.95 and n = -0.423 and total flow time (T) using Eq. 6. In addition of using total flow time (T) and three empirical functions, total advance time (t_L) and recession time (t_R) were used to determine average infiltrated depth and coefficient of variation using Eqs. 8 and 11, respectively. For the same shape of border strip and slope, the power (m) of advance function decreased when discharge increased, but the constant value (a) was almost the same. Reversely, the constant value (c) of recession function increased, but the power (x) was almost the same.

Table 1: Input data from the experimental advance and recession functions.

Discharge	Advance coefficients		Recession coefficients		T	t_L	t_R
m^3/h	a	m	c	x	min	min	min
23	0.018	1.76	0.52	1.12	27	20.2	65
38	0.018	1.65	0.67	1.1	36	13	54
60.6	0.018	1.53	0.72	1.13	44.5	8	45

MATHEMATICAL ANALYSIS

The schedule depth (d) determined as d = 600 (0.475-0.353) = 73.2 mm water depth, was used to equivalent water depth (Z) in Eq. 6 to find out the value of L_d by trial and error for 23, 38, and 60.6 m^3/h inlet discharge (Q) as illustrated in Table 2. Deficit area (A_3 in Eq. 13), water usable by plant area (A_1 in Eq. 14), and deep seepage area (A_2 in Eq. 15) were determined and used to calculate deep seepage (P_{DS}) and deficit (P_D) percentages as well as application (E_a in Eq. 21) and storage (E_s in Eq. 22) efficiencies. Uniformity coefficient (UC in Eq. 19) as well as distribution uniformity (DU in Eq. 20) was determined using average infiltrated depth ($\overline{Z}$ in Eq. 8) all illustrated in Table 2. The results concluded that the lower the inlet discharge, the higher the coefficient of variation. The percentage of deep seepage increased when discharge decreased and CV decreased, but water deficit percentage decreased. Uniformity coefficient (UC) as well as distribution uniformity (DU) as related to coefficient of variation (CV) increased when discharge increased and achieved acceptable value for all treatments. For 60.6 m^3/h inlet discharge, CU and DU achieved excellent values. Application efficiency (E_a) achieved a high value of 98.3% for 23 m^3/h discharge due to most of applied water was usable by plant, but storage efficiency (E_s) achieved the low value of 87.5% due to maximal of water deficit. In general, E_a decreased but E_s increased when schedule depth (d) is increased inbetween minimum (Z_{min}) and maximum (Z_{max}) infiltrated depths respect to increasing of coefficient of variation.

Table 2: Output parameters of surface irrigation by mathematical analysis.

Q m^3/h	$\overline{Z}$ mm	L_d m	CV %	P_{DS} %	P_D %	UC %	DU %	E_a %	E_s %
23	65.6	38.87	16	1.7	12.6	86.2	78.5	98.3	87.4
38	70.4	31.87	12.6	3.1	7.4	89.8	83.1	96.9	92.6
60.6	74.46	24.44	10.3	5.1	3.7	91.2	86.5	94.9	96.3

Statistical Analysis

The schedule parameter (α) determined from the following assumption:

$$1+\alpha CV=\frac{d}{\overline{Z}}$$

By arranging the foregoing equation, the parameter α will be as follows:

$$\alpha=\frac{1}{CV}\left(\frac{d}{\overline{Z}}-1\right) \quad -------- \quad (32)$$

By setting d as 73.2 mm, and $\overline{Z}$ for the three discharge treatments, the value of α was 0.777, 0.358, and -0.14 for 23, 38, 60.6 m^3/h inlet discharge, respectively as illustrated in Table 3. Using α and CV from Table 3, percentages of both deep seepage (P_{DS} in Eq. 26) and deficit (P_D in Eq. 27) were merely determined and used to calculate both of application (E_a in Eq. 28) and storage (E_s in Eq. 29) efficiencies. Uniformity coefficient (UC in Eq. 30) as well as distribution uniformity (DU in Eq. 31) was determined using coefficient of variation of infiltrated water depth all data illustrated in Table 2.

Table 3: Output parameters of surface irrigation by statistical analysis.

Q m^3/h	$\overline{Z}$ mm	α m	CV %	P_{DS} %	P_D %	UC %	DU %	E_a %	E_s %
23	65.6	0.777	16	1.6	12.5	86.2	78.7	98.4	87.5
38	70.4	0.358	12.6	2.8	7	89.2	83.2	97.2	93
60.6	74.46	-0.14	10.3	5.2	3.2	91.1	86.3	94.8	96.8

Both mathematical and statistical analyses were achieved almost the same results of predicting P_{DS}, P_D, UC, DU, E_a, and E_s as shown in Tables 2 and 3. Statistical analysis achieved abbreviation in output calculation because of simplicity of determining α-value (using Eq. 32) directly from the schedule depth (d) and coefficient of variation (CV). However, mathematical analysis achieved the same output data in complexity calculation as a result of finding indirectly the length (L_d) where the schedule depth (d) was occurred along border strip or furrow by trial and error method. Also statistical method was typically applied for both of water distribution shapes where maximum depth occurred at up-field or down-field. In contrast, mathematical analysis should be analyzed each shape due to switching the places of deep seepage and water deficit.

Conclusion

Surface irrigation systems is widely used to irrigate most of the traditional crops in northern of Egypt where most of the old irrigated lands located. It can be managed and evaluated by using three functions for the field situation, these are water infiltration, advance rate, and recession rate. Infiltrated water distribution depth was mathematically derived based on the three functions. Evaluation of surface irrigation was done by using both mathematical and statistical analyses for infiltrated water distribution profile and compared to field data. A study was conducted on a grape grown at the Agriculture College farm at Shibin El-Kom area on a clay loam soil with 1.28 gm/cm^3 bulk density and 32 mm/h saturated hydraulic conductivity. Border irrigation was used to feed water into strips with 0.148% downslope, 54 m long and 2.5 m width. Inlet discharge rates of 23, 38, and 60.6 m^3/h were applied. Power empirical relationships were found among advance time and strip length, horizontal recession time and strip length, and infiltrated water depth and opportunity time in field situations. The results were found as follows:

- Infiltrated water depth along strip was found and averaged as 65.6, 70.4, and 74.5 mm at 23, 38, and 60.6 m^3/h, respectively.
- The coefficient of variation was 16, 12.6, and 10.3% at 23, 38, and 60.6 m^3/h, respectively.
- The amount of water each irrigation was 650, 700, and 743 m^3/ha at 23, 38, and 60.6 m^3/h, respectively.
- Uniformity coefficient as well as distribution uniformity increased when inlet discharge increased but acceptable values achieved for all discharge treatments, although the UC for 60.6 m^3/h was the highest.
- Application efficiency achieved a high value of 98.3% for 23 m^3/h discharge due to maximal of water deficit, but storage efficiency achieved the high value of 96.3% for 60.6 m^3/h due to minimal of water deficit.
- Mathematical and statistical analyses were achieved almost the same results of predicting output parameters.
- Statistical analysis achieved an abbreviation in output calculations than mathematical analysis due to simplicity of application in evaluating and scheduling irrigation systems.

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SUBDIVISION PRESSURIZED IRRIGATION SYSTEMS FROM AGRICULTURAL WATER

Prepared for
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Introduction

This paper explains how one area in Idaho met the future growth of subdivisions that displaced farm ground by converting agriculture irrigation to pressurized irrigation. It will define some areas of design essential for the successful conversion of agricultural land to subdivided, urban and suburban communities. In Idaho some communities have doubled and tripled in population in the last ten years. Good irrigation designs are needed to accommodate this growth.

The guidelines covered are not all inclusive as the standards are being updated regularly to meet the needs of the communities. An attempt is made to provide the basics to design an adequate system. The presentation follows the process of taking raw land and water rights through to the final completion of the pressurized irrigation system for a typical subdivision. Local codes may supersede some of the principles of design that are presented herein.

Agency Direction

In 1997, the city of Boise, Idaho adopted a pressurized irrigation requirement. The goal was to separate potable water from irrigation water. Ada County cities and irrigation districts followed Boise's lead and adopted essentially the same requirement. Land developers converting agricultural land with surface water rights are required to provide a pressurized irrigation system in subdivisions utilizing irrigation water. The water use of the farmer (full time tenant) contrasts sharply from use of the urban subdivision home owner (part time tenant). When and how water is used is a challenge for the designer of the pressurized irrigation system. Pump graphs for a season of water use give the basis of what the system requirements entail. The graphs show when the water use occurs and the quantity of water use.

Pump type and size are also critical as are the intake screens and the discharge filters. Irrigation districts control the water source which comes from reservoirs of stored water. The larger irrigation districts have their own set of standards and regulations that makes the whole process more complicated.

In a particular area around Boise, Idaho, agriculture land has been the prime target of subdivision development. The farm community has become somewhat aged and the value of the land for subdividing has far exceeded the value for farming. It has given the farmers an avenue for a better retirement and so prime agricultural land has been bought by developers. These land parcels have water rights that typically transfer with the land and that water is by ordinance converted from agricultural use to a pressure irrigation system that delivers water to each subdivision lot.

Land Measurement

The land was historically divided by Township and Range. Township being a measure North and South of an initial point or baseline and Range a measure East and West of a line called a meridian. The unit measure is 6 miles. The boundary formed by a township and range is 6 miles by 6 miles and the total area is 36 square miles. Those 36 square miles are then described by sections 1 through 36; each section being 1 mile square or 640 acres. A section is further divided into quarters, and the quarters then divided into quarter-quarters, etc. These measurements were generally used for large acreages such as ranches and farms, open range and forests.

There are corrections in some sections to account for variations such as the curvature of the earth and other miscellaneous factors. One section will not always measure one mile, etc.

As cities were formed and continue to be urbanized, land is further divided into lots and blocks and tax numbers. All of the lots and blocks are a part of the sections. Generally all land parcels are filed in a county office in the form of a “land description”. The land description is often in the form of a survey using meets and bounds.

The task of an irrigation designer is to determine how much land is going to be irrigated and the most efficient method to apply a sustaining amount of water. One must determine the net amount of irrigated area. This means one must determine the raw land before any buildings, paving or plaza areas are constructed and subtract these features from the raw land to find a net area to be irrigated.

Demand for Water

Water is often allocated to irrigated land. As demand for water increases from industry, recreation, municipalities and agriculture the true value of water is realized. In Idaho right now, several entities are challenging the rights to use the water. Idaho Power, a utility for power, is said to have been able to generate 100% of its power through hydro generators in the past, but at present only half of the company’s power is hydro generated. It is important to know that water for a project is secure and will not be taken from a project through some legal wrangling in the future. Even the water-use graphs from one pumping plant have caused agencies to speculate on how much water could be saved and used for other purposes.

In Idaho, water was allocated to the land through districts or legal entities (organizations), which in the early years sorted out the claims to water. Where reservoirs were constructed, owners of land purchased or claimed the stored water in the form of Acre Feet, Shares of water and Miner’s inches. These definitions of water were attached to the land and we refer to them as “water rights”. You will need to know the equivalent measurements of gallons per minute for each of the ways water volume is expressed. For instance, in Idaho, a miner’s inch equals nine gallons per minute. In some of the neighboring states a miner’s inch equals 11 gallons per minute. Shares of water vary between districts as shares may equate to different amounts of miner’s inches. Some districts allot water solely based on a finite amount in Acre feet per year. Nearly all of these measurements are based on a normal year of precipitation. All of the ensuing calculations in this presentation, where these varying amounts apply, will use Idaho’s interpretation of water amounts.

WATER CONVERSION FACTORS

1 cubic foot of water……………..…7.4805 gallons……………….62.37 pounds of water
1 cubic foot per second (CFS) ...448.83 gallons per minute……26,930 gallons per hour
1 cubic foot per second (CFS) ……646,315 gallons per day… 1.9835 acre-feet per day
1 cubic foot per second…..for 30 days = 59.502 acre-feet…..for 1 year = 723.94 acre-feet
1 acre-foot…………………….………enough water to cover 1 acre of land one foot deep
1 acre-foot…………………………………………………………..43,560 cubic feet
1 acre-foot ……………………………………………………………325,850 gallons
1 acre-inch ……………………………………...…………………. 27,154 gallons
1 cubic meter per second……………35.31 CFS……………… 15,850 gallons per minute
1 million gallons……………………………………………………..3.0689 acre-feet
1 million gallons per day (MGD)…………………..………1,120,147 acre-feet per year
10 cents per 1,000 gallons……………..……………………………. $32.59 per acre-foot
1 miner's inch………………………9 gallons per minute……………………….0.02 CFS

From the above table one can further calculate 50 miner's inches equals 1 cubic foot per second (CFS).

With the above background in land and water, a parcel of ground will be broken down to show the process of designing a pressurized irrigation system.

An Example
John Doe owns 80 acres of land. A developer becomes interested in the 80 acres for a subdivision. The developer probably has determined the zoning and density of units he will be able to divide the land into and still profit from the purchase. An agreement is reached between John Doe and the developer and the developer purchases the land and all the appurtances (including water). Typically the developer will have an engineer/planner draw a preliminary plat showing his intent for the land for approval by the government authorities. This allows the developer to move ahead with the plans knowing if certain conditions are met, final approval for the sale of the lots will be approved.

After the preliminary plat is approved engineering design begins. Roads, common areas, lot lines, water lines, sewer lines, electrical services and/or gas lines, cable, etc. and pressure irrigation lines begin to be designed. Under the standards in Ada County, Idaho a common trench is used for all the utilities other than pressure irrigation. This common trench is located at the road side of the lots and the pressure irrigation line is located at the rear or common lot line.

Pressure irrigation is the subject that will be discussed. After the roads, common areas, commercial lots (if any), and residential lots are delineated, the design for the pressure irrigation system may begin.

Step One involves determining what the *total irrigated ground* will be under the subdivision design.

There are two possible ways to start.

1. Usually a preliminary plat will summarize the amount of land designated to roads, common areas, residential lots and commercial lots. The net amount of ground for building can be taken from these notes.
2. A more laborious method is to determine the gross amount of ground in the property. Subtract the roads by determining the length of the roads and multiplying the width (between the curbs). Subtract the sidewalks by determining the length and multiplying by the width.

Based on the parameters of the subdivision, the square footage of the houses will be stated. Determine the average square footage of the houses and add the garage, driveway, patio, and any other hardscapes that can be determined. Multiply the number of homes or lots in the subdivision to find the area subtracted from the net land of 1. and 2. above. This will yield the net area that will be irrigated.

Depending on the rules of zoning and local density allowances for subdivisions a general finding is the irrigated area is approximately half of the original raw land. A commercial development will have irrigated land of only about one quarter of the original land area.

There are now two more steps or decisions that must be made.

Step 2. What will the water window (time for irrigation) be. Will the project water in 24 hours, 18 hours, or 12 hours?

Step 3. The evapotranspiration (ET) that will be used. One can begin by finding the historical ET from an agency who has those records. The ET should be adjusted for the efficiency of irrigation systems. For example use 60% efficiency. Therefore, it is (for example) .3 (ET at peak season) divided by .6 (sprinkler efficiency) equals .5.

$$\text{GPM} = \frac{\text{Acres x 27154 x .5}}{\text{Hours for Irrigation x 60}}$$

27,154 is obtained from the table above as the number of gallons of water required to cover one acre one inch deep. Sixty is the number of minutes per hour.

Compare the gpm required for the landscaped area to the available flow for the property. If the gpm that is required to be pumped during the watering window exceeds the flow of the water right, a pond or storage amenity must be considered. The total irrigation demand must not exceed the 24-hour water right. This calculation is as follows:

Total gallons pumped = GPM x 60 x Hours in the watering window

Step 4. Compare the total gallons pumped to the water right of the property for a 24-hour flow.

Total gallons available = [(inches)(9 in Idaho)] x 60 x 24 hours

Also, the result of the gpm calculation will provide the information needed for sizing the pump with the precaution that it is often important to up-size the capacity to 1.25 to 1.4 times the base capacity to account for the peak flows demanded by the irrigation water users (see the Demand Chart).

If there is doubt that the homeowners will adhere to a schedule, it is advisable to adjust the pumping capacity (gpm) to 1.4 times the result of the above equation

If the results from all these calculations show the irrigation requirement exceeds the water right or water available for irrigation, then dryscapes and other landscaping options must be considered to reduce the irrigation requirements.

Step 5. Consideration of the individual lot requirement.
To find the square foot water requirement:

1. Determine the watering window for the lot.
2. Use the same ET and sprinkler efficiency as the calculation for the project.

$$GPM = \frac{.623 \times \text{Square Feet} \times .5}{\text{Hours (water time)} \times 60}$$

.623 is gallons per square foot = 27,154 gallons divided by 43,560 square feet per acre

The result of this calculation should be reviewed to see if the time of watering or the gpm is practical. The results might be adjusted to find a practical flow (based on a typical irrigation zone). Once this judgment is made, the pump capacity is divided by the lot gpm to determine the number of lots that will irrigate at one time.

$$\text{Irrigated Lots} = \frac{\text{GPM (pump capacity)}}{\text{GPM (lot requirement)}}$$

As a check for the anticipated schedule it is a good practice to divide the total lots by the number of lots that will irrigate at one time. This will yield the number of watering windows in the schedule.

$$\text{Water windows} = \frac{\text{Total number of lots}}{\text{Lots watering at the same time}}$$

An example using the above calculations could proceed as follows:

Given;

A plot of raw land ………………………….. 80 acres
Water Right ………………………………… 56 miner's inches
Preliminary plat …………………………… 4.5 acres the common lots
Roads ……………………………………….. 19 acres
Sidewalks …………………………………… 5 acres
Minimum Residence footprint …………….. 2000 S.F.
Average lot size …………………………….. 7000 +- S.F.
Garage size ………………………………….. 500 S.F.
Patio   ……………………………………….. 150 S.F.
Sidewalk …………………………………….. 150 S.F.
Residential Lots ……………………………… 252

Irrigated Land:

80 acres (raw land)
- 19 acres (streets)
- 5 acres (sidewalk)
- <u>16.2 acres</u> (2000 + 500 + 150 + 150)(252 lots)/43560
39.8 net irrigated acres

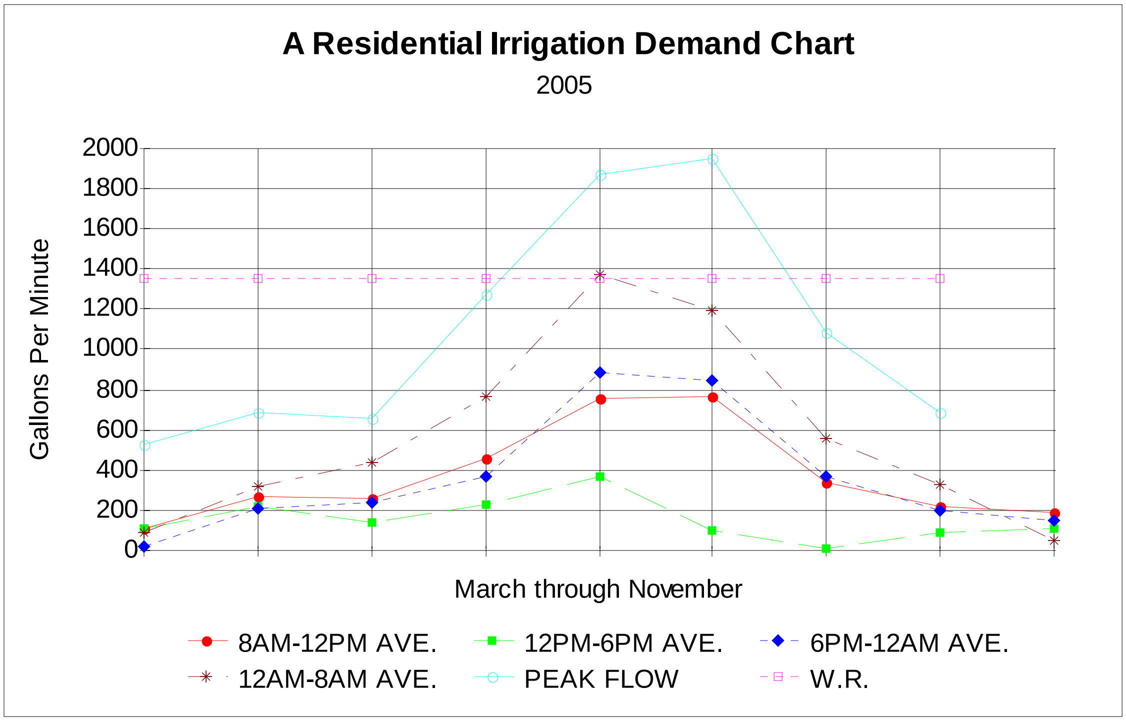
Step 6. Pump Station capacity

$$750 \text{ gpm} = \frac{(39.8 \text{ acres })(27154)(.5)}{12 \text{ hr. water window} \times 60}$$

.

(750 gpm)(60 min/hr)(12 hr.) = 540365 gallons
(56 M.I.)(9 gpm/m.i.) = 504 GPM
(56 M.I.)(9 gpm/m.i.)(60 min/hr)(24) = 725760 gallons

It now becomes evident that some form of storage is the answer to enable 250 gpm +- above the water right flow during the 12 hours of pumping. The above also shows that during the water window less water is used than appropriated during a 24-hour period.



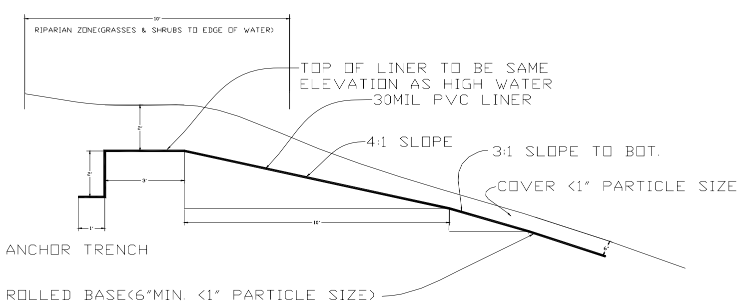
The above chart points out the reason for a storage or pond. Before the subject of constructing a pond is covered it is graphically important to show why that storage is necessary.

Locate the Water Right (W.R.) line on the above chart. It is the Horizontal Line at 1,356 gallons per minute. This is the typical method by which agricultural irrigation water is delivered to a property. Now locate the line representing the irrigation between 12 A.M. – 8 A.M. It varies from March to November. It is a line which indicates the average of water use in that water window. Compare this line to the line above it (Peak Flow) that does not average the flow, but shows what the pump must produce to meet the demand for the period. Comparing these lines will point out that the average line does not exceed the water right but the peak demand exceeds the water right by a factor of 1.4 times. This illustrates some of the basis in the previous example of having a water right of 504 gpm but needing 750 gpm to meet the demand. The deficit of 250 gpm is drawn from the storage or pond.

<u>Pond Construction</u>

In sizing and constructing a pond there are some basic principles to follow.

1. The pond should be safe. Either a fence or some barrier to prevent public access that is acceptable for the area or meets governmental standards.
2. The minimum depth of the pond should be four feet of depth after maximum draw down.
3. A liner is often needed to prevent seepage out of the pond. At least 6 inches of rock-free soil over the liner. This protects the liner from UV rays and prolongs the life of the plastic.



POND LINER DETAIL

4. Ground water needs to be considered so that it does not float the liner. There are one-way valves on the market.
5. The pond should have a drain or overflow for excess water or in the event that the pump shuts down while water is flowing into the pond.
6. An aeration pump that delivers air to the bottom of the pond and diffuses the air upward to create circulation in the pond.

The deficit of 250 gpm must be reduced to cubic feet in order to know the size of the pond. Therefore:

250 gpm x 60 min per hour x 12 hours = 180,000 gallons

180,000 gallon divided by 7.48 gallons per cubic foot = 24,064 cubic feet.

Thus 24,064 square feet x 1 foot deep = 24,064 c.f.

This results in a pond that is 5 feet deep and covers 24,064 s.f. divided by 43,560 s.f. per Acre or .55 of an acre. This calculation is based on the fact that there are 504 gpm available from the water right and 250 gpm of stored water available and the pond will recharge the storage during the other twelve hours of water right.

Alternate to Storage

Advances in technology have created a competitive alternate that is acceptable by some jurisdictions. The technology provides specific times when water is delivered to each lot and is thus able to control the use and spread of water in the system. The engineer can better predict the flows within the system and the water window when homeowners use irrigation water. These systems consist of a Windows-based PC computer, a central control that communicates with remote field units via a two-wire communication system. The remote field units communicate with decoders for remote control valves at the lot services via a two-wire communication line. Landscaping and common areas may be incorporated with the lot service controls. The central computer is capable of communicating with up to 20 remote control units. Each remote unit is capable of communicating with about 120 valves with up to 8 valves operating simultaneously. Generally the remote base units will require 117v single phase power. The central computer can be either a desk top installation or installed within a wall mount cabinet. The computer can plug into a 117 v. single phase service and a standard telephone service. Generally a communication program can be installed for remote control of the system. Some programs come with this capability. The system should be capable of automatically recovering from power failures. Many systems have the capability of verifying the electrical components and maintaining a system operation history. Some systems have mapping capabilities and commands for decoder locations, system status, on/off commands and system adjustments. Flow monitoring features are very useful. Separate programs in the system help various watering strategies including timing for lot watering or fully automated soil moisture controls for landscaped common areas. The computer may be installed in a centrally located clean environment on site.

The Pumping Plant

Step 6. The total horsepower for the pumping plant may be estimated with the following formula:

$$HP = \frac{(\text{head in feet})(Q)}{(\text{efficiency})(3960)} = \frac{750 \times 185}{.7 \times 3960} = 50 \text{ HP}$$

The heart of the system is the pumping plant. It must supply the determined amount of water during the peak demand periods and also during the hours when minimal water is needed. Stations of 4500 gallons per minute must also provide 25 gpm to 50 gpm without cycling on and off. Cycling is detrimental to the piping and fittings because of the potential water hammer and other associated problems. It is therefore important to specify a pumping plant with the proper equipment to attain suitable performance. Early installations consisted of a simple centrifugal pump with a manual on-off switch box and perhaps a priming apparatus to get the system running. That system is no longer acceptable and more sophisticated pumping plants have replaced or upgraded those early installations.

Some typical requirements of current standards:

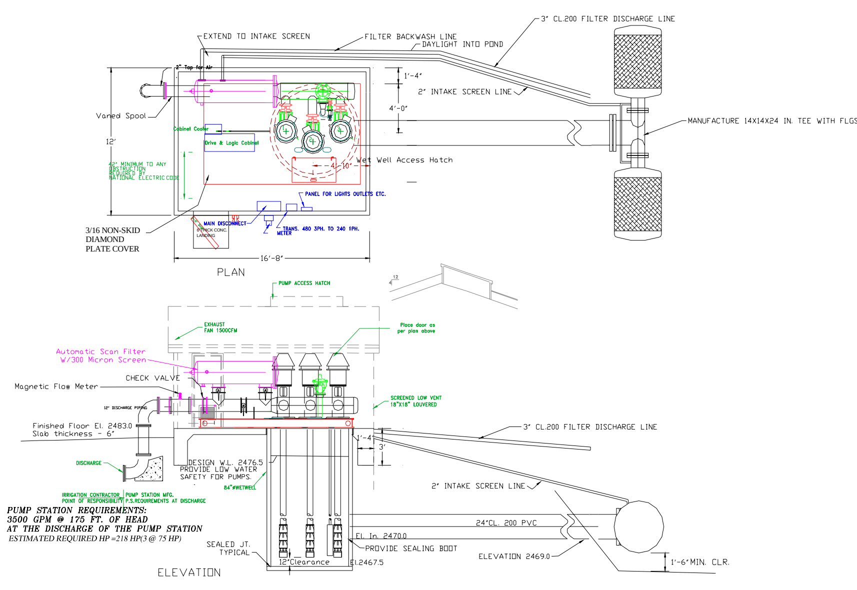
1. A self cleaning, pre-pump screen with suitable screen size to protect the pump from foreign debris. The screen size required by many agencies is 30 mesh (.025 inch) and located in a structure where the overflow will carry the foreign debris into a waste ditch. The screen is often located in a pond with a pipe carrying the screened water to the pump. This pipe should be sized not to exceed a flow velocity of more than one-and-one-half feet per second flow velocity. $V=.408(Q)/d^2$
2. Unless the pump has a flooded suction, a sealed wet well will be designed, which is a structure consisting of a rectangular or cylindrical concrete vessel over which the pump sits. The wet well provides suitable submersion of the pump intake for proper pump performance. Wet wells are typically 48 to 84 inches in diameter and 10 feet deep.
3. Small systems may only require a submersible pump or pumps that sit in the wet well (50 -200 gpm and 50 – 120 psi). Larger systems may justify short coupled vertical turbines. Short coupled vertical turbines generally have a longer operating life than submersibles. Multiple pumps are desirable to a single pump to meet the total flow requirement.
4. The platform or skid on which the pumping plant is built should be a minimum of 10 gauge metal with a substructure of I beams or channel iron. Tubing is generally not allowed as the interior of the tubes cannot be coated with corrosion proofing.
5. A pressure relief valve (PRV) capable of total flow of the pumps should be located on the discharge piping and vented to the wet well.
6. A concrete pad for the pump of suitable size to support the pump and a shelter.
7. A small jockey or pressure maintenance pump (PMP) to maintain pressure in the system that may decrease due to fitting seepage or minimal use. The PMP should not be included to meet the capacity of the pumping system.
8. A post pump filter that removes particles to 200 microns. Automatic filters prove to be economically feasible due to the cost of the equipment and labor for keeping all of the pumping plant filters clean.
9. A reliable meter to record the instantaneous flow in gpm as well as the accumulative flow in gallons or cubic feet.
10. Lightning Protection
11. Low Water Shut-off
12. If a building encloses the pump or pumps, it should exceed the pump mounting skid by 2 feet on each side of the skid. A ventilation fan should exchange the building cubic feet of air every 2 minutes.

Pumping Plant Controls

1. A Main Disconnect to completely isolate all controls and motors from incoming power.
2. Variable Frequency Drive (VFD) or valving to maintain system pressure at various flows.
3. Motor warranties that are not affected by VFD controls.
4. Programmable logic integrated into the VFD controls.
5. Soft start capabilities.
6. Equalized use of the pumps for alternating the lead motor on VFD systems.
7. Pump and motor protection from low water in the wet well or surges through the electrical lines.
8. A remote monitoring feature is a good option.
9. The power utility will often require a filter to prevent harmonic distortions from entering its power grid.
10. Phase failure or unbalance or reversal and overload protection.
11. All controls and panel shall conform to the National Electrical Code.

Pumping Plant Pad

At the top of the wet well and at ground surface, a 6 inch thick concrete pad and collar is placed as a foundation for the pumping plant. The slab shall be of sufficient dimension to accommodate the skid on the pumping plant plus an average of two feet on all four sides of the skid. The slab can have an expanded perimeter footing or a foundation wall for a pump building. The fused disconnect and breakers may be placed on the wall of the building. All NEC (National Electrical Code) electrical clearance codes must be met. The concrete base material under the slab should consist of six inches of one inch minus gravel compacted to 95 percent density. A protective building that meets building codes and the pump manufacturer's requirements for venting and air flow will reduce vandalism and keep ambient temperatures under control.



Lightning Protection

It is advisable to include lightning arresters or other protective devices to be installed per manufacturer's recommendations. Where grounding for the equipment is specified, the contractor should provide verified letters of tests describing and meeting the requirements. A form of insurance that could be checked on is Property Damage Coverage Insurance and Boiler Machinery with comprehensive coverage insurance.

System Piping

Generally standards for golf course irrigation systems may be used. System piping, Pressure Rated PVC 1120, Class 200, SDR 21, Conforming to ASTM D2241, IPS, Gasketed pipe is generally adequate for most systems. Where possible, the mainline should form a looped system. Some jurisdictions require a minimum size of the mainline pipe not less than 4 inches unless a pipe is on a spur lateral. Design flow velocities in the system should not exceed 4.5 feet per second in any section of the system outside the pumping plant.

Deflection in the bell end of the pipe should not exceed manufacturer's recommendation. Fittings of $11{}^{1}/_{4}{}^{0}$, $22{}^{1}/_{2}{}^{0}$, 45^{0}, and 90^{0} in the ductile iron fitting line have proven to more reliable than plastic. In order to follow the prescribed alignment or the lot lines as shown on the plans, proper fittings should be used to maintain a uniform offset from the lot lines.

Separation of pressure irrigation piping and potable water lines should conform to governing codes and State Health Department regulations.

Elevation changes within the system should be carefully considered so that the pressure in the system does not exceed 90 psi. If there is no more than a 20% pressure variance in the system, pressure regulators can be used at the individual lot services. Mainline pressure regulators should be used if larger elevation variations occur within the pipe lines.

Secondary Source

A secondary source of water needs to be incorporated into the systems in Northern climates for preseason and postseason system demands. A typical irrigation season for surface water is from April 15 to October 15. The secondary source shall provide adequate flows and pressure for typical evapotranspiration rates for Spring and Fall conditions. A connection to potable water or a well should have an approved backflow device. Cost of the water is usually the responsibility of the Homeowner's Association.

Service Tees

Service Tees should be located uniformly from the lot corner. Piping beyond the Lot Shut Off Valve shall be the owner's responsibility for maintenance.

Warning Post

Most installations require a flat fiberglass stake measuring 3" X 60" driven into the ground or an approved post at the terminal of the service line. A decal placed on the marker stating, "NON POTABLE WATER - DO NOT DRINK" marks the service.

Isolation Valves

Some road standards require isolation valves on each side of a road crossing. The valves often provide adequate isolation within the system. The idea is to be able to shut down sections of a distribution system without interrupting service to other users.

Excavation and Backfill

Standard installation practices for pipe line construction is a good standard to follow. It is prudent never to lay pipe in non-compacted fill. Thrust blocks should be located at all angle changes in the line and at tees and valves. Always back thrust blocks to a vertical native wall of trench. The thrust block should be sized based on the type of material backing it. Thrust blocks should not be placed while the pipe is in an expanded condition in the heat of the day.

Tracing Wire

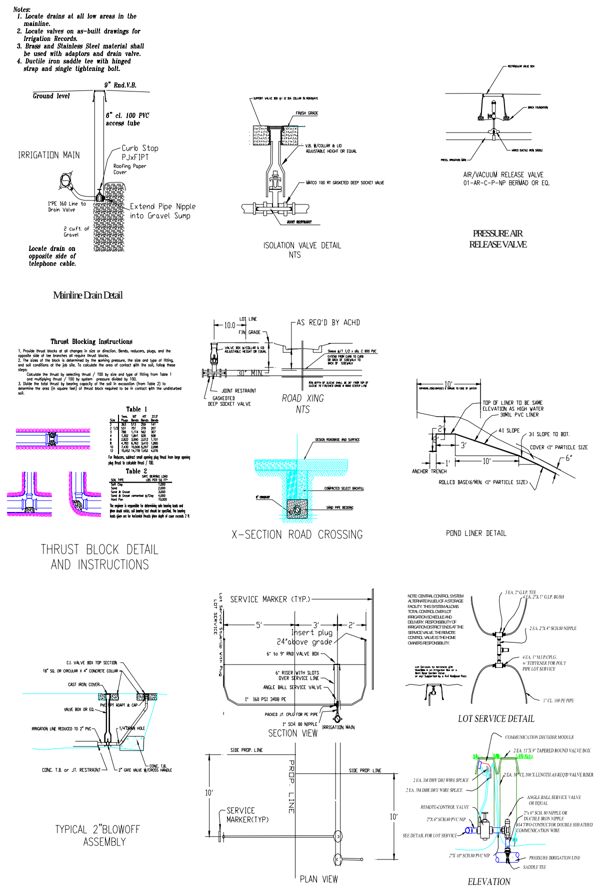
In order to trace the location of the installed mainline, a green #14 single strand copper wire with PVC coating and rated UF may be placed or taped on top of the mainline and terminated or looped into each shut-off valve box so that the entire system can be traced with tracing equipment from the pumping station throughout the piping network. The mainline can also be protected with a purple 2 inch wide warning tape with 1 ½ inch letters indicating a buried irrigation line below. Bury the tape 12 inches below the surface.

Road Crossings

All road crossings, as far as practical should be 90^0 to the center line of the road. Clearances between potable water lines and other utilities shall be as required by the governing agency. Make sure backfill and compaction meet road crossing standards.

Air Vents

Systems that have elevation variations will require continuous acting air release valves installed at high points in the system or on continuous long runs. Manufacturers recommend that air release valves spaced at a maximum of 1000 feet and sized per recommendations for the size of the pipe being vented.



Exposed Ditch or Similar Crossings

Where the pressurized irrigation mainline is exposed as in crossing a main ditch or canal within the system, mild steel pipe with a pressure rating of 250 psi can be used. Extend the steel two feet inside the point of exposure. Any steel pipe covered with earth or gravel material should be cold tar wrapped or epoxy coated to protect it from corrosion and extend the coating one foot beyond the point of contact with the soil. The steel pipe should have adequate support so that there is no deflection due to the weight of the water flowing in the pipe. Provide a concrete bulkhead on each end of the exposed pipe. If the pipe spans another flowing body of water (a ditch or canal), there should be no contact with the existing flow.

Blowouts

Some jurisdictions require a blowout. At a mid point in the system loop or at the end of laterals, the system may be flushed to a drain ditch or road drainage, a valved discharge pipe that surfaces to atmosphere for the purpose of flushing the line. The vented pipe can be 2 inch and equipped with a removable, threaded cap.

Drains

It is recommended to install drains at low points in the system.

Testing

Pressure testing of the installed piping will prevent future problems. Any immediate shortcomings in the installation will show from a pressure test. Often the knowledge that a pressure test will be conducted will prompt the contractor to a more quality conscious installation.

As-built drawings

As-built drawings are invaluable and should be required in all construction. Rarely are systems installed completely as shown on the plans. Recording these changes is essential.

Warranty

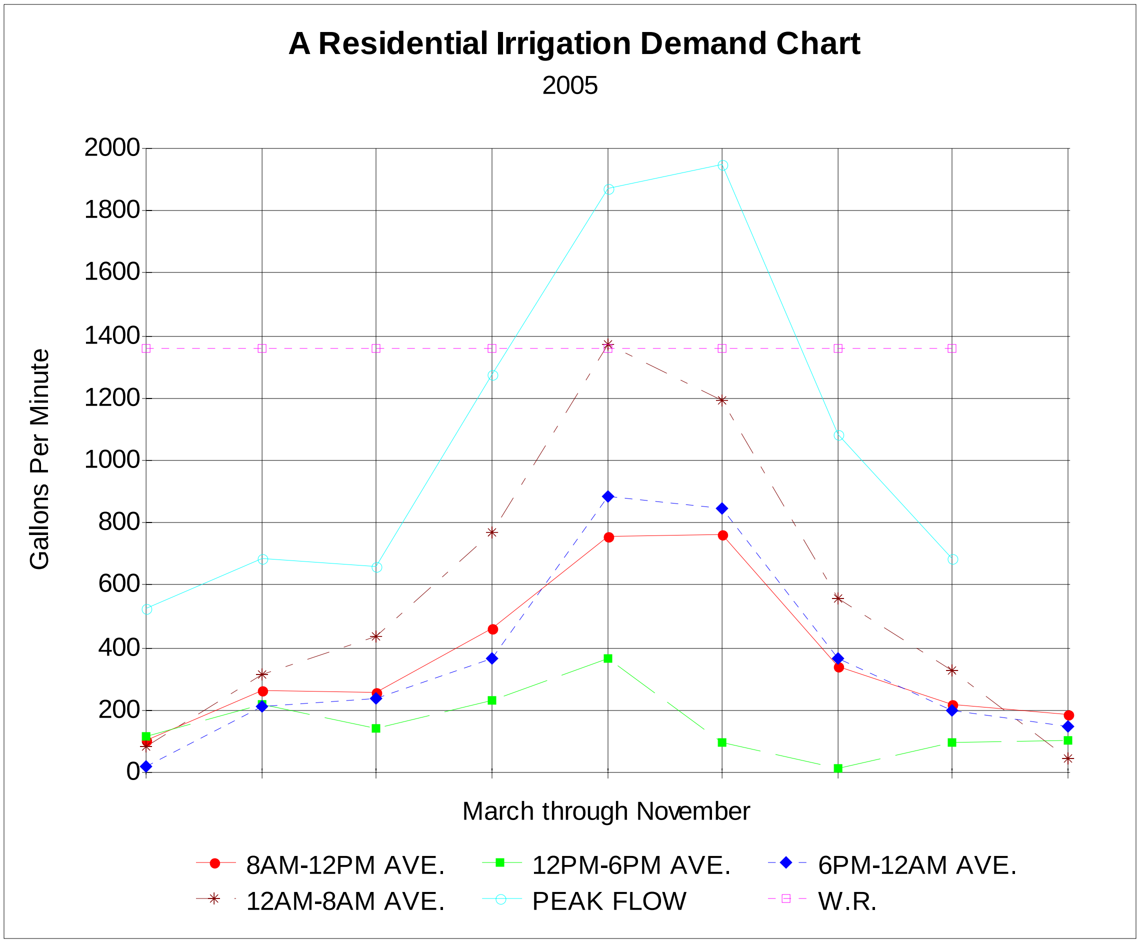
It is a good idea to require that all material, pumping plant components and workmanship be warranted for a minimum of one year from the time Home Owner's Association accepts the operation and maintenance of the system. Some components such as pumps, motors, etc. are warranted more than one year. All warranty cards or contracts for warranty should be handed to the Irrigation District at the time of acceptance. A letter of acceptance should be issued by the entity having jurisdiction over the system. Acceptance should not occur until the contractor can demonstrate full working operation of the system with acceptable tests showing full system parameter flows and adjustments. Motor amperage draw and other tests should be witnessed and recorded to the satisfaction of the controlling entity(ies). An authorized individual qualified to represent the owner may submit a letter to Home Owner's Association verifying he/she witnessed the installation to be in full compliance with the specifications.

Operation and Maintenance Manual

The designer should prepare or require two copies of a manual covering all aspects of the daily operation and upkeep of the system for optimum performance and service. The manual should include cut sheets of the material used in the installation, method of winterization, start up procedures, and local sources of materials used in the installation as well as companies and contacts that can provide services to the entity assuming maintenance of the system.

Water Savings

Now that the system has been constructed and the phases of construction completed. Are there any water savings? In studying the following graph, there appears to be considerable potential water savings.



The area above and left of the peak pump line on the left half of the graph and the area above and right of the peak pump line on the right half of the graph indicate unused water. This constitutes about 25% of the annual water right.

As more technology and control of the water is universally available this unused water may become a valuable commodity to a manufacturing plant or some other entity needing water for operations. In Idaho there is a law that prevents "water spreading". This means that if you save water that is designated to a given tract of land, that water cannot be used to the benefit of other land.

Legislation will probably modify this law as more demand is placed on this valuable resource. There are areas of drought in the United States where it is necessary to get a permit to use *potable* water. Conservation laws, where water is not being used to its highest and best use, will surely be at the top of the list for many legislative agendas.

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Comparison of Water Application to Turfgrass
Utilizing Different Irrigation Equipment

Brent Q. Mecham

Abstract

This small study and demonstration was established in 2006. The purpose of the study is to measure the amount of water applied to the tall fescue turfgrass by sub-surface drip irrigation (SDI) compared to traditional pop-up spray head irrigation. Each plot is a mirror image of the other with straight edges, sharp angles and curved borders. One plot has pop-up spray heads with its own valve and water meter. The other plot uses in-line drip emitter tubing evenly buried and spaced throughout the area with its own valve and water meter. The irrigation for each plot is controlled by the use of soil moisture sensors which determines the frequency and duration of irrigation events. The results provided are for the 2007 growing season.

Background

The plot of ground where the study and demonstration is located is at the Conservation Gardens of Northern Water located in Berthoud, Colorado. The soil type is a clay / silty-clay soil. The turf plot was prepared by deep tilling (6-12 inches) five cubic yards of composted organic matter per thousand square feet into the existing disturbed soil. The turf-type tall fescue grass was established from seed that was planted in July of 2006. The area was divided in half so that each plot had approximately 1,410 square feet as shown in the diagram.

One half of the plot was irrigated with traditional pop-up spray heads with a built-in pressure regulator set for 30 psi. The majority of the nozzles were fixed arc and difficult angles utilized adjustable-arc nozzles. Because of the geometry of the area, a mix of 12', 15' and 17' nozzles were installed into the spray heads. A catch-can test was performed to measure the lower-quarter distribution uniformity and the result on the date of the test gave a DU_{LQ} of 68%.

The subsurface drip irrigation utilized drip emitters that were .26 gph with the emitter spacing being 18" on center in the ½"tubing and the tubing lines were installed 15" on center buried 5" below the soil level. Tubing was carefully installed and measured to have a constant depth of bury and spacing between the lines and so that the emitters were in a triangle pattern as much as possible.

Each plot had its own valve and water meter. The irrigation events were controlled with a soil moisture sensing system. The water source for the spray heads utilized water from a holding pond and pump station. The window of opportunity to irrigate was every other day between set hours that would not conflict with the other sprinkler zones that were supplied by the pump station over the course of the season. Hours for irrigation were set for night watering with maximum run time of 10 minutes per cycle with a 30 minute soaking period. The soil moisture controller system would determine the number of cycles to irrigate to maintain soil moisture between upper and lower thresholds which are based upon soil type. During peak water demand parts of the season the every-other-day watering would mean there was about a half-inch deficit in soil moisture depletion. However, irrigation would not occur if the minimum threshold for soil moisture had not been reached. When this happened because of cooler weather or rainy periods the frequency of irrigation was automatically stretched out. Because of pump-station capacity, there were fixed limitations on when irrigation could take place and sometimes the soil moisture deficit could be greater than the desired 50% managed allowed depletion, but that was rare.

For the sub-surface drip irrigation the source of water was from a municipal supply. The time for irrigation was set for 1 p.m. each day, again utilizing a cycle and soak method of 20 minutes of irrigation and 20 minutes of soak time. The upper and lower thresholds for soil moisture were set in the soil moisture controller system. The concept is for irrigation to initiate when the lower threshold for moisture was reached and stopped when the upper threshold of soil moisture was reached. The thresholds are determined by soil type and management decisions on what the managed allowable depletion should be.

The goal was to have very nice looking grass. Mowing took place usually twice a week with a mowing height of three inches. Fertilization used an organic-based fertilizer with 7% nitrogen with 2 applications for the season. Each application was applied at 1.5 pounds of Nitrogen per thousand square feet.

An on-site weather station collected the weather data on 15 minute intervals and the ASCE Standardized Penman-Monteith Evapotranspiration equation was used to calculate reference ET for grass or ET_O. ET values were calculated from midnight to midnight each day.

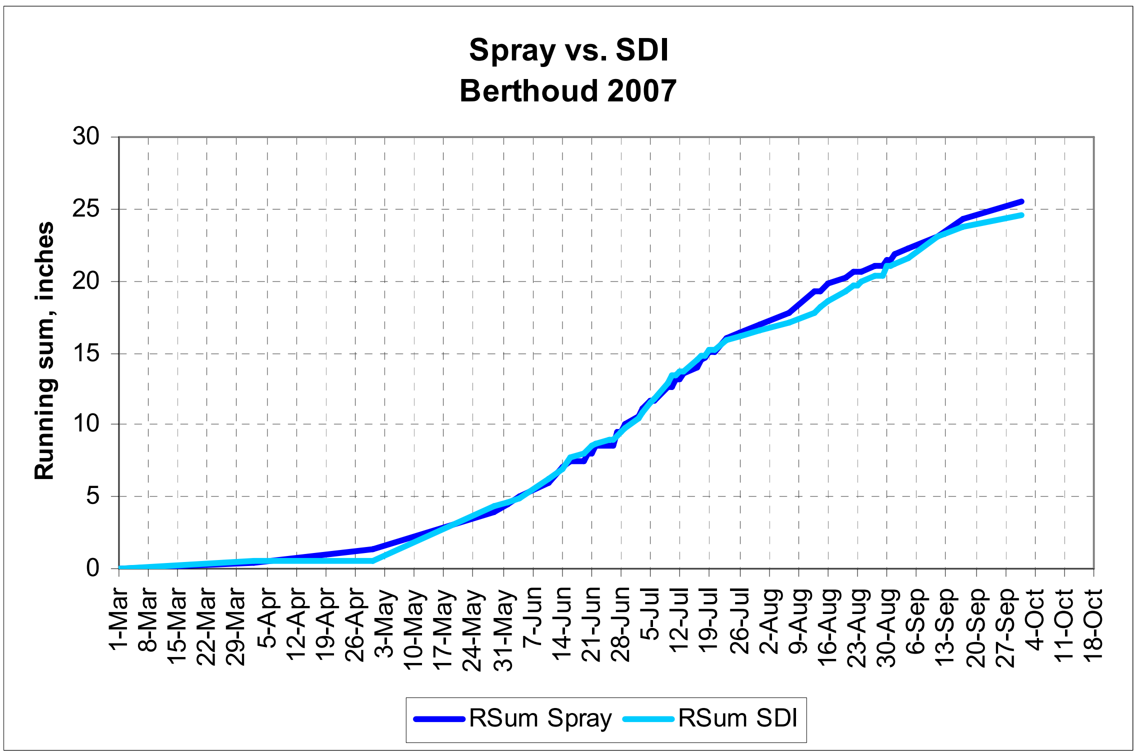
Picture 1 shows the general configuration of the test plot. It was divided in half so that each part of the plot was a mirror image of the other. The foreground of the photograph is the location of the pop-up spray heads. The sub-surface drip is toward the back. This photograph was taken in October of 2006, 3 months after the initial seeding.

Results

The results for 2007 cover the period of March 1 through September 30. By allowing the soil moisture sensors to control the irrigation, essentially the grass irrigated itself without human management making changes to the irrigation schedule other than to set the schedule based on site specific requirements and limitations. Once set, the schedule was left alone. The water meters for each plot were read at least weekly and during the hottest part of the growing season when irrigation would be the greatest, the meters were read almost daily.

Figure 1. shows that the two different application methods applied nearly an identical amount of water over the period. The spray zone applied 25.48 inches and the sub-surface drip irrigation system applied 24.63 inches which is about a 3.5% difference which could be within the tolerance of water meter accuracy.

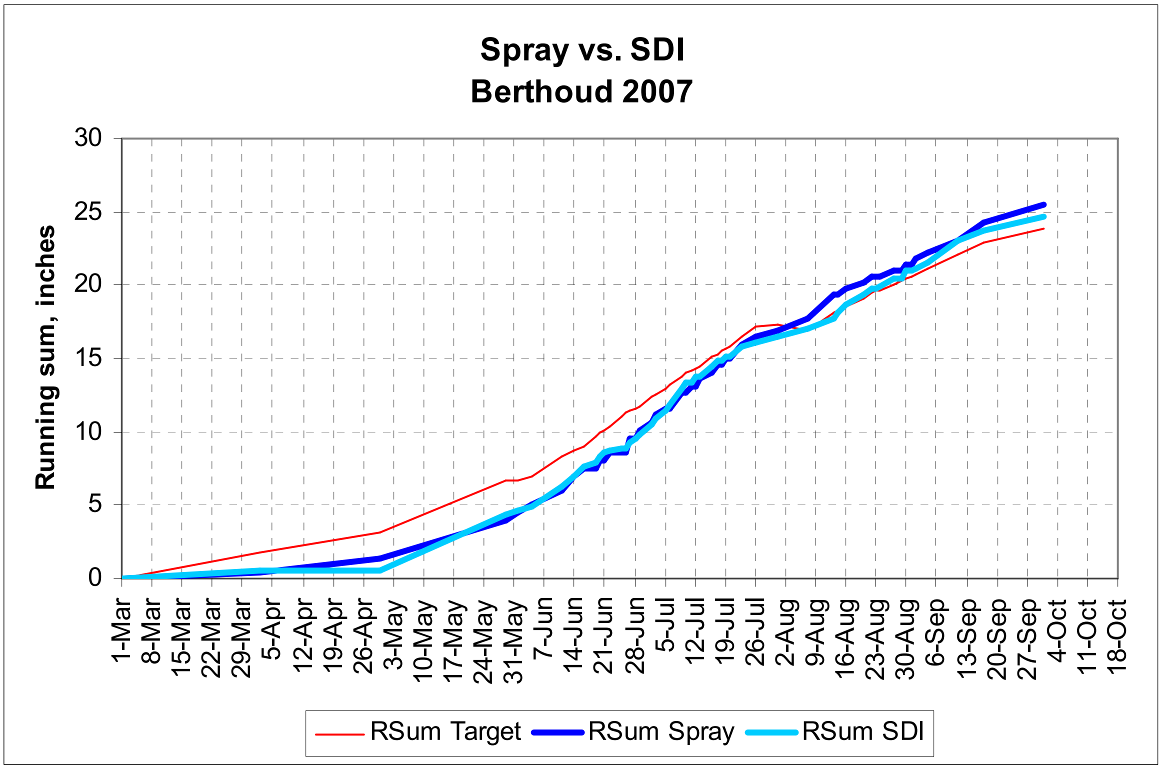
Figure 1.



The reference evapotranspiration (ET_O) for the period was 38.79 inches and site rainfall for the period 14.36 inches. Sufficient rainfall fell in March and April that the irrigation systems were not activated until late April which is fairly typical for the region

Figure 2 is a graph that shows the amount of water applied compared to the target amount of water for the same period. The target amount of water was calculated by adjusting the ETO by a .80 a crop coefficient subtracting 50% of the rainfall. A running sum was created by converting the number of gallons recorded from the water meters into inches so it could be compared to the target inches of water. As will be noted, the target amount seems to be somewhat high early in the season and slightly low at the tail end of the season. The dip in the early part of the season makes sense as the grass is coming out of dormancy and the full amount of water as calculated by ET equations is not actually needed by the turfgrass.

Figure 2.



Figures 3 and 4 are for examining the results of water applied compared to reference ET and striving to identify the target amount of water that should be applied. The comparison is now for the period of greatest water demand in the area of June, July and August which is fairly typical of most regions in North America. Depending on the crop coefficient use, the results and conclusions can change. Figure 3 is utilizing the .80 crop coefficient as used in the previous graphs and it would seem to indicated the water applied is greater than the need. However, the modifier is one commonly used with a number of equations when striving to make irrigation schedules. Figure 4 utilizes a .90 crop coefficient which would be similar to literature that is published for using the Standardized Penman-Montetih Reference ET equation for a well cared for cool season turfgrass. When looking at this graph then the water applied matches closely to the target amount of water estimated.

Figure 3.

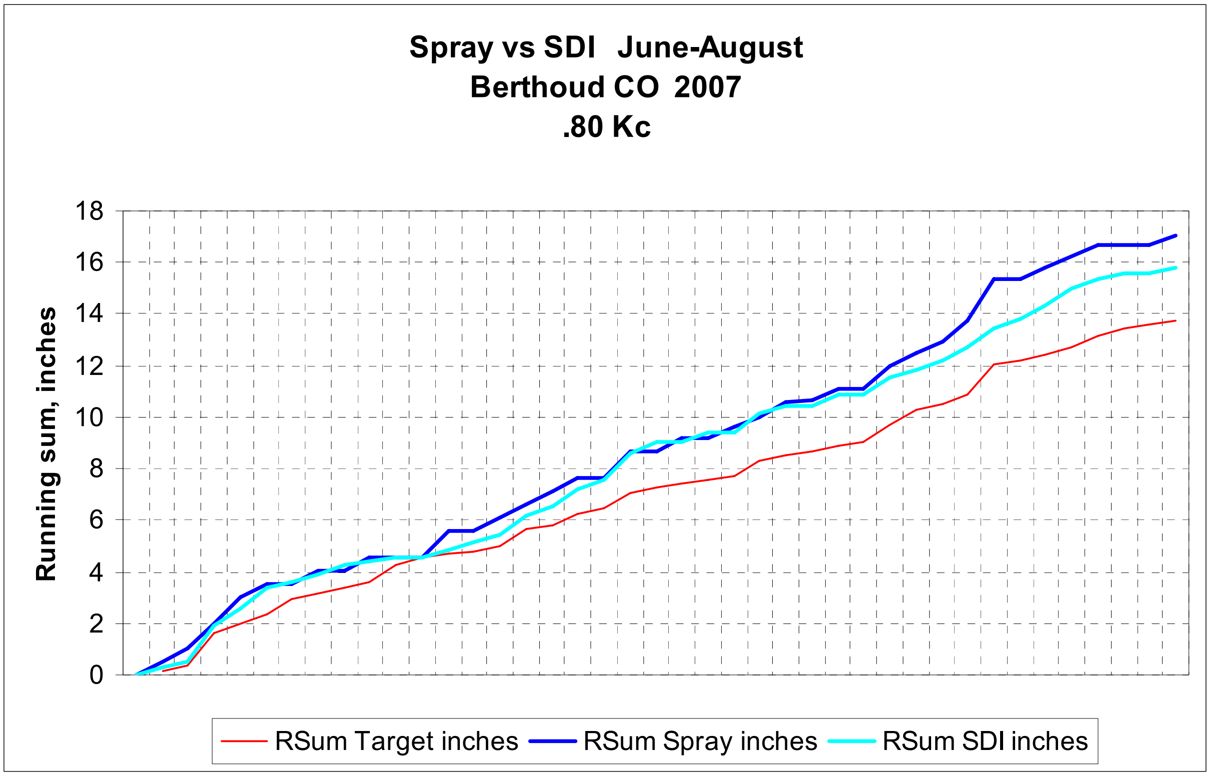
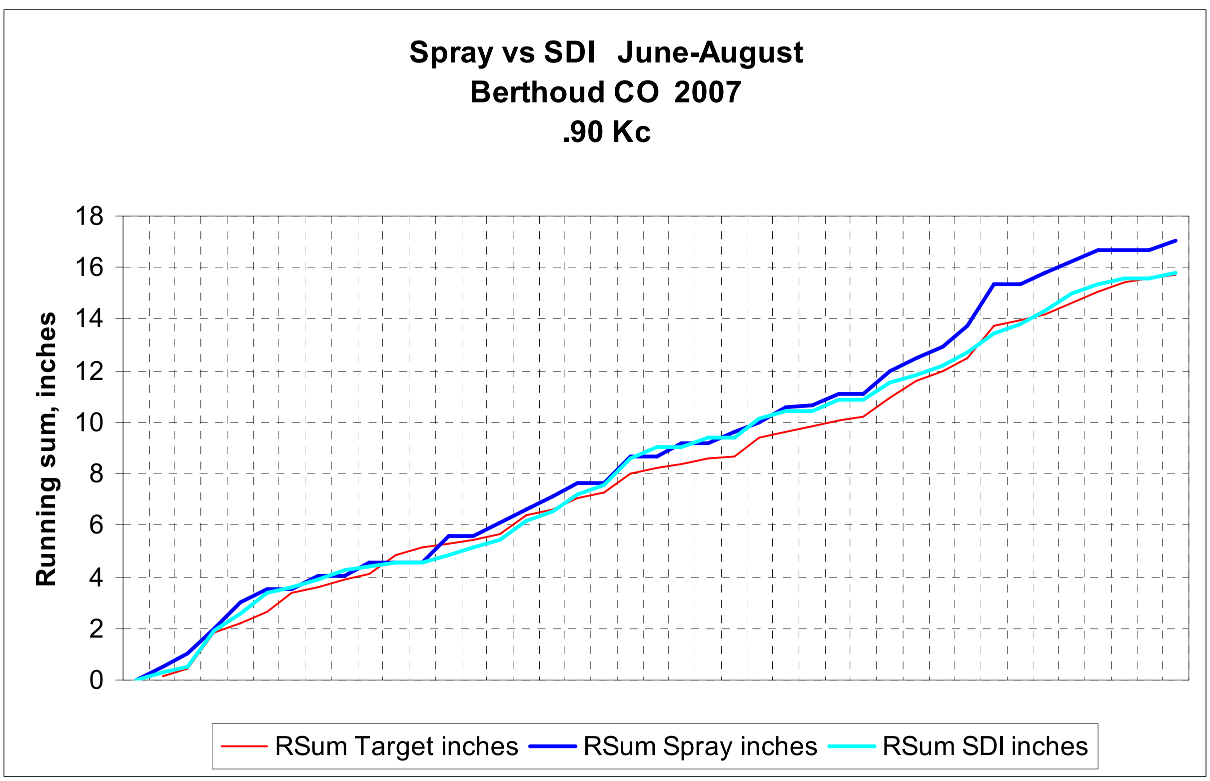


Figure 4.



Observations

By looking at Figure 4 one might make the conclusion that the SDI zone was applying the right amount of water and that the Spray zone applied too much water. However, visual observation toward the end of the season showed that the turfgrass growing in the SDI plot was showing stress and was actually under-irrigated and that the grass in the spray head area appeared better. This would then be an indication that even the .90 crop coefficient may under-estimate the amount of water required. This actually shows some of the challenges in scheduling irrigation in urban landscapes because of the many variables that influence the amount of water required including the type of horticultural maintenance taking place.

The amount of water applied showed that the grass needed that amount of water and did not care in what manner the water was delivered. It could be argued that with over-head irrigation you have the challenge of keeping all of the water on the target and we know that frequently it is blown off-target by Mother Nature. SDI does not have this problem, but because it is below grade, the waste may not be obvious because it would take the form of deep percolation, water going deeper than the roots can acquire and use.

No extra water was allowed because of distribution uniformity issues. While the pop-up spray zone had very acceptable uniformity, it is difficult to measure uniformity of sub-surface drip irrigation. Usually that is done visually when stripping or numerous hot spots appear in the turf. In both plots we could observe hot spots develop.

Some important observations can be noted.

1. Uniform soil conditions are essential for SDI to be effective.
2. Better performance of SDI is achieved by irrigating in the heat of the day which is often contrary to many recommendations. SDI depends upon the capillary movement of water to uniformly wet the soil profile. The capillary movement of water is greatly enhanced during periods of active evapotranspiration. This helps minimize the stripping effect that is often associated with the use of sub-surface drip irrigation.
3. Crop coefficients are general in nature and not specific for a species of grass and the associated horticultural practice utilized in caring for the grass. More research is needed to help identify crop coefficients that may change during the growing season as grass goes through growth phases.
4. Proper design, installation, maintenance and management have big impacts upon how much water is used to get desired results. Proper application to irrigation methods and technology will get better results. This is not new news, but it is yet fully practiced and embraced.
5. Trying to establish seed using SDI did not work and supplemental over-head irrigation was needed.
6. Watering in fertilizer is easily achieved with spray heads, but needed a timely rain to active the fertilizer on the SDI plot.

Conclusion

This is the first year of a study that needs to be repeated for several more years before conclusive results can be identified. Until then the grass wants its water and it doesn't too much how it gets delivered, spray, SDI or rainfall.

REDUCING RUNOFF LOSSES OR IRRIGATION WATER BY IMPROVING CULTURAL PRACTICES

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Abstract

Wetting agents are mainly used to manage water repellency in soils but they do provide other benefits like increase in water retention and reduction in physiological moisture stress in plants. Experiments were conducted at the California State Polytechnic University, Pomona on a loamy sand soil situated on an 8% slope with an established turfgrass maintained under golf course fairway management conditions. The effect of cultural practices like core aerification followed by sand topdressing and application of a wetting agent in reducing runoff of irrigation water was evaluated. Runoff events after the cultural practices and the wetting agent treatment (Dispatch applied at 877 ml/ha) was repeated four times over a time period when the matric potential ranged from 15–40 kPa. An empirical formula based on Horton's equation was used to predict maximum runtime of sprinklers to prevent runoff from turf on slopes. Total irrigation runoff was calculated based on overspray, surface runoff and percolation or seepage over a specified period of time. When Dispatch was added to the irrigation water vertical movement of water was more pronounced than the control (water alone). The least runoff occurred when the soil had the highest matric potential. Dispatch treatments resulted in 43% and 55% higher total wetting surface area at 30 minutes and 60 minutes respectively compared to the water alone treatment. Cultural practices like core aerification, topdressing with sand and using a wetting agent reduced

the volume of surface runoff by increasing the infiltration rate and the time period when visible surface runoff was first observed since the start of the irrigation event.

Key words: infiltration, runoff, wetting agent, aerification, topdressing

Introduction

The rate at which a particular soil can absorb water is called the infiltration rate (IR). The infiltration rate depends on the soil texture, organic matter content, soil moisture content, compaction and other cultural practices which can affect soil physical properties. The rate at which an over-head sprinkler system applies water is called the precipitation rate (PR) of the sprinkler. The PR is calculated based on the total volume of water applied over a period of time at a specified pressure using a particular type of nozzle. If the PR is more than the IR for a particular soil some of the applied irrigation water will collect on the surface creating a potential for runoff. Runoff of irrigation water is not only a wastage of water but also leads to soil erosion and is a source of pollution since it can carry excess fertilizer, pesticides and other contaminants. Since runoff is closely related to IR several researchers have developed mathematical models to predict the infiltration capacity into the soil as a function of time. The most popular equation was developed by Horton (HORTON, 1939) which can be used to predict cumulative infiltration:

$$f_p(t) = f_c + (f_o - f_c)e^{-kt} \qquad (1)$$

where, f_p (t) is infiltration rate in a given time (t), f_c is final equilibrium infiltration rate, f_0 = initial infiltration rate at time t = 0, t is elapsed time, and k is decay coefficient.

Horton's equation assumes an infinite water supply rate at the surface, that is, it assumes saturated conditions at the soil surface. Hence the cumulative infiltration that would occur under conditions of unlimited water supply at the surface could be predicted using a modified form of Horton's equation (HORTON, 1940):

$$F(t) = f_c t + \frac{f_o - f_c}{k}(1 - e^{-kt}) \tag{2}$$

where, $F(t)$ is the cumulative infiltration over time (t) since the start of infiltration. The actual infiltration rate is less than water supply rate when the sprinklers are turned on and the actual infiltration rate does not decay as predicted by Horton's equation. This is because Horton's equation assumes that the supply rate exceeds the infiltration rate from the start of infiltration. Therefore, in order to determine the true infiltration rate at a given time we need to solve the following equation to first determine the time t_p, the time at which water is starting to accumulate at the soil surface - (ponding time) and then evaluate $f_p(t_p)$;

$$F(t) = \int_0^t i(t)dt = f_c t_p + \frac{f_o - f_c}{k}(1 - e^{-kt_p}) \tag{3}$$

where, $F(t)$ is the cumulative infiltration over time (t) since the start of infiltration and $i(t)$ is the infiltration rate. Equation 3 represents the accumulated volume of actually infiltrated water; up to time t_p (ponding time) if the actual rate of infiltration had been equal to the infiltration capacity.

These equations were modified by researchers to develop a practical equation based on a series of maximum sprinkler irrigation runtime curves for different sprinkler precipitation rates vs. soil types to maximize the sprinkler application efficiency and conserve water (HUNG & KRINIK, 1995). However, it is necessary to develop different infiltration capacity data for various types of soil so that the equation can be applied in the field. The United States Department of Agriculture-National Resource Conservation Service (USDA-NRCS) published a series of infiltration data for several soil families (CUENCA, 1989). An equation for determining the maximum sprinkler irrigation runtime in order to reduce runoff was developed by HUNG & KRINIK (1995). The following equation can be used to calculate maximum irrigation runtime:

$$t_{max} = \frac{\{f_o - P + f_c\,[\ln (f_o - f_c)/(P - f_c)]\}}{Pb} \qquad (4)$$

where, t_{max} is maximum irrigation runtime without runoff (hours), P is average sprinkler precipitation rate, b is Horton's constant, f_o is initial infiltration rate at time $t = 0$, and f_c is final equilibrium infiltration rate. In equation 4, the Horton constant b can be obtained by solving Horton's equation using the infiltration rate curves for the particular soil textural class. The infiltration data obtained from the USDA-NRCS were based on 50% available soil water depletion which has been used in irrigation applications in the United States for almost a century. The relationship between infiltration rate and elapsed time in different soils has been reported by researchers (KOSTIAKOV, 1932; KUTILEK & NIELSEN, 1994.

Wetting agents can wet hydrophobic surfaces and help carry or keep water available for turfgrass (RUITER, 2005). Furthermore, wetting agents reduce the surface tension of water and increase infiltration and percolation rates of root zones, which helps water to penetrate into soil and decreases moisture stress on turfgrasses (LEINAUER, 2002). Moreover, soil wetting agents are considered as a tool in turf management to improve irrigation efficiency and water conservation (KOSTKA et al., 2000). The objective of this research was to evaluate the effect of a wetting agent application on the wetting pattern, infiltration rate and runoff of irrigation water.

Materials and methods

Runoff collection

Experiments were conducted at the California State Polytechnic University, Pomona on a loamy sand soil with established hybrid bermudagrass (GN-1) turf maintained under fairway management conditions. The plot size was 0.03 hectare situated on an 8% slope. Runoff experiments were conducted over a matric potential range of 15–40 kPa in the soil to study the relationship between irrigation water runoff and matric potential. Based on the runoff experiment a matric potential range of 15–25 kPa was selected to further investigate the effect of the various treatments in reducing irrigation runoff. The treatments (cultural practice of aerification followed by topdressing with sand and the use of a wetting agent) were designed in a randomized block design with four replicates which were repeated over time under similar soil moisture conditions (15–25 kPa). Soil moisture sensors (Watermark, Irrometer Co, Riverside, CA, U.S.A.) were buried in the soil at 10 and 20 cm from the soil surface. The sensors measured the matric potential every 5 minutes before and after the irrigation event till 24 hrs after each irrigation event. The maximum irrigation runtime was calculated using the modified Horton's equation (equation 4, HUNG & KRINK, 1995). Extended irrigation runtimes were calculated to create runoff. Total runoff was monitored through surface runoff and subsurface seepage. The sum of surface runoff and surface flow or seepage of water till 1 h after the start of the irrigation event was reported as total runoff. Surface runoff was measured by installing rain gutters which drained into a collection pit with a tipping bucket. The subsurface seepage was monitored through a collection bucket placed at the bottom of the collection pit. Horton's constant for loamy sand soil was used to calculate the maximum runtime for sprinklers based on their precipitation rate (PR).

Cultural practice

Cultural practices like core aerification and top dressing with sand were done before and after a set of runoff experiments. Core aerification is a process of removing soil cores from the soil to reduce compaction due to traffic on an established turfgrass surface in golf courses, sports fields and landscapes to increase air and water movement in the soil profile. Aerification can be done with a solid tine when the soil cores are not removed from the soil or by using hollow tines where the soil cores are removed after the operation. The pore spaces created by the solid tine after aerification can be filled in with sand to increase the porosity of the soil. Core aerification was done with a 10 cm hollow tine using a walk behind aerifier (John Deere Co, Moline, Illinois, U.S.A.). The cores were picked up with a turf-vac and the turf was top dressed with sand.

Wetting agent application

A wetting agent (Dispatch applied at 877 ml/ha) was applied to the plots before each of the four irrigation events. The cultural practice of aerification followed by topdressing with sand and the incorporation of a wetting agent were two treatments in the experimental design which were repeated four times over a time period when the matric potential was 15-25 kPa. Runoff was monitored after each treatment for all the four repeated irrigation events at the same site.

Distribution uniformity (DU)

Fourty nine plastic cone shaped cans were placed on the plots in a grid pattern. Ring can-holders were used to place catch cans in upright position to avoid any can movement. The four cans in the corner of the plot were placed 1 m away from the sprinkler heads, while the others were placed approximately 2 m apart in a uniform grid pattern throughout the plots. All the cans had a diameter of 11.5 cm, and a height of 15 cm. The sprinklers were run for a total of 10 minutes for each plot, and the collected water in each catch can was recorded in milliliter (ml). Distribution uniformity (DU) was calculated based on the low quartile distribution uniformity (LQDU). The collected water reading in catch-cans was re-ordered from low to high. The lowest 25 percent of catch-can readings were averaged, and divided by the average of the overall can reading, and expressed in percentage.

Percent of LQDU = Average catch in the low quartile x 100/Average catch overall (8)

Infiltration rate

The infiltration rate in the experimental area was measured with a double ring infiltrometer (Turf-Tec International, Coral Springs, Florida, U.S.A.) at specified matric potential of 15–40 kPa. Raw data of soil infiltration rates in a loamy sand soil was obtained from the USDA-NRCS and was compared to the infiltration tests in the experimental sites. The change in infiltration rate over a matric potential range of 15-25 kPa was plotted against the elapsed time (Fig. 1).

Wetting area

Experiments were conducted to study the wetting pattern of water with and without an added wetting agent in a plexiglass soil bin using the same soil as the field runoff experiment. The soil was loamy sand with a pH of 6.6, electrical conductivity (EC) of 1.8 dS/m and an organic matter content of 0.13%. Dispatch was added to the irrigation water at a rate of 877 ml/ha. Separate experiments were conducted using two drip emitters, one rated as 3.8 l/h and another at 1.9 l/h. The experiments were repeated four times. Actual flow rates were within 5% of the rated flow rates at the operation pressure (210 kPa). A micro tube of 45 cm length was attached to each emitter to facilitate the location of the emission point in the soil bin. The system was run for 30 minutes. A dye was not used in the experiment since the dry soil and the wet soil had contrasting colors which could be easily seen through the plexiglass. Lines were drawn with a marker on the plexiglass to indicate the wetting pattern. Wetted areas measurements were taken at 15 and 30 minutes. The 60 minute measurement was taken 30 minutes after the end of the run time (a total of 60 minutes from the beginning of the run time). Approximately 180 minutes after the beginning of the run time a cross section was made in the soil directly under the location of the emission point and perpendicular to the plexiglass in the front of the bin. The wetted areas were given in cm^2 and were calculated based on the shape of the wetted area or were measured with a planimeter.

Statistical analysis

The data was subjected to analysis of variance (ANOVA) program of SAS (SAS, 1988). Regression models were used to study the relationship for continuous variables while mean separation techniques like protected least significant difference (LSD) test and Duncan New Multiple Range Test (DNMRT) ($p = 0.05$) were used to separate the means of discontinuous variables. Data for treatments and interactions that were not significant at the $p = 0.05$ level were pooled to conduct an overall ANOVA analysis. The interactions that were significant were split and analyzed further using the proc glm program of SAS (SAS, 1988).

Results and discussion

Distribution uniformity (DU)

The low quartile distribution uniformity (LQDU) ranged from 56% to 68% and the precipitation rate (PR) varied from 2 cm/h to 3 cm/h depending upon the wind direction and velocity during the runoff experiments. The mean matric potential between the different moisture sensors ranged from 15–40 kPa. Least surface runoff occurred when the soil had the highest matric potential (Fig. 2). The wind direction and speed also influenced surface runoff; hence experiments were conducted at similar wind speeds. Wind speeds ranged form 4 to 6 km/h during the runoff experiments.

Infiltration rate

The infiltration rate in a loamy sand soil was calculated based on raw data obtained from USDA-NRCS and then compared to the infiltration tests using a double ring infiltrometer. Cumulative infiltration for the particular soil texture was obtained by the integration of the equation (3) for a total elapsed time of 400 min. The infiltration rate for a loamy sand soil was plotted in a graph against the elapsed time when the matric potential was 15-25 kPa (Fig 1). The infiltration rate in the loamy sand soil increased when a wetting agent (Dispatch) was applied on the turfgrass before the runoff event compared to the untreated control plots. Highest infiltration rate was observed after the core aerification and topdressing program (Fig 3).

Runoff

A normal runtime for the loamy sand soil for a 15 cm root zone was 25 minutes to bring the root zone from 50% depletion to field capacity. A runtime of 60 minutes was used to ensure that runoff was observed for the study; however the runtime had to be reduced to 40 minutes for several of the tests because the volume of runoff exceeded the runoff collection device capacity. The time from the beginning of the irrigation to the time for surface water to be visible was recorded to compare with the T_{max} as determined by equation 4. HUNG & KRINIK (1995) had reported a maximum runtime approximately of 100 minutes using a Horton constant of 2.48 for a loamy sand soil on 6–8% slope (Table 1). The results from our infiltration tests using a double ring infiltrometer on the experimental area was used to calculate Horton's constant (Fig. 1). Horton's constant was found to be 5.89 in the loamy sand soil with an 8% slope. Modifying equation (4) with this Horton's constant resulted in a maximum irrigation runtime for loamy sand soil as 42 minutes. The actual times for surface water to be visible ranged from 15 to 29 minutes with a mean of 20 minutes in the untreated plots.

On an average overall the wetting agent treated plots did not have any appreciable runoff till 45 minutes of irrigation runtime while it took 60 minutes since initiating the irrigation event to observe any surface runoff after the aerficiation and topdressing with sand treatment was performed. The application of a wetting agent significantly reduced surface runoff of irrigation water compared to the untreated check. The aerification followed by topdressing treatment resulted in the least surface runoff between all the treatments but the seepage losses were higher than the wetting agent treatments. Hence there was no statistical difference in the volume of total runoff between the wetting agent and aerification treatment (Fig. 4). The aerification program significantly reduced total runoff compared to the untreated control. The initial soil moisture levels affect the infiltration rate in soils and hence soil moisture would influence the length of time when first surface runoff would be observed (Fig. 2). These results from this research study would suggest that the Horton's equation over estimates the time before runoff would begin.

Wetting area

Addition of a wetting agent (Dispatch) to water increased the vertical movement of water compared to the water alone treatment in a loamy sand soil. The wetted soil surface area was determined by the contrast in color between dry soil and wet soil. The wetted soil area in the horizontal direction between the wetting agent treatment and water was not significantly different (Table 2). Dispatch treatments resulted in 43% and 55% higher total wetted surface area at 30 minutes and 60 minutes respectively compared to the water alone treatment (Table 2). Incorporation of the wetting agent with water increased the vertical movement of water in the soil profile and the difference in wetted vertical soil surface between the wetting agent and the water alone treatment was more pronounced under unsaturated condition when the soil was dry. This difference during unsaturated condition may be pronounced since the moisture in soils is held at a higher tension or matric potential in a dry soil and the wetting agent may help in reducing the matric potential. Hence the addition of a wetting agent may facilitate movement of water in the vertical direction and increase the retention capacity of soil.

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Table 1. Horton's constant (b) for the different soil textural classes (HUNG & KRINIK,1995).

Soil Textural class	Horton's Constant
Sandy	2.76
Loamy sand	2.48
Loam	2.57
Clay loam	2.60
Clay	2.81

Table 2. Mean wetting pattern of water with and without an added wetting agent (Dispatch 877 ml/ha) in a loamy sand soil using a 1.9 l/hr emitter.

Treatment	Horizontal surface area (cm^2)			Vertical surface area (cm^2)			Total surface area (cm^2)			Vertical cross section area (cm^2)
Minutes	15	30	60	15	30	60	15	30	60	180
Water alone	283	374	503	0	13	26	283	387	529	147
Water + wetting agent	302	412	555	45	142	264	347	554	819	287
LSD (p = 0.05)	22.6	34.8	29.0	16.5	55	67.4	55.8	66.8	75.8	80.6

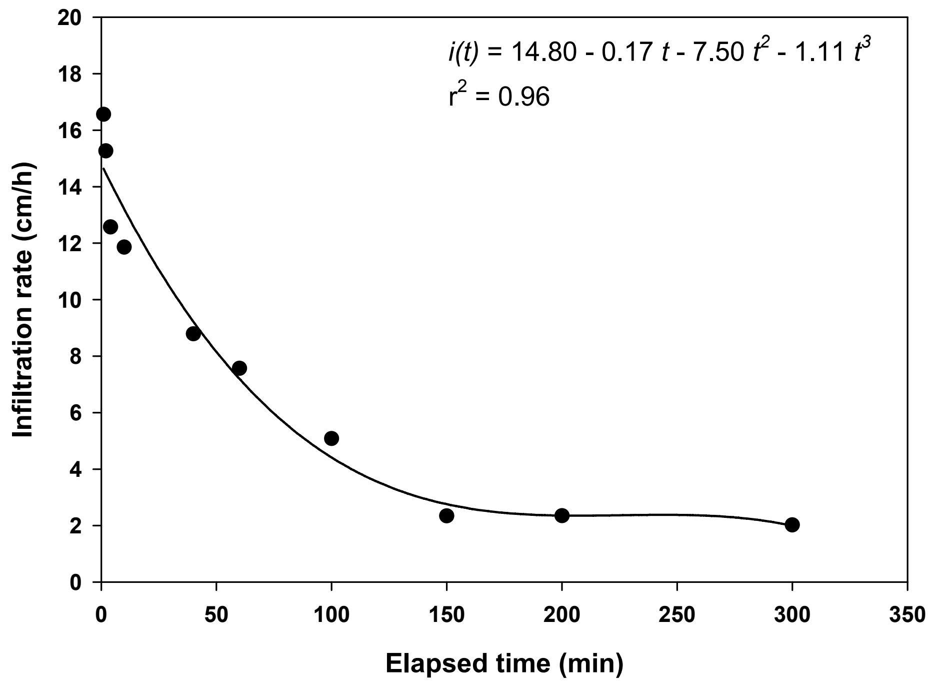

Fig. 1. Infiltration rate [$i(t)$] (cm/h) in a loamy sand soil as observed over a period of time since the start of infiltration (t). The matric potential was 15-25 kPa during the infiltration experiment.

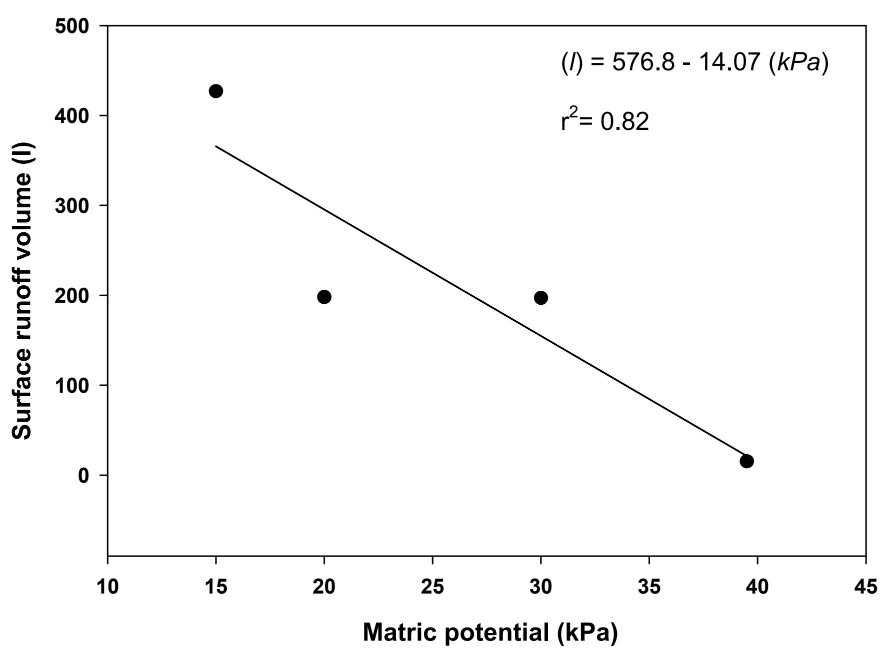

Fig. 2. Effect of matric potential on surface runoff (l) of irrigation water from a bermudagrass turf surface maintained under normal fairway management conditions on a loamy sand soil. Matric potential range was 15-40 kPa.

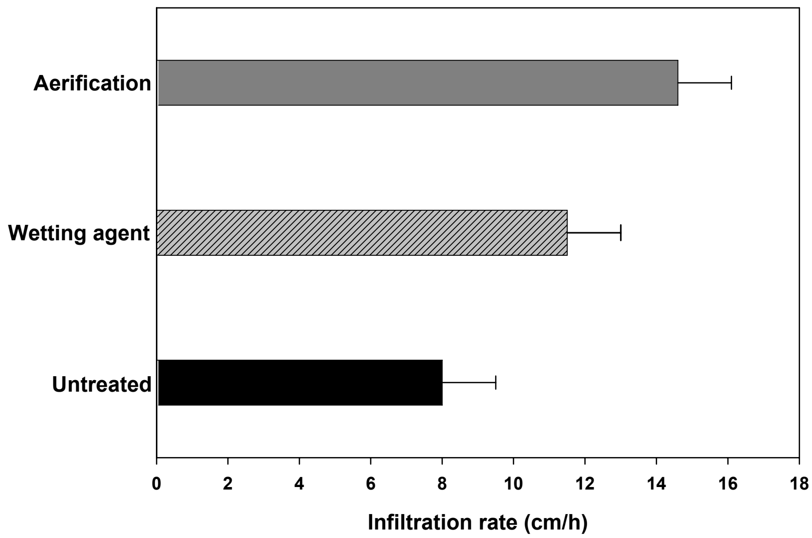

Fig. 3. Mean infiltration rate in a loamy sand soil on an 8% slope with an established turf stand as affected by cultural practices like core aerification and topdressing with sand or application of a wetting agent (Dispatch applied at 877 ml/ha) every time before the four repeated irrigation events. The matric potential in soil was 15-25 kPa during the infiltration experiment. The error bars indicate the standard deviation.

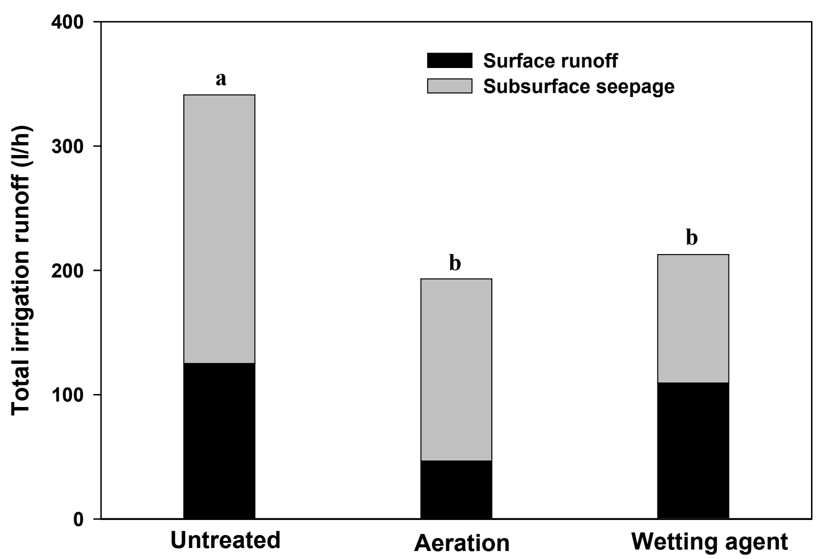

Fig. 4. Mean irrigation runoff volume collected as surface runoff and subsurface seepage into the collection pit. The aeration and topdressing was done a week prior to the runoff event. The wetting agent (Dispatch) was applied at 877 ml/ha rate 7 days before the each of the four runoff events The means were separated with Duncan's New Multiple Range Test (DNMRT) at p = 0.05 level. Bars with the same letter were not statistically different.

Levels of Design

(LEED, High Efficiency, Utilizing Reuse & Rainwater)

“Are all irrigation systems created equal? For that matter are they designed with efficiency in mind? What about maintenance issues?”

By Lorne Haveruk, CID, CIC, CLIA, WCP

DH Water Management Services Inc.

The Scenario

I have created a leading edge landscape concept for an upcoming project. However, I know the plant material that I have selected will require supplemental watering to get them through the harsh weather days ahead during the establishment period. What am I to do?

Have you heard about irrigation systems? Oh, you mean those things that get buried and come on automatically and get the landscape wet? Yea. But I hear they are lots of trouble and don’t work well, especially those drip irrigation ones.

Sound familiar? For the past 18 years I have heard this kind of talk over and over again till I am blue in the face from holding back my comments. It’s time to clear the air. I have just completed presenting at two large green industry conventions – one in Minnesota and another in Toronto. Your right – most people just don’t get it! The questions that I am asked and the comments that I am told bring me back to the days of old when I did not no the difference – or that their even was a difference. Boy – was I wrong! I have spent the past 17 years reading about irrigation and the massive array of parts produced all over the world that can come together to create a “SYSTEM.”   I emphasize system here because that is what it is.   A professionally design irrigation system (CID) utilizing the correct and most efficient parts to meet the sites unique watering needs, installed by pre-qualified contractors (CIC), maintained by certified irrigation technicians (CIT) with the entire process overseen by a qualified experience irrigation consultant (ASIC) – is like a hot red Ferrari, pushed to the limit on a European Autobahn. This is what life is all about!

Reality Bites

Oh, this is not your experience with irrigation on your past projects? Why? Did you follow the process? Oh, you thought irrigation systems were just something thrown together by someone claiming to be a qualified contractor, sorry, a qualified irrigation contractor? And those pipes still sticking out of the ground, they really don’t go with your landscape dream do they? But, they threw in the car wash and the sidewalk and driveway washing that occurs daily for free. What a bargain.

Ok, I will lay off the typical problems that are plaguing the irrigation trade, now and in the future. Unless we work together to put an end to water wasting inferiorly designed, installed and maintained so called irrigation systems – the problems will persist.

There are three things going for irrigation right now that I pray will change the way irrigation is looked at, treated at the concept table, talked about by those that design landscape projects – plants that do not need water do not exist – as far as I am aware of.   So, we need irrigation systems – correct? What we do not need is JUNK! Low Bid gets junk. Design/Build most times gets junk. If the process required to have a professionally conceptualized efficient irrigation system designed, installed and maintained is not adhered to you get what? JUNK! This brings confusion and mistrust from those who wish to do the right thing but do not know where to turn.

The three things working to straighten out the irrigation industry are: The Irrigation Association (IA) educational offerings, The EPA's new initiative creating WateSense (like Energy Star) to promote WaterSense recognized designers, contractors and water auditors who have stepped up to the plate to receive certification and many more educational opportunities being offered by Rain Bird, Toro, Hunter, Irrigatorteck, Cal Poly Pomona, and people like myself that are saying – enough is enough.

Levels of Irrigation

Once upon a time there was only irrigation or no irrigation systems. You either had water or you didn't. This picture shows an aqueduct in Turkey which carries water from the hills to the house and fields. Our current levels of irrigation equipment are light years ahead of this technology. The problem we are having is that the trade is for most part not versed in the latest available technology. The water efficient parts are there – the knowledge to create the most practical efficient site specific systems for most players is missing. Time is on our side and the next generation will be much better stewards of this finite natural resource – or they will not have it to use in the first place.

With the introduction of LEED – Leadership in Energy and Environmental Design, new classifications for irrigation appeared. LEED is defined as:

"*The Leadership in Energy and Environmental Design (LEED) Green Building Rating System™ is the nationally accepted benchmark for the design, construction, and operation of high performance green buildings. LEED gives building owners and operators the tools they need to have an immediate and measurable impact on their buildings' performance. LEED promotes a whole-building approach to sustainability by recognizing performance in five key areas of human and environmental health: sustainable site development, water savings, energy efficiency, materials selection, and indoor environmental quality." USGBC*

The new classifications for water efficiency credits noted in LEED documents, or for that matter sites with well thought out water efficient irrigation systems are:

- Traditional (conventional),
- High Efficiency,
- LEED, which includes rainwater or recycled site water harvesting systems.

The goal is to get sites off of potable water systems – city supplied water. This water is becoming to valuable and scarce in areas to be used for anything but human consumption.   Besides, plants do not like chlorinated water and do far better using what Mother Nature provides.

These are the new emerging words used to describe a certain type and efficiency level of the new breed of irrigation systems, currently being undertaken by a select few in Canada and the USA.

- **Traditional** also called conventional is an old school spray sprinkler and rotary sprinkler irrigation system. Controlled by an irrigation controller (timer) which when the time and day line up to indicate a watering occurrence has been programmed, sends an electrical current through a wire to a valve solenoid causing the valve to hydraulically open. The water flows through the lateral pipe line to the various sprinkler heads and as the line pressurizes sprinklers rise up to perform their duty – watering for however long the operator has set them to run. Spray sprinklers covering areas from 5' to 15' are used for smaller areas while rotors that move the stream of water throughout a preset pattern water form 16' to 40' or more for larger applications. These systems are usually measured in gallons per minute (GPM) of water.
- **High Efficiency** systems with city water sources utilize technology that has come from the agricultural side of irrigation. Netafim, a leading edge company from Israel is the technology responsible for greening the dessert, drip by drip. These systems usually utilize what is commonly known as Drip irrigation. I like to call it Low Volume as there are numerous devices that utilize  gallons per hour (GPH) watering rather than GPM. Sub-surface used for crop production is making itself known in landscape planters and small turf areas. Boulevard strips of grass typically around 4' to 5' wide are perfect for the use of sub-surface technology – if and when the system is designed and installed by professionals that know what they are doing. Soaker hose used for rows of hedges, soaking shrubs and other uses has been around for a long time. It works similar to your own skin that allows moisture to come to the surface for cooling. Soaker hose works the same way where little drops of water are forced through the pipe causing the pipe to bleed water slowly but effectively. Drip emitters are devices placed on a distribution pipe that carries water to many devices. Each device is rated for a certain water discharge in GPH. They vary for .5 gph to 24 gph. The higher flow can place a small stream of water about 6' into the air so the old saying that drip does not deliver very much water does not hold true. Inline drip emitters are extruded inside of a pipe typically ½" or 5/8th". The water is forced through a labyrinth   which slows the flow to a drip and pressure regulates at the same time. This pipe is currently being installed in turf areas by those who are adventurous and will slowly become the norm. Coated in root inhibitor the old saying that roots followed the water into the emitter and stopped the flow is now old school. Surface installed dripline spaced in a triangular layout with distance dictated by soil type is used to flood irrigate mass planted areas. Tree root watering systems utilizing micro-bubblers are available to deep root water them while also providing air deep into the planter pit. Micro sprays are also used for mass planting areas to broadcast water over the entire planter bed.
- **LEED** would be based upon the High Efficiency model. Differences are where the water comes from. Rainwater harvesting has become a commonly used word around leaders in this field as well as recycled site water. LEED Credits are awarded as noted:
  - WE Credit 1.1: Use high efficiency irrigation technology, OR, use captured rain or recycled site water to reduce potable water consumption for irrigation by 50% over conventional means. (1 point)…

- WE Credit 1.2: Use only captured rain or recycled site water for an additional 50% reduction (100% total reduction) of potable water for site irrigation needs, OR, do not install permanent landscape irrigation systems. (1 point)…

Captured rain also known as Rainwater harvesting (pictured are Bushman Tanks) and the use of reuse site water require a knowledgeable consultant in this specialized field of irrigation –to get it right the first time. The mention of non-permanent irrigation to me sounds like agricultural fields where an irrigation system is laid out on the surface to satisfy the crops water requirements to produce the desired marketable results for that particular crop. I would view an irrigation laid on the surface for a period of up to 2 years or longer as an eye sore detracting form the overall vision and outcome of the project that so many landscape design teams spend countless hours creating. A more pleasing method is to design an irrigation system where stations (zones) can be shut off once the plant material has established itself –with the use of supplemental irrigation – delivered in a just in time methodology.

Credit:

Lorne Haveruk, CID, CIC, CLIA, WCP is a certified irrigation designer, certified auditor, certified contractor, water conservation practitioner, and Accredited Provider for IA educational offerings. His unique experience is derived from managing all technical aspects of irrigation design, consulting and project management since 1989. Principal of DH Water Management Services Inc. his firm excels in designing water efficient systems including rainwater, graywater, reuse, LEED and Green Roof. DHWMS has been conducting certification and educational training for more than 10 years. DHWMS facilitates SWAT, SMART, ET & Central Control system implementation for clients throughout North America and Europe. To view more of their products, forms, articles, books and training opportunities, go to www.dhwatermgmt.com. To contact the author directly email lorne@lornehaveruk.com

References/ Credits:

USGBC
http://www.usgbc.org/DisplayPage.aspx?CategoryID=19

Rain Bird Irrigation - Root watering system and drip emitter photos.

Bushman irrigation and water storage (rain harvesting tanks)

Residential Irrigation Water Application Influenced by Socio-economic Parameters

Melissa B. Haley[1] and Michael D. Dukes[2]

Paper presented at the 28th Annual International Irrigation Show
San Diego, CA
December 9-11, 2007

Abstract

This paper investigates the relationship between socio-economic parameters and applied irrigation water. Irrigation water use was correlated to property value, property size, aerial estimated irrigated area, and existence of a swimming pool. This project includes 142 homes in Pinellas County irrigating with potable water, from the public water supply, 56 of which are participating in a sensor technology irrigation conservation study. To properly evaluate irrigation water based on utility data, outdoor and indoor water was separated from five years of utility water use data. Winter water consumption was assumed to only be indoor use. The subtraction of the minimum winter use allowed for estimated monthly outdoor use. To determine actual irrigation application amounts, the outdoor usage in gallons was then converted into depth, based on irrigated area estimated by a combination of both property appraisal information and measured areas from GIS aerial images. Increased outdoor water use was positively correlated with property value and negatively correlated with irrigated area. These relationships probably exist because on larger homes the economic effect of increased water use is less important to homeowners and on smaller homes the economic penalty for over-irrigating is minimal.

Introduction

Nearly all new homes in Florida are constructed with in-ground automatic irrigation systems. Studies have shown that residential landscape irrigation can account for more than 64% of a home's total water use and recent research in Florida has indicated that homeowners are over irrigating by applying more than the plant water needs (Haley *et al.*, 2007). Irrigation water use conservation efforts are necessary due to the increase in overall water use that is related to increased population. The Southwest Florida Water Management District (SWFWMD), which is one of the five Florida water management districts, accounts for a quarter of the state's overall population, with more than four million inhabitants. Between 1990 and 2000, the population in this region grew by over 640,000 residents, approximately 19%, and is projected to increase another 1.8 million by 2025. The 2000 population for Pinellas County, the study area, was 921,482 and is forecasted to be 1,078,600 by 2025, increasing 17% by 2025 (SWFWMD, 2005).

Within the SWFWMD, public water use accounts for 42% if the total freshwater use, the second largest water use sector after agriculture. Although there has been considerable population growth, the water use amount has remained fairly constant from 1993-2002. This is a result of an 11% decrease in per capita water use, from 140 to 123 gpd. However, when the per capita water use is normalized for drought or excessively wet seasons; the total public water use shows an

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upward trend. It is expected that as population growth continues, public water use will become the dominant water use sector. According to the SWFWMD 2005 District Management Plan, the projected water demand for the public supply is expected to increase to 223 million gpd (SWFWMD, 2005). More than 80% if this water withdrawn from groundwater sources, most of which comes from the Floridan aquifer, which has increasingly been regarded as a limited resource.

In a study on residential irrigation efficiency with the St. Johns River Water Management District (SJRWMD), setting irrigation controllers according to historical turfgrass water requirements resulted in a 30% reduction of water use (Haley *et al.*, 2007). Rain sensors have been shown to save 34% of irrigation water when set at ¼ inch of rainfall (Cardenas-Lailhacar, 2006). Soil moisture sensor controllers have been shown to reduce irrigation water use up to 92%, under rainy conditions, with no decline in turf quality (Cardenas-Lailhacar *et al.*, 2008).

Although within the SWFWMD, twice weekly irrigation is permitted, Pinellas County has more stringent water use regulations. In accordance with Pinellas County Code 82-2, irrigation is only authorized for one day a week between the hours of 6:00 pm and 8:00 am (PCU, 2007a). Water use, ordinance compliance, and conservation knowledge influence the domestic irrigators' tendency to employ the automatic settings of irrigation controllers, rain sensors, and soil moisture based controllers versus manual adjustment.

Other human factors, such as the inclination to manually override the automatic system, relate to conservation psychology. Research has been conducted proving the effectiveness of technology in reduction of outdoor (lawn and garden) water use. However, these studies have been primarily conducted in controlled settings. When attempting to incorporate the recommendations of the research into the residential arena savings are less apparent than those found in the controlled settings (Geller *et al.*, 1983; Campbell *et al.*, 2004).

Baumann (1990) established three factors which affect the intensity of water use by residential users. The first two are economically driven: the consumer's ability to pay for and the willingness to pay for water at a given price. The non-economic factor is the consumer's conservation behavior. This reflects the motivation to employ effort or technological innovations for water conservation. Campbell et al. (2004) has suggested that when looking at the correlation between water use and socio-economic level alone, lower income homeowners may use more water because of limited resources available to fix leaks and install new water saving devices in the home. However, the common assumption regarding household size is that with a larger house there is greater water consumption. Higher value homes tend to have more features that consume water than homes of lower value. According to Whitcomb (2005), the main concern of homeowners with respect to increased costs is outdoor use. The current rate for potable water from Pinellas County Utilities is $4.04 per 1000 gal as of October 1, 2006, resulting in nearly a 25% increase over the previous two years (PCU, 2007b).

Previous studies have looked at aerial images to determine irrigation area and outdoor water use as a fraction of utility records. However these studies primarily focused on the water needs relative to evapotranspiration, suggesting water savings in relation to plant water needs. Kjelgren et al. (2002) looked at relative water use between residential and commercial properties, but did not look at the correlation between residential irrigated area and property value. Irrigation increased midsummer through early fall due to increased evapotranspiration rates, if there was limited rainfall. Dewees and Woods (2006) also looked at aerial images and evapotranspiration in relation to reduced outdoor water use, focusing on over irrigation in summer months. The aerial photography was used to target the highest residential water users as part of a water conservation program in Austin, TX. The program has been expanded to include commercial costumers with irrigation sub-meters. Because this study focused on excessive water consumption it also neglected the small-yard over-irrigator.

The objectives of this paper are to assess the effect of socio-economic attributes on residential irrigation water use in Southwest Florida. The attributes included are: property value, irrigated area, the presence of a pool, and the participation in irrigation study. Through statistical analysis, conclusions will be drawn regarding socio-economic effects on water use.

Materials and Methods

This project included 142 homes in Pinellas County selected as a cluster sample. All homes irrigate with water from the public supply. As part of the total sample, 56 are participating in a sensor technology irrigation conservation study (Haley and Dukes, 2007). The study area is Pinellas County, Florida (Figure 1) which is part of the Pinellas-Anclotte River Basin within the Southwest Florida Water Management District. Pinellas County has a humid subtropical climate, with frost and freezing temperatures occurring at least once annually. The average annual rainfall within the SWFWMD is 53 inches, with 60-65% occurring between in the summer months when evapotranspiration rates are highest. The groundwater supply in southwest Florida comes from the Floridan aquifer. This aquifer is recharged by rainfall which occurs in the district as the sole source of natural replenishment (SWFWMD, 2005).

Property information was gathered from the Pinellas County property appraisal public records (www.pcpao.org) for each home included in the analysis. These records included information on the comparable sales from 2005-2006 (which denotes property value), the property size, total gross living area (i.e. gross structural footprint), and residential extras (e.g. pool, enclosure, patio, shed, etc.). A calculated irrigated area was determined by subtracting the gross structural area and residential extras from the property size. From the Pinellas County public GIS records (www.gis.pinellas.org), the residential parcels are outlined and an aerial layer from Jan/Feb 2006 was overlaid (Figure 2.). Using the GIS layers, the irrigated areas were outlined with a polygon tool (note the red polygons in Figure 2) and the area of each polygon was calculated by GIS to determine the aerial estimated irrigated area. Actual irrigation area from site visits to homes participating in the irrigation conservation program was used to verify assumptions in the aerial estimated irrigation area methodology. The aerial estimated irrigated area was then compared to the calculated irrigated area from the property appraisal information.

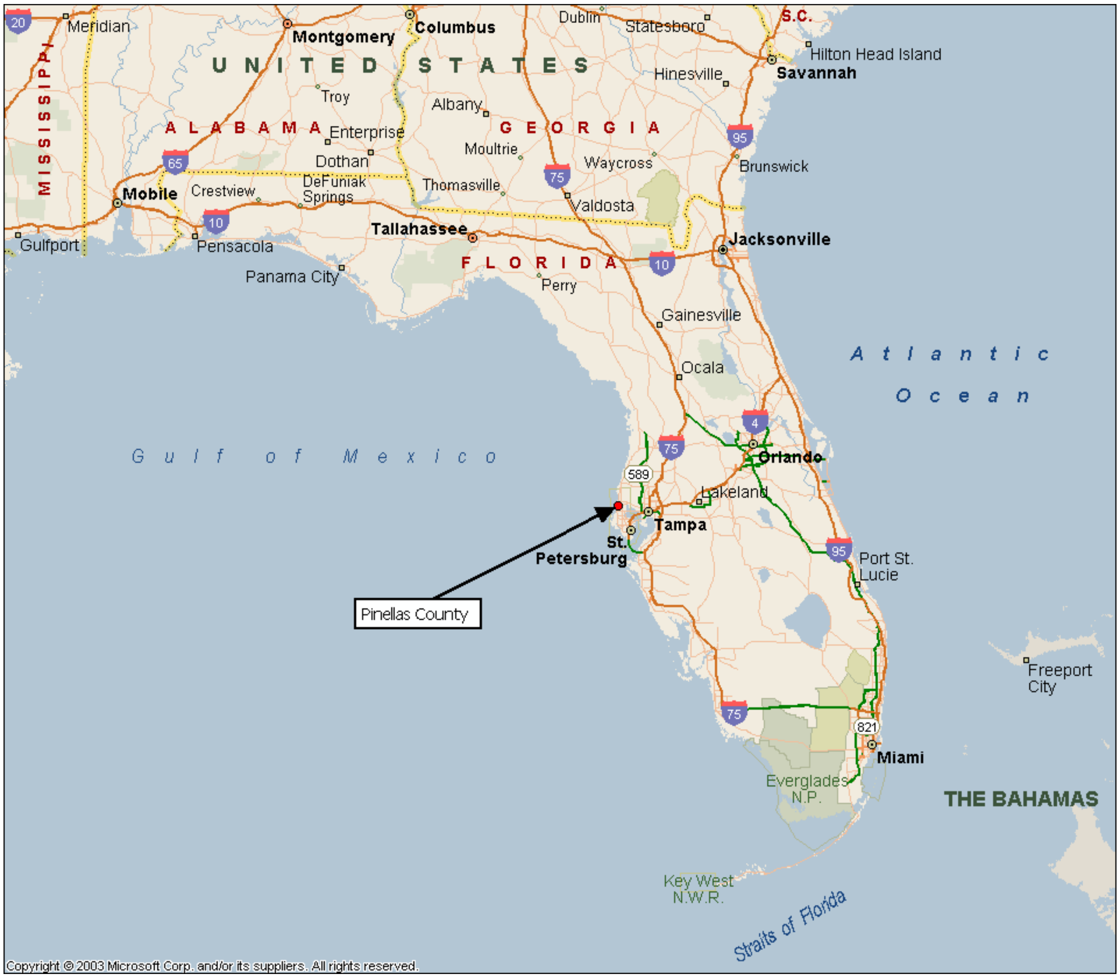

Figure 1. Map of the Florida, including location of data collection (Pinellas County).

Monthly water data was obtained from Tampa Bay Water Authority for a period of five years for each residence. Irrigation use was estimated based on the volume of monthly water used outside and the aerial estimated irrigated area. To calculate the monthly outdoor water use, the winter (December, January, and February) water use was analyzed for each parcel to determine the winter minimum usage. The minimum winter water use was assumed to be only indoor use; therefore, any use greater than the winter minimum was assumed to be assumed outdoor use. If a monthly use was less than the winter minimum, the outdoor use was estimated as zero for that month. The homes participating in the sensor based irrigation study have sub-meters for their irrigation water use which were used to verify the winter minimum method.

Data analysis was performed using SAS software. Procedures included measurement of correlation coefficients, ANOVA analysis, and frequency tables with chi-square statistics. Positive and negative correlations were based on Pearson's correlation coefficient. The multivariate analysis enables assessment of the direct and indirect effects for related variables. An analysis of variance was used to determine main effect differences through PROC GLM and means comparisons were performed with Duncan's Multiple Range Test at a 95% confidence level (SAS, 2004).

Figure 2. Aerial view of residential parcels with red polygons denoting irrigated area and black polygons denoting parcel boundaries.

Results

To estimate the monthly outdoor water use, the winter (December, January, and February) water use was analyzed for each parcel to determine the winter usage. For the five years of utility data, winter average, low quartile (lowest 25%), and minimum use were compared. The calculated outdoor use by winter average, low quartile, and minimum for the 2006-2007 billing period was compared to the actual irrigation water use from the participating homes that had sub-meters for irrigation water consumption. The average actual monthly average use for the 2006-2007 time period was 2.0 in/month. Using the average winter use, the monthly average consumption resulted in 0.91 in/month, a 54% error. The low quartile outcome was 1.5 in/month, which is a 25% difference form the actual value. The minimum winter water use over the billing period resulted in 2.2 in/month average use which was the lowest error at 9%.

The GIS aerial images proved to be more accurate estimations of actual irrigated areas than the property appraisal data. To determine the accuracy of the GIS measurement method, the true irrigated area was measured on-site at homes in the participant group, with the average error within 5%, with no over or under-estimation greater than 10%. Although 35% of the calculated irrigated areas where also within 5% of the aerial estimated areas, the error ranged from 49% under-estimation to 180% over-estimation. Sources of error can be found for both methods of determining irrigation area. The property appraisal information may include enclosures, patios, and pools. However, it is not clearly defined whether the pool/patio is housed within the enclosure or additional area. Additionally, the property appraisal information rarely includes driveways, child play grounds, and sheds. When looking at the property size, from the public records, the parcel may consist of two lots or a fenced portion, were there are obviously non-irrigated areas. The parcel lines can also cause discrepancy; within GIS the boundaries do not always coincide with the actual parcel size, sometimes including lakes or natural areas adjacent to the property. Possible irrigated areas beyond the total property size and not included in the recorded parcel area are easements, walkways, and buffer zones. These areas which are irrigated and considered part of the actual irrigated area were included in the aerial estimated irrigated calculations.

From the correlation analysis, there were associations between irrigation application depths with property value, house size, presence of a pool, and aerial estimated irrigated area. Overall, there was a positive correlation between property value and irrigation application depth (r = 0.66) and a negative correlation between irrigated area and water application depth (r = 0.85); note Figures 3 and 4 respectively. This trend is most evident when looking at the homes without pools (Table 1). There was a significant difference ($p<0.001$) between the water use in homes with and without a pool on the property. The homes with pools used on average over 0.5 inches more water per month. Upon further investigation, the presence of a pool can be considered a conditional relationship, where the impact is greater for one group than for another when other factors are included. This could be caused by a combination of two factors. First, the pool may consume a notable fraction of the average monthly consumption, and the monthly use should be offset accordingly. Additionally, external factors may need to be considered. For example, people who reside in homes with pools may tend to spend more time outdoors, consequently having a stronger motivation for increased landscape aesthetics.

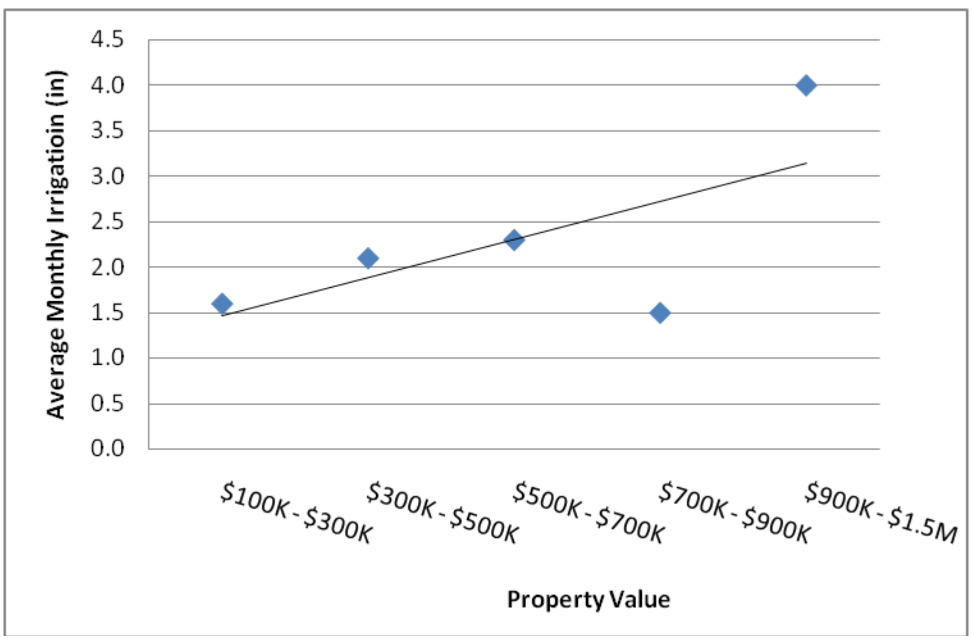

Figure 3. Effect of property value on average monthly irrigation for all homes.

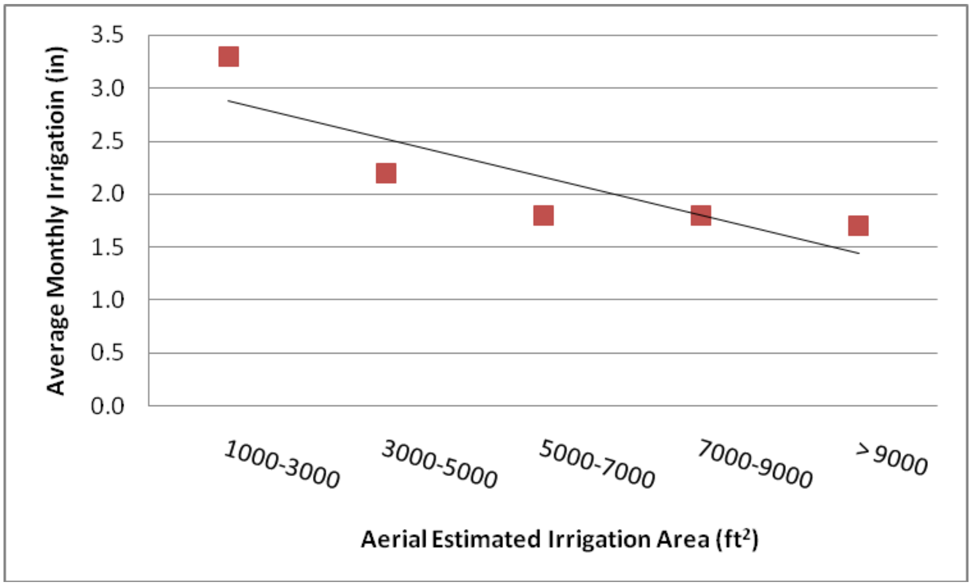

Figure 4. Correlation between irrigated area and monthly irrigation for all homes included in analysis.

Property values were categorized in to five profiles: $100,000 to $300,000, $300,000 to $500,000, $500,000 to $700,000, $700,000 to $900,000, and $900,000 to $1,500,000 (Table 1). The interaction of a having pool can also be seen here, nearly all homes valued above $500,000 have a pool. The positive correlation between property value and irrigation application depth suggests socioeconomic level affects conservation behavior, likely because cost is less of a primary motivation. From the analysis of property value and outdoor water application, it can also be observed that the homes ranging from $900,000 to $1,500,000 used the largest amount of water for outdoor use ($p<0.001$). This trend concurs with the literature, suggesting that sensitivity to water cost results in reduction of use (Whitcomb, 2005). For homes participating in the sensor based technology program, the trend between increased water applications with increased property value is most apparent. For the total sample, the same trend exists, aside from the $700,000 to $900,000 range, which has the lowest calculated outdoor water application depth.

Conversely, the smaller the property, the more water was applied, described by the negative correlation in Figure 4. It is also interesting to note that the homes with smaller irrigated areas all have property values ranging from $100,000 to $500,000. The increase in negative correlation between irrigated area and water application could be due to a misunderstanding of irrigation scheduling principles and the over-design of irrigation systems (e.g. too many heads per hydrozone). Moreover, high consumption of outdoor water use is typically flagged by excessive volume use, not taking area into consideration. Therefore, over irrigation in smaller irrigated areas are rarely flagged by local purveyors or felt as an excessive economic stress.

Of the 142 homes included in this analysis, 56 have been part of an irrigation conservation study since 2006. In Table 1, it can be observed that the homes associated with the irrigation study applied more irrigation on average, 2.2 inches per month, versus 1.7 inches per month for the non-participant group ($p<0.001$). The increased outdoor water use for participating homes might be attributed to consistent use of an automatic irrigation system, as it was one of the criteria for participation in the sensor based irrigation water conservation program. However, since the commencement of that study there has been a significant ($p<0.001$) reduction, from 2.5 to 2.1 inches per month of average outdoor water application during 2006-2007 for participating homes due to treatment effects in that study (Haley and Dukes, 2007)

Table 1. Average outdoor water application depth per month for the time period of 2002-2007.

Category		Overall Use$_{avg}$ (in)	Overall No.	With Pool Use$_{avg}$ (in)	With Pool No.	Without Pool Use$_{avg}$ (in)	Without Pool No.	Participants Use$_{avg}$ (in)	Participants No.
Property Value Range	\$100K - \$300K	1.6 c*	66	2.1 b	32	1.2 b	34	2.0 c	25
	\$300K - \$500K	2.1 b	54	2.2 b	43	1.5 a	11	2.0 c	21
	\$500K - \$700K	2.3 b	7	2.3 b	7	-	0	2.1 c	4
	\$700K - \$900K	1.5 c	8	1.5 c	7	-	1	3.2 b	3
	\$900K - \$1.5M	4.0 a	7	4.0 a	6	-	1	4.7 a	3
Aerial Est. Irr. Area Range (ft^2)	1000-3000	3.3 a	7	3.7 a	5	2.3 a	2	5.4 a	3
	3000-5000	2.2 b	31	2.6 b	19	1.5 b	12	2.0 bc	13
	5000-7000	1.8 c	60	2.1 c	38	1.2 bc	22	1.9 c	22
	7000-9000	1.8 c	31	2.2 c	21	0.9 c	10	2.1 bc	10
	> 9000	1.7 c	13	1.8 d	12	0.3 d	1	2.2 b	8
	Average	*1.9*		*2.3*¤		*1.3*¤		*2.2*	
	Total		*142*		*95*		*47*		*56*

* Lower case letters denote significant differences at the 95% confidence level based on Duncan's Multiple Range Test.
¤ Means comparisons between homes with and without pools show these averages to be significantly different.

Summary and Conclusions

To properly evaluate irrigation water based on utility data, outdoor and indoor water consumption must be separated. Three methods for calculating outdoor water use as a fraction of total water use were compared: winter average, low quartile (lowest 25%), and minimum use. The winter water use was assumed to only be indoor use, and subtracting the winter use provided the estimated monthly outdoor use. The minimum winter water use over the billing period was calculated as 2.2 in/month (6,700 gal) on average. The minimum winter method yielded the lowest error, 9%, compared to the actual irrigation water use collected from participating homes. To determine actual irrigation application amounts, the usage in gallons was then converted into inches, based on irrigated area. To estimate these areas, a combination of both property appraisal information and measured areas from GIS aerial images was used. The property appraisal information alone may vastly over and under estimate the actual property size, which will in turn cause substantial error when calculating the irrigated area. For this sample, to verify the accuracy of the areal estimated irrigated area, the true irrigated areas were measured on homes in the participant group.

A pro-environmental behavior such as water conservation can stem from reluctance to over-use irrigation water based on cost. Two barriers to this conservation behavior, observed in this study were economic level, displayed in the form of property value, and irrigated area. The property value analysis showed that the highest value range (\$900,000-\$1,500,000) used the most water even when normalized for irrigated area. Overall there was a trend of increased water application with increased property value. Conversely, the smaller the irrigated area, the more water was applied. A primary cause for the increased use in both homes of higher property value or smaller irrigated area is likely due to minimal impact water cost for excessive use. The homes with pools used on average over 0.5 inches more water per month. This increase irrigation water use could be due to the pool or some other factor not considered in this analysis but correlated to the presence of a pool.

Acknowledgments
The authors thank the Pinellas-Anclote Basin Board of the South West Florida Water Management District, Tampa Bay Water, and Pinellas County Utilities. In addition, the authors appreciate the assistance of Bernard Cardenas-Lailhacar and Thomas Olmsted.

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Comparison of Distribution Uniformities of Soil Moisture and Sprinkler Irrigation in Turfgrass

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Project funded by the CLCA Environmental Research Funding Program

Introduction:

A uniform distribution of water by sprinkler systems on turf is essential for good turf quality and efficient use of water. Observations by water managers have raised the issue that the use of lower-quarter distribution uniformity, DU_{LQ} for irrigation scheduling results in over watering of landscapes The Irrigation Association (IA) proposes in their recent water management publications, the use of the lower-half distribution uniformity, $DU_{LH,}$ for landscape irrigation scheduling. A related question is the relationship between DU as determined by a catch can test and the distribution of water in the soil.

Irrigation scheduling is based on irrigation efficiency which is determined by irrigation management efficiency and the distribution uniformity, DU. Catch can uniformity data is used to calculate sprinkler low quarter distribution uniformity, DU_{LQ}, to assess sprinkler system performance and for irrigation scheduling purposes. The applied irrigation water can move laterally as surface flow when the soil surface layer is saturated, and laterally and vertically due to capillary action in the soil. This redistribution of water in the soil may result in a more uniform distribution of water than the catch can DU_{LQ} data would suggest.

Distribution uniformity as measure by the low quarter distribution (DU_{LQ}) is a common measurement to determine performance of installed systems. This distribution uniformity is determined by the following:

$$DU_{LQ} = \frac{V_{LQ}}{V_{avg}}$$

where: V_{LQ} = average of the lowest one fourth of catch cans measurements, ml

V_{avg} = average all catch cans, ml.

One approach to the calculation of runtime for an irrigation schedule is to use a runtime multiplier (RTM) to calculate the irrigation water requirement (IWR). Where:

$$RTM = \frac{100}{DU_{LQ}}$$

and:

$$IWR = RTM \ x \ PWR$$

where:

PWR = Plant water requirement

A study in Colorado (Mecham 2001) compared the DU_{LQ} based on catch cans and a DU_{LQ} for soil moisture at the catch can locations. For example one irrigation zone had a catch can DU_{LQ} of 68% and DU_{LQ} in the soil of 87%. The author suggested use of DU_{LH}, based on the lowest half of the catch can readings, for scheduling. A preliminary California study (Curry 2004) found that the soil DU_{LQ} values were an average of 33% higher than the catch can DU_{LQ}. An additional find was that the soil moisture DU_{LQ} was similar to the catch can DU_{LH} in clay soils with turfgrass. The results appear to be similar in both studies and suggest use of DU_{LH} for turfgrass irrigation scheduling. The Irrigation Association (IA 2005) recommended using a lower half distribution uniformity (DU_{LH}) calculated from the lower half of catch can data.

An extensive study in Florida (Dukes, 2006) in sandy soil concludes that soil moisture uniformity distribution approximates DU_{LH} calculated from catch can measurements.

Based on the early reports and the Irrigation Association recommendations, this 2005 study expanded the previous work of soil moisture distribution with sprinkler irrigation of cool season turfgrass (Curry, 2004). The research objective was to study the relationship of sprinkler distribution uniformity, DU, as measured with catch can tests, with soil moisture distribution in the root zone of turf as measured with a TDR.

Methods and Procedures:

Three cool season turf plots with different soil and turf conditions were setup for this project. At the beginning of the project several procedures to collect catch can sprinkler distribution data and measurements of volumetric soil moisture were explored and evaluated. The procedures selected were to conduct catch can tests twice at each plot, once before the beginning of the series of irrigations where soil moisture was measured with a TDR at each catch can location, and a second time after the irrigations and soil moisture measurements were completed for each plot. The volumetric soil moisture was measured with time-domain reflectometry (Field Scout TDR 300, Spectrum Technologies, Inc.[1]).

Each plot had 49 points uniformly distributed (equidistant from each other) throughout the plots for catch can locations. Catch can data were recorded immediately after the end of each irrigation. For each irrigation event, TDR readings were recorded within one hour before the irrigation, and 1, 2, 6, 24, and 48 hour intervals after the end of irrigation. Total number of TDR soil moisture measurement for each plot was 245 after each irrigation event. Soil moisture was measured within one foot diameter of each catch can location. Since 6 TDR measurements were taken at each location over a 2 day period, the TDR probe locations were rotated in a one foot diameter area to minimize the effect of the probes on the soil. Table 1 gives additional information for each plot.

1. Mention of trade names or other proprietary information is made for convenience of the reader and does not imply endorsement by authors.

Table 1. Summary of turf plot and data collection information.

Plot Number	Soil	Turf	Irrigation System	Catch Can DU_{LQ} (Ave of 2 tests)	TDR Probe Length
1	Clay Loam	Fescue, good condition	Half Circle Rotor Sprinklers, 35 ft spacing, Pr = 0.44 in/hr. Runtime = 68 minutes	0.73, 5 foot square spacing for catch cans, 49 cans	4.8 inch (12 cm)
2	Sandy Clay Loam	Fescue, new planting, medium condition	Quarter Circle Rotor Sprinklers, 50 ft Spacing, Pr = 1.4 in/hr. Runtime = 15 minutes	0.72 7 foot square spacing for catch cans, 49 cans	3 inch (7.5 cm)
3	Sandy Loam	Fescue, good condition, 4 - 6 inch height	Full Circle Rotor Sprinklers, 50 ft Spacing, Pr = 0.36 in/hr. Runtime = 60 minutes	0.65 7 foot square spacing for catch cans, 49 cans	4.8 inch (12 cm)

The irrigation systems were tuned up before the tests to correct sprinkler arc orientation, vertical plumb, and head height. Three inch probes on the TDR were used on plot 2 because the soil was compacted and the 4 inch probes could not be inserted to their full length in this compacted soil. There were about 8 locations out of the 49 locations in this plot where the TDR could not be used with the 3 inch probes. The TDR probe developed problems and had to be rebuilt with new firmware in midsummer; only the data with the rebuilt TDR are included in this report.

<u>Results:</u>

Comparison of the distribution uniformities in Figure 1 show that the soil moisture distribution had a higher DU_{LQ} than the catch can DU_{LQ} for all three sites. The mean TDR DU_{LQ} is the mean volumetric moisture content (VMC) of soil based on 49 measurements with the TDR probe for each time interval of 1, 2 , 6, 24, and 48 hours after the irrigation.

The mean catch can DU_{LQ} is the mean of two catch can tests, one test before the series of irrigations at each plot and one immediately after the last data collection at that site.

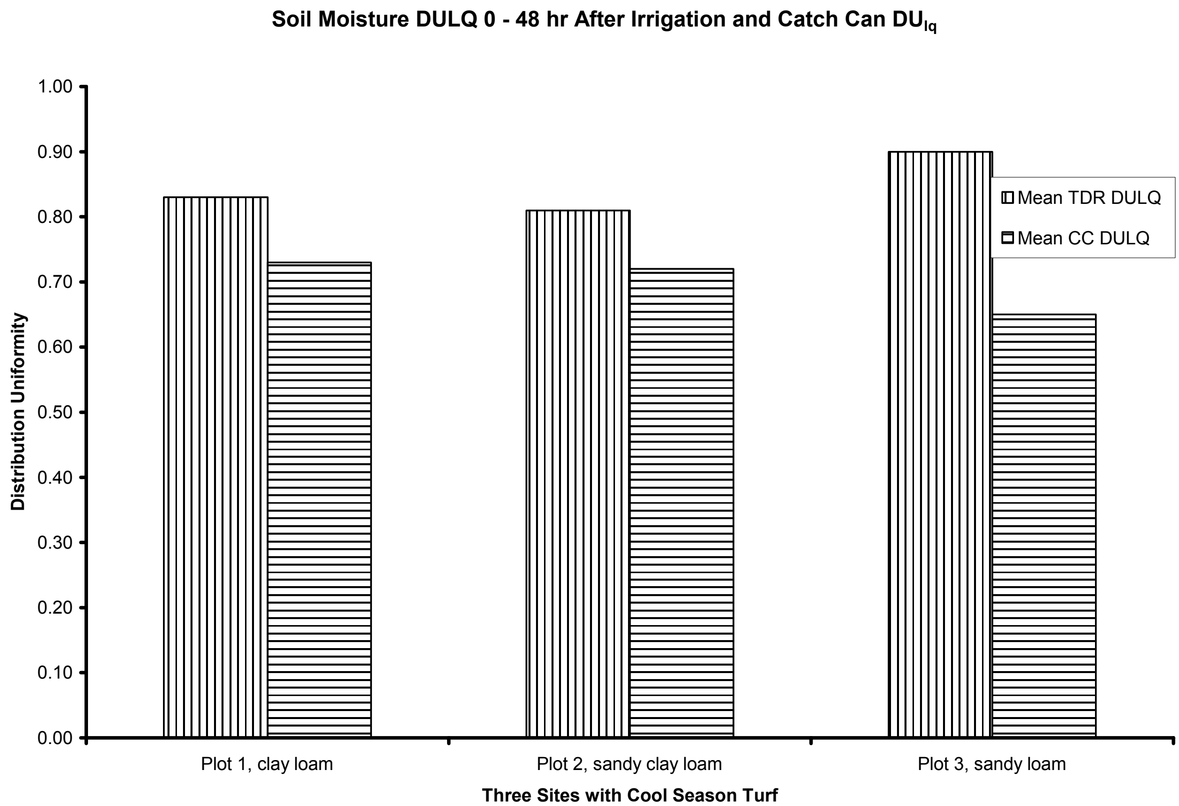

Figure 1. Comparison of distribution uniformity for the soil moisture after irrigation (Mean TDR DU_{LQ}) and sprinkler catch can distribution (Mean CC DULQ).

The largest difference between the catch can and soil moisture DU_{LQ} was at the plot 3 site for 1, 2 and 6 hours after the irrigation (Figure 2). The catch can DU_{LQ} was lower at this site and the turf quality is good, dense turf, maintained at approximately 4 - 6 inch height. The dense turf at this site may contribute to more dispersion of the applied sprinkler water and higher level of irrigation management at this site may contribute to the high soil moisture DU. Mean soil moisture distribution was higher than catch can distribution uniformity for all sites for each time interval. Plot 3 was located on a CIMIS weather station site in a very open area. The second catch can test was conducted on a day with slightly higher winds which may have been a factor in the catch can distribution uniformity DU_{LQ} of 0.55 compared 0.74 for the first measurement. Therefore, the mean differences for plot 3 may be greater due to the low catch can DU_{LQ} for that site.

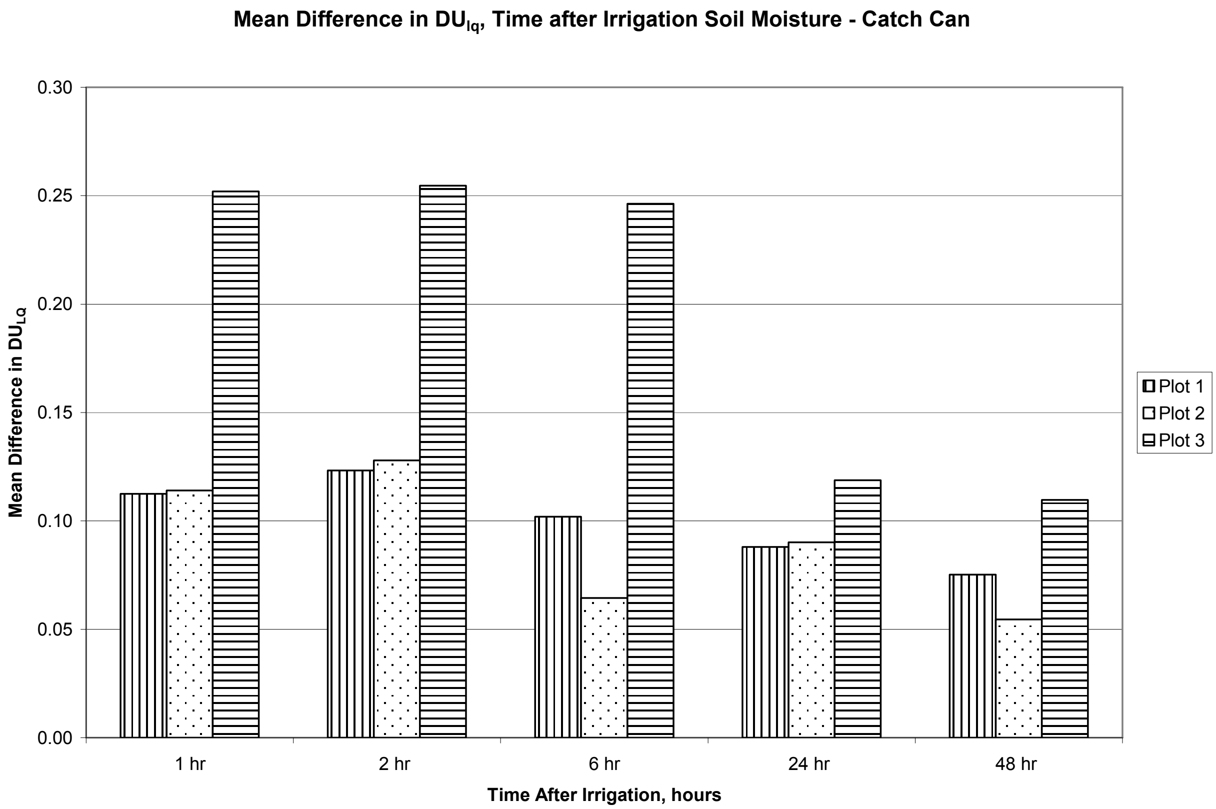

Figure 2. Summary of the differences between the catch can DU_{LQ} and soil moisture DU_{LQ} at the indicated time after irrigation.

Data analysis was performed using the Statistical Analysis System software (SAS Institute, Inc.). Mean differences between the DU for soil moisture and catch can using Duncan multiple range test at the 95% confidence interval.

Table 2 Distribution uniformity of soil moisture based on TDR measurements and sprinkler distribution uniformity based on catch can tests.

Location	Replication	Soil TDR Post Irr. 1 hour DU_{LQ}	Catch Can[1] DU_{LQ}
1	1	0.84	0.69
1	2	0.84	0.71
1	3	0.86	0.71
1	4	0.83	0.75
1	5	0.85	0.77
Mean[2]		0.84a	0.72b
2	1	0.81	0.71
2	2	0.81	0.72
2	3	0.87	0.71
2	4	0.88	0.72
2	5	0.83	0.71
Mean		0.84a	0.71b
3	1	0.93	0.74
3	2	0.93	0.60
3	3	0.85	0.65
3	4	0.93	0.55
3	5	0.89	0.65
Mean		0.91a	0.64b

1. There were two actual catch tests per location, once before the irrigation events and once after the irrigation events. Sprinkler DU_{LQ} for other irrigation events were assumed to vary based on hourly average wind data. Wind speeds for the GR site ranged from 2.7 - 4.9 mph, CIMIS, 2.6 – 6.1 mph, and TS 1.6 - 5.6 mph.

2. Mean values in rows followed by different letters are statistically different at the 95 % level by Duncan's Multiple Range Test.

There was significant differences between the means of DU_{LQ} for catch can and soil moisture measured one hour after the end of irrigation for each of the three sites. In each case the soil moisture was more uniform.

The equation in the IA publication, Landscape Irrigation Scheduling and Water Management, $DU_{LH} = 38.6 + (0.614 * DU_{LQ})$, can be used to calculate the DU_{LH} based on the DU_{LQ}, or the DU_{LH} can be calculated directly from the catch can data. The catch can DU_{LH} is 82% when calculated using the above equation with a 70% mean CC DU_{LQ} (overall mean for the 3 plots). DU_{LH} of 82% is a better indicator of the mean soil moisture DU_{LQ} of 85% than the catch can DU_{LQ} of 70% for this study (Table 3).   .

Table 3. Summary of mean volumetric soil DU_{LQ} (TDR), mean catch can DU_{LQ} (CC) and calculated runtime multipliers.

	Soil Mean TDR DU_{LQ}	Soil Runtime Multiplier	Catch Can Mean DU_{LQ}	Catch Can Runtime Multiplier
Plot 1, clay loam	0.83	1.20	0.73	1.40
Plot 2, sandy clay loam	0.81	1.23	0.72	1.39
Plot 3, sandy loam	0.90	1.11	0.65	1.54
Mean of three sites	0.85	1.18	0.70	1.43

As can be seen from Table 3, the runtime multiplier is decreased by 17% when the soil moisture DU_{LQ} is used rather than the catch can DU_{LQ}. Therefore, for irrigation scheduling purposes it may be appropriate to use a catch can DU_{LH} as the indicator of soil moisture distribution.

Distribution uniformities for the two catch can tests at the CIMIS site (Plot 3) were 0.74 with 2.8 MPH and 0.55 at 4.2 MPH wind. This site is an open area and the wind appears to affect the CC DU_{LQ} substantially. The catch can DU_{LQ} for both catch can tests at the plot 2 location were very similar and the hourly wind speed recorded at a nearby CIMIS weather station were nearly the same for both test dates (Table 4). There was a 2.9 MPH difference in wind speeds at Plot 1 area and a small difference in a catch can DU_{LQ}. However, this plot is near tree rows and buildings which may limit the effects of wind on catch can DU_{LQ} at this site.

Table 4. Average hourly wind speed and catch can results.

Date	Hour	Wind Speed (MPH)	Catch Can DU_{LQ}, %	Location
4/18/2005	1100	5.6	0.69	Plot 1
10/21/2005	1000	2.7	0.77	
			Mean = 73	
9/14/2005	1000	3.0	0.71	Plot 2
11/23/2005	800	2.9	0.72	
			Mean = 72	
9/13/2005	1000	2.8	0.74	Plot 3
11/23/2005	900	4.2	0.55	
			Mean = 0.65	

Soil moisture DU_{LQ} did not increase or decrease in any consistent pattern with soil volumetric water content for all three plots. We expected soil moisture uniformity might increase with higher soil moisture volumetric moisture contents.

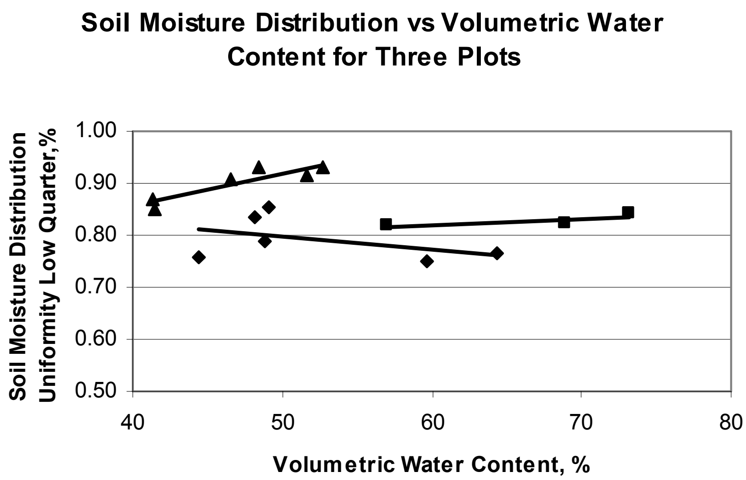

Figure 3. Soil moisture distribution uniformity relationship to the volumetric soil water content as measured with the TDR.

Summary and Conclusions:

Three plots with cool season turf and rotor sprinklers were monitored to compare catch can DU_{LQ} and soil moisture DU_{LQ}. Soil moisture was measured with a TDR with 4 inch probes on two plots and 3 inch probes on one plot at 1, 2, 6, 24, and 48 hours after the irrigation. The series of measurements were analyzed for 6 irrigation events for plots 2 and 3, and 3 irrigation events for plot 1.

1. The mean soil moisture DU_{LQ} was 85% when combining data from the three plots for time after irrigation from 1 to 48 hours. The mean catch can DU_{LQ} was 70%.
2. There was a significant difference in the mean values DU_{LQ} of catch can and soil moisture DU.
3. The catch can DU_{LH} was 82% when calculated from the equation in IA publications.. The soil moisture DU_{LQ} was 85%. This data may suggest that the catch can DU_{LH} may better represent the soil moisture distribution in the 3 – 4 inch root zone.
4. Irrigation scheduling based on the soil moisture DU_{LH} would apply about 17% less water than using the catch can DU_{LQ}. The question of turf quality with irrigation water management based on the DU_{LH} was not addressed in this study
5. The largest differences between soil moisture and catch DU's were at Plot 3 at the 1, 2, and 6 hour measurements. This weather station site has very dense turf maintained at a 4 – 6 inches height which may contribute to a more uniform distribution of the irrigation water in the soil.

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California Friendly
LANDSCAPE CONTEST

California Friendly LANDSCAPE CONTEST

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Background

Challenges:

- Finding ways to encourage outdoor water conservation
- Finding ways to drive interested parties to view The Water Conservation Garden's exhibits
- Finding ways to reward individuals who respond to the call for low-water-use landscape
- Finding ways to change the attitude of "beautiful" from water-guzzling to water-efficient
- Finding ways to make outdoor water saving "cool"

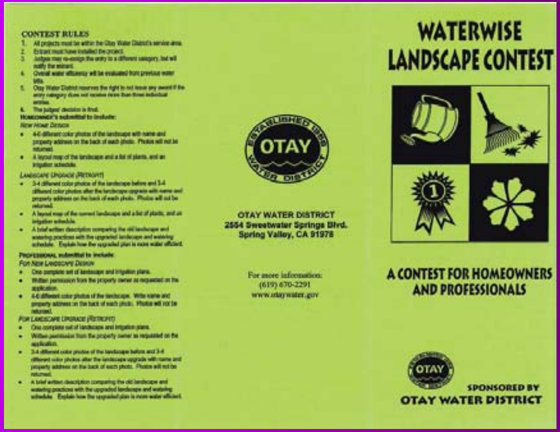
Landscape Participants 2003 - 2004

Goals 2003 - 2004

- A quick way to get some photos of a group of water-wise gardens
- Photos to be used to promote water-wise gardening
- Create a link to the Water Conservation Garden

Landscape Contest 2003 – False Start

- **Began in April 2003**
- **Spring Garden Festival to promote – brochure**



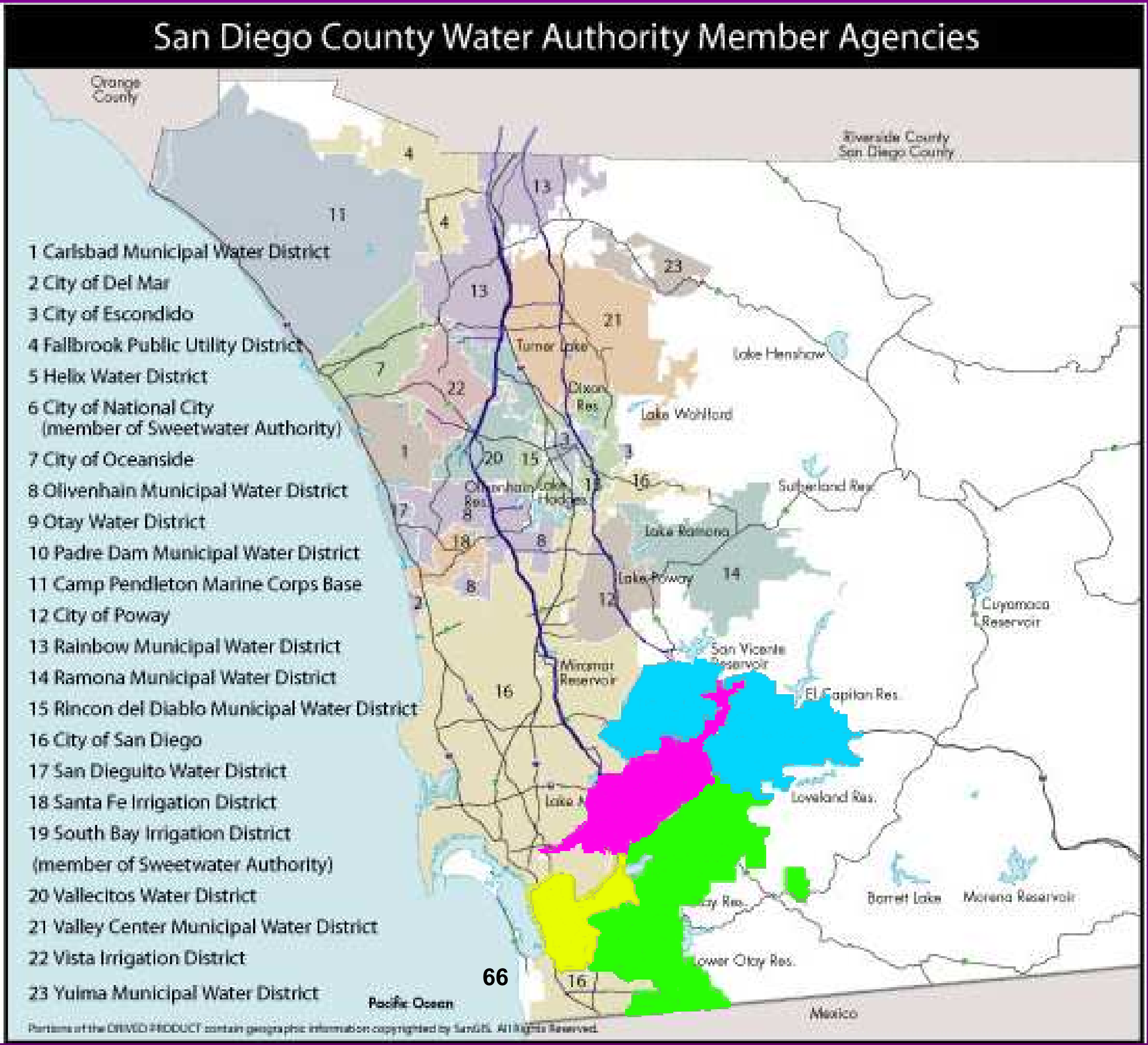
- **Bill insert in May**

- **4 entries**
- **Determined not enough interest**

Landscape Contest 2004

- Began again in October 2003
- Distributed brochures to local nurseries in the Otay District, bill insert, newsletter articles, point-of-purchase displays
- Made contacts with area nurseries
- Received and reviewed applications (10 entries)
- Awarded four winners
- $100 gift certificates to nurseries
- Felt this was good, but not reaching enough
- Realized they did not want to do this alone

Landscape Participants 2005



Challenge – Objective & Tactics

Challenge: How to promote California-Friendly landscaping—linking the Water Conservation Garden to customers' yards

Objective: Promote California-Friendly (water saving) landscaping in San Diego County in order to save water & promote MWD/SDCWA/local district water-saving programs

Tactics:

- Recognize and reward individuals and landscapers who have done an outstanding job at water-wise gardening
- Promote the winners within the San Diego media to attract the attention of a regional audience; therefore encourage MORE homeowners to plant California-Friendly landscapes
- Obtain current, beautiful photographs of water-wise landscapes to be used in other promotional materials, etc.
- Involve local nurseries in the process in order to encourage them to stock native and water-wise plant materials

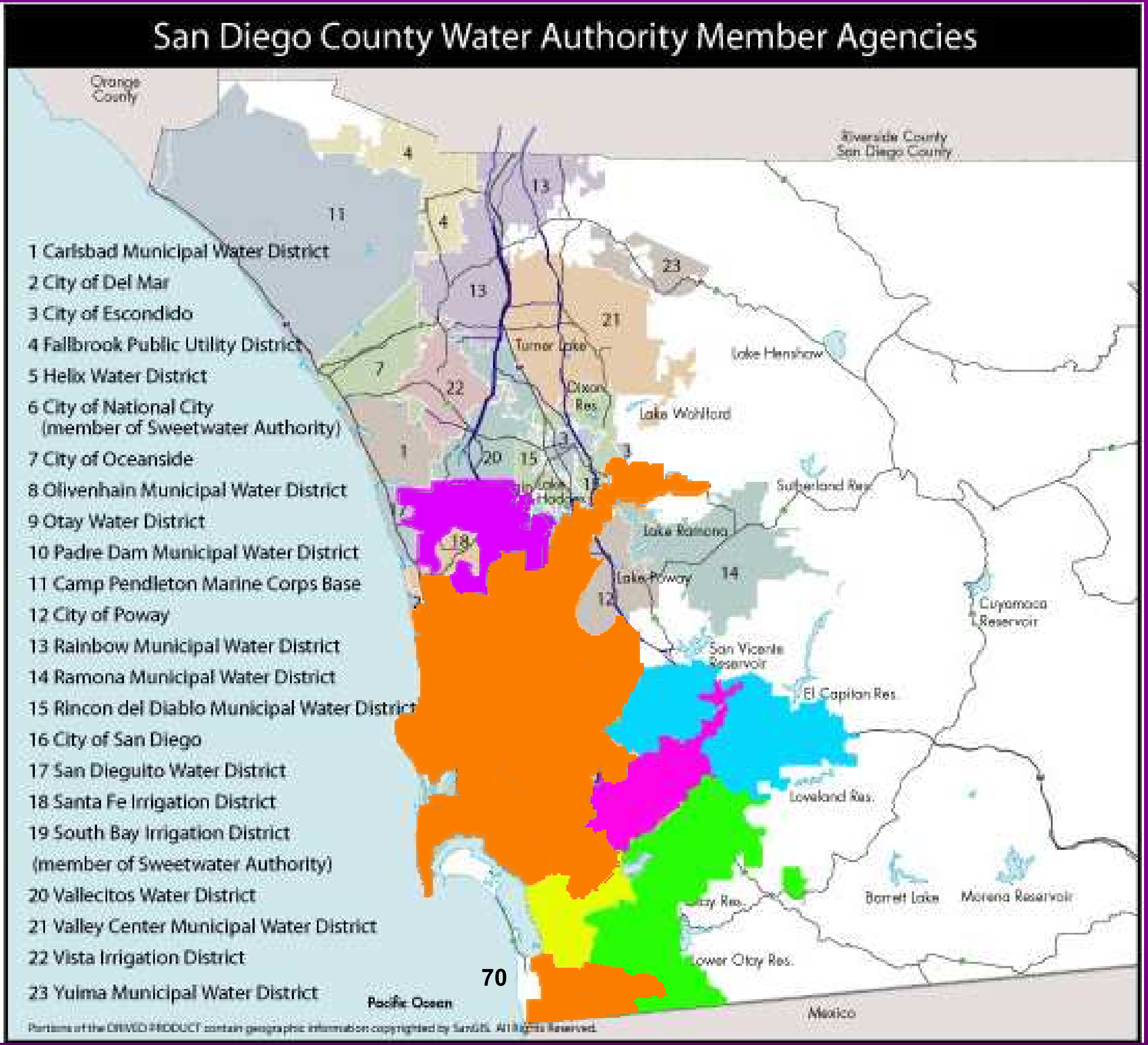
Timeline - 2005

December 1 – January 15	Production of materials, criteria, design & print posters, brochures, applications
January 16 – April 15	Distribution of information Public Relations Applications accepted
April 16 – May 20	Judging, photography, sign making
May 21 -	Winners announced at WCG Spring Garden Festival

Budget 05

Brochures (5,000)	$1,856.90
Mock-Check Laminating	183.18
Photo Processing	76.10
Yard Signs	820.70
Grand Prizes	900.00
Regional Prizes	1,000.00
Judging Expenses	23.55
Ads – Californian & Star News	1,376.54
+ In-kind from agencies	
Total Paid Expenses	**$6,236.97**

Landscape Participants 2005 - 2006



Timeline – 2005 - 2006

September – January 15	**Production of materials, criteria, design & print posters, brochures, applications**
January 16 – April 15	**Distribution of information** **Public Relations** **Applications accepted**
April 16 – May 15	**Judging, photography, sign making**
May 19 -	**Winners announced at WCG Spring Garden Festival**
May 20 -	**Press Coverage**

Budget 2006

Metropolitan Water District of Southern California

$10,000 grant

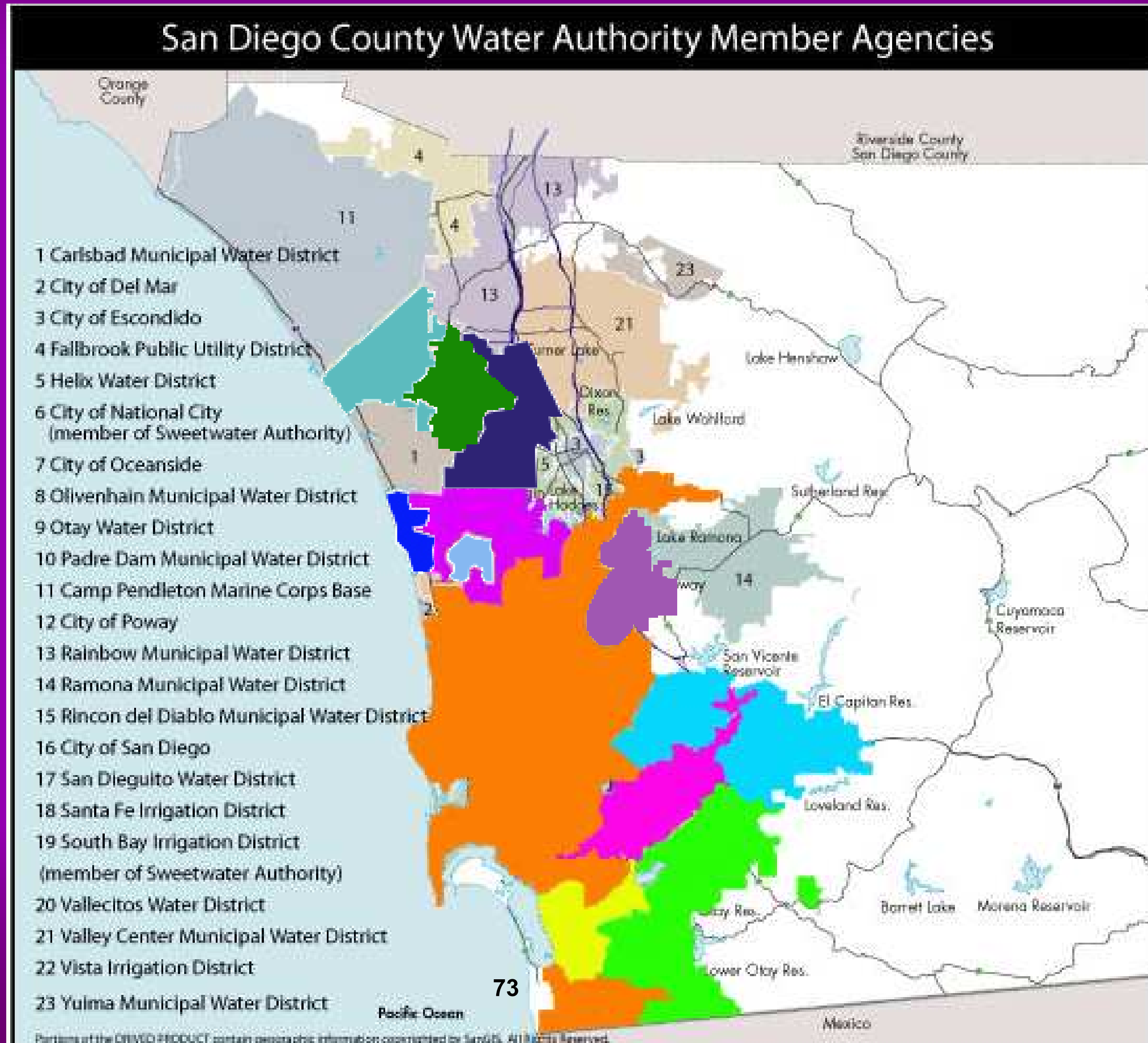
San Diego County Water Authority Communications Partnership grant

$3,300

Spent: $17,700

Final cost to each participating agency: $407.32

Landscape Participants 2006 - 2007



Budget 2007

San Diego County Water Authority Grant

$25,000

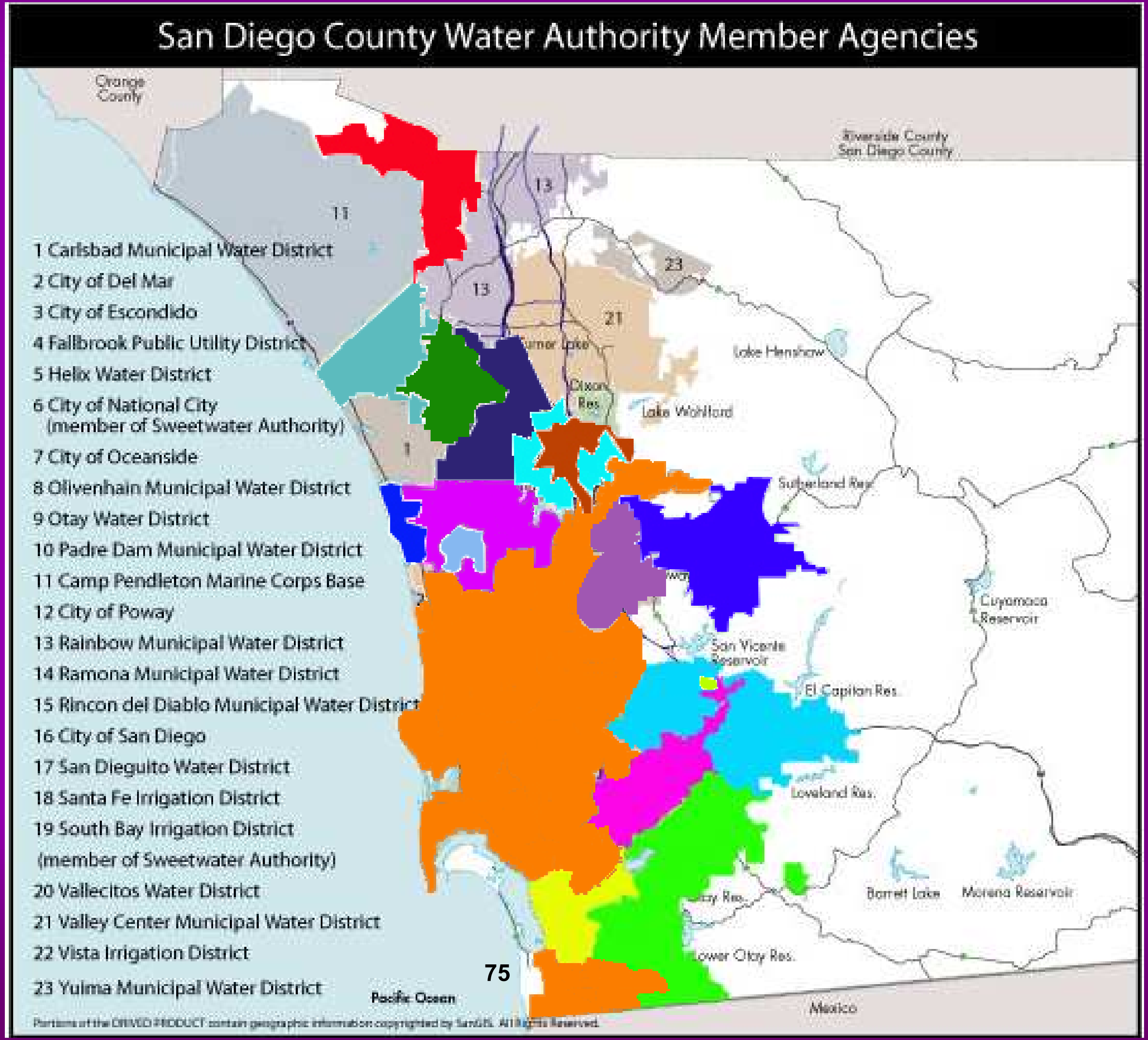
Rainbird Sponsorship

$ 4,000

Total Cost: $29,491.26

Final cost to each participating agency: $49.13

Landscape Participants 2007 - 2008



Budget 2008

San Diego County Water Authority Grant

$25,000

Miramar Nursery

$ 2,500

Grangetto's Farm & Garden Supply

$1,000

Total Cost: ?

Final cost to each participating agency: ?

Process - Getting the Word Out

Preliminary Judging

Representatives from each agency

6 FINALISTS

Judgment Day

Photo by Armando Buelna, Otay Water District

Send in the Photographers

Winners

Winners

Winners

Big Checks at the Spring Garden Festival

Signs Over San Diego County

Outcomes

Print articles:

- *Union-Tribune*
- Helix, Otay, Padre Dam, Sweetwater websites
- Newsletters
- CLCA *Offshoot*
- AEP *Environmentor*
- East & North County newspapers

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San Diego County's 3rd Annual California-Friendly Landscape Contest

More than two million homeowners eligible to compete for $2,500 in prizes

By Jeff Barnes

Grow a water-wise landscape and you could win a $500 grand prize! This year's San Diego County California-Friendly Landscape Contest has expanded to include residents of the City of San Diego and part of the North County.

The contest was developed to reward homeowners who have explored the beauty of California-Friendly plants and installed water-wise landscapes. "California-Friendly" essentially means more beauty with less water. Low-water-use landscaping helps conserve San Diego's water supply and leads to a lower water bill. Up to 50-70% of household water in San Diego County is used outdoors.

Six local water agencies are proud to be sponsoring the 3rd Annual California-Friendly Landscape Contest: City of San Diego, Helix Water District; Olivenhain Municipal Water District, Otay Water District, Padre Dam Municipal Water District and Sweetwater Authority. The more than two million residents who live in these water agency service areas are eligible to enter their yards and compete for up to $2,500 in prizes!

Judges will review landscapes for one or more of the following elements of water-wise landscaping: innovative design with water conservation and function in mind, use of California-Friendly plants, use of color and texture in the landscape, use of zoning

continued on page 11

Bonnie Graney of La Mesa, the Regional Winner in the do-it-yourself category, basks in her front yard full of color.

It's so easy to be green

Stick out your green thumb and hitch a ride on an express headed for big awards in three garden and landscaping competitions that are currently seeking entrants:

• Tomato growers are invited to enter a contest to find San Diego's best tomatoes held by NatureSweet Tomatoes. Contestants can pick up and submit entry forms at any California Ralphs store starting tomorrow. Entrants will take three home-grown medium or large tomatoes or 10 small tomatoes to the Ralphs at 4239 Genesee Ave., between 9 and 11 a.m. Sept. 24, when the tomatoes will be tested on overall appearance, color and sweetness. A panel of local judges will then taste-test the 10 top entries. A winner and three runners-up will be announced at noon. The winner will receive $5,000; runners-up will win $250 store vouchers each.

contest's name means "more beauty with less water," according to Barnes. Up to 50 percent to 70 percent of household water in San Diego County is used outdoors. Landscaping with drought-tolerant plants obviously uses less water, and also leads to lower water bills.

For a contest application, call (619) 670-2291. The deadline to enter is April 15. To learn more about California-friendly landscaping, visit the Water Conservation Garden at 12122 Cuyamaca College Drive West, El Cajon, or log on to www.thegarden.org.

— CATHY LUBENSKI

be announced on Saturday, May 20th during the Spring Garden Festival at The Water Conservation Garden.

For more information, visit www.bewaterwise.com.

Outcomes

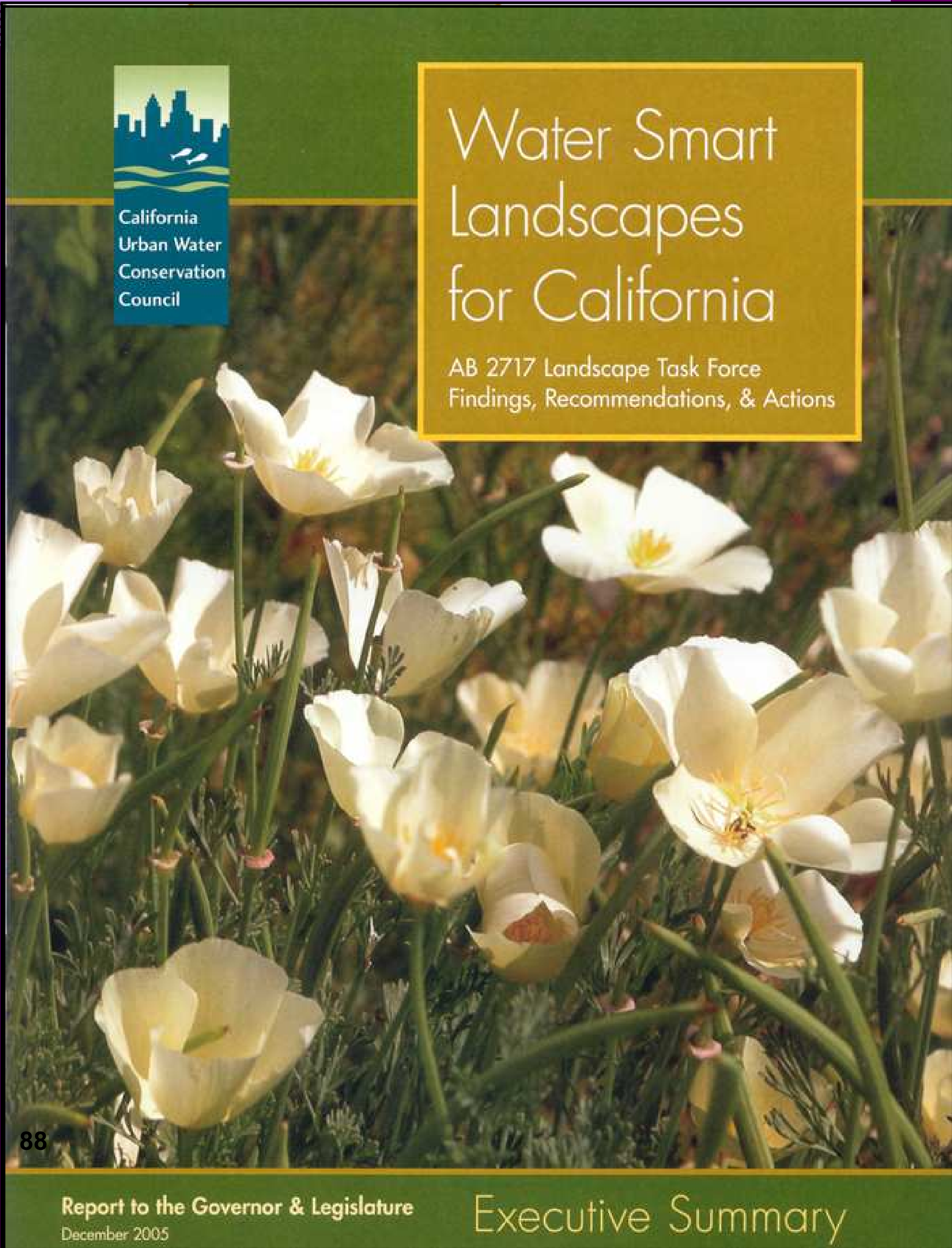
Photos used:

- SDCWA Non-Calendar
- SDC runoff program – Project Clean Water – examples of water-wise landscapes
- DWR Publication
- Gardensoft CD

Outcomes

Photos used:

"Water Smart Landscapes for California" AB 2717 Landscape Task Force Findings, Recommendations and Actions – Report to the Governor & Legislature – December 2005



Outcomes

Displays:

- Spring Garden Festival - WCG
- Fall Garden Festival - WCG
- Spring Plant Sale - WCG
- Lobby Exhibits at all participating agencies
- Master Gardeners
- County Fair

Outcomes

- Signage up through August
- Friends of East County Arts Garden Tour – 2006/7
- Interest expressed by several local nurseries
- Continued use of photos throughout the year and with the expressed permission of Contest – MWD, U-T, DWR, SDCWA, CDs, etc.
- Speaking engagement –

  Garden Clubs

  AWWA Conference

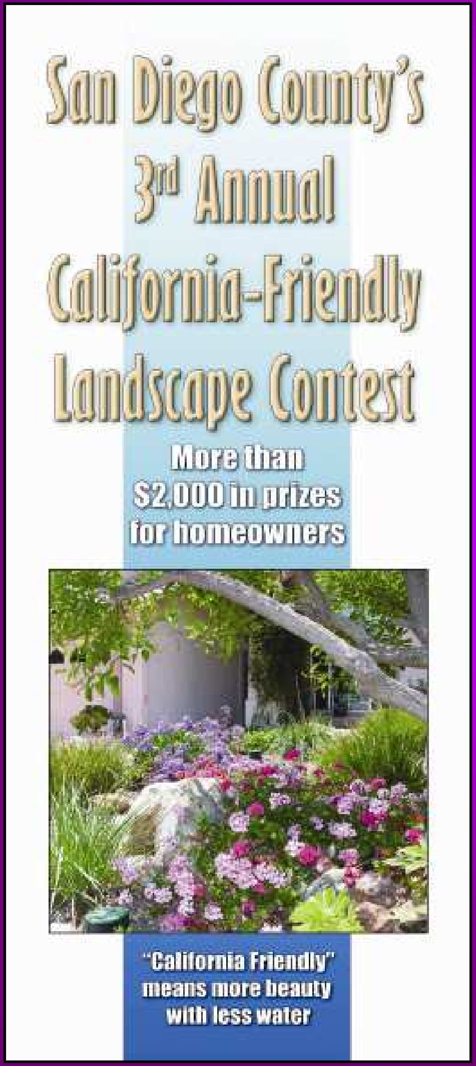
  IA Conference

Lessons Learned

Promotion – Social Marketing

- During Residential Survey
- Meter Readers
- Agency Publications
- Point of purchase - brochures
- Purchased advertisement
- *Union-Tribune* - contest regional and growing
- Posters in chain coffee houses
- www.landscapecontest.com
- Photographs – ripple effect

Brochures


San Diego County's
3rd Annual
California-Friendly
Landscape Contest
More than
$2,000 in prizes
for homeowners
"California Friendly"
means more beauty
with less water


San Diego County's
4th Annual
California
Friendly
Landscape Contest
More than
$3,500 in prizes
for homeowners
California Friendly
program
Sponsors
San Diego County Water Authority
Rain Bird


California Friendly
program
More than
$3,500 in prizes
for homeowners
San Diego
County's
5th Annual
California
Friendly
Landscape
Contest

More to Come

2007 – 2008 Contest Members

All but 5 of the 24 San Diego County Water Authority Members

Reach

2004 Contest = 170,000 customers

2005 Contest = 728,000 customers

2006 Contest = 2,000,000 customers

2007 Contest = 2,500,000 customers

2008 Contest = 3,000,000 customers

Sunday, December 9, 2007
IA07-1007

WaterSaver Landscape Specialist - A Year Later

Mark A. Peterson and Erin Kutschbach. San Antonio Water System, 2800 Hwy 281 North, San Antonio, TX 78212
The WaterSaver Landscape Specialist Program was introduced at the 2006 Irrigation Association meetings in San Antonio. It is a professional and technical development and recognition program for landscapers and irrigators that work in the San Antonio area. The programs primary goal is to provide consistent information to the local industry on the Best Management Practice's that focus on efficient water use for landscape installation and maintenance. Companies that sign up to participate in the program agree to have both professional and field staff attend a series of modules that cover the WaterSaver Specialist Best Management Practice's for landscapes in the San Antonio region. Participating companies agree to adhere to these BMP's in the course of their daily business.

From the results of a preliminary survey and meetings with the steering committee comprised of green industry professionals, both the focus and format of the program changed. Field staffs were also recognized as essential partners in promoting and implementing the BMP's, and their attendance at specially designed modules which emphasize ‘hands-on” education was required. The format changes included lengthening the number of modules for field staff but reducing their duration and organizing the modules around the Seven Principles of Xeriscape™. All partners agreed that initial “buy-in” from the green industry for both professionals and field staff is the key to the program's success.

See more of Turf/Landscape: General
See more of The 28th Annual International Irrigation Show (December 9-11, 2007)

Sunday, December 9, 2007
IA07-1008

New homeowners in San Antonio, Texas and outdoor water use habits

Juan A. Soulas and Rick Gomez. San Antonio Water System, PO Box 2449, San Antonio, TX 78298
San Antonio is among the fastest growing cities in the country. One population projection estimates 1 million people will be added over the next 25 years. In 2006 approximately 19,000 new homes were built, 17,000 are forecasted for 2007. Many of these new homes have irrigation systems installed during construction or within the first year of occupancy. Initial analysis of outdoor water uses shows that new homeowners use more water in their first two years than expected. Is it possible that irrigation systems are not being set or used correctly therefore using more water than what is needed to establish a new landscape? Additional analysis of new homeowner outdoor water-use will be conducted in order to identify the specific form of help these new customers would find beneficial. If viable, a conservation plan based on this study will be created and specific programs will be developed.

See more of Turf/Landscape: General
See more of The 28th Annual International Irrigation Show (December 9-11, 2007)

Urban Rainwater Harvesting for Landscape Irrigation
Dick Peterson
Austin Energy Green Building
Austin, Texas

Rainwater harvesting has been practiced for over 4,000 years in the desert of southern Israel. The ancient Romans had systems of aqueducts and cisterns. In the early 1900's, American farms and ranches depended on rainwater and groundwater. Rainwater harvesting is mandated in many Caribbean and European countries.

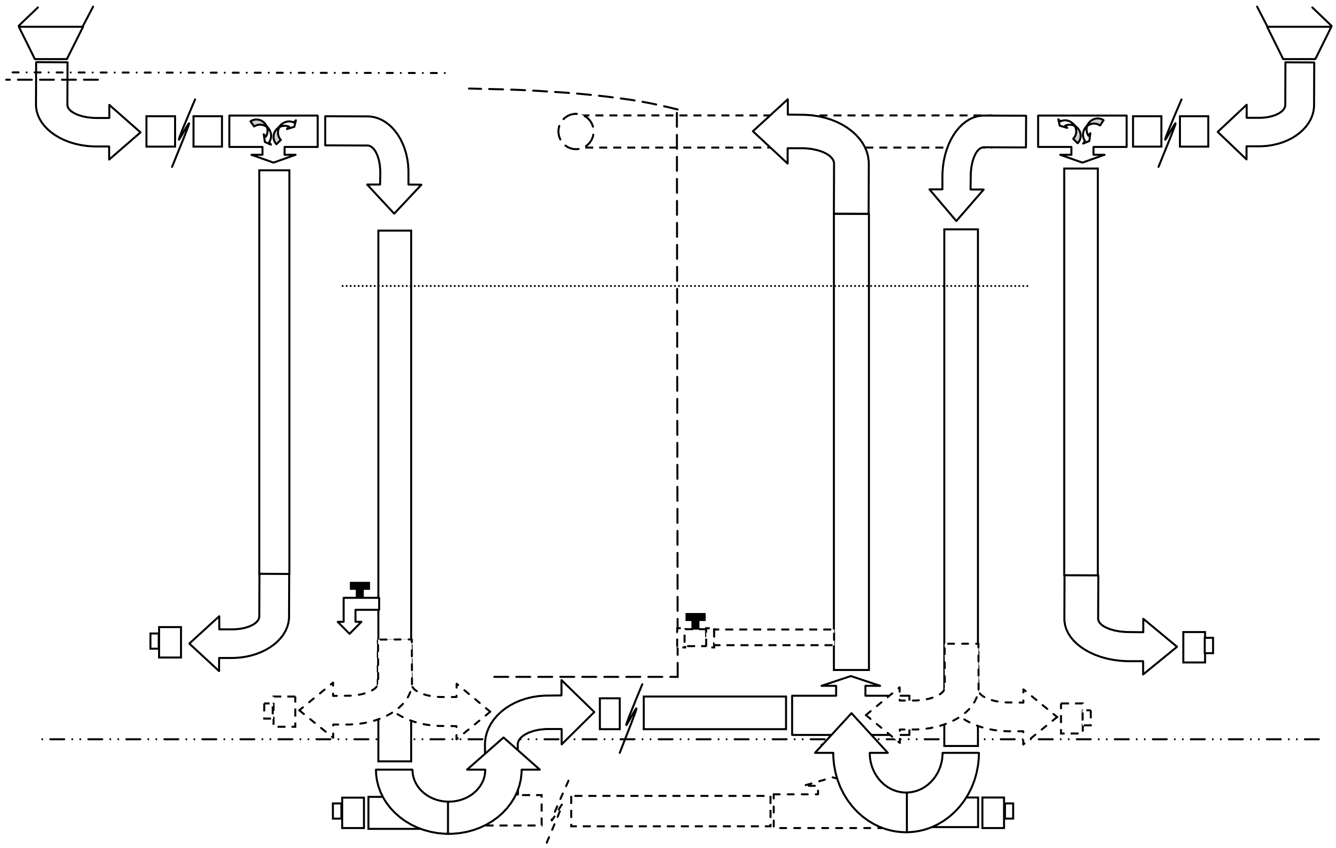
Why do we collect rainwater? The pH is almost neutral except in areas of heavy industry. Most plants love rainwater, because it does not have dissolved minerals from the soil as groundwater does and it does not have chemicals from water treatment plants. Careful planning for a rainwater system can also reduce erosion. Finally, it can reduce your water bill! Using rainwater reduces the need to use expensive potable water on your landscape plants.

In Texas, we have made rainwater harvesting components exempt from sales tax, saving over 8% of the cost in most jurisdictions.

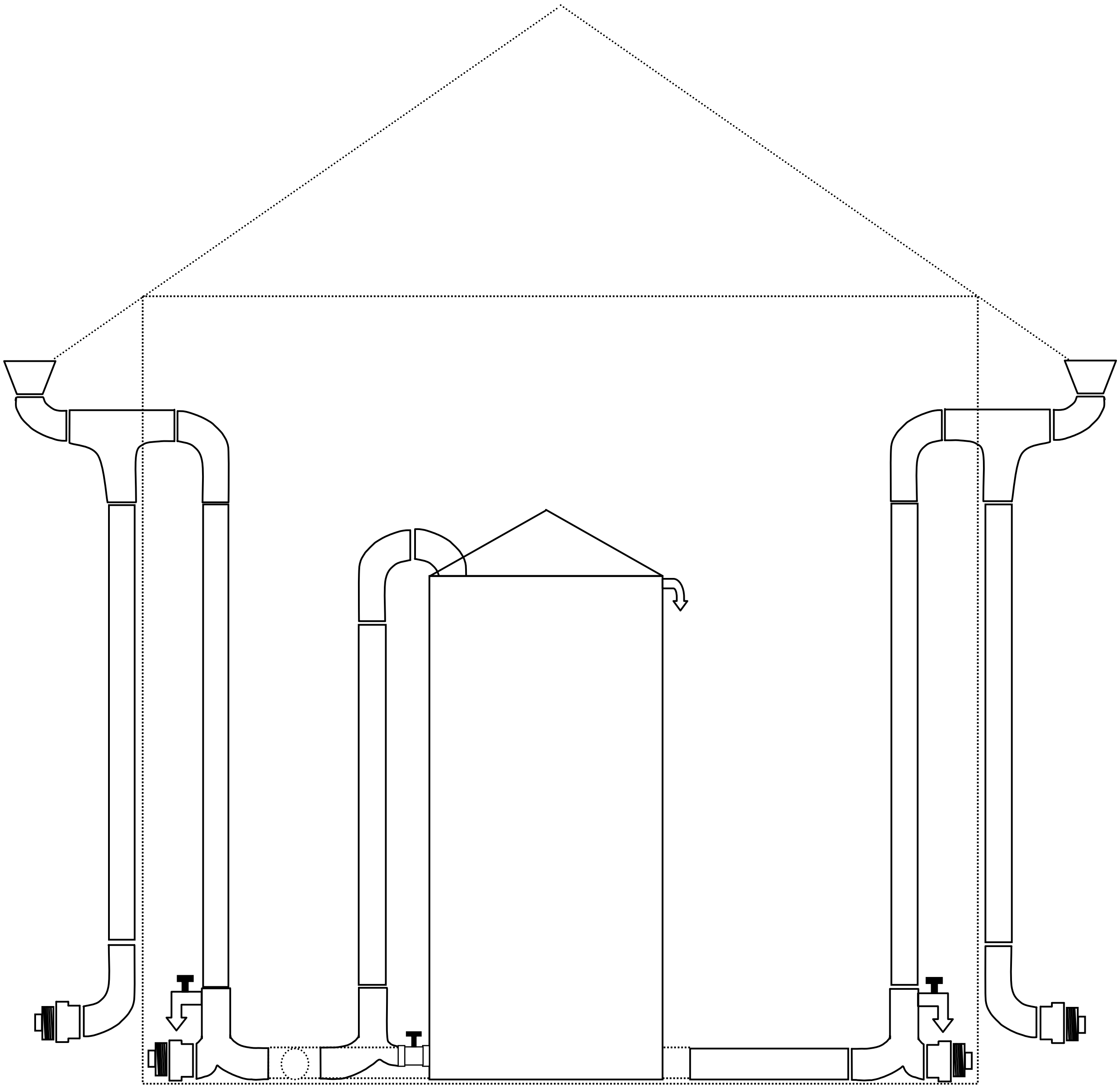
A simple system starts with a first-flush filter or "poor man's roof washer". The PVC components are found at local plumbing stores or "big box" retailers. The use of a first-flush filter reduces silt buildup in the cistern and avoids the need for frequent removal of debris from the tank.

Starter systems can be made from recycled food-grade drums linked together. Other sources of recycled containers may be a nearby industrial plant, or in the case of Austin, the computer industry.

Larger tanks (or cisterns) are available in many sizes and configurations. The least costly are the "poly" tanks available at feed and ranch stores or rural fencing supply houses.



This diagram shows several options for moving water from the gutters to the tank. A “bottom fill” option allows the collection system to become the distribution system. A method to clean out the pipes at the lowest points helps drain the pipes during freezing weather. In mild climates, the tanks do not freeze. In cold weather areas, the tank should probably not be used if there is a chance of the water turning to ice.



In cold weather areas, the tank should probably not be used if there is a chance of the water turning to ice. In central Texas, we do not have long-term freezing temperatures.

If you want to use rainwater for potable water, it will probably not be for financial reasons, if you have water available from a centralized water system. If you are “off the grid”, rainwater systems are comparable in cost to well water. Safety is of primary importance. You become your own water purveyor.

There are various materials used to make cisterns, including polyethylene, fiberglass, wood and ferrocement. Both above ground and below ground cisterns may be utilized. Cost and site issues will dictate the best choice. The expected life span for all cisterns is over 20 years. It is usually less expensive to purchase one large tank than multiple smaller tanks, but again, the site available comes into play. For a simple landscape system, a pump is usually not necessary. Most household systems are NOT connected to the irrigation system. Watering the typical lawn requires 3,000 gallons or more in just one watering cycle. A 3,000 gallon tank would be empty with just one irrigation cycle.

How much water can you collect? A one-inch rain provides about 60 gallons of water for every 100 square foot of roof area. So, even a 10' x 10' garden shed can fill a 55 gallon drum in a one-inch rain.

There are many examples of both commercial and residential rainwater systems in central Texas and many in the City of Austin received rebates. The total cost of a system depends on many choices, but a simple, gravity system for a home landscape typically costs about $1,000. An irrigation or landscape contractor has the necessary tools, except perhaps bits for 3 and 4 inch holes. Hey, it's just PVC pipe! Add a rainwater harvesting system onto your next bid and pocket another $1,000 profit.

Sunday, December 9, 2007
IA07-1029

Smart Irrigation Management during Drought

Karen Guz and Mark A. Peterson. San Antonio Water System, 2800 Hwy 281 North, San Antonio, TX 78212

San Antonio faced Stage One drought restrictions for six months of 2006. Customers were permitted to use irrigation systems on a designated day during the allowed watering window. Larger properties had to establish early in drought restrictions how to use their limited time for irrigation. Landscape variances for non-athletic fields were considered only when sites could show that plant material could not be sustained within the watering window. Sites with excellent irrigation systems capable of isolating priority plants or with microirrigation exempt from watering windows maintained healthy landscapes. Controllers with features such as cycle and soak made the most of water applied in tight watering windows. In contrast sites where poor irrigation never put water down deeply into woody plant root systems resulted in plant death with no rains came. In deeper levels of drought smart irrigation becomes even more crucial to keeping long-term landscape investment while coping with drought reality.

See more of Turf/Landscape: Advances in Sports Turf Irrigation
See more of The 28th Annual International Irrigation Show (December 9-11, 2007)

WATER AUDITS
of
LAWN BOWLING GREENS and CROQUET COURTS

Richard A. Sanger, CLIA, CIC, CID

ABSTRACT

Lawn Bowling Greens and Croquet Courts are unique when it comes to designing an efficient irrigations system. The restraint of not having fixed irrigation heads on the actual playing surfaces makes it difficult to obtain good water distribution and scheduling efficiency.

Club members want hard, level playing surfaces, short green grass and no fixed irrigation heads on the playing surface. Water audits can be utilized to explain to club members the problems with maintaining healthy turf under these conditions and the need for extensive maintenance practices by the turf professionals.

Turf professionals assigned to these facilities can use the water auditing tools to offset criticism thrown their way by club members, officials and their immediate supervisors regarding the turf conditions at these facilities. Growing healthy turf under these conditions is difficult even when using the water auditing tools to demonstrate existing problems.

Lawn Bowling and **Croquet** (not the kid's game) are two unique sports that impose somewhat severe restrictions on the design and operation of irrigation systems. These two games are played by serious adults demanding a level playing field to within ± 1/8 inch, hard almost to the point of serious compaction, a very low growing grass (typical of the region of the country or world. Tifgreen - 328 for this area of Florida) and no sprinkler heads located on the playing surface.

Good water distribution becomes very difficult under these conditions. We have experienced these problem with the three Lawn Bowling Greens and three Croquet Courts. Sarasota County, Community Service Business Center, Parks and Recreation, Athletic Division's Irrigation Unit, maintains these greens and courts for the cities of Sarasota and Venice.

We have reuse water to irrigate the lawn bowling green that is available twenty four hours per day. We do not water during the time frame between 10:00 a.m. and 3:00 p.m. We comply with existing water ban rules and regulations imposed by the Florida Water Management Districts. They have imposed limits to irrigation between these hours for those users utilizing potable, well or surface waters for their irrigation source.

We abide by this same restriction to eliminate problems with the public and law enforcement agencies and the lengthy explanation of why we are not bound by these same water restrictions.

I am only discussing the irrigation problem and the water audit conducted on the newest south Lawn Bowling Green. A very similar situation exists with the Croquet Courts. These were not audited due to current modifications to the entire court layout. These modifications may entail moving existing irrigation heads.

This audit has already shown us some modifications that need to be implemented in order to improve the distribution uniformity and water scheduling. It is eventually going to require the placing of a full circle irrigation head located in the exact center of each of these Lawn Bowling Greens. This full circle head was not provided for when this green was built nor were provision made for a solenoid valve controlled by the irrigation controller.

Recent budget cuts have limited our staffing levels for these specialty sports and we must have the assistance of members of the Sarasota Lawn Bowling Club to offset these budget restraints. This will probably require the clubs assistance in the placing and removal of the full circle heads to be located in the middle of each bowling green. These portable heads located in the center of the greens will give us better water distribution and improved scheduling efficiency.

HISTORY of the GREENS

Lawn Bowling Greens are typically laid out as a 120 foot square (this is the playing surface). This green is surrounded by a ditch, which may become part of the games playing surface on occasion. The board defining the ditch that is adjacent to the playing surface (called the plinth) is actually considered part of the playing surface and its levelness to ± 1/8" determines the levelness of the entire playing green. Irrigation heads are placed outside of this ditch and far enough away so the boards that make up the ditch can be repaired or adjusted after top-dressing of the green without damaging the irrigation system.

This south green was constructed by the City of Sarasota's Recreation & Parks Department in 1984 as a sand green generally following the construction guidelines in the book THE CONSTRUCTION OF THE LAWN BOWLING GREEN by Edgar R. Haley, Greenskeeper, Escondido, CA.

This lawn bowling green was constructed over some old shuffleboard courts that were partially removed. These courts were built on top of a well drained fine yellow sand. Large holes were jack-hammered into those courts that were not removed to "provide continuity" and "drainage" between the existing soil and the graded fine sand that makes up the new green. We have a graded 6 to 7 inch deep fine sand layer that holds more water that the typical native Florida sand.

Original irrigation system used TORO 690 series irrigation heads connected to a 3 inch mainline loop to minimize pressure loss. These were *hydraulic valve in head sprinklers* that were individually controlled by a TORO Controller.

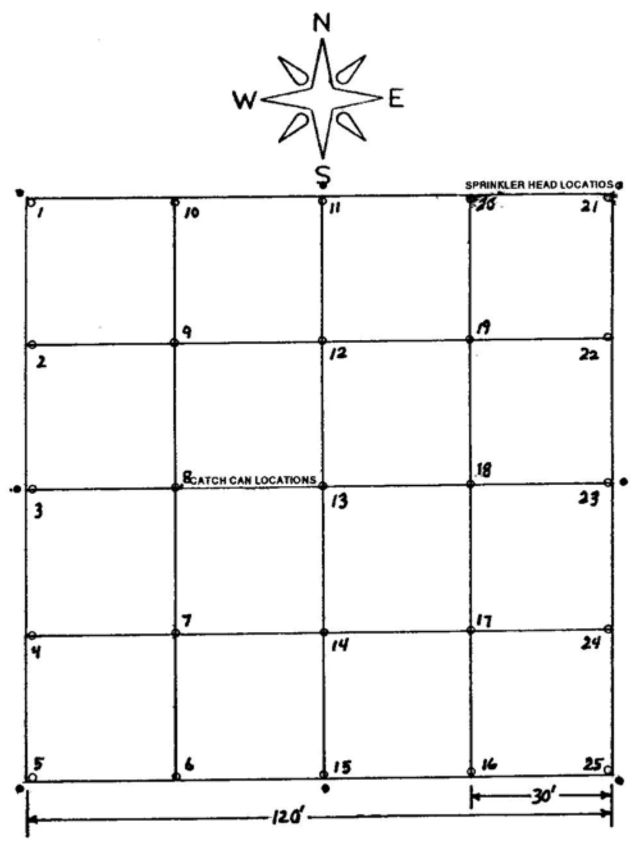
We modified the irrigation design when we obtained reuse water from the City of Sarasota to a Rain Bird system that can eventually be connected to a Maxicom 2 Centralized Irrigation Control System. We replaced the TORO heads with Rain Bird E*agle 750 Rotor Series*. This sprinkler head with a yellow # 36 nozzle operates at 70 psi, radius of 65 feet and flow of 20.4 gpm. All eight heads are adjusted to a "90° arc" to minimize overlap.

The cities reuse water main has a static pressure between 50 and 70 psi. A booster pump was installed to increase the mainline pressure to 85 psi which is high enough to provide the required 70 psi at the base of the sprinkler head.

A proper irrigation design would have utilized nine irrigation heads consisting of four ¼ circle, four ½ circle and one full circle head. The eight head design limitation has resulted in poor water distribution. A full circle head (if currently available) would provide a more uniform watering pattern and better distribution uniformity. This (portable) full circle head would be placed in the center of the green before any schedule irrigation cycle and then removed from the green the next morning so games could be played on the green.

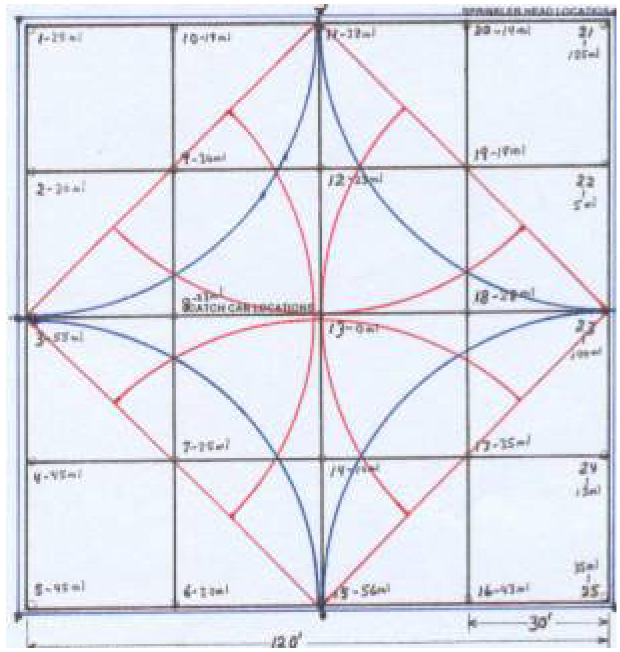
We were not permitted to add a full circle head to the middle of the green and we could not get cooperation from the Sarasota Lawn Bowling Club to move a portable head on and off of the green every time there was a scheduled irrigation cycle. The resulting poor distribution became evident when we conducted the irrigation audit.

The diagram below shows the typical layout of our south green, placement of the sprinkler heads outside of the playing surface and locations of the twenty five catch cans on a thirty foot square grid. All eight sprinkler heads cover a 90° arc to “minimize overlap” There is no full circle sprinkler head that can be placed in the center of the green.



SOUTH LAWN BOWLING GREEN IRRIGATION PATTERNS

Corner heads are outlined with a blue arc, red arc’s outline the heads located in the middles. All are set for a 90° arc with minimal overlap. Not the most desirous of designs but it works.



IRRIGATION SCHEDULES

The irrigation chart shows the schedule for all irrigation *valve in head* sprinklers used to water the three greens, the syringe cycle used for over-seeding and the zone valve scheduling for the facility landscaping. Details are provided on the schedule. Varied run times for the south green should not exit on a bowling green constructed with a 6 to 7 inch deep fine sand over on top of an existing 15" deep sand layer.

FACILITY: Lawn Bowling Greens - North - Middle - South

CONTROLLER LOCATION: East side of the restroom bldg. between the north and middle greens								
CONTROLLER: Rain Bird ESP-MC - Programs Stacked								
Rain Shut Off Device		ON (X)	OFF ( )	Setting ¼"		Date Tested	8/20/2007	
Controller Programs		Descriptions		Program A	Program B	Program C	Program D	
Watering Days				Daily	Daily	Daily	Daily	
Start Times:		1		11:00 p.m.	11:00 p.m.	10:00 a.m.	3:00 a.m.	
		2				3:00 p.m.		
		3						
Water Budget %				65%	65%	100%	100%	
Station #	Description			Run Times	Run Times	Run Times	Run Times	
1	North Green Middle (E) Side			6 minutes				
2	North Green Middle (S) Side			6 minutes				
3	North Green (SW) Corner			6 minutes				
4	North Green (NW) Corner			8 minutes				
5	Middle Green Middle (N) Side			8 minutes		5 minutes		
6	Middle Green Middle (E) side			8 minutes		5 minutes		
7	Middle Green (NW) Corner			4 minutes		5 minutes		
8	Middle Green (NE) Corner			6 minutes		5 minutes		
9	South Green Middle (N) Side			10 minutes		5 minutes		

10	South Green Middle (E) Side	8 minutes		5 minutes		
11	South Green (SE) Corner	8 minutes		5 minutes		
12	south Green (NE) Corner			5 minutes		
13	North Green Middle (N) Side		10 minutes			
14	North Green Middle (W) Side		8 minutes			
15	North Green (NE) Corner		8 minutes			
16	North Green (SE) Corner		4 minutes			
17	Middle Green Middle (S) Side		8 minutes	5 minutes		
18	Middle Green Middle (W) Side		6 minutes	5 minutes		
19	Middle Green (SE) Corner		6 minutes	5 minutes		
20	Middle Green (SW) Corner		6 minutes	5 minutes		
21	South Green Middle (S) Side		10 minutes	5 minutes		
22	South Green Middle (W) Side		8 minutes	5 minutes		
23	South Green (NW) Corner		6 minutes	5 minutes		
24	South Green (SW) Corner		8 minutes	5 minutes		
25	Blank					
26	Landscape Tree Bubblers				60 minutes	
27	Landscape Turf Spray Zone				15 minutes	
28	Landscape Turf Spray Zone				15 minutes	
29	Landscape Turf Spray Zone				15 minutes	
30	Landscape Turf Spray Zone				15 minutes	

NOTES: These three Lawn Bowling Greens are irrigated with reuse water supplied by the City of Sarasota Utility Department

Program A & B are used to irrigate the greens during the night when the prevailing west winds off of Sarasota Bay is minimal and drift is not a problem (reuse water regulation, minimum drift).

Program C is used as a syringe cycle when the greens are over seeded.

Program D provides irrigation for the landscaping trees and shrubs and the Bermudagrass turf surrounding all of the greens and common areas.

IRRIGATION NOTES: ***Athletic Field Maintenance Supervisor suggests/determines station run times and water budget percentages.*** Irrigation Unit's crew is responsible for setting and adjusting station run times to match weather, season and growing conditions. They test all irrigation heads for rotation, speed, arc, function and wetted pattern on a fixed schedule

WATERING SCHEDULE for the SOUTH LAWN BOWLING GREEN

Rain Bird Eagle 750 Adjustable 30° to 345° Sprinkler Heads were used for all locations and "adjusted to a 90° arc for minimal overlap". This was done to "reduce" the amount of water applied in the overlap areas.

This is not a proper design element, run times should have been adjusted for the corner sprinkler heads. They should run for ½ of the run time for the half circle heads (which have been adjusted for a 90° arc, also not a proper design element).

Station #	Description of sprinkler Head Locations	Start Time 11:00 p.m.	Start Time 11:00 p.m.	Start Times 10:00 a.m. & 3:00 p.m.
	Water Budget in Percentage	Daily @ 65%	Daily @ 65%	Daily @ 100%
	Stacked Programs	Program A Run Times	Program B Run Times	Program C Run Times
9	Middle North Side 90° Arc	10 Minutes		5 Minutes
10	Middle East Side 90° Arc	8 Minutes		5 Minutes
11	Corner Southeast Side 90° Arc	8 Minutes		5 Minutes
12	Corner Northeast Side 90° Arc		10 Minutes	5 Minutes
21	Middle South Side 90° Arc		10 Minutes	5 Minutes
22	Middle West Side 90° Arc		8 Minutes	5 Minutes
23	Corner Northwest Side 90° Arc		6 Minutes	5 Minutes
24	Corner Southwest Side 90° Arc		8 Minutes	5 Minutes

Run times for Programs “A” and “B” were determined by the Athletic Field Maintenance Unit’s Operations Supervisor I. based on “existing soil conditions, compaction, and puddling.

Program “C” was used for the water audit due to the uniform run times.

ACTUAL AUDITING CONDITIONS

The first audit was run during the day utilizing the syringe cycle for the south green. Prevailing wind conditions were measured in both the north/south direction and the east/west directions. The wind at 11:00 a.m. in both directions was ≤ than 4.0 mph. All heads were checked with a bubble level and any grass that interfered with the irrigation nozzles was removed prior to the audit.

The next audit was run on Friday during the 10:00 a.m. syringe cycle when the wind speed was within auditing guidelines. Wind speeds were measured with a Kestrel 3000 and indicated an average wind speed in both direction of less than five mph which is within the auditing guide lines. We have been checking the auditing conditions daily to get the best audit results possible that most closely mimics the actual operating conditions of this Lawn Bowling facility.

SOUTH LAWN BOWLING GREEN
AUDITING RESULTS

Catch Can Number	Run Time in minutes	Milliliters Collected (ml), Audited at 3:00 p.m. 10/28/07	Milliliters Collected (ml), Audited at 11:45 a.m. 11/02/07
1	5	24 ml	19 ml
2	5	30 ml	25 ml
3	5	30 ml	55 ml
4	5	25 ml	30 ml
5	5	32 ml	34 ml
6	5	15 ml	23 ml
7	5	18 ml	30 ml
8	5	20 ml	33 ml
9	5	27 ml	35 ml
10	5	4 ml *	5 ml *
11	5	36 ml	24 ml
12	5	38 ml	27 ml
13	5	0 ml *	2 ml *
14	5	20 ml	13 ml *
15	5	80 ml	38 ml
16	5	15 ml	45 ml
17	5	24 ml	30 ml
18	5	15 ml	30 ml
19	5	15 ml	24 ml
20	5	4 ml *	7 ml *
21	5	8 ml *	15 ml
22	5	0 ml *	13 ml *
23	5	25 ml	54 ml
24	5	8 ml *	5 ml *
25	5	24 ml	44 ml
Total All Catch Cans Averaged		527 ÷ 25 = 21.1 ml average	660 ml ÷ 25 = 26.4 ml average
Lowest Quarter (*) Totaled and Averaged		24 ml ÷ 6 (*) = 4.0 ml average for the lowest quarter	26.4 ml ÷ 6 (*) = 7.5 ml average for the lowest quarter

The first audit indicated that only minor improvements in the distribution uniformity could be obtained with some tweaks to the system. A major improvement occurred when the booster pump was repaired and back on line.

Nobody knew how long this pump had been down since it typically operates at night when no one is around to observe the irrigation patterns or check the pressure on the mainline when the system was operating.

The new pump added a significant boost to the mainline pressure from 65 psi to between 80 to 85 psi. This increase in mainline pressure had a significant impact on the distribution uniformity but not enough to overcome design flaws.

CALCULATIONS
DISTRIBUTION UNIFORMITY:

Sunday, 10/28/07 @ 3:00 p.m.
Booster Pump Off-line for Repairs

$$\mathbf{DU_{LQ}} = \frac{Average\ lowest\ quarter}{Average\ of\ all\ catch\ cans} \times 100 = \frac{4.0\ ml}{21.1\ ml} \times 100 = 18.9\%$$

Friday, 11/02/07 @ 11:52 p.m.
Booster Pump On-Line

$$\mathbf{DU_{LQ}} = \frac{Average\ lowest\ quarter}{Average\ of\ all\ catch\ cans} \times 100 = \frac{7.5\ ml}{26.4\ ml} \times 100 = 28.4\%$$

RECOMMENDATIONS

These two audits have revealed a serious problem with the current design. It appears that with out the center irrigation head and adjustments to the existing heads that we have obtained the best possible distribution uniformity.

There may be some improvements if the corner ¼ circle heads are adjusted for a minimum rotation of six 90° arc's and are set for the lowest run time that will accomplish this criteria. The four heads located in the middle of the N, E, S and W sides of the green need to be adjusted to a 180° arc and the run times double of the ¼ circle heads in the corners.

The best solution would be to install a portable full circle *Rain Bird Eagle 700 Series* on a base that can be pegged down in the middle of the green. This portable head can be stored off of the court during play and after play ends be placed in the middle of the green for the irrigation cycle.

This proposed solution would place irrigation heads in all four corners, the four sides and the full circle head in the middle. We should be able to get good overlap of all sprinklers and each one contributing its portion to the green with out excess overlap.

I would like to be able to give a more detailed follow-up of this report at next years Irrigation Association 29th International Irrigation Show in Anaheim, CA. If we are able to make the suggested improvements and modifications I expect to see a better distribution uniformity and scheduling efficiency.

I can be contacted at Sarasota County, Community Services Business Center, Parks and Recreation. 6700 Clark Road, Sarasota, FL 34241-9328, Telephone 941-861-9877, Fax Number 941 861-9885
e-mail: Richard A.Sanger@scgov.net

Sunday, December 9, 2007
IA07-1031

GCSAA Environmental Profile Project – Water Use and Conservation Study

Greg T. Lyman, Environmental Programs Director, Golf Course Superintendents Association of America (GCSAA), 1421 Research Park Drive, Lawrence, KS 66049-3859

The GCSAA is conducting a series of surveys over the next few years to determine the physical features found on golf courses; maintenance practices used by superintendents; and inputs associated with the management of golf courses. This information will better describe natural resource attributes, management inputs and current environmental stewardship practices on golf properties. As part of this project, the water use and conservation survey was conducted in October-November, 2006. The results of this study have been analyzed and a manuscript will be submitted to the Applied Turfgrass Research Journal. It is anticipated that the journal review process will be completed in late 2007. Results will be shared with the participants at the IA Technical Conference.

See more of Turf/Landscape: Advances in Sports Turf Irrigation
See more of The 28th Annual International Irrigation Show (December 9-11, 2007)

Sunday, December 9, 2007
IA07-1032

How Catch Cup Quantity Affects Audit Results

Brian Vinchesi, President, Irrigation Consulting, Inc, 4 Hotel Place, Pepperell, MA 01463, Jeff Gilbert, University Of Arizona, University of Arizona, 1349 E Fort Lowell Rd Apt D, Tucson, AZ 85719-2201, and Gene Smith, Hunter Industries, 1940 Diamond Street, Sam Marcos, CA 01463.
Using field auditing data collected by the University of Arizona extension service and uniformity tests conducted at Hunter Industries spray sprinkler uniformity lab the results of an analysis to determine how the number of catch cups affects the Distribution Uniformity and Net Precipitation rate of irrigation audits will be reported. The presentation will discuss results as to whether the quantity is statistically influencing the results and if so attempt to identify what minimum number of cups might be necessary for an audit.

See more of Turf/Landscape: Advances in Sports Turf Irrigation
See more of The 28th Annual International Irrigation Show (December 9-11, 2007)

Sunday, December 9, 2007
IA07-1033

Irrigation Analysis for Water Savings - One Year Later

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In an effort to maximize year around water conservation efforts the San Antonio City Council passed a water conservation ordinance addressing a variety of water conservation opportunities. One of the provisions included in the ordinance requires that properties over 5 acres, athletic fields and golf courses with in-ground irrigation systems submit an annual irrigation check up to the San Antonio Water System Conservation Department by May 1 each year. The intent of this ordinance provision is to ensure that a minimum standard of irrigation system maintenance is performed. Regularly scheduled maintenance of irrigation systems contributes significantly to water savings. A well maintained irrigation system should be checked at a minimum, monthly, weekly in high traffic areas. Any maintenance issues found should be repaired in a timely matter. Properties that do not have a current irrigation system check-up on file will loose their courtesy water waste warning if the irrigation system is reported being run outside designated irrigation hours or if water from the irrigation system is found running down the street or other impervious cover. The property will immediately be placed on the water waster list and the property owner or manager will receive a personal citation if any Conservation Enforcement Officer observes an additional violation. Design issues such as the desire to change a spray zone to drip, cap off a zone that is irrigating well established trees and shrubs, or if the landscape design has changed should be considered. San Antonio Water System customers may qualify for rebates for these design changes that result in water savings. Compliance rates in regards to this provision of the ordinance will be discussed as well as what our Conservation Field Technicians find during “spot checks” of large properties over the summer.

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Turfgrass Irrigation Controlled by Soil Moisture Sensor Systems

Bernard Cardenas-Lailhacar[1] and Michael D. Dukes[2]

Abstract

More than 15% of all new homes in the U.S. were built in Florida between 2005 and 2006, most of them with an automatic irrigation system, resulting in an increase in the demand for limited potable water resources. Soil moisture sensor (SMS) irrigation control systems have recently been released to the market, which could help prevent excess irrigation. The objectives of this research were to: 1) analyze the performance of SMS systems relative to actual soil moisture content, and 2) quantify irrigation water use and assess turf quality differences between a) a time-based scheduling system with and without a RS, b) a time-based scheduling compared to a SMS-based irrigation system, and c) different commercial irrigation SMS systems. The experimental area consisted of common bermudagrass [*Cynodon dactylon* (L.) Pers] plots (3.7 x 3.7 m), in a completely randomized design, located in Gainesville, Florida. Treatments consisted of four different commercial SMS brands (Acclima, Rain Bird, Irrometer, and Water Watcher) compared to time-based treatments (with rain sensor, without rain sensor). All of these treatments were scheduled at a two days a week irrigation frequency. Non-irrigated treatments were also implemented. Significant differences in turfgrass quality among treatments were not detected, including the non-irrigated plots, due to frequent rain during the 308-day study period. Including a rain sensor in the irrigation system resulted in 34% water savings. Among the SMS-based treatments, brands Acclima, Rain Bird, Irrometer, and Water Watcher, reduced irrigation

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water application by 77%, 88%, 27%, and 82%, respectively, compared to the time-based treatment without rain sensor. Therefore, SMS-systems represent a promising technology for water conservation on turfgrass irrigation in the humid region.

Introduction

Historically, Florida exhibits dry and warm weather in the spring and fall, as well as frequent rain events in summer (National Oceanic and Atmospheric Administration [NOAA], 2003). These climatic conditions, coupled with low water holding capacity of Florida's predominately sandy soils, make irrigation indispensable for the high quality landscapes desired by homeowners (Haley et al., 2007; National Research Council, 1996). More than 15% of all new homes in the U.S. were built in Florida between 2005 and 2006 (United States Census Bureau [USCB], 2007); most of them with automatic in-ground irrigation systems (Tampa Bay Water, 2005; Whitcomb, 2005); which has been reported to result in higher water use compared to manual irrigation or manually moved sprinklers (Mayer et al., 1999).

A recent study carried out by Haley et al. (2007) in Central Florida, found that homeowners tended to irrigate by as much as 2-3 times the plant requirements. Over-irrigation can not only negatively affect landscape/turfgrass quality, but tends to have environmentally costly effects because of wasted water and energy, leaching of nutrients or agro-chemicals into groundwater supplies, degradation of surface water supplies by sediment-laden irrigation water runoff, and erosion. In turfgrass, it has also been reported that over-irrigation promotes the establishment and survival of some turfgrass weeds (Busey and Johnston, 2006; Colbaugh and Elmore, 1985; Youngner et al., 1981), increase in severity of some pathogens (Davis and Dernoeden, 1991; Kackley et al., 1990), and increased evapotranspiration (Biran et al., 1981).

Irrigation time clocks, or timers, are an integral part of an automatic irrigation system and, when correctly programmed, are an essential tool to apply water in the necessary quantity and at the right time. Modern irrigation timers provide a large number of features, including the possibility to receive feedback from one or more sensors, allowing accurate control of irrigation water and automation of the irrigation systems (Zazueta et al., 2002; Boman et al., 2002).

Numerous types of soil moisture sensors have been used for decades to measure soil water content, including neutron scattering, resistance blocks, tensiometers, and granular matrix sensors (Gardner, 1986; Seyfried, 1993; Leib et al., 2002; Leib et al., 2003; Or, 2001) including turfgrass and landscape irrigation applications (Augustin and Snyder, 1984; Qualls et al., 2001). Newer methods to measure soil water content ($\boldsymbol{\theta}$), based on the dielectric properties of the soil, are being used in greater numbers, because they are non-destructive, provide almost instantaneous measurements, require little or no maintenance, can provide continuous readings through automation, and their cost has decreased substantially in recent years. An additional advantage of these modern sensors is that accurate measurements may be made near the surface (important for shallow rooted crops such as turf) compared to techniques such as the neutron probe. Some of the techniques based on the dielectric methods have been classified as time domain reflectometry (TDR) and time domain transmissometry (TDT). Most TDR and TDT instruments operate by sending an electromagnetic step pulse signal down steel rods buried in the soil. When the signal reaches the end of the probes (TDT), or is reflected back to the control unit (TDR) the signal is then detected and analyzed. The time taken for the pulse varies with the soil dielectric properties, which are related to the water content of the soil surrounding the probe (Topp, 2003; Blonquist et al., 2005). Muñoz-Carpena (2004) summarizes the working principle, description, advantages, and drawbacks of different field devices for monitoring soil water content, and gives evaluation criteria for the selection of a specific soil moisture sensor (SMS).

Modern commercially available SMS-systems include a controller that interfaces with the irrigation timer. This piece of equipment is a milestone in the development of the SMS industry because it sends a signal to the buried SMS, interprets the signal behavior and converts it to a sensed soil moisture content ($\boldsymbol{\theta}_S$). At the same time, the controller acts as a switch and allows the operator to choose a desired soil moisture content threshold ($\boldsymbol{\theta}_{Th}$), above which scheduled irrigation events will be bypassed. Typically, the adjustable $\boldsymbol{\theta}_{Th}$ can be set between relatively dry to relatively wet soil moisture conditions; depending on the plant material, soil type, installation depth of the SMS, etc. These features, coupled with a simple and user-friendly design, and a substantial reduction in the purchase cost, have allowed the use of the SMS technology for control of residential irrigation systems.

An automatic SMS-based irrigation system is designed to maintain a desired $\boldsymbol{\theta}$-range in the root zone that is optimal or adequate for plant growth and/or quality, by eliminating unnecessary irrigation cycles. This type of system adapts the amount of water applied according to plant requirements and actual weather conditions (Dukes, 2005; Pathan et al., 2003). Modern commercially available SMSs work under the bypass configuration, which skips or allows an entire scheduled irrigation cycle based on $\boldsymbol{\theta}_S$ relative to $\boldsymbol{\theta}_{Th}$ at the beginning of that event (Muñoz-Carpena and Dukes, 2005).

In order to achieve these goals in sandy soils, where the storage of water is minimal, coupled with shallow turfgrass root depth, the continuous and accurate monitoring of the soil moisture status becomes of great consequence. Automatic control of irrigation, based on SMSs, has been successfully reported in coarse textured soils, achieving water savings without diminishing yields of vegetable crops (Nogueira et al., 2002; Dukes and Scholberg, 2005; Dukes et al., 2003; Muñoz-Carpena et al., 2003; Shock et al., 2002; Zotarelli et al., 2008) nor quality of turfgrass (Pathan et al., 2003). Automatic irrigation systems with a rain sensor feedback have been also recommended to save water in Florida (Cardenas-Lailhacar and Dukes, 2008).

The goal of this research was to find out if modern SMS systems could reduce irrigation water application while maintaining acceptable turf quality compared to time-based irrigation schedules used by homeowners in Florida. The objectives of this research were to: 1) analyze the performance of SMS systems relative to actual soil moisture content, and 2) quantify irrigation water use and assess turf quality differences between a) a time-based scheduling system with and without a RS, b) a time-based scheduling compared to a SMS-based irrigation system, and c) different commercial irrigation SMS systems.

Materials and Methods

The experiment was carried out at the Agricultural and Biological Engineering Department facilities, University of Florida, Gainesville, Florida. Turfgrass plots (3.7 m x 3.7 m) were established on a field covered with common bermudagrass [*Cynodon dactylon* (L.) Pers] and were sprinkler irrigated by four quarter-circle pop-up spray heads (Hunter 12A, Hunter Industries, Inc., San Marcos, CA). Turfgrass management was carried out according to recommendations by the University of Florida (Trenholm et al., 2003). The soil is an Arredondo fine sand (loamy, siliceous, semiactive, hyperthermic Grossarenic Paleudults) (Carlisle et al., 1981; Thomas et al., 1985; United States Department of Agriculture [USDA], 2003). The field site and experimental setup was described in detail by Cardenas-Lailhacar (2006).

Soil Moisture Sensor Systems

Four SMS systems were evaluated: Acclima Digital TDT RS500 (Acclima, Inc., Meridian, ID), Watermark 200SS probe with a WEM controller (Irrometer Company, Inc., Riverside, CA), Rain Bird MS-100 (Rain Bird, Inc., Glendora, CA), and Water Watcher DPS-100 (Water Watcher, Inc., Logan, UT). These systems were codified as AC, IM, RB, and WW, respectively. The probes were buried in the soil were the majority of the roots were present, at a depth of 7-10 cm.

The controllers were connected in series with common residential irrigation timers; model ESP-6 (Rain Bird International, Inc., Glendora, CA). As recommended by manufacturers of the controllers with relative set points (RB and WW), $\boldsymbol{\theta}_{Th}$ were set 24 hours after a significant rainfall event filled the soil profile with water (i.e. to ensure field capacity). The $\boldsymbol{\theta}_{Th}$ were adjusted by means of a knob between “moist” and “dry” on the RBs (on a 1 to 8 scale), and on the WWs (on a -3 to +3 scale). On the RB controllers, $\boldsymbol{\theta}_{Th}$ was found by turning the dial until an LED (indicator of irrigation need) turned ON and OFF, and was ultimately set at position #2.5. On the WWs, the knob was set in the midway position and then the calibration button was pushed, which allowed its auto-calibration and set point. The IM controllers were set at #1, which corresponds to 10 kPa of soil water tension according to the manufacturer (approximately, field capacity). Finally, the AC controllers were set at a soil volumetric water content of 7%, which is field capacity for this soil (Thomas et al., 1985; Cardenas-Lailhacar, 2006).

Soil Moisture Content

The actual $\boldsymbol{\theta}$ of each plot was monitored with a capacitance probe (20 cm ECH_20, Decagon Devices, Inc., Pullman, WA), which were buried diagonally, between 7 and 10 cm from the surface, and between 10 and 30 cm from the SMS system probes. The ECH_20 probes were connected to HOBO micro-loggers (Onset Computer Corp., Bourne, MA) and readings were recorded every 15 minutes. Before the beginning of the experiment, calibration of the ECH_2O probes was performed at the research site using the thermogravimetric (or gravimetric) soil sampling method described by Gardner (1986). Four probes were installed in the field and connected to a HOBO micro-logger. Undisturbed soil samples were collected from the field (using a core sampler of 137.4 cm^3) at less than 20 cm from the probes, and at the probe burial depth. Samples were taken at a $\boldsymbol{\theta}$ between 5% and 14% by volume (all water contents expressed as volume of water per volume of sample). The $\boldsymbol{\theta}$ of each sample was then compared to the ECH_2O probe readings recorded with the HOBO micro-loggers at the same date and time when the samples were taken.

Field Treatments

Three time-based and four SMS-based treatments (brands AC, RB, IM, and WW) were established (Table 1). All these treatments were tested at an irrigation frequency of two days per week; which represents the most common irrigation restriction imposed in Florida and current watering restriction in the study area (Florida Department of Environmental Protection [FDEP], 2007; St. John's River Water Management District, 2007). Two time-based treatments were connected to a rain sensor: with-rain-sensor (WRS) and deficit-with-rain-sensor (DWRS). The rain sensor (Mini-click II, Hunter Industries, Inc., San Marcos, CA) was set at a 6 mm rainfall threshold. A without-rain-sensor treatment (WORS) was also included, in order to simulate homeowner irrigation systems with an absent or non-functional rain sensor, which has been reported as high as 75% in Florida (Whitcomb, 2005). Finally, a non-irrigated treatment (NI) was implemented as a control for turfgrass quality.

All treatments were scheduled to apply the same amount of water per week, except for treatments DWRS (60% of this amount), and NI (non-irrigated). Therefore, differences in water application among treatments were the result of sensors bypassing scheduled irrigation cycles. The weekly irrigation amount was adjusted on a monthly basis to completely replace historical ET, according to guidelines recommended by Dukes and Haman (2002). The system to record the data of the irrigation applied to each plot is described in Cardenas-Lailhacar et al. (2008). Turfgrass quality was visually assessed and rated using a scale of 1 to 9, where 1 represents brown, dormant or dead turf, and 9 represents the best quality (Skogley and Sawyer, 1992). A rating of 5 was considered the minimum acceptable turf quality for a homeowner. For turfgrass quality assessment, all experimental treatments were replicated four times with respect to turfgrass quality, in a completely randomized design.

Data Collection

Data were obtained from 20 July through 14 December of 2004 and from 25 March through 31 August of 2005. Turfgrass quality ratings were carried out by the same person in July, October and December of 2004, and in April, May and July of 2005. Weather data were collected every fifteen minutes by an automated weather station (Campbell Scientific, Logan, UT), located beside the experimental site. Statistical data analyses were performed using the general linear model (GLM) procedure of the Statistical Analysis System software (SAS, 2000). Analysis of Variance was used to determine treatment differences for a completely randomized design and Duncan's Multiple Range Test was used to identify mean differences.

Results and Discussion

Environmental Conditions

In general, favorable conditions prevailed for the growth and development of the bermudagrass during the experiment. However, in December of 2004 the average air temperature began to gradually decline and, on 15 December of 2004, the bermudagrass went dormant. The irrigation treatments were discontinued until the bermudagrass greened up again, on 24 March of 2005.

Both 2004 and 2005 were rainy years (Figures 1 and 2), with high frequency rainfall and a large amount of cumulative precipitation, which is not uncommon in this region. During the experiment, the average frequency of rainfall events, as percent of rainy days, was similar to historical records (Unied States Department of Commerce [USDC], 2007) for the same periods (31% vs. 34% during 2004, and 38% vs. 37% in 2005). The cumulative rainfall during 2004, however, was 73% higher than a normal year (944 mm vs. 546 mm). This difference was mainly caused by a tropical storm and two hurricanes that hit the research area during late-August and September; accounting for 530 mm, or 56% of total rainfall. Most of the rain fell during August and September (793 mm), and the least rain fell in October and November (116 mm). During 2005, it rained 732 mm, which was very close to a normal year (711 mm), and with frequencies very close to historic rainfall in all months except in April (above) and June (below).

SMS Performance

To analyze the performance of the SMSs, it was important to detect when actual irrigation cycles occurred and how were they related to $\boldsymbol{\theta}$. To determine actual $\boldsymbol{\theta}$, ECH_2O probes were installed in every plot. These sensors were previously calibrated (Figure 3) and a site-specific calibration curve was developed (y = 0.6991x - 0.0174). The degree of linear association (R^2=0.70) was considered adequate, and was used to determine $\boldsymbol{\theta}$ on the different plots.

Figure 4 shows the $\boldsymbol{\theta}$ and daily rainfall in 2004 for the treatment that received no irrigation (NI), so every single increment in $\boldsymbol{\theta}$ was due to a rainfall event. Differences between the dry and wet periods were reflected in $\boldsymbol{\theta}$ as well. It can be seen that most of the time wet conditions prevailed; except for a dry period between 21 October to 24 November, when the two small rain events occurred (1.5 and 2.5 mm, respectively).

Figures 5 and 6 show the $\boldsymbol{\theta}$, during 2004, in plots that contained the SMSs treatments. These figures are shown as examples of when the SMS-based treatments allowed or bypassed scheduled irrigation events and what the level of $\boldsymbol{\theta}$ was at that time. It can be seen that, in general, the SMS-based treatments followed the dryer and wetter periods, controlling the number of irrigation cycles on the different treatments. More scheduled irrigation cycles were allowed during the dryer periods of late July-early August and late October-mid November. However, most of the controllers were not found to be precision instruments, which was evidenced when sometimes the different SMS systems bypassed irrigation cycles and sometimes they did not, even when reading the same or a lower $\boldsymbol{\theta}$. Moreover, according to the range of $\boldsymbol{\theta}$ over which the different SMS brands allowed irrigation AC and RB had a narrowest range (3.9 and 2.5 percentile points, respectively) suggesting that they were more accurate and consistent to measure $\boldsymbol{\theta}$ than IM and WW (that had a range of 5.5 and 4.5 percentile points, respectively). Finally, the IM controllers were set at position #1, which corresponds to a tension of 10 kPa (i.e. field capacity) according to the manufacturer. However, according to the example of Figure 6, it looks that these sensors were reading a dryer soil condition, allowing irrigation cycles when actually not necessary.

Irrigation Events

As complimentary information to Figures 5 and 6, the proportion of the scheduled irrigation cycles that were allowed by the different treatments, during the main research months of 2004, is shown in Table 2. The time-based treatment without rain sensor (WORS) was programmed to run independently of the weather and/or soils moisture conditions, so every (100%) irrigation cycle was allowed. Regarding the SMS-based treatments, on average, a lesser amount of irrigation events were allowed in August and September (25% and 13%, respectively) compared to October and November (39% and 42%, respectively). These tendencies were concordant with the dryer/rainier periods (Figures 1, and 4 through 6). Moreover, the average of the SMS-based treatments allowed 30% of the scheduled irrigation cycles to run. The IM allowed 67% of them during this period, whereas sensors from brands AC, RB, and WW, allowed just 26%, 14%, and 14% of the irrigation cycles, respectively. These results show that all SMS treatments worked under these conditions, but with variable results.

Irrigation Application

Table 3 shows the results of the irrigation depth applied during the whole experiment by the different treatments, statistical comparisons between them, and the percent of water savings that they achieved compared to the time-based treatments.

Time-based treatments

Table 3; Comparison A, shows that the three time-based treatments (WORS, WRS, and DWRS) were significantly different (P<0.0001) from each other during this study. Treatment WRS (with a rain sensor) was established to mimic a homeowner complying with irrigation regulations and setting the timer according to recommended practices. This treatment accounted for 995 mm of water, or an equivalent of 98 mm/month. A recent study, carried out by Haley et al. (2007) in Central Florida, found that homeowners with automatic irrigation systems applied 149 mm/month on average. Therefore, the comparisons made here may be considered conservative and differences in the results for actual homeowners could be larger.

The well-managed or water conservative homeowner profile, imitated by treatment DWRS (with a rain sensor, and 60% of WRS), applied 63% of the water applied by WRS, close to the target of 60%. The total depth was 623 mm, or an equivalent of 61 mm/month. Haley et al. (2007) found within this homeowner profile (also programmed to replace 60% of historical ET) an irrigation water use of 105 mm/month.

The treatment simulating an irrigation system with an absent or non-functional rain sensor (WORS) accounted for 1514 mm, or 148 mm/month. Thus, this treatment applied 52% more water than the treatment with a functional rain sensor (WRS), whereas WRS saved 34% of the water applied by WORS. These results demonstrate the importance of a functional and well-maintained rain shut-off device on all automated irrigation systems in Florida; where rainy weather is common (Figures 1 and 2). Moreover, as the study prepared by Whitcomb (2005) recently found, just 25% of the surveyed homeowners in Florida with automatic irrigation systems reported having a rain sensor, and the author speculated that they are often incorrectly installed. Therefore, appropriately installed and properly working rain sensors could signify not only substantial water savings to homeowners, but could also lead to sound environmental and economic benefits to the state. Moreover, Cardenas-Lailhacar and Dukes (2007) found that rain sensors, under the climate conditions of this study, have a payback period of less than a year when set at thresholds of 13 mm or less.

Time-based treatments vs. SMS-based treatments

Table 3 (Comparison B) shows that there was a significant ($P<0.0001$) difference between the averages of time-based and SMS-based treatments; with 1044 and 420 mm of cumulative irrigation depth, respectively. Thus, the SMS-based treatments, on average, significantly reduced the amount of irrigation water applied compared to the time-based treatments, even when an operative rain sensor was an important component on two of the three time-based treatments. In addition, 68% of the water applied by WORS was saved, on average, by the SMS-based treatments.

Water savings

Table 3 shows the water savings (%) of each treatment compared to the time-based treatments DWRS, WRS, and WORS. As expected, WORS applied more water than all the other treatments. On the other hand, IM allowed more water to be applied compared to the other brands and to the other time-based treatments. This could be due to their reported limitations to timely sense differences in soil water content, their hysteretic behavior, the high variability of readings, and their limitations in sandy soils, where low tension values are necessary to prevent plant stress (Irmak and Haman 2001; Taber et al., 2002: Intrigliolo and Castel, 2004; McCann et al., 1992).

When compared to the water conservative DWRS treatment, brands AC, RB and WW showed water savings of 44%, 70% and 57%, respectively. On the other hand, IM applied 77% more irrigation than DWRS.

Treatment IM was the only SMS-based treatment that applied more water than the time-based WRS (11%), and far from the water savings achieved by the other SMS-based treatments: AC recorded irrigation water savings of 65%, RB 81%, and WW 73%. It is important to remark that these water savings were on top of those already achieved by WRS. Therefore, these results show that, in general, SMSs can also act as rain shut-off devices, although with a superior performance in terms of water savings. When the irrigation treatments were compared to more than 75% of the surveyed homeowners in Florida (Whitcomb, 2005), this is with a non-functional or absent rain sensor (WORS), the difference in water savings increased: 77%, 88% and 82% for AC, RB, and WW, respectively. Even IM (which applied 11% more water than WRS) showed water savings (27%) with respect to WORS, indicating that this sensor was operative but did not bypass as many scheduled irrigation cycles as other SMS-based treatments.

This experiment was carried out as a closed control loop irrigation system, where the decision whether to initiate an irrigation cycle was regulated by a SMS. These results clearly demonstrate that the use of SMSs (along with traditional timers in residential irrigation systems, scheduled to run two day a week) could lead to water savings more than twice as much as a rain sensor device alone, even when the time schedule is programmed to provide 60% of historical irrigation requirements. However, a recent study suggests that, during wet or frequent rainfall weather conditions, to schedule high frequency irrigation cycles (i.e. everyday) appears to be a better strategy regarding water conservation in turfgrass irrigation, than to schedule them for one or two days a week (Cardenas-Lailhacar et al., 2008).

Turfgrass Quality

Differences in turfgrass quality, including non-irrigated plots, were not detected among treatments, and always exceeded the minimum acceptable rating of 5. This could be explained in part by the generally wet weather conditions that prevailed through most of the experiment, which favored the growth and development of the bermudagrass (Figures 1 and 2). Another factor contributing to the general good turf quality observed, even during the short "dry" periods, could be found in the species itself. Common bermudagrass is known as a more drought-tolerant grass compared to the pervasive St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze] found in North-Central Florida landscapes (Harivandi et al., 2001; Baldwin et al., 2006; Turgeon, 2005). As a result, the treatment effects were buffered with respect to the turfgrass quality parameters, and it could be concluded that no irrigation was necessary to maintain an acceptable turf quality during the experiment time-period.

Conclusions

High frequency rainfall events, which were close to a normal year, occurred during the time frame of the experiment. Rainfall was 73% higher than a normal year in 2004, and normal in 2005. Most of the SMS-based treatments automatically canceled the majority of the irrigation cycles during the rainy periods, and responded to dry periods by allowing irrigations to occur.

The three time-based treatments (WORS, WRS, and DWRS) were significantly different from each other during the study period. The treatment with a functional rain sensor (WRS), set at 6 mm, applied significantly less water (34%) than the without-rain-sensor (WORS) treatment, showing the importance of a well-maintained rain shut-off device in all automated irrigation systems in Florida. On the other hand, treatment DWRS, applied close to the desired 60% of the water applied by WRS. These time-based treatments were established to mimic the operation of irrigation systems carried out by different homeowner profiles. However, according to the results of this research, these treatments were fairly well managed compared to homeowners' actual operation practices in the Central Florida Ridge. Therefore, results in water use from this experiment can be considered conservative and differences for actual homeowners could be even larger.

It was concluded that irrigation was not necessary to maintain an acceptable turf quality during the experimental period, which was evidenced by acceptable quality in non-irrigated plots, due to the propitious environmental conditions that favored the growth and development of the bermudagrass.

Results showed that, on average, the SMS-based treatments were significantly more efficient as a means to save water than the time-based treatments. However, not all SMS-treatments tested performed the same. The IM treatment was the only SMS-based treatment that applied more water than WRS (11%), whereas the other brands (AC, RB, and WW) resulted in irrigation water savings compared to WRS (65%, 81%, and 73%, respectively). These results showed that most SMSs can also act as rain sensors, but with superior performance in terms of water savings. When these last brands were compared to WORS, the differences in water savings increased to 77%, 88%, and 82%, for AC, RB, and WW, respectively. Even IM showed 27% in water savings compared to WORS over the 308-day study period.

It should be noted that specific performance of the individual sensors largely depends on the threshold setting, the sensor burial depth, and individual probe installation. Even when sensor burial depths and installation were as similar as practically possible in this experiment, the sensor thresholds might have varied slightly, hence affecting the results to some extent. In spite of this, and even when not yet precision instruments, soil moisture sensor systems appear to be a promising technology that could lead to a complete automation of residential irrigation systems, to attain important water savings, and to achieve sound environmental and economic benefits to the state if implemented. Testing this technology under real household conditions is recommended to validate these results.

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Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the University of Florida and does not imply approval of a product or exclusion of others that may be suitable.

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Table 1. Irrigation treatment codes and descriptions.

Treatment Codes	Soil Moisture Sensor Brand or Treatment Description
Time-based	
WORS	Without rain sensor
WRS	With rain sensor
DWRS	Deficit with rain sensor, 60% of WRS
SMS-based [a]	
AC	Acclima
RB	Rain Bird
IM	Irrometer
WW	Water Watcher
NI	No irrigation

[a]SMS = Soil moisture sensor

Table 2. Scheduled irrigation cycles allowed by treatment (2004).

Treatment	Allowed per Month (%)				Total Allowed
	Aug	Sep	Oct	Nov	(%)
WORS	100	100	100	100	100
AC	22	13	22	33	26
RB	33	0	0	22	14
IM	33	38	100	100	67
WW	11	0	33	11	14
SMS-based (Avg.) [a]	25	13	39	42	30

[a]SMS = Soil moisture sensor;   Avg.= Average

Table 3. Total cumulative irrigation depth applied to treatments, statistical comparisons, and percent water savings compared to time-based treatments DWRS, WRS, and WORS. Data based on Cardenas-Lailhacar et al. (2008)

Treatment	Cumulative depth (mm)	Comparisons[a]		Water savings (%) vs.		
		A	B	2-DWRS	2-WRS	2-WORS
Time-Based						
2-WORS	1514	***a***[b]		-143	-52	0
2-WRS	995	***b***		-60	0	34
2-DWRS	623	***c***		0	37	59
Time-Avg	**1044**		a			
SMS-Based						
2-AC	348			44	65	77
2-RB	188			70	81	88
2-IM	1105			-77	-11	27
2-WW	270			57	73	82
SMS-Avg[c]	**478**		b	23	52	68

[a]A = Between time-based treatments
B = Time-based treatments vs. SMS-based treatments
[b]Different letters within a column indicate statistical difference at P<0.0001 (Duncan's Multiple Range Test)
[c]SMS =Soil moisture sensor; Avg = Average

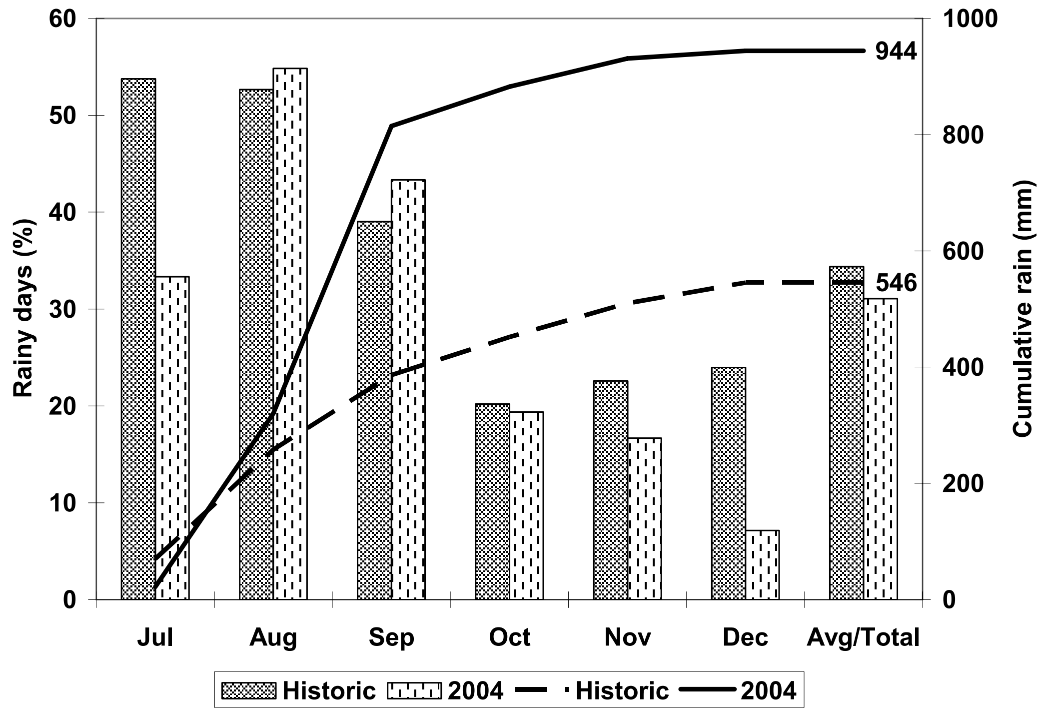

Figure 1. Percent of rainy days per month and cumulative rainfall in 2004 (21 July through 14 December 2004). Historic data based on USDC (2007).

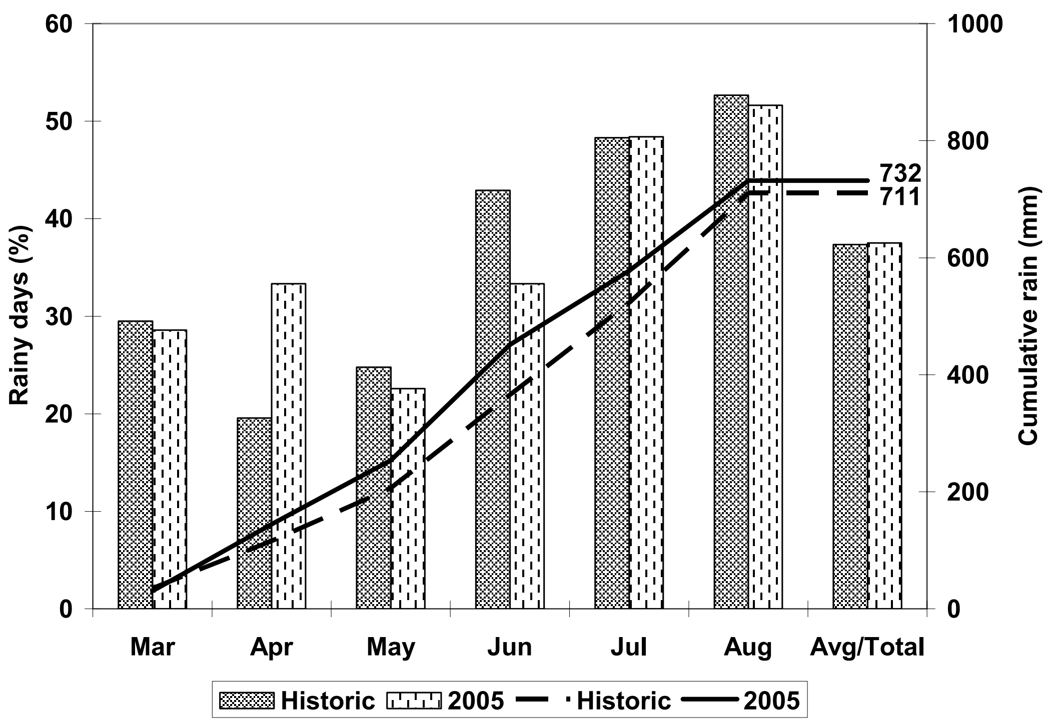

Figure 2. Percent of rainy days per month and cumulative rainfall in 2005 (25 March through 31 August 2005). Historic data based on USDC (2007).

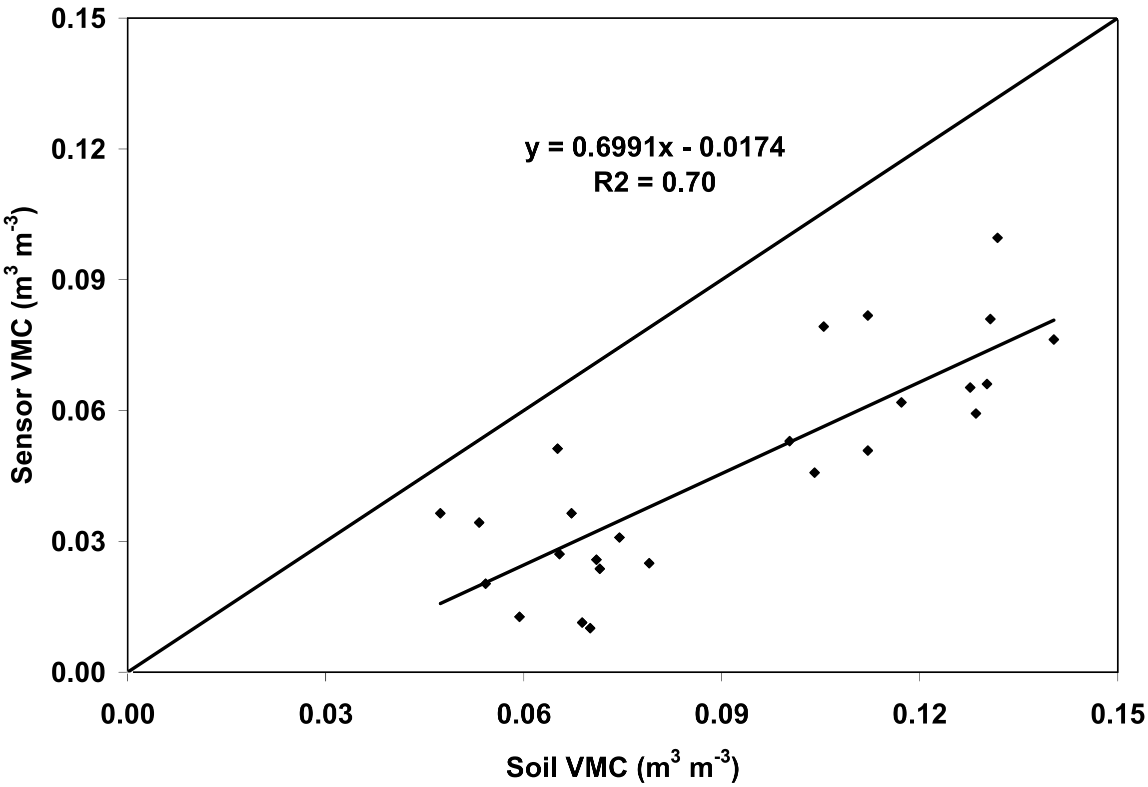

Figure 3. ECH_2O calibration results for an Arredondo fine sand; linear regression (VMC= volumetric moisture content).

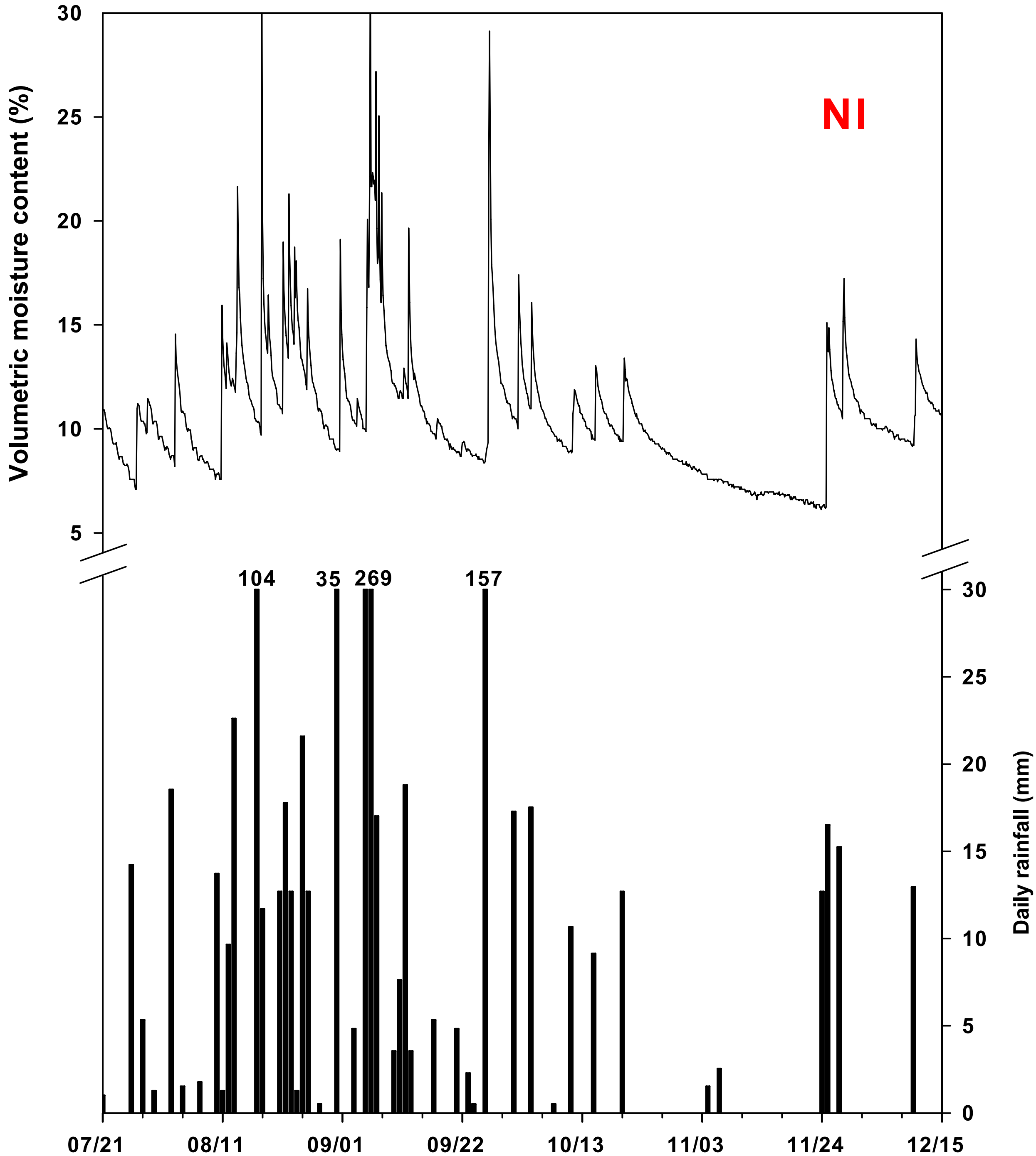

Figure 4. Relationship between soil volumetric moisture content on the non-irrigated treatment and daily rainfall through the experimental period of 2004.

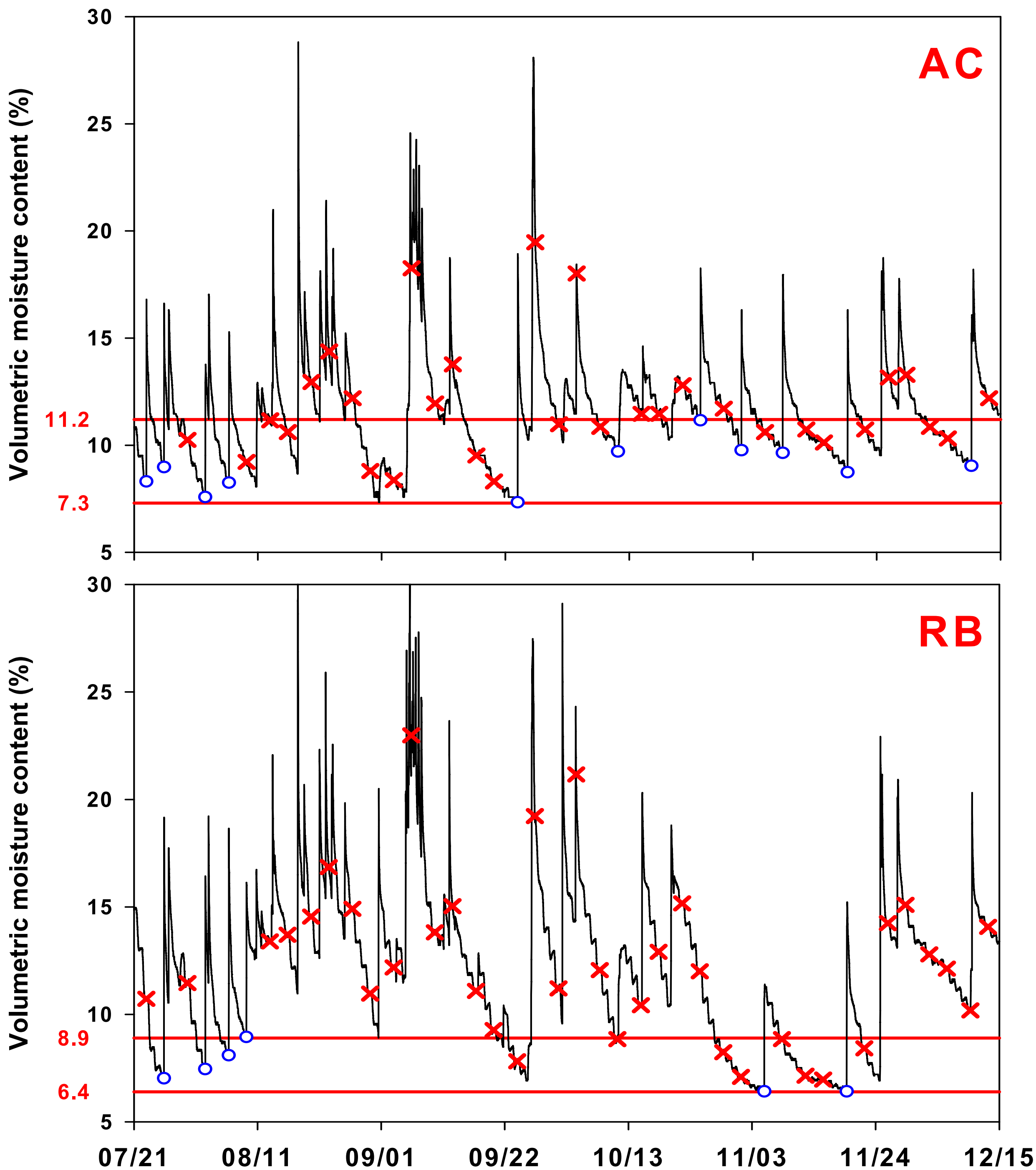

Figure 5. Volumetric moisture content (θ) through the experimental period of 2004, showing results of the scheduled irrigation cycles (SIC), where a red "x" represents a bypassed SIC, a blue circle represents an allowed SIC, and the red lines represent the range of θ when the SIC were allowed; treatments Acclima (AC) and Rain Bird (RB). When an increment in the θ does not have a blue circle on the bottom of the curve, it means that a rainfall event occurred.

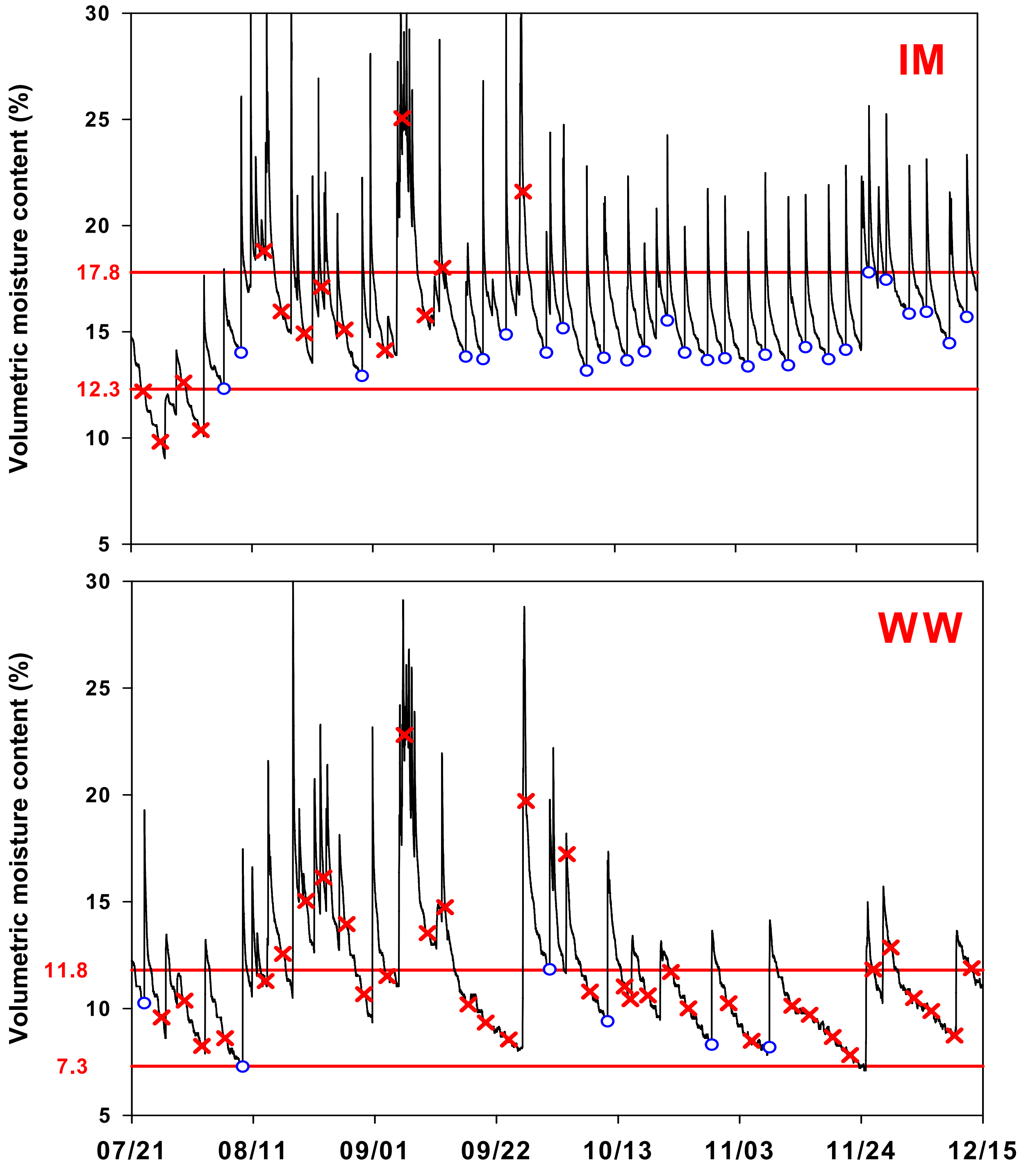

Figure 6. Volumetric moisture content (θ) through the experimental period of 2004, showing results of the scheduled irrigation cycles (SIC), where a red "x" represents a bypassed SIC, a blue circle represents an allowed SIC, and the red lines represent the range of θ when the SIC were allowed; treatments Irrometer (IM) and Water Watcher (WW). When an increment in the θ does not have a blue circle on the bottom of the curve, it means that a rainfall event occurred.

EVALUATION OF EVAPOTRANSPIRATION-BASED AND SOIL-MOISTURE-BASED IRRIGATION CONTROL IN TURF

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ABSTRACT

A study was initiated in Fall of 2006 to compare two types of commercially available irrigation control technologies, one based on estimates of evapotranspiration (ET) and the other based on feedback from soil moisture sensors. Water applied and turf quality from one ET-based system and two sensor-based systems were compared to a standard time-based irrigation schedule. Irrigation frequency was also a component of the study. Estimates of turf ET were obtained from the Penman-Monteith equation using on-site weather data, and also from an atmometer. On average the “add-on” soil-moisture-based system applied the least amount of water while the ET-based treatment applied the most water. Once-a-week irrigation frequencies used the least amount of water and daily frequencies the most when averaged across all technologies. In general, minimally acceptable turf quality was maintained by all technologies and frequencies, although during the last month of the study some treatments became noticeably stressed. The “on-demand” sensor-based system resulted in the best combination of water efficiency and turf quality.

INTRODUCTION

Turfgrass is a major part of the urban and sub-urban landscape in the state of North Carolina, with acreage equal to 44% of the state’s harvested crop acreage (NCDA 2001). North Carolina residences using irrigation systems increased 29.4% between 1994 and 1999 (NCDA, 2001). With drought a recurring problem, several municipalities in North Carolina have imposed water-use restrictions on turf and landscape irrigation.

Variability and irregularity in rainfall make irrigation scheduling difficult in North Carolina and an efficient irrigation schedule (applying the right amount of water at the right time) is essential in meeting the dual goals of water conservation and acceptable turf quality. Under-irrigation and over-irrigation can negatively affect turfgrass quality (Cardenas-Lailhacar et al., 2005) and over-irrigation results in waste of water and leaching of nutrients. With increasing competition for water resources, controllers that use feedback technologies show promise for improved water management.

So-called “smart” irrigation technologies can be separated into two categories - those that use a feedback sensor to monitor the amount of moisture in the root zone, and those that use weather data and a soil-water budget to adjust irrigations.

Controller clock systems are an essential part of automated turf irrigation systems. There are two types of controller systems; open loop systems and closed loop systems. In the open loop system, the operator decides on the amount of water that will be applied and when the irrigation will occur. This information is programmed into the controller and water is applied accordingly. Open loop systems normally have a clock to start irrigation. In a closed loop system, the operator develops a general control strategy using feedback from various sensors. The controller uses sensor data to make detailed decisions of when to apply water and how much to apply (Zazueta et al., 2002; Boman et al. 2002).

The simplest form of closed loop irrigation system is an irrigation system that is controlled by a soil moisture sensor. The sensor is wired in series with the electrical solenoid valve. The sensor acts as a switch opening the circuit between the controller and the valve when the water content is high preventing any pre-programmed irrigation and closing the circuit when watering is needed.

Another type of system used in turfgrass irrigation control is based on controllers that use weather information to estimate ET and adjust irrigation using a soil-water budget. An ET controller can make adjustments to the watering schedule based on weather conditions without requiring human interaction. ET controllers receive information from local or on-site weather stations and adjust watering durations to match ET.

The objective of the research presented in this paper is to compare two general types of commercially available irrigation control technologies; one based on estimates of evapotranspiration (ET) and the other based on feedback from soil moisture sensors. Water use and turf quality from these technologies were compared to results from a standard time based irrigation schedule. The study also incorporates the effect of irrigation frequency.

MATERIALS AND METHODS

This study was initiated in Fall 2007 at the North Carolina State University Lake Wheeler Turf Field Laboratory, Raleigh, North Carolina. The soil is a Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludults), having a field capacity of approximately 32% by volume.

The experiment site was established to `Confederate' tall fescue (Festuca arundinacea Schreb) using sod. Forty 13ft x 13ft plots were irrigated independently by four quarter circle pop-up spray head sprinklers (Toro 570 12' series with 23º trajectory) with a discharge rate of 0.5gpm at 30 psi. Prior to sodding, the field site was leveled and the irrigation system installed. The irrigation system uses water from a nearby irrigation pond that is filtered with a 60 mesh filter and pressure regulated at 30 psi. Water meters (5/8 in x 3/4 in, 20 gpm max flow, 5 gallons per pulse, AMCO Water Metering Systems Inc. Ocala, Florida) measure flow to four plots each, and flow to each plot is controlled by a separate solenoid valve.

A transformer (Model no: 9070TF100, 100Va 24volts, Square D) was installed to power 4 zones since the irrigation controller clocks do not have sufficient power to activate them simultaneously. An anemometer was connected to the datalogger to log wind data and also to interrupt the power supply if wind exceeded 10 mph during irrigation. This ensured that water did not drift to adjacent plots. A weather station (Watchdog 700, Spectrum Technologies, Plainfield, Illinois) was installed at the site to record weather data and estimate reference evapotranspiration by the Penman-Montieth method. A separate tipping bucket rain gauge was logged by the CR10X logger, and a recording atmometer with a #30 canvas cover to simulate grass reference ET (ET0) was installed on site.

Experimental Design and Monitoring

Two factors, control technology and irrigation frequency, were examined in this study. The irrigation control treatments included a standard time-based controller programmed with historical ET data, an ET controller system and two soil moisture sensor feedback systems.

Two soil moisture sensor based systems, the Acclima Digital TDT RS-500 and CS-3500 (Acclima Inc., Meridian, Idaho) were selected for evaluation of soil moisture sensor based systems. The RS-500 soil-moisture feedback system is designed as an "add-on" system to be added to any standard irrigation clock. A single soil-water content setpoint is used to prevent irrigation when the soil-water content is above the setpoint. The CS-3500 system is an "on-demand" system that uses two soil-water content setpoints, one to initiate irrigation and one to terminate irrigation. An Intellisense TIS-240 series (Toro Inc) controller was chosen as the ET-based system. Rain sensors (Irritrol Systems Inc., Riverside, Calif.) were added to the Intellisense controller and the standard time based controller. All treatments, except the on-demand system, were set to water daily, twice a week, or once a week.

There were ten treatments combining control type and watering frequency (3 technologies x 3 frequencies + 1 on-demand technology), with four replicates of each arranged in a randomized complete block design (figure 1). All the plots in the second block (rep) were individually monitored for soil-water content by Acclima digital TDT sensors. These sensors were wired to the Acclima CS3500 system to record soil moisture every 10 minutes. Monitoring sensors where placed 12 inches from control sensors for those plots using sensor feedback. The ten water meters were logged by a Campbell Scientific CR10X and a pulse count multiplexer (Campbell Scientific Inc., Logan, Utah). Irrigations were scheduled such that only one of the four plots served by each water meter was irrigated at one time.

All controllers except the ET controller were programmed to start between 0030 and 0600 hrs, to reduce potential wind drift and decrease evaporation. The ET controller was allowed to irrigate only after the other treatments were irrigated (after 0600 hr) so that flow through the water meters could be traced to the ET controller as irrigation durations of the ET controller constantly changed.

Turf quality was rated weekly using the standard turf quality index. This index is based upon a 1-9 scale with 9 representing the best possible turf quality. Turf quality was assessed once a week in the morning to minimize confounding of temperature-induced stress. Canopy temperatures were taken once a week late in the afternoon in sunny conditions to maximize temperature differences between treatments. Twenty weeks of water use data were collected while fifteen weeks of turf quality and canopy temperature were recorded.

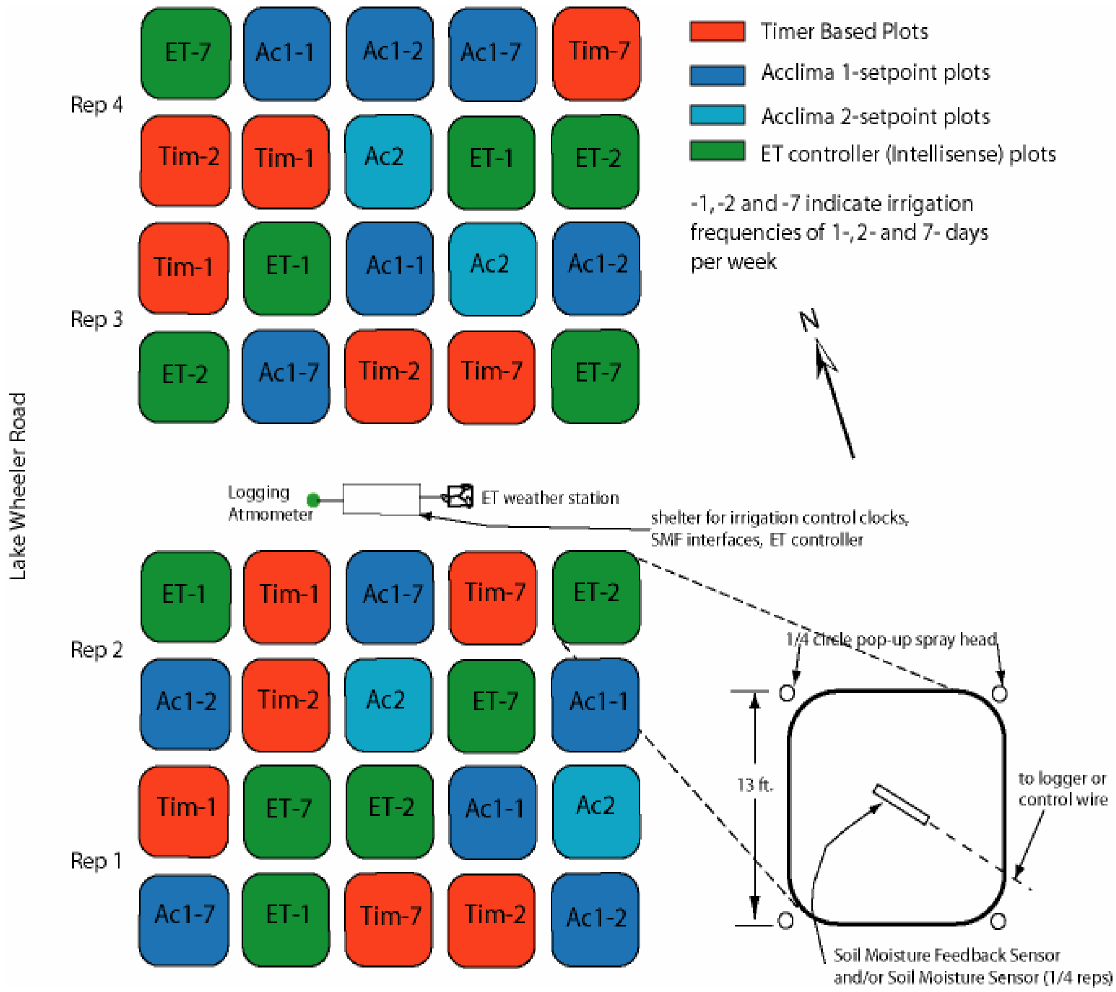

Figure 1. Site schematic showing plot layout and irrigation treatments

Standard timer-based irrigation

These treatments represent an average homeowner system set to apply water at a fixed interval (1, 2, 7x per week) and duration to replace the historical irrigation requirement (adjusted monthly) of a cool season turf. A rain switch was set with a different threshold for each frequency treatment (1x – 0.75 in, 2x – 0.50 in and 7x – 0.25 in). Monthly long-term gross irrigation requirements based upon local 30 year climate averages are given in table 1.

Soil moisture-based add-on system (one setpoint)

Soil-moisture feedback sensors were placed in block 2 plots of each irrigation frequency and connected to the Acclima RS500 modules. These modules were connected to a Toro controller with three independent programs similar to the time based controller. The controller was set to apply the same amount of water as the standard time-based system. The RS500 system has a Time Domain Transmissivity (TDT) moisture sensor that measures the volumetric moisture percentage of the soil and prevents irrigation above a user-supplied moisture content. The volumetric soil-water setpoint used in this study was 24%, equivalent to 75% of field capacity per manufacturer directions.

Table 1 Monthly long-term reference ET, turf ET, precipitation, effective precipitation, net irrigation requirement, and gross irrigation requirement (inches)

Month	ETo	ETc[1]	Precipitation	Eff. Ppt.[2]	NIR[3]	GIR[4]
April	5.91	4.72	2.59	1.56	3.17	3.96
May	6.94	5.56	3.92	2.32	3.23	4.04
June	6.67	5.34	3.68	2.08	3.26	4.08
July	7.43	5.95	4.01	2.46	3.49	4.36
August	6.87	5.50	4.02	2.36	3.14	3.92
September	5.54	4.43	3.19	1.74	2.69	3.36

[1] $ETc = ET_0$ x crop coefficient (k_c). A k_c of 0.8 was used for cool season turf
[2] Effective precipitation calculated using the SCS-TR21 method
[3] Net irrigation requirement (NIR)= ET_c-Eff. Ppt.
[4] Gross irrigation requirement (GIR) = NIR/0.8. (Field determined CU = 80%).

Soil moisture based on-demand system (two setpoints)

The Acclima CS3500 soil moisture feedback controller system uses the same sensor as the RS500 system; however it is designed as a “water on demand” system. The upper and lower setpoints were set at 30% and 21% volumetric moisture, respectively, with the lower setpoint (turn-on) corresponding to a depletion of 67% of plant-available soil water, and the upper setpoint (turn off) being just below field capacity. Cycle and soak times of 10 minutes were programmed to allow for water infiltration and movement to the sensor.

Evapotranspiration based system

The ET-based controller (Toro Intellisense TIS 240) was evaluated at the same irrigation frequencies as the timer-based and RS500 systems. The plots irrigated by the ET controller system received irrigation amounts based upon reference ET estimates downloaded daily from the WeatherTRAK "ET Everywhere" service (Hydropoint Data Systems, Petaluma, Calif.) and a soil-water budget. The local zip code was input to the controller for identification of local weather stations. User inputs that affect the soil-water budget include root depth, soil type, crop coefficients, and sun exposure. In this study the rooting depth was set at 6 inches, the soil type set for sandy loam, and the factory-supplied cool-season turf crop coefficients were used. The system evaluated does not use local rainfall data in the soil-water budget but rather puts the system into a rain pause in the event of regional rainfall. A rain sensor set at a threshold of 0.50 in. was added to the controller to account for site rainfall.

Data Analysis

Weekly water use data for all plots were compiled from water meter data. The data were analyzed using a "mixed" effects statistical model (SAS Proc Mixed, Cary, North Carolina) with technology type, irrigation frequency and their interaction as fixed effects, and block (rep), week, and week x technology x frequency interaction as random effects. Mean values for weekly water use, turf quality, and canopy temperature was separated using least-squared means. All tests were conducted at an α=0.05 significance level.

RESULTS AND DISCUSSION

The study period in 2007 was warmer and drier than normal. Total rainfall during the 20 week study period was 11.4 inches, with over three inches falling in one event. Turf water demand was estimated to be 20.9 inches using the Penman-Monteith ET_0 estimates generated from the Watchdog weather station and using a crop coefficient of 0.8 to convert to turf water demand. Water demand estimated from atmometer data was 19.11 inches using the same crop coefficient. Pump failures occurred during the course of the study preventing scheduled irrigations for a total of six days. This impacted the once a week irrigation frequencies more severely, as the next available irrigation was delayed for seven days. While the pressure regulators were set for 30 psi, cycles of de-pressurization and re-pressurization during pump failures or filter cleaning altered the pressure settings. In general blocks three and four were pressurized slightly higher for these instances and received greater irrigation amounts until the regulators were manually reset.

Standard time based irrigation system

Cumulative net irrigation for the three frequencies were; once a week – 16.88 inches twice a week – 16.92 inches and daily – 15.62 inches. The values for the cumulative irrigation are nearly the same for the three frequencies as they were programmed to apply the same irrigation amounts weekly and only differed in the setting of rain sensor threshholds. The daily treatment skipped irrigation on 28 occasions (22 due to the rain sensor override and 6 due to pump failures).

Acclima add-on system (one setpoint)

The Acclima add-on system used less water than the timer based system. This was due to the volumetric soil water content being above the setpoint on several occasions when irrigation was scheduled. The cumulative gross irrigation amounts were, once a week – 8.56 inches twice a week – 12.81 inches and daily – 13.87 inches. Figure 2 shows rainfall, irrigation and the soil-water content for the system set to irrigate daily. The lower amount of applied water for the daily irrigation is mainly because of a higher proportion of skipped irrigation opportunities. The daily irrigation treatment skipped 34 potential irrigations.

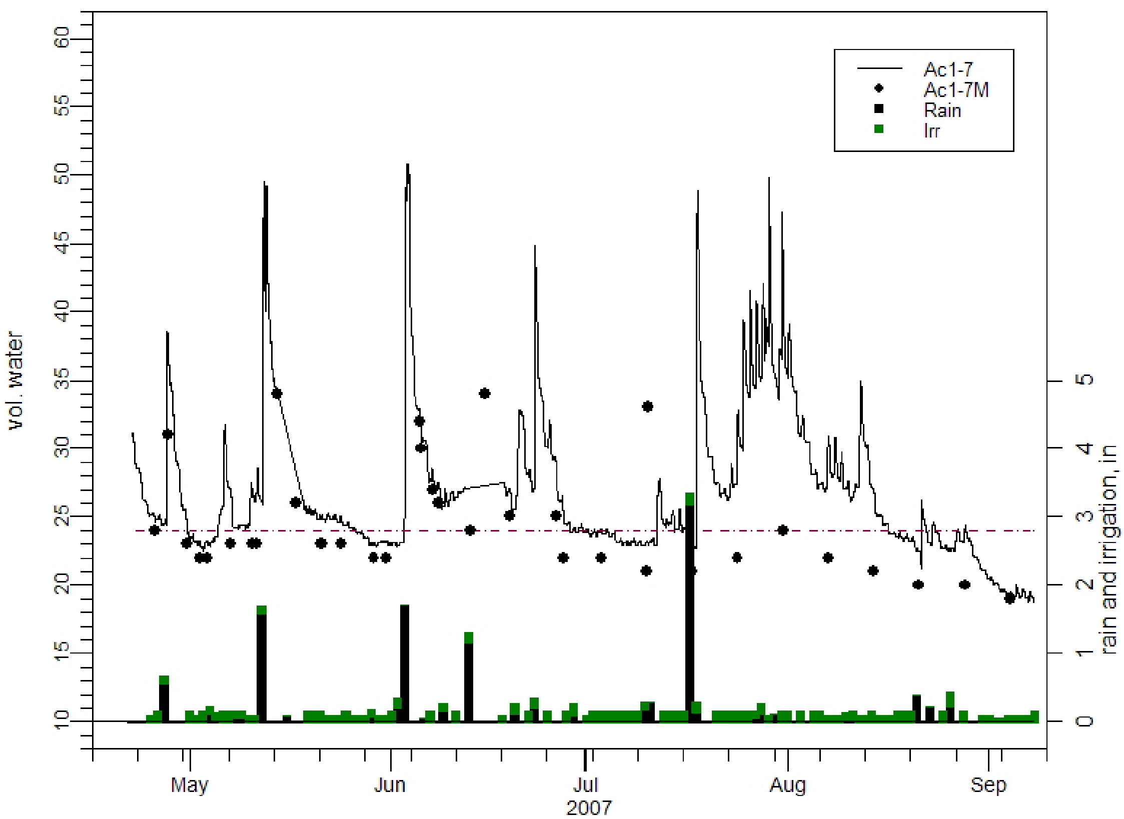

Figure 2. Soil-water content, rain, and irrigation for the Acclima add-on system set to irrigate daily. The horizontal dashed line represents the setpoint above which irrigations were disabled. Dots represent soil-water measured by the control sensor. This sensor was placed 12 inches from the monitoring sensor.

Acclima on-demand system (two set-point)

The cumulative gross irrigation over the twenty week period was 17.64 inches. The Acclima CS3500 system failed twice during the experimental study once on the 14th of May and again on the 12th of June. No soil-water data was collected by the monitoring (continuous) sensors for all the treatments from 14-18 May and 12-18 June. No irrigation occurred for the on-demand treatment during these periods. Figure 3 shows soil-water content, irrigation and rainfall during the study period.

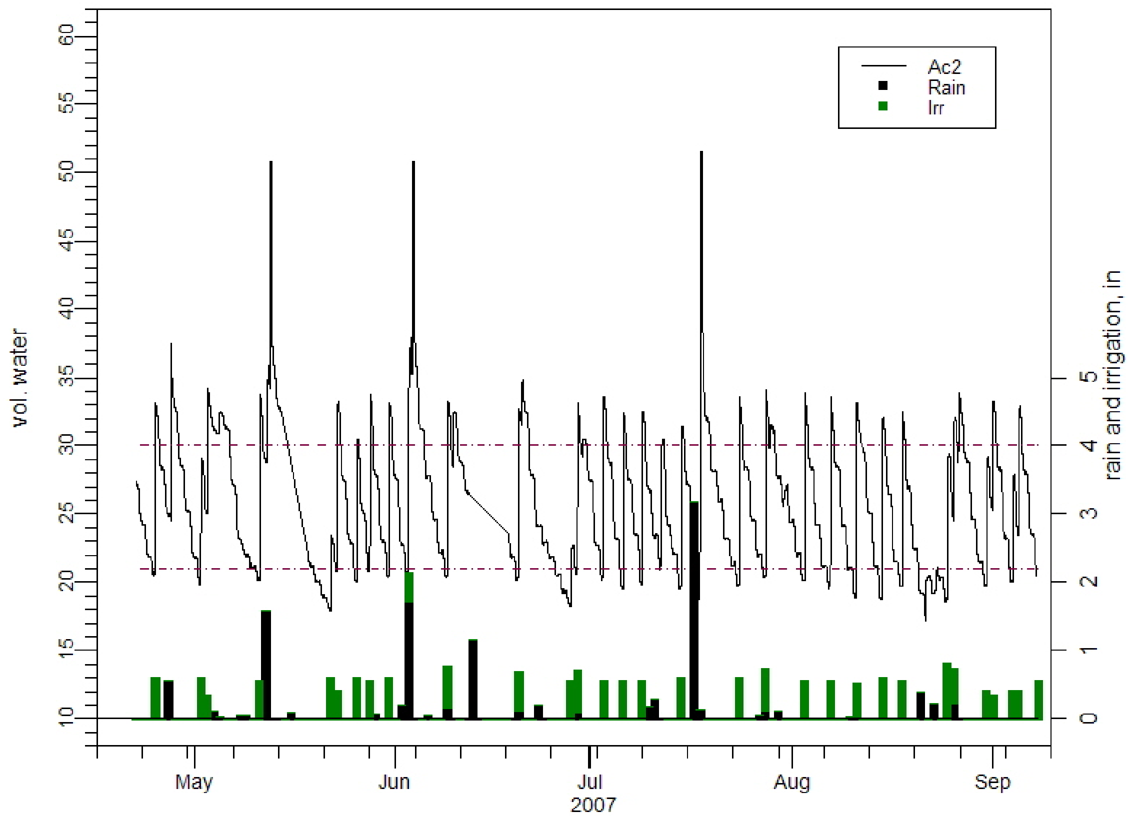

Figure 3. Soil-water content, rain, and irrigation for the Acclima on-demand system set to allow irrigation daily. The horizontal dashed lines represents the upper and lower setpoints

ET controller system

The cumulative gross irrigation amounts over the twenty week study period were once a week –16.27 inches, twice a week – 24.54 inches and daily – 25.66 inches. These amounts were substantially higher than most of the other treatments. The high values for the twice a week and daily frequencies may have been because the system did not account for the local rainfall events that occurred. It also appeared that the reference ET estimates of the system were high. The once a week gross irrigation amount was not as high as the twice a week or daily amounts because the controller limited the application to the amount that could be stored in the 6 inch root zone. The cumulative irrigation application for all treatments and frequencies are given in table 2.

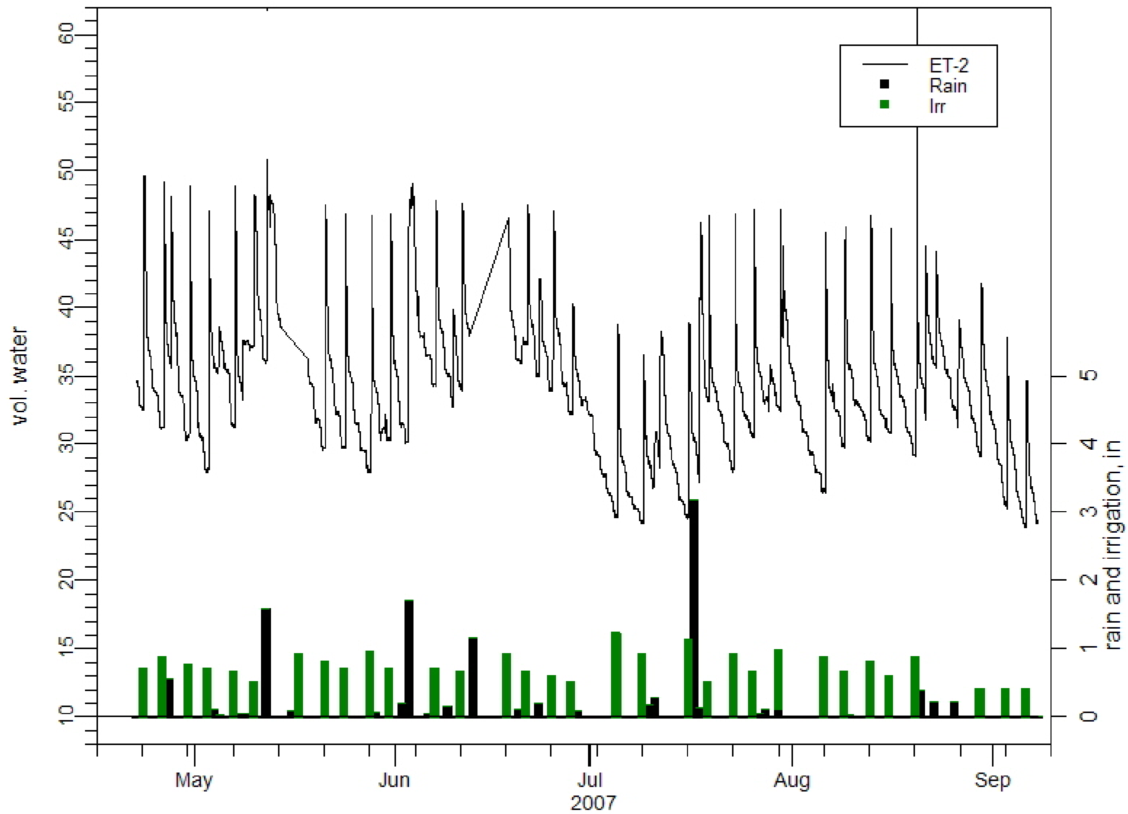

Figure 4. Soil-water content, rain, and irrigation for the Intellisense TIS 240 controller set to irrigate twice a week.

Table 2. Cumulative gross irrigation depth (inches) applied between 22nd April and 8th September 2007

Technology	frequency		
	once a week	twice a week	Daily
Timer[1]	16.88	16.92	15.62
AC1[2]	8.56	12.81	13.87
ET[3]	16.27	24.54	25.66
On demand system			
Ac2[4]	17.64		

[1] Standard timer-based treatment
[2]Acclima add-on system (one setpoint)
[3]Toro TIS-240 Intellisense controller
[4]Acclima on-demand system (two setpoint)

Weekly water application

Analysis of variance revealed that the technology effect, frequency effect and their interaction were all significant. The lsmeans estimates for weekly total applied water are given in table 3.

Comparison between technologies: The means of the technologies were different when compared across frequencies. The Acclima add-on system applied the least water while the ET system applied the most water.

Table 3 Least-squared mean estimates for average weekly total applied water, inches[1]

		Frequency			
		once a week	twice a week	Daily	Average of Frequencies
Technology	Ac2	**on demand system**			0.85b
	Ac1	0.44a	0.68b	0.72bc	0.62a
	ET	0.79cd	1.24e	1.37e	1.13c
	Tim	0.94d	0.90d	0.83cd	0.89b
	Average of Technologies	0.72a	0.94b	0.97b	-

[1]Numbers with the same letters in the last row represent no significant difference in frequencies across all technologies; numbers with the same letters in the far right column indicate no statistically significant difference between technologies across all frequencies; and numbers in the body of the table with the same letters indicate no statistically significant difference between technology x frequency combinations.

Comparison between frequencies: Similar analysis of different frequencies across technologies showed that the once a week treatments were significantly different from both the twice a week and daily frequency treatments. On average the once a week schedules used the least amount of water followed by twice a week frequency and then the daily treatment.

Technology by Frequency Comparisons: The Acclima add-on system (Ac1) at a once a week frequency applied the least amount of water, followed by the twice a week and daily Ac1 treatments. The once a week ET treatment, was not statistically different than the Ac1 daily treatment or any of the timer-based treatments. The ET controller at twice a week and daily frequencies applied the most water.

Canopy Temperature

The statistical model was similar to that used for water use. There were significant differences in canopy temperature between treatments. ET treatments had the lowest temperatures and the Ac1 treatments had the highest temperatures. The temperatures were inversely correlated to applied water. There were no differences in average canopy temperatures between frequencies across technologies.

Turf Quality

The means of the turf quality ratings were not statistically different for most of the treatments and frequencies and the minimum acceptable turf quality (4-6) was met by all the plots. Though the plots had healthy turf for most of the experimental period, quality declined in some of the treatments in the last month of the study when the daily ET values were high and no appreciable rainfall occurred. In addition there were six days when irrigation did not occur due to pump failures. Some plots suffered from the effects of substantial soil cuts that occurred when the two terraces were built and leveled. This seemed to affect both fertility and soil physical properties (infiltration rate and water holding capacity). The plots that looked the worst also had the highest canopy temperatures. Since the statistical model include block (rep) as a random effect, the effect of the cuts and fills on turf quality were blocked as the cuts and fills tended to be associated with certain blocks.

Table 4 Least-squared mean estimates for turf quality[1]

	frequency				
		once a week	Twice a week	Daily	Average of Frequencies
Technology	Ac2	**on demand system**			8.97a
	Ac1	8.37b	8.45b	7.83c	8.22d
	ET	8.33b	8.5b	8.87a	8.57b
	Tim	7.9c	8.58b	8.96a	8.36c
	Average of Technologies	8.22b	8.52a	8.43a	-

[1]Numbers with the same letters in the last row represent no significant difference in frequencies across all technologies; numbers with the same letters in the far right column indicate no statistically significant difference between technologies across all frequencies; and numbers in the body of the table with the same letters indicate no statistically significant difference between technology x frequency combinations.

CONCLUSIONS

- The Acclima water on demand system was the most effective system applying less than the ET controller while maintaining excellent turf quality. This system is expensive but maybe ideal for commercial landscaping applications.
- The Acclima add-on systems can reduce water use, but if the timer is not programmed to apply enough water, turf quality can suffer as it operates on prohibiting irrigation rather than initiating irrigation. These systems may be more effectively used by setting the controller to daily apply an amount equal to a management allowable depletion, e.g. 25% of field capacity with a setpoint of 75% of field capacity, and letting the system override scheduled irrigation events until that condition is met. In this study, the daily frequency was set to apply a maximum of only 0.15 inches or 8% of field capacity to satisfy a long-term daily irrigation requirement. Since the season was warmer and drier than normal, the system “fell behind”.

- The Toro Intellisense controller followed trends in weather, but applied more water than required. The use of more representative weather stations or adjustment of the controller would be beneficial for water conservation. Quality of turf irrigated by this system was excellent.
- "Smart" irrigation technologies hold promise for efficient irrigation by conserving water while maintaining acceptable turf quality.

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Calibration and Evaluation of an Improved Low-Cost Soil Moisture Sensor

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Abstract
Irrigation scheduling in agriculture and turf requires a soil moisture sensor (SMS) that is accurate, reliable, and low-cost. Although there are many SMS on the market, their use is limited because they fall short in one of these areas. A need exists for a sensor that offers high quality measurements yet is inexpensive enough to appeal to all in commercial irrigation. The objectives of this study were to determine how a new, low cost SMS performed in a variety of soils with varying water contents and electrical conductivities (EC) and study its durability in the field. The SMS showed no differences in calibration between the sand, silt loam, and clay soils that were tested, even over a wide range of EC. Field tests also showed good reliability over a season of measurements. Results indicate that the new SMS would be a useful tool to measure soil moisture and schedule irrigation.

Introduction
Fresh water is a finite resource that requires vigilant management to ensure it is available for generations to come. One of the largest anthropomorphic sinks of fresh water is irrigation, whether in commercial fields, golf courses, or residential lawns and gardens. The key to conserving water is in decision-making based on plant water needs and soil water availability. Although significant progress has been made to estimate water loss from plants, the use of soil moisture measurements as an irrigation tool has lagged behind. There remains a need for a soil moisture sensor (SMS) that will combine good accuracy and stability with low price to allow it to be used as much as it is needed.

Soil moisture sensing technology has been available to the irrigation market for many years. However, its adoption into common usage has been very slow, possibly because of the poor measurement associated with some sensors and the high price of others. To be viable, a SMS must be accurate and reliable and also be affordable to the end user. The goal of this study was to develop and test a low cost SMS and to evaluate its viability for use in the irrigation market.

Background
Over the years, numerous techniques have been used to monitor soil moisture *in situ*. Early methods often employed electrical resistance or low-frequency capacitance to infer water content. Although these techniques were correlated with water content, they were also affected by soil salinity and texture. It is probably the unreliability of these types of sensors that has led to a general mistrust of soil sensors by the irrigation market as a whole.

Sensors which measure the dielectric constant of bulk soil and use that measurement to infer the volumetric water content (VWC) of the soil are becoming increasingly popular. Improved understanding of the working theory together with improvements, over time, in electronics has combined to produce a large number of sensor designs in the market place with excellent capability at an ever decreasing cost. The availability of high-quality, low-cost sensors has resulted in an enormous increase in new sensor applications from geospatial monitoring in research to improved irrigation management in farming and turf operations.

Two general classes of dielectric sensor are available. One class measures the time taken for an electrical impulse to traverse a transmission line of fixed length in the soil. The other measures some component of the impedance of a capacitor in which the soil is the dielectric. Sensors of the first type are called time domain (time domain reflectometer, or TDR; time domain transmissometer, or TDT). Members of the second class are sometimes referred to as frequency domain sensors since they typically operate at a fixed frequency, but more often are referred to as capacitance sensors.

The belief is sometimes expressed that time domain sensors are inherently better or more accurate than frequency domain sensors. Several reasons may exist for this belief. Typically, time domain sensors are much more expensive than capacitance sensors, implying accuracy through cost. Also, capacitance sensors have been tried for over a century while time domain methods have come into use within the past 30 years. Early capacitance sensors had many limitations, and even though those have been overcome by modern electronics and better understanding of the theory, the method may still have a bad name from experiences with early versions.

Whatever the reason for the perception that a difference exists between the performance of the two sensor types, that perception is aided and abetted by purveyors of time domain sensors wanting to promote their own products. These claims form a good basis for discussion of the relative merits of frequency domain and time domain sensors.

Accuracy

Dielectric sensors do not sense water content; they sense the bulk dielectric permittivity of the soil. Two elements are therefore involved in determining accuracy: the accuracy with which the sensor is able to determine bulk dielectric constant and the accuracy of the relationship between bulk dielectric constant and soil water content. Considering the latter first, we can analyze accuracy using a typical dielectric mixing model:

$$\varepsilon_b^{1/2} = x_a \varepsilon_a^{1/2} + x_m \varepsilon_m^{1/2} + x_w \varepsilon_w^{1/2} \qquad (1)$$

where ε is the relative dielectric permittivity, x is the volume fraction, and the subscripts *b, a, m,* and *w* refer to bulk, air, mineral and water. The permittivity of air as 1. The permittivity of soil minerals can range from 3 to 16, but a value of 4 is often used. We can substitute for x_a the expression $1 - x_w - x_m$, and for x_m the ratio of bulk to particle density of the soil, ρ_b/ρ_s, to get an equation relating water content to measured permittivity:

$$x_w = \frac{\varepsilon_b^{1/2} - 1 - (\varepsilon_m^{1/2} - 1)\rho_b / \rho_s}{\varepsilon_w^{1/2} - 1} \qquad (2)$$

This equation can be used to determine the sensitivity of predicted water content to uncertainties in the various parameters that determine water content. Calculations can be done for any set of parameters. For purposes of illustration the nominal values in Table 1 were chosen. For those values, Table 1 gives the sensitivities.

Table 1. Nominal values and sensitivity analysis for Eq. 2.

Quantity	symbol	nominal value	sensitivity[1]
bulk permittivity	ε_b	10	-5
water permittivity	ε_w	80	8.5
mineral permittivity	ε_m	4	16.2
bulk density	ρ_b	1.3	16.2
particle density	ρ_s	2.65	-16.4

[1]sensitivity is the percent change in the indicated quantity that produces a 1% change in predicted volumetric water content

Effects of bulk density on accuracy

Bulk density of soils varies widely. In typical mineral soils used for agriculture the bulk density can vary from 0.8 to 1.8 g cm^{-3}, roughly an 80% change. If one considers organic soils or soils in geotechnical applications the range is much wider. Considering just the range of mineral agricultural soils, eq. 2 predicts a change in water content of 0.05 m^3m^{-3} in going from 0.8 to 1.8 g cm^{-3}. If there is no independent measurement of density (as is the case with dielectric moisture sensors), then the limits of accuracy for mineral, agricultural soils, considering only uncertainty in density, is ±2.5% in water content. Considering organic and compacted soils the error is much larger. Clearly a claim that any dielectric sensor has absolute accuracy, independent of soil type, of 1% is overstatement. Table 1 indicates that the sensitivities to uncertainty in mineral permittivity and particle density are nearly the same as for bulk density adding to the overall uncertainty from variation in solid soil properties.

Effects of dielectric permittivity of water on accuracy

The dielectric permittivity of free water is around 80 at room temperature. It decreases with increasing temperature at about 0.5%/C. An error of 8.5% in water permittivity results in a 1% error in predicted moisture content at 20% volumetric water content. At this water content a ±20C temperature change only results in a ±1.2% change in predicted water content, which for most purposes is negligible. The effect is larger at higher water content, but many sensors measure temperature, so an appropriate correction can often be applied making this effect negligible.

"Bound water" effects on water permittivity

"Bound water" can also have an effect on TDR and TDT sensors. The dielectric permittivity of free water is relatively constant with frequency below the relaxation frequency of 15 GHz. Crystalline water, however, (such as in ice) has a high dielectric constant only below frequencies of a few kHz. The binding or structure of the water can therefore strongly affect its dielectric constant at a particular frequency. Water adsorbed on soil minerals and organic matter is not free. It has a wide range of binding energies, some strong enough to lower the relaxation frequency of the water below the frequency at which many TDR and TDT sensors operate (high MHz to low GHz range). The effect on accuracy of this bound water fraction is negligible in coarse textured soils with little organic matter, but can lead to substantial underestimation in high clay soils. Because capacitance sensors typically operate at lower frequencies they are not subject to these errors unless the soil water freezes. In frozen soil both types of sensor “see” only the unfrozen water.

Another effect arises because the relaxation frequency of bound water is temperature dependent giving rise to a higher than normal temperature dependence of bulk permittivity when it is measured by high frequency TDR and TDT sensors. Again, the lower frequency sensors are free of this effect.

Effects of bulk dielectric permittivity on accuracy

From Table 1, the accuracy in bulk permittivity required for 1% accuracy in water content determination is 5%. It changes with water content and ranges from around 3% for saturated soil to around 10% for dry soil. Time domain and capacitance sensors generally have no difficulty meeting this requirement, but there are pitfalls. The most serious of these have to do with the sensor’s ability to correctly sample the dielectric constant of the surrounding medium and the ability of the sensor to separate capacitive from conductive effects in soils which contain salt. The sampling problem will be addressed later. The salt problem can be understood by realizing that the soil can be modeled as a resistor in series with a capacitor. The resistance of the resistor is proportional to the bulk electrical conductivity of the soil. The capacitance of the capacitor is proportional to the bulk permittivity of the soil. If the electrical conductivity of the soil is negligibly small then a measurement of permittivity by either time domain or frequency domain methods is easy and accurate. As electrical conductivity increases the TDT and TDR wave forms which are analyzed to determine travel time become increasingly attenuated, especially at high frequencies. To some point algorithms can sort out the start and end of the wave, but finally no signal is discernable. One can shorten the wave guides and again obtain some signal, but the attenuation of high frequencies makes the inferred bulk permittivitity too large, and the effect must be compensated for correct water content measurement. These problems typically occur above 2 dS/m pore water EC. Since agricultural production can occur on soils with EC up to about 10 times this value, this can be a severe limitation.

Frequency domain methods may also be adversely affected by soil EC. Some sensors separate the signal into a real and an imaginary part. The real part is due to capacitance and the imaginary part to resistance. Increasing soil EC is not a problem for these sensors because they measure the two components separately. Most capacitance sensors, however, are not able to separate the two components, so the resistive part adds to the apparent capacitance which can result in substantial error. The impedance of a capacitor decreases with frequency, while the resistance (imaginary component) is not affected by frequency. Increasing frequency therefore decreases the relative effect of soil electrical conductivity compared to permittivity. Thus, the higher the frequency of a dielectric sensor, the higher the soil salinity can be without affecting the reading. In non-saline soils frequencies in the range 1-10 MHz are adequate for good permittivity measurements, but at higher salinity higher frequencies are necessary. With Decagon’s EC-10 and EC-20 sensors which operate at 6 MHz EC effects are negligible up to about 1 dS/m. The higher frequency sensors, which operate at 70 MHz show negligible salt effects up to about 10 dS/m. When the pore water EC exceeds these thresholds, sensors still show changes in output with water content, but the permittivity computed from the output is no longer the true soil permittivity. This apparent permittivity can be calibrated for the particular soil in question, but shows a stronger and positive temperature response because of the 2%/C temperature response of EC.

Sampling volume of time domain and frequency domain sensors

The greatest weakness of dielectric soil moisture sensors comes from their sampling volume. Both time domain and frequency domain sensors form an electrical field around the sensor with the field strongest near the sensor surface, and decreasing in strength with distance from the sensor. Increasing the permittivity of the surrounding medium collapses the field even more strongly around the sensor surface. Regions of high or low permittivity in the field of influence distort the shape of the field in a non-linear way making the measured permittivity differ from the average of the permittivities of the materials in the field. Any air gaps between the sensor and the medium it senses cause large errors in the measured permittivity. Measurements in liquids are made without difficulty, but soils are much more difficult.

The volume of influence of either sensor type is determined entirely by the shape and size of the wave guides for the time domain instrument or the shape and size of the capacitor plates for the capacitance sensor. These differ from one sensor design to another, but the volume of influence is not dependent on whether the sensor is time domain or frequency domain. When one seeks to model the sensor performance of either sensor in soil one uses the exact same simulation software for both.

Laboratory and Field Evaluation of Sensors

Five randomly selected commercial soil moisture sensors (EC-5, Decagon Devices, Inc., Pullman, WA) were selected for calibration and evaluation. Four mineral soils (dune sand, Patterson Sandy Loam, Palouse Silt Loam, and Houston Black Clay) were collected to represent a broad range in soil types (Table 2). Soils were crushed in a soil grinder to break up large peds and allow uniform packing. Additional steps were taken to provide a wide range of soil salinities. First, several solutions were made up with EC values from ~1 to >15 dS/m. Soils were then subdivided into smaller portions and solutions added to selected soils to create a range of soil electrical conductivities. The soils that had solutions added to them were oven dried, crushed, and a saturation extract was used to determine the actual soil EC (U.S.Salinity Laboratory Staff, 1954). During the testing, calibration, and characterization procedures (see below), these soils were wet with distilled water then oven dried to ensure that the salinity would remain relatively constant.

Table 2. Fractionation and native electrical conductivities of soils tested.

Soil	Sand	Silt	Clay	Native electrical conductivity
	-------------- kg kg^{-1}	---------------		dS m^{-1}
Dune Sand	0.87	0.03	0.03	0.04
Patterson Sandy Loam	0.79	0.09	0.12	0.34
Palouse Silt Loam	0.03	0.71	0.26	0.12
Houston Black Clay	0.13	0.34	0.53	0.53

Sensor Calibration in soil

Sensors were calibrated by adapting the technique recommended by Starr and Paltineanu (2002). A detailed description of the procedure is given by Cobos (2006). Briefly, an air dry soil was packed in a container around a sensor. Care was taken to pack the soil evenly so not to bias the measurements. After a reading was taken from the sensor, a volumetric water content (VWC) was obtained using a small cylinder, and the gravimetric water content determined using a drying oven and scale (Topp and Ferre, 2002). The next water content was then created by dumping the soil into a larger container, thoroughly mixing in a known volume of water, then again packing the soil around the sensor in the original container. This was repeated four or five times for each soil type and electrical conductivity to create a correlation between sensor output and VWC. The data were plotted to determine the effect of soil type and electrical conductivity on sensor output.

Statistical Analysis

To determine statistical significance, data from each calibration were considered to be unique. That is, each soil water content along with its measured electrical conductivity was taken to be one unique soil type combination. Soil type/EC combinations were compared using analysis of covariance with moisture content as the dependent variable and electrical conductivity as the independent variable. Analysis of covariance was conducted using PROC GLM (SAS Institute, 2006). Individual sensors were considered replicated observations and not treatment effects because sensors within soil type were not a significant source of variation (data not show). The estimate function of PROC GLM was used to compare the slopes of the individual calibration curves for each soil type/EC combination.

Sensor Characterization

The sensitivity of an accuracy estimate to confounding soil factors has already been discussed. However, there is still a need to characterize how the manufacturer supplied calibration equation compares to the actual volumetric water content under typical soil conditions. To test this, an EC-5 and a ThetaProbe (Model ML2, Delta-T Devices, Cambridge, UK) were randomly selected from a production lot and tested in sand, silt loam, clay, and potting soil. Results were compared to directly measured volumetric water content..

Field Evaluation

Three EC-5 sensors were installed in a commercial potato field at 15, 30, and 60 cm depths in a fine sandy loam soil. The field was under center pivot irrigation whose frequency varied depending on crop needs. A tipping bucket rain gauge (1 mm resolution) was situated above the buried sensors to record irrigation events and amounts. Sensors were monitored across an entire growing season to investigate their reliability, sensitivity to irrigation events, and long term stability.

Results and Discussion

Calibration of five standard EC-5 sensors in four soil types (Table 2) at several levels of electrical conductivity are shown in Fig 1. No significant sensor to sensor variation was observed between all the sensors tested (data not shown.). Statistical comparisons between the calibration slopes of individual soil type/electrical conductivity combinations show there no significant difference between 11 of the 12 calibration curves (Table 3). Interestingly, the slope that was significantly different was the Palouse soil at 0.7 dS/m saturation extract EC which was the middle electrical conductivity of these three Palouse soils tested. It does not seem likely that either soil type or electrical conductivity is driving these differences.

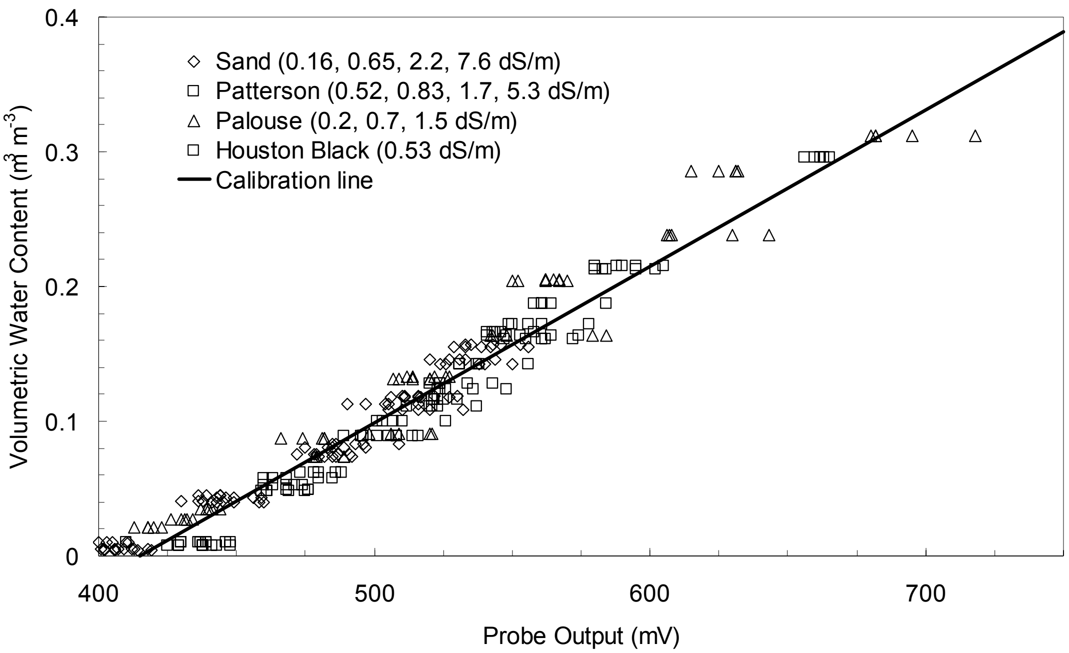

Figure 1. Calibration data for five water content sensors running at 70 MHz in four mineral soils over a range of electrical conductivities (shown in parenthesis).

Table 3. Slopes and statistical comparisons between individual soil type/electrical conductivity (EC) combinations.

Soil Type	Solution EC ($dS\ m^{-1}$)	Slope of Calibration Curve ($x\ 10^{-4}$)*
Sand	0.65	9.8a
Sand	7.6	9.9a
Patterson	5.3	10.3a
Palouse	1.5	10.3a
Sand	2.2	10.5ab
Patterson	0.52	11.9ab
Patterson	0.83	12.1ab
Palouse	0.2	12.5ab
Patterson	1.7	12.7ab
Houston Black	0.53	12.8ab
Palouse	0.7	13.4b

* Slopes followed by the same letter are not significantly different ($p < 0.01$)

The lack of significant differences between calibration curves at different salinities is not surprising considering findings on sensors running at similar measurement frequencies (Campbell, 1991). Similar tests of an earlier version of the sensor (EC-20, Decagon Devices, Inc.) showed considerable variation in the calibration depending on the soil type (Campbell, 2001). Data in Fig. 1 suggest that the sensor will not require calibration when used in mineral soils.

Figure 2 shows the same five EC-5 sensors calibrated in three types of potting soil. Again, the sensor output is correlated linearly with the gravimetrically-obtained volumetric water content with an R^2 value of 0.977. The data show that the same calibration equation can be used for any of the potting soils tested, regardless of potting soil mixture or electrical conductivity. The calibration for potting soil is different from mineral soils due to large difference in bulk density as noted above

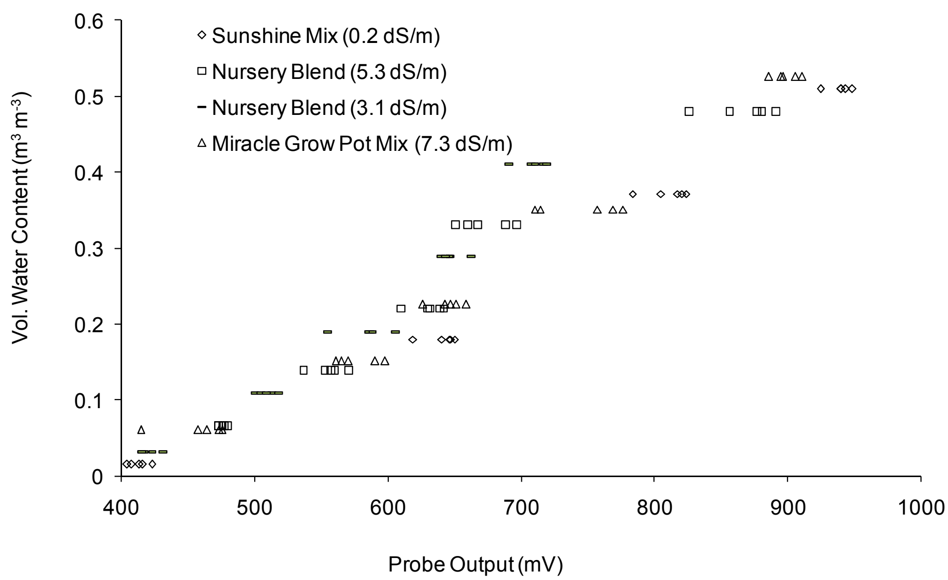

Figure 2. Calibration of five EC-5 sensors in various mixtures of potting soil. Saturation extract EC values are shown in parenthesis.

Testing on the EC-5 and ML2 showed very good agreement between actual VWC and those generated from the manufacturer calibration (Fig. 3). Standard deviations for both sensors on all soils tested were very good (0.0089 and 0.013 $m^3 m^{-3}$ for the EC-5 and ML2, respectively). These data suggest that accurate water content data should be obtainable from either sensor in the field. However, it is clear that a 1% VWC accuracy specification (as noted in some product specifications) is difficult to obtain even in laboratory conditions, let alone the field.

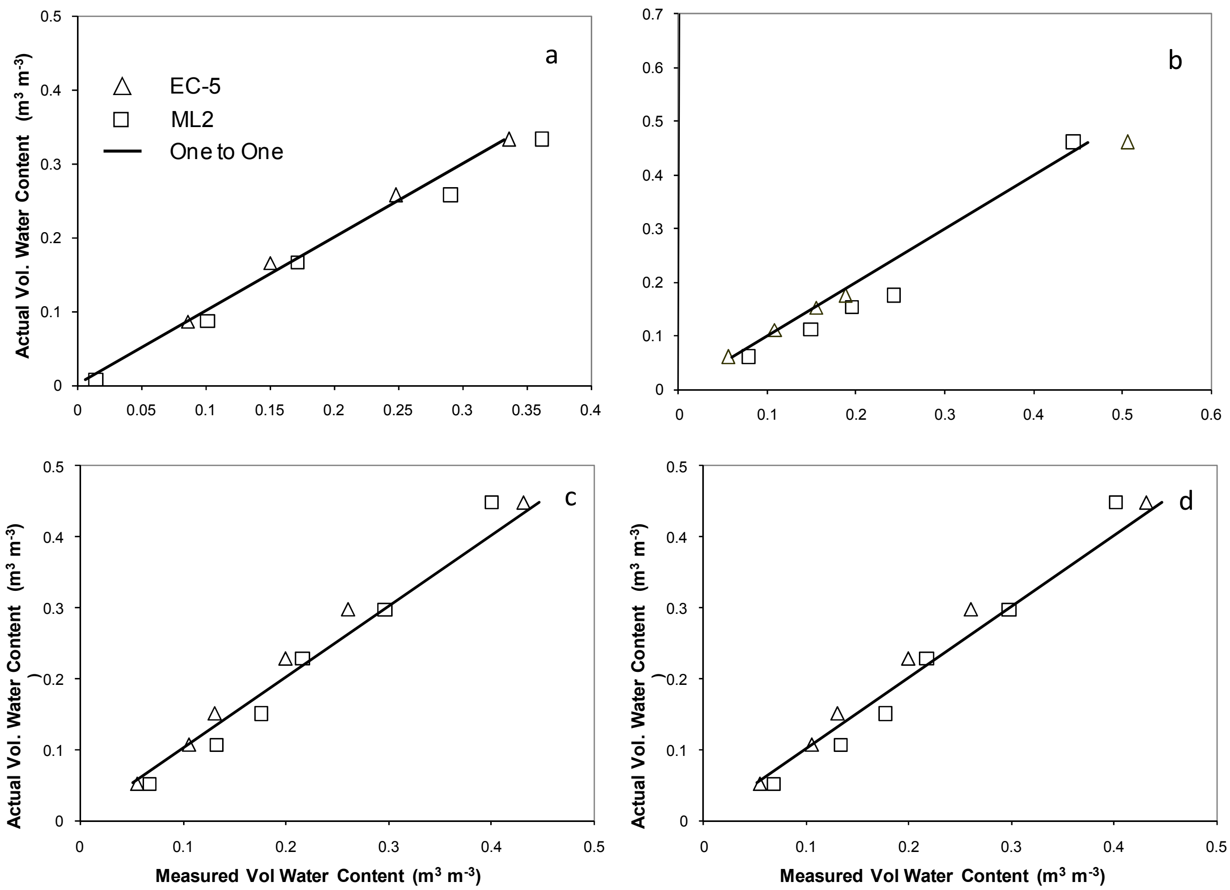

Figure 3. Comparison of actual VWC versus VWC calculated using the manufacturer's calibration for (a) sand, (b) clay, (c) silt loam, and (d) potting soil.

The sensors installed in the commercial potato field provided reliable, stable results for the entire growing season (Fig. 4). Figure 4 shows how the sensors responded to heavy irrigation during some parts of the season, as well as some dry-down events during critical stages in the crop maturation cycle. Changes in water use by depth can also be seen where water content at 15 cm is lower, initially, than at 30 cm when the crop is relatively young, but as it matures, roots begin to move deeper and irrigation becomes heavier, pushing water content at both depths to become similar. Water content at 60 cm remained much more constant for the entire season, suggesting roots were not taking as much water from that depth as well as not as much water was moving that low in the profile.

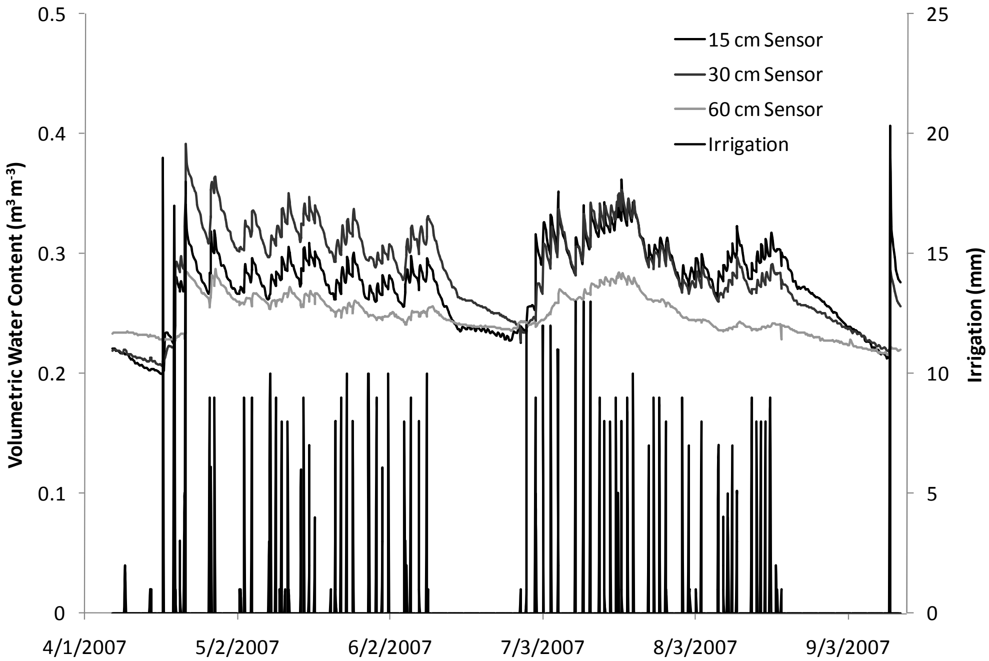

Figure 4. Soil moisture and irrigation data across a growing season in a center-pivot irrigated potato field.

Figure 5. shows a subset of water content and irrigation data from a dry-down and wet-up period. These data show the relative response of the water content sensors to each irrigation event. It is clear that irrigation produced an increase of water at every level in the profile, but the relative response lagged with the deeper sensors. On the 60 cm sensor, irrigation water caused the sensor to respond slightly, but the overall change is a general increase in water content instead of large water content spikes followed by draining as is seen in the shallower sensors.

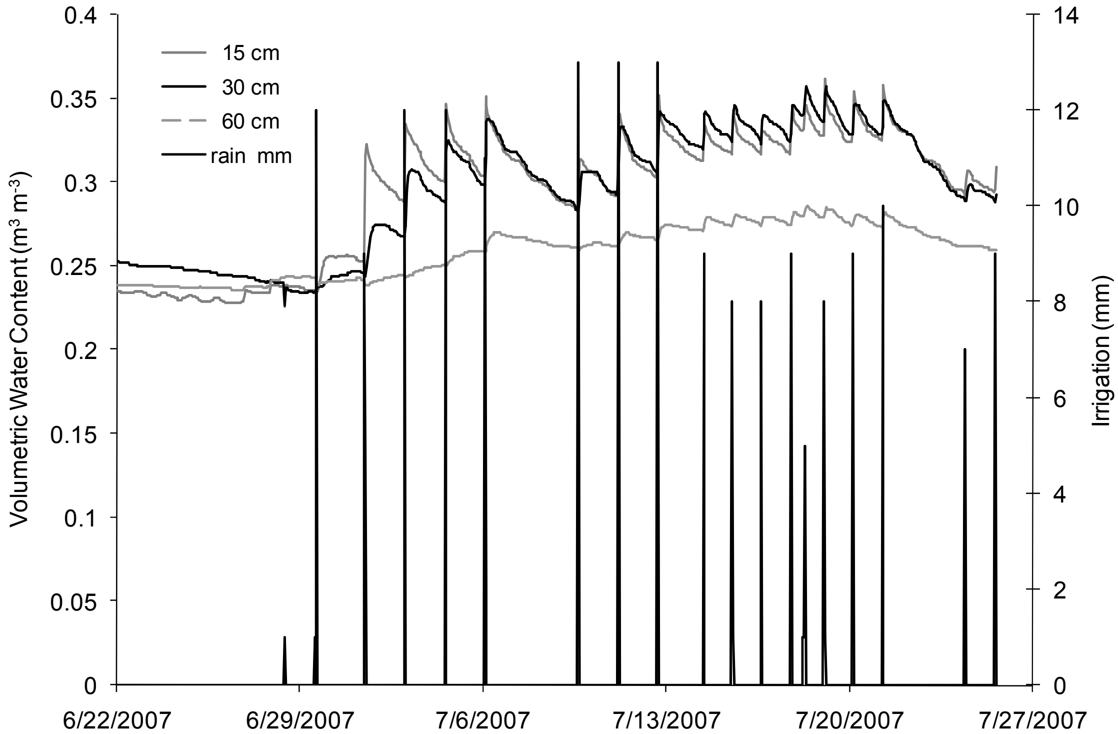

Figure 5. Subset of data for the irrigated potato field showing individual irrigation events along with SMS response.

Conclusion

SMS calibrations were not significantly affected by soil type or salinity in several mineral soils and potting soils tested. This finding suggests that relatively untrained users could install the sensors in intact soil and measure accurate soil VWC. This is a particularly important finding because most monitoring and control applications include sensor installation into soils of unknown texture. In addition, changing salinity conditions, either from soil or irrigation water, have little effect on sensor measurements. This is a very important quality considering the failure of past sensors in this area. Further, the manufacturer's calibration provided accurate water content measurements in all soils tested in the laboratory. Season-long irrigation and VWC measurements in a potato field showed the SMS were robust and responded as expected to irrigation events.

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Turfgrass Irrigation Requirements Simulation in Florida

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Abstract

A number of turfgrass (i.e. landscape) irrigation scheduling methods exist in Florida. Due to the variety of methods, there is often confusion as to which method balances water conservation with plant needs. As water supplies become more strained, irrigation management will become more important. In this paper the irrigation scheduling recommendations that are available were reviewed and irrigation water requirements were simulated for a 30 year period with a daily soil water balance to compare net irrigation requirement, drainage below the root zone, and the influence on effective rainfall. An optimized irrigation schedule was simulated based on refill of the soil profile when the soil water content reached allowable depletion. This schedule is representative of soil moisture sensor and ET controllers (Smart controllers) and reduced irrigation requirements 60% compared to a recommendation of 0.75 inches when turf wilts. Drainage was reduced accordingly. The optimum schedule should be verified in field studies and possibly used as a benchmark for Smart controller performance.

Introduction

Irrigation of urban landscapes is standard practice in new construction in many urbanizing areas of the U.S. In some locations this standard practice coupled with rapid growth in recent years has resulted in a strain on water supplies. In Florida, municipal groundwater accounts for 43% of total water use (Marella 2004) and more than half of this water is thought to be used for urban landscape irrigation. Many utilities estimate that half of all water supplied is used for irrigation; whereas, Haley et al. (2007) found that the fraction of total household supply used for irrigation can be as high as 74% under well-drained sandy soils that are common to many new housing development areas in Florida. Although agricultural water use exceeds municipal supply, agricultural water use has increased by 12.5 MGD from 1975 to 1995 while municipal demand has increased by 57.5 MGD over the same time period. This trend in water

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use will likely continue as more agricultural land is urbanized due to the influx of more than 1,000 people per day (USCB 2006). It has also been documented that residential irrigation results in a substantial amount of wasted water with homeowners in parts of the state applying two to three times plant water requirements (Haley et al. 2007). Competition between agricultural and municipal water users will likely become more acute in the future, thus there is a need to maximize irrigation efficiency.

Numerous landscape irrigation scheduling recommendations exist for Florida (Table 1). The variety of recommendations attempt to provide a compromise between recommendations that can easily be implemented statewide as opposed to accurate information to provide the correct amount of irrigation to meet plant water requirements. The resulting compromise is a simplification of a complex process that varies depending on soil type, plant type and distribution, weather patterns, and irrigation system design and installation. The simplest recommendations suggest watering 0.5" to 0.75" when turfgrass shows signs of stress (see Table 1 for references). Several publications utilize a soil water balance to give guidelines on the amount of turfgrass irrigation required on a monthly basis (Augustin 1983) and also time required on a typical irrigation time clock for two day per week irrigation frequencies (Dukes and Haman 2002) from the monthly soil water balance calculated by (Augustin 1983).

The simplistic recommendations ignore the fact that in-ground irrigation systems are installed with time clocks to facilitate the convenience of automatic irrigation. The disadvantage to time clock based irrigation schedules is that the time must be adjusted to account for plant water demand over the season and for different plant types across irrigation zones. This type of adjustment is not straightforward for the typical user. However, Dukes and Haman (2002) have attempted to provide a practical guide for residential irrigation scheduling considering irrigation equipment types with variable application rates

The objective of this paper is to compare the long term irrigation requirements of various recommended irrigation schedules using a daily soil water balance. This methodology assumes optimum irrigation resulting in no stress or only the onset of minimal stress prior to initiating irrigation.

Materials and Methods

A daily soil water balance was used to compare irrigation scheduling recommendations over a 30 year period of record. Inputs to the water balance were precipitation (P) and irrigation (I) while potential outputs consisted of crop evapotranspiration (ETc), drainage of water below the root zone (D), and surface runoff (RO). The general approach for the soil water balance determination was adapted from several references (e.g. Allen et al. 1998; Smajstrla 1990).

Soil hydraulic properties were used to set upper and lower boundaries for the determination of irrigation amount, drainage and effective rainfall. Soil physical properties were defined as follows:

$$AWHC = FC - FWP \qquad [1]$$

$$AW = AWHC * RZ \qquad [2]$$

$$PAW - AW * MAD \qquad [3]$$

where AWHC is available water holding capacity, FC is soil field capacity or an estimate of how much water can be held in a soil after gravity drainage ceases, PWP is permanent wilting point and these three quantities have units of volume of water per volume of soil (in^3/in^3). AW is available water and RZ is the depth of the root zone that extracts the bulk of the water for plant needs and both have depth units (inches). Finally, PAW is the plant available water determined by the product of AW and the maximum allowable depletion (MAD) which is a function of plant type, soil type, and climate and is a dimensionless number between 0 and 1 resulting in depth units for PAW. The MAD for turfgrass was assumed to be 0.5 based on data from St. Augustinegrass irrigation experiments in Florida where over 50% wilt was observed at a MAD level of approximately 0.5 (unpublished data).

The soil type used for the analysis was assumed to be a sandy soil common to much of Florida where most soils are classified as sands (Irmak and Irmak 2005). The representative soil chosen for the simulations was an Arredondo fine sand. The particular soil series is not as important as the soil physical properties, which were FC = 0.10 in^3/in^3 and PWP = 0.03 in^3/in^3 (Carlisle et al. 1989) which gives available water holding capacity (AWHC) = 0.07 in^3/in^3 or 0.84 in/ft of soil.

The root zone of turfgrass is highly variable and is a function of climate, soil, watering frequency, turfgrass variety. Boman et al. (2002) studied root length density on several turfgrass varieties including St. Augustinegrass, bermudagrass, and zoysiagrass and found that across all varieties 80% to 99% of the root length density was in the top 30 cm of soil. The authors found that 81% of warm season turfgrass roots were in the top 18 cm of soil. Our work in Florida on St. Augustinegrass has shown that the majority of roots were in the top 6 inches across a variety of irrigation treatments on plots established for one year (unpublished data). Since most of the research indicates that 70% to 80% of warm season turfgrass roots typically occur in the top 6 inches of soil, we used an 8 inch root zone to ensure that the simulations would represent a well established stand of warm season turfgrass.

Daily turfgrass water use, ETc was calculated as follows:

$$ETc = ETo * Kc \qquad [4]$$

where Kc is the crop coefficient and ETo is reference ET calculated by the ASCE-EWRI Standardized Method (Allen et al. 2005). The Kc values used here were recommended for warm season turfgrass by Jia et al. (2007) as measured by the eddy covariance method for bahiagrass in North Florida. The Kc values ranged from 0.35 in January to 0.90 in May (Fig. 1).

Daily irrigation and soil water content were calculated according to the following equations:

If,

$$SWC_t \leq AW - PAW \qquad [5]$$

Then,

$$I_t = AW - SWC_t$$

Else,

$$I_t = 0$$

If,

$$SWC_{t-1} + P_{t-1} + I_{t-1} - ETc_{t-1} < AW \qquad [6]$$

Then,

$$SWC_t = P_{t-1} + I_{t-1} - ETc_{t-1}$$

Else,

$$SWC_t = AW$$

where SWC is soil water content, P is precipitation, I is irrigation, and ETc is crop evapotranspiration. All variables have units of depth (inches) and subscripts i and i-1 indicate the current day and previous day, respectively. Equation 5 establishes the lower boundary (AW-PAW) for allowable water storage in the root zone, while Equation 6 establishes an upper boundary for the SWC (AW).

It is recognized that not all rainfall is stored in the root zone. It was assumed that all rainfall infiltrated the soil which is a reasonable assumption for well-irrigated sandy soils in Florida that have infiltration rates as high as 35 inches/hr on undisturbed sites and over 6 inches/hr on relatively compacted construction sites (Gregory et al. 2006). Equations 5-6, prevent irrigation from causing deep percolation (D); however, many rainfall events exceed the storage capacity of shallow rooted turfgrass resulting in drainage below the root zone. Effective rainfall (ER) was defined as rainfall stored in the root zone up to the AW limit. Any excess water from precipitation is assumed to runoff or result in drainage below the root zone and was calculated as the difference between the precipitation and effective rainfall. The following equations were used to calculate D and ER both with depth units:

If,

$$SWC_t + P_t + I_t - ETc_t > AW \qquad [7]$$

Then,

$$D_t = SWC_t + I_t + P_t - ETc_t - AW$$

Else,

$$D_t = 0$$

$$ER = P - D \qquad [8]$$

Finally, in the case that SWC or ER became negative due to the model calculations, these quantities were set to zero. For the optimum irrigation simulation (see OPT below), drainage only included that due to rainfall and not excess irrigation since there was no excess irrigation. For all other simulations, drainage included both excess rainfall and irrigation.

Weather data were gathered as part of the development of the Agricultural Field Scale Irrigation Requirements Simulation (AFSIRS) project (Smajstrla 1990) and were originally gathered from weather stations located throughout the state at the airports of major cities and are now available through NCDC (USDC 2007). Measured data included daily maximum and minimum temperature, maximum and minimum relative humidity, daily average wind speed at 10 m height, a cloudiness index (0 = clear and 10 = cloudy), and daily total precipitation. Daily average solar radiation values were estimated based on Hargreave's equation as presented by

(Allen et al. 1998). It is important that all data are screened, but in particular that solar radiation data are accurate since this is the most sensitive input for the calculation of ETo under humid conditions (Irmak et al. 2006) during the summer months. All other weather data were screened according to procedures outlined by (Allen et al. 1998).

Irrigation Schedule Simulations

Five irrigation schedules based around the various recommendations in Florida (Table 1) were simulated by the daily SWB as follows with codes indicated in brackets:

1. [OPT] Optimal scheduling to refill the root zone when SWC was at or below the lower limit established by the MAD. This simulation emulated perfect control that could be established by careful manual scheduling or by real time soil moisture sensor or ET control. This methodology simulates optimum irrigation resulting in minimal plant stress prior to initiating irrigation.
2. [FIX] Irrigation of 0.75" when SWC was at the lower limit established by the MAD to simulate simplified irrigation recommendations.
3. [FIX-RS] Simulation #2 plus a rain sensor that would bypass irrigation if rainfall of at least 0.25" occurred the same day.
4. [HIST] Time-based irrigation schedule based on net irrigation requirement as given by Augustin (1983) and adjusted by (Dukes and Haman 2002) to provide an irrigation time assuming 2 d/wk irrigation frequency, Kc = 1. The weekly schedule for North Florida is given in Table 2.
5. [HIST-RS] Simulation #4 plus a rain sensor that would bypass irrigation if rainfall of at least 0.25" occurred.

Simulated irrigation schedules did not consider irrigation efficiency, thus calculated irrigation amounts are net irrigation requirements and total irrigation delivery would need to consider application and other efficiency terms.

Results and Discussion

Weather Data

A 30 year record (1961-1990) of weather data for Jacksonville, Florida was available from the AFSIRS modeling effort as mentioned previously. Weather characteristics of the 30 year data set are presented in Table 3. During the quality control screening procedures, it was found that the average wind speed frequently exceeded the threshold for concern of 5 mi/hr (Allen et al. 1998) as seen in Fig. 2. Through detailed investigation of the site including photos of the station, it was determined that the wind velocity was measured at 10 m height. Wind velocity data were adjusted to 2 m accordingly by standard methods (Allen et al. 1998). In addition, it was found that maximum relative humidity was slightly depressed and minimum relative humidity was slightly higher than would be expected for humid Florida conditions (Fig. 3). Solar radiation appeared reasonable and did not exceed the Rso envelope as recommended by Allen et al. (1998) and shown in Fig. 4. Measured dew point temperature was found to diverge substantially from the daily minimum temperature (Fig. 5). In a humid climate, these two temperatures should match on most days. The divergence of these two temperatures indicates arid characteristics from the weather data collection site (Allen 1996). The weather data were collected at airports which have substantial non-vegetative fetch and are prone to the heat island effect as a result. The weather data impacted the resulting calculated ETo to a great degree with an average annual total of 62.1 inches which is relatively high considering annual average rainfall across the 30 years was 51.1 inches.

The Simplified Aridity Adjustment (SAA) was used to correct the dew point temperature to reflect weather data collection under well-watered conditions (Allen 1996). This adjustment reduces maximum and minimum daily temperature as well as the daily dewpoint temperature based on the difference between minimum daily temperature and dew point temperature. The resulting annual average ETo was 50.7 inches and approximated values for ETo as given by Smajstrla (1990).

Irrigation Simulations

Rainfall and ETc varied dramatically over the 30 year period. Rainfall ranged from 31.2 inches in 1991 to 70.6 in 1973. The mean rainfall and ETc for the 30 year period were 51.1 inches/yr and 33.9 inches/yr, respectively (Tables 3 and 4). Net irrigation required varied for the OPT, FIX, FIX-RS, and HIST-RS schedules which simulated varying irrigation in response to rainfall events (Fig. 6). The HIST schedule did not respond to rainfall since the schedule is fixed irrigation run times two days a week (Dukes and Haman 2002) and this schedule did not simulate a rain sensor. Thus, the HIST schedule applied 21.6 inches of irrigation every year in the 30 year simulation. Adding a rain sensor with a ¼ inch threshold to both the FIX and HIST irrigation schedules did reduce average net irrigation requirements by 10.5% and 16.7%, respectively (Table 4). This savings is substantially lower than the savings reported by field research studies ranging from 17% to 34% for ⅛ to ½ inch thresholds compared to homeowner irrigation schedules similar to HIST (Cardenas-Lailhacar and Dukes In press; Cardenas-Lailhacar et al. In press). The addition of a rain sensor did not result in more savings due to the limited storage capacity of the root zone (0.56 inches completely dry) as a result of limited root depth and coarse textured soil. Also, in previous studies the 2005 year used for comparison had very frequent rainfall which could have differed from the "average" year represented in these simulations.

Generally, irrigation is required in North Florida in the spring months beginning in March and until the rainy season starts in June (Fig. 7). Depending on rainfall distribution, irrigation is likely required in the fall months of September through November and into December depending on when the first frost causes turfgrass dormancy. However, irrigation can be required most of the year including the rainy summer period due to short drought periods of one or two weeks. Effective rainfall contributed to 37% of the crop water demand in the OPT schedule, with the remaining 21.4 inches applied by irrigation (Table 4).

Both FIX and FIX-RS schedules resulted in substantial over-irrigation of 78.4% and 59.8%, respectively more than the OPT schedule (Table 4). Both of these schedules could be improved by basing the depth on site specific soil and root zone conditions. However, making this recommendation site specific is not practical due to lack of soil and rooting depth knowledge by users. Over-irrigation for both of these recommendations was evident for the entire year (Fig. 8). Adding a rain sensor or ceasing irrigation in response to 0.25 inches of rainfall contributed to irrigation savings May through September. In contrast, the HIST and HIST-RS schedules simulated under-irrigation until May where HIST then resulted in over-irrigation until November when both schedules under-irrigated. HIST-RS matched the OPT schedule quite well in June July and August but resulted in over-irrigation in September and October. The under irrigation early and late in the year and over-irrigation in the summer resulted in HIST average net irrigation requirement (21.6 inches) closely matching the OPT schedule (21.4 inches). However, the HIST-RS simulation was about 16% lower (18.0 inches) than the OPT schedule (Table 4). Both HIST schedules increased effective rainfall by 11.3% and 30.2% with the addition of a rain sensor. Differences between the HIST schedules and the OPT schedule are likely due to differences in the methodologies where OPT is a result of the daily soil water balance as described in this paper and the HIST schedules were generated from a different set of historical data

Figure 9 shows the trend of net irrigation requirement, deep percolation (drainage), and effective rainfall cumulatively across the year. Effective rainfall across the irrigation schedules ranged from 10.7 inches/yr to 16.2 inches/yr (Table 4). This limited variation was likely due to the limited root zone and small amount of water depletion prior to the onset of turfgrass stress (0.28 inches). The HIST-RS schedule had the highest effective rainfall at 16.2 inches/yr (Fig. 9) because of the under-irrigation for part of the year as described earlier. The lowest effective rainfall was observed for the FIX schedule with the highest amount of over-irrigation.

It can be seen in Fig. 9 that HIST matched the simulated net irrigation requirement fairly closely but as stated previously, HIST-RS resulted in under slight irrigation. Both FIX and FIX-RS schedules result in over-irrigation after March which continued to accumulate through the year. Thus, it is not surprising that both of these schedules resulted in the largest amount of drainage. As mentioned earlier, effective rainfall was not greatly different across treatments.

Summary and Future Work

This study showed that optimizing irrigation scheduling could reduce irrigation application relative to current irrigation recommendations as much as 60% (FIX-RS vs OPT). The OPT schedule is a good example of what might be achieved by new soil moisture-based or ET-based irrigation controllers. The irrigation recommendation of the HIST-RS schedule appears to be a reasonable schedule that balances water conservation with practicality. The OPT schedule should be attainable with ET-based and soil moisture sensor irrigation controllers and can be used as a performance comparison for these controllers.

The greatest uncertainty in the soil water balance approach for Florida conditions is the root zone depth where the majority of water is extracted as well as the maximum allowable depletion (MAD) level that can be tolerated by a particular plant type. This depth probably varies in time, especially in climates where there is winter dormancy as in North Florida. Net irrigation requirements can also be reduced by increasing the root depth of turfgrass or by increasing the soil water holding capacity through the addition of soil amendments.

Weather data from seven additional sites throughout Florida are available and will be used to simulate turfgrass irrigation water requirements in future work. Future simulations should also investigate variation in irrigation, drainage, and effective rainfall across a range of root depths that might be expected and a range of soil water holding capacities for a given location.

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Table 1. IFAS turfgrass and landscape irrigation recommendations published in EDIS (http://edis.ifas.ufl.edu).

Reference	Title	Irrigation Requirement or Scheduling Recommendation
(Augustin 1983)	Water requirements of Florida turfgrasses	Net irrigation requirement ranging from 19.02 to 34.58 inches per year.
(Trenholm et al. 1991)	St. Augustinegrass for Florida lawns	Irrigate 0.5 to 0.75 inches when lawn show signs of wilting. Vary watering frequency and not amount
(Smajstrla and Zazueta 1995)	Estimating crop irrigation requirements for irrigation system design and consumptive use permitting	Daily soil water balance with historical data to determine mean annual irrigation requirement.
(Zazueta et al. 1995)	Turf irrigation for the home	Gives general guidelines on water holding capacity for sandy Florida soils. Gives allowable depletion of 0.50 inches per foot not including irrigation efficiency. Guidelines are also given on days between irrigation events. Recommends tensiometers to automate irrigation scheduling.
(Smajstrla et al. 1997)	Basic irrigation scheduling in Florida	Describes water budget irrigation scheduling. Recommends tensiometer/soil moisture sensors to assist with scheduling.
(Zazueta et al. 2000)	Reduced irrigation of St. Augustinegrass in the Tampa Bay area	Described a study that evaluated turfgrass quality under deficit irrigation conditions where acceptable quality turfgrass was maintained with 60% of crop water requirement replacement. Recommends applying only the amount of water that can be stored in the root zone at each irrigation event and a general value of 0.75 to 1.0 inches is given for Florida soils. Gave irrigation intervals ranging from 2.7 to 11.6 days, 2.2 to 9.3 days, and 1.7 to 7.5 days for high, medium, and low water savings and a 6" root zone in Tampa Bay; 6.1 to 27.8 days, 5.2 to 21.6, and 4.4 to 20.2 days for a 12" root zone.

Table 1. Continued.

(Trenholm and Unruh 2003)	Let your lawn tell you when to water	Recommends irrigation when turf appears stressed by observing wilting. Encourage roots to grow deep by watering only when stressed and by mowing at highest recommended height. Apply 0.5 to 1 inches of water per application. General required watering frequencies are given for three geographic areas of the state.
(Garner et al. 2001)	A guide to environmentally friendly landscaping: Florida yards and neighborhoods handbook	Water early morning between 4 am and 7 am. Apply 0.5" to 0.75" when turfgrass shows signs of distress. Water less in cooler months.
(Trenholm et al. 2001)	Watering your Florida lawn	Over watering results in a less developed shorter root system. On average we receive over 60 inches of rain each year. Water when grass shows signs of wilting apply 0.75" of irrigation. Watering every 2-3 days is adequate in the summer and once every 10-14 days in the winter.
(Dukes and Haman 2002)	Operation of residential irrigation controllers	Controller run times given based on historical ET and rainfall data for three regions in the state. Assumptions include 60% efficiency and two d/wk irrigation. NIR data were taken from Augustin (1983).

Table 2. Recommended irrigation depths for landscape irrigation in North Florida based on (Augustin 1983).

	Weekly Irrigation (inches)	Monthly Irrigation (inches)
Jan	0.04	0.16
Feb	0.00	0.00
Mar	0.09	0.34
Apr	0.49	1.98
May	0.84	3.34
Jun	0.75	3.00
Jul	0.70	2.79
Aug	0.64	2.57
Sep	0.82	3.28
Oct	0.54	2.15
Nov	0.34	1.34
Dec	0.13	0.52
Total		21.5

Table 3. Weather parameters for 30 year period of record, Jacksonville, Florida.

Parameter		Mean	Maximum	Minimum
Daily T_{max}	(°F)	78.3	102.9	32.0
Daily T_{min}	(°F)	58.5	82.9	15.1
Daily RH_{max}	(%)	75.3	97.7	26.3
Daily RH_{min}	(%)	51.7	97	13
Daily Avg R_s	(MJ m^{-2} d^{-1})	16.5	30.8	3.4
Daily Avg U_2	(mph)	7.6	30.0	0.7
Rainfall	(in d^{-1})	0.14	7.82	0.00
	(in yr^{-1})	51.1	70.6	31.2
Uncorrected ETo	(in d^{-1})	0.17	0.42	0.02
	(in yr^{-1})	57.3	65.4	52.1
Corrected ETo	(in d^{-1})	0.14	0.28	0.02
	(in yr^{-1})	50.7	54.5	47.3

Table 4. Summary of water balance components for simulated irrigation schedules.

							Compared to OPT Schedule		
Irrigation Schedule	ETc (in)	Rainfall (in)	Irrigation (in)	Effective Rainfall (in)	Drainage (in)	Balance (%)	Irrigation (%)	Effective Rainfall (%)	Drainage (%)
OPT	33.9	51.1	21.4	12.5	38.7	0.0	0.0	0.0	0.0
FIX	33.9	51.1	38.2	10.7	55.5	0.0	78.4	-14.0	43.4
FIX-RS	33.9	51.1	34.2	13.0	51.5	0.0	59.8	4.7	33.1
HIST	33.9	51.1	21.6	13.9	41.4	3.6	0.9	11.3	7.2
HIST-RS	33.9	51.1	18.0	16.2	37.8	3.8	-16.2	30.2	-2.1

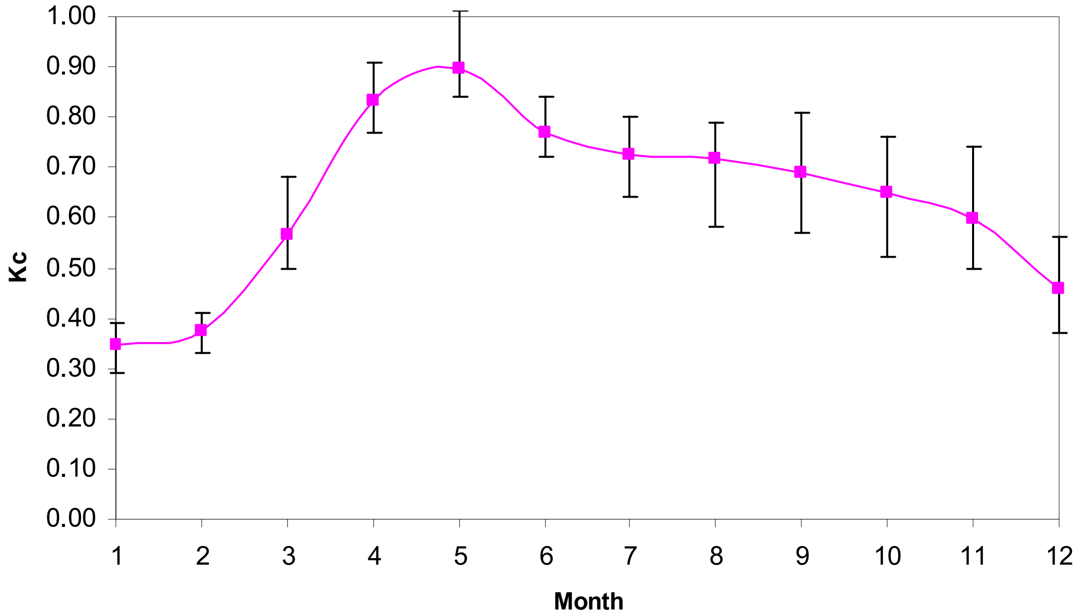


Fig. 1. Crop coefficient (Kc) values use in the simulation as reported by Jia et al. (2007). Error bars indicate minimum and maximum values observed during the multi-year study to determine warm season turfgrass Kc values.

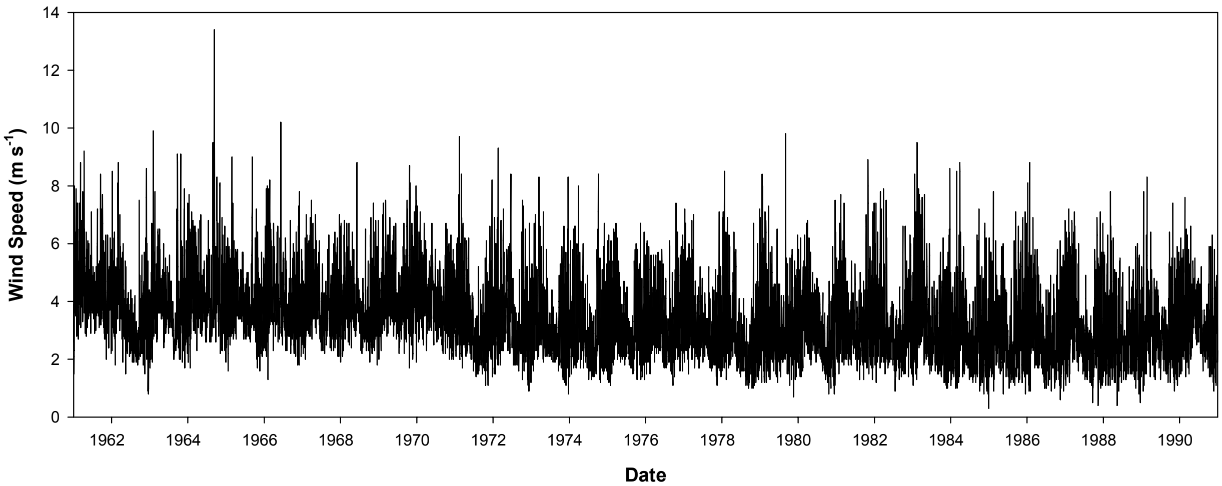


Fig. 2. Average daily wind speed 1961-1990 for Jacksonville, Florida. Note that 1 m s^{-1} = 2.24 mi/hr.

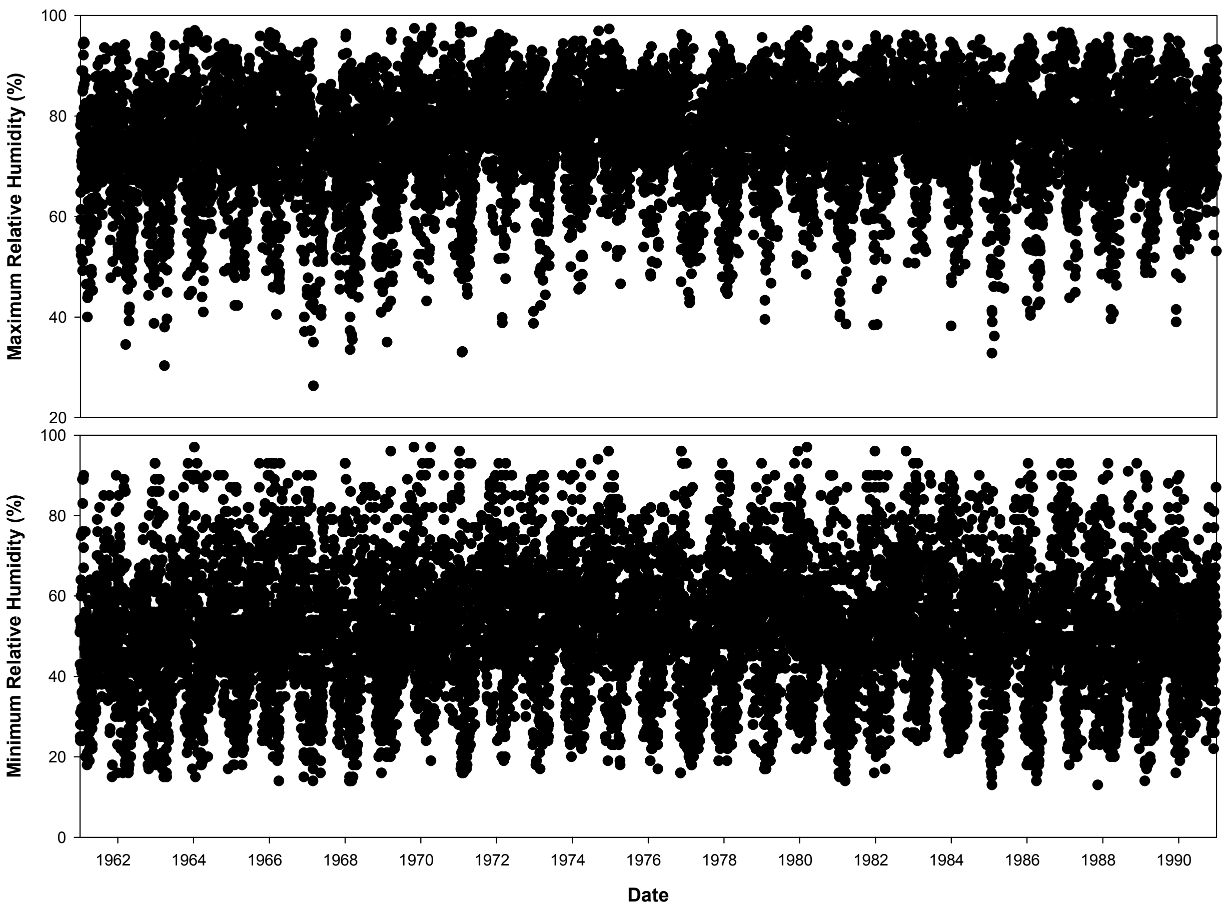


Fig. 3. Maximum and minimum relative humidity 1961-1990 for Jacksonville, Florida.

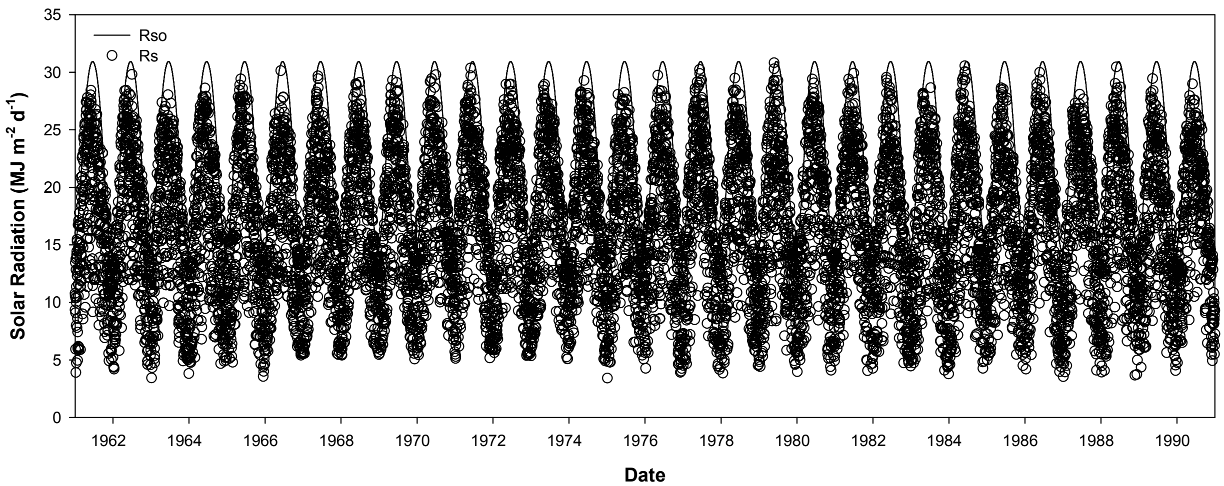


Fig. 4. Average daily solar radiation (Rs) and clear sky solar radiation (Rso) 1961-1990 for Jacksonville, Florida.

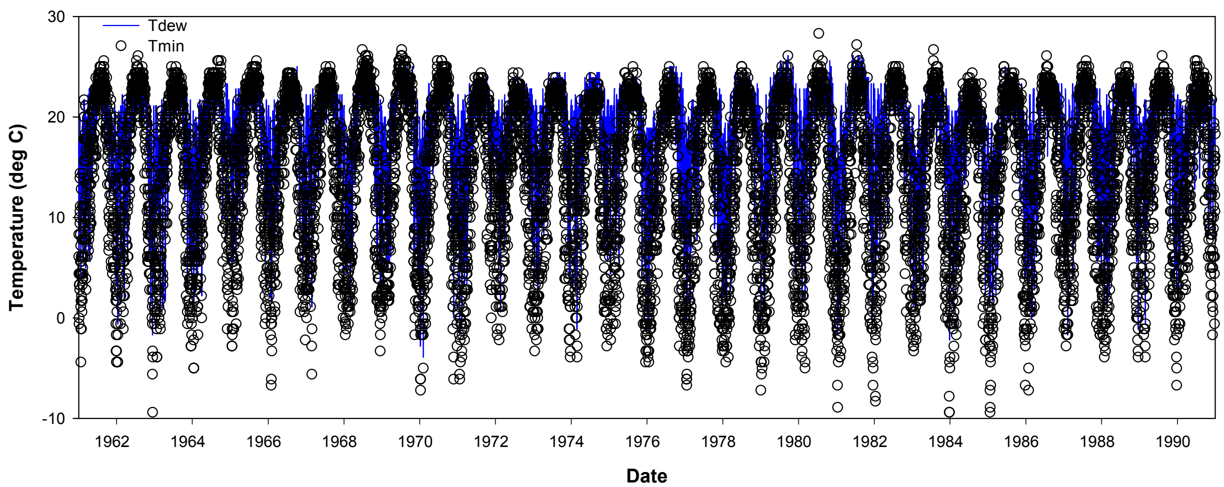


Fig. 5. Dew point and minimum temperature 1961-1990 for Jacksonville, Florida.

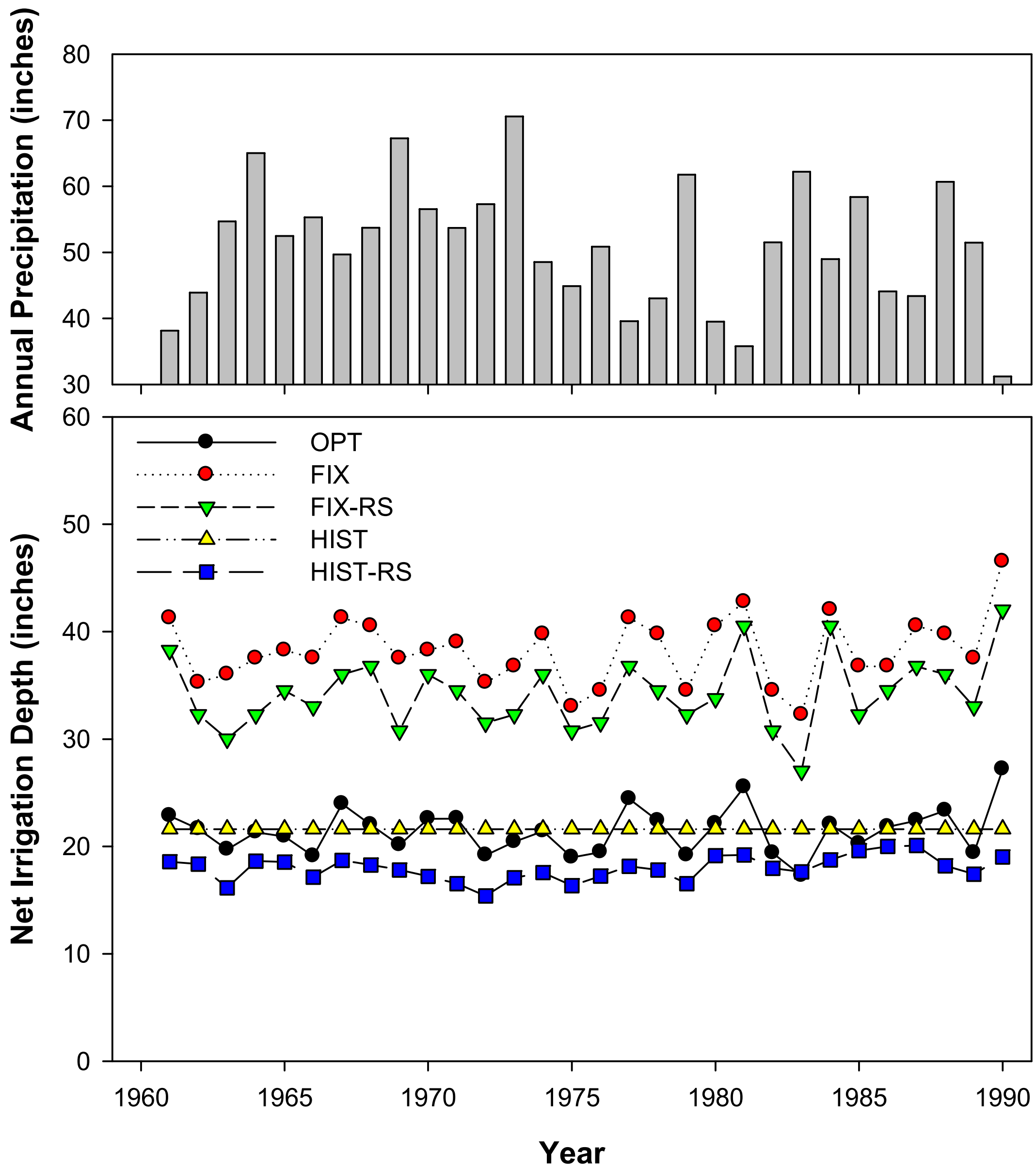


Fig. 6. Annual variability in net irrigation simulated across various irrigation schedule simulations.

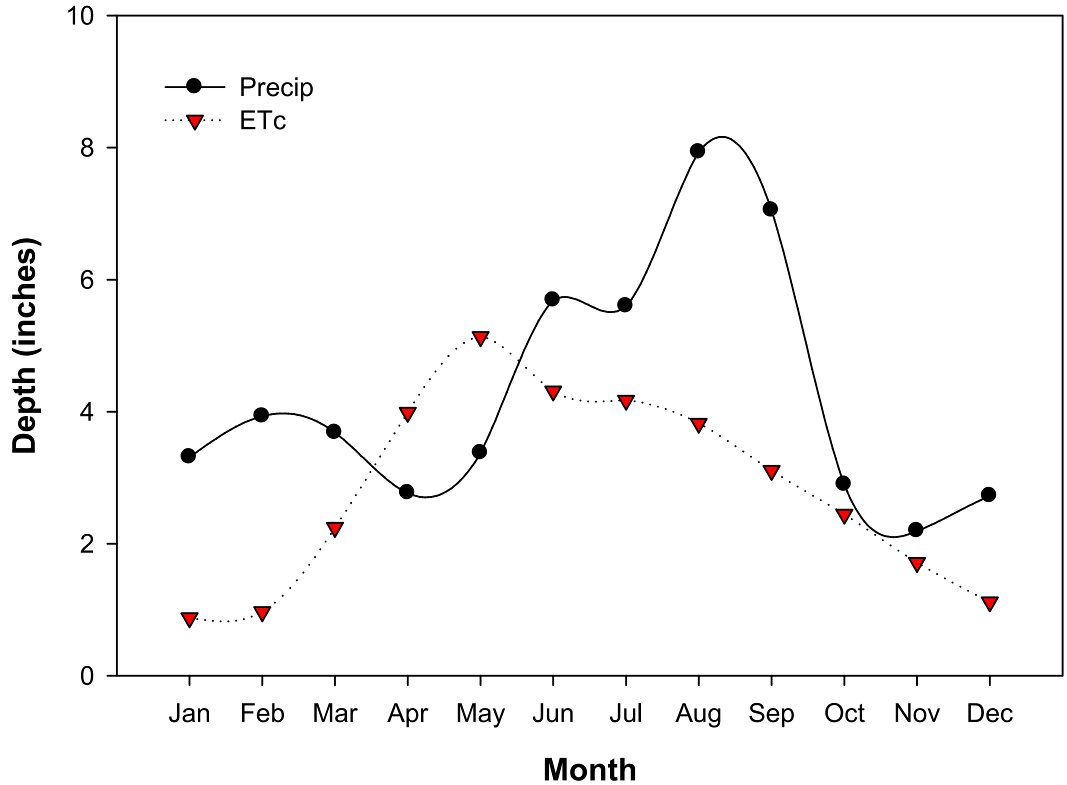


Fig. 7. Monthly average long-term precipitation and turfgrass ETc for Jacksonville, Florida.

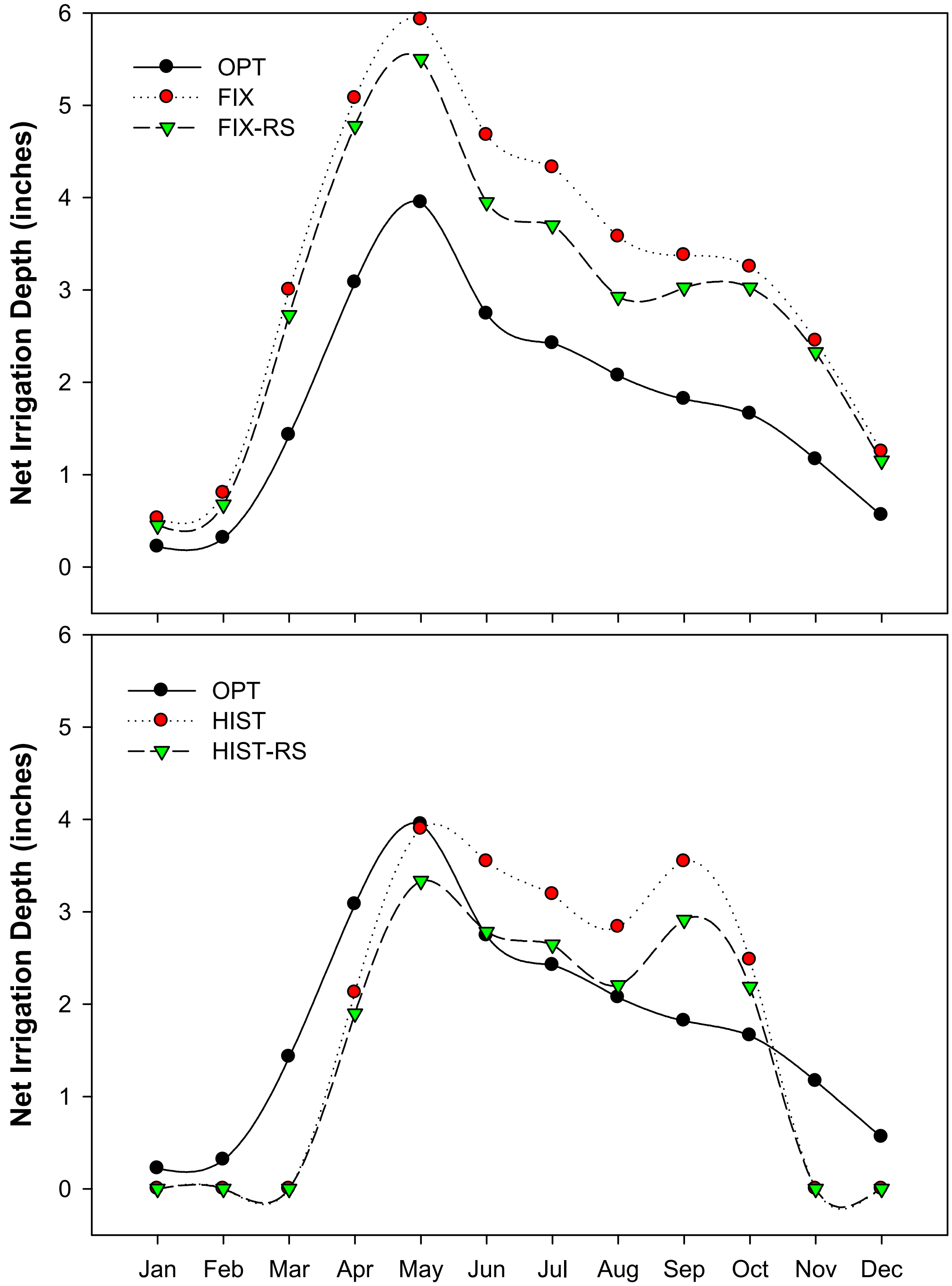


Fig. 8. Monthly average net irrigation requirements across various irrigation schedules simulated.

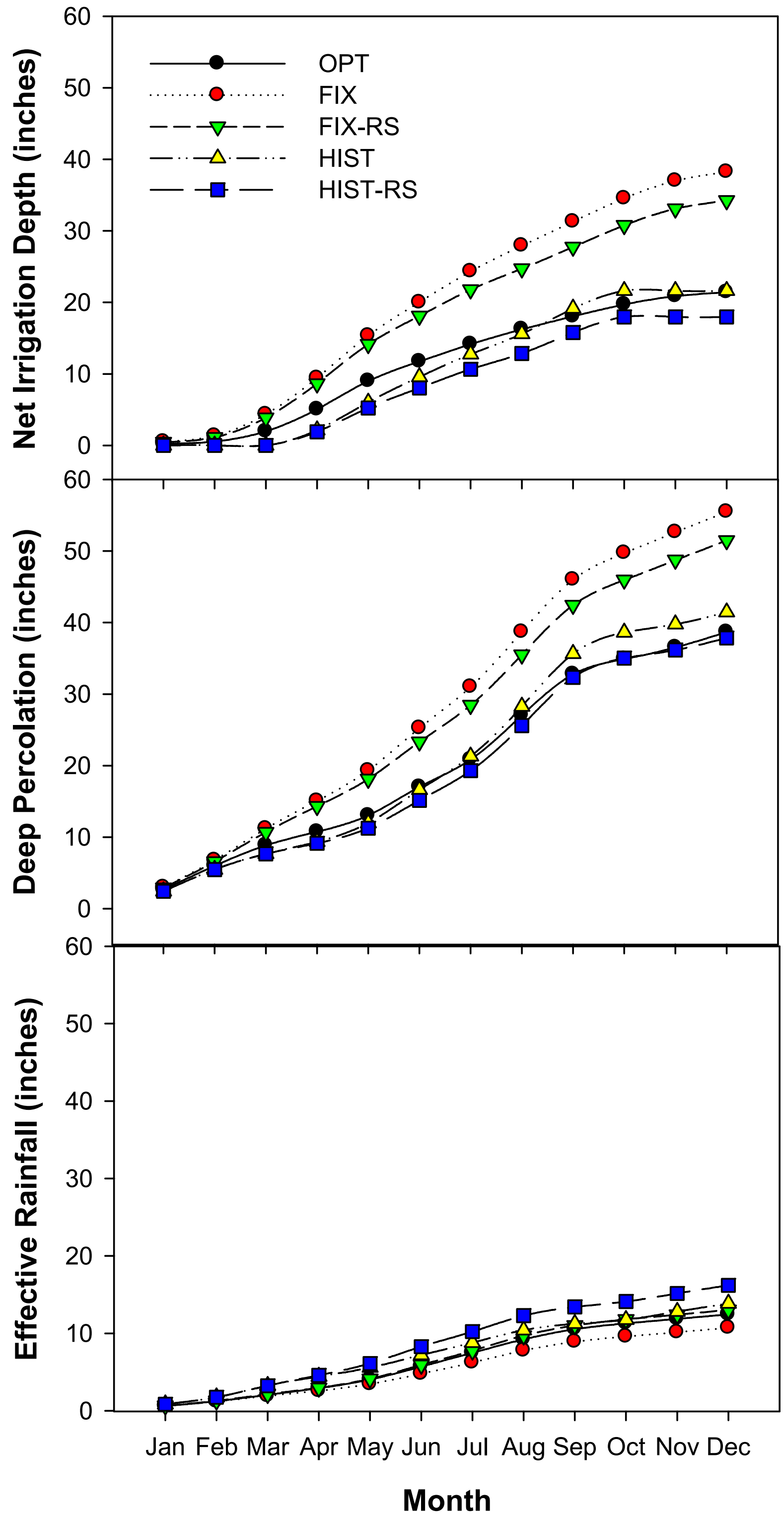


Fig. 9. Monthly average of cumulative net irrigation, deep percolation below the turfgrass root zone and effective rainfall simulated across various irrigation schedules.

Monday, December 10, 2007
IA07-1047

Weather Based Irrigation at Large Commercial Sites - Portland Water Bureau Pilot Project

Brad M. Galpern, Portland Water Bureau, 1120 SW 5th Ave, Suite 500, Portland, OR 97204

In 2004, the Portland Water Bureau initiated a three-year study to measure the effectiveness of weather-based irrigation controllers. These devices use hourly weather data comprised of various factors to calculate the amount of water lost by plants, known as evapotranspiration, and adjust irrigation schedules accordingly. A service provider broadcasts weather data to the controllers from local weather stations. It was predicted that the technology would save water and promote healthier landscapes. Currently, 12 receivers are operating at 8 sites in Portland. 3 additional sites were originally part of the pilot but were taken offline due to technical difficulties. Sites that are currently online have shown an average decrease in outdoor consumption of 23 percent. The presentation of this project would focus on three key elements: The technology, and its operation; the problems and successes experienced over the life of the project; and the pre and post consumption of study participants.

See more of Turf/Landscape: Climate-based Irrigation Scheduling
See more of The 28th Annual International Irrigation Show (December 9-11, 2007)

Using Smart Controllers to Reduce Urban Runoff in the City of Newport Beach

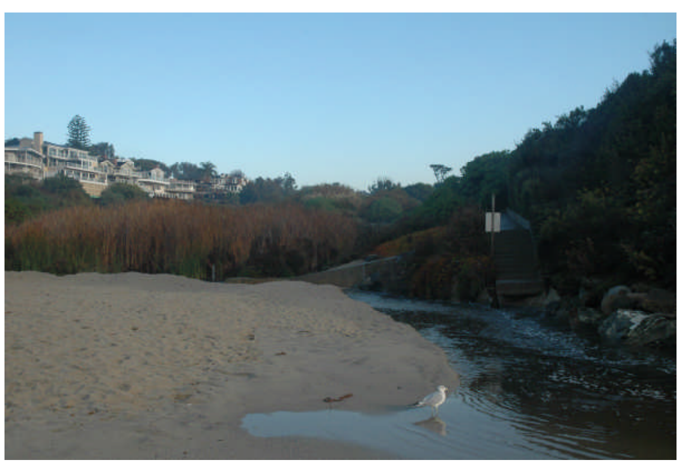
Project Manager
Robert Stein, City of Newport Beach
Project Conducted By
Tom Ash
Director of Conservation
WeatherTRAK

Background

The City of Newport Beach is known for miles of beach and a sparkling bay. The cities coastal setting draws at least 8 million visitors per year. For residents, Newport has an ideal year-around climate and sports homes from the beachfront on up through the hills of the Newport Coast where new home prices can start at $5 million.

Newport Beach, with miles of shoreline, is ground-zero for an all too common problem for the landscape and irrigation industry…urban runoff coming from home and commercial landscapes. Newport is well aware of where polluted runoff is coming from…home landscapes in the Newport beach and bay watersheds. Excess or improperly applied landscape irrigation easily runs off of thousands of landscapes. The runoff carries nitrates, phosphates, herbicides and pesticides directly to water of the bay and beach. The State of California Regional Water Quality Control Board, who acts to enforce the Clean Water Act, is driving Newport Beach and other communities to take action to reduce and eliminate polluted urban runoff.

This image shows continuous runoff coming from a Newport watershed, as much as 20 million gallons per month.



How does a City, who does not control the irrigation on home landscapes, stop the daily flow of polluted runoff?

The first action the City of Newport Beach is taking is to conduct a free smart controller program. The City contacted HydroPoint Data Systems for help. Hydropoint owns the patents and licenses the WeatherTRAK smart controller technology. The City selected this technology because **WeatherTRAK is the only smart controller ever tested by public agencies for water runoff reduction** (www.mwdoc.com), and is the first smart controller to record perfect SWAT scores (100% Adequacy, 0% Excess). The City asked HydroPoint to develop a turn-key program to install smart controllers in high runoff areas of the City.

The keys to the development of a successful program to reduce urban runoff were the following:

- Use a smart controller that has proven runoff abilities
    - Published public agency studies
    - Published runoff study (www.mwdoc.com)
    - Automated scheduling engine (*soil type, plant type, exposure, precipitation rate, slope settings*) that calculates the efficient **minutes**, **days, cycles and soak time** for each irrigation station (*no user schedule or guessing of irrigation run times*)
- Provide the City with a full turn-key program (no additional City time or staff needed) that included:
    - Grant writing
    - Program design
    - Contractor/installer training
    - Marketing
    - Scheduling installations
    - Report and paperwork administration
- Provide customer service for the city/agency
    - Train and/or respond to customer needs
    - Field customer follow-up calls

- Select and manage trained landscape contractor(s) for installations
- Provide residents with sources for quality irrigation system upgrades
    - Find, train and monitor landscape contractors with knowledge of smart controller technology, new sprinkler technologies, expertise in retrofitting

The Program

Funding for the runoff reduction program came from existing City funds for water quality efforts. The City expanded the program through a grant to match City funds. The funding covered the cost of the smart controller, installation, irrigation system audit and two years of real-time daily ET data broadcasted to the controllers. The City was therefore able to offer a **"free"** smart controller for 650 homes. As an added bonus to the City, regional rebates for smart controllers "reimbursed" the City approximately ½ the total cost of the program.

Outreach to customers focused on the high water runoff areas in the city. With newspaper articles, direct letters, city signage, and local cable TV reports. Residents quickly called the "runoff hotline" 800# set up to screen and schedule customers wanting the "free" smart controller offer.

Images from the Field:

Installing contractor meeting homeowner, filling out paperwork and educating the customer on the process.

Installing contractor conducting an irrigation system audit.

Typical observations of irrigation systems at Newport Beach homes

Program Details:

The process of installing smart controllers into homes in Newport Beach revealed both the major difficulties and the major opportunities for the landscape and irrigation industry. Program details include:

Total controllers installed - 640
Average time – 1.2 hours (including ET service activation, irrigation audit, paperwork, customer education w/ 2 person crew)
Average # stations – 9
Average # installations per day – 5
Average water savings per home – 37% (first 3 months compared to previous year)
Monitored runoff reduction – 20%+
Homes denied for installation – 5% (due to extremely poor irrigation systems)
Wait list of residents wanting to participate (after program funds ran out) - 177

Irrigation System Findings:

- **31% of all homes had at least 1 leak in the irrigation system**
- **89% of homes had "easy to see" inefficiencies**
  - **Overspray**
  - **Blocked heads (by plants)**
  - **Clogged heads**
  - **Mis-matched heads** (24% of homes had rotors and spray heads mixed on the same station)
- **55% of all homes had high pressure**
- **All home contracted gardeners needed smart controller training/education**

Landscape Irrigation Industry Opportunity:

- **89% of the homes required some level of irrigation system fixes and/or upgrades**
- **25% of program participants asked for referrals for irrigation specialists**
- **Others needing irrigation assistance suggested they would use their current gardeners**

Opportunity #1: Finding Irrigation System Inefficiencies

It was clear that even in relatively new, high-end homes irrigation systems are inefficient across the board. All of the irrigation **"auditing"** was performed from a "**visual inspection"** by simply turning each station on for 2 minutes. **Every landscaper, gardener and/or homeowner could have discovered every irrigation system problem found by the installing team.** It is clear that irrigation system **"maintenance" is simply not being performed**, even in an area where the water costs are high ($2.05/ccf).

Opportunity #2: Finding Irrigation System Inefficiencies

The installation process for the WeatherTRAK smart controller technology (Toro, Irritrol and HydroPoint models) **requires** that every station be turned on, site characteristics noted (for inserting into the controllers' scheduling engine) including soil type, plant type, root depth, sun/shade, slope, and sprinkler type (precip rate). At the same time any irrigation system problems are identified and noted for the homeowner. This **process** enabled irrigation system inefficiencies to be **"discovered"**. (Note: In contrast, weather based controllers without a scheduling engine, receiving a basic "user schedule" would not have "discovered" any irrigation system problems.) The process of turning on stations and using a critical eye toward the irrigation system was only being done at these homes due to the City-initiated program. While runoff and high water bills (and some site damages) were occurring due to poor irrigation systems and over-watering, no effort was being made by residents and/or landscapers to keep systems efficient.

Opportunity #3: Turning Irrigation System Findings into Business

When irrigation system inefficiencies were found and shown to homeowners, the owners wanted to pay for those fixes to be made. For the landscape contractors referred as irrigation system “experts” by the City program, irrigation retrofit business increased by more than 50% with one contractor increasing revenues by 300%.

Opportunity #4: Using WeatherTRAK to Reveal More Irrigation System Opportunity

With the installation of a smart controller that calculates an efficient schedule for the site conditions, water is likely to be turned down. If there is low irrigation uniformity (less than 70%) it will show-up in the landscape as “hot spots” within weeks. (Note: With controllers that require installers to insert a starting schedule, irrigation uniformity weaknesses are not likely to be revealed. Why? Each landscape will be over-watered up to the point of “**no hot spots**” that masks irrigation system uniformity. With the WeatherTRAK technology over-watering typically does not occur and this reveals more irrigation system weaknesses.) This process and technology revealed significant irrigation system uniformity problems, in both home and in large homeowner association landscapes in the city.

An example of The City program/WeatherTRAK technology driving new irrigation system retrofit business was at least 5 HOA’s retrofit approximately 200 acres of landscape with new sprinkler nozzle technology to increase uniformity. The HOA’s were willing to spend money to (1) reduce water bills, (2) reduce runoff and (3) use improved technology to protect their community landscapes.

Opportunity #5: Making Existing Landscapes Water Efficient to Avoid Water Restrictions

The Newport Beach program found that the 1st 100 homes retrofit with smart controllers saved 458,000 gallons in the first comparison billing period.

One HOA, who first retrofit with smart controllers and them retrofit for irrigation system uniformity, saved 1.3 million gallons in the first comparison billing period.

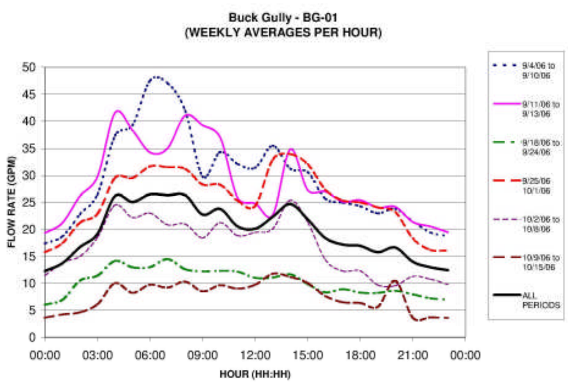
By making every landscape water efficient, the landscape and irrigation industry certainly increase business opportunity. As well, making every landscape water efficient helps reduce the need for local water restrictions to be implemented by the water provider. In this case, making landscapes more water efficient is reducing polluted urban runoff. This helps the City of Newport and water use customers avoid potential **water quality fines** that can be imposed by regulatory agencies.

Conclusions from the City of Newport Beach Smart Controller Runoff Reduction Program:

- Cities may need outside landscape and irrigation experts to design and conduct water efficiency programs
- Finding qualified and committed landscape contractors to (1) install smart controllers, (2) evaluate irrigation systems and (3) become referrals was more difficult than expected
- Significant water is being wasted in home landscapes due to general over-watering and inefficient irrigation systems

- Home gardeners did not have the expertise to find and fix irrigation system problems
- Home gardeners did not find or fix leaks with any consistency
- Installing smart controllers revealed irrigation system inefficiencies
- Educating and training was imperative for the home gardeners
- Education and training was imperative for homeowners
- Significant runoff can be reduced with proven smart controllers and irrigation system repairs
- Significant business opportunity exist for the landscape and irrigation industry in finding irrigation system problems, offering expert irrigation system repairs and installing smart controllers

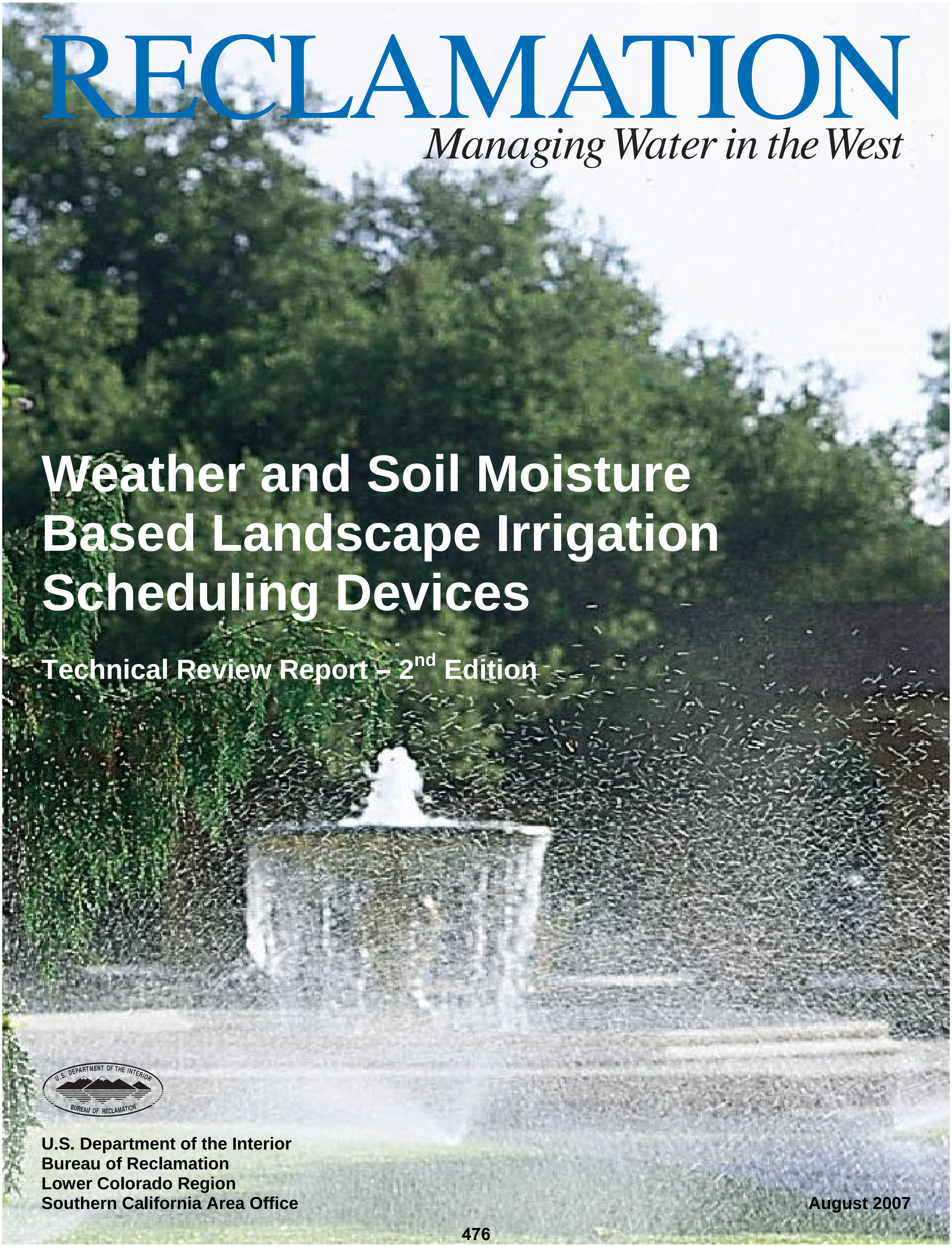
Runoff Reduction Monitoring Example



Post-script:

The City of Newport Beach is developing a series of ordinances designed to reduce/eliminate non point source water pollution. Those ordinances could include:

- *Tiered water budget rate structure based on the local ET*
- *Business license and/or certification for gardeners and contractors*
- *Tickets or fines for water runoff coming from the property*
- *Any remodel or new home is required to have a certified smart controller*
- *Rogers Gardens, the #1 Nursery in the US has retrofit their retail site with the WeatherTRAK smart controller and MP Rotator nozzles to eliminate runoff and be a local example for water efficiency. The City is funding a runoff display at the Rogers retail site.*



RECLAMATION

Managing Water in the West

Weather and Soil Moisture Based Landscape Irrigation Scheduling Devices

Technical Review Report – 2nd Edition

U.S. Department of the Interior
Bureau of Reclamation
Lower Colorado Region
Southern California Area Office

August 2007

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

For copies of this report contact
Reclamation's Southern California Area Office at 951-695-5310
or download at http://www.usbr.gov/waterconservation/docs/SmartController.pdf

Weather and Soil Moisture Based Landscape Irrigation Scheduling Devices

Technical Review Report – 2nd Edition

prepared by

Southern California Area Office
Temecula, California

and

Technical Service Center
Water Resources Planning and Operations Support Group
Denver, Colorado

U.S. Department of the Interior
Bureau of Reclamation
Lower Colorado Region
Southern California Area Office **August 2007**

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The preparers of this report acknowledge the significant input provided by these agency and district staff and extend their thanks to the following individuals: Ms. Stephanie Tanner, EPA; Ms. Joanna Kind and Ms. Christy Milstead, Eastern Research Group, Inc. for EPA; Mr. John Wiedman, MWDSC; Mr. Steve Hedges and Mr. Joe Berg, MWDOC; Ms. Fiona Sanchez, IRWD; and Mr. Brent Mecham, NCWCD.

Representatives of the reviewed product manufacturers provided product information and approval of their respective product discussion sections of the report. The preparers of this report very much appreciate each of these individuals' input. It is acknowledged the report's level of detail could not have been achieved without the significant assistance provided by the product manufacturers' representatives. These individuals are identified in the product information and features summary tables located at the end of the report.

Disclaimer

Nothing in this report constitutes endorsement by the Bureau of Reclamation of a particular product or method. A significant portion of the information presented in this document was provided by the product manufacturers' representatives. Some of this information was verified by third parties as appropriate and as possible given the scope of the review. Every effort was made to accurately incorporate the information provided and to avoid errors and oversights, but it is recognized some may exist. The Bureau of Reclamation plans to update this report periodically and any identified deficiencies will be corrected at that time. Errors, omissions and new product information should be reported to Mark Spears at 303-445-2514 or mspears@do.usbr.gov or to Reclamation's Southern California Area Office at 951-695-5310.

Introduction

Water agencies implementing water use efficiency programs have long struggled to achieve quantifiable and reliable water savings. Historically, programs targeting landscape savings have focused on education pertaining to irrigation system maintenance, irrigation scheduling and climate appropriate plantings. Although these efforts have garnered savings, much potential exists for further landscape irrigation efficiency improvements.

In the late 1990's, the Irvine Ranch Water District, Municipal Water District of Orange County and Metropolitan Water District of Southern California learned of an emerging irrigation management technology using weather based irrigation scheduling devices. This technology removes the need to make manual scheduling adjustments because the "smart" device adjusts the schedule automatically as weather changes. A water savings evaluation of this technology was implemented which is known as the "Residential Weather-Based Irrigation Scheduling – The Irvine ET Controller Study". This evaluation identified an average single-family home savings rate of 37 gallons per day (irwd.com, 2001).

In an effort to address non-point source pollution, a second weather based irrigation scheduling study was performed to evaluate the linkage between improved residential irrigation management and reduced dry-weather runoff. The "Residential Runoff Reduction (R3) Study" reported comparable water savings of 42 gallons per day per single-family home (irwd.com, 2004). Savings at non-residential sites were 545 gallons per day. The R3 Study also quantified a reduction in runoff ranging from 64 to 71 percent. With this change in runoff volume, concentrations of pollutants did not change therefore pollutants were reduced by a like amount.

Although soil moisture sensors have been used in agricultural and research applications for many years, this technology has only recently been applied successfully in the landscape irrigation field. Initial attempts to use soil moisture sensors to control landscape irrigation were unsuccessful due to the state of the technology, maintenance requirements and cost. Within the past several years, soil moisture sensor technology has advanced significantly with accurate and maintenance free systems being offered by several companies at competitive prices. Recent study findings indicate water savings resulting from soil moisture based smart systems are similar to those discussed above for weather based systems (Allen, 1997; Cardenas-Lailhacar et al., 2005; DeOreo et al.; Mecham).

Water agencies throughout the country recognize smart irrigation control as an emerging tool to achieve landscape water savings and reduce non-point source pollution. When the first study began, the study team was aware of only a few smart technologies. Today, nearly 30 smart irrigation control manufacturers exist and others are quickly emerging into the marketplace.

In 2003, the Municipal Water District of Orange County approached the Bureau of Reclamation, Southern California Area Office and requested an objective evaluation of weather based residential irrigation scheduling technologies available to consumers. A technical review was performed to document the overall status of weather based residential technologies and provide general descriptions of these products. The purpose of the review was to compile existing information and allow water agencies to quickly gain knowledge about the technologies for use in their residential incentive programs.

The results of the review were published in Reclamation's May 2004 Technical Review Report "Weather Based Technologies for Residential Irrigation Scheduling." Since 2004 Reclamation has monitored the status of the products reviewed in the original report and researched many other smart irrigation scheduling products, including soil moisture sensor based and commercial products. An updated technical review report entitled "Weather and Soil Moisture Based Landscape Irrigation Scheduling Technologies" was published in August 2006, which included information on smart irrigation control products by 26 companies that were available as of June 2006.

This report includes information on smart irrigation control products by 28 companies that were available as of June 2007. Three additional companies have been added and one companies' products are no longer available in the U.S. Previously reported product information (models, pricing, etc.) has been updated and minor revisions have been made throughout the document. It is Reclamation's intention to continue to update the report as often as needed in an attempt to keep all information current.

Smart Irrigation Technology Overview

Smart irrigation control systems typically include either a stand alone controller or an add-on device which interfaces with a conventional clock-type controller. The weather or soil moisture based technologies incorporated into these devices allow them to function similar to a thermostat. Like a thermostat, the devices permit irrigation to occur when needed rather than on a preset schedule. Regardless of the specific method or technology, the concept is for the appropriate irrigation quantity to be applied at the appropriate time.

Most of these systems are available in a variety of sizes appropriate for small residential to large commercial applications. For this report, a device with more than a 12 station (zone) capacity is considered large residential or light commercial. In most cases, light commercial products possess the same features as the residential products, but have greater station capacity. Larger industrial type commercial products possess high station capacity and offer additional features such as flow sensing, surge and lightning protection, multiple master valve circuits, concurrent station operation, and other sophisticated features.

Computerized central control system type products are beyond the scope of this review. These consist of multiple "satellite" controllers that are controlled through a centralized computer system allowing for monitoring and control of multiple irrigation system parameters including flow rates, pressures, pumps, master valves, etc. from a single location. Several of these systems are mentioned since they are offered by the companies that sell stand-alone devices. Also, some of the stand-alone controllers reviewed possess central control system type features.

SWAT Testing

In an effort to set an industry conservation standard, the Irrigation Association® (IA) has organized the Smart Water Application Technologies™ (SWAT™) initiative. This initiative functions as a partnership with constituents from public entities and private companies from the landscape irrigation industry. The first products for which testing protocols have been developed are for climatologically based irrigation control products. The current climatologically based testing protocol (7^{th} Draft) was approved in November 2006 and has been implemented for testing. The current draft soil moisture sensor based protocol (Phase 2, 1^{st} Draft) was posted in April 2006 and implementation is pending further review and preliminary testing.

The Center for Irrigation Technology at California State University – Fresno (CIT) has been contracted by the IA to conduct SWAT bench mark testing. Climatologically based testing began in 2005. The testing is done in a laboratory environment using a "virtual landscape" that is subjected to a representative climate based on weather station data. The purpose of the testing is to evaluate the ability of a device to adequately and efficiently irrigate the virtual landscape. Although actual irrigation does not occur, the test measures the irrigation quantities prescribed by the device for 6 different zones with varying site conditions (soil and plant types, ground slope, sun/shade, irrigation system, etc.) The test duration is for 30 consecutive days with total minimum rainfall and evapotranspiration (ET) of 0.4 and 2.5 inches, respectively. Testing results are summarized in performance reports (performance summaries and technical reports) which are posted on the IA's website (http://www.irrigation.org/SWAT/Industry/ia-tested.asp) as test results are released by manufacturers. The summaries include percentage scores in the categories of Irrigation Adequacy and Irrigation Excess. The technical reports include details associated with these scores.

At the time of this report, performance reports for 9 manufacturers had been posted. Since the IA does not disclose which products have been tested until a performance report is released, it is unknown how many of the other weather based products have been submitted for testing. Certain manufacturers have indicated concerns regarding the SWAT testing and reported they will not submit their products for testing unless certain protocol changes are made. Whether or not a device has been submitted for SWAT testing and the status of the testing, when a performance report is not posted, is discussed in this report only if this information was made available by the manufacturer.

EPA WaterSense Program

In 2006, the EPA introduced its voluntary public-private partnership WaterSense Program. The mission of the WaterSense Program is to protect the future of our nation's water supply by promoting and enhancing the market for water-efficient products and services. It is being modeled after the EPA's successful Energy Star Program. The WaterSense logo will be displayed on the labels of certified products. EPA staff are evaluating the potential for adoption of the SWAT protocols discussed above for WaterSense certification of weather and sensor based landscape irrigation control devices.

Reported Water Savings

Most of the product descriptions in this report discuss water savings. In some cases, water savings associated with various studies and demonstration projects are discussed. In most cases the water savings discussed are as reported by the manufacturer. It is discussed if water savings related study reports were submitted as part of this review, and or if the reports are publicly available. It is significant to understand water savings can be calculated by numerous methods and verification can be difficult.

In some cases the reported water savings are average values for multiple installations, and in other cases savings for a selected site are reported. Regardless of a product's reported water savings potential, actual savings will vary significantly from user to user depending on weather, irrigation system and site conditions, and previous irrigation practices. A properly installed irrigation system (piping and sprinkler heads) with acceptable distribution uniformity is critical to realizing water savings and maintaining a healthy landscape.

No Rating of Products

No attempt has been made to rate the products relative to each other. Certain comparison criteria are discussed, and it is left to the reader to research further and determine which products may suit various applications most appropriately.

Weather Based Irrigation Control System Principles

All of the weather based products reviewed operate on the principle of scheduling irrigation as a function of weather conditions. Most of the products use real time or historic weather data to schedule irrigation based on evapotranspiration (ET), which is a function of weather conditions and plant type. ET is defined as the quantity of moisture that is both transpired by the plant and evaporated from the soil and plant surfaces.

The American Society of Civil Engineering's (ASCE) standardized reference ET equation parameters are maximum and minimum air temperature, net solar radiation, average vapor pressure and average wind speed. Vapor pressure can be calculated from humidity, dry and wet bulb, or dew point data and solar radiation can be derived from pyranometer or sunshine recorder data. The standardized reference ET equation is widely recognized as the best empirical method for estimating ET (Allen et al., 2005). Other less accurate equations are also used which require only temperature and solar radiation parameters, and solar radiation is sometimes estimated as an average value based on historic data for a given site latitude. The problem with using estimated solar radiation values is the significant variability due to cloud cover is neglected, and solar radiation is the single most important parameter in ET calculation using the ASCE standardized equation. Some of the products evaluated use these empirical ET equations in their scheduling algorithms. It is significant to consider which equation is used with regard to ET estimation accuracy, or what parameters are measured if the equation used is not referenced.

Each of the weather based irrigation scheduling systems evaluated utilize micro-processing devices which calculate or adjust irrigation schedules based on one or more of the following parameter sets: weather conditions (temperature, rainfall, humidity, wind and solar radiation), plant types (low versus high water use and root depth), and site conditions (latitude, soils, ground slope and shade). Some of the systems are fully automatic, and others are semi-automatic. The semi-automatic systems typically require the user to enter a base daily irrigation schedule, and then the device determines the frequency (which days) irrigations occur or adjusts run times. Some of the semi-automatic system manufacturers provide guidelines for establishing the base schedule and others do not.

A significant factor in comparing the products that use real time weather data is the quality of the data used. The cost to install and maintain a complete weather station onsite in order to collect the data necessary to use the standardized reference ET equation is prohibitive in most cases. Two techniques are used to collect current weather data as alternatives to onsite weather stations. Specifically, irrigation demand is calculated either using a limited set of on-site measurements, or using a full set of weather station data from a remote site. There are trade-offs associated with both methods.

If only a limited set of data are used to calculate ET with onsite sensors, the accuracy of the calculated ET may be poorer than ET calculated with a full set of weather station data. Conversely, if the remote weather station data used are not representative of the irrigator's site, the calculated ET value and or rainfall sensing or measurement may not be accurate. Some of the weather station data being used may not be adequate for ET calculation. Specifically, some weather stations being used do not measure radiation, but calculate it from other parameters, and some stations are not properly located for ET parameters data collection.

Certain products reviewed use on-site temperature measurements combined with historic monthly ET or solar radiation data in the daily ET calculation. The historic data used are a function of the site location. An obvious consideration with this technique is the accuracy of the historic data relative to a specific site. In one case only five sets of data are available for the entire U.S.

Several of the products reviewed calculate ET using a full set of remotely collected data from local weather stations or a network of weather sensors. The weather station data are collected from public and or private weather stations. The weather station and sensor network data are processed by a centralized computer server, and transmitted to the irrigation sites. There are ongoing service provider costs associated with the operation of the weather stations, sensor networks, computers, and information transmission systems associated with these products. These costs are either absorbed by water entities or are paid by the users.

In some cases, compelling study results were submitted by the manufacturers showing accurate ET calculation and or significant water savings associated with their product as discussed under the product descriptions. In addition to the SWAT testing discussed above, a science-based evaluation of 4 of the weather based products reviewed was conducted by the University of California Cooperative Extension in 2003 and the results are reported by Pittenger et al. (2004). Most studies to date have evaluated individual products rather than comparing the performance of multiple products. Given the general lack of data, it is difficult to draw conclusions about the overall performance of one product or technique versus another.

Weather Based Control Product Features and Comparison Criteria

Significant weather based controller product components and features are discussed below. The discussion also identifies different methods used to achieve similar results by the various products, and associated advantages and disadvantages.

Installation

Although most of the manufacturers recommend professional installation and programming of their products, several indicate installation and programming of its residential models can be done by “do-it-yourself” type homeowners. Most of the individuals associated with residential product demonstration programs and pilot studies who were interviewed during this review expressed concerns about homeowner installation and programming. Based on the review of installation and programming instruction materials only, it appears some devices could be more difficult to install and program than others. The degree of difficulty to install any of the products can vary significantly depending on site-specific conditions. It appears that all of the commercial products should be professionally installed. Installation and programming instructions are available for many of the products at their websites. All potential customers should review this information when shopping for a device regardless of whether they plan to do their own installation and programming.

In the development of Smart irrigation device promotion programs, water agencies should consider requiring professional installation or requiring users to attend workshops to receive training before performing self-installation.

Stand-Alone Controller Versus Add-on Device

The primary component of most of the products reviewed is an automatic irrigation controller in place of a traditional clock type controller. Alternatively, several of the products include a receiver or scheduler that is connected to an existing controller. In some cases, the lower cost of the add-on device is a significant attraction. Regardless of cost, the quality of an existing controller should be a factor when considering replacement. If the existing controller is a high quality unit with adequate features, an add-on receiver may be an attractive alternative. The level of automation is limited with some of these units relative to some of the stand-alone controller systems. Specifically, some devices only prescribe irrigation frequency or adjust preset run times and do not automatically calculate run times.

Irrigation Schedules and Run Time Calculation and Adjustment

Some of the products reviewed will automatically generate irrigation schedules and run times for various zones as a function of sprinkler application rate, plant and soil types, slope and sun/shade conditions, and distribution uniformity. The ability of the automatic controllers to accurately generate an efficient schedule is dependent on the controller, the user's knowledge of the landscape parameters and proper programming. Other devices require a base irrigation schedule with specific run times which are entered by the user. In which case, the user must manually calculate run times based on experience and or guidelines provided by the manufacturer. Some of these controllers adjust the preset run times based on weather conditions, and others only control the irrigation run frequency. The product descriptions identify the manufacturers that provide guidelines for determining appropriate run times for the devices that require a base schedule. Automatic run time calculation can be a significant advantage if the required programming inputs are known and the controller calculates accurately.

Regardless of automatic or manual run times, many of the products have a fine-tune feature which allows adjustment of station run times by a percentage factor or by minutes giving the user the ability to compensate for inadequate run times.

Application Rates and Distribution Uniformity

Some of the products reviewed allow the user to enter actual sprinkler application rates versus preprogrammed rates based on irrigation type (spray, rotor, drip, etc.). Application rates can be measured by the user if not provided by the sprinkler manufacturer.

The irrigation system's distribution uniformity or efficiency factor (typically a percentage) describes the effectiveness of the sprinkler head coverage, and reflects the quality and layout of the sprinklers. This setting allows the controller to compensate for low uniformity. The majority of a system with low distribution uniformity must be over irrigated in order for all areas to receive adequate water.

Irrigation Run and Soak Cycles

All of the stand-alone controllers reviewed provide for multiple run and soak times to limit runoff. Some calculate them automatically by zone based on soil and ground slope conditions, and others require manual programming. Of those that require manual programming and for the add-on devices, certain manufacturers provide guidelines or computer programs for calculating the times.

Regardless of automatic or manual calculation, by zone multiple run/soak cycles ability is a very advantageous feature.

Landscape Establishment/Fertilizer and Syringe Programs

Some stand alone controllers provide landscape establishment or fertilizer programs which allow for programming high irrigation quantities for a certain time frame before reverting to the weather based programming. Plant establishment programs can preclude over-irrigation and runoff occurring for extended periods due to a landscape contractor programming for establishment of a new landscape.

Syringe programs are designed for installation and system testing purposes. The program provides a convenient means of executing a short run time for each station.

Crop Coefficients

All of the controllers that automatically calculate run times can utilize pre-programmed crop coefficients set by the manufacturer by plant type. Some provide the user the option of programming custom crop coefficients. This can be advantageous since crop coefficients typically vary geographically.

Rain Sensors and Gauges and Rain Interrupt or Delay

Most of the products reviewed include a rain sensor or gauge with the system, or as an optional add-on accessory. These have a rain interrupt and or delay feature triggered by the sensor or gauge, or irrigation schedule adjust feature. Some of the products' only interrupt ongoing irrigation when significant rainfall is detected and others initiate an adjustable irrigation delay period. Some systems adjust the irrigation schedule based on the amount of rainfall measured. Although no documentation was reviewed for this report on the measurement accuracy of different types of rain gauges and sensors, it is assumed the tipping bucket type gauges are more accurate than hygroscopic type rain sensors (sensors that absorb rainfall). Some of the receiver type systems have the ability to initiate a rain interrupt/delay or adjust the irrigation schedule based on rainfall detected or measured at a nearby weather station. Other receiver type systems use an on-site rain sensor or gauge that has the advantage of detecting or measuring rainfall that actually occurs at the site.

Other Sensors

Some of the products reviewed include standard or optional solar radiation, humidity, wind, temperature and flow sensors. In addition to calculating irrigation demand using temperature data, some of the devices interrupt or delay irrigation when wind and or temperature conditions are adverse to irrigation. Alternatively, some of the systems delay irrigation based on wind and temperature conditions measured at a local weather station. Most of the commercial products include flow sensor input terminals. In addition to monitoring to detect for high and low flows indicative of irrigation system problems, some of the controllers factor flow conditions into automatic scheduling decisions.

Power Supply and Surge and Lightning Protection

With one exception, all of the stand-alone controllers include a power transformer that converts 110-120 volts of alternating current (VAC) to 24 VAC. The transformers are either hardwired inside the controller cabinet (internal), or plugged into a power outlet (external). The Alex-Tronix controller operates on a pulsed 9 volts of direct current (VDC) using battery power. The add-on scheduling devices operate on either 24 VAC, 9 VDC or 12 VDC and either receive power from the existing controller or from an external transformer. Most of the transformer devices include some type of current overload protection such as a fuse or breaker switch. Some controllers include lightning and or surge protection, or offer these as an optional feature. Surge and lightning protection limits damage to the controller's circuitry from transient voltage and current from the power source (surge) and from the valve circuits (lightning).

Station Circuit Rating, Wiring and Terminal Wire Sizes

The compatibility of the existing electrical circuits (wiring from the controller to the station valves) should be considered in the selection of a replacement irrigation controller. If the station wire terminals on the controller will not accept the existing wire, adapters must be used. Also, the circuit current capacity required for an existing system should be checked prior to installing a new unit. Reports from demonstration studies indicate installation problems associated with insufficient circuit capacity to operate some irrigation valves with high circuit resistance.

The traditional wiring system (circuitry) used for most controllers consists of a common and a dedicated wire from the controller to each valve and sensor. Some controllers utilize “2-wire” circuitry that consists of a single pair of wires connected to all of the valves and sensors in the system. These systems require the installation of a decoder device for each valve and sensor. Applications include large systems and linear systems (e.g., highway corridors) with large quantities of wiring required for traditional circuitry.

Clock Mode Operation

Most of the controllers reviewed will operate in a standard clock mode. Some of them can be programmed for clock mode operation by station. One of the controllers that receives a scheduling signal does not have clock mode capability. Therefore, if the signal subscription is cancelled the controller must be replaced.

Display and Data Review

It is advantageous for a device to have a large easy-to-read display which displays settings and data. Ideally, the data review control should be backlit and easy to use. It should display information by zone for run times, soak times, irrigation amounts, percent adjustments, ET and other weather information, watering window and irrigation history.

Non-volatile Memory and Batteries

All of the products reviewed have non-volatile memory to protect their programming during power outages. Some of the products also include a backup battery for maintenance of the date and time during power failures, and those that do not provide this back-up protection within the non-volatile memory.

Warranty and Reliability

All of the products reviewed come with a warranty. Warranty periods are discussed separately in the review of each product. In some cases, the manufacturers' warranty periods vary for its different products. Although the warranty periods may or may not be indicative of the life expectancy of the products, in some cases there appears to be a correlation between the cost and overall quality of the product to the warranty period. It is assumed the cost of a product somewhat reflects the quality of the construction materials and electronic components. Hence the less expensive residential devices should not be expected to last as long and function as reliably as the more expensive residential and commercial products. Since most of the devices are relatively new products, it is difficult to speculate on how long they should last.

Depending on site conditions and maintenance, the weather sensors and other outdoor components may be vulnerable to degradation due to exposure to the elements. The availability of replacement sensors and their costs should be considered for those systems with on-site weather sensors.

Weather Based Product Descriptions

The following product descriptions address operational characteristics and features, and include discussions of available information from demonstration and pilot studies relative to documented water savings and operation. Each of the manufacturers was provided with copies of the product descriptions for their input prior to being incorporated into this report.

Accurate WeatherSet

Accurate WeatherSet is located in Winnetka, California. WeatherSet has manufactured commercial weather based irrigation controllers for landscapes, golf courses and greenhouses since 1979. The company started development of its first residential controller prototypes in 2000, and began marketing the residential controllers in September 2001. All WeatherSet controllers utilize a solar sensor and rain sensor to automatically adjust irrigation schedules. The solar sensor, designed and fabricated by WeatherSet, measures solar radiation which is the major factor affecting the controller's ET calculation.

The WeatherSet controller is called the Smart Timer™, and it comes in 8, 12, 16, 24, 32, 40 and 48 station models. The Smart Timer is a stand-alone controller and does not require communication with remote servers to obtain weather data or irrigation schedules, and there are no ongoing service costs. The controller calculates ET with input from an onsite solar radiation sensor. WeatherSet reports the solar sensor has functioned reliably in demanding environmental conditions to control greenhouse and outdoor misting systems since the early 1990's.

Operational Features

The WeatherSet controller calculates a daily ET estimate based on solar sensor SunFall™ measurements that are logged by the controller on a 2-minute frequency. The sensor must be installed in a mostly sunny location in order to function accurately. Adaptive control logic allows the controller to function with some shading. From their work with commercial controllers, WeatherSet reports that SunFall reduces by about two-thirds from a clear day in summer to a clear day in winter, and that their 5 self-adjusting programs follow these changes.

The calculated ET information is combined with rain sensor data and user programmed information to schedule irrigation. To program the controller for automatic adjustments, the user assigns each station to one of three programs, which are labeled Flowers™, Lawns™ and Shrubs™. The Flowers, Lawn, and Shrubs programs are for shallow, medium and deep-rooted plants, respectively. A fourth program called LWU (low water use) will deliver water to California native plants that expect no rain from May through September and winter rains from October through April. A runoff limit, in minutes per hour, may also be entered for each station to stop runoff. The user enters a MAX Runtime for each station and the Smart Timer automatically adjusts the watering days and runtimes for each valve. The controller has a manual start function, and an optional irrigation history review function. With the H-option, the controller keeps a running tab of total run time for each station.

The controller's rain sensor is an Ecologic RainBrain™. The sensor signals the controller to interrupt irrigation in its rain shut-off mode, and the rain sensor signals are also used by the controller for irrigation scheduling. The WeatherSet controller is preprogrammed to account for the duration that the rain shut-off circuit has been interrupted when scheduling irrigations.

The WeatherSet irrigation controller provides 7 different runoff limits that are set for each station. A maximum cycle run time of 2, 4, 6, 8, 11, 15, 20 and unlimited number of minutes per hour may be set for each valve. The default cycle limit factor is four minutes per hour. As an example, if the controller calculates a total 12-minute run time for a station, this station will be irrigated in three 4-minute increments over a 3-hour period, with the default setting. For stations that generate runoff, WeatherSet recommends the user measure the time required to cause runoff (using the manual run mode), divide the time by two and use that time to choose the runoff factor for the station. The runoff factor may be shut off to allow continuous watering when required. For example, valves controlling drip systems in LWU programs may best be watered with the runoff limit shut off.

Descriptions, Prices and Warranty

Two Smart Timer indoor residential controller models and seven outdoor commercial models are available. The indoor controller cabinets are constructed of aluminum with dimensions of 5.5" x 7.5" x 1.5", and the indoor power transformer is an external plug-in type unit. The lockable outdoor cabinets are constructed of zinc plated steel with powder coating and stainless steel hinges, and they come in three sizes. The respective dimensions for 8-12, 16-24 and 32-48 station models are 9" x 10.5" x 4", 10.5" x 9.5" x 4.5" and 14" x 12" x 4.5". The outdoor models include internal power transformers. The 16-station and larger models include flow sensor connectivity, station circuit testing and surge/lightning protection features. The station circuit current rating for the indoor units is 0.75 amperes and it is 1.5 amperes for the outdoor units. All models' station circuit terminals will accommodate wiring sizes from 12 to 20 gauge. The controller's program memory is non-volatile, and the time-keeping microprocessor chip uses a 3.3-volt coin-type battery that has a reported life of ten years.

Low volume rebate program prices are summarized in Table 1. (Retail prices are approximately 150 percent higher.) The prices include the solar and rain sensors. The controllers are available directly from WeatherSet by telephone (818-993-1449) or e-mail (www.weatherset.com). The company plans to also distribute the product through select specialty irrigation contractors. The Smart Timer controllers come with a 3-year warranty.

Table 1 - Accurate WeatherSet Prices (Include Solar and Rain Sensors)

Controller Type	Model No.	Price
8-Station Indoor	ST8R	$148
12-Station Indoor	ST12R	$168
8-Station Outdoor	ST8C	$240
12-Station Outdoor	ST12C	$275
16-Station Outdoor	ST16C	$320
24-Station Outdoor	ST24C	$480
32-Station Outdoor	ST32C	$640
40-Station Outdoor	ST40C	$800
48-Station Outdoor	ST48C	$960
Solar and Rain Sensor Unit		$50
Irrigation History Function	H-option	$35

Installation

WeatherSet reports that 95 percent of homeowners included in the Municipal Water District of Orange County rebate program using the Smart Timer installed the controller themselves. Based on this, it appears that the typical homeowner can understand and program the WeatherSet Smart Timer. Technical support is available by telephone and through the company's internet site. Service by factory-trained contractors is limited to California, Oregon, Washington, and Colorado at this time. WeatherSet reports this area will grow as their market expands. The installation and programming instructions, which include directions for locating the solar sensor, appear to be adequate and easy to follow.

Track Record, Water Savings and SWAT Testing

WeatherSet has provided data showing close correlation between ET estimate calculation by their controller and that calculated by an AZMET (Phoenix, Arizona ET network) weather station. A graph of this data is shown in Figure 1.

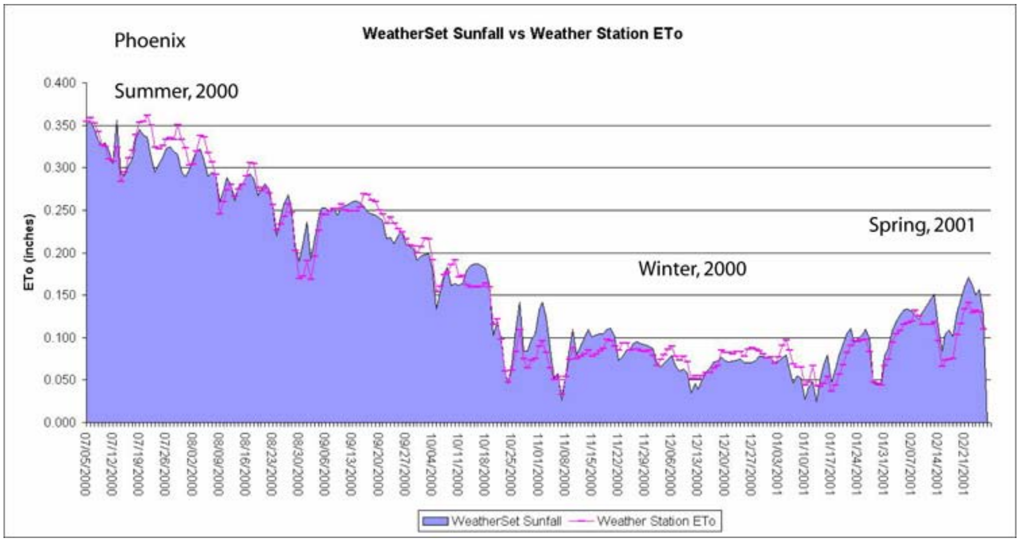


Figure 1 - Accurate WeatherSet ET compared to AMETS ET

WeatherSet controllers have not been included in any formal demonstration studies and no water savings data were evaluated for this report. A SWAT test performance report for the Smart Timer controller was not available for this report. The WeatherSet controller appears to be a simple and relatively economical stand-alone weather based irrigation controller which comes with onsite rain and solar sensors.

AccuWater

AccuWater, Inc. was incorporated in October 2002 and is based in Austin, Texas. The company has developed a centralized, weather-based irrigation management system for residential and commercial property applications. The AccuWater system has been in development since mid-2000 and pilot testing was performed from October 2002 through July 2004. The company has been actively marketing their system within Texas since July 2004. Sales outside of Texas began in July 2005.

AccuWater™ is a network-centric irrigation control system that is based on the latest Internet hardware and software technologies. AccuWater controllers are designed to irrigation industry standards and connect directly to all 24 VAC valves, replacing any existing “clock.” The AccuWater data center is located in Austin, Texas in a professionally managed Internet co-location facility. Communication and data transfer between the controllers and the data center is accomplished through an Internet connection.

Currently supported configurations include: wireless (802.11b/g), wired (Cat5 Ethernet), GPRS (digital cellular) radio.

The AccuWater system schedules irrigation based on calculated soil moisture in each irrigation zone. Soil moisture is updated hourly for each zone taking into account local weather (rainfall and ET) and actual irrigation (as reported by the AccuWater controller). To ensure the accuracy and timeliness of the weather data, AccuWater utilizes a combination of attached weather sensors and publicly available weather sources including the National Oceanic and Atmospheric Administration (NOAA), the California Irrigation Management Information System (CIMIS), and the Missouri Agricultural Bulletin Board (AgBB). A backup schedule, based on recent ET, allows the controller to irrigate for up to 21 days without network connectivity. This schedule can be modified through an ethernet computer connection to the controller.

One of the unique attributes of the AccuWater system is that it can share weather data between nearby units via the AccuWater data center. The AccuWater controllers send weather data to the data center, and the data center fills in missing data elements from nearby sites by searching a pre-defined hierarchy. The server then sends each controller a complete weather context for that location including temperature, humidity, barometric pressure, wind speed and rainfall. As a result, AccuWater controllers can receive current weather conditions and make decisions (adjust, delay or abandon) without the benefit of on-site weather sensors.

Operational Features

AccuWater controllers are configured and managed by the end user on the company's website.

Configuration information for each controller includes:

- Location (latitude, longitude and elevation)
- Environmental limits (temperature and wind speed)
- Watering window (including "no water" days)

Configuration information for each zone includes:

- Plant type
- Soil type and depth
- Precipitation rate
- Flow rate
- Distribution efficiency
- Sun and rain exposure
- Cycle-and-soak
- Soil moisture depletion limit
- Minimum and maximum irrigation limits

Controllers can be grouped into "locations" and any location can be delegated to another user (free accounts) or to one of AccuWater's landscape maintenance partners. This allows owners to maintain control and monitor water usage while simultaneously allowing authorized third parties to manage AccuWater systems remotely. AccuWater provides a free, cell phone remote control program. This program enables the end user (or their authorized delegate) to access and control his/her AccuWater controller from anywhere.

At 6:30 pm local time each day, the AccuWater data center calculates a one-time-use irrigation event for each irrigation zone based on calculated soil moisture and the National Weather Service (NOAA) local rain forecast. If the forecast includes a high probability of rain and soil moisture levels allow, irrigation may be deferred for 24 hours. Irrigation events are sent to and stored on the controller for execution during the watering window. If weather conditions are not appropriate for irrigation, the controller will wait for conditions to improve. If conditions do not improve before the watering window closes, no irrigation will occur. In the event data are not available, a 21-day back-up schedule is calculated based on recent ET.

Descriptions, Prices and Warranty

The model R116 AccuWater controller is an indoor unit with a 16-station capacity, including one station terminal that may run concurrently with all the other stations to control a master valve or pump start relay. The controller housing is constructed of injection-molded ABS plastic, and the transformer is external to the controller. The station circuit terminals will accept 14 gauge and smaller wire sizes and the station circuit current rating is 0.75 amperes. All AccuWater controllers include percent adjust, syringe cycle, distribution setting features and surge and lightning protection. The retail price for the R116 controller is $549. Up to three R116 controllers can be interconnected to create 32 or 48 station units.

AccuWater also sells commercial grade 16, 32 and 48 station models in ventilated outdoor steel enclosures priced at $1099, $1699 and $2499, respectively. The outdoor unit has an internal transformer with 2.0 ampere circuit capacity. The optional GPRS radio is priced at $495 and requires an Internet wireless plan from T-Mobile or Cingular.

Annual service fees start at $149 for 16 stations. Fees are based on the number of equipped stations at a "location" and the cost per station declines as the number of stations increases. A location is defined as a contiguous property under a single owner/operator.

AccuWater's circuitry is based on a 75 megahertz Java-based central processing unit. It has one megabyte of volatile storage and 4 megabytes of non-volatile memory, as well as a 10-year lithium ion battery just for the onboard clock. All configuration and operating data for AccuWater controllers are stored in the AccuWater data center. After a power or network interruption, the controller will synchronize itself with the data center. If a connection to the data center cannot be made, the controller will reload its operating program and configure data from non-volatile memory.

To ensure accurate rainfall data, AccuWater recommends the use of their wired, tipping bucket rainfall gauge ($150). The gauge is commercial grade and is constructed of UV-resistant, heavy-gauge, white nylon. AccuWater also offers temperature, humidity, barometric pressure, wind speed/direction and solar radiation sensors for direct connection to the controller. Additionally, AccuWater controllers can utilize real-time weather data from Campbell Scientific Turf Weather and WeatherHawk weather stations over an Internet connection. In the absence of a local weather station on the AccuWater network, the system will automatically utilize data from NOAA, CIMIS or AgBB. Other state-wide weather networks will be integrated as needed.

AccuWater provides a one-year limited warranty on their products. AccuWater products are currently available directly from the company or from AccuWater-certified irrigation contractors.

Installation

AccuWater reports that many homeowners are capable of installing and configuring the controller, but professional installation is recommended. The AccuWater website (www.accuwater.com) provides a step-by-step guide to installing and configuring the product. Technical support is available by telephone at 512-331-9283 and through the company's website, and local technical service representatives are available for service calls.

Installation of the AccuWater system involves (1) installing the AccuWater controller in place of the existing controller; (2) installing weather instrument(s) and connecting to the new controller; (3) performing an initial site survey to determine flow and precipitation rates; and (4) configuring the stations and performing a test run of all stations.

Because of its Internet-centric design and web-based controls, the AccuWater system integrates easily into most home automation systems. As of this writing, the following companies have committed to integrating AccuWater into their whole-home automation solutions: Crestron, AMX, Control4, Vantage Controls and Convergent Living.

Track Record, Water Savings and SWAT Testing

As of November 2005, AccuWater had accumulated over 700 controller-months of operating data. AccuWater reports its analysis of these data suggest that average water savings are in the 30 percent range, with individual controllers yielding savings as high as 55 percent. The chart shown in Figure 2 is taken directly from the AccuWater web site for a residential property in Austin, Texas. It shows the AccuWater prescribed irrigation quantity relative to reference ET as reported by Texas A&M University.

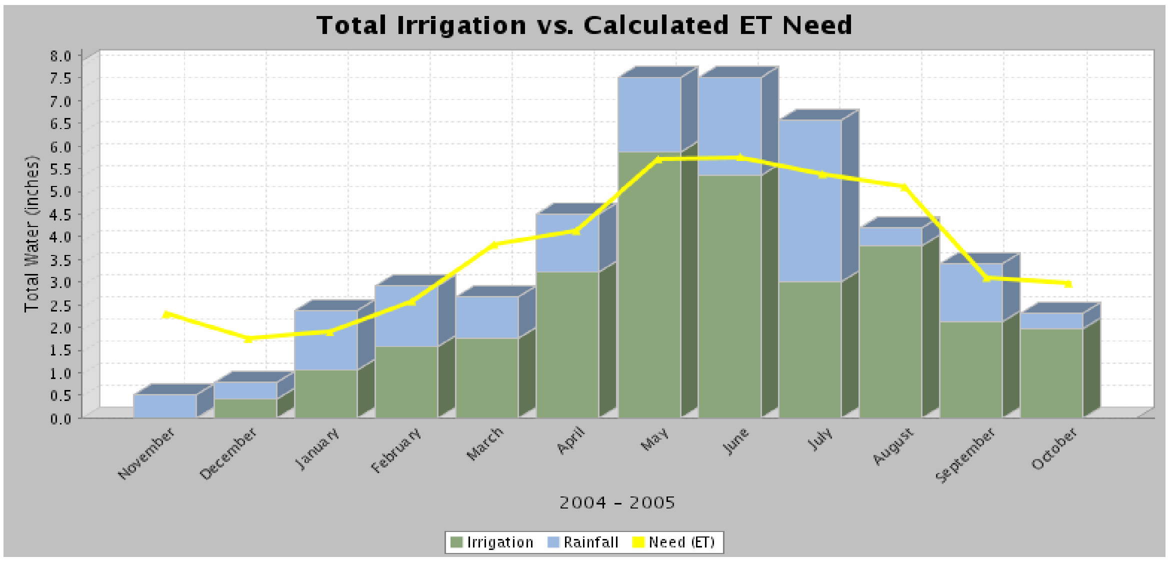


Figure 2 - AccuWater prescribed irrigation quantity relative to reference ET

The Accuwater System's computer interface provides an apparently easy and effective method for monitoring irrigation information and weather conditions. This system should satisfy the more demanding and affluent portions of the residential weather based irrigation controller market. Accuwater has not submitted its product for SWAT testing.

Alex-Tronix

Alex-Tronix® Controls is a division of GNA Industries, Inc. and is located in Fresno, California. This manufacturer of turf irrigation controllers was established in 1977 and specializes in battery operated controllers. The Alex-Tronix Smart Clock® and Enercon Plus are the industries' only battery operated weather based residential and commercial controllers, respectively.

The Smart Clock and Enercon Plus controllers entered the market in 2005 after 3 years of research and development. They are lithium battery powered controllers which operate using the temperature budgeting based Set It, Don't Sweat It® Program. The program incorporates a weather parameter estimation model developed at the University of Oregon known as PRISM (**P**arameter-elevation **R**egressions on **I**ndependent **S**lopes **M**odel). Daily irrigation schedules are calculated by the controller as a function of site latitude (radiation), real time temperature, and maximum annual high temperature. An optional rain switch is available which stops and prevents irrigation when significant rainfall occurs.

The Set It, Don't Sweat It program is based on a temperature budget theory. Once a schedule is programmed into the controller for peak summer irrigation, daily schedules are calculated as a function of the actual temperature for the day relative to the maximum annual temperature. Alex-Tronix believes this simple and logical programming concept is easy for the user to understand, thus encouraging proper utilization.

Operational Features

To program the Smart Clock, the site zip code is entered along with the peak summer irrigation schedule. A minimum irrigation temperature may be entered for cold regions to prevent irrigation during freezing weather. The schedule entered may be based on either days of the week or interval of days.

The key to optimizing this system is proper programming of the peak summer irrigation schedule. Appropriate station run times and soak cycles must be determined and entered manually. Once peak summer run times and the zip code are set; the temperature sensor is connected. The rain delay feature can be triggered manually or automatically, with an optional rain sensor, for an adjustable irrigation delay of up to 99 days.

Descriptions, Prices and Warranty

The Smart Clock controller is suitable for indoor or outdoor installation. It is powered by three 9-volt lithium batteries and is suited for residential applications with 6 stations plus a master valve terminal. Each station may be programmed for up to 4 cycles per day. This allows for the total station run times to be divided into multiple cycles in order to minimize run off. Specific days of the week or interval of days for irrigation may be programmed by the user.

The battery operation of the controller eliminates potential surge problems and burned out coils due to excessive voltage. The pulsed DC current eliminates capacitive problems associated with AC powered systems and galvanic copper wire deterioration caused by steady DC operation.

The standard Smart Clock is a locking powder coated 8.25” x 7.5” x 5.2” commercial grade metal enclosure. A stainless steel pedestal option for mounting the Smart Clock is available. The controller terminals will accept wire sizes up to 12 gauge. The station circuit capacity is 5 amperes. The controller includes a self-powered removable panel for programming at a convenient location. The controller’s high temperature rated liquid crystal display is 2.4” x 0.7” and is easy to read. The controller possesses a unique valve test function that allows cycling through each station for a programmed amount of time without the need to return to the controller.

The Enercon Plus includes all of the features as the Smart Clock and more, and provides more capacity with 4, 8, 12, 16, 20 and 24 station models. It comes standard with a stainless steel pedestal and internal temperature sensor. An external rain and temperature sensor is also available. The overall dimensions are 35.6” x 7.5” x 5.1”. This arrangement provides a large wiring area for ease of installation and service. Optional output board lightning protection is available for the Enercon Plus.

Alex-Tronix reports the current water and energy savings technologies used by the Smart Clock and Enercon Plus controllers are recognized and sponsored by the U.S. Department of Energy. Alex-Tronix controllers may be purchased through the recognized turf and landscape irrigation distributors Ewing, John Deere and Hughes. The current list price for the standard Smart Clock (with integrated temperature sensor) is $995. The optional stainless steel pedestal is listed at $995. The base Enercon Plus list price with stainless steel pedestal is $1,950 including a 4-station output module, and each additional 4-station module is $199. The optional rain and temperature sensor for pole mounting for either model is $149. Lightning protection for the Enercon Plus is $460.

The Smart Clock and Enercon Plus controllers both come with a two-year warranty, including the batteries.

Installation

Alex-Tronix reports installation and setup are reported to be easy, and it is reported that installation of the residential controller may be accomplished by most homeowners. The time required for an inexperienced user for installation and setup is reported to be 2 hours. An experienced professional should be able to install and setup the Smart Clock in one hour or less. Detailed step-by-step installation and setup instructions are included in the owner’s manual which is available with the controller and at www.alex-tronix.com.

The Alex-Tronix battery powered controllers are compatible with Hunter and Rain Bird latching solenoids as well as the Alex-Tronix latching solenoid. In general, they are compatible with nearly all currently manufactured valves.

Track Record, Water Savings and SWAT Testing

Alex-Tronix performed a five year analytical study comparing their Set It, Don't Sweat It temperature budget calculated irrigation demands at 25 locations to nearby CIMIS station reference ET. Results of the study are summarized in the graph shown in Figure 3. The plot shows monthly percentage of peak temperature budget demand compared to the monthly percentage of peak CIMIS reference ET.

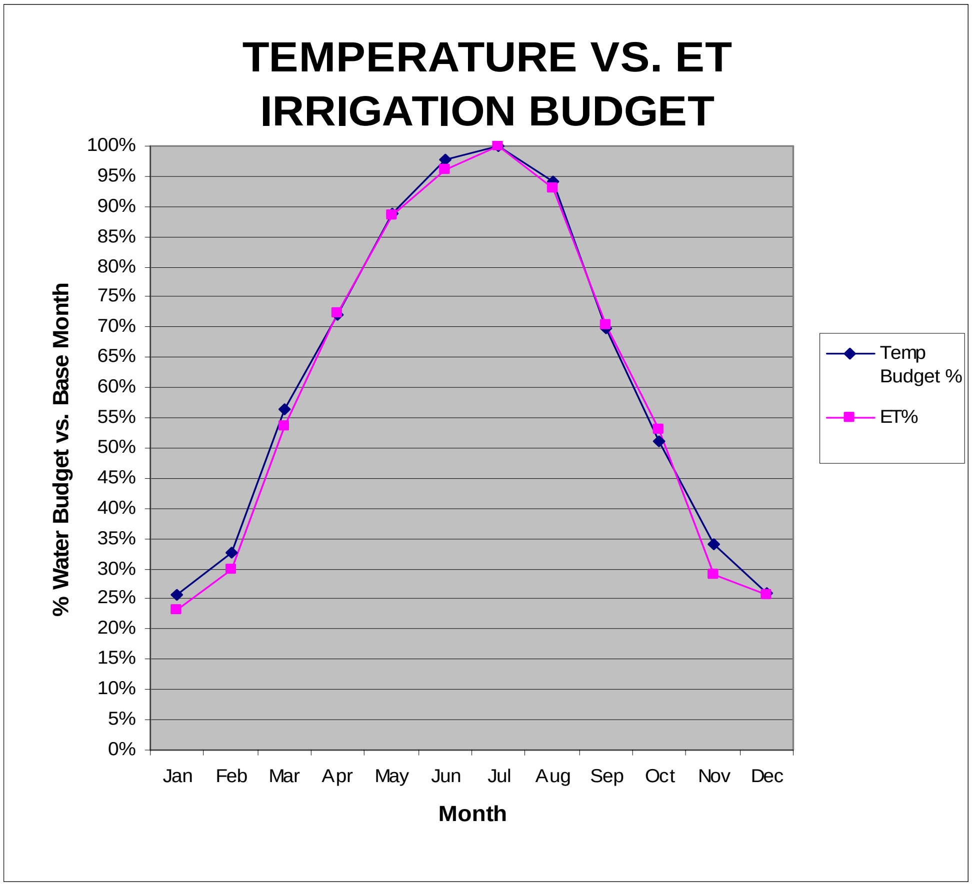


Figure 3 - Alex-Tronix temperature budget compared to CIMIS ET

The Alex-Tronix Smart Clock and Enercon Plus controllers have completed SWAT testing and performance summary reports are posted at the Irrigation Association website. These are the first battery powered controllers to complete SWAT testing.

Aqua Conserve

Aqua Conserve, Inc., located in Riverside, California has been in business since 1996. The company manufactures 5 residential ET controller models, a large variety of commercial ET controllers, and controller replacement panels and accessories. The Aqua Conserve® controller operation is based on adjusted historic ET data, with the adjustment made as a function of on-site temperature sensor readings. Combined rainfall/temperature sensors are included with some controller models and are available as add-on components for the other models which include only a temperature sensor.

Aqua Conserve's residential and commercial controllers have been on the market for approximately 8 years. Three indoor residential models are available, which accommodate 6, 9 or 14 stations, and the two outdoor residential models accommodate 8 or 12 stations. Aqua Conserve offers two types of commercial controllers, both of which come in wall mount and top entry models. The commercial controllers are outdoor units and will accommodate from 16 to 66 stations. Aqua Conserve's basic commercial models come in 16, 24 and 32 station models. The ULTIMO commercial controller series offer additional features and include 16, 26, 36, 46, 56 and 66 station models.

Operational Features

Aqua Conserve's ET controllers are preprogrammed with 16 individual historic ET curves, each representing geographic regions within the states of Arizona, California, Washington, Nevada, New Mexico, Utah, Colorado and Texas. The user enters one of the 16 regions into the controller. The controller then makes automatic seasonal changes to the run-times based on the historic ET curves, and daily changes based on the onsite temperature sensor. July run-times are entered into the controller for each station by the user. Aqua Conserve provides suggested run-times that are specific for plant types and for either spray or rotor sprinkler heads. Suggested run-times for drip systems are not provided. The suggested run-times are available at Aqua Conserve's web site (www.aquaconserve.com) for each of the 16 geographic regions mentioned above. Refinements to the suggested run-times to compensate for soil, slope and shade conditions are also provided. Further refinement of run-times can be made based on visual observations.

The various Aqua Conserve controllers provide 4 programs that allow the user to specify different watering days for different stations. 4 to 8 start times are available for each program to allow for refinement of total run-times into multiple cycle and soak times to compensate for soil and slope conditions to limit run off. The maximum station run time is 99 to 240 minutes for the various models. The minimum irrigation frequency is once per week for low water plants. A new plant/landscape establishment option (2 additional non-adjusting programs) allows added watering by station for a specified period (1-60 days) to establish new landscaping, and then automatically reverts to the ET based schedule. The controllers include 1 to 4 station circuits that may run concurrently with all the other stations to control a master valve, drip system or other accessories. On residential and small commercial controllers, other stations may not run concurrently. On the ULTIMO controllers, up to 6 stations, on other programs, may run concurrently.

The actual irrigation run-times for a given day are dependant on the programming described above and an automatic adjustment made by the controller, which is based on the measured on-site average temperature and historic ET data. The controllers have an accumulation feature that eliminates short cool period run-times. The short cool period run-times are accumulated until 50 percent of the July run time has been reached and then irrigation will occur.

Descriptions, Prices and Warranty

Aqua Conserve commercial models come with a wired temperature sensor. Combined rain and temperature sensors are included with residential models and are an optional add-on with the commercial models. The combined sensors signal the controller once every second, initiating the rain delay (shut-off) function when significant rainfall is detected. In the rain delay mode, the controller will not re-initiate irrigation for at least a 24-hour period after significant rainfall has ceased. Depending on the duration of the rain event, the rain delay can cause the controller to interrupt irrigation for up to 5 days. The user also has the capability to trigger the controller's rain delay feature manually.

All controllers have non-volatile memory and a 9-volt back-up battery. The back-up battery powers the controller clock in the event of a power outage for the residential and basic commercial units. The ULTIMO controllers include a storage capacitor that maintains the clock in the event of a power outage. All of the controllers can be programmed when powered only by the backup battery. The controller terminals accept 12 to 18 gauge wiring.

The residential indoor controllers provide 4 programs and 4 start times, and the outdoor models provide 4 programs and 4 start times. Both have one station circuit that may run concurrently with all the other stations to control a master valve or drip system. The indoor models are constructed of plastic and the outdoor controllers are housed in lockable stainless steel cabinets. The indoor models' dimensions are 8.3" x 6" x 2" and the outdoor models' dimensions are 9" x 8.8" x 3.3". The controller panel features dial type controls and a 2-line LCD display. The indoor controller models have a station circuit current capacity of 0.5 amperes, and the outdoor models' station circuit current capacity is 0.75 amperes. All residential indoor controllers are powered through an external transformer (included with purchase). Residential outdoor units are hardwired to the electrical system and supplied with an internal transformer.

All commercial controller models are housed in lockable stainless steel wall mount or top entry cabinets. The top entry units are designed for placement on a concrete foundation and are vandal resistant. The ULTIMO commercial controllers include all of the features of the basic models, plus additional master circuits, flow meter monitoring and other features.

The basic wall mount commercial models are powered through an internal 24VAC transformer (included with purchase), and provide 4 programs and 4 start times. The basic top entry commercial models are powered through an internal transformer, and include 4 programs and 4 start times. The wall mount cabinet dimensions are 9.8" x 10.8" x 4.3", and the top entry dimensions are 34.5" x 17.5" x 11.5". All of the basic commercial models' panels feature dial type controls and a 2-line LCD display. The station circuit capacity for the basic commercial controllers is 0.75 amperes, and one station circuit may run concurrently with all the other stations to control a master valve or drip system.

All of the ULTIMO models are powered through an internal transformer, and provide 4 programs and 8 start times. The wall mount cabinet dimensions are 12" x 14.3" x 14.3", and the top entry dimensions are 34.5" x 17.5" x 11.5". The ULTIMO controllers provide for manual, semi-automatic and timed operations. The ULTIMO controllers can also detect leaks and excessive flows, and notify the operator or shut down the affected zone or master valve. Other ULTIMO features include water meter connections, large 4-line LED display, current and historic programming information access, ATM type push button programming, and start time stacking for all programs. The station circuit capacity for the ULTIMO controllers is 1.0 amperes, and they have four station circuits that may run concurrently with all the other stations to control a master valve or drip system. In addition, up to 6 programs can run concurrently.

All products are available directly from Aqua Conserve by telephone and Internet order, and through a limited number of local distributors. Controller retail prices are summarized in Table 2. The residential models come with combined rain/temperature sensors, which are available as on optional add-on for the commercial models. The additional cost for the wired rain/temperature sensor is $83.50. The commercial models come with wired temperature sensors. There is no ongoing service cost associated with these controllers, and All Aqua Conserve products come with a limited 3-year warranty.

Table 2 - Retail Prices for Aqua Conserve Controllers

Controller Description	Model No.	2006 Price
6-Station Indoor Residential Wall Mount	ET-6	$264
9-Station Indoor Residential Wall Mount	ET-9	$281.60
14-Station Indoor Residential Wall Mount	ET-14	$393.80
8-Station Outdoor Residential Wall Mount	ET-8B	$477.40
12-Station Outdoor Residential Wall Mount	ET-12B	$581.90
16-Station Commercial Wall Mount	ET-16B	$884.90
24-Station Commercial Wall Mount	ET-24B	$1,024.10
32-Station Commercial Wall Mount	ET-32B	$1,151.70
16-Station Commercial Top Entry	ET-16SP-1	$2,410.10
24-Station Commercial Top Entry	ET-24SP-1	$3,210.80
32-Station Commercial Top Entry	ET-32SP-1	$3,744.40
16-Station ULTIMO Wall Mount	ET-16u	$1,472.90
26-Station ULTIMO Wall Mount	ET-26u	$1,939.30
36-Station ULTIMO Wall Mount	ET-36u	$2,404.60
46-Station ULTIMO Wall Mount	ET-46u	$2,871.00
16-Station ULTIMO Top Entry	ET-16uSP-1	$3,531.00
26-Station ULTIMO Top Entry	ET-26uSP-1	$4,063.40
36-Station ULTIMO Top Entry	ET-36uSP-1	$4,595.80
46-Station ULTIMO Top Entry	ET-46uSP-1	$5,128.20
56-Station ULTIMO Top Entry	ET-56uSP-1	$5,660.60
66-Station ULTIMO Top Entry	ET-66uSP-1	$6,193.00

Installation

The findings of a 2003 study by the University of California Cooperative Extension indicate installation and programming of an Aqua Conserve residential controller is relatively simple and that the controller performed well (Pittenger et al., 2004). Professional installation of commercial controllers is recommended. Aqua Conserve provides toll free telephone technical support and provides technical information on their web site. Aqua Conserve will participate in training contract installers upon request. Aqua Conserve reports that their support system meets or exceeds industry standards and the installation and programming instructions reviewed for this report are complete and easy to understand.

Track Record, Water Savings and SWAT Testing

Reported outdoor water use savings for pilot studies with Aqua Conserve controllers, which were performed by the City of Denver, Colorado, Sonoma, California, and the Valley of the Moon Water District in Northern California were 21, 23 and 28 percent, respectively (Addink and Rodda, 2002).

SWAT test performance reports for Aqua Conserve controllers were not posted at the Irrigation Association's website at the time of this review.

Calsense

Calsense®, started in 1986, is a Carlsbad, California based company that manufactures water management systems for large commercial customers. Since its startup, the company has specialized exclusively in water management systems using weather-based irrigation, real-time flow monitoring, moisture sensors and a wide variety of communication technologies. Calsense markets its products to municipalities, school districts, universities, transportation departments, and other high volume landscape irrigators. Calsense provides free onsite training with its products, and emphasizes their commitment to customer service, support, and successful utilization of its products.

The Calsense ET2000e controller functions as either a stand-alone unit or as a field controller component for their water management central control system. The Calsense Command CENTER Software is the central component of the system. Although the ET2000e is a new product for 2006, its basic design is unchanged from its predecessor, the ET2000 and favorably improved from the ET1, originally introduced in 1993.

Operational Features

The ET2000e can automatically adjust daily irrigation schedules with onsite reference ET measurements from the optional Calsense ET Gauge, a Campbell Scientific Weather Station, California Irrigation Management Information System (CIMIS) real-time data, or with historic average monthly ET. (Use of weather station or CIMIS data require computer interface to calculate ET and communicate it to the controller.) CIMIS based historic monthly average values are preprogrammed into the controller, or the user can enter monthly values to serve as a back-up ET source. Measurements from an optional tipping rain bucket are incorporated into the irrigation schedule calculation to account for effective precipitation. Irrigation can be interrupted in the event of rain, and high winds with the use of optional switch type sensors. A soil moisture sensor can be used with the ET2000e also and override the decision determined through on-site ET. (See Calsense discussion under Soil Moisture Sensor Products section.)

In the ET scheduling mode, the user programs the controller's run times based on field knowledge for the time of year and soil moisture content. This base schedule is adjusted daily as a function of weather conditions. Monthly ET adjustment percentage factors are fine tuned for each station depending on plant types, sun/shade conditions, and soil moisture content. Crop coefficients can be entered as well, for each month for seven different kinds of plant material. Cycle-and-soak times are manually programmed into the base schedule to minimize runoff.

The Calsense ET Gauge is an automated atmometer for estimating reference ET for turf (tall fescue). The covered ceramic evaporator at the top mimics solar energy absorption and vapor diffusion resistance of irrigated plants. A reservoir below the evaporator holds distilled water. The evaporator draws water from the reservoir at approximately the same rate that grass removes water from soil by ET. Water drawn from the reservoir passes through a calibrated measuring vial and corresponds to 0.01 inch of ET. Electronic circuitry components sense when the vial is empty. It is then immediately refilled and the 0.01 inch event is marked by a switch-closure type pulse which is transmitted to the controller. The controller uses a 28-day ET table to calculate runtimes based on station precipitation rates. The ET Gauge operates on 24 VAC supplied from the controller. An optional stainless steel vandal proof enclosure is available for the ET Gauge.

Descriptions, Prices and Warranty

The ET2000e is available in 8, 12, 16, 24, 32, 40 and 48 station models. The controllers have two additional outputs for master valve and pump circuits. In addition, the controllers may be ordered with hardware and software for 4 additional 24 VAC outputs for the operation of lights, gates, water features, etc. at no additional cost. These outputs are controlled independently from the irrigation programs.

The controller has 7 regular programs and several syringe/propagation programs. A maximum number of start times or repeats per station is determined by station total minutes (programmed or ET calculated) and by a fixed set run time per cycle and a fixed set soak time between cycles. The cycle-and-soak times are set manually. The user selects 7, 14, 21 or 28-day watering schedules to accommodate watering requirements, and no-water days can be designated by program. Programs can operate simultaneously based on the system capacity of the mainline and flow management. The ET2000e is typically installed by a landscape contractor and then Calsense provides assistance programming assistance to the user following the landscape establishment period.

A Calsense Model FM flow meter can be connected to the controller to continuously monitor flow through the irrigation mainline and learn each station's flow rate automatically when irrigation occurs. This feature detects and alerts the user to mainline breaks, no flows, high flows (due to broken risers and pipe) for each individual station, and low flows due to pressure drops, malfunctioning valves, and or clogged heads.

An optional remote control receiver board is integrated into the ET2000e allowing the user to activate valves and view operational details without going to the controller. The Calsense Remote SENSE remote control transceiver allows the user to view valve-on, area description, flow rate, electrical use and remaining time.

A water volume budget feature determines when monthly use, with projected usage, will exceed the programmed monthly budget and alerts the user before the month ends. This capability helps maintain water rates and keep staff accountable to a water management program. Table 3 and Figure 4 show data from an actual site that demonstrates the utilization of the water budget feature, and shows the correlation between historical and measured ET. The adjusted budget shown is the result of the automatic scheduling performed by the controller. The controller also possesses a laptop computer interface for field uploads and downloads so that detailed reports can be produced and potential expansion to a central system can be evaluated.

Table 3 - Calsense ET2000e water budget feature data

Date	# of Days	CONTROLLER HISTORICAL ET	*ACTUAL ET TABLE	ADJ %	**CONTROLLER BUDGET GALLONS	***ADJUSTED BUDGET GALLONS	****USAGE ACTUAL GALLONS	SAVINGS GALLONS	PERCENT SAVED
Jan-2004	31	2.17	1.96	-10 %	135,997	122,836	124,985	-2,149	**-2 %**
Feb-2004	29	2.61	2.51	-4 %	156,722	150,717	93,164	57,553	**38 %**
Mar-2004	31	3.41	3.30	-3 %	199,228	192,801	170,397	22,404	**12 %**
Apr-2004	30	3.30	4.03	22 %	206,679	252,399	203,713	48,686	**19 %**
May-2004	31	4.34	4.46	3 %	264,385	271,694	235,704	35,990	**13 %**
Jun-2004	30	3.90	3.59	-8 %	238,227	219,291	187,099	32,192	**15 %**
Jul-2004	31	4.65	4.86	5 %	276,207	288,681	255,869	32,812	**11 %**
Aug-2004	31	4.65	4.58	-2 %	276,606	272,442	224,724	47,718	**18 %**
Sep-2004	30	3.90	4.59	18 %	232,492	273,625	221,700	51,925	**19 %**
Oct-2004	31	3.41	2.91	-15 %	196,724	167,879	103,225	64,654	**39 %**
Nov-2004	30	2.10	2.17	3 %	133,555	138,007	84,064	53,943	**39 %**
Dec-2004	31	1.86	2.04	10 %	116,526	127,803	63,363	64,440	**50 %**
TOTAL	366	40.30	41.00	2 %	2,433,348	2,475,614	1,968,007	**507,607**	**21 %**

ET values and usages set to zero when budget is zero
*County and city settings for controller are San Diego and San Diego
** Controller Budget was Calculated at 100% of Controller Historical ET.
*** Adjusted budget uses actual ET to modify the controller budget.
**** Usage based on: Test usage, manual usage, scheduled usage, radio remote usage

Extensive current and historic irrigation information can be viewed at the display or downloaded from the controller. The controller monitors and keeps a record of all site water usage by month for up to 2 years. Scheduled irrigation usage is recorded on a station-by-station basis and on a total controller basis for the current month and the previous month. Unscheduled water usage (pressing the manual water or test key), and non-controller water usage (e.g. quick-couplers, manually bleeding valves, etc.) is recorded separately showing how the water is being applied.

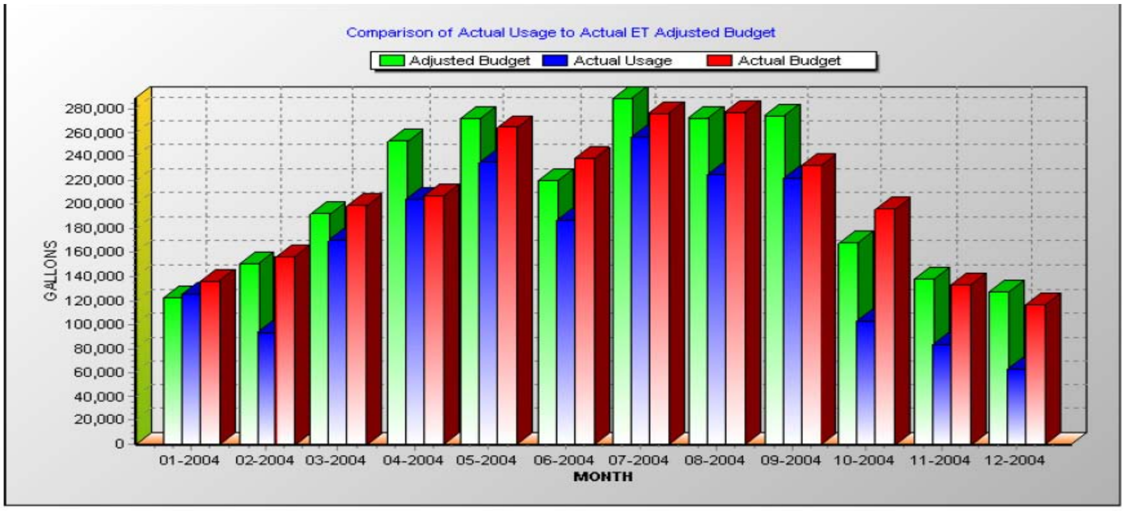


Figure 4 - Graph of Calsense 2000e water budget feature data

The ET2000e is a weatherproof wall mount unit and the cabinet is powder coated rolled steel. The front panel includes an ergonomic key layout and a large16-line by 40-character LCD display (English or Spanish). The cabinet dimensions are 11.4" x 11.1" x 7.3". The controller has non-volatile memory and the clock maintains time during power outages without the need for a backup battery. It is powered through an internal transformer. The controller accepts up to 14 gauge wire size, and the station current capacity is 1.5 amperes. Optional AC power line overload protection consists of a sealed unit suitable for outdoor installation and carries full UL approval. Optional transient (lightning and surge) protection is provided with the TP-1 board. The transient protection board can be purchased either with or without an outdoor cabinet. The ET2000e will detect, alert and identify open and shorted circuits in field wires and solenoids. The affected station is skipped until repaired.

Calsense products are available from many distributors located throughout the U.S. A list of these distributors is available from Calsense upon request (1-800-572-8608 or www.calsense.com). Current prices for all ET2000e models and certain accessories are summarized in Table 4. All Calsense products come with a 5-year warranty.

Installation

Calsense recommends professional installation of the ET2000e and installation time varies significantly depending on site conditions.

Track Record, Water Savings and SWAT Testing

Although Calsense has not participated in any outside studies or demonstration projects, its track record speaks for itself. During Calsense's 20 years of existence, they have developed a large data base on its products' performance and customer success.

Table 4 - Calsense Products Price Summary

Description	Model No.	Price
8-Station ET2000e Controller	ET2000e-8	$1,290
12-Station ET2000e Controller	ET2000e-12	$1,790
16-Station ET2000e Controller	ET2000e-16	$1,980
24-Station ET2000e Controller	ET2000e-24	$2,350
32-Station ET2000e Controller	ET2000e-32	$2,890
40-Station ET2000e Controller	ET2000e-40	$3,280
48-Station ET2000e Controller	ET2000e-48	$3,680
ET Gauge	ETG	$1,310
ET Gauge Controller Interface	-G	$435
Rain Gauge	RG-1	$575
Rain Gauge Controller Interface	-RG	$435
Wind Gauge	WG-1	$545
Wind Gauge Controller Interface	-WG	$435
Soil Moisture Sensor	1000-S	$199
1-inch Brass Flow Meter*	FM1B	$575
1.5-inch PVC Flow Meter*	FM1.5	$490
Transient Protection	TP-1	$265
Enclosure for TP-1	TPB	$199
AC Line Protection	TP-110	$165

* Other brass and PVC flow meter sizes are available up to 3-inches.

Calsense submitted data for this report prepared by their in-house research and development department showing average water savings of 22 and 33 percent for two typical installations. Calsense reports an overall average water savings rate of approximately 20-40 percent depending on past water usage and project history.

Although the controller models have evolved, the Calsense ET scheduling technology has been in place since 1992. Many of the Calsense systems installed since that time continue to function today. Several articles written by end users in Calsense's niche market testifying to the successful operation of their Calsense systems were submitted for this report. The ET2000e has completed SWAT testing and a performance summary report is posted on the Irrigation Association website.

Calsense provides potential clients with a reference list of all past and current users so that they can learn of their personal and professional experiences. In some cases, Calsense loans controllers to potential clients to demonstrate its system. The ET2000e provides a complete water management system as a stand-alone field controller, which can easily be expanded into a central control system.

Cyber-Rain

Cyber-Rain, Inc. came into existence in 2006 and is based in Oak Park, California. The Cyber-Rain XCI is a weather-based wireless stand-alone controller that works with the user's personal computer (PC) and adjusts irrigation scheduling based on weather forecasts downloaded from the Internet. Development of the Cyber-Rain XCI began in 2005 and the company received venture funding and began marketing the XCI in January 2007.

Cyber-Rain has incorporated several new technologies into its 8-station XCI controller. It uses a modern wireless mesh networking system (IEEE 802.15.4 ZigBee) to maintain two-way wireless communication between the controller and the user's PC located anywhere within 300 feet of the controller. Wire-free expansion of the system can occur by adding more controllers (for more zones) and devices such as wireless sensors (moisture, rain, temperature, humidity) and flow meters. The company plans to introduce these complimentary wireless products in 2007. The system adjusts a base irrigation schedule using information from a variety of Internet sources such as the Weather Channel and NOAA websites. Cyber-Rain is currently developing interfaces for local weather stations. The Cyber-Rain system concept is to use state-of-the-art technologies to conserve water and provide broad functionality while hiding the complexities of these technologies from the user.

The Cyber-Rain system allows full control of irrigation scheduling and offers water usage reports using a Windows® graphical user interface as shown in Figure 5. The system monitors weather forecasts and wirelessly transmits irrigation schedule adjustments to the controller. Two-way communication allows each controller's activities, such as manual or scheduled activation of valves, to be centrally reported to the PC and logged.

Operational Features

The Cyber-Rain XCI can be installed as a new controller or one that replaces an existing clock type controller. The XCI controller comes with a small wireless device called an Access Point that is connected to an internet-accessible PC's USB port to let the Cyber-Rain software wirelessly communicate with one or more XCIs. The XCI is programmed using the PC and all scheduling operations can be performed through the PC user interface. In addition, users have the option to operate the XCI using the buttons on the controller.

Cyber-Rain reports that after the initial setup and schedule entry, no further user intervention should be required. The system is designed to run "in the

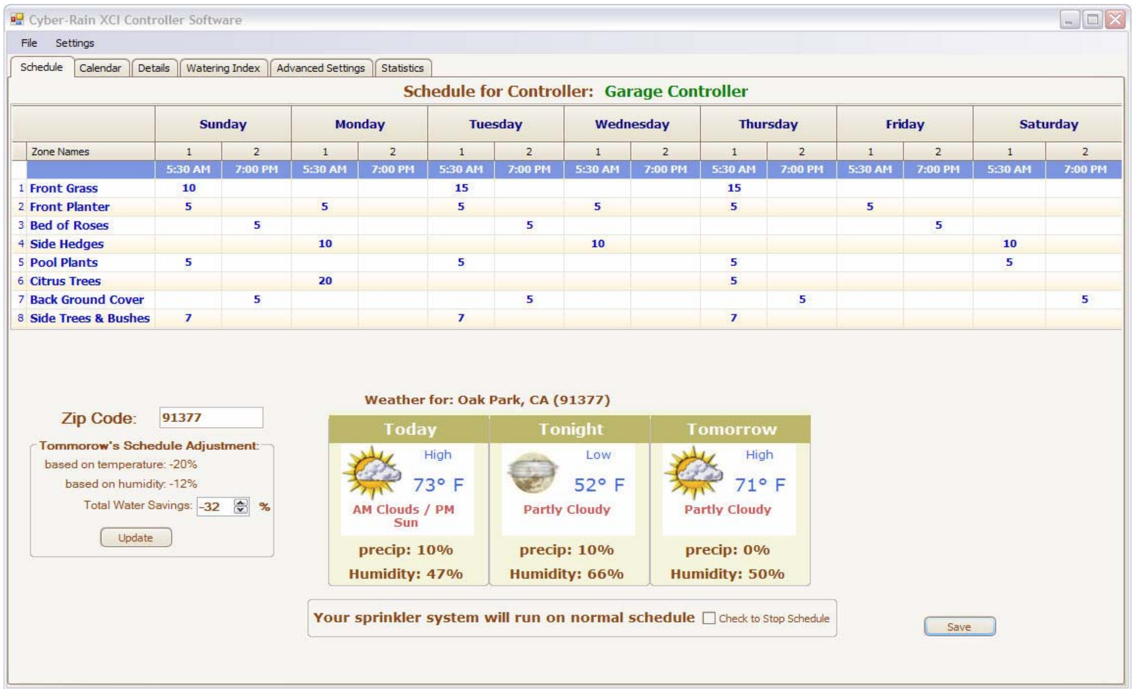


Figure 5 - Cyber-Rain graphical interface example

background" without interfering with any other PC operations. The system does not require that the PC is turned-on to operate, but the PC must be turned-on and connected to the internet for access to weather forecasts. The weather forecast is checked automatically via the PC's internet access and irrigation schedule adjustments are calculated based on temperature and humidity and transmitted to the controller. If rain is forecasted, irrigation is suspended until it stops raining. The suspension may continue to compensate for the duration of the rain.

The XCI includes a cycle and soak feature to eliminate or reduce run-off. Individual zones can be put on a temporary hold for a user-defined number of days. A fertilizer watering feature allows the temporary increase of watering for a user-defined number of days, and then the system returns to its normal schedule. An anti-freeze feature will automatically suspend all watering when the forecast temperature approaches freezing point. Cyber-Rain maintains a log of all water usage and displays a variety of water usage and saving statistics.

During normal usage, Cyber-Rain receives weather forecasts then schedules irrigation accordingly; however, if the PC is offline for many days (e.g., when the homeowner is away on vacation) the system reverts to irrigation schedule adjustments based on a built-in Watering Index. The Watering Index is based on historical temperature, precipitation and other weather patterns for a given geographical area. A graphical example of Watering Index settings are shown in Figure 6.

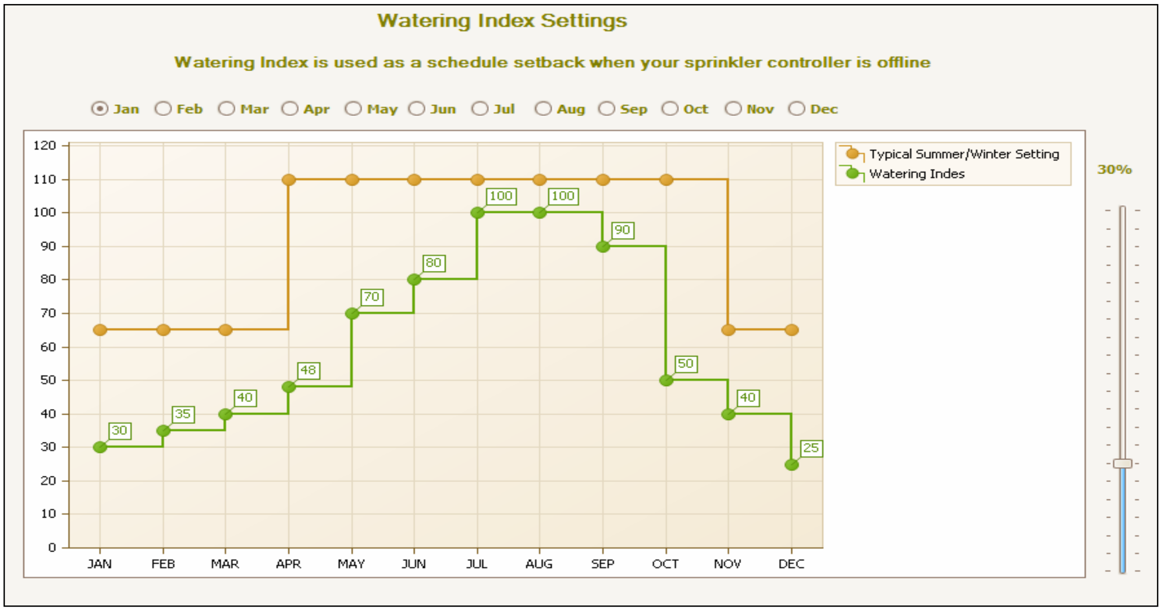


Figure 6 - Cyber-Rain Watering Index settings example

Custom zone names are entered by the user as text such as “Rose Bushes” or “Front Grass” and can be in any language. When the controller operates, the names are displayed. A base irrigation schedule is entered by the user consisting of irrigation days, total run times and cycle and soak times for each zone. Information on determining the base schedule is included in the Cyber-Rain user manual and there are shortcut keys to make the initial entry easier.

Cyber-Rain is designed with remote policy functions that can ensure automatic compliance with city or water district regulations such as limiting watering to certain hours of the day or blocking watering certain days. The system can “look-up” changes in these regulations and apply them immediately. Cyber-Rain can also aggregate individual watering and report, via a central internet reporting site, the percentage of water savings in a given geographical area.

Description, Prices, and Warranties

The Cyber-Rain system consists of one or more 8-station XCI controllers, a wireless USB Access Point device that connects to the user’s PC, and Cyber-Rain computer software. Additional controllers can be added at any time that will integrate through the original Access Control and are all controlled from the same Cyber-Rain XCI software. In this way any size property can be managed from a single PC’s user interface.

The XCI is constructed of fire-retardant ABS plastic and is suitable for indoor installation only. Its dimensions are 8.5” x 4.25” x 1.75” and it includes a 2-line by 24 character LED display panel. The XCI is powered by an external 24VAC transformer. Station circuit capacity is 1A and the controller accepts wire sizes up to 14 gauge solid or 16 gauge stranded. The XCI has non-volatile memory to retain programming during power outages and its clock is maintained during power outages with a super capacitor and real-time clock chip. Surge and lightning protection is provided with metal oxide varistors (MOV) and extra inductors on each circuit.

A single-controller system is priced at $295 and includes one Cyber-Rain XCI 8-zone controller, wireless USB Access Point, 24VAC transformer, USB cable, software, and user manual. Additional 8-zone controllers (including transformers) may be purchased for $245. Cyber-Rain has a 30-day “satisfaction or money back” guarantee, plus a 1-year limited manufacturer’s warranty. There are no monthly fees or additional charges. Software and firmware updates are free and can be downloaded from the Cyber-Rain web site.

Installation

Cyber-Rain reports a typical single-XCI controller system can be installed in less than one hour by anyone who knows how to use a PC. Cyber-Rain does not recommend professional installation.

Track Record, Water Savings and SWAT Testing

Cyber-Rain reports systems installed during January through June 2007 reported an average water savings of 36%. No study data are available on the Cyber-Rain XCI, which is understandable since it is such a new product. A SWAT test performance report was not posted for Cyber-Rain at the time of this review.

ECO Research

ECO Research LLC, located in Nampa, Idaho, began work on the weather based ECO 100™ Sprinkler Optimizer in January 2003. The first prototypes were tested during April to October of 2003. In 2004, production units were distributed for testing at additional locations. In 2005, the ECO 100 was introduced to the general market.

The ECO 100 works with any existing clock/timer controller to irrigate based on calculated ET. The device calculates ET from on-site temperature measurements and site location average solar radiation. No remote or historical data are used, and any industry standard rain sensor can be connected to the system to improve performance. The ECO 100’s ET calculation algorithm is based on the Hargreaves equation for estimating ET. The device is connected to an existing controller and interrupts the controller from irrigating until calculated ET accumulates to the appropriate level.

Operational Features

Hourly temperature sensor readings are logged by the ECO 100, and solar radiation is calculated as a function of minimum and maximum temperatures and site latitude. Latitude is entered during system setup as one of 5 zones covering all of the U.S. These data are used to calculate daily ET, and daily ET is accumulated to determine when irrigation should occur. When rain is detected by an optional sensor, the system will stop or prevent watering and adjust ET accumulation. ET accumulation adjustment is based on the amount of time the rain sensor is tripped, and an adjustable delay switch setting. The delay switch is set by the user during setup to delay ET accumulation from 0 to 7 days when the rain sensor is tripped. If no rain sensor is installed, the user can also manually enter a rain delay and cause ET accumulation adjustment.

The ECO 100 Sprinkler Optimizer is an add-on product that can be used with any existing electrical clock/timer type controller. The intent of this design is to minimize product installation and setup costs. It also simplifies operation since the existing controller is not replaced and it is not necessary for the user to learn a totally new system.

The ECO 100 manages watering by controlling watering frequency. This is accomplished by controlling the electrical connection from the common valve circuit to the controller. The controller is typically set to water every day, but watering will only occur when the ECO 100 has determined that the ET accumulation (soil moisture deficit) is equal to the last amount watered. The controller will water the same amount every time, but the frequency of irrigation is controlled by the ECO 100. The user adjusts the individual station times on the controller during setup, as recommended in the installation manual.

The recommended station run times are based on the sprinkler head application rate and irrigation of either 0.5 or 0.75 inches per watering. The manual provides instructions for measuring application rates, and discusses division of total run times to reduce run off. The method discussed for dividing total run times requires the user to observe the irrigation time which induces runoff and adjust accordingly. Specific adjustments based on soil, slope and shade conditions are not included in the manual. Consideration of soak cycles is also discussed. The Wetter/Dryer control is used to make minor frequency adjustments. This allows the user to slightly increase or decrease irrigation frequency as conditions warrant.

The ECO 100 may be programmed to only control certain stations of the controller. This allows the user to have stations irrigate at high frequency for plant germination, or for long run times to accommodate drip irrigation. The clock controller can be set to skip a day of the week and irrigation will occur the following day, if needed. The unit has a low temperature shut off which prevents irrigation at temperatures below 38° F. Watering history is displayed on the ECO 100, showing irrigation activity for the past two weeks.

The ECO 100 has no specific number of zones that it can control. The only limit is that the zones all have to be set to water in a single 24-hour period. This is because when the ECO 100 determines that watering is needed, it enables the connection from the station valves common circuit to the controller for 24 hours. There are existing installations with 36 station controllers. The ECO 100B Sprinkler Optimizer, planned for later in 2007, will enable watering for up to 48 hours. This will allow additional watering options such as the use of two programs watering on alternate days.

Description, Pricing and Warranty

The ECO 100 cabinet is a 4" x 6" x 1.5" extruded plastic unit and the panel includes a 2.6" x 0.6" two-line LED information display. The panel controls are touch pad type. A lockable steel weatherproof enclosure is available for outdoor installations. The ECO 100 has non-volatile memory and battery backup to retain all settings in the event of a power failure. A 24 VAC power supply must be provided by the controller to which the ECO 100 is connected.

The retail price for the ECO 100 is $198, as is the planned price for its upcoming replacement, the ECO 150. The weatherproof enclosure is priced at $79. The ECO 100 and accessories may be purchased from ECO Research or from its distributors which are listed at www.ecoresearch.com.

Installation

Installation and setup are reported to be easy, and may be accomplished by most homeowners. The time required for an inexperienced homeowner for installation and setup is reported to be 2-3 hours. An experienced professional should be able to install and setup the ECO 100 in one hour or less. Detailed step-by-step installation and setup instructions are included in the owners manual which is available at the ECO Research website (www.ecoresearch.com). Additional setup time (1-2 hours) is required to measure station flow rates if sprinkler head flow rates are not known. This procedure is covered in the owner's manual.

Track Record, Water Savings and SWAT Testing

During the development of the ECO 100, the ET algorithm was tested by comparing simulated EC100 ET to reference ET for an Orange County, California CIMIS station using the temperature data from the CIMIS station. The results of this test are shown in the graph included in Figure 7. The graph shows the ECO 100 calculated ET pattern generally follows that of the CIMIS ET.

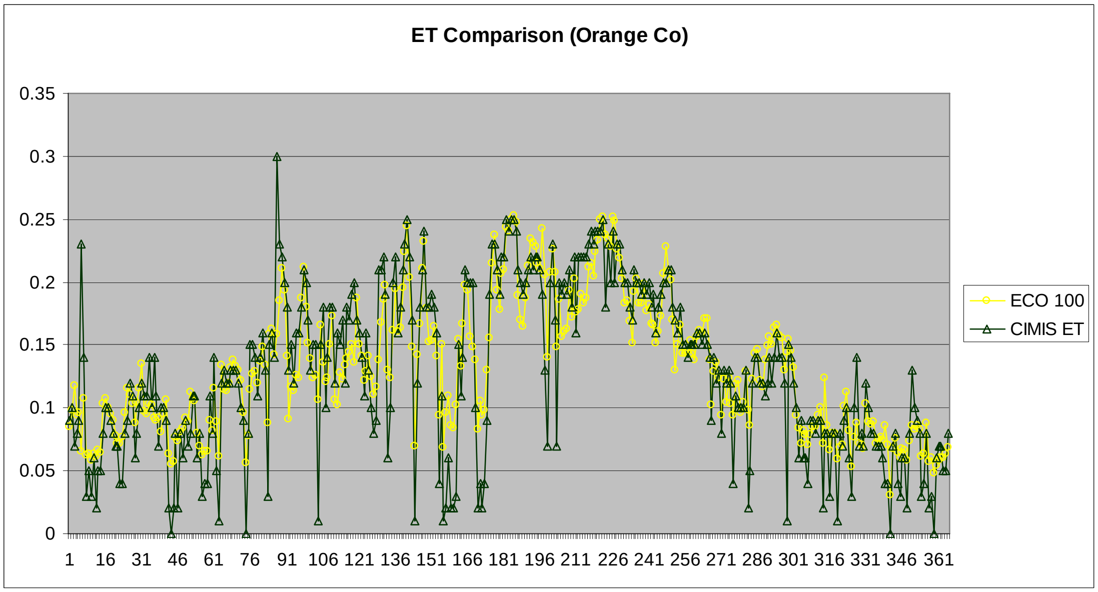


Figure 7 - ECO 100 calculated ET versus CIMIS reference ET

ECO Research reports water savings of 20 to 40 percent with the ECO 100, based on its own pilot testing. The ECO 100 is included in an ongoing study being conducted at Lake City Community College, Lake City, Florida. This study is comparing the performance of several ET and soil moisture based controllers and preliminary results are anticipated late in 2006. The ECO 100 is also included in an ongoing study being conducted by the Salt Lake City, Utah Department of Public Utilities. This study includes ease of installation, landscape appearance and water savings evaluations. Results from the Salt Lake City study will also be available late in 2007. A SWAT test performance report for the ECO 100 was not available for this report.

The ECO 100 provides a relatively economical weather based irrigation system control option, using real time onsite sensors.

ET Water Systems

ET Water Systems LLC, based out of Corte Madera, California, is a manufacturer of weather based irrigation controllers for the residential and commercial markets. ET Water™ controllers operate under its centralized weather-based irrigation management system. ET Water was incorporated in 2002 and began manufacturing controllers in March 2005. The company sells its system in California, Nevada, Colorado, Texas, Oregon, Washington and Idaho and plans to expand sales to other states.

The ET Water system schedules irrigation based on ET and precipitation data received from existing weather stations and user programmed information associated with specific landscape features. Currently, the ET Water system uses a data network of approximately 8,500 public and private weather stations, most of which are located in populous areas. ET Water controllers are sold in single station increments from 6 to 48 stations, thus the customer only pays for what it uses. Additional stations (up to 48) may later be activated by paying a per station fee. The ET Water commercial controller models begin at 12 stations, and the 2-way communication service offered with the commercial controllers provides features similar to a central control system.

With the ET Water System, ET and precipitation data are automatically retrieved daily from the weather station network by the ET Water's host server. The data are obtained from existing weather stations that provide localized weather, most often available at the town or even the suburb level in most metro areas. A WeatherBug® weather station can be installed on-site and the on-site data is utilized via the ET Water server as discussed below.

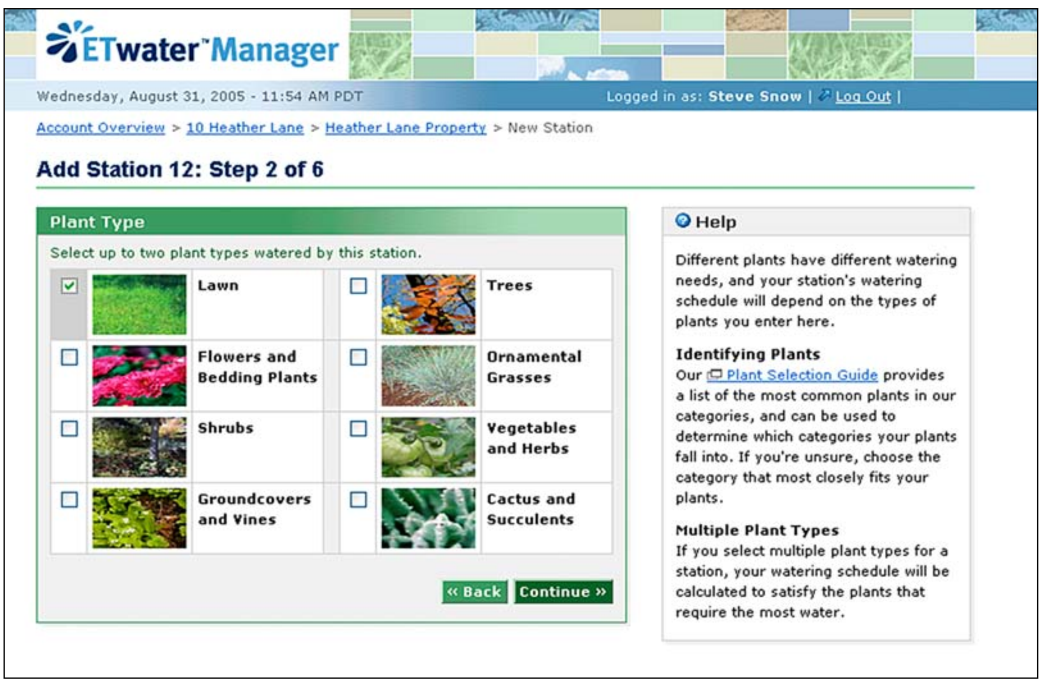
Operational Features

The ET Water server automatically processes the ET and rainfall data in combination with the user-programmed landscape information to develop irrigation schedules. The user enters the landscape information from any computer with an Internet connection via the ET Water website (www.etwater.com); however, a personal computer is not required at the installation site for the system to function. In commercial applications, the user may access special screens that enable selection of multiple accounts and thereafter select any controller or zone for each account. Scores of accounts may be accessed remotely from any computer at any time.

Communication between the user's controller and the ET Water server may be by wireless connection or land-based telephone link. Broadband access is planned for late 2007. The ET Water central server communicates with each field controller on a daily basis to send any required watering adjustments. In addition, all ET Water controllers send a 30-day log of all watering activity so users can review their watering history on the ET Water website. ET Water controllers can operate independently if communication to the server is temporarily interrupted. In such a case, the controller continues to operate using the latest schedule stored in memory, and then revises the schedule once communication is re-established with the server. The ET Water controller can accommodate schedules of any duration and frequency, including schedules that require watering on a very infrequent basis (e.g., every 30 days).

To enter landscape information, users go to the ET Water website and log into their account using a user name and password. The program interface to enter the site-specific landscape information is set up with a choice of either Windows® based pull-down menus or click-on picture options (e.g., plant type pictures) and it is intuitive and easy to use. The program is well organized and covers a comprehensive set of landscape factors including; plant type, irrigation type or optional application rate, soil type, slope, root depth, sun exposure and distribution uniformity. User-defined sprinkler precipitation rate (PR) and distribution uniformity (DU) may be entered or default measures may be selected in the absence of precise PR and DU information. A wide selection of plant types is available. Multiple plant types may be selected for one station and the program will automatically set the watering schedule based on the plants with the highest water requirement. Irrigation types available include spray, rotor, high efficiency matched precipitation rate rotors, impact, stream spray, drip emitter, bubbler and sub-surface inline tubing. The default distribution uniformity factor is 55 percent for pop-up spray heads. The user may specify customized distribution uniformity for any zone. All default settings can be changed at any time by ET Water.

The user may also enter non-irrigation days, adjust the total station run times by a percentage factor, and initiate manual irrigations by station. The user may review system and irrigation history information on the website. The ET Water setup program includes help screens to answer questions common to first time users. Once the user becomes familiar with the program, an advanced setup mode may be used which offers a more efficient means of programming. Adjustments to specific site factors may be made at any time via the ET Water website. Site factor changes will generate new irrigation schedules.



The ET Water controller also has an offline programming feature that allows users to manually set a watering schedule for each station. This feature is intended for use during periods when phone service is temporarily unavailable (e.g., a newly constructed home prior to sale). Offline programming may be performed at the controller using the keypad and the 2-line LCD display. The manual start mode may also be initiated at the controller. ET Water's objective is for the system to automatically generate and execute irrigation schedules. The need for program modification in the field is typically limited.

ET Water provides email alerts when there is a failure of communication between the field controller and central server. It also provides email alerts when manual adjustments are made on the field controller – the user may review such changes and override them remotely from any PC if desired.

ET Water Systems reports the irrigation scheduling algorithms it uses are based on current state-of-the-art horticultural science. The program reportedly incorporates all landscape factors needed to accurately determine soil moisture depletion and irrigation scheduling. ET Water uses a different algorithm for scheduling sprinkler and drip irrigation stations. The company's proprietary algorithms automatically generate daily schedules for each station with run and soak times based on a station's sprinkler application rate, soil intake rate, and slope conditions. The station run/soak cycles for each irrigation period remain constant, based on replenishment of a 50 percent plant root zone moisture depletion level. Irrigations are delayed until a soil moisture depletion level of 50 percent is calculated, based on the measured daily ET and rainfall. If the user desires more frequent watering, it may adjust the depletion level downward.

Descriptions, Prices and Warranty

All ET Water controllers are currently constructed of weatherproof fabricated aluminum enclosures with a key lock. Starting in 2008, ET Water will manufacture residential controllers with an injection molded plastic enclosure. In addition to the regular station circuits, the controllers provide a master valve/pump start circuit. The station circuit capacity is 1.1 amperes and the station terminals will accept 12-20 gauge wire.

The use of a standard rain sensor (approximately $59) will cause circuit interruption and suspend irrigations when significant rainfall occurs. In addition, ET Water enables online set-up and control of station-by-station fertilizer dispensing through the irrigation system. This is achieved by installing an EZ-FLO® fertigation tank that is wired to a terminal on the controller.

Remote monitoring features for commercial applications include email notification of any adjustments to a controller; such as suspend, power interruption, failure to connect to the internet, increase in percent watering for any zone and flow monitoring. For response to these occurrences, the user may remotely re-set or adjust these features from its PC.

An ET Water residential controller sells for approximately $499 to $549, depending upon the number of stations and the communication method – a 6 station telephone connected unit costs about $499, while a 12 station “powerline” connected unit sells for $549. The ET Water controller will accommodate popular brands of rain sensors or rain gauges. The annual residential service fee is $75 per year, but multiple year service plans reduce this amount as discussed below.

An ET Water commercial controller sells for approximately $1,219 to $2,399, depending upon the number of stations and the communication method – a 12 station telephone connected unit costs about $1,219, while a 48 station wireless connected unit sells for $2,399. The ET Water Manager Service includes daily watering schedule updates, telecommunication and wireless access charges, ability to remotely monitor and adjust the controller from any PC, email alerts in case of on-site problems, and online and phone-based customer service. The annual service fee ranges from $139 per year for commercial telephone connect to $199 for wireless connectivity.

Five and ten year service plans are available for both residential and commercial controller service, providing 33 and 50 percent savings off of the annual rate, respectively. This can bring annual service costs down to approximately $40 for residential service, and as low as $70 for commercial service.

ET Water offers panel replacements for certain non-weather based models of popular brand controllers. These panels make installation very rapid and sell for less than a full ET Water controller, saving the customer up to 40 percent off of the price of a new controller.

Since telephone or wireless communication allows two-way information transfer, ET Water can manage the information received from individual controllers. This may be beneficial to water agencies by allowing analysis of customer water use data.

Installation

ET Water Systems reports its controllers do not require professional installation, although the company recommends professional installation and will provide factory trained individuals or irrigation contractors to install all units. A typical professional commercial installation should take 1 to 3 hours, which includes a site assessment and discussion of the assessment with the user. Typical residential installations can be completed in less time. The professional installation/consultation cost is estimated to be $75 - $225 depending on location, size, and other site conditions. Technical support is available by toll free telephone (800-685-5505), in addition to the support provided on the company’s website.

Track Record, Water Savings and SWAT Testing

The ET Water system has completed SWAT testing and a performance report is posted on the Irrigation Association website. ET Water submitted information from three of its large commercial customers documenting significant water savings. ET Water reports overall average water savings in the range of 20 to 50 percent.

The ET Water Manager Service includes daily watering schedule updates, telecommunication and wireless access charges, ability to remotely monitor and adjust the controller from any PC, email alerts in case of on-site problems, and online and phone-based customer service.

The ET Water computer interface method of programming and monitoring the system is comprehensive and user friendly. The water use monitoring option should also be attractive to progressive water agencies interested in quantifying water savings.

Hunter

Hunter Industries was established in 1982 and is headquartered in San Marcos, California. Hunter® manufactures and distributes a full line of landscape irrigation products worldwide. Hunter introduced its ET System™ to the market early in 2006. The ET System consists of the ET Sensor (onsite weather station) and the ET Module (add-on irrigation scheduler). It is compatible with most Hunter irrigation controllers less than ten years old, including any Hunter controller equipped with a SmartPort™. The ET System is not compatible with other brands of controllers. Depending on the controller, the ET System is suitable for residential and commercial applications.

The ET System creates an irrigation program automatically based on weather conditions measured onsite. The programs are operated via the compatible irrigation controller and run automatically on water days and at start times set by the user. Compatible controllers include Hunter Models SRC/SRC Plus, Pro-C, ICC, and ACC with SmartPort® technology. The irrigation schedule is based on the ET Sensor's calculated ET value and programmed plant, soil, slope, sun/shade and sprinkler type information provide the basis for calculation of the irrigation schedule. The result is a new revised irrigation program every water day, based on the weather conditions measured onsite. Once installed, each zone is scheduled from the ET Module, rather than the controller itself.

Operational Features

The ET Sensor calculates ET by its daily measurement of solar radiation, air temperature, and relative humidity. The accuracy of the ET calculation can be improved with the addition of an optional anemometer (ET Wind), along with an automatic wind shutdown capability. The ET System will also shutdown irrigation if the air temperature drops below 35^{o} F. The ET Sensor includes a tipping bucket type rain gauge, which measures rainfall to one-hundredth of an inch. The user programs the ET Sensor to stop irrigation in progress at a specific rainfall depth, and a percentage of the rainfall is accounted for in the irrigation schedule. The ET Module calculates specific run times for each zone individually. The ET Module also possesses an optional wilt guard feature (Wiltgard™) that triggers irrigation when extreme temperatures occur if enabled by the installer. The user-selectable WiltGard triggers emergency irrigation (regardless of time of day) when the ET System determines that plants are threatened by monitored conditions.

To program the ET Module, the user first enters the type of controller used, date and time, water days and start times. Then the site condition settings are made for each station. These settings consist of plant type, soil type, sprinkler type, percent ground slope, sun/shade, and plant maturity. The rain sensor setting is programmed for the minimum amount of rainfall that will cause interruption of irrigation. The minimum shutoff setting is 0.02 inches and it is set in 0.01 inch increments.

Available plant type settings include numerous types of grasses, shrubs, ground covers, vines, trees, perennials and desert plants. Alternatively, a custom crop coefficient setting can be used in place of plant type. Available soil type settings consist of sand, sandy loam, loam, clay loam, silt, clay and silty clay. Soil type selection determines both infiltration rate (used for cycle-and-soak calculation, along with the slope setting) and water-holding capacity of the soil. Sprinkler type can be set to rotor, spray, drip, bubbler or custom. The custom option allows for entering a sprinkler application rate (0.01 inches/hour or 0.254mm/hour increments). The ground slope setting is by percentage. Available sun/shade settings consist of full sun, part shade (75 percent sun), part sun (50 percent sun) and full shade. The maturity setting is set to either new or established. With maturity set to new, the irrigation quantity is doubled and then decreases linearly to the normal or established rate based on the plant type. The ET source setting can be set to manual to override automatic ET calculation. The wilt guard feature is programmed either on or off (default out of the box is Off).

The ET Module is plugged into the controller's SmartPort, and once programmed; it uses the controller's Program "A" to create and run irrigation on water days (except with the Hunter ACC controllers where it works independently of any programs). Each day, the ET System evaluates the current soil moisture depletion level, ET rate, plant type (crop coefficient and root zone), and whether the next day is an allowable watering day. Then the system performs a "look ahead" on the allowable watering days, to see if not watering at that time would deplete soil moisture critically by the time a watering day is scheduled. Irrigation will not occur, however, if the calculated quantity is below the minimum irrigation amount, to prevent shallow watering. The calculation for minimum sprinkler runtime is based upon the soil type and capacity.

Descriptions, Prices and Warranty

The ET Module is housed in a weatherproof extruded plastic cabinet and it dimensions are 6" x 4" x 1.8". The ET Sensor standard model dimensions are 10.5" x 7.3" x 12", and the ET Sensor with ET Wind standard model dimensions are 11.5" x 7.3" x 20". The ET Module operates on 24 VAC from the controller's SmartPort and requires no additional AC wiring. It has non-volatile memory and a replaceable 10-year lithium battery.

The ET System is available from Hunter distributors worldwide and a distributor search engine can be accessed at Hunter's website. The retail price for the ET System basic model is $429, and the optional ET Wind is an additional $429. The price range for the ET System compatible Hunter controllers is from $115 to $799. The ET System comes with a 2-year warranty.

Installation

Installation and programming of the ET System can be performed by the user or irrigation professional. First time installation and programming for a typical setup is reported to require 2 hours. The ET Module is wall mounted near the controller and the ET Sensor is installed within 100 feet of the ET Module. The ET Sensor can be wall mounted or attached to a pole or eave. The ET System owner's manual is available at Hunter's website (hunterindustries.com). It contains detailed installation and programming information.

Track Record, Water Savings and SWAT Testing

The ET System's ET calculation algorithm uses the Modified Penman-Monteith equation. In creating the ET System's crop coefficients for the various plant type settings, Hunter has generally followed the principles of Water Use Classification of Landscape Species as prescribed on the State of California Office of Water Use Efficiency website (www.owue.water.ca.gov/index.cfm). Use in other states may require some adjustment for crop coefficients, which can be customized in the ET System.

The ET System has completed SWAT testing and a performance report is posted on the Irrigation Association website. The ET System was two years in development and beta testing. Hunter has had 10-15 years experience with ET-based irrigation, but this is its first ET System aimed at stand-alone residential applications.

Although Hunter did not provide water savings data for this report, it reports an approximate water savings of 30 percent, which is similar to the study results for other weather based irrigation control products discussed in this report.

HydroPoint

WeatherTRAK® ET is the line of residential and commercial weather based irrigation controller products by HydroPoint Data Systems Inc. of Petaluma, California. WeatherTRAK ET provides a wireless, real-time ET data service combined with the controller's Scheduling Engine™ software that updates irrigation schedules daily for each valve in a landscape. Network Services, which developed patents on the broadcasting of ET data used by HydroPoint, began business in 1997. HydroPoint was incorporated in 2002 and entered into a partnership with The Toro Company in 2003. Toro manufactures irrigation controllers under its name and under its subsidiary, Irritrol, which also use the WeatherTRAK system (see Toro and Irritrol sections).

HydroPoint's WeatherTRAK ET plus residential controller comes in 9, 12, 18 and 24 station models, and its WeatherTRAK ET pro commercial controller comes in 24 station models. The new WeatherTRAK ET Pro^2 commercial controller series provides 12 to 48 station capacity and integrated flow management. The irrigation scheduling features are similar for all models, but the commercial controllers offer optional 2-way communication ability and other features.

The WeatherTRAK system uses data from over 14,000 weather stations across the U.S., including the National Oceanic and Atmospheric Administration's (NOAA) network, state and county networks and private weather stations. The WeatherTRAK system uses advanced climatologic modeling techniques developed at Penn State University. This proprietary system is called ET Everywhere™, and has proven accuracy to a standard deviation of .01 inch of daily ET down to one square kilometer. The WeatherTRAK ET Everywhere service provides local ET (microzone) without the need for any additional weather stations or single sensors on a site. The WeatherTRAK system calculates ET using the standardized Penman-Monteith equation. The HydroPoint Data Center validates the weather data and transmits calculated ET through three satellite servers to each controller everyday. The three satellite servers provide over-lapping coverage of the U.S. to ensure signal reception to WeatherTRAK controllers located anywhere.

Operational Features

The WeatherTRAK ET controller calculates irrigation schedules for each independent valve on a site. The controller does not use pre-set irrigation schedules input by the user. Instead, it asks a series of questions to define the site variables that influence water need. The controller is programmed by entering the following station specific information: sprinkler type or precipitation rate, plant type, root depth, soil type, microclimate (sun or shade), slope (including if the valve is at the top, middle or bottom of the slope, and system efficiency (percentage). The schedule for each station is adjusted daily according to the local weather data received via the ET Everywhere service.

With these inputs, the WeatherTRAK ET calculates an irrigation schedule for each irrigation valve. Soil moisture depletion tracking, triggered at a 50% depletion level, along with daily ET updates allow the controller to adjust schedules as the weather changes. The number of water days, minutes and cycles (with appropriate soak times between cycles) are generated automatically and change as weather and water need fluctuates. The WeatherTRAK ET has an eight-week scheduling window. This allows for infrequent watering of low water use or native plants.

Programming options for all WeatherTRAK ET controllers include sequential stacking of overlapping start times, or the ability to run two programs simultaneously. The WeatherTRAK ET controllers have a manual feature providing any amount of time setting for plant establishment or to check the irrigation system on a valve by valve basis. An adjust feature provides percentage adjustments (in 5 percent increments) to increase or decrease the run time for any station. The controller accepts rain, wind, freeze and flow sensors and possesses a master valve circuit. A rain pause mode allows the user to shut-off irrigation for up to 14 days during or after rain. HydroPoint can also be contacted to automatically “rain pause” controllers and groups of controllers using the wireless data service. Non-waterering days can be selected. A “help” mode alerts the user to the WeatherTRAK customer service center toll free telephone number (800-362-8774) to answer questions and walk users through any situation occurring on the site.

Other features include inputs for crop coefficient values, community water restrictions (odd/even or selected watering days) and unlimited programs. The independent station adjust feature allows for individual station adjustments from

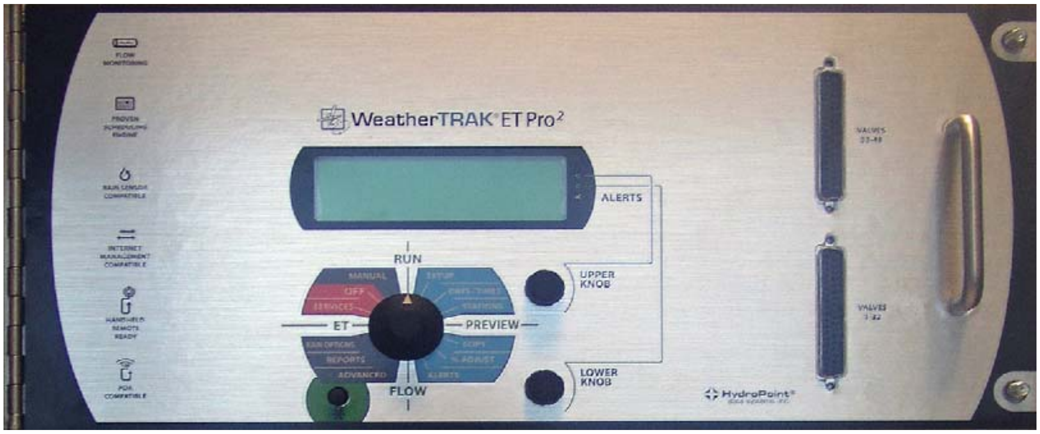
-50 to +25 percent in 5 percent increments. All WeatherTRAK ET controllers have heavy duty surge protection on the 24 VAC output board. The WeatherTRAK ET controllers have non-volatile memory and do not require a back-up battery to maintain date and time information. The controller terminals will accept 12 to 20 gauge size wiring. In some cases, an optional antenna is required to receive the scheduling signal.

Descriptions, Prices and Warranty

The WeatherTRAK ET plus is an indoor/outdoor residential controller. Its cabinet is of extruded plastic with dimensions of 8.6” x 11” x 4.7”. Programming is done with the programming dial, copy button, two selector knobs and three-line LCD display. The internal power transformer for the 9 and 12 station models includes a 2.0 ampere fuse, has a maximum total circuit capacity of 1.0 amperes and the individual station circuit current capacity is 0.375 amperes. The 18 and 24 station models include the same fuse and individual circuit capacity, but the total circuit capacity is 2.0 amperes. The 18 and 24 station models also include a manual valve test program to identify open valves and short circuits. A 2 year subscription to the ET Everywhere service is included with the purchase of 9 and 12 station models, and a 1 year subscription is included with the 18 and 24 station models.

The WeatherTRAK ET pro commercial controller comes in an indoor chassis model with dimensions 14.5” x 27” x 4” and two indoor/outdoor lockable stainless steel cabinet models. The wall mount cabinet dimensions are 8.5” x 18.5” x 8” and the front access pedestal cabinet dimensions are 16.8” x 30” x 8.3”. The ET pro does not include a typical front panel with programming access, but programming is done from a remote location using the WeatherTRAK.net service, as discussed below. Additional features included with the ET pro include automatic short circuit detection and alarm, programming conflict alarm, ability to run two stations concurrently, and additional circuit capacity. The ET pro comes with a vandal resistant antenna. The internal power transformer includes a 2.4 ampere fuse, has a maximum total circuit capacity of 2.4 amperes and individual station circuit current capacity of 0.5 amperes.

The ET pro is compatible with the WeatherTRAK.net service that allows Internet-based irrigation control 24/7 with a secure web-hosted service. With WeatherTRAK.net, the user can manage single or multiple controllers from any location with access to the Internet. WeatherTRAK.net delivers instant



notifications of adjustments made in the field and enables fast, one-click synchronization. Through wireless, two-way communication, WeatherTRAK.net transmits real-time updates and system alerts to the user's personal computer, mobile phone or PDA (personal data assistant). HydroPoint sells a Hewlett Packard® iPAQ PDA with all necessary hardware and software to utilize Weather TRAK.net. A 3-month subscription to WeatherTRAK.net and ET Everywhere is included with the purchase of a WeatherTRAK ET pro.

WeatherTRAK ET controllers are available directly from HydroPoint or local distributors. A distributor search engine can be accessed at HydroPoint's website. WeatherTRAK ET controllers come with a 3 year warranty, and toll-free telephone customer service is available Monday through Saturday during business hours, and on-line customer service is available 24/7. A partial listing of WeatherTRAK ET controller list prices is provided in Table 5 (a complete price list is available from HydroPoint Sales through its toll free telephone number or website).

Table 5 - WeatherTRAK Controller and Accessories Prices and Fees

Description	Model	Price
9-Station Residential Controller	WTPLS-09	$549-$559
12-Station Residential Controller	WTPLS-12	$579-$589
18-Station Residential Controller	WTPLS-18	$759-$769
24-Station Residential Controller	WTPLS-24	$859-$869
24-Station Chassis Commercial Controller	WTPRO-24-CHA	$3,125
24-Station Wall Mount Commercial Controller	WTPRO-24-SSW	$3,325
24-Station Pedestal Commercial Controller	WTPRO-24-SSP	$4,525
Hewlett Packard iPAQ PDA	WT-PDA-KIT	$1,200
WeatherTRAK.net Annual Fee	CIM-PROC-24-1Y	$225
9-12 Station ET Everywhere Annual Fee	ETE-912-1Y	$48
18-24 Station ET Everywhere Annual Fee	ETE-1824-1Y	$84

Installation

Hydropoint reports the WeatherTRAK ET controllers do not require professional installation, although it is recommended. Typical installation times, as seen in public agency studies and distribution programs, range from 1 hour to 2.5 hours, depending upon the size of the landscape covered and mounting issues. Installation should include a site assessment, and discussion with the user about the site irrigation system and how the controller operates with the user. Technical support is available by a toll free number, at HydroPoint's website (www.weathertrak.com) or through field-certified contractors.

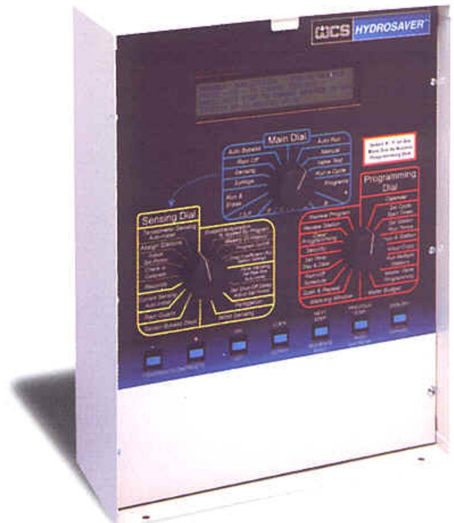
Track Record, Water Savings and SWAT Testing

WeatherTRAK ET has completed SWAT testing and a performance report is posted on the Irrigation Association's website. The WeatherTRAK ET controllers have been tested in 20 public agency settings since 1998. WeatherTRAK reports the overall results from these tests indicate significant water savings (16 to 58 percent) and reductions in runoff (64 to 71 percent). Information provided by WeatherTRAK about several of these studies is summarized in Table 6.

Table 6 - Summary of WeatherTRAK Demonstration Projects

Test Sponsor	No. of Test Sites
Irvine, California	180
Los Angeles Dept. of Water and Power	540
Boulder, Colorado	10
Colorado State University, Ft. Collins	3
University of Las Vegas, Nevada	15
Santa Barbara, California	200
Lake Arrowhead, California	78
Victor Valley, California	12
Marin, California	8
Park City, Utah	24
Santa Clara Valley Water District, California	125
Newhall County Water District	25

Hydrosaver



Water Conservation Services (WCS) Hydrosaver™, of Signal Hill, California, has been a manufacturer of water conservation based commercial landscape irrigation technologies for over 20 years. Hydrosaver entered the Smart controller market in 1992 with a soil moisture based controller. Its current ET controller, the ETIC, was introduced in 1994. The Hydrosaver ETIC functions as either a stand-alone controller, or as a satellite controller of a centralized control system, managed by WCS' partner HydroEarth Solutions. WCS developed its own electronic tensiometer soil moisture sensor, electronic rain sensor and ET sensor. It reports over 2,500 of their commercial weather based controllers have been installed, mostly in Southern California.

The ETIC controller comes in standard sizes from 12 to 56 stations and can be customized with the WCS Hydromaster to handle up to 164 stations. The ETIC adjusts irrigation schedules based on ET data received from the WCS Hydrosaver ET sensor. The controller comes with the ET sensor and the Hydrosaver Rain Guard™ rain sensor. Optional soil moisture and flow sensors may also be connected to the ETIC.

Operational Features

As a stand-alone controller, the user programs the ETIC with a base irrigation schedule. The base schedule includes irrigation days and run times. Total run times are entered for July and the controller automatically decreases the run times based on the accumulated ET sensor inputs since the last irrigation. The controller includes an ET percent feature that allows the user to vary the ET adjustment rate by program up to 300 percent, in 10 percent increments. The ET schedule adjustment function can be switched ON or OFF. The controller's ET scheduling feature is based on real time ET utilizing historical ET as a baseline. Historical ET data are programmed into the controller by the user.

The Hydrosaver ET sensor measures temperature, humidity and solar radiation. The controller calculates ET using these measurements. (The ET calculation assumes a 3 mph wind speed.) The ET sensor is in a vandal resistant housing and is maintenance-free. ET is calculated to within 100th of an inch using the Penman-Monteith equation. When the Rain Guard detects one-quarter of an inch of rain, irrigation is interrupted and the controller can be programmed for a rain delay up to 99 days. The Rain Guard includes a built-in bypass switch for controller testing during periods of extended rain.

The controller accepts Data Industrial or Fluidyne flow sensors. Once the user programs flow limits, the flow-sensing feature will trigger an alarm and shut off irrigation when flow limits are exceeded in the event of line breaks and valve failure. A shut off delay feature is provided and the flow sensing capability can also be used for fertigation purposes. The controller also possesses a faulty circuit feature that senses valve and wiring problems.

The ETIC includes 6 regular programs with up to 12 start times each. The controller has a valve test program and up to 4 stations may run concurrently. In addition to the regular station circuits, the controller has 3 independently programmable master valve outputs. There is also a pump start output that goes on with all irrigation. The controller automatically divides total run times into appropriate cycle-and-soak times to minimize runoff based on soil and slope conditions entered by the user for each zone. The irrigation schedule calendar options include 7, 14 and 28 day and even or odd day. Irrigation days can be specified and the controller has a watering window feature.

Descriptions, Prices and Warranty

The ETIC comes in standard wall mount models and complete stainless steel (CSS) top entry enclosure models The standard wall mount cabinet is constructed of rolled steel with dimensions of 12" x 16" x 6". The CSS dimensions are 16" x 14" x 36" and the enclosure must be mounted to a concrete foundation. Both models are designed for outdoor installation and are lockable, weatherproof and vandal resistant. The controller's 4-line by 48 character LCD display can be set to English or Spanish. Current and historic irrigation, ET, weather and flow information is displayed. All ETIC controllers include an internal transformer and the station circuit capacity is 2 amperes. The controller has non-volatile memory and the date and time information is protected without backup batteries. Surge and lightning protection is provided through a relay system to create circuit isolation protection, separate power transformers for controller processing and valve circuitry, MOVs, and an isolation transformer.

WCS Hydrosaver products are available directly from Hydrosaver and HydroEarth (949-636-7749 or hydroearth.com), or from commercial distributors. The current retail price for a standard wall mount 24-station ETIC controller with the Rain Guard and ET sensor is $1,800. A 24-station CSS controller is currently priced at $2,800. Prices for other controller sizes and accessories can be obtained from Hydrosaver or HydroEarth. The CSS controllers come with a 5-year warranty and the standard controllers come with a 3-year warranty. The warranties include free field service, with a renewable option.

Installation

According to WCS Hydrosaver, the ETIC should be installed by an irrigation professional. Installation and programming time will vary depending on system size and site conditions. Toll-free telephone customer support is available during business hours at 800-821-1322.

Track Record, Water Savings and SWAT Testing

WCS Hydrosaver reports its controllers are being included in several current studies including research work on wireless valves and ET controllers. Hydrosaver reports significant variance in ET measurements by multiple ET sensors tested within close proximity to a CIMIS weather station. Specifically, hill top ET measurements were found to be significantly higher than those at the bottom of the hill and at the nearby CIMIS site. A SWAT test performance report for Hydrosaver controllers was not available at the time of this study.

Irrisoft

Irrisoft Inc. offers weather-based control to residential and commercial irrigation systems through the Weather Reach Water Management System™. Established in 1999, Irrisoft™ became a subsidiary of Campbell Scientific Inc. in 2001 and has now partnered with Rain Bird Corporation to offer weather-based irrigation control solutions to both homeowners and commercial water users. Rain Bird® has a longstanding relationship with Irrisoft and Campbell Scientific, Inc.

The Weather Reach Water Management System provides wireless, real-time ET data to any standard irrigation controller through a Weather Reach Receiver. There are two "smart" receivers offered with this system; the WR-7 Weather Reach Receiver and the ET Manager™, which is offered through Rain Bird Corporation (see Rainbird Section).

The Weather Reach Water Management System uses Campbell Scientific weather stations with a full set of sensors to gather accurate weather data. The Weather Reach Signal Providers maintain computer servers with an Irrisoft computer software program to communicate with the weather stations (often using existing stations in an area), and broadcast weather information hourly through a pager network to Weather Reach Receivers. Data includes temperature, wind speed, relative humidity, solar radiation and rainfall. Weather Reach Receivers use this information to calculate ET accumulation on an hourly cycle, and process it into a running ET balance.

The WR-7 and ET Manager are used in combination with a user's existing irrigation controller to schedule irrigation based on ET demand. These receivers are compatible with any standard irrigation controller and interrupt irrigation until it is needed.

Operational Features

Weather Reach manages the frequency of irrigation and does not adjust run times. To help a user create an irrigation schedule for a controller, Weather Reach provides a free program called InSite Irrigation Scheduling™. InSite tailors the schedule to a specific sprinkler controller's capabilities as well as the capabilities of the sprinkler system and factors in the landscape dynamics such as plant type, soil type, root depth, slope and sprinkler precipitation rates.

Users enter the information through a series of questions that help to tailor the schedule to each station on the property. InSite performs all the calculations automatically but still allows a user to adjust any of the calculations for a custom schedule and gives users the opportunity to see how the calculations are made. InSite can also calculate accurate settings for programming the Weather Reach Receiver.

Once the schedule has been created, the user enters it into the sprinkler controller, and programs the Weather Reach Receiver with the proper settings. Weather Reach will then automatically manage the frequency of irrigation based on ET. Weather Reach Receivers can accommodate any available or non-available watering day requirement.

Most weather conditions are relatively constant over large areas, but rainfall can be very localized. A tipping bucket rain gauge is offered as an optional add-on component to a receiver to measure on-site rain as opposed to the rain measurement provided at the weather station. This allows the receiver to more accurately calculate the amount of water a landscape will need, and to interrupt irrigation when a user specified amount of rainfall occurs.

A growing network of Weather Reach Signal Providers exists throughout the U.S. For a covered area, data from multiple weather stations are received, processed, and then transmitted by a Signal Provider. The Weather Reach Receivers are programmed to receive data from the appropriate weather station based on a weather region code. The data are transmitted hourly by the provider using a Motorola® Flex® paging system.

Potential ongoing costs are dependent on the signal provider for a given area. Public providers typically absorb the cost of the weather stations, computer server and software, and paging system, and there is no ongoing user cost. Commercial providers pass on these costs to the end user. Private providers offer the service to a specific entity such as a Home Owners Association. A list of current Signal Providers is maintained at www.irrisoft.net. The typical price range for private providers surveyed for this report is $50 to $350 per year. Where a signal is not available, Irrisoft offers a variety of solutions to establish a public or private Weather Reach Signal. (Irrisoft should be contacted for details.)

The existing controller is programmed based on a plant root zone moisture depletion and ET threshold balance concept using the InSite software. This balance is maintained based on ET minus effective rainfall. This type of schedule will allow the root zone to dry out to a manageable level before irrigation occurs, and then irrigation is set to refill the root zone without over-watering.

The controller schedule is set to irrigate every day, unless certain days are to be excluded for a variety of reasons. The receiver then allows the controller to irrigate when the ET threshold is reached, and the prescribed irrigation amounts are applied to replenish the root zone depletion. The receiver includes two programs so that two ET thresholds and landscape adjustment percentages may be used. This provides for different stations to be scheduled separately to meet the needs associated with varying plant types and conditions.

Descriptions, Prices and Warranty

The WR-7 is a small (4.8” x 5.3” x 1.5”) plastic cabinet designed for indoor installation. A lockable fiberglass outdoor enclosure is available as an accessory for both receivers. In the event a power supply is not available from the existing controller, an optional power transformer is available. A 9-volt backup battery is included for operation during power outages. In some cases, an external antenna is required for the receivers. Receiver and add-on component prices are summarized in the Table 7. The WR-7 comes with a one year warranty.

Table 7 - Irrisoft Product Prices

Component	Model No.	Price
Weather Reach Receiver	WR7	$795
Pronamic Rain Gauge	WR-PRG	$165
Power Supply	WR-PS	$42
External Antenna	WR-ANT-B	$58
Outdoor Enclosure	WR-OE	$230

Installation

Irrisoft recommends installation by a professional irrigation system specialist, and it markets its products through specialty irrigation product suppliers. The typical installation cost ranges from $100 to $400.

Track Record, Water Savings and SWAT Testing

Irrisoft reports that during recent years, numerous demonstration projects using the Irrisoft System have proven its ability to save water. Irrisoft reports the overall results from these projects indicate water savings of 20 to 50 percent. A sampling of these projects is provided in Table 8. A SWAT test performance report for the WR-7 was not available at the time of this study

Table 8 - Summary of Irrisoft Demonstration Projects

Sponsor	No. of Test Sites
Denver Water Department	12
Utah Division of Water Resources	8
Northern Colorado Water Conservancy District	10
Southern Nevada Water Authority	10
EPA Evaluation Project (Massachusetts)	25
Aquasave, Ipswich, Massachusetts	118
WaterLogic, Houston, Texas	40

Irritrol

Irritrol™ Systems is a brand of professional irrigation products manufactured by the Toro™ Irrigation Division, located in Riverside, California. The Toro Company was established in 1914, and acquired the Irritrol brand of products in the early 1990s. The Irritrol Smart Dial™ series of residential and commercial weather based irrigation system controllers entered the market during 2005.

The Smart Dial controllers utilize the ET Everywhere™ subscription service and WeatherTrak™ scheduling engine to provide weather based irrigation control. Toro and Irritrol are partners with Hydropoint Data Services. Toro and Hydropoint controllers also utilize ET Everywhere and WeatherTrak, as discussed in the Toro and Hydropoint sections of this report.

The Smart Dial series includes six residential controllers, comprised of indoor and outdoor models for 6, 9 or 12 zones (plus a pump/master valve circuit), and a 24 zone commercial model. The controllers' WeatherTrak-enabled software creates a scientifically calculated zone-specific baseline irrigation schedule. The schedule is updated daily using weather data delivered by the ET Everywhere subscription service.

ET Everywhere uses data from the NOAA's system of 14,000 nation-wide weather stations to deliver ET to any area in the US. ET Everywhere has a proven accuracy to a standard deviation of .01 inch of daily ET at a resolution of one square kilometer. The ET Everywhere data service provides local ET (microzone) without the need for a weather station on site. The ET Everywhere Data Center validates the weather data and transmits calculated ET through three satellite servers to each controller everyday. The three satellites provide over-lapping coverage of the U.S. to ensure signal reception anywhere.

Operational Features

The Smart Dial controllers calculate schedules for each irrigation zone. The controller does not use pre-set irrigation schedules input by the user. Instead, a series of questions are answered by the user to define the site variables that influence water need. The controller is programmed by entering the following station specific information: sprinkler type or precipitation rate, plant type, soil type, microclimate (sun or shade), slope (including if the zone is at the top, middle or bottom of the slope), and system efficiency (percentage). The schedule for each station is adjusted daily according to the local weather data received via the ET Everywhere service.

With these inputs, the controller calculates an irrigation schedule for each zone. Soil moisture depletion tracking, triggered at a 50 percent depletion level, along with daily ET updates allows the controller to adjust schedules as the weather changes. The number of water days, minutes and cycles (with appropriate soak times between cycles) are generated automatically and change as weather and water need fluctuates. The controllers have an eight-week scheduling window. This allows for infrequent watering of low water use plants. The controllers can initiate irrigation even if the daily ET page is not received by using the last download and loop-up table included in the WeatherTrak software. Non-watering days can be specified in the controllers' schedule programming. The controllers are compatible with Irritrol's Wireless RainSensor™ series (rain and rain/freeze), which eliminate irrigation during rainfall and freezing weather if added as an optional accessory.

Descriptions, Prices and Waranties

Both the indoor controller models' cabinet is constructed of ABS plastic while the outdoor units are comprised of Lexan. The dimensions of the indoor models are 7.8" x 7" x 3.8" and the dimensions of the outdoor models are 7.8" x 10.8" x 4". The controllers have a large (3.5" x 0.8") LED information display, dial type controls, and a copy button for simplifying setup. All controllers include internal UL/CSA listed transformers. The current capacity for each zone circuit is 0.5 amperes, and the current capacity for pump/master valve circuit is 0.375 amperes. The controllers will accept wire sizes from 12 to 18 gauge. The non-volatile memory maintains programming, and the back-up battery maintains the date and time during power outages.

Other controller features include surge protection up to 6 kilovolts and valve malfunction detection. The irrigation schedule, irrigation history and program review can be viewed with the LED information display. In addition to the wireless rain and rain/freeze sensors, an external bow tie antenna kit, pump starter relay and wired rain sensor are available as optional accessories.

A snap-in Smart Dial Module is also available which directly interchanges with a users existing Rain Dial™ Plus controller panel to convert it to a WeatherTRAK-enabled controller. A converted controller possesses all of the same features as the Smart Dial controllers.

The Smart Dial controllers, modules and accessories may be purchased from authorized Irritrol distributors and retailers. Current controller, module and accessory prices are summarized in Table 9. Purchase of a Smart Dial controller requires a paid subscription to the ET Everywhere service. The ET Everywhere annual service fee is $48 for the 6 to 12 station controllers and $84 for the 24 station controller, as discussed in the Hydropoint section of this report. The Smart Dial products come with a 5-year warranty.

Table 9 - Irritrol Smart Dial Controller, Module and Accessory Prices

Description	Model	Price
6-station Indoor Controller	SD-600-INT	$399
9-station Indoor Controller	SD-900-INT	$449
12-station Indoor Controller	SD-1200-INT	$499
6-station Outdoor Controller	SD-600-EXT	$419
9-station Outdoor Controller	SD-900-EXT	$469
12-station Outdoor Controller	SD-1200-EXT	$524
24-station Outdoor Controller	SD-240-OD	$889
6-station Module	SD-600-MOD	$299
9-station Module	SD-900-MOD	$349
12-station Module	SD-1200-MOD	$399
Wireless Rain Sensor	RS1000	$85.33
Wireless Rain/Freeze Sensor	RSF1000	$114.71
Wired Rain Sensor	RS500	$25.20
Pump Starter Relay	SR-1	$75.60
External Bow Tie Antenna	SD-ANT	$87.50

Installation

The Smart Dial controllers and modules do not require professional installation, although trained installation is recommended. Typical installation times range from 1 hour to 2.5 hours, depending upon the size of the landscape covered and mounting issues. Installation should include a site assessment and discussion with the user about the irrigation system and how the controller operates. Installation and setup instructions are included in the owner's manual. Technical support is available from Irritrol at its website (www.irritrolsystems.com), by toll free telephone (800-634-8873) and through field certified contractors.

Track Record, Water Savings and SWAT Testing

Irritrol reports the technology behind the Smart Dial controller and module series is proven by several multi-year independent studies showing water savings. These studies were performed using Hydropoint's WeatherTrak controller and the ET Everywhere service. The studies are discussed in the Hydropoint section of this report.

A Smart Dial controller SWAT test performance report is posted at the Irrigation Association's website.

Rain Bird

Rain Bird Corporation, based in Glendora, California, began business in 1933. Over 4,000 Rain Bird® products are sold domestically and in more than 120 countries. Rain Bird owns more than 130 patents and 30 additional trademarks. For more than two decades Rainbird has used weather technology in the golf and commercial irrigation markets with their central control products, including the Maxicom™, SiteControl™ and Nimbus™ II systems.

Rain Bird recently joined forces with Irrisoft Inc., a Campbell Scientific company, to offer a weather-based solution for homeowners and commercial water users. The ET Manager™, or ETMi, is an add-on scheduler that works with an existing controller to manage irrigation frequency based on weather conditions. Rain Bird began field testing the ET Manager in the Fall of 2005 and it entered the market in June 2006. Its predecessor, Irrisoft's WR7 Weather Reach Receiver, has been in use since 2001. Rain Bird has used private-labeled Campbell Scientific weather stations for nearly 20 years with its central control systems.

The Rain Bird ET Manager uses weather information, typically from fully instrumented Rain Bird and or Campbell Scientific weather stations. The ET Manager receives the weather data in the form of an hourly broadcast through a paging network provided by a local Weather Reach Signal Provider. This approach enables thousands of users to benefit from accurate, reliable weather data from a single or network of weather stations depending on the size of the region covered. The weather data broadcast includes temperature, wind speed, relative humidity, solar radiation, and rain. An optional rain gauge is available for on-site rainfall measurement, and to interrupt irrigation when a user specified amount of rainfall occurs.

A growing network of Weather Reach Signal Providers exists throughout the U.S. Potential ongoing costs are dependent on the Signal Provider for a given area. Public providers typically absorb the cost of the weather stations, computer server and paging system, and there is no ongoing user cost. Commercial providers pass on these costs to the end user. Private providers offer the service to a specific entity such as a Home Owners Association. A list of current Signal Providers is maintained at Irrosoft's website (www.irrisoft.net). The typical price range for private providers surveyed for this report is $50 to $350 per year.

Operational Features

The ET Manager uses the ASCE standardized ET equation to calculate ET on an hourly basis and maintain a user specified soil moisture balance. Typically, controllers irrigate on time-based (day, time, and minutes to water) schedules regardless of changing weather and landscape needs, whereas the Rain Bird ET Manager interrupts the controller only allowing it to irrigate when calculated soil moisture levels reach user set levels. Historical ET is programmed into the ET Manager and used as back-up in the event the Weather Reach Signal is not received.

The ET Manager is compatible with nearly any existing standard irrigation controller by interrupting the common wire thus managing the frequency of irrigation. The Rain Bird ET Manager schedules the irrigation frequency (how often watering occurs), but not controller run times. Additionally, the ET Manager provides pulse output of ET and rainfall to compatible controllers (0.01-inch per pulse). This feature allows for automatic scheduling by the clock controller based on ET accumulation and rainfall amounts as reported by the ET Manager.

To help users create an irrigation schedule for an irrigation controller and program settings in the ET Manager, Rain Bird offers the ETMi Scheduler. This computer program tailors an irrigation schedule to a specific irrigation controller's capabilities, and the characteristics of the irrigation system. The user enters information for each station and landscape characteristics including plant type, soil type, root depth, ground slope, and sprinkler precipitation rates to create the schedule. All calculations are done automatically and the user has the ability to adjust any of the results for a custom schedule. Once a schedule has been created with ETMi Scheduler, it can be printed out and entered into the irrigation controller. The ETMi Scheduler program can be downloaded at no charge from Rain Bird's website (www.rainbird.com).

The optional ETMi Programming Software allows settings for the ET Manager to be programmed quickly and easily. Users select the appropriate local weather station, site elevation, and available watering days (the ET Manager can accommodate any available or non-available watering day requirement). When the required parameters have been entered, the user can transfer the settings automatically into the ET Manager through the cable supplied with the optional ETMi Programming Software kit. This kit is very convenient for professionals performing higher volumes of ET Manager installations.

The controller schedule is set to irrigate every day, unless certain days are to be excluded for a variety of reasons. The ETMi then allows the controller to irrigate when the Irrigation Amount is reached. The Irrigation Amount is the amount of water that is allowed to evaporate and be used by the plants before irrigation will occur. The ET Manager "enables" watering cycles to refill the plant root zone by applying the Irrigation Amount. The irrigation controller is programmed to apply the Irrigation Amount. By applying the Irrigation Amount, the root zone is refilled without over-watering.

The ET Manager includes two programs so that two Irrigation Amounts may be used. This provides for different stations to be scheduled separately to meet the needs associated with varying plant types and conditions.

Descriptions, Prices and Warranty

The Rain Bird ET Manager has a large graphic display and is designed for indoor installations for convenient viewing of hourly weather conditions, ET and irrigation amounts. Its dimensions are 5.6" x 6.5" x 2". A lockable outdoor enclosure is available as an accessory. In the event power is not available from the existing irrigation controller, an optional external power transformer is available. A 9-volt backup battery is included for operation during power outages. In some cases, an external antenna is required for the receiver.

Rain Bird products are available from irrigation supply distributors throughout the U.S. A distributor search engine can be accessed at Rainbird's website. Current suggested list prices for the ET Manager and accessories are summarized in the Table 10. All Rain Bird controller products come with a 3-year warranty.

Table 10 - Rain Bird ET Manager and Accessories Prices

Description	Model No.	Price
ET Manager	ETMi	$741.00
Optional ET Manager Antennae	ETM-ANT	$238.10
Optional ET Manager Outdoor Cabinet	ETMi-OE	$230.00
Optional Transformer Power Supply	ETMi-TRAN	$23.95
Optional Tipping Rain Gauge	ETM-RG	$200.00
Optional ETMi Programming Software Kit	ETM-PS	$603.18

Installation

Although installation by a Rain Bird trained professional is preferred, Rain Bird reports installation may be performed by some homeowners.

Track Record, Water Savings and SWAT Testing

Rain Bird has field tested 150 ET Managers throughout the U.S. and a SWAT test performance report is posted at the Irrigation Association's website for the ET Manager. Water savings information for the ET Manager's predecessor, the Weather Reach WR-7, is included in the Irrisoft section of this report.

The ET Manager combined with any standard irrigation controller should provide users with accurate real-time weather based irrigation scheduling and help maintain healthy landscapes.

Rain Master

For the past 25 years, Rain Master Irrigation Systems has specialized in the design and manufacture of commercial irrigation controllers, handheld remote controls, and central computerized irrigation control systems. Located in Simi Valley, California, Rain Master introduced its first ET based water management system in 1990. In 2002, Rain Master introduced the RME Eagle™, weather based commercial irrigation controller that functions either as a stand-alone unit, or as a satellite controller component of the Rain Master iCentral™ Internet-based system. The RME Eagle /iCentral system (Patent No. 6,823,239) was designed to address the single controller as well as low to mid-sized control system markets.

Rain Master provides several ET source options for the Eagle. ET may be manually entered into the controller; alternatively the controller may be directly connected to a Rain Master Weather Center II weather station, or receive CIMIS data. When configured with Rain Master's iCentral 2-way wireless card, ET may be disseminated over the Internet using Rain Master's ZipET national dissemination weather service, or California users may obtain their daily ET from CIMIS.

Operational Features

When the Eagle's programs are enabled for ET operation, station runtimes are automatically adjusted on a daily basis when connected to the Internet or a Weather Center II weather station. If daily ET is unavailable, the controller will intelligently utilize average monthly historic ET entered by the user to adjust its daily schedules. Historic ET data by zip code are available at Rain Master's website (www.rainmaster.com). The controller computes ET adjustment granularity to the nearest second, which eliminates rounding errors commonly found in controllers that round on incremental minute basis (i.e., a 5 percent programming error can occur based on just a 10 minute run time).

Rain Master's ZipET is an ET data collection and dissemination service for Rain Master iCentral Internet customers. Rain Master collects raw weather information on a daily basis from thousands of Federal Aviation Administration and NOAA weather stations throughout the U.S. The weather information is validated, and converted as necessary to generate industry accepted ET values. The ET values are interpolated by zip code using a three-dimensional surface regression model. Site-specific ET information is then automatically delivered to each controller via the 2-way wireless communications card (iCard). Rain Master's iCentral website provides daily reports on all ET weather information which was successfully delivered to each controller (2-way confirmation).

An alternative to the ZipET service is available for users who require the accuracy of an on-site weather station. Rain Master's commercial grade, computer controlled, Weather Center II measures wind, rain, temperature, solar radiation and relative humidity and calculates ET at a frequency of ten seconds. A contact closure signal is transmitted from the weather station to the controller by wired connection to signal accumulation of 0.01 inch of ET. The electrical signals are counted and stored in the memory of the controller, which uses the ET data to adjust the irrigation schedule. The Weather Center II measuring devices are permanently mounted on a 10-foot tall, vandal-resistant tower with all connections made within the tower's terminal block. The controller supplies power to the system. The graph in Figure 8 shows the accuracy of the Weather Center II as compared to a nearby CIMIS station.

The Eagle user also has the ability to manually enter daily ET information at any time. When used in conjunction with historic ET, manually input ET can mitigate for extreme conditions. Utilization of manually entered ET data in conjunction with historical ET data can significantly improve irrigation efficiency. The controller will utilize the manually entered ET value for a period of one week, and then automatically revert back to the use of the selected ET data source. Manual ET data can be entered at any time; each time it is entered it will over-write the last data value stored and supersede all other ET data sources.

When the RME Eagle controller is coupled with the optional 2-way wireless iCentral plug-in card, irrigation control and monitoring may be performed via the Internet. Activation of the wireless service to the controller is performed directly from the Rain Master website. Because it is wireless, installation is reportedly

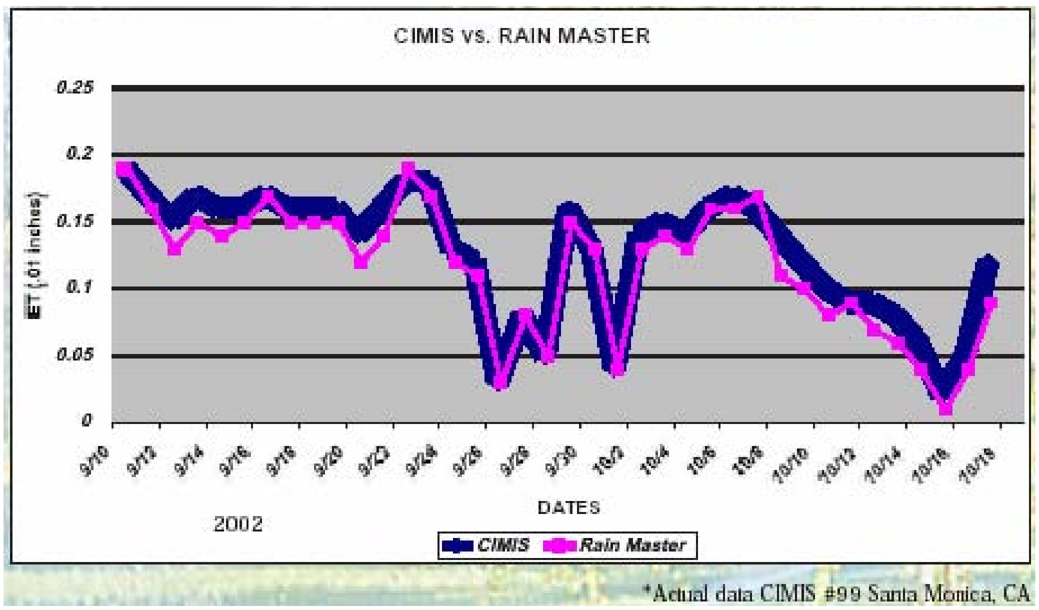


Figure 8 - Rain Master Weather Center II ET versus CIMIS reference ET

simple for either new or retrofit applications. A knock-out at the bottom of the controller enclosure is provided for mounting the 3-inch antenna.

The iCentral website automatically informs the user anytime a field change has occurred, including controller alarms (sensors and wiring fault detection) which are also e-mailed to the user. The website allows the user to command a rain shutdown, modify controller setup information, and manually turn on/off any station or program. The website also provides an automatic schedule generator so that users may generate representative irrigation schedules taking into consideration plant type, irrigation system design, and climatic conditions. Once the user enters all the *scheduling constraints and station attributes* for a controller, as described below, suitable programs are downloaded throughout the year in addition to the daily ET adjustments that are sent to the controller. The scheduler algorithms utilize the Irrigation Association "Landscape Irrigation Scheduling and Water Management" equations dated March 2005.

The *scheduling constraints* define the irrigation season, the controller water window, the stations, programs, and the allowable water days that are available for the scheduler, and any hydraulic constraints the system may have.

The *station attributes* include plant type, precipitation rate, soil type, root zone depth, slope, station efficiency, allowable soil moisture depletion, distribution uniformity, and seasonal plant crop coefficients.

In the absence of the iCentral scheduler, the user must program the controller with a base schedule. The base schedule's total run times and soak/cycle times are adjusted automatically each day by the controller based on ET.

Descriptions, Prices and Warranty

The RME Eagle controller is available in 6, 12, 18, 24, 30, and 36 station configurations. It has four independent programs each with five start times. Water days may be programmed on a weekly basis or by skip-by-day water day cycles with skip days ranging from 1 to 30 days. Station runtimes may be programmed up to 10 hours in one-minute increments, and may be increased/ decreased using the program percent feature from 0 to 300 percent in 1 percent increments. Programmable overlap protection provides for programs to be stacked or run concurrently, and provision is made for a separate master valve and or pump. The controller has non-volatile memory and the time and date are updated without backup batteries. Electronic overload protection is provided, with automatic reset (no fuses or circuit breakers). The Eagle's standard water savings features are summarized in the bullets below.

- Programmable rain shut off in order to delay the start of irrigation after a rain event (1 to 7 days)
- Manual Rain Switch (Automatic Watering – No Watering) provides a means of quickly turning off all irrigation programs without disturbing the stored program(s)
- Connectivity for any one of the following options: rain, moisture, or freeze sensor devices on a per program basis - when the sensor is "active" irrigation will stop and the display will indicate that the sensor is active
- The ability to select either ODD or EVEN day watering on a per program basis
- Selectable cycle-and-soak irrigation programming or conventional programming on a per-program basis
- Programmable cycle runtime, Max Cycle Time, and Soak time on a per station basis
- Automatic minimization of the water window by intelligently scheduling station starts when other stations are satisfying their SOAK TIMES

- The controller provides the ability to display total program duration, real time flow in GPM, alarm information related to flow and station field wiring conditions, daily ET values, sensor status and total water usage

When connected to an optional Rain Master Flow sensor, the RME Eagle controller will suspend irrigation in the event of a station break, catastrophic main line failure, or unscheduled flow. Station limits may be automatically “learned” by the controller and irrigation will be suspended for any station that fails its limit checks while it irrigates. The controller display shows real-time flow measured in GPM as well as flow and station field wiring fault conditions.

The standard size RME Eagle controller dimensions are 13.1” x 10.4” x 4.4”, and the extended size cabinet is approximately 7 inches taller. The enclosures are constructed of rolled steel with jet coat®, and are suitable for outdoor installation. An optional stainless steel pedestal mount is available. The controller is UL approved and includes an internal 24 VAC transformer and the current capacity is 1.0 ampere per station or master valve circuit. The controller has terminal screw connections and will accept 12 gauge wire. Optional heavy duty lightning and surge protection is available.

Rain Master’s products are available throughout the U.S. at all major irrigation distributors. A distributor search engine can be accessed at Rain Master’s website. The MSRP for the standard RME Eagle 6 station controller starts at $640. A 36 station price of $4,264 includes a full year of on-line technical support, internet service and ZipET. Individual internet service plans for wireless 2-way communications range from $9.95 to $14.95 per month. The MSRP for the Weather Center II is $3,500. All Rain Master Controllers come with a 5-year warranty. Nationwide product support is available by a network of Rain Master sales representatives. Toll free factory phone support is available from 8:00 AM thru 5:00 PM PST at (800) 777-1477.

Installation

Rain Master reports installation of the controller is straightforward. The AC power however has to be hard-wired, and a contractor is recommended. Installation time and cost varies depending on site-specific conditions.

Track Record, Water Savings and SWAT Testing

Rain Master reports that thousands of Eagle controllers have been installed throughout the U.S. and that the Rain Master RME Eagle controller has been recognized and accepted by more than 40 water purveyors/agencies across the nation. A list of water agencies that accept Rain Master’s products in their water saving incentive programs can be accessed at Rain Master’s website.

Although water savings data were not available for this report, Rain Master reports average water savings of 25 to 40 percent. Rain Master’s reputation and the controller’s 5-year warranty are significant factors when considering the reliability and overall performance of their products. A SWAT performance report for the RME Eagle was not posted at the time of this report.

Toro

The Toro Company, which was established in 1914, is a Fortune 1000 internationally recognized supplier of irrigation and landscape products. Toro's corporate headquarters is located in Bloomington, Minnesota and its Irrigation Division resides in Riverside, California. Toro's Intelli-Sense series of residential and commercial controllers utilize the ET Everywhere™ subscription service and WeatherTrak™ scheduling engine to provide weather based irrigation system control. Toro also manufactures Irritrol products and is a partner with HydroPoint Data Services. Irritrol and HydroPoint controllers also utilize ET Everywhere and WeatherTrak, as discussed in the HydroPoint and Irritrol sections of this report.

The Intelli-Sense series entered the market in 2005 and includes seven controllers, comprised of indoor and outdoor models for 6, 9, 12 and 24 zones (plus a pump/master valve circuit). The WeatherTrak-enabled software creates a scientifically calculated zone-specific baseline irrigation schedule. The schedule is updated daily using weather data delivered by the ET Everywhere subscription service.

ET Everywhere uses data from the NOAA system of 14,000 nation wide weather stations to deliver ET to any area in the U.S. ET Everywhere has a proven accuracy to a standard deviation of .01 inch of daily ET at a resolution of one square kilometer. The ET Everywhere data service provides local ET (microzone) without the need for a weather station on site. The ET Everywhere Data Center validates the weather data and transmits calculated ET through three satellite servers to each controller everyday. The three satellites provide over-lapping coverage of the U.S. to ensure signal reception anywhere.

Operational Features

The Intelli-Sense controllers calculate irrigation schedules for each zone. The controller does not use pre-set irrigation schedules input by the user. Instead, a series of questions are answered by the user to define the site variables that influence water need. The controller is programmed by entering the following station specific information: sprinkler type or precipitation rate, plant type, soil type, microclimate (sun or shade), slope (including if the zone is at the top, middle or bottom of the slope, and system efficiency (percentage). The schedule for each station is adjusted daily according to the local weather data received via the ET Everywhere service.

With these inputs, the controller calculates an irrigation schedule for each zone. Soil moisture depletion tracking, triggered at a 50 percent depletion level, along with daily ET updates allows the controller to adjust schedules as the weather changes. The number of water days, minutes and cycles (with appropriate soak times between cycles) are generated automatically and change as weather and water need fluctuates. The controllers have an eight- week scheduling window. This allows for infrequent watering of low water use plants. The controllers can initiate irrigation even if the daily ET page is not received by using the last download and loop-up table included in the WeatherTrak software. Non-watering days can be specified in the controllers' schedule programming. The controllers are compatible with Toro's wired & wireless rain and rain/freeze sensors, which eliminate irrigation during rainfall and freezing weather if added as an optional accessory.

Descriptions, Prices and Warranty

The indoor controller models' cabinet is constructed of ABS plastic while the outdoor units are comprised of Lexan. The dimensions of the indoor models are 7.5" x 6.5" x 3.3", and the dimensions of the outdoor models are 7.5" x 9.5" x 5.8". The controllers have a large (3.5" x 0.8") LED information display, dial type controls, and a copy button for simplifying setup. All controllers include internal UL/CSA listed transformers. The current capacity for each zone circuit is 0.5 amperes, and the current capacity for pump/master valve circuit is 0.375 amperes. The controllers will accept wire sizes from 12 to 18 gauge. The non-volatile memory maintains programming, and the back-up battery maintains the date and time, during power outages.

Other controller features include surge protection up to 6 kilovolts and valve malfunction detection. The irrigation schedule, irrigation history and program review can be viewed with the LED information display. In addition to the rain and rain/freeze sensors, pancake and bow tie antennas are available for sites with poor reception.

The Intelli-Sense controllers may be purchased from authorized Toro distributors and retailers. Current controller and accessories prices are summarized in Table 11. The Intelli-Sense controllers come with a 5-year warranty. The purchase of an Intelli-Sense controller requires a paid subscription to the ET Everywhere service through WeatherTrak. The ET Everywhere annual service fee is $48 for the 6 to 12 station controllers and $84 for the 24 station controller, as discussed in the HydroPoint section of this report.

Table 11 - Toro Intelli-Sense Controller and Accessories Prices

Description	Model	Price
6-station Indoor Controller	TIS-06-ID	$399
9-station Indoor Controller	TIS-09-ID	$449
12-station Indoor Controller	TIS-12-ID	$499
6-station Outdoor Controller	TIS-06-OD	$419
9-station Outdoor Controller	TIS-09-OD	$469
12-station Outdoor Controller	TIS-12-OD	$524
24-station Outdoor Controller	TIS-24-OD	$889
Wireless Rain Sensor	TWRS	$99.70
Wireless Rain/Freeze Sensor	TWRFS	$120.70
Wired Rain Sensor	TRS	$27.25
Pancake Antenna	TIS-ANT	$87.50

Installation

The Intelli-Sense controllers do not require professional installation, although trained installation is recommended. Typical installation times range from 1 hour to 2.5 hours, depending upon the size of the landscape covered and mounting issues. Installation should include a site assessment and discussion with the user about the site's irrigation system and how the controller operates. Installation and setup instructions are included in the owner's manual. Technical support is available from Toro by a toll free number (800-664-4740), or www.Toro.com, and through field certified contractors.

Track Record, Water Savings and SWAT Testing

Toro reports the technology behind the Intelli-Sense controller series is proven by several multi-year independent studies showing water savings. These studies were performed using Hydropoint's WeatherTrak controller and the ET Everywhere service. The studies are discussed in the Hydropoint section of this report.

An Intelli-Sense controller SWAT test performance report is posted at the Irrigation Association's website.

Tucor

Tucor, Inc. is headquarted in Wexford, Pennsylvania and has been in business since 1995. Tucor®, along with their Danish partner, SRC, manufactures commercial irrigation controllers which use decoder-based two-wire technology. Two-wire technology carries both power and signal to each irrigation valve, eliminating the need to run individual wires by instead using decoders at each valve, sensor or pump. Two-wire systems are easily extended without the need to install additional wires back to the controller.

The Tucor PROCOM© is a stand-alone controller with weather-based irrigation scheduling capability. The PROCOM is a modular, commercial grade controller that comes in its base form as a 50 valve (station) model. The controller's capacity can be increased through simple software registrations to 100, 200, 300, 400 or 500 valves. The controller connects to a PC (via wired or wireless) using software supplied with the controller, which provides a Windows®-based interface for programming and monitoring.

The Tucor ProCom ET-100 Weather Station is connected to the PROCOM controller to provide automatic weather-based irrigation scheduling. The controller calculates ET from the weather station sensor inputs and develops a daily irrigation schedule that provides efficient landscape watering. Housed in a sealed enclosure, the weather station is powered by a rechargeable (AC or solar panel) battery.

Weather station standard sensor inputs include solar radiation, air temperature, relative humidity, rainfall and wind speed and direction. Optional sensor inputs include soil temperature and moisture content. The station's battery charger is powered by either a 10 watt solar panel or AC power.

The weather station data are transmitted to the controller by telephone modem, and ET is calculated using the FAO-56 Penman Monteith equation. The irrigation schedule is calculated based on station application rates entered by the user. Other parameters that can be used in calculating the irrigation schedule include vegetation type, growing degree days, wet bulb temperature, dew point, and wind chill. The ET-100 comes with software and modem, a two or three meter pole mount, battery charger with solar panel or AC transformer and optional sensor inputs.

Operational Features

The PROCOM can run up to 40 stations simultaneously, manage up to 16 pumps and monitor up to 10 flow sensors. It can execute up to 30 schedules with up to 12 start times per schedule. Schedules can be executed sequentially as programmed, in priority as programmed with automatic execution based on flow data, or fully automatic based on a flow optimization protocol. Scheduling is based on a 14 day cycle.

The controller includes a rain sensor input for utilizing the automatic rain delay feature. The rain delay feature can be independent of the weather station. An auxiliary sensor input can be used for non irrigation related alarms. These are typically pump related. Additionally, the controller will actuate an alarm on wind speed, rain limits and temperature.

The PROCOM can monitor and react to flow conditions for up to 10 flow points. The controller can distinguish between multiple flow meters that are used for water sources and those flow meters that are used for monitoring main and sub main failures within a large system. Select flow meters can be identified for inclusion in the water consumption reports. In the event of a high flow condition during irrigation, the controller can shut down that sequence, continue to the next sequence, send an alarm to a pager, and report to an Excel® file. In the event of an unscheduled flow event (main line failure), the user has the option to activate or deactivate a valve or device. The controller can then alarm to a pager and report to an Excel file.

While considered to be a stand alone controller, the PROCOM must be programmed through the RMS management software that is included with the controller. The RMS software allows for the management of up to 25 individual controllers. All data logged by the controller can be exported to the Tucor Logviewer program, which is a series of Excel-based reports. This format allows for the customization of usage reports, unique to each application. The controller can perform a dry run prior to the actual running of a schedule, to project total run times and water usage. The dry run can be displayed as a flow graph to help manage the efficient use of water and time. The controller allows for the option to apply water based on time, application rate, or ET. Communication to the controller can be a choice of a direct serial connection, phone line, cellular, or GSM/GPRS. Internet connectivity is also available utilizing an existing LAN/WAN or WIFI broadband. A WIFI network, featuring mesh technology, can be created in the event of the existence of multiple controllers on a single site.

Descriptions, Pricing and Warranty

The PROCOM is designed for indoor installation, but several optional outdoor cabinets are available. The controller's dimensions are 11.5" x 13" x 3". The outdoor cabinets come in wall mount or top entry models.

The PROCOM has automated diagnostics capabilities. The controller detects wiring faults and turns off power and sends an alarm to the user when detection occurs. Diagnostics can be performed with the controller, to trace short circuits, line current and solenoid ground faults. Optional lightning protection is available for protection against lightning on the two-wire path.

Tucor products are available through certified distributors. A list of distributors is available from Tucor upon request (800-272-7472). Current retail prices for the PROCOM controller, ProCom ET-100 Weather Station, and accessories are summarized in Table 12. Tucor products come with a 3-year warranty that can be extended to 5 years through an installation certification process.

Installation

Tucor controller systems require professional installation.

Table 12 - Tucor Controller Product Prices

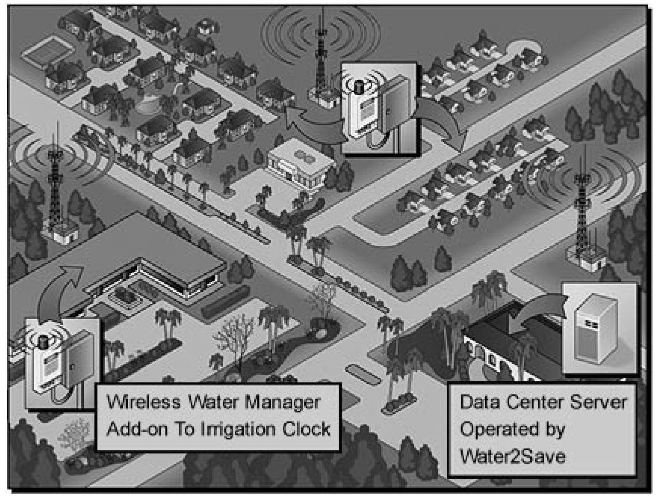
Description	Model No.	Price
50 Station PROCOM Controller	ProCom 50	$ 7,150
100 Station PROCOM Controller	Procom 100	$ 7,750
200 Station PROCOM Controller	Procom 200	$ 8,500
300 Station PROCOM Controller	ProCom 300	$ 9,250
400 Station PROCOM Controller	ProCom 400	$ 10,000
500 Station PROCOM Controller	ProCom 500	$ 10,750
Stainless Steel Outdoor Wall Mount Cabinet	CAB-200	$ 740
Weather Station	ProCom ET-100	$ 13,000
Surge Protection	SP-100	$ 55
1-inch Inline Flow Sensor*	FS-100	$ 730
4-inch Inline Flow Sensor*	FS-400	$ 730
Decoder: 1 address	LD-050	$ 95
Decoder: 1 address, 2 valves per address	LD-100	$ 120
Decoder: 2 addresses, 2 valves per address	LD-200	$ 190
Decoder: 4 addresses	LD-400	$ 270
Decoder: 6 addresses	LD-600	$ 330
Sensor decoder	SD-100	$ 280

* Inline flow sensors in intermediate sizes and larger saddle models are available.
Flow sensors require an SD-100.

Track Record, Water Savings and SWAT Testing

Although Tucor did not provide water savings data for this report, it appears proper use of the PROCOM controller may potentially result in water savings and runoff reductions similar to the other weather based irrigation control products discussed in this report. A SWAT test performance report is not posted for the Tucor PROCOM.

Water2Save



Water2Save, LLC is located in San Diego, California, and is a subsidiary of WaterLink Systems, Inc. WaterLink specializes in weather-based irrigation control and conservation management. In 1992, WaterLink began research and development, patent applications, and beta testing of a weather based irrigation control and feedback monitoring system using wired and wireless data telecommunications. WaterLink obtained two patents in 1997 and 1999 for a method of using forecasted weather and ET data to adjust irrigation schedules. Water2Save was formed in 2000 under a technology license from WaterLink to market and sell the patented technology along with its patented forecasted weather based ET adjustment service to optimize irrigation water use for large residential and commercial irrigation systems. Both Look-Ahead ET ™ and WaterLink System® are trademarks or registered trademarks of WaterLink Systems, Inc.

Property owners contract with Water2Save to be their remote irrigation water manager on a performance guarantee basis. Water2Save offers a multiple-controller add-on hardware package, fully automatic Look-Ahead ET irrigation scheduling, landscape audits, historic and real time irrigation runtime monitoring, savings tracking/reporting, and guaranteed savings.

Two patents, Evapotranspiration Remote Irrigation Control System and Evapotranspiration Forecasting Irrigation Control System, cover methods of using forecasted ET, called Look-Ahead ET, with any type of wired or wireless communications to provide weather-based irrigation system control. According to patent claims, approximately 15% more water savings can be achieved when predictive data are used with the ET equations versus when only real-time or historic weather data are used. Water2Save is the only ET irrigation control service provider that can offer its patented forecasted weather based irrigation control.

In 1993, Water2Save began testing its first prototype ET controller. The initial technology replaced the existing controller and required site-specific data for each irrigation zone (plant type, soil type, root depth, irrigated area, flow rate, precipitation rate, and distribution uniformity). The programmed site information and Look-Ahead ET weather data were used to automatically calculate the irrigation schedule.

After years of testing, the company concluded that obtaining and entering site-specific data for each landscape zone was impractical and too labor intensive for most users. In addition, the company determined that many users did not want to learn how to install and operate a new high-tech controller. Therefore, in 1996, the company developed a 2-way (send and receive) add-on technology using its patented method which factors down runtimes set in the controller in accordance with forecasted and measured weather data. Further, the technology monitors watering schedule changes made by the user for each zone and sends such information to Water2Save's Data Center for analysis. This technology has now been in operation with customers for over 12 years.

Operational Features

Water2Save's add-on technology is fully transparent and independent of the irrigation controller and is not operated by the user. Hardware is operated remotely by Water2Save and no training is required for the user. The user continues to use the familiar irrigation controller to set and "fine tune" baseline watering schedules. Water2Save is developing a commercial controller that will function similar to the add-on unit for those customers that wish to replace their existing controller with an integrated wireless ET based controller using Water2Save's Look-Ahead ET, valve runtime monitoring service and water usage/savings reporting.

With Water2Save, the user is responsible for setting a baseline schedule that is consistent with recommended summertime irrigation schedules and runoff guidelines established by Water2Save. Baseline schedules are set to the maximum peak ET or 100 percent that remain set at the summertime level the entire year. However, the user may "tune" specific valve schedules as needed. These changes are remotely monitored by Water2Save. The installed technology will interrupt runtimes and reduce irrigation based on normalized weather data (ratio of Look-Ahead ET to the peak summer ET). Normalizing the data reduces the need to obtain site-specific absolute values for ET. Such percent adjustments are not a straight percentage per cycle. The technology considers both daily and weekly runtime minutes. This allows the technology to "store-up" minutes so as to drop cycles and or drop days from the irrigation schedule as appropriate. Water2Save monitors all start-times for daytime irrigation runs and records all manual valve activations that are made by the landscaper using the existing controller.

Although the user can manually run one or more stations during a daytime window of time with no interrupt, Water2Save can prevent all daytime manual watering from the controller if over-watering occurs from excessive runtime programs. Water2Save remotely monitors and manages each valve independently (e.g., color, turf, shrubs, ground cover, drip, slopes, etc.).

Measured weather data and weather forecasts are reviewed daily from numerous sources including the National Weather Service and other government operated weather stations such as CIMIS and AZMET in California and Arizona. Weather data review is done by qualified technical staff knowledgeable in meteorology and evapotranspiration, as well as weather forecasting. Water2Save retrieves forecasts and weather changes for numerous climate zones where its systems are installed. Once the climate zone adjustments are determined, sending weather adjustment factors to the technology installed at customer sites is done via the Internet and wireless networks with confirmation of receipt of the adjustment update.

Water2Save operates a dual redundant server Data Center that retrieves data from properties installed with the company's equipment and monitors both the runtimes programmed by the landscaper and those adjusted by Look-Ahead ET factors. These factors (updated with both forecasts and corrections from measured weather data) are sent and then "receipt" is confirmed by Water2Save staff at its Data Center everyday. Water2Save staff review the meteorological measurements for bad data, out of range data, calibration problems with weather instrumentation, and rainfall errors. This allows Water2Save staff to troubleshoot and then correct problems before processing, thus preventing incorrect adjustments from occurring.

Using 2-way wireless cellular data communications, Water2Save's Data Center retrieves irrigation runtime minutes (those programmed by the user into the controllers and those actually watered after the daily weather adjustments were made). Irrigation history is compiled into a database for analysis by Water2Save and is also made available to the user via the Internet. Servers automatically scan data to find baseline schedule changes that have been made by the user, which are flagged for investigation by Water2Save staff.

Water2Save's staff also obtains monthly or bi-monthly utility billing information to track water meter consumption. A baseline is established using water consumption history prior to installation and the monthly or bi-monthly use after install allows Water2Save to track and calculate achieved savings for "like periods" of the year. Utility meter read data are correlated with watering minutes to identify potential discrepancies. Water2Save mails or e-mails utility meter specific savings reports to its customers to document if and how much savings is being achieved.

The company's Wireless Water Manager (WWM) is designed to enable Look-Ahead ET control for up to 64 irrigation valves on up to 4 separate existing or new irrigation controllers (any type of electronic controller with low voltage solenoid operated valves). Each WWM receives weather-based adjustments via wireless data communications from the Data Center over a national cellular data network and optimizes irrigation. WWM adjusts runtimes using an electronic relay to turn-off water when a daily allowance is reached.

Modular multi-valve sensing monitoring cards are used with the WWM. Each electronic card measures activation time for 12 or 16 separate irrigation valves and records the number of seconds-on of all watering cycles. Up to 4 sensing monitoring cards (maximum of 64 valves) can be connected to one WWM via direct cable or wireless link. Each multi-valve sensing monitoring card is connected between the existing irrigation controller and solenoid driven valves. Also, the common wire is connected between the card and controller to turn-off water to each valve according to the Look-Ahead ET requirement. Each valve is programmed to run a specific schedule at the controller and the sensing monitoring card interrupts the run time specific for each valve in accordance with the adjustments.

Descriptions, Pricing and Warranty

The WWM panel, wireless cell modem (activated on Cingular's network) and antenna are shipped inside a steel housing (10.8" x 6.5" x 2.5") that is to be mounted next to the existing irrigation controller. The valve sensing monitoring cards are usually mounted below each of the existing controllers to be enabled with Look-Ahead ET. The wireless modem is a completely separate module (not designed into the electronic circuit board) and is easily upgradeable should wireless technology infrastructure change over time. A standard rain sensor or rain gauge can be connected to the WWM to enhance the system's scheduling capability by triggering rain delays and or accounting for effective precipitation. The WMM power supply is an external 9 VDC transformer that is fused for power line surges, and the multi-valve sensing monitoring cards have opto-isolation type surge protection.

The price for a basic add-on WWM model, with the capacity to schedule up to 16 valves on a single controller is $1,598. This price includes the main panel and CPU, a 5-year lithium ion battery, housing, power supply, wireless 2-way cell modem, antenna, a 16-valve sensor card, and all necessary cables. When connected to 4 controllers with three additional valve sensing cards for up to 64 valves, the price is $ $2,108 (or about $527 per controller). The basic service fee for wireless airtime and Look Ahead ET daily adjustments is $39 per month ($468 per year total or $117 per year per controller- $9.75 per month assuming that all 4 controllers are connected to one WWM) and includes feedback confirmation that schedule data were received. Equipment rental plans are also available directly from Water2Save. Water2Save provides a 3-year parts and labor warranty with equipment purchase.

Planned pricing on Water2Save's forthcoming commercial ET controller was not available at the time of this report.

Additional services include tracking runtimes, number of cycles, start times, time of day watering, and manual watering time. The Data Center also checks to confirm that each valve's runtime does not exceed a range of weekly watering minutes established by Water2Save for specific head type and plant type. The Data Center checks if the number of cycles set for slopes have been modified in the existing controller. If so, user follow-ups are conducted until such issues are resolved.

Additional data monitoring includes power outages, future day factors, daytime irrigation, start-time of each valve, end time, number of cycles, and the default factors (based on long-term meteorological conditions). Should wireless communications be interrupted, the WWM will use a set of specific climate zone default factors (provided that updated factors are not received over a several day period).

Installation

Water2Save reports the typical installation time for a WWM system with one controller is 2 hours and that professional installation is usually required.

Track Record, Water Savings and SWAT Testing

Water2Save reports its systems have proven to deliver maximum achievable savings reliably year after year with a guarantee. In-house savings reports show typical savings of over 2,000 gallons per day from installation of Water2Save on a one-acre site as shown in Figure 9.

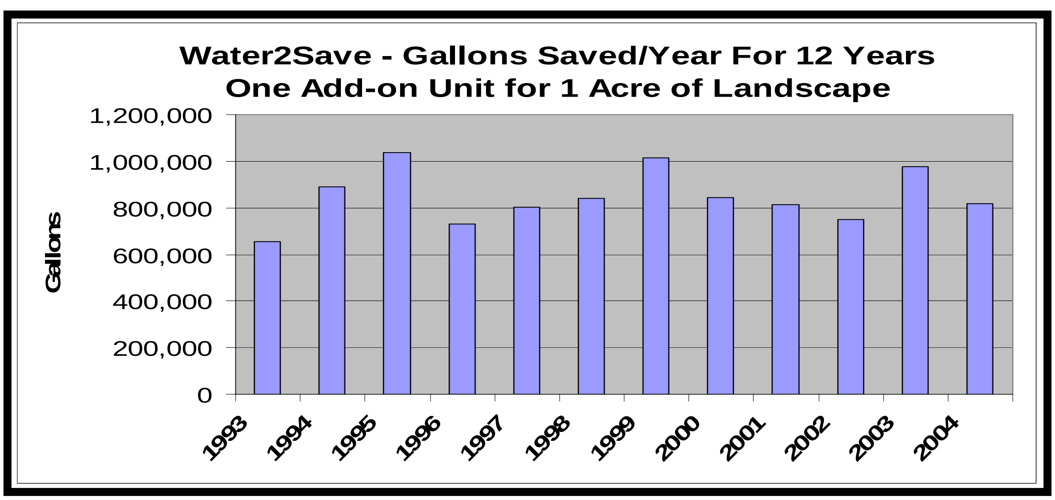


Figure 9 - Water2Save water savings data

The City of Los Angeles, California Department of Water and Power recently performed a pilot study of Water2Save over a one-year period. Water2Save reports the average percentage water savings achieved for the properties installed with its system was over 28 percent.

A SWAT test performance report for the WWM was not available for this report.

Water2Save offers a complete turn-key water manager package which includes hardware, patented Look-Ahead ET adjustments with receipt confirmation, runtime monitoring, flagging of problems, on-site field support, full reporting via the Internet, consumption tracking and guaranteed performance savings agreements.

This system appears to provide significant water savings and requires minimal on-site monitoring and adjustment. The Data Center interface appears to provide an easy and effective method for remotely monitoring an extensive set of irrigation related information.

Weathermatic

Weathermatic®, established in 1945, is a worldwide manufacturing company of a full line of irrigation products. The company, headquartered in Dallas, Texas, began developing water conserving products in the 1950's when it used soil moisture sensors which were later followed by its innovation of the industry's first rain sensor shut off device in the 1970's. Weathermatic's SmartLine™ residential and commercial irrigation controllers operate based on weather conditions using onsite sensors.

Operational Features

The Weathermatic SmartLine controller technology patent was filed in 1998 and granted in 2000. SmartLine controllers accept user inputs by zone for sprinkler type, plant type, soil type, slope, and a zone fine-tune adjustment factor. The units then incorporate a ZIP code input (for solar radiation) and an on-site weather monitor (sensing temperature and rainfall) to calculate real time ET estimates that are used with user inputs to calculate proper zone run times, including cycle/soak, at user selected start times and watering days. The Weathermatic SmartLine controller/weather monitor package operates stand-alone and does not require communication with remote servers to obtain weather data or irrigation schedules and no ongoing service costs are associated with the unit. After 8 years of development, testing, and field trials, the SmartLine controller line entered the market in November of 2004. As of July 2005, Weathmatic reports shipment of tens of thousands of SmartLine controllers with less than 60 units returned.

The Weathermatic controller platform is built around zone modules that allow expandability from 4 to 8 zones for their SL800 model and 4 to16 zones for the SL1600 to accommodate various size residential and commercial landscapes. The SL1620 and SL1624 have fixed zone capacities 20 and 24. A larger commercial model, the SL4800 (scheduled for release in June 2007) will provide module and wiring space for up to 48 zones. The SL1600, SL 1620, SL1624 and the SL4800 are all suitable for indoor or outdoor installation. The SL800 is an indoor model.

Descriptions, Prices and Warranty

The SL800 is a fixed 4-zone unit that can be expanded to 6 or 8 zones with 2-zone modules. The SL1600 controller is shipped standard with a 4-zone module and can be expanded to 8, 12 or 16 zone with additional 4-zone modules. The SL1620 and SL1624 controllers are fixed 20-zone and 24-zone units. The SL4800 will be shipped with 12 zones included. The controller housing dimensions are: SL800 – 7" x 7.8" x 1.8"; SL1600 series – 9.1" x 10.1 x 4 and SL4800 – 15" x 16.5" x 5.8". The SL800 has an external transformer power supply with a barrel connector that plugs in to the side of the controller for fast installation. The SL1600 Series controllers have internal transformers with a pre-wired plug-in cord that will accept 120V or 240V. The SL4800 will also have a 120/240V internal transformer but without a pre-wired plug-in cord (professional installation required). For the SL800 controller, either a 120V power supply or a 240V power supply with connectors for the EU or Australia can be specified when ordering. The controller output circuit capacities are 1.0A for the SL800 and 1.2A for the SL1600 series and the SL4800. Weathermatic reports these capacities are adequate for running 3 zone valves concurrently with a master/pump valve for the SL800 and SL1600 series, and 5 zone valves concurrently plus a master/pump valve for the SL4800. Accepted wire sizes range from 14 to 18 gauge.

The SmartLine controllers have advanced functions including zone-to-zone and master valve timing delays, a built-in valve locator, as well as a unique diagnostic function that displays the electrical current by zone for troubleshooting. Additionally, the user can omit specific calendar event dates, days of the week, and times of the day when no watering is allowed. A remote control option planned for 2008 will feature a handheld remote nested in the back of the programming module. The handheld will have a 600 foot line-of-sight range. Units with the remote capable operating panel will also enable a second remote capable operating panel to be mounted independent of the base.

Weathermatic offers a 2-wire option with the SL1600 series controllers. The SmartWire™ decoder module for 2-wire systems (model SLM48DM) can be integrated into these controllers and is considered cost effective for 18 zones and larger systems. The SLM48DM includes connections for up to 3 different 2-wire paths and includes an LED display and status lights for programming, operation status and troubleshooting. The valve decoders used to decode the signals from the SLM48DM come in 1-, 2- and 4-valve capacity (models SLDEC-1, SLDEC-2 AND SLDEC-4). Additional valve decoder features include: shock and freeze/heat resistant, 14-guage wiring, surge protection and functional distance up to 100-feet from the valve.

The on-site weather monitor includes a temperature sensor and rain sensor. The unit has a microprocessor to record and process measurements. The temperature-sensing unit is encased in a solar shield. The hygroscopic disc type rain sensor can be set to trigger rain delay at rainfall depths from 1/8” to 1”. A wired weather monitor is currently available and a wireless unit is planned for 2008.

SmartLine controllers are distributed through Weathermatic’s established wholesale suppliers (specialty irrigation suppliers) and installation professionals. The list prices for currently available and planned residential controllers and components are listed in Table 13.

Programming of the “Auto Adjust” ET portion of the controller requires inputs by zone for sprinkler type, plant type, soil type, and slope. Sprinkler type can be entered on a basic level by the user by selecting the type of sprinkler in a zone – SPRAY, ROTOR, or DRIP. A more advanced user can scroll past these basic inputs with default precipitation rates and prescribe an exact numerical precipitation rate for the zone from 0.2”/hour to 3.0”/hr. Plant type works similarly to the sprinkler type input in that the user can simply select the type of plant life in the zone – COOL TURF, WARM TURF, ANNUALS, SHRUBS, NATIVE, or TREES. Again, a more advanced user can scroll past these basic inputs with default percentages and prescribe an exact numerical percentage for the zone from 10 to 300% based on the plant life in the zone and sun/shade consideration. The soil type – CLAY, SAND, LOAM - and slope (numerical degree of slope 1 – 25+ degrees) are used to automatically calculate the cycle/soak function by zone.

In addition to these inputs by zone, the user programs the ZIP CODE of the site, or primarily for locations outside the United States, the latitude of the site. This input and the calendar day of the year is used to determine the solar radiation at the site, which is a variable in ET calculation. These static inputs are combined with the dynamic on-site weather monitor inputs to perform the overall equation that determines proper zone run times.

The SmartLine user has the ability to fine tune the zone run times by zone through a MORE/LESS function. This allows the user to increase watering by zone up to 25 percent or decrease watering by up to 50 percent.

Table 13 - Weathermatic SmartLine Controllers and Component Prices

Description	Model	Availability	Price
4 to 8 Zone Indoor Controller*	SL800	Currently Available	$99.95
4 to 16 Zone Residential Controller*	SL1600	Currently Available	$159.95
20 Zone Commercial Controller	SL1620	Currently Available	$389.95
24 Zone Commercial Controller*	SL1624	Currently Available	$549.95
48 Zone Commercial Controller*	SL4800	June 2007	na
2-Zone Module for SL800	SLM2	Currently Available	$24.95
4-Zone Module for SL1600	SLM4	Currently Available	$49.95
12-Zone Module for SL4800	SLM12	June 2007	na
2-Wire Decoder Module	SLM48DM	Currently Available	$699.00
2-Wire Decoder for 1 valve	SLDEC1	Currently Available	$99.00
2-Wire Decoder for 2 valves	SLDEC2	Currently Available	$185.00
2-Wire Decoder for 4 valves	SLDEC4	Currently Available	$295.00
Wired Residential Weather Monitor	SLW10	Currently Available	$199.95
Wireless Residential Weather Monitor	SLW15	2008	na
Wired Commercial Weather Monitor	SLW20	Currently Available	$299.95
Hand-held Remote Control for SL1600	SLHRR	2008	na
Control Panel Remote Module for SL1600	SLCPX	2008	na

*Weather Monitor required for weather-based irrigation scheduling not included in price

The controller's irrigation schedule is based on the user prescribed irrigation days, start times, and omit times (dates, days, and times of day) so as to conform to local watering restrictions and also accommodate site-specific hydraulic issues, which vary by time of day. Once programmed, the controller calculates ET for the period beginning at the end of the last irrigation cycle, or measurable rainfall, and ending at the next prescribed irrigation day. Irrigation will occur if the calculated run time is sufficient for an effective irrigation watering. If sufficient demand has not been reached, irrigation will not occur and the controller will carryover the accumulated ET to the next prescribed irrigation day and time. This accumulation threshold, which prevents ineffective irrigation, is calculated based on a default accumulation factor.

Installation

Installation and programming of SmartLine controllers are designed to be simple and intuitive for both the novice homeowner and the advanced professional who are familiar with the unit's industry standard programming dial. Advanced user functions are located in an "Advanced Functions" position on the programming dial so as to not complicate the set up for novice users. While programming the unit is simple, Weathermatic recommends installation by a professional who will give the site the highest rate of success not only for controller programming, but also for complete system operations with an emphasis on water conservation. Based on Weathermatic's solid reputation and well-established support network, it appears the SmartLine controllers' technical support system is outstanding. Installation and programming instructions are available on Weathermatic's internet site (weathermatic.com), and a programming video and DVD are available to supplement the standard user manual.

Track Record, Water Savings and SWAT Testing

Weathermatic tested its Hargreaves equation based ET calculation algorithm and controller functionality extensively for 8 years. For comparing ET calculations, CIMIS weather station reference ET values were compared to those using the Weathermatic controller/weather monitor methodology at 10 geographically diverse sites over a seven-year period for 70 years of combined data. Weathermatic reports good correlation between the CIMIS and Weathermatic ET data at all sites. The graph shown in Figure 10 is one example that is representative of the study.

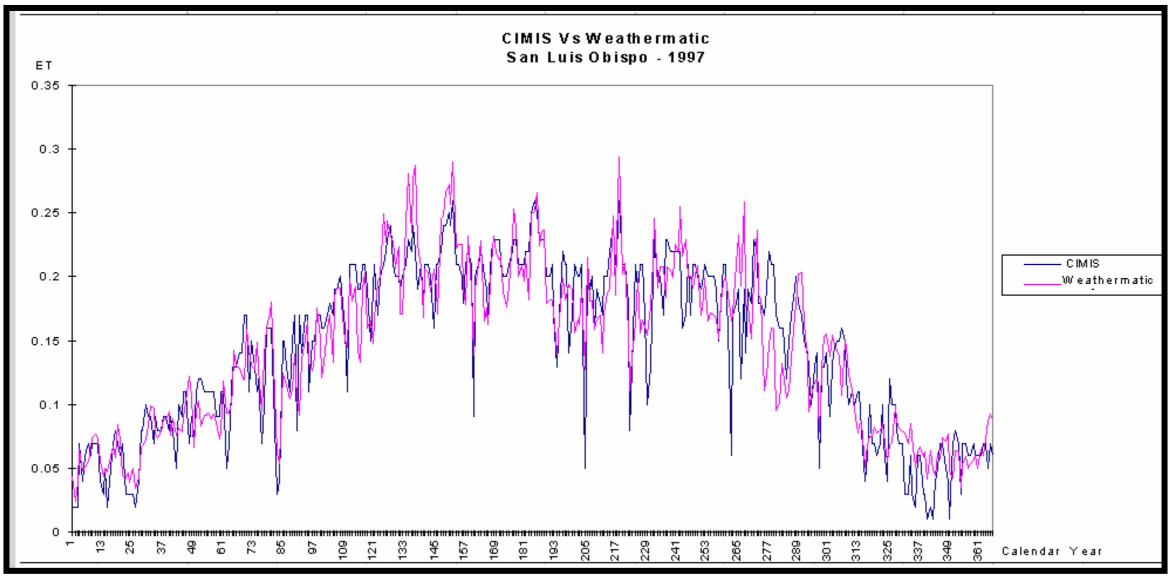


Figure 10 - Comparison of Weathermatic ET to CIMIS ET

In addition to comparing the ET calculation, the Weathermatic SmartLine controllers were included in a field study performed by a Rocky Mountain Region Water Conservancy District. This three-year study analyzed the Weathermatic controller's accumulated water output in comparison to actual ET (as measured by lysimeter), reference ET (ET_o calculated with on-site weather station data), and net plant watering requirements (PWR). The study results sample graph of Figure 11 shows the Weathermatic unit watered consistent with plant demand.

The Weathermatic SmartLine controllers were also part of a field pilot program conducted by the Marin Municipal Water District. In this study, 13 controllers were installed at 7 sites to compare water usage in 2002 and 2003 to the base year usage in 2001. Weathermatic reports that in 2002, sites installed with the Weathermatic ET controller saved 26%. In 2003, the water savings climbed to 32%. Based on documentation from this program submitted by Weathermatic, it appears the Weathermatic controller performs well and yields significant water savings.

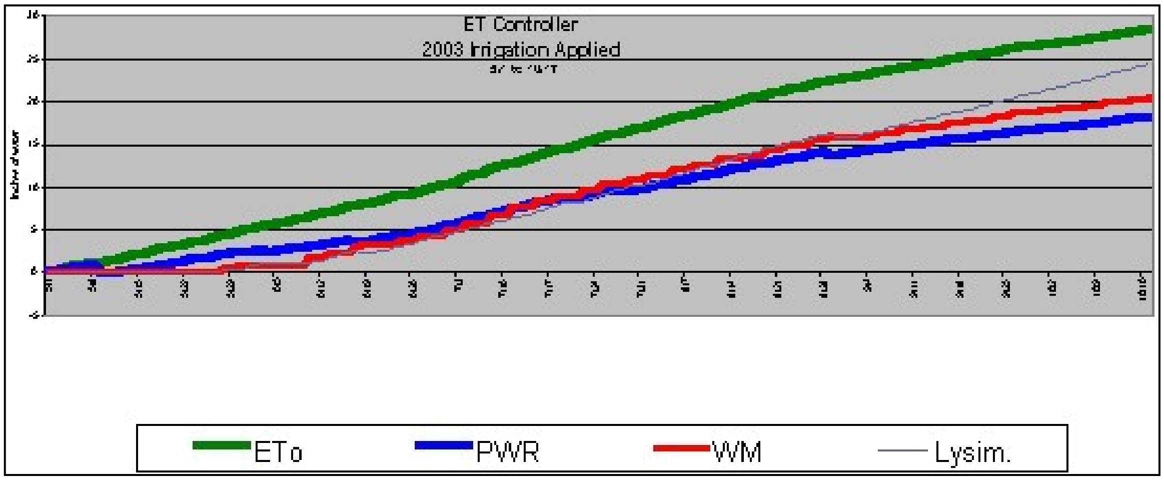


Figure 11 - Sample of Weathermatic field study results

Weathermatic’s test center has conducted testing on the controllers and weather monitors in the following areas affecting reliability: mechanical stress testing, environmental testing, software testing, and functional/characterization testing. The Weathermatic SmartLine has completed SWAT testing and a performance report is posted on the Irrigation Association website

The SmartLine controllers are relatively economical and appear to offer effective real time onsite ET measurements and inputs by zone for key programming parameters.

Weathermiser

The Weathermiser Company, based in Albuquerque, New Mexico manufactures a patented add-on controller device that works with any clock-type irrigation controller to schedule irrigation based on weather conditions. Weathermiser has been in business since 1997 and its first controller models entered the market in 2003. The Weathermiser devices include integrated temperature and humidity sensors, and these sensor inputs provide the basis for scheduling irrigation. Weathermiser reports the ability to forecast precipitation and as a result, the ability to interrupt irrigation cycles before precipitation occurs.

The Weathermiser monitors humidity in real-time to determine the need to irrigate. Irrigation may be delayed when humidity readings are high, since ET is lower and since humidity is high before, during and after rainfall. Irrigation frequency increases as a function of high temperatures and low humidity. The temperature sensor is factory set to interrupt irrigation at temperatures below 37 degrees F and an optional high-wind interrupt is also available.

Operational Features

The relative humidity sensor setting is adjustable and the controller interrupts irrigation when the ambient relative humidity exceeds the variable dial set point. The dial is set just above the highest average relative humidity for a given geographical area, at a specific time of day. Two relative humidity settings for all major cities are included in the Weathermiser instructions. The user programs the higher setting for morning irrigation and the lower setting for irrigation after dusk. The controller is designed to track dew point, evaporation rate and solar radiation based on temperature, humidity and optional wind sensor readings. The Weathermiser device interrupts the common valve circuit from the clock-type controller until it determines irrigation is needed. The clock controller is set to irrigate every day and then irrigation occurs on the days the Weathermiser initiates it. A base schedule is programmed into the clock-type controller by the user.

Descriptions, Prices and Warranty

The Weathermiser controller models include the basic model (RSFI), basic steel enclosure model (RSFIS), wireless model (WLRSFI) and steel enclosure wireless model (WLRSFIS). Each of the Weathermiser controllers includes a dial-type humidity sensor setting control and a bypass dial position. Setting the dial to the bypass position deactivates irrigation interruption by the device. The RSFI and RSFIS have no power requirement; and the clock controller common valve circuit is interrupted by the action of the spring operated humidity and temperature sensors. The RSFI is housed in a polycarbonate enclosure and its dimensions are 7” x 2” x 1.5”. The RSFIS is simply a RSFI mounted in a 7” x 5” x 3.5” vented steel security enclosure, and includes lock and key. The wireless WLRSFI is a 2-component system consisting of a combined controller and radio frequency transmitter and a receiver. The controller/transmitter is housed in a polycarbonate enclosure (7” x 2” x 2”) and is powered by two 3V lithium batteries. The controller/transmitter communicates an on/off signal to the receiver that is connected to a clock controller (not included). The receiver is housed in a polycarbonate enclosure (2” x 4” x 1”) that is mounted in or near the clock controller and is powered by the controller 24VAC supply. The WLRSFIS includes the same controller/transmitter electrical components as the WLRSFI, housed in a lockable and vented steel security enclosure (7” x 7” x 4”), and the same receiver.

An optional wind sensor can be connected in series between the RSFI or RSFIS and the clock controller. The wind sensor is a Hunter® Wind-CLIC with a variable setting control, which is set to interrupt irrigation at high wind speeds.

Weathermiser also sells a freeze sensor that interupts irrigation when the temperature falls below 37 degrees.

Current Weathermiser controller prices are summarized in Table 14. Products can be ordered directly from Weathermiser by telephone (505-235-6999). Weathermiser provides a 5-year warranty on all controller devices (including batteries) and a 1-year warranty on the transmitter, receiver and wind sensor.

Table 14 - Weathermiser Prices

Description	Model	Price
Basic Weathermiser System	RSFI	$85.95
Basic System with Steel Enclosure	RSFIS	$124.95
Wireless Weathermiser System	WLRSFI	149.95
Wireless System with Steel Enclosure	WLRSFIS	$159.95
Remote Control	RSFIE	$1,295.00
Hunter Wind-CLIC Wind Sensor	na	na
Freeze Sensor	FSI	$64.75

Installation

The Weathermiser controller devices are mounted on a shady outside surface, free from the influence of irrigation spray, and machinery exhaust. Relative humidity dial settings for major cities are included in the instructions and may require a seasonal adjustment depending on the user's mini-climate and preferences for determining landscape needs. Monthly and yearly settings are available.

Weathermiser reports its systems can be installed by most "do-it-yourselfers" or any landscape professional. The typical first-time installation is estimated to be 1-2 hours, depending on site conditions.

Weathermiser product service is offered through a hotline and an internet troubleshooting guide. Field consultations are offered for large commercial and residential installations.

Track Record, Water Savings and SWAT Testing

The performance of the Weathermiser controller is illustrated by the graph shown in Figure 12. The maximum relative humidity (RH) and average temperature information is actual weather data from a Western Regional Climate Center weather station. The graph illustrates the Albuquerque, New Mexico daily interrelationship between relative humidity, temperature and precipitation for the month of April. The rise in relative humidity that precedes precipitation and/or drop in temperature are evident except during the gusty windy period that occurred on the 6th and 10th and the steady windy period that occurred between the 15th and 22st of the month. The relative humidity limit setting shown in the figure is 70 percent and the freeze limit is also shown. The Weathermiser interrupted irrigation on the days the relative humidity and temperature were outside these limits (19 days) and irrigation occurred on the days when the readings were within the limits (11 days).

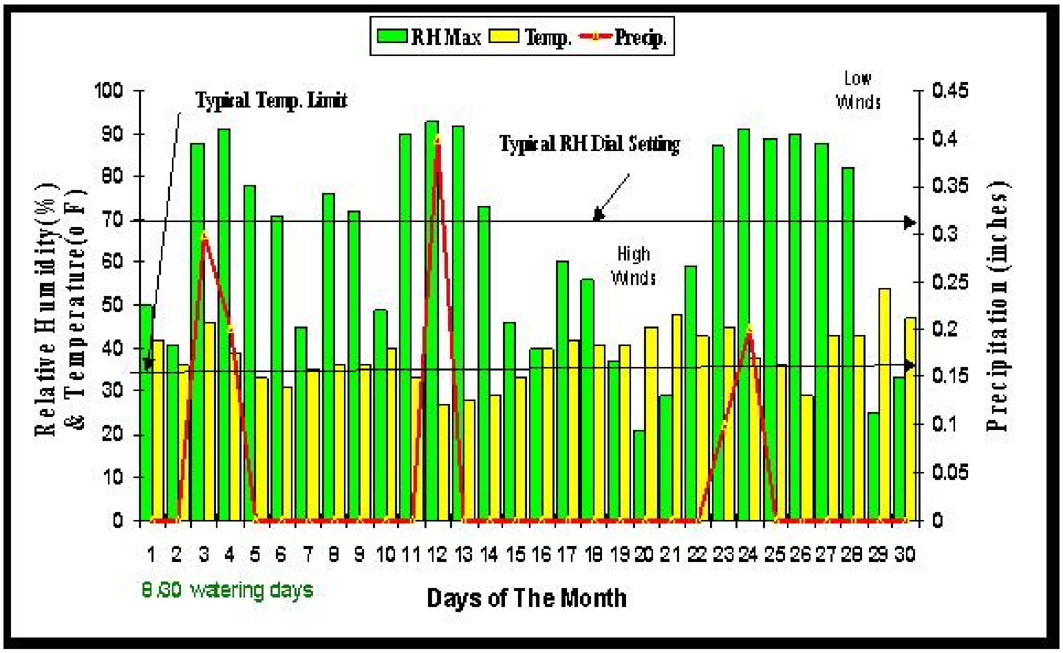


Figure 12 - Weathermiser performance related to weather data

Track Record, Water Savings and SWAT Testing

Weathermiser reports that over two thousand Weathermiser controllers were installed and water savings were evaluated in the Denver, Colorado and Albuquerque, New Mexico areas. Weathermiser reports the results of these studies indicated an average savings between 34 and 52 percent after four years of formal testing between 2000 and 2004. The water savings for the Denver area were calculated by comparing the water savings of 100 Weathermiser users to that of a 800 control group of typical Denver Water customers having no weather sensing devices applied. An adjustment factor based on the past 5 year rolling average usage for each of the participants was applied to the water meter readings taken by the Denver Water Company. Based on the results of the Denver Water Board study, which included 12 other products, Weathermiser received a water conservation award by the Denver Water Board.

Weathermiser and the Albuquerque Academy won the 2003 New Mexico Green Zia award for its cooperative water conservation efforts.

Weathermiser began developing its weather based controller over nine years ago. Weathermiser's inventor, Alphonse E. Caprio holds a patent for applying differential relative humidity and temperature to control irrigation.

Weathermiser reports its product is currently in the SWAT testing process, but a performance report was not available for this report.

Soil Moisture Based Irrigation Control System Principles

All of the soil moisture based products reviewed operate on the principal of scheduling irrigation as a function of soil moisture conditions measured onsite with one or more soil moisture sensors. The concept is for an appropriate amount of irrigation to occur when needed to maintain adequate soil moisture levels.

Landscape soil moisture conditions should be maintained such that root zone moisture levels are between field capacity and the wilting point. Field capacity conditions occur following irrigation or precipitation when the maximum amount of water is retained in the soil after seepage and surface drainage ceases. The wilting point occurs when soil moisture is depleted to the point at which plants wilt without recovery during the night. The soil moisture levels at which field capacity and wilting point occur are a function of soil characteristics.

Soil moisture is typically reported in terms of volumetric soil water content, or as soil tension. Soil moisture content is the ratio of the volume of water in the soil to the volume of void spaces between the soil particles, and is reported as a percentage value. Soil tension is a measure of the negative pore pressure that occurs in the void spaces (increasingly negative as the moisture level drops), and is reported as a negative pressure reading.

Most of the soil moisture based products reviewed function such that a preset irrigation quantity is applied when the measured soil moisture level drops to a threshold point set by the user. Ideally, the irrigation quantity applied replenishes the soil moisture to field capacity with minimal surface runoff and seepage below the root zone (over-watering). Some of the products reviewed begin and end irrigation based on two preset thresholds; the first is set at a moisture level well above the wilting point and the second is set at near field capacity. One product adjusts run times based on soil moisture data. Most of the devices, however, do not automatically calculate total run times or cycle and soak times.

As with the weather based products, some of the soil moisture based systems include a stand-alone controller and others include an add-on device that works with an existing clock-type controller. Regardless of stand-alone versus add-on controller type, some of the devices control the irrigation of all zones based on measurements from one soil moisture sensor. Others control individual zones or groups of zones based on measurements from multiple sensors placed in representative zones.

In general, all of the soil moisture based systems' operate similarly and comparison is more straight-forward relative to that of the weather based systems. Most of the products possess similar components and features. All of the systems reviewed provide potentially effective methods for scheduling irrigation based on soil moisture sensing, which should result in water savings.

Several different types of soil moisture sensors are used with the systems reviewed. In recent years, significant technological advances have been made in the field of soil moisture sensors. In general, the accuracy of all types of sensors has improved and costs have gone down significantly for some types of sensors. However, all types of soil moisture sensors possess one or more inherent deficiencies that should be considered. Several types of sensors function based on the dielectric properties of the soil, which vary depending on the soil type. Hence, calibration of these devices is soil specific to varying degrees depending on the specific type of device. Specifically, a factory calibrated sensor may not function accurately for certain soil types and should be field calibrated. Salinity or fertilizer content, as well as temperature, affect the measurement accuracy of some sensors. Certain tensiometer type sensors will not tolerate freezing temperatures and or require maintenance anytime the soil becomes exceedingly dry.

Soil Moisture Based Control Product Features and Comparison Criteria

Significant product components and features are discussed below. The discussion identifies different methods used to achieve similar results by the various products, and associated advantages and disadvantages.

Soil Moisture Sensor Types

Soil moisture sensors have been used for laboratory and outdoor testing purposes and for agricultural applications for over 50 years. There are many types of sensors, but only those used in the present generation of landscape irrigation scheduling systems are discussed.

Electrical Resistance Granular Matrix – This type of sensor consists of two electrodes embedded in a reference matrix material which is confined within a corrosion-proof and highly permeable case. The matrix material includes gypsum to buffer against the effects of salts and fertilizer, but these sensors do not dissolve like gypsum block sensors. Soil moisture is constantly absorbed or released from the sensor as the surrounding soil moisture conditions change. As the soil moisture changes, the sensor moisture reacts as reflected by the change in electrical resistance between the electrodes. Reaction time, however, is relatively slow compared to some other types of sensors. As the moisture level increases, conductivity increases and the sensor is calibrated to output the moisture level in terms of soil tension. Calibration is temperature and soil type dependant. This type of sensor has been used in agricultural and landscape applications for approximately 20 years, and their performance is well documented. They are relatively inexpensive and their manufacturer reports a minimum useable life of 5 to 7 years.

Electrical Conductivity Probes – This type of sensor measures soil moisture by how well a current of electricity is passed between two probes (electrodes) that are inserted directly into the soil. As the soil moisture changes, the sensor moisture reacts as reflected by the change in electrical resistance between the electrodes. Reaction time is relatively fast. As the moisture level increases, conductivity increases and the sensor is calibrated to output the moisture level in terms of volumetric soil water content by percentage. Since the probes have direct contact with the soil there is no buffer against salt and fertilizer affects on the measured conductivity. These devices are very sensitive to the spacing of the probes as well as being influenced by soil type, salts and fertilizers. Specifically, bent probes and improper calibration for soil type can result in poor performance. Also, fluctuations in salt and fertilizer levels can affect measurement accuracy/consistency.

Time Domain Transmissometry (TDT) – This type of sensor measures the time required for an electromagnetic pulse to travel a finite distance along steel rods or length of wire (wave guide), and the travel time is dependent of the dielectric properties of the soil surrounding the wave guide. As moisture increases in the soil, the pulse travel time decreases and the sensor's time signal is converted into a volumetric soil water content measurement by percentage. This technology, which evolved from and is similar to time domain reflectometry, provides high accuracy which is independent of low and moderate salt and fertilizer levels in the soil. The original time domain reflectometry type sensors were expensive and difficult to use. The recently developed time domain transmission devices are less expensive, and more suitable for landscape irrigation applications. The manner in which a TDT signal is processed is unique to its manufacturer and at least one manufacturer has a patented its digital signal analysis process. The significance of the signal processing method, with regard to accuracy and consistency, is beyond the scope of this review and it is recommended the reader research this matter as warranted.

Frequency Domain Reflectometry (FDR or Capacitance) – This type of sensor contains a pair of electrodes (either an array of parallel spikes or circular metal rings) which form a capacitor with the soil acting as the dielectric in between. The electrodes are inserted into the soil or in an access tube in the soil. An oscillating frequency is applied to the electrodes, which results in a resonant frequency, the value of which depends upon the dielectric constant of the soil. The moisture content changes the dielectric constant of the soil, thereby changing the resonant frequency. The change in frequency is then converted to a soil moisture measurement. FDR sensors which operate at high frequency (greater than 20 mega hertz) are relatively independent of soil salt and fertilizer levels. This type of sensor is especially sensitive to undisturbed soil contact. (See discussion of undisturbed soil contact under the Installation heading below.)

Tensiometers – This type of sensor measures the soil moisture tension, or negative pore pressure, as it changes with soil moisture content. Tensiometers operate by allowing the soil solution to come to equilibrium with a reference pressure indicator through a permeable ceramic piece that is in contact with the soil. A vacuum gauge measures the soil moisture tension and high tension reflects low soil moisture. Tensiometers accurately measure wet soil moisture levels independent of salt and fertilizer levels, but are less accurate for dry soils. They can require maintenance to refill the tensiometer with liquid and maintain the integrity of the soil/ceramic tip interface. (This typically occurs only when the soil dries beyond the wilting point.) Some tensiometers must be removed from the soil during winter months in northern climates where the soil freezes.

Installation

All of the soil moisture system manufacturers recommend professional installation and programming of their commercial products, and report that installation and programming of their residential models can be done by a non-professional. Based on discussions with third party individuals with experience installing most of the reviewed residential models, it appears homeowner installation may not be a realistic option with certain products. The degree of difficulty to install any of the products can vary significantly depending on site specific conditions. A significant factor is the soil moisture sensor wiring configuration. Some sensors are connected to the existing nearby valve wiring, and some must be connected to the controller with potentially long runs of new wiring. Wiring the sensors to the irrigation valves should be easy in most cases, but the ease of connecting to the controller depends on site specific conditions (distance, obstacles, etc.). It is difficult to determine what percentage of homeowners successfully install and program the various residential products. Installation and programming instructions are available for some of the products at their websites. All potential customers should review this information when shopping for a device regardless of whether they plan to do their own installation and programming.

Additional installation issues to be considered are associated with the placement of the soil moisture sensor(s) in the root zone. A soil moisture sensor should be in contact with relatively undisturbed soil that is representative of the irrigated landscape. Contact with disturbed soil with a higher void space ratio may result in soil moisture readings that are not representative of the landscape. Some sensor types are more sensitive to this than others. Therefore, the sensor shape and method of placing the sensor with regard to undisturbed soil contact should be considered when comparing systems. Installation of the sensor may also result in disturbance of the turf root system and affect the health of the turf for a period following installation. This may cause the soil moisture in the vicinity of the sensor to be higher than typical due to reduced ET by the disturbed turf until it "heals".

Stand-alone Versus Add-on Controller

The controller component for most of the soil moisture products reviewed is an add-on device which works with an existing clock type controller. The other products include a stand-alone controller with many of the features of typical clock type controllers. In some cases, the cost of the add-on device is a significant attraction. Regardless of cost, the quality of an existing controller should be a factor when considering replacement with a stand-alone control device. If the existing controller is a high quality unit with adequate features, an add-on device may be an attractive alternative.

The primary stand-alone controller features which should be considered include: automatic scheduling, number of programs and start times, cycle and soak, master valve circuits, compatibility with other sensors (rain, flow, temperature, wind, etc.), remote control, and system testing capabilities.

Irrigation Schedules and Run Time Calculation and Adjustment

Most of the devices reviewed do not automatically calculate irrigation run times, although some adjust user-entered run times based on soil moisture measurement data or control run times with on and off soil moisture thresholds. None of the soil moisture sensor devices automatically calculate cycle and soak times. Some manufacturers (stand-alone and add-on) provide guidelines or computer programs to assist the user in calculating total run times and cycle and soak times. The product descriptions identify the manufacturers that provide guidelines or computer programs for determining appropriate run times and cycle and soak times.

Single Versus Multiple Soil Moisture Sensors

Most of the residential systems reviewed use one soil moisture sensor to control operation of the entire system, and varying zone conditions are accommodated for by adjustment of run times. For complex residential landscapes and commercial systems, some systems have the capacity to use multiple sensors to control a single valve or groups of valves. For complex systems, the user should consider the sensor capacity of the controller. In some cases, multiple controllers with single sensor capacity can be used to build a multiple sensor system. Some of the multiple sensor controllers allow for bypassing the soil moisture control mode and running in clock mode by station. All of the products reviewed will allow for system-wide clock mode operation.

Soil Temperature and Conductivity Measurement and Display

Some of the sensors included with the products reviewed measure soil temperature and conductivity in addition to soil moisture. Soil temperature is necessary for calibration of the soil moisture measurement by certain types of sensors. Some of the controllers allow for display of the temperature and conductivity measurements. Display of the conductivity measurements is a significant feature for users irrigating with wastewater effluent or water that contains high levels of salts in order to know when to flush the soil. When the user is informed that the salt levels in the soil have reached a critical point based on the conductivity readings, the landscape should be irrigated heavily to leach (flush) the salts to below the root zone.

Soil Moisture Sensor Accuracy and Calibration

As previously discussed, the measurement of soil moisture by some sensors is affected by soil type, temperature and salinity. All of the sensor products reviewed are factory calibrated to measure moisture content for a spectrum of soil types. The manufacturers typically report a level of accuracy that is good for a range of soil types. In some cases, the accuracy may vary significantly for the different soil types. Also, the accuracy may be inconsistent for different moisture, temperature and salinity levels.

For the purpose of landscape irrigation scheduling, the consistency of a sensor is as important as, or more so, as its accuracy. For practical purposes, the user of a sensor based landscape irrigation control system typically performs a quasi-calibration of the sensor during set-up. This is accomplished when the user observes the moisture level reading that occurs with the soil at field capacity. Regardless of the accuracy of the reading, the user typically sets the irrigation trigger moisture level as a percentage of the field capacity reading. If the sensor does not read consistently, the percentage relationship between field capacity and the irrigation trigger will be affected. As an example, if a sensor reads 36 percent at field capacity and the user wants to set the irrigation trigger at 50 percent of field capacity the controller would be set to irrigate at a reading of 18 percent if the sensor reads consistently. If the sensor does not read consistently, the controller would need to be set to irrigate at a reading higher or lower than 18 percent.

Power Supply and Surge and Lightning Protection

Most of the controllers and devices operate on 24 VAC and few are battery powered. The stand-alone devices typically include a power transformer that converts 110-120 VAC to 24 VAC. The transformers are either hardwired inside the controller cabinet (internal), or plugged into a power outlet (external). The add-on scheduling devices that operate on 24 VAC either receive power from the existing clock/controller or from an external transformer. Most of the transformer devices include some type of current overload protection such as a fuse or breaker switch. Some of the controllers include lightning and or surge protection, or offer these as an optional feature. Surge and lightning protection limits damage to the controller's circuitry from transient voltage and current from the power source (surge) and from the valve circuits (lightning).

Station Circuit Rating, Wiring and Terminal Wire Sizes

The compatibility of the existing electrical circuits (wiring from the controller to the station valves) should be considered in the selection of a stand-alone controller. If the station wire terminals on the controller will not accept the existing wire, adapters must be used. Also, the circuit current capacity required for an existing system should be checked prior to installing a new unit. Installation problems associated with insufficient circuit capacity to operate some irrigation valves with high circuit resistance are a possibility.

The traditional wiring system (circuitry) used for most controllers consists of a common and a dedicated wire from the controller to each valve and sensor. Some controllers utilize "2-wire" circuitry that consists of a single pair of wires connected to all of the valves and sensors in the system. These systems require the installation of a decoder device for each valve and sensor. Applications include large systems and linear systems (e.g., highway corridors) with large quantities of wiring required for traditional circuitry.

Warranties and Reliability

All of the products reviewed include a warranty. Warranty details are discussed in the product descriptions section. In some cases, the manufacturers' warranty periods vary for its different products. Although the warranty periods may or may not be indicative of the life expectancy of the products, in some cases there appears to be a correlation between the cost and overall quality of the product to the warranty period. It is assumed the cost of a product somewhat reflects the quality of the construction materials and electronic components. Hence the less expensive residential devices should not be expected to last as long and function as reliably as the more expensive residential and commercial products. Since most of the devices are relatively new products, it is difficult to speculate on how long they should last.

Soil Moisture Based Product Descriptions

The following product descriptions address operational characteristics and features, and include discussions of available information from demonstration and pilot studies relative to documented water savings and operation. Each of the manufacturers were provided copies of the product descriptions for input prior to being incorporated into this report.

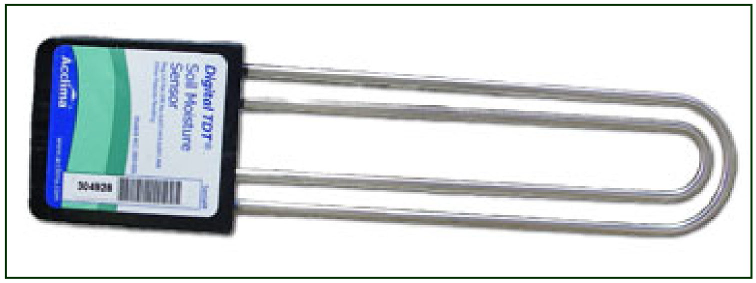
Acclima

Acclima, Inc., of Meridian, Idaho, manufactures soil moisture sensor based landscape irrigation control systems. Acclima began development of its system components in 1997, and Acclima products entered the market in 2003. Acclima's sensor technology is sold throughout the United States, Europe, South Africa, Asia and Australia.

Acclima Closed Loop Irrigation® systems are governed by real-time root zone soil moisture content as measured by its patented Digital TDT® absolute soil moisture sensor. The Acclima sensor is the industry's only digital process time domain transmissometry soil moisture sensor. Acclima reports its digital process sensors measure the absolute soil moisture content regardless of changing soil types, electrical conductivity and temperature. All systems accommodate one or more soil moisture sensors and either an add-on or stand-alone controller. Controllers suitable for all residential and commercial applications are available.

Sensor Description and Operation

The heart of all Acclima irrigation systems is the sensor. The sensor dimensions are 8" x 2" x 0.5", and the sensor is constructed of Type 316 stainless steel rods and electronic components embedded in moisture-resistant epoxy resin molded in heavy duty plastic. Sensor rods are electrically isolated from the circuit board to prevent galvanic corrosion and each sensor includes lightning protection. Sensors



are buried in the soil among the active rootlets of turf, trees and shrubs. The sensor reports the moisture content to the controller via the same wiring used for valve control in resolution of tenths of one percent. A typical residential installation employs one sensor. Commercial systems typically use multiple sensors, one for each microclimate or landscape vegetation type. Various zones may be programmed to track any sensor.

Acclima reports its patented Digital TDT sensor is unique because it provides *absolute* percentage volumetric water content whereas other sensors provide only *relative* moisture data. The sensor generates a unique high frequency pulse along the sensor rods with a sampling interval of 5 picoseconds -- the time required for light to travel 1.5 millimeters. This high speed sampling minimizes the dielectric relaxation properties found in clay soils. Acclima reports this characteristic, combined with its patented digital analysis process, produces superior stability and accuracy in all soil types. The Acclima sensor can detect the addition of 0.002 inches of water to 4 inches of soil, yielding maximum water savings.

Upon installation, the soil surrounding the sensor is doused to saturation and then allowed to percolate to field capacity. A sensor reading is taken at this time to determine the unique field capacity of the microclimate and the irrigation threshold is calculated.

All Acclima irrigation controllers use the Digital TDT sensor as a “closed loop” feedback mechanism in controlling the irrigation process. The controller polls the sensor for accurate soil moisture readings; if the sensor returns a reading below the irrigation threshold, the system will intelligently replace only the amount of moisture lost through ET since the last irrigation cycle. Thus, root zone moisture levels are perpetually maintained at user-specified levels, resulting in optimized economy and healthier landscapes.

Controller Description, Prices and Warranty

Acclima offers a variety of control devices suitable for any application. All stand-alone Acclima controllers allow multiple sensors with highly flexible programming. On all models, volumetric soil moisture content is displayed from 0 to 100 percent. Soil temperature is displayed in degrees Fahrenheit or Celsius and soil conductivity in dS/m (10^{-1} Siemens per meter).

Acclima’s Suspended Cycle® systems are programmed just as a standard irrigation clock. When the programmed time arrives, the system polls the sensor to see if irrigation is allowed. If not, the cycle is suspended; if water is required, irrigation takes place. Acclima's Water on Demand® systems require no programming whatever. The user enters the irrigation threshold, specifies times when irrigation is *not* allowed, and the system irrigates only as needed, without any programming.

The Acclima RS500 is an add-on controller that supports most existing clock type controllers. It sets, maintains and monitors any desired moisture level by suspending an irrigation cycle when there is sufficient moisture in the soil. The sensor is linked to the controller through the existing wiring for the valve irrigating the sensor location. Sensor readings are periodically transmitted to the controller. When the programmed existing timer prompts an irrigation cycle, the RS500 first checks the moisture level and either allows or suspends the cycle, depending on the moisture level. The RS500 includes a Moisture Control ON/OFF switch to by-pass the controller if necessary. Moisture readings continue, but there will be no interruption of the programmed cycles. Also, one or two zones may be operated by the existing controller independent of interruption by the RS500 to assure special zones such as xeriscape or newly-seeded areas receive appropriate moisture. The RS500 cabinet dimensions are 4.5" x 2.4" x 1" and it is suitable for indoor installation. The 24V power supply comes from the existing controller or external transformer. Each RS500 is sold with a Digital TDT soil moisture sensor.

The Acclima SC Series Controllers are stand alone Suspended Cycle control units. It is available in 6, 12, 24 and 36 zone configurations and in two cabinet models. These controllers employ standard zone wiring with typical programming processes.

The Acclima SC6/12 controller is designed for residences and light commercial applications with up to 12 zones. The controller has an LCD display and accepts as many sensors as there are zones. The controller's programming features include timer or sensor control; simple push-button control; pre-set factory default schedules including, sod, new seed, rotors and spray pop-ups; three independent programs with six start-times each; automatic threshold set-up; non-volatile program memory which preserves programming during power and battery failures; program and circuit test modes; zone error reporting; master valve/pump start capability; rain sensor/accessory terminal and enhanced surge protection. This controller has an exterior 24V transformer and includes a weatherproof cover, making it suitable for outdoor mounting.

The Acclima SC24/36 controller uses traditional valve wiring with four available programs and six start times. Each controller accommodates as many sensors as it has zones, and each sensor adds a new program to the controller. For multiple sensor set-up, each sensor is connected to the valve for each reference zone and sensor readings are transmitted to the controller via the valve wiring. Zones without sensors are assigned to a reference zone and irrigation occurs based on the soil moisture measured in the reference zone. Unique soil moisture thresholds may be programmed for each reference zone.

The controller may be operated in automatic soil moisture based, timed or manual modes. Up to 4 zones, plus a master valve circuit, may run concurrently, dependent on system water volume capacity. Multi-zone watering may be configured per-zone based on the water usage of that zone versus available water. This may be done automatically when a flow meter is attached to the system, or the configuration can be adjusted manually at any time. These controllers support rain, wind, and freeze sensor inputs to shut off the water when weather does not permit irrigation. Flow meter support checks for broken pipes and valves. Connection of a flow meter requires an interface device manufactured by Acclima.

The controller's calendar/clock automatically compensates for leap years. The clock can be maintained for up to 2 months without power using 2-AA alkaline batteries. The non-volatile program memory maintains configuration information even if the power fails and the batteries are dead. Watering day schedules include Custom, Every Day, Odd Day, Even Day, Every nth Day watering (where n may range from 3 to 31). Zone stacking ensures that all zones will eventually be watered even though program start times may overlap. Other features include soak/cycle, valve circuit test, programmable pause, rain delay (0-14 days) and water budget adjustment (5 to 500 percent). Remote control is available with optional hand-held radio and interface devices.

The controller cabinet measures 12.3" x 10" x 5.9" and is weather resistant extruded ABS plastic, suitable for outdoor installation. The internal power transformer includes over-under detector that automatically detects loads exceeding 2.1 amperes and over-load backup fuse (slow-blow, self-healing fuse: 2.5 A). Station circuit capacity is 0.6 amperes. The controllers possess surge and lighting protection consisting of the following:

Input:	Transient voltage suppressor (TVS)
Common Wires, Signal Ground:	5,000 Amp gas discharge tube to earth ground
Each Terminal:	Metal oxide varistor (MOV)
Earth Ground Terminal:	Up to #6 copper wire to divert surges to ground

The Acclima CS 3500 controller is a Water on Demand® device operating over a 2-wire communications line, saving copper and allowing flexibility for system modification. Up to 60 sensors may be used with this 64 zone system. The controller operates without programming. The user identifies blocks of time when irrigation is restricted, and sets an upper and lower irrigation threshold. Water is applied when the sensor reports moisture below the lower threshold and will irrigate until the upper threshold is reported.

The 2-wire circuit requires valve adapters (decoders) to establish the 2-wire communications bus to valve interface. These adapters contain electronic switches that apply power to the solenoid valves upon command from the controller. Acclima sensors also contain a single electronic switch so that there is no need for a valve adapter when a sensor is installed in the valve circuit.

The CS3500 offers features similar to the Acclima SC Series, and has central control capabilities using the Acclima Irrigation Manager™ software and advanced communications capabilities through serial cable, dial-in modem, cell phone or radio communications. The clock can be maintained for up to 10 years without 24 volt power using a CR2032 battery. The CS3500 cabinet is the same size and material as the SC24/36 and is suitable for exterior mount. Surge and lightning protection are also similar to the SC24/36.

Prices for selected Acclima products are summarized in Table 15. Acclima products may be purchased through distribution by referring to the Acclima website, www.acclima.com or by contacting Aquarius Brands, Inc. of Ontario, California. Acclima products carry a 2-year warranty.

Table 15 - Acclima Product Prices

Description	Model No.	Price
RS500 Add-on Controller*	ACC-SYS-0500	$ 265
SC6 Residential Controller*	ACC-SYS-0006	$ 292
SC12 Residential Controller*	ACC-SYS-0012	$ 358
SC24 Commercial Controller	ACC-SYS-0024	$ 995
SC36 Commercial Controller	ACC-SYS-0036	$1,495
CS 3500 Commercial Controller	ACC-SYS-3500	$2,978
Digital TDT Soil Moisture Sensor	ACC-SEN-006	$ 198
Flow Meter Interface	ACC-FPM-015	$ 650

*Includes one (1) Digital TDT Soil Moisture Sensor

Installation

Detailed installation instructions, manuals and videos are available on the Acclima website. Acclima reports the RS500, SC6 and SC12 controllers may be installed by homeowners, but recommends professional installation of the SC24, SC36 and CS3500 control systems.

Track Record and Water Savings

The accuracy of Acclima's Digital TDT soil moisture sensor is well documented by independent laboratories, and their patented irrigation systems have been tested and researched by numerous academic institutions. Acclima's sensor technology was first evaluated by the Center for Irrigation Technology in 2003. Since then, dozens of independent university studies have validated unprecedented savings of water and fertilizer. Acclima reports average water savings are approximately 30 to 40 percent. Acclima submitted their technology for independent verification before placing their products on the market. Testing entities include the following:

University of Arkansas
Oregon State University

New Mexico State University
University of Tennessee

University of Florida
Utah State University

Brigham Young University
California State University, Fresno

Information on the above testing and research, and certain study report documents are available on Acclima's website.

Agrilink

Agrilink Holdings Pty Ltd is a manufacturer of irrigation management products headquartered in Adelaide, South Australia. Agrilink has been in business since 1997 and has U.S. offices in Santa Rosa and Santa Ana, California.

Agrilink supplies a range of soil moisture sensing products and a specific soil moisture based landscape irrigation scheduling device.

The AquaBlu® soil water regulator was introduced by Agrilink in December 2006. This device works with any 24VAC clock-type controller to schedule irrigation based on soil moisture sensor input from an Agrilink AquaBlu Sensor.

Sensor Description and Operation

The AquaBlu Sensor is a capacitance (or FDR) type soil moisture sensor. It is a fully sealed double sided "paddle" shaped sensor made from ABS plastic. The sensor has overall dimensions of 7.5" x 2.8" x 0.5". The AquaBlu Sensor comes with 16 feet of multicore cable for connection to the regulator. The soil moisture signal and power supply for the sensor are transmitted through the cable. The

cable can be extended up to 90 feet without signal degradation using conventional multicore irrigation cable (4 cores are required). Further distances (up to 660 feet) can be covered using specialized cable available from Agrilink.

Agrilink recommends installing the sensor using a flat spade to slice a groove in the soil to the required root zone depth. The sensor is inserted into the groove and the surrounding soil is pressed in from both sides of the sensor to ensure complete contact around the sensor.

The AquaBlu system interrupts irrigation when soil moisture exceeds the threshold set by the user. Irrigation is interrupted immediately as opposed to interrupting before the next cycle. A base irrigation schedule is programmed into the clock type controller by the user which typically would irrigate every day without interruption imposed by the AquaBlu regulator. The total run times and cycle and soak times programmed into the clock controller must be calculated by the user.

Controller Description, Prices and Warranty

The AquaBlu regulator has two parts, a body and an opaque dust cover. It is designed to be wall mounted indoors in the vicinity of the clock controller, and can also be mounted outdoors or within a valve box if placed in a watertight housing. The body is made of ABS plastic and its overall dimensions are 6.5" x 3" x 1". The irrigation interruption threshold is set with its dial type adjustment component and two LED indicator lights show power and interruption status. The system can be powered by either AC or DC, at 9V to 14V at 100mA with a maximum power consumption of 1W. Agrilink’s optional “Line Regulator (24V to 12V)” can be used to convert from the clock controller’s 24VAC supply or an optional “AC power pack” can be used.

The soil moisture threshold adjustment dial has settings corresponding to the spectrum of soil types over a 270 degree control range. Confirmation that the AquaBlu is powered on is provided by a green LED. Indication of soil moisture being at or over the set point is provided by a red 'superbright' LED.

AquaBlu updates soil moisture readings once every second. This allows for the setup of the selected soil moisture point on the regulator to be intuitive and instant. When selecting the desired moisture point with the dial on the regulator, the red 'superbright' LED will come on and correspond with the current soil moisture content without waiting a day for a response.

For a simple residential installation, a single AquaBlu system is installed. The AquaBlu can be connected to the 'sensor' input on most modern clock controllers to cancel irrigation across all zones when soil moisture is sufficient. Alternatively (for older controllers that do not have a 'sensor' input) the AquaBlu is connected to interrupt the valve common wire within the controller.

Multiple AquaBlu devices can be used to control irrigation for different zones or groups of zones. This is achieved by connecting the AquaBlu to interrupt the active valve wire for a single zone or to interrupt a common valve wire for a group of zones. A typical split would be to use one AquaBlu for lawn areas and another for garden areas.

The listed retail price for the AquaBlu Soil Regulator, including the AquaBlu Sensor, is $139. The optional “Line Regulator (24v to 12v)” and optional “AC power pack” are $10 each. Agrilink warranties the AquaBlu for 2 years.

Installation

Agrilink recommends professional installation by a contractor with an understanding of where to best locate the sensor(s) and how to adjust the AquaBlu based on soil conditions. Installation time will vary according to how much digging is required to install the cable. If this is completed during irrigation system installation, minimal additional time is required. Agrilink reports it takes about 15 minutes to install the AquaBlu and wire it to the clock controller, and that a homeowner with some basic skills could retrofit an existing clock controller with an AquaBlu in under an hour if minimal digging is required.

Track Record and Water Savings

Agrilink submitted information for this review showing how multiple AquaBlu devices tracked soil moisture levels at the Townsend House (Adelaide, South Australia) demonstration project.

Data collection for the demonstration project began in early 2007, with initial results being positive. Figure 13 includes a graph of soil moisture status with increases due to irrigation and rainfall and decreases due to daily turf water use as a result of ET. Soil moisture was measured with a commercial probe (AquaSpy™ Turf Probe) documenting the current irrigation practice for a period of time before the AquaBlu was engaged. What followed was the documentation of the reduction of the number of irrigations when the clock controller was interrupted by the AquaBlu after it was engaged.

There were 14 irrigations prevented out of a possible 20 irrigations that were scheduled by the clock controller during the time the AquaBlu was active. Irrigations were also prevented over the period in response to minor and major rainfall events while the soil moisture was still adequate for viable plant and turf growth.

Timed irrigation events that would have normally occurred by the irrigation timer and were switched off by the AquaBlu are indicated by the red arrows.

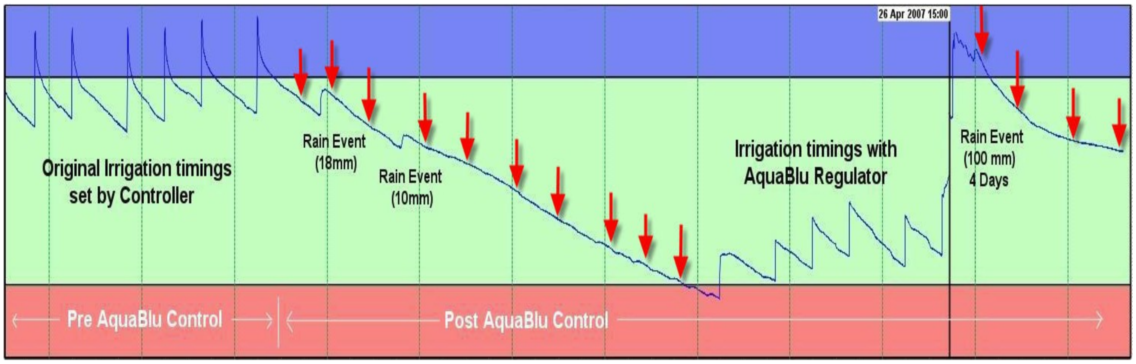


Figure 13 - AquaBlu Demo Site Irrigations and Soil Moisture Tracking

The locations of twenty other commercial installations were also provided. No other information on the product's track record or water savings studies was available, which is understandable for such a new product.

Baseline

Baseline, LLC, located in Boise, Idaho, manufactures soil moisture sensor based landscape irrigation control systems. Baseline began business in 1998, and its first soil moisture sensing products entered the market in 2002. Its systems include add-on and stand-alone controllers, as well as centralized control systems.

The Baseline irrigation control systems are based on real-time soil moisture content as measured by Baseline's patented biSensor™ TDT (time domain transmission) soil moisture sensor. All systems (non-centralized) function with one or more soil moisture sensors that are offered with three controller options: a stand-alone controller, an add-on controller that interfaces with an existing clock-type controller, or a computerized system of multiple stand-alone satellite controllers. Baseline manufactures systems that are suitable for both residential and commercial applications.

Sensor Description and Operation

The biSensor comes in three models: a 6-inch rigid sensor used with the S100 controller, a 1.5-foot rigid sensor and a 5-foot flexible sensor. All measure the

volumetric soil moisture content near the sensor. The sensors are buried in the root zone, and transmit soil moisture and temperature information to the controller via the same wiring used for valve control. A single sensor can control multiple irrigation zones. A typical residential system includes just one sensor. A commercial system may use numerous sensors associated with various microclimates or landscape types. Baseline recommends installation in a v-shaped trench to minimize soil disturbance where contact is made to the sensor. The biSensor is constructed of corrosion-resistant fiberglass.

The biSensor functions by sending an electronic pulse along an imbedded wire path. The wire is embedded in fiberglass providing desired characteristics by not being in contact with the soil, but the speed of the pulse is delayed by the soil's water content. The higher the water content, the slower the pulse moves around the biSensor. The biSensor measures the pulse speed to determine the amount of water in the soil. biSensors can reportedly resolve the travel time in increments as small as 10 pico seconds. Baseline's biSensors measure distortion caused by salts and temperature changes and adjust moisture readings accordingly. All sensor-related electrical components are insulated from the soil, including the actual sensing elements.

Controller Descriptions, Prices and Warranty

Baseline's controllers include one add-on model and four stand-alone models. Three of the stand-alone controllers utilize two-wire valve control wiring and the other supports conventional valve wiring. The add-on model is designed for use with a single biSensor and functions with any clock/controller. The standalone models can be connected to multiple biSensors. All of Baseline's controllers are rain sensor compatible and have a bypass feature that disables the soil moisture based control. The soil moisture reading for all controllers is displayed as volumetric water content from 0 to100 percent. The stand-alone models include an internal power transformer and the add-on models power supply is from the clock/controller or from an external transformer. The standalone controllers operate on Baseline's Time/biSensor control system allowing for several smart watering strategies from fully automatic to timer type controls and many options in-between.

The Baseline WaterTec™ S100 controller is an add-on device for use with an existing clock/controller and a single biSensor. The S100 cabinet is constructed of heavy duty plastic and is available in an indoor model. Its dimensions are 5.8" x 2.6" x 1.5" and it has a 3-character, one line LCD display and touch pad type controls. The S100 comes with a 6-inch biSensor soil moisture sensor.

Guidelines for performing a site audit and determining appropriate total run times and soak and cycle times are available from Baseline for programming the clock/controller connected to the Watertec S100.

The BaseStation 3000R is a stand-alone commercial controller supporting new or existing conventional irrigation wiring and scales from 12 to 200 zones. Baseline biSensor moisture sensors may be connected directly to existing valve lines for existing (or new) sites. The BaseStation 3000R also includes a two-wire expansion port, which allows system expansion using either conventional wiring or two-wire. The 3000R offers 10 programs with 8 start times for each program. The user programs a base schedule and then the total run times are adjusted by the controller based on its evaluation of soil moisture data. (Guidelines are provided for determining an appropriate base schedule.) Other features include day interval calendar, event scheduling, self-test diagnostics and adjustable soak cycles. The 3000R is remote access capable with Baseline's BaseManager™ computer software package.

The 3000R is available in lockable indoor wall mount and outdoor pedestal models. The wall mount cabinet is constructed of powder coated steel, and its dimensions are 12" x 10" x 4". The pedestal cabinet is constructed of stainless steel and its dimensions are 36" x 17.5" x 12.5". The controller face includes a dial and touch pad controls. The controller's 3.5-inch QVGA display provides 240x320 resolution. The BaseStation BL3000 is a stand-alone commercial controller with two-wire biLine™ valve wiring configuration. The two-wire system requires the use of biCoder™ devices at each valve to convert the two-wire signal to power and control the valve. The BL3000 has 200 zone and 25 biSensor capacities. This controller offers the same features of the BL3000R including 10 programs with 8 starts and an event scheduling feature that allows for restrictions for future events. Also, the user has the option of setting the controller to adjust run times or run frequency. The BL3000 is available in wall mount or pedestal cabinets of the same construction and sizes as the BL3000R. The control and display features are also the same.

Current suggested retail prices for Baseline products are summarized in Table 16. Baseline products are available from its distributors, and a distributor list is available at the Baseline website (www.baselinesystems.com). Baseline controller products have a 1-year warranty (with ability to extend up to 5 years) and the biSensors have a 5-year warranty.

Table 16 - Baseline Product Suggested Retail Prices

Description	Model No.	Price
Indoor Add-on Controller	S100	$149*
200-Zone Stand-alone Wall Mount Controller	BL3000C	$1,599
200-Zone Stand-alone Pedestal Controller	BL3000P	$3,199
12-Zone Expandable to 200 Wall Mount Controller	BL-3000CR-12	$1,999
24-Zone Expandable to 200 Wall Mount Controller	BL-3000CR-24	$2,399
12-Zone Expandable to 200 Pedestal Controller	BL-3000PR-12	$3,495
24-Zone Expandable to 200 Pedestal Controller	BL-3000PR-24	$3,695
48-Zone Expandable to 200 Pedestal Controller	BL-3000PR-48	$4,295
biSensor Soil Moisture Sensor (1.5-foot)	BL5315B	$249
biSensor Soil Moisture Sensor (5-foot)	BL5305B	$249
biCoder Two-wire Valve Adapter (single zone)	BL5201	$137.50
biCoder Two-wire Valve Adapter (two zone)	BL5202	$192.50
biCoder Two-wire Valve Adapter (four zone)	BL5204	$270.00

* Price includes biSensor

Installation

Although Baseline recommends installation by a landscape professional, it reports the S100 can be installed by most homeowners. The reported average homeowner installation time is about an hour.

Track Record and Water Savings

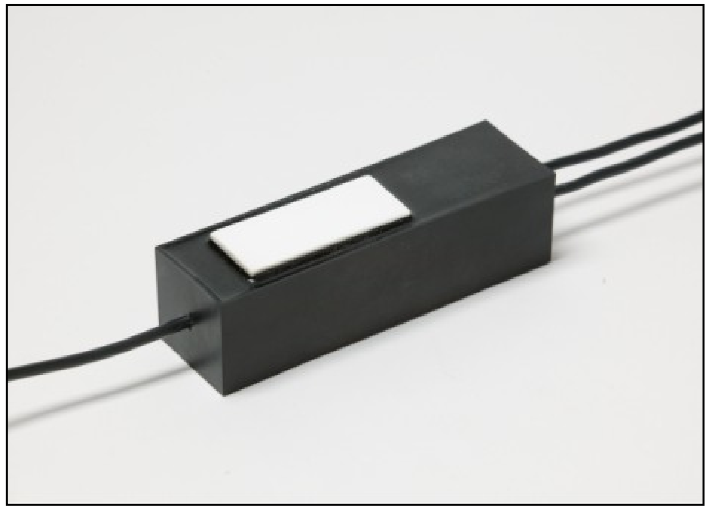
Although no information was submitted for this report on formal studies and testing, Baseline submitted documentation from numerous customers reporting significant water savings (30 to 50 percent) resulting from installation of Baseline systems.

Calsense

As discussed in the Weather Based Product Descriptions section, Calsense manufactures water management systems for large commercial customers. The Calsense Model 1000-S soil moisture sensor measures and transmits soil moisture readings to a Calsense ET2000e irrigation controller to provide efficient landscape irrigation. The ET2000e will automatically suspend irrigation when the soil moisture level is above the threshold set by the user. A full description of the ET2000e and its features is included in the Calsense discussion in the Weather Based Product Descriptions section.

Sensor Description and Operation

The 1000-S is a solid-state tensiometer type soil moisture sensor that provides consistent long-term soil moisture readings to the Calsense irrigation controller. The moisture sensor electronics are encased in epoxy and the sensor is constructed of heavy duty plastic. There is no maintenance or calibration required for the life of the sensor. The 1000-S readings are unaffected by temperature, salinity or changes in soil pH. The sensor's dimensions are 6.4" x 1.9" x 1.6".



The 1000-S is installed in the root zone and is connected to the valve that controls the area where the sensor is located. Soil moisture data are transmitted to the irrigation controller via the valve control wiring. Special wire runs between the irrigation controller and the sensor are not necessary. The only additional wiring required is between the valve and the 1000-S sensor. The total combined maximum wire run between the moisture sensor and the irrigation controller is 3,000 feet. Calsense reports that maintenance of the 1000-S is only required when the soil becomes extremely dry, requiring the device be removed and soaked and then placed into moist soil. If the soil freezes, removal is not required.

The Calsense ET2000e controller, using the sensor to measure available water in the pore space of the soil, makes a decision before the start of each cycle/soak run whether or not to apply water. This decision is based on the actual moisture reading compared to the user-input moisture set point. Total run times and cycle and soak times are included in the base program entered by the user, based on field knowledge and soil moisture content for the time of year.

A 1000-S is connected to a representative station for each different climatic and plant material zone, which is defined as a master station. Slave stations are stations without sensors and are assigned to a master station that shares similar water requirements. The user chooses groups of stations controlled by the same sensor during initial setup. Stations can be easily changed or moved from one sensor to another through user friendly programming. Calsense recommends a general guideline of one moisture sensor per four active valves to cover varying moisture needs. Up to one soil moisture sensor per every valve may be connected using the ET2000e controller.

Controller Description, Prices and Warranty

The 2000e features are discussed in more detail under the Calsense portion of the Weather Based Products section.

Calsense products are available from many distributors located throughout the U.S. A list of these distributors is available from Calsense upon request (800-572-8608 or www.calsense.com). The current retail price for the 1000-S is $199. It has a 5-year warranty. The price range for the various ET2000e models is from $1,290 to $3,680, as detailed in the Calsense discussion in the Weather Based Products section. Calsense provides technical support at no-charge to assist in the proper installation of the moisture sensors for the most efficient system.

Installation

Calsense recommends professional installation of the ET2000e and installation time varies significantly depending on site conditions.

Track Record and Water Savings

Although Calsense has not participated in any outside studies or demonstration projects, its track record speaks for itself. During Calsense's 20 years of existence, they have developed a large data base on its products' performance and customer success.

Dynamax

Dynamax, Inc. manufactures a wide variety of products used for water status applications, water cycle measurement, plant-water relations, carbon flux instruments, as well as weather stations. Dynamax is located in Houston, Texas and has been in business for 20 years. Distribution of its soil moisture based landscape irrigation control systems began in 1999.

Dynamax offers two add-on systems and a third system that works as an add-on or stand-alone device. The Moisture Clik™ (IL200-MC) and the Moisture Switch™ (IL200-MS) are add-on only devices that function with newer model non-mechanical clock type controllers. Dynamax's Data Logger/Irrigation Monitor (GP-1) can function as a stand-alone controller or as an add-on device. All three systems utilize the Dynamax SM200 soil moisture sensor.

Sensor Description and Operation

The SM200 is a frequency domain reflectometry (FDR) type of dielectric sensor that measures volumetric soil moisture content from 0 to 60 percent with a Dynamax reported 3.0 percent accuracy. The SM200 soil moisture sensor consists of a waterproof housing that contains the electronics and two sharpened stainless steel rods that are inserted into the soil. The rods are threaded and may be removed from the housing for replacement if damaged or bent. Each SM200 is adjusted during manufacture to provide a consistent output when measuring media of known dielectric constant, making them readily interchangeable without system re-calibration. Specifically, Dynamax reports soil temperature effects and low to moderate salt and fertilizer (conductance levels below 2,000 micro siemens) effects are negligible. The overall length of the sensor is 5.4” and the housing diameter is 1.6”. It comes with 85-feet of 4-wire cable. The SM200 is installed into the root zone by pushing the rods into the wall of a shallow trench, resulting in contact with relatively undisturbed soil. The sensor cable is connected to the irrigation scheduling device.

The SM200 is designed to measure volumetric soil water content using a novel technique that the manufacturer reports matches other methods, such as time-domain reflectometry, for accuracy and ease-of-use, while reducing the complexity and expense. A simplified standing wave measurement is used to determine the impedance of a sensing rod array and hence the volumetric water content of the soil matrix.

The SM200 applies a 100-megahertz sinusoidal signal via a specially designed transmission line to a sensing array whose impedance depends on the dielectric constant of the soil matrix. Because the dielectric constant of water (80) is significantly greater than that of the other soil matrix materials (3-4) and of air (1), the dielectric constant of the soil depends primarily on soil water content. The signal frequency has been chosen to minimize the effect of ionic conductivity.

Controller Descriptions, Prices and Warranty

The Dynamax add-on only systems (Moisture Clik and Moisture Switch) regulate irrigation by continuously monitoring the soil condition at the sensor, and interrupting the clock controller schedule when enough water is available in the root zone. As soon as the soil dries out below the user programmed set point, an

internal switch closes the signal to the clock controller to irrigate. The clock controller to which the device is connected operates as programmed by the user to replenish the depleted soil moisture. The Dynamax owner's manuals include information regarding appropriate run, cycle and soak times. The GP-1 Irrigation Monitor controls irrigation frequency and run times automatically with on and off soil moisture triggers that are programmed by the user.

The Moisture Clik and Moisture Switch devices come with normally open, and separate hot or neutral outputs providing for several connection options. Specifically, a single Moisture Clik or Moisture Switch controller may be connected to the existing clock controller such that one Dynamax controller and soil moisture sensor will control all stations or multiple Dynamax controllers and sensors may be used to control groups of stations, or individual stations.

The Moisture Clik is recommended for residential and smaller commercial applications. It is typically connected to a clock controller to control and regulate all valves, and up to 3 valves may operate simultaneously. The Moisture Clik controller may also be used where multiple sensors are desired for individual soil moisture control of one or more stations. However, only one SM200 soil moisture sensor may be attached to each individual Moisture Clik. The Moisture Clik may be programmed using its dial settings based on soil type and the desired allowable soil moisture depletion level. Alternatively, advanced users may verify sensor settings and measure soil moisture field capacity with a voltage meter to improve performance.

The Moisture Clik controller cabinet is constructed of polycarbonate and ABS plastics, and is rated for indoor or outdoor installation. Its dimensions are 4.6" x 4.6" x 2.4". The 24 VAC, 3 amperes power supply is either from the clock controller or from an external transformer. (Dynamax recommends using its optional external transformer.) It possesses a 3 ampere input fuse and 0.5 ampere internal fuse. Approximately 6-foot of minimum 12 gauge wire is required to connect the Moisture Clik to the existing controller.

The Moisture Switch controller features are suited for large landscape applications where simultaneous control of multiple valves is necessary. It is typically connected to a clock controller to control and regulate all valves, and up

to 10 valves may operate simultaneously. Multiple Moisture Switch controllers may be used where multiple sensors are desired for individual soil moisture control of stations. However, only one SM200 soil moisture sensor may be attached to each individual Moisture Switch. The Moisture Switch requires the use of a standard voltage meter for installation and programming.

The Moisture Switch controller cabinet is constructed of fiberglass reinforced polycarbonate plastic, and is rated for indoor installation only. Its dimensions are 5" x 3.5" x 3". The 24 VAC, 10 amperes power supply is either from the clock controller or from an external transformer. (Dynamax recommends using its optional external transformer.) The Moisture Switch possesses a 10 ampere input fuse and 1.0 ampere internal fuse. Approximately 6-foot of minimum 12 gauge wire is required to connect the Moisture Switch to the existing controller. The Moisture Switch includes an alarm display and a terminal for connection of an external alarm mechanism. As discussed above, installation of the Moisture Switch requires the use of a voltage meter to determine the irrigation set point.

Dynamax's GP-1 Data Logger/Irrigation Monitor is a more sophisticated commercial product with numerous applications, including use as a stand-alone or add-on landscape irrigation scheduling device. One or two SM200 soil moisture sensors may be connected to it, and it has terminals for up to two temperature sensors, a flow sensor and a rain gauge. It also has a terminal for connection of an external alarm mechanism. The GP-1 has several unique features, including two soil moisture level thresholds for irrigation on and off.

As a stand-alone controller, the GP-1 can be programmed to initiate continuous irrigation at a prescribed soil moisture level and then discontinue irrigation at a second soil moisture level. This is best suited for precision irrigation applications and or drip irrigation systems. As an add-on device, irrigation frequency and total run times are controlled automatically by utilizing the two soil moisture level set points. When the soil moisture drops to the first trigger, irrigation run and soak cycles are initiated. The cycles are discontinued when the second soil moisture level is measured. With the GP-1 connected to a clock controller, it will control and regulate all valves with one SM200 sensor or two groups of valves with two sensors. Up to 10 valves may operate simultaneously, and multiple GP-1 units can be used to control individual valves or groups of valves as with the other devices.

The GP-1 is constructed of polycarbonate and ABS plastics and is suitable for outdoor installation. Its dimensions are 5.5" x 4.1" x 1.8". The GP-1 operates on 11-24 VDC power from batteries (alkaline or lithium) or an external transformer. Approximately 6-foot of minimum 12 gauge wire is required to connect the GP-1 to the existing controller. The GP-1 is programmed using a personal computer or a personal digital assistant (PDA) device. Programming software is included with the GP-1 and an optional PDA and PDA kit is available.

Current retail prices for Dynamax soil moisture sensor based irrigation control products are summarized in Table 17. (Moisture Clik, Moisture Switch and GP-1 prices include one SM200 soil moisture sensor, cable and owner's manual.) Dynamax products may be ordered directly by contacting the sales department through their website (www.dynamax.com) or toll free telephone (800-896-7108), and through its distributors and irrigation design consultants. A distributor search engine is also available at its website. Dynamax provides a one year warranty with its soil moisture sensor control systems.

Table 17 - Dynamax Products Retail Prices

Description	Model No.	Price
Moisture Clik Add-on Controller	IL200-MC	$425*
Moisture Switch Add-on Controller	IL200-MS	$575*
Data Logger Irrigation Monitor	GP-1	$911*
Moisture Sensor	SM200	$276
Temperature Sensor	ST3	$90
Tipping Bucket Rain Gauge	TR4-L25	$350
Pocket PC (iPAQ® 2200) PDA	PPC-1	$950
Pocket DeltaLINK Kit	PDLK1-M8	$247
24 VDC Power Transformer		
24 VAC Power Transformer	IL200-ADP	$20

* Price includes one soil moisture sensor, 82-feet of cable and owners manual

Installation

Dynamax recommends installation by an irrigation professional, however, it reports installation and programming of the Moisture Clik is relatively easy and may be accomplished by some homeowners. Dynamax reports installation time reportedly varies from 1 to 1 1/2 hours.

Track Record and Water Savings

The Macaulay Land Use Research Institute, Aberdeen, UK and Delta-T Devices, Cambridge developed Theta Probe soil moisture sensors jointly. Since its' development and release, Delta-T has sold over 17,500 of its Theta Probe ML2 units into the scientific and research community. The SM200 is very similar to the ML2, but is constructed to meet a slightly less stringent specification.

Copies of several published reports from studies including the Theta Probe ML2 were submitted as part of this review, all reporting favorably on the ML2. A list of websites with product comparisons, technical reports, and completed studies pertaining to Dynamax products are available from Dynamax. Dynamax will also provide a list of their SM200 customers upon request.

Irrometer

The Irrometer Co., Inc., located in Riverside, California, has been in business since 1951. Irrometer manufactures irrigation optimization equipment including soil moisture sensors and control devices, soil solution access tubes for nutrition management, and pressure gauges. Their original tensiometer type soil moisture sensing products have been on the market since 1951. The Watermark resistance type sensor was introduced in 1985.

Irrometer offers 4 different add-on control devices for soil moisture based residential and commercial landscape irrigation control. The controllers use one or more of the Watermark soil moisture sensors to interrupt the existing clock/controller schedule until the soil moisture reaches the user prescribed level. Included with the purchase of an Irrometer control system is its WaterPerfect turf and landscape irrigation scheduling and water management software. This software program aids the user in the proper scheduling of irrigation utilizing Watermark soil moisture sensors, including calculation of total run times and cycle and soak times based on site conditions.

Sensor Description and Operation

The Watermark is a solid state electrical resistance type sensor which Irrometer reports provides accurate readings from 0 to 200 centibars. This covers the entire soil moisture range required in irrigated landscapes, including heavy clay soils. The sensor is installed by placing it into a hole made with a 7/8” diameter rod to the desired sensor depth. If a larger diameter hole is made, then a “grout” of the soil and water is poured into the hole.

The sensor consists of two concentric electrodes embedded in a reference matrix material, which is surrounded by a synthetic membrane for protection against deterioration. The exterior surface is of ABS plastic and a stainless steel mesh. The internal matrix includes gypsum, which provides some buffering for the effects of salinity levels normally found in irrigated landscapes. The sensor is 7/8” in diameter by 3” long. The original Watermark (model 200) was improved in

1993 to the current model 200SS, which has improved its soil moisture response characteristics. The sensors are maintenance free and are not damaged by freezing. The reported minimum life span for a Watermark sensor is five to seven years.

Irrometer's soil moisture sensor based control devices include the WaterSwitch (WS1), Watermark Electronic Module (WEM), Battery WEM (WEM-B), and Watermark Multiple Hydrozone System (MHS). As mentioned above, all of these devices use the Watermark sensors and interrupt the common power supply to the clock/controller or interface with the controller's sensor circuit, and the WEM may be used to control individual valves. The sensor wiring is connected directly to the control module, which is connected to either the clock/controller or the valve(s). The maximum run between the sensor and controller is 1,000 feet using 18 gauge wire. Larger wire sizes can be used for longer distances.

Controller Descriptions, Prices and Warranty

The Watermark Electronic Module is Irrometer's flagship controller. It is a versatile device that can be used in multiple connection scenarios, and in combination with the Multiple Hydrozone System as discussed below. The WEM can be used to control an individual valve, a group of valves watering areas of similar water demand, or all the valves on any clock/controller. In a typical residential application, a pair of Watermark sensors is connected to the WEM and the wiring configuration for the connection to the clock/controller provides for interruption of the power supply common connection. Alternatively, a pair of sensors and a WEM may be installed and connected to a single valve at the valve box. When a new system is being installed for a large landscape with a need for multiple sensor pairs, multiple common wires can be installed to provide for the use of multiple WEMs and sensors. For a retrofit of an existing system where multiple sensors are needed, a Multiple Hydrozone System device should be used rather than installing the needed additional common wiring.

The WEM's cabinet is constructed of heavy duty plastic and it can be installed indoors or outdoors. It may be installed at the controller or at the valve. The WEM's dimensions are 3" x 2" x 1.5". The WEM is adjustable from 10 to 120 centibars by a simple dial that has an OFF position to allow for overriding the sensors. The WEM's indicator light comes on when the clock/controller is powering a valve controlled by the WEM, and the soil moisture conditions are drier than the selected setting indicating irrigation is allowed. It is powered by a 24 VAC supply from the clock/controller.

The WaterSwitch and the Battery WEM are designed for use with clock/controllers that possess switch terminals (rain, master valve, etc.). This provides for a simple wiring configuration and easy installation. Both function similar to the WEM and possess the same features.The WaterSwitch is constructed of heavy duty plastic and is suitable for indoor or outdoor installation. Its cabinet dimensions are 2" x 2" x 1.25" which make it small enough to mount inside many controller cabinets. The WaterSwitch is powered by the 24 VAC supply from the clock/controller.

The Battery WEM is designed for use with a DC powered clock/ controller. It is constructed of heavy duty plastic and is suitable for outdoor installation. Its cabinet dimensions are 2.5" x 1.5" x 2". The Battery WEM is powered by a 9-volt battery housed inside its waterproof battery compartment.

The Multiple Hydrozone System device functions with multiple WEMs and is designed for commercial applications where numerous sensor pairs are used, or retrofit of an existing system with a need for more than one sensor pair. The MHS can control valves for up to 8 separate moisture sensing areas. Each area is monitored using a WEM and Watermark sensors allowing for individual adjustment of the soil moisture threshold and a manual override feature is included. This device communicates with the clock/controller such that individual valves or groups of valves can be controlled without the need for multiple power supply common connections.

The MHS is constructed of heavy duty plastic and is suitable for indoor installation. A weatherproof stainless steel cabinet (shown in photograph) is available for outdoor installations. Its dimensions are 11" x 16" x 2" and the outdoor cabinet dimensions are 18" x 18" x 7". The MHS is powered by a 24 VAC supply from the clock/controller.

Current retail prices for Irrometer soil moisture sensor based irrigation control products are summarized in Table 18. Irrometer products are available through irrigation equipment distributors, some of which are listed at its website (www.irrometer.com). Irrometer provides a one year warranty with its soil moisture sensor control systems.

Table 18 - Irrometer Products Retail Prices

Description	Model No.	Price
WaterSwitch Add-on Controller	WS1	$100*
WEM Add-on Controller	WEM	$200**
Battery WEM Add-on Controller	WEM-B	$250**
MHS Device	MHS-_-_	$655 and up
MHS Stainless Steel Cabinet	-CM	$870
Watermark Soil Moisture Sensor	200SS-5	$31

* Price includes one Watermark soil moisture sensor

** Price includes two Watermark soil moisture sensors

Installation

Irrometer recommends professional installation, but it reports a typical residential system can be installed by some homeowners in approximately 2 to 4 hours.

Track Record and Water Savings

Irrometer's Watermark sensors have been used in soil science research by universities, as well as in production agriculture and landscape applications, worldwide for over 15 years. Their use in landscape applications has been documented for the longest period of time by a study that originated in 1993 for the city of Boulder, Colorado. The consulting firm conducting the study, Aquacraft, Inc., published numerous papers from 1995 to 2001 for the Irrigation Association, the American Society of Agricultural Engineers, the American Water Resources Journal and the American Water Works Association. The graph shown in Figure 14 is from one of these papers and the following is an excerpt from one of the papers:

"The results of this study were quite encouraging from the standpoint of both irrigation efficiency and cost effectiveness. On a seasonal basis, the systems limited applications to an average of 76% of theoretical requirement when all sites are combined."

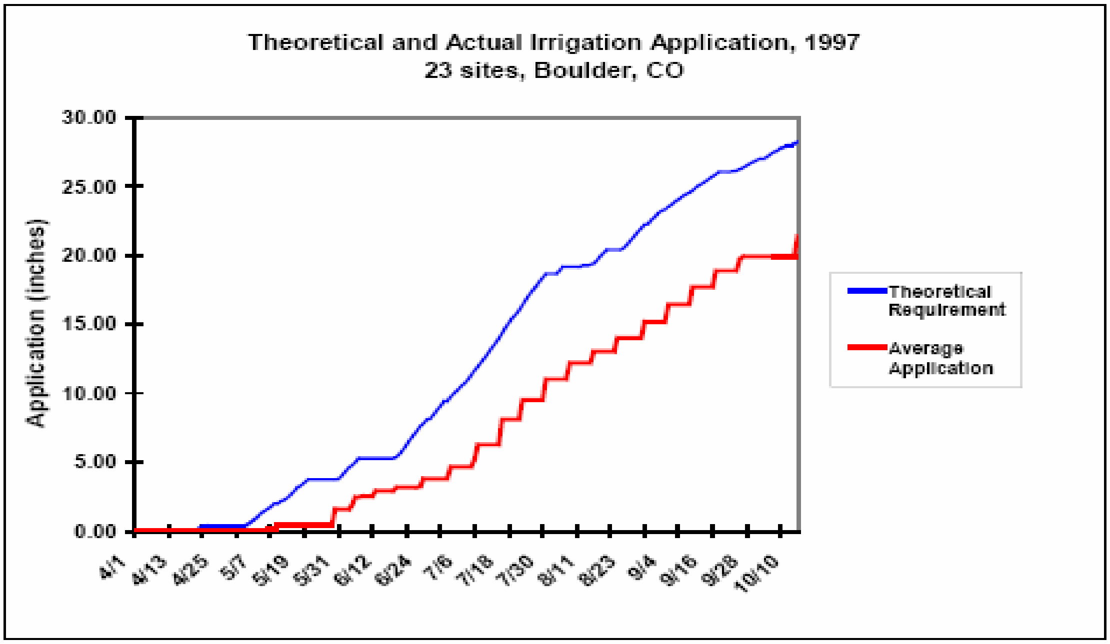


Figure 14 - Watermark performance compared to turf water requirement

Irrometer's Watermark control products have also received the *Smart Approved WaterMark* designation**,** Australia's water saving labeling program for products to reduce outdoor water use.

LawnLogic

LawnLogic® products are manufactured by Alpine Automation, Inc., of Aurora, Colorado. The company began business in 1997 as a soil moisture based irrigation systems supplier. Research and product commercialization began on the LawnLogic system in 2003 and it was introduced in the spring of 2004. In June 2006, it was reported that over 400 LawnLogic systems were in place, many of which were operating in their third irrigation season.

The LawnLogic system works with any clock/ controller to independently control individual irrigation zones. Each system consists of one or more control modules and four soil moisture sensors per module. The system is compatible with any combination of sub-surface, pop-up and rotary irrigation system designs.

Sensor Description and Operation

The LawnLogic soil moisture sensor is an electrical conductivity type sensor. It measures the current and resistance between two non-corrosive stainless steel probes that are 3” long and 3” apart from each other. The sensor body is 1/2” wide. Sensor readings are calibrated to volumetric soil moisture content. The probes are embedded in an impact resistant plastic housing and the wiring and electronics are encased in electrical potting epoxy. The sensors are installed by pushing the probes into relatively undisturbed soil in the wall of a shallow trench and connecting the sensor wiring to the appropriate valve solenoid connectors within the valve box.

The sensors communicate with the control module via the valve wiring and clock controller. When a sensor determines the moisture level is at or above the user-defined set point the system does not allow an irrigation cycle. When moisture levels drop below the user adjustable setting, irrigation cycles are allowed. The control module wiring is connected to the existing clock/timer and the sensor wiring is connected to the valve for each respective zone. The user must program a base schedule into the clock controller, and LawnLogic does not provide information on calculation of total run times and cycle/soak times.

Controller Description, Prices and Warranty

The LawnLogic controller module (model No. LL-1004) connects to any existing 24 VAC clock type controller. The instrument operates with exclusive Alpine Automation developed MLD (Mixed Logic-Dynamic) and MCC (Measurement and Control) software. The LawnLogic system automatically tailors a moisture profile for each zone when the appropriate zone button is held down. For example, the switch marked “2” controls irrigation zone 2 and when the switch is held down for 5 seconds, the LCD displays the message “READING ZONE 2”. The LawnLogic sensor buried in zone 2 measures the amount of soil moisture present. The message “CALIBRATING 2” then appears on the screen. The system is then operational and the user can increase or decrease the soil moisture threshold in each zone by four levels. If no sensor is present in the zone the message “NO SENSOR 2” appears.

Each module has a one-line,16 character backlit LCD display which displays auto-prompt information for installation and programming. Zone selection, bypass and moisture adjustment controls are two position rocker switches. The module is rated for use with solenoid valves holding 0.5 ampere circuit capacity maximum. Power to the control module is typically from the existing clock/controller, but an external transformer may be used. Surge suppression is integrated into the measurement and control circuitry.

Each irrigation zone can be bypassed independently, which allows the clock/controller to operate without the benefit of the LawnLogic system. All settings are stored in non-volatile memory and no battery backup is required in the case of a power outage. Soil moisture status is updated every 15 minutes and the real time status of each zone is displayed 24/7.

The module enclosure is constructed of heavy duty plastic. Its dimensions are 5" x 3.2" x 2.5". It is designed for indoor installation, but an optional locking outdoor plastic cabinet is available for mounting outdoors. Up to four modules can be installed in the outdoor cabinet. The dimensions of the outdoor cabinet are 12" x 12" x 4". Up to 6 modules can be combined to control up to 24 zones, and up to 32 zones can be accommodated for custom projects.

Current retail prices for LawnLogic systems are summarized in Table 19. Prices include the control module and all sensors. LawnLogic products are available through its distributors, which are listed at its website (www.lawnlogic.com). Alpine Automation provides a one year warranty with its LawnLogic soil moisture sensor control systems.

Table 19 - LawnLogic Current Retail Prices

Description	Model No.	Price*
4-Station Add-on Controller System	LL-1004	$379.95
8-Station Add-on Controller System	LL-1008	$749.00
12-Station Add-on Controller System	LL-1012	$1,099.00
16-Station Add-on Controller System	LL-1016	$1,449.00
20-Station Add-on Controller System	LL-1020	$1,799.00
24-Station Add-on Controller System	LL-1024	$2,149.00

* Prices include soil moisture sensors to compliment the number of zones

Installation

Alpine Automation recommends installation of large systems by an irrigation professional, however, it reports most homeowners can install a small system. The reported first-time installation time for a small system is estimated to be 1 hour, depending on site specific conditions. The company can make arrangements for professional installation through its distributor/dealer network.

Track Record and Water Savings

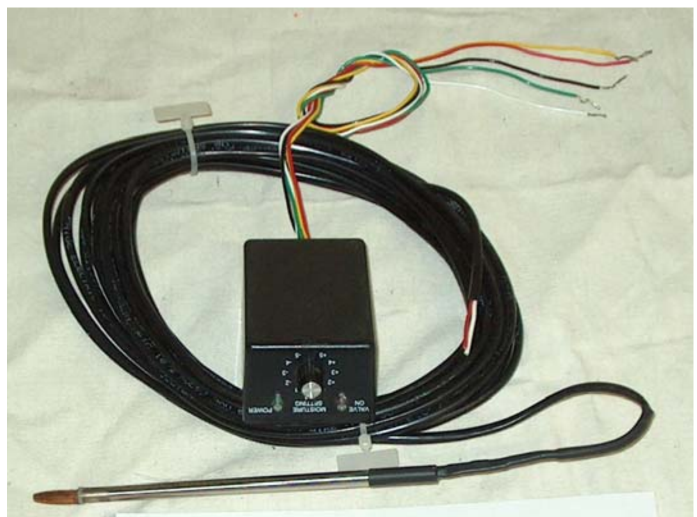
Based on performance and warranty tracking, Alpine Automation reports successful overall performance of LawnLogic systems and negligible problems.

LawnLogic was included in the University of Florida County Extension Madera home project study of soil moisture sensor based irrigation control. Study results submitted for this report showed a 44 percent average water savings during April to October 2005 for a single study site.

Alpine Automation reports LawnLogic systems have been successfully integrated with dozens of different clock/controllers ranging from unsophisticated 25 year old controllers to state of the art systems.

LawnLogic systems are installed across North America and Australia, and are in use on a variety of landscapes. The University of Florida recently initiated a study that incorporates LawnLogic systems on St. Augustine grass. Alpine Automation is working with both standard and ET controller manufactures, and companies that produce automated fertilization systems to facilitate the integration of LawnLogic with their products.

Waternomics



Waternomics soil moisture sensor based irrigation control products are manufactured by ManyWaters, Inc. of Denver, Colorado. ManyWaters has been in business since 2001, and carries a variety of water conservation related products. Distribution of its soil moisture based landscape irrigation control systems began in 2001.

ManyWaters offers the WW1 System which is an add-on soil moisture sensor landscape controller system that functions best with any clock/controller and utilizes an electrical conductivity type soil moisture sensor. The WW1 can also be used to control individual valves with or without the use of a clock/controller.

Sensor Description and Operation

The WW1 soil moisture sensor consists of a stainless steel and plastic probe that is inserted into the root zone. The sensor measures volumetric soil moisture content based on the electrical impedance measured between the probe’s two electrodes. Each sensor is calibrated at the factory to provide a consistent output when measuring media of known dielectric constant. The reported accuracy of the sensor is plus or minus 5 percent, but no information on sensitivity to salts/fertilizer was provided for this report. The overall length of the sensor is 6” and the housing diameter is 0.25”. It comes with 25 feet of 4-wire cable. The sensor is installed into the root zone by pushing it into the wall of a shallow trench, resulting in contact with relatively undisturbed soil. The sensor cable wiring may be connected to the existing valve wiring or to the add-on controller.

The WW1 System regulates water applied by continuously monitoring the soil condition at the sensor, and interrupting the clock/controller schedule or individual valve when enough water is available in the root zone. When connected to a clock/controller, the WW1 serves as a switch by overriding the common circuit to all station valves. When one or more controllers are used without a clock/controller, the controller causes irrigation to occur when the soil moisture falls below the user specified threshold and then irrigation ceases once the soil moisture content is measured to be at the threshold. This mode does not allow for prescribing irrigation days, times or soak/cycle periods.

Controller Description, Prices and Warranty

The WW1 controller comes with normally open, and separate hot or neutral outputs providing for several connection options. It may be integrated with an existing clock/controller such that one soil moisture sensor will control all stations or multiple sensors may be used to control groups of stations. The controller may be set from zero to 100 percent saturation soil moisture content in 5 percent increments.

For control of all stations using one sensor, the WW1 controller is typically installed near the clock/controller. When using multiple sensors, the controller may be installed in the individual valve box(es) or at the clock/controller.

The WW1 controller cabinet is constructed of high impact shock resistant plastic, and is rated for indoor or outdoor installation. Its dimensions are 3” x 2” x 1” with a rotating moisture level control knob and LED indicator lights. The controller’s circuitry is epoxy-encapsulated. The power supply is either from the clock/controller or from an external transformer. Approximately 6-foot of minimum 12 gauge wiring is required to connect the WW1 to the existing clock/timer.

The current retail price for the Waternomics WW1 System is $179. Waternomics products may be ordered directly from ManyWaters by contacting them at 720-529-3980. ManyWaters provides a one year warranty with their Waternomics soil moisture sensor control systems.

Installation

ManyWaters recommends installation by an irrigation professional; however, installation and programming a one sensor setup may be accomplished by some homeowners. Reported installation time for a simple residential system is less than 1 hour.

Track Record and Water Savings

Waternomics is participating in an ongoing demonstration program with the State of New Mexico which includes the installation of its soil moisture based irrigation control systems at several urban parks and school grounds. These systems are being monitored to evaluate performance and water savings, and monitoring results should be available from Many Waters during 2007.

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Weather Based Irrigation Technologies - Summary of Product Information and Features

Company Name		Accurate WeatherSet	AccuWater	Alex-Tronix	Aqua Conserve	Calsense	Cyber-Rain	ECO Research	ET Water Systems	Hunter Industries	HydroPoint WeatherTRAK
Telephone		(818) 993-1449	(512) 331-9283	(888) 224-7630	(951) 352-3891	(800) 572-8608	(818) 585-7178	(208) 562-3680	(415) 945-9383 ext. 205	(760) 591-7344	(800) 362-8774
Contact Person		Andrew Davis	Tom Watson	George Alexanian	Dan Oshaben	Rick Capitanio	Reza Pourzia	Larry Haley	Bruce Cardinal	Dave Shoup	Chris Manchuck
Website		www.weatherset.com	www.accuwater.com	www.alex-tronix.com	www.aquaconserve.com	www.calsense.com	www.cyber-rain.com	www.ecoresearch.com	www.etwater.com	www.hunterindustries.com	www.weathertrak.com
Number of Residential Model Types		2	1	1	2	0	1	1	2	1	1
Number of Commercial Model Types		1	1	1	2	1	1	1	4	1	1
Date Product(s) Entered Market		1994	2004	2005	1998	1993	2007	2005	March 2005	February 2006	1997
Method of Operation and Water Savings											
Basis for Schedule	Historical Data			•	•	•	Back-up				Back-up
	On-site Sensor(s)	•	•[1]	•	•	•[1]		•	•[1]	•	•[1]
	Remote Weather Station(s)/Sensors		•						•		•
	Weather Forecasts						•				
Weather Data Source		On-site solar and rain sensors	On-site sensors or weather station and/or public data managed by centralized server	On-site temperature sensor and solar radiation estimated based on geographic location	16 preprogrammed ET curves with on-site temperature sensor	Historic ET data, evaporative atmometer type ET sensor, weather station or CIMIS data	Weather forecasts automatically from Internet and historic weather data	On-site temperature sensor and solar radiation estimated based on geographic location	Public & ETWS weather station data managed by centralized computer server	On-site weather station with full set of sensors	Public and private weather stations managed by central computer and wireless delivery
Manufacturer Reported Water Savings (Percent)		Not Available	30	Not Available	21 to 28[2]	20 to 40[2]	36	20 to 40	20 to 50	30	16 to 58[2]
Product Features											
Stand-alone Controller or Add-on to Existing		Stand-alone	Stand-alone	Stand-alone	Stand-alone	Stand-alone	Stand-alone	Add-on	Stand-alone	Add-on	Stand-alone
Station or Zone Capacity		8-48	16-48	4-24	6-66	8-48	8-unlimited	Not Applicable	1-48	1-48	6-48
Master Valve or Pump Circuit(s)		1	1	1	1-4	2	0	Not Applicable	2	Not Applicable	1
Internal Power Transformer		Outdoor Models Only	Commercial Only	Not Applicable	Commercial Only	•			•	Not Applicable	•
Battery Powered - DC				•						Not Applicable	
Station Circuit Current Rating (Amperes)		0.75 and 1.5	0.75	5.0 (DC pulse)	1.0	1.5	1.0	Not Applicable	1.1	Not Applicable	0.375 and 0.5
Terminal Wire Size Range (Gauge)		12-20	14 and smaller	12-18	12-18	14	max 14 solid & 16 stranded	Not Applicable	12 and smaller	Not Applicable	12-20
Outdoor Installation		•	Commercial Only	•	All Comm. & 2 Res.	•		•[1]	•	•	•
On-site Rain Gauge or Sensor w/ Rain Shutoff/Delay		•	•[1]	•[1]	Incl. w/ Res, Comm Option[1]	•[1]	Planned for late 2007	•[1]	•[1]	•	•[1]
Rain Shutoff/Delay by Remote Sensor or Rain Forecast			•				•			•	•
Rainfall Irrigation Schedule Compensation		•	•			•		•	•	•	•
On-site Wind Gauge w/ High Wind Shut-off			•[1]			•[1]				•[1]	•[1]
High Wind Shut-off by Remote Sensor			•							•[1]	•[1]
On-site Temperature Sensor w/ Freeze Shut-off			•[1]	•	•		Planned for late 2007	•		•	•[1]
On-site Temperature Sensor w/ High Temp On or Off			•[1]				Planned for late 2007			•	
Freeze or High Temp Shut-off by Remote Sensor			•								•[1]
On-site Evaporative Atmometer Type "ET Sensor"						•[1]					
On-site Solar Radiation Sensor		•	•[1]			•[1]				•	
On-site Humidity Sensor			•[1]			•[1]	Planned for late 2007			•	
Flow Sensor(s) Connectivity		5 models	•		12 Models	•	Planned for late 2007		•		•[1]
Additional Sensor Terminals			•		With Adaptor[1]	•			•	•	•
Internet or Computer Interface			•			•	•		•		
Remote Control Device(s) for Controller			•[1]			•[1]			•	•[1]	•[1]
Two-way Communication between Server and Receiver			•						•	Not Applicable	Commercial Model
Station Circuit Testing		5 models	•	•		•			Planned for Late 2007	Not Applicable	•
Surge and/or Lightning Protection		5 models	•	•	Etu & ET-SP Models	•[1]	•		•	•	•
SWAT Test Performance Report Available				•		•			•	•	•
Scheduling Features											
Fully Automatic Schedule (No Base Schedule Required)			•						•	•	•
Base Irrigation Schedule Required		•		•	•	•	•	•	Optional		
User May Define Non-Irrigation Days		•	•	•	•	•	•	•	•	•	•
Operable in Manual Clock Mode		•	-[5]	•	•	•	•	•	•	•	•
Manual Operation by Station or Program		•	•	•		•	•	•	•	•	•
Variable Total Run Times		•	•	•	•	•	•		•	•	•
Irrigation Schedule Period(s)		Weekday or daily to 40 days	Unlimited Days	Week or up to 99 Day	Week or Odd/Even	7, 14, 21 or 28 Day		Not Applicable	Unlimited Days	Weekday,1-31 day, odd/even	8 Weeks,Odd/Even&Weekday
Available Start Times		10	Unlimited	4 per program	4-8	6 per manual program	4	Not Applicable	9		8 starts with 20 repeat cycles
Cycle/Soak Manual Input		•	•	•	•	•	•	Not Applicable			Optional
Cycle/Soak Periods Automatically Calculated			•					Not Applicable	•	•	•
Runs Concurrent Stations		•		•		•		Not Applicable	Planned for August 2007		•
Number of Programs		5	Unlimited	4	4	7	4	Not Applicable	Unlimited	Not Applicable	Unlimited
Percent Irrigation Adjust Feature			•	•	•	% of ET Adjust per station		Not Applicable	•	•	•
Station Distribution Uniformity/Efficiency Setting			•						•		•
Syringe Cycle or Program		•	•		•	•			•		•
New Landscape Establishment/Fertilizer Program					•	•	•	Not Applicable	•	•	
Review of Weather Information			Using Web Browser			•	•		•	•	•
Review of Irrigation or Water Use Information		•	Using Web Browser	•	•	•	•	•	•	•	•
English and Spanish Languages Display			Cell Phone Remote Only			•	•				
Product Support and Warranty											
Warranty		3 Years	1 Year	2 Years	3 Years	10 Years	1 Year	1 Year	3 Years	2 Years	3 (Res) and 5 (Comm) years
Support	On-site Service Technicians	In Southern California	•	•		•			•		•
	Telephone Technicians	•	•	•	•	•	•	•	•	•	•
	Local Distributors	In Southern California		•	•	•		•	•	•	•
Installation and Maintenance Requirements											
Professional Installation & Programming Recommended		•	•	•	Commercial Models	•			•	•	•
Ongoing Maintenance Required			Clean Sensors			Clean Sensors				Clean Sensors	
Battery Replacement Required				•	•			•	•	•	
Cost											
Suggested Retail Price		$220-$1,440	$549-$2,999	$995-$2,695	$240-$5,630	$1,290-$3,680	$295 and up	$198	$419-$2,399	$429	$449-$3,675
Annual Service Cost		0	$149 minimum	0	0	0	0	0	$40-$199	$0	$48-$225

1 - Optional add-on feature not included in controller price(s) shown
2 - Reported water savings documentation is published or publicly available
3 - Scheduling guidelines or assistance provided with purchase
4 - Complete pricing information was not available for this report
5 - Controller back-up schedule based on recent ET good for 21 days without network connectivity which can be modified by user
6 - Includes remote monitoring of irrigation operation and tracks meter usage for savings reports

Weather Based Irrigation Technologies - Summary of Product Information and Features (cont.)

Company Name		HydroSaver	Irrisoft Weather Reach	Irritrol Systems	Rain Bird	Rain Master	Toro Company	Tucor	Water2Save	Weathermatic	Weathermiser
Telephone		1-562-494-8686	(435) 755-0400	(800) 664-4740	(520) 741-6162	(805) 527-4498	(800) 664-4740	(800) 272-7472	(858) 361-9700	(972) 278-6131	(505) 235-6999
Contact Person		Tom Carr	Steven Moore	Robert Starr	Kraig Wilson	Steve Springer	Robert Starr	Larry Sarver	Gary Gelinas	Brodie Bruner	Al Caprio
Website		www.hydrosaver.net	www.irrisoft.net	www.irritrol.com	www.rainbird.com	www.rainmaster.com	www.toro.com	www.tucor.com	www.water2save.com	www.smartline.com	www.weathermiser.com
Number of Residential Model Types		0	1	1	1	0	1	0	1	2	1
Number of Commercial Model Types		1	1	1	1	1	1	1	1	1	1
Date Product(s) Entered Market		1994	2002	2005	April 2006	2002	2005	1995	1996	2004	2003
Method of Operation and Water Savings											
Basis for Schedule	Historical Data	•	Back-up		Back-up	•			Back-up		
	On-site Sensor(s)	•	•[1]	•[1]	•[1]	•[1]	•[1]	•	•[1]	•	•
	Remote Weather Station(s)/Sensors		•	•	•	•[1]	•	•	•		
	Weather Forecasts										
Weather Data Source		Historic ET data and on-site "ET sensor"	Public & private weather stations data managed by centralized computer server	Public weather stations data managed by centralized computer server	Public & private weather stations data managed by centralized computer server	Automatic, historic or manually entered ET or with optional on-site weather station	Public weather stations data managed by centralized computer server	On-site weather station	Public & patented forecasted weather data managed by their centralized computer server	On-site temperature sensor and solar radiation estimated based on geographic location	On-site temperature and humidity sensors
Manufacturer Reported Water Savings (Percent)		Not Available	20 to 50	Not Available	Not Available	25 to 40	Not Available	Not Available	28[2]	20 to 50	34 to 52
Product Features											
Stand-alone Controller or Add-on to Existing		Stand-alone	Add-on	Stand-alone	Add-on	Stand-alone	Stand-alone	Stand-alone	Add-on (up to 4 controllers)	Stand-alone	Add-on
Station or Zone Capacity		12-56	Not Applicable	6-24	Not Applicable	6-36	6-24	50-500	12-64	4-48	Not Applicable
Master Valve or Pump Circuit(s)		1	Not Applicable	1	Not Applicable	1	1	16	Not Applicable	1	Not Applicable
Internal Power Transformer		•		•		•	•				
Battery Powered - DC											
Station Circuit Current Rating (Amperes)		2.0	Not Applicable	0.5	Not Applicable	1.0	0.5	Not Reported	Not Applicable	1.5	Not Applicable
Terminal Wire Size Range (Gauge)		12-20	Not Applicable	12-18	Not Applicable	12	•	14	14-22	14-18	Not Applicable
Outdoor Installation		•	•[1]	•	•[1]	•	3 Models		•	•	•[1]
On-site Rain Gauge or Sensor w/ Rain Shutoff/Delay		•	•[1]	•[1]	•[1]	•[1]	•[1]	•	•[1]	•	
Rain Shutoff/Delay by Remote Sensor			•	•	•	•[1]			•		
Rainfall Irrigation Schedule Compensation			•	•	•	•[1]			•	•	
On-site Wind Gauge w/ High Wind Shut-off				•[1]				•			•[1]
High Wind Shut-off by Remote Sensor					•	•[1]					
On-site Temperature Sensor w/ Freeze Shut-off		•		•[1]		•[1]	•[1]	•		•	•
On-site Temperature Sensor w/ High Temp On or Off						•[1]					
Freeze or High Temp Shut-off by Remote Sensor			•		•	•[1]					
On-site Evaporative Atmometer Type "ET Sensor"											
On-site Solar Radiation Sensor		•				•[1]		•			
On-site Humidity Sensor		•				•[1]		•			•
Flow Sensor(s) Connectivity		•				•		•			
Additional Sensor Terminals						•				•	
Internet or Computer Interface								•			
Remote Control Device(s) for Controller						•[1]					
Two-way Communication between Server and Receiver						•[1]			•		
Station Circuit Testing				•		•	•				
Surge and/or Lightning Protection		•		•		•[1]	•	•[1]	•	•	
SWAT Test Performance Report Available				•	•		•			•	
Scheduling Features											
Fully Automatic Schedule (No Base Schedule Required)				•		•[1]	•	•		•	
Base Irrigation Schedule Required		•	•[3]		•[3]	•			•[3]		•
User May Define Non-Irrigation Days		•	•	•	•	•	•		•	•	
Operable in Manual Clock Mode		•	•	•	•	•	•		•	•	•
Manual Operation by Station or Program		•				•			•	•	
Variable Total Run Times				•		•	•	•	•	•	
Irrigation Schedule Period(s)		7,14 & 28 Days, Odd/Even	Not Applicable	Not Applicable	Not Applicable	7 or 30 Day	Not Applicable	14 Day	Not Applicable	Up to 31 Days & Odd/Even	Not Applicable
Available Start Times		12	Not Applicable		Not Applicable	5		12	Not Applicable		Not Applicable
Cycle/Soak Manual Input			Not Applicable		Not Applicable	•				•	Not Applicable
Cycle/Soak Periods Automatically Calculated		•	Not Applicable	•	Not Applicable	•	•		•	•	Not Applicable
Runs Concurrent Stations		3	Not Applicable		Not Applicable	•		•	•	•	Not Applicable
Number of Programs		6	Not Applicable	Up to 64 cycles	Not Applicable	4	Up to 64 cycles	30	Not Applicable	4	Not Applicable
Percent Irrigation Adjust Feature		•	Not Applicable	•	Not Applicable	•	•		•	•	Not Applicable
Station Distribution Uniformity/Efficiency Setting			Not Applicable		Not Applicable	•					Not Applicable
Syringe Cycle or Program						•					
New Landscape Establishment/Fertilizer Program											
Review of Weather Information		•	•	•	•	•	•	•	•	•	
Review of Irrigation or Water Use Information		•	•	•	•	•	•	•	•	•	
English and Spanish Languages Display		•									
Product Support and Warranty											
Warranty		3 and 5 years	5 Years	5 years	3 Year	5 Years	5 Years	3 Years	3 Years	2 Years	1 Year
Support	On-site Service Technicians	In Southern California							•		•
	Telephone Technicians	•	•	•	•	•	•	•	•	•	•
	Local Distributors		•	•	•	•	•	•	•	•	
Installation and Maintenance Requirements											
Professional Installation & Programming Recommended		•	•	•	•	Recommended	Recommended	•	Included with purchase		
Ongoing Maintenance Required						Clean Sensors		Clean Sensors	Included with service cost		
Battery Replacement Required			•	•	•		•			•	
Cost											
Suggested Retail Price		$1,800-$2,800[4]	$795	$399-$899	$741	$640-$4,264	$399-$889	$20,150-$23,750	$527-$1,598	$299.90-$816.80	$129.95-$1,295
Annual Service Cost		0	0-$350	$48-$84	0-$350	0-$180	$48-$84	0	$117-$468[6]	0	0

1 - Optional add-on feature not included in controller price(s) shown
2 - Reported water savings documentation is published or publicly available
3 - Scheduling guidelines or assistance provided with purchase
4 - Complete pricing information was not available for this report
5 - Controller back-up schedule based on recent ET good for 21 days without network connectivity which can be modified by user
6 - Includes remote monitoring of irrigation operation and tracks meter usage for savings reports

Soil Moisture Based Irrigation Technologies - Summary of Product Information and Features

Company Name	Acclima	Agrilink	Baseline	Calsense	Dynamax	Irrometer	LawnLogic	Waternomics
Telephone	(866) 887-1470	(714) 966-1975	(866) 294-5847	(951) 352-3891	(800) 896-7108	(951) 689-1701	(925) 286-6185	(760) 591-7344
Contact Person	Kingsley Horton	Drew Gordon	Jon Peters	Rick Capitanio	Gary Woods	Tom Penning	Michael McLaughlin	Dean Cramer
Web Page	www.acclima.com	www.agrilink.net	www.baselinesystems.com	www.calsense.com	www.dynamax.com	www.irrometer.com	www.lawnlogic.com	
Number of Residential Model Types	5	1	2	0	1	1	1	1
Number of Commercial Model Types	3	1	2	1	2	3	1	1
Date Product(s) Entered Market	2003	2006	2002	1986	2006	1985	2004	2001
Method of Operation and Water Savings								
Interrupts Operation of All Stations	●	●	●		●	Residential Models		●
Interrupts Operation of Individual or Groups of Stations	●	Requires Multiple Controllers	●	●	Requires Multiple Controllers	Commercial Models	●	Requires Multiple Controllers
Manufacturer Reported Water Savings	30 to 40[1]	20-50	30 to 50	20 to 40[1]	Not Available	24[1]	44 (one site only)	Not Available
Product Features								
Stand-alone Controller or Add-on to Existing	Both	Add-on	Both	Stand-alone	Both	Add-on	Add-on	Add-on
Type of Soil Moisture Sensor(s)	Digital Time Domain Transmission	Frequency Domain Reflectometry	Time Domain Transmission	Tensiometer	Frequency Domain Reflectometry	Electrical Resistance	Electrical Conductivity	Electrical Conductivity
Multiple Soil Moisture Sensors May Be Used	●	Requires Multiple Controllers	Commercial Models	●	Requires Multiple Controllers	Commercial Models	Multiple Sensors Required	Requires Multiple Controllers
Soil Moisture Sensor Capacity	1-36	1per Controller	6 & 25	48	1 or 2	1 to 8	1-32	1
Sensor(s) or Controller Connects to Existing Valve Wiring	●	●	●	●		Commercial Models	●	●
Number of Soil Moisture Settings	1,000	Unlimited	Unlimited	Unlimited	51 and 0-60%	4, 9 and 11	9	20
Measures and Adjusts for Soil Conductivity	●			●				
Controller Displays Soil Conductivity	●							
Measures and Adjusts for Soil Temperature	●	●	●					
Controller Displays Soil Temperature	●		Commercial Models					
Controller Station Capacity	6,12, 24, 36 & 64	Unlimited	16-200	8-48	Unlimited	Unlimited	1-32	Unlimited
Master Valve or Pump Circuit(s)	Commercial Models	Not Applicable	Commercial Models	2		Not Applicable	Not Applicable	Not Applicable
Internal Power Transformer	Commercial Models		Commercial Models	●			●[2]	
Battery Powered - DC	Commercial Models	●			Option Available	1 Model		
Station Circuit Current Rating (Amperes)	0.7	Not Applicable	Not Reported	1.5	3 & 10	Not Applicable	Not Applicable	Not Applicable
Outdoor Installation	●	●[2]	●[2]	●	●[2]	All Models, Commercial option	●[2]	
Rain Gauge or Sensor Compatible w/ Rain Shutoff/Delay	●		●	●				
Flow Sensor Compatible	Commercial Models		Commercial Models	●	●			
Additional Sensor Terminals	●		Commercial Models	●	●			
Remote Control Device for Controller	Commercial Models[2]		Commercial Models	●[3]	●			
System Testing and Diagnostics	●		●	●				
Surge and/or Lightning Protection	●		●	●[3]			●	
Scheduling Features								
Fully Automatic Schedule (No Base Schedule Required)	Commercial Models		Commercial Models		Commercial Models			
Variable Total Run Times	●		Commercial Models	●	Commercial Models		●	
User May Define Non-Irrigation Days	●	Not Applicable	Commercial Models	●		Not Applicable	Not Applicable	Not Applicable
Operable in Manual Clock Mode	●	Not Applicable	●	●		Not Applicable	Not Applicable	Not Applicable
Manual Operation by Station or Program	●	Not Applicable	Commercial Models	●		Not Applicable	Not Applicable	Not Applicable
Irrigation Schedule Period(s)	Odd/Even, Nth Day & Custom	Not Applicable	All options available	7, 14, 21 or 28 day		Not Applicable	Not Applicable	Not Applicable
Cycle/Soak Manual Input	●	Not Applicable	●	●		Not Applicable	Not Applicable	Not Applicable
Cycle/Soak Periods Automatically Calculated		Not Applicable				Not Applicable	Not Applicable	Not Applicable
Available Start Times	Up to 6 or On Demand	Not Applicable	8	6		Not Applicable	Not Applicable	Not Applicable
Irrigation Pause/Resume	●	Not Applicable	Commercial Models	●		Not Applicable	Not Applicable	Not Applicable
Runs Concurrent Stations	●	Not Applicable	Commercial Models	●	●	Not Applicable	Not Applicable	Not Applicable
Number of Programs	Up to 40	Not Applicable	Up to 10	7	2	Not Applicable	Not Applicable	Not Applicable
Syringe Cycle or Program	●	Not Applicable	Commercial Models	●		Not Applicable	Not Applicable	Not Applicable
Review of Recent Irrigation Information	●		Commercial Models	●				
English and Spanish Languages Display	Commercial Models	Universal Display		●				
Product Support and Warranty								
Warranty	2 Years	2 Years	1 and 3 (sensor only) Years	10 Years	1 Year	1 Year	1 Year	1 Year
Support: On-site Service Technicians	Some Locations			●	Some Locations			
Support: Telephone or Internet Technicians	●	●	●	●	●	●	●	●
Support: Local Distributors	●	Some Locations		●	Some Locations	●	●	
Installation and Maintenance Requirements								
Professional Installation & Programming Recommended	Commercial Models	●	Commercial Models	●	Commercial Models	Commercial Models	Commercial Models	●
Battery Replacement Required	5 to 10 years				Optional			
Cost								
Suggested Retail Prices[3]	$265-$3,078	$139	$149-$10,120	$999-$3,760	$425-$1,242	$100-$3,040	$379.95-$2,149	$199

1 - Reported water savings documentation is published or publicly available
2 - Optional add-on feature not included in controller price(s) shown

For copies of this report contact
Reclamation's Southern California Area Office at 951-695-5310
or download at http://www.usbr.gov/waterconservation/docs/SmartController.pdf

Automating Landscape Sprinkler Control Using Weather Data, Broadcast to Unlimited Properties

Steven E. Moore[1] - North Logan, Utah – October 25, 2007

Abstract

Experts estimate landscape irrigation systems waste 25% of culinary water. Inefficiencies in control and distribution are the cause.

Weather conditions drive evaporation. Water lost from the landscape through evaporation is replaced by rainfall and irrigation. Effective management maintains healthy soil moisture levels. Evapotranspiration, rainfall, plants, soils, and irrigation system capabilities must be considered. Large landscapes have measured weather conditions to automate water management for many years.

Evapotranspiration can be calculated from weather sensor input: solar radiation, temperature, wind, and humidity. Precision sensors must be properly sited and well maintained. Previously cost and complexity has been a barrier for most landscapes.

Wireless technology allows weather data to be shared. A single weather station can provide weather information to unlimited landscapes. A controller interface calculates evapotranspiration from weather data and provides accurate irrigation management.

This technology provides significant water savings and has proven reliable while not burdening end users with purchasing, or maintaining weather sensors.

Introduction

Reports across the country and in many places worldwide conclude landscapes receive twice the needed water (Kjelgren, 2003). A majority of this waste comes because sprinkler controllers are often set and forgotten. Water requirements of the landscape change with changing weather conditions. Unnecessary watering not only wastes water, but can adversely affect the health of the landscape. Weather-based technology, which automates landscape sprinkler control, reduces water waste without impacting the health of the landscape.

Expensive high-tech precision water management has been successfully implemented in large turf and agricultural environments for more than twenty years (Irrigation Association, 2005). The increasing need to conserve water resources pressures commercial and residential landscape water users to find a cost-effective solution to reduce water waste (Bureau of Reclamation, 2006). A cost effective automated solution for residential and commercial properties must be reliable, achieve sustainable results, and not sacrifice the health of the landscape.

Automated systems are dependent on sensors to provide data essential for accurate control. A community weather station can measure wind, temperature, humidity, and solar radiation conditions which affect landscape water use. Wireless technology provides a cost-effect, reliable method to broadcast measurements to an unlimited number of irrigation control systems. An overview of the science will provide a better understanding of the purpose behind each component implemented in the technology to reduce water use while sustaining beautiful landscapes.

Weather Influences Landscape Water Use

Weather conditions affect evaporation. As quickly as the weather changes, so does the evaporation rate. Water that evaporates from the landscape is replaced by rainfall and is supplemented by irrigation. To avoid wasting water, landscape irrigation schedules need to respond to changing weather conditions.

Solar radiation and temperature are energy sources that change liquid water to vapor. Wind accelerates evaporation. Humidity also affects the evaporative rate; in high humidity, evaporation slows as more energy is needed to convert liquid to vapor. Evaporation rates are higher in arid climates as compared to moist environments. In the summer, landscapes are exposed to more intense solar radiation and high temperatures, so the evaporative rate is higher. But on a cool overcast day, solar radiation drops, humidity increases, and landscapes dry out slower.

Scientists have developed methods to quantify evapotranspiration (ET) which is the amount of water lost from soil, and leaf surfaces by evaporation, and water used by plants through transpiration (ASCE, 2005). ET is expressed as a rate of water lost from the landscape in either inches or millimeters over a period of time. Evapotranspiration losses can be estimated using meteorological data measured by a weather station. Weather parameters measured to calculate ET include: solar radiation, temperature, wind, and relative humidity. Each weather parameter has a significant impact on evaporative rates. An exact calculation of ET is dependent on complete, accurate real-time data.

Numerous formulas have been developed, tested and refined over the years to calculate ET. In January 2005 the Irrigation Association endorsed the "ASCE Standardized Reference Evapotranspiration Equation." The standard sets forth the preferred formula which uses hourly measurements of all climatological conditions affecting ET (Solar Radiation, Temperature, Wind, and Humidity). The publication also details recommended station sighting criteria and the importance of sensor accuracy and maintenance.

The basic principle behind ET-based landscape water management is to replace water lost from landscapes due to evapotranspiration. In addition to the weather parameters used to calculate ET, rainfall must also be measured as it replaces evaporated water.

Rainfall rates and intensities can vary. When rain falls faster than the soil can absorb, run-off occurs; this water is not available to plants. Prolonged rain may saturate the soil and percolate below the root-zone. In either case, not all rainfall may be available to the plants. Just as ET is measured in inches (millimeters) of water evaporated from the soil, effective rainfall is measured in inches of water applied to the landscape. Effective rain can be quantified by considering soil absorption rates, soil moisture capacity and current moisture levels.

Plant Water Soil Relationships

The soil is a habitat for roots, providing stability, water, oxygen, and nutrients. Root depth and soil composition limit the capacity of the soil reservoir. To promote a deep healthy root system, soil moisture must be depleted to allow air into the root zone. Best Management Practices published by the Irrigation Association teaches the Managed Allowed Depletion (MAD) method of irrigation scheduling. Soil moisture levels should typically be depleted by 50% before watering (IA BMP, 2005). The cycle of deep, less frequent watering promotes a deep healthy root system. If the plant root zone is kept at or near a saturated condition, the roots remain shallow because they are deprived of essential oxygen. Frequent shallow watering evaporates faster and does not promote deep healthy roots.

Irrigation should provide a deep watering to refill the soil reservoir. The “Checkbook Method” (see table on page 7) of irrigation scheduling compares ET to a “withdrawal” of moisture from the soil moisture balance, while rainfall and irrigation are considered “deposits” (Wright, 2002). Once the “balance” reaches “0” (soil moisture is depleted), the irrigation system must make a “deposit” to replenish soil moisture.

Landscape Water Management

Irrigation scheduling practices take many approaches. In the worst case, sprinkler controllers are set to water for the hottest months, and are not adjusted to changes in weather. If watering schedules are adjusted, it is because the condition of the landscape prompts the change such as “the grass is drying out” or “it seems too wet.” The user often does not know how much to adjust the schedule. Some users may turn sprinkler controllers off when it begins to rain, but are unsure when to resume watering. This reactive method of water management wastes water and negatively affects the health of the landscape. Users tend to over-water as much as four times the needed amount (Maheshwari, 2006).

Some water agencies attempt to cut this water waste through programs such as day-of-the-week watering restrictions and water budgeting. These approaches to water conservation do not reflect plant water needs (Kjelgren, 2000).

Responsible water managers consider all factors which influence the health of the landscape, including current weather conditions to adjust watering schedules. In some cases, computerized irrigation control systems connected to weather stations automate irrigation control. Internationally, golf courses, parks, school districts, campuses, theme parks, and large-scale landscapes successfully utilize automated weather-based control systems (Ali, 2006). Water waste is reduced, landscape health improved, and water and labor savings are achieved. Computerized central control systems are complex, expensive, and require the purchase and maintenance of precision weather stations.

Solution

A system has been developed that manages a network of weather stations and broadcasts weather data, via wireless commercial paging, to irrigation system controllers. The controllers are capable of managing irrigation systems by calculating ET, accounting for effective rainfall, recognizing the soil reservoir capacity and considering the capabilities of an irrigation system.

There are three key elements to sensor-based control:

- Sensors – Accurate weather data to calculate ET
- Connectivity – Communicate sensor measurements to the control system
- Control – Data input, processing, and output to control the irrigation system

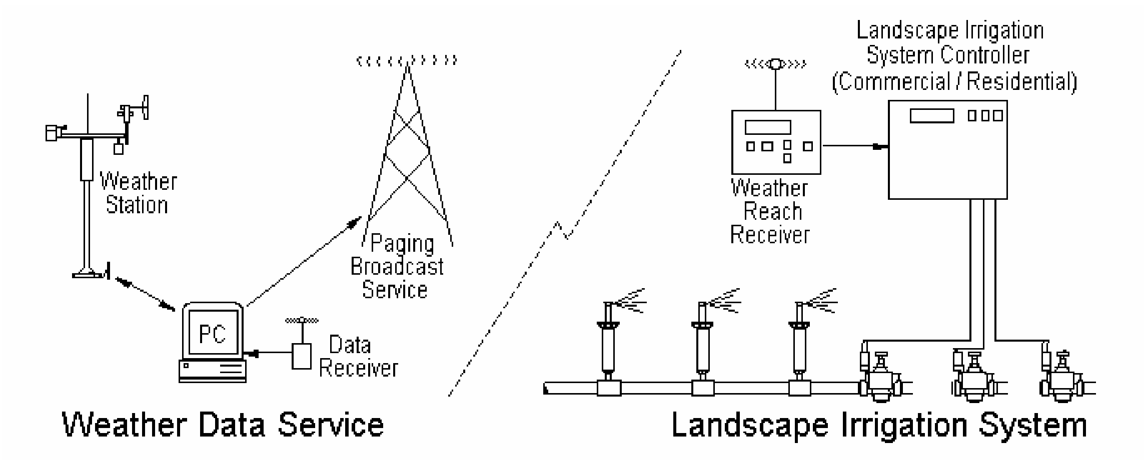
Sensors - This system begins with a weather station, properly sited and well maintained, within a community. Weather stations consist of weather sensors connected to a data logger, which stores sensor measurements. The location must be representative of community landscape conditions. Station sensors collect essential measurements including solar radiation, temperature, wind, humidity, and rainfall. Accurate results are dependent on precise reliable equipment.

Connectivity - A computer communicates with the weather station each hour to collect the last hours' sensor measurements. The system supports a variety of communication methods with the weather station. Once data is collected and stored, the computer encodes a "message" containing current weather data and a weather region identification number. The "message" is sent, via the Internet, to a wireless commercial paging system to be broadcast in a local area to an unlimited number of controllers.

Commercial paging is used to share weather data with controllers because it has a well-established infrastructure. It is a fast, reliable, low cost means of delivering small amounts of information. An unlimited number of controllers with paging data receivers may be programmed to receive the same "message."

An entity that needs to improve control of landscape irrigation systems may own and operate the system to service the needs of the controllers it represents. The system is scaleable to support one weather station for a small community or multiple stations for a statewide conservation program. Paging costs are paid by the system operator and are based on paging airtime. All controllers serviced by an entity receive the same message, so the cost of operating the system is the same for one controller or ten thousand. Cost increases as data from additional weather stations are broadcast. System operating costs may be recovered through a variety of methods.

The following diagram depicts the flow of data and components in the system:



Irrigation Control - A controller interface includes a paging radio which receives weather data from a user-selected weather station. With each hour's weather data, ET is calculated to automate watering schedules.

Because rainfall can be localized, rainfall measurements at the community weather station may not represent on-site conditions. The controller interface can accept measurements from an on-site tipping bucket rain gauge.

Because there are numerous methods to control irrigation systems the controller interface offers several different methods to automate the control of an irrigation system.

- Integrated
- Common Interrupt
- Pulse
- Serial
- Trigger

Integrated - This control technology, integrated into a sprinkler controller, receives the weather data broadcast, calculates ET, and controls irrigation zone valves.

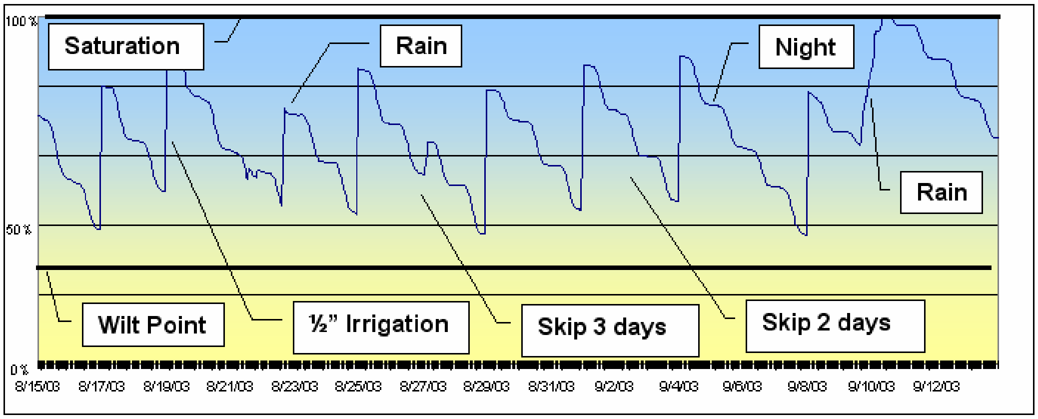
Common Interrupt - The controller interface can interrupt the common output of most standard 24 VAC sprinkler controllers and prevent watering until soil moisture has been depleted to an allowable level (MAD). A sprinkler controller is typically programmed to water every day, but the controller interface only allows watering when needed based on ET. The control interface keeps a running moisture balance, similar to the "Checkbook Method." The common output of a controller is enabled, once soil moisture is depleted, to a user-programmed allowable level. The Common Interrupt method considers soil type and root depth to determine soil reservoir capacities and proper irrigation amounts.

The following table is an example of modeling moisture balance using ET, effective rain, and irrigation to determine watering frequency:

Date	ET	Effective Rain	Irrigate	Moisture Balance
4/1/06	0.15	0.05		0.65
4/2/06	0.11	0.23		0.75
4/3/06	0.05	0.68		0.75
4/4/06	0.08	0.75		0.75
4/5/06	0.06	0.12		0.75
4/6/06	0.13			0.62
4/7/06	0.18	0.02		0.46
4/8/06	0.14			0.32
4/9/06	0.11			0.21
4/10/06	0.08	0.03		0.16
4/11/06	0.11	0.05		0.10
4/12/06	0.17		0.50	0.43
4/13/06	0.18			0.25
4/14/06	0.05	0.21		0.41
4/15/06	0.11			0.30
4/16/06	0.09	0.18		0.39
4/17/06	0.19			0.20
4/18/06	0.17			0.03
4/19/06	0.19		0.50	0.34
4/20/06	0.18			0.16
4/21/06	0.17		0.50	0.49
4/22/06	0.06	0.01		0.44
4/23/06	0.02	0.52		0.75
4/24/06	0.13			0.62
4/25/06	0.12	0.02		0.52
4/26/06	0.09	0.03		0.46
4/27/06	0.12			0.34
4/28/06	0.20			0.14
4/29/06	0.20		0.50	0.44
4/30/06	0.20			0.24

An example of one full year of watering managed with the moisture balance method to control the frequency of watering is demonstrated in Appendix I.

Hourly data provides accurate soil moisture modeling as shown in the following example:



Current commercial models of the controller interface manage two valve commons independently. Typically, turf is watered more frequently than shrubs. One group of valves could be wired and programmed for turf zones and the second group for shrubs. This accommodates different soil types, root depths, and plant types at a site.

Pulse - Several sprinkler controller manufacturers recognize a pulse (momentary switch closure) as an ET value. The controller interface provides an ET pulse output. As weather data is received, ET is calculated and the controller interface creates a pulse for every 0.01" of ET. The accumulated ET value is used by sprinkler controllers to automatically adjust watering schedules.

Serial - A sprinkler controller can acquire ET, rainfall, and other weather data using a serial data transport interface connection to a small controller interface card. The controller interface card provides real-time conditions so the sprinkler controller can manage the irrigation system.

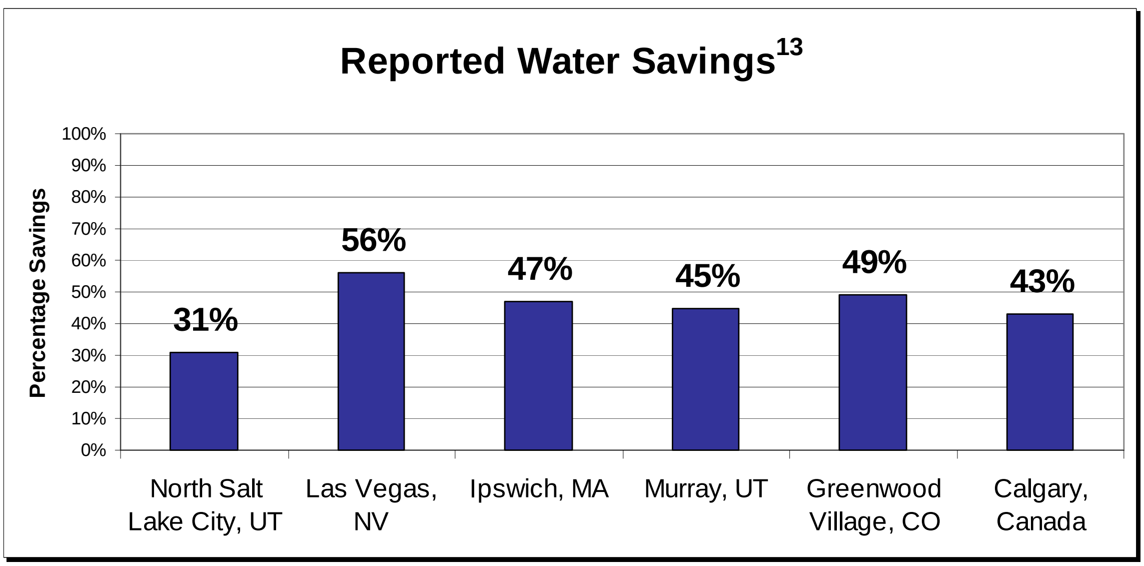
Trigger - A trigger method in the controller interface is very similar to the common interrupt method. The difference is that the controller interface triggers the start of a watering cycle. A sprinkler controller starts watering when it receives the trigger to begin a cycle.

CIT Testing

The Irrigation Association Smart Water Application Technology (SWAT) committee developed a protocol to validate the effectiveness of climatologically based or "Smart" irrigation controllers. One of the commercially available products that incorporates this technology was tested at the Center for Irrigation Technology (CIT) in Fresno. The results were released June 26, 2006. The report focuses on three factors; irrigation adequacy, schedule efficiency, and irrigation scheduling excess. In each of these areas, the product received a perfect score.

Independent Field Testing

The system became commercially available in July 2002. Field tests conducted by end users reported considerable amounts of water savings as indicated in the chart below.



Conclusion

The increasing demand for water is straining water resources in many parts of the world. Automated management can reduce waste to make more water available to meet the growing demand. To achieve successful results, automation must be reliable and effective, while maintaining the health of the landscape.

Weather based control of irrigation systems has been proven for more than 20 years to reduce water waste without sacrificing the quality of the landscape. As advancements are made in technology, cost-cutting efforts should not compromise proven science. The demands to reduce waste, coupled with technological advancements, allow commercial and residential customers to benefit from weather based automated control. It is not practical or necessary to put a weather station on every property.

Precision weather stations with the essential sensors (solar radiation, temperature, wind, humidity and rainfall) are expensive. Stations must be maintained and properly located. Sharing weather sensor data in a community is a cost effective way to assure accurate, reliable data to achieve sustainable conservation. Wireless technology provides an easily implemented link between sensors and an unlimited number of controllers. End users need not purchase and maintain on-site weather sensors to benefit from ET based control.

Water savings have been documented, improved landscape health has been reported, and time has been saved because watering schedules are automatically adjusted based on real-time conditions. Wireless weather-based sprinkler control will improve landscape health and help alleviate growing strain on water resources.

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10. California Irrigation Management Information System (CIMIS). Urban Resource Book. State of California Department of Water Resources, May 2000.
11. EPA Water Sense. "Outdoor Water Use in the United States." 22 Feb. 2007. 5 March 2007 <http://www.epa.gov/watersense/pubs/outdoor.htm>
12. Reference material for "Reported Water Savings":

    North Salt Lake City, Utah – 31% Water Savings

    Water Use: 2000 -2001 – 13,068,000 gallons/year avg. 2002-2004 – 9,017,000 gallons/year avg.
    http://www.irrisoft.net/wr/sites/North%20Salt%20Lake.pdf

    John Cherek - Las Vegas, Nevada - 56% Water Savings

    Water Use: 2003 – 16,035 gallons, 2005 – 7,000 gallons (April to September)
    http://www.irrisoft.net/wr/sites/Las%20Vegas.pdf

    Stanley Jacobs - Ipswich, Massachusetts - 47% Water Savings

    Water Use: 2002 – 2,120,000 gallons, 2003 – 1,130,000 gallons (May to October)
    http://www.irrisoft.net/wr/sites/Ipswich%20Jacobs.pdf

    Murray City Hall, Murray, Utah - 45% Water Savings

    Water Use: 1999 - 2002 – 2,735,062 gallons/year avg. 2003 – 1,499,366 gallons (April to September)
    http://www.irrisoft.net/wr/sites/Murray%20City%20Hall.pdf

    Greenwood Village Parks, Greenwood Colorado - 49% Water Savings

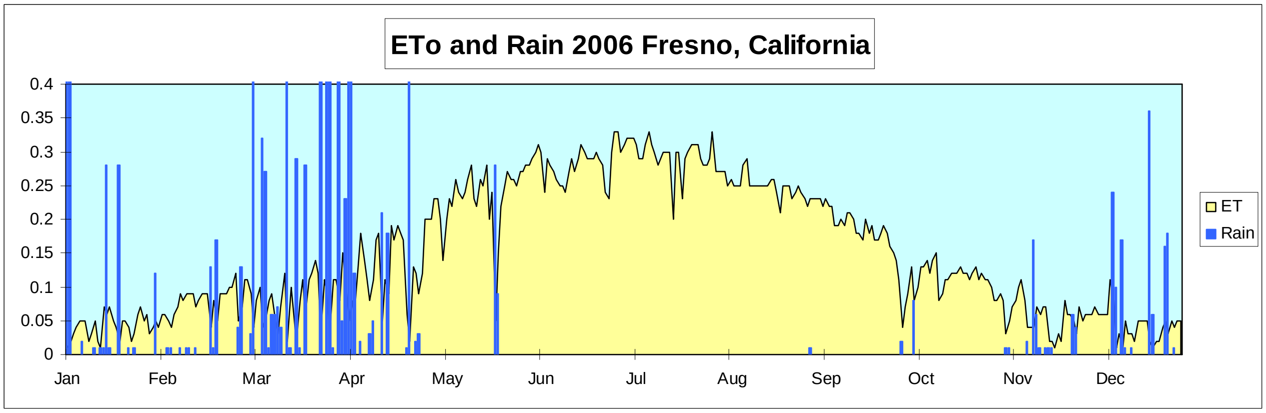
    Water Use: 2003 – 1,044,000 gallons, 2004 – 538,000 gallons (May to October)
    http://www.irrisoft.net/wr/sites/Greenwood%20Village.pdf

    Southcentre Mall - Calgary, Alberta - 43% Water Savings

    Water Use: 2005 – 2,296,140 gallons, 2006 – 1,309,800 gallons
    http://www.exactet.com/results.asp

Appendix I

The flowing data comes from California Irrigation Management Information System (CIMIS) Fresno State - San Joaquin Valley - Station 80, and demonstrates soil moisture modeling based on ET, rainfall and irrigation. In this example the irrigation amount was set to 0.50" and is not crop specific using ET_o as opposed to a crop specific ET_c.



Watering Frequency Controlled by Real Time Weather Conditions				
	Total Eto	**Total Rain**	**Watering Days**	**Irrigation Amount**
JAN	1.28	3.46	0	0.0
FEB	2.19	0.54	3	1.5
MAR	2.46	4.58	1	0.5
APR	3.84	3.10	4	2.0
MAY	7.17	0.37	14	7.0
JUNE	8.46	0.00	17	8.5
JULY	9.20	0.00	18	9.0
AUG	7.79	0.00	16	8.0
SEP	5.75	0.01	11	5.5
OCT	3.43	0.10	7	3.5
NOV	1.72	0.41	2	1.0
DEC	1.38	1.30	1	0.5
TOTALS	**54.67**	**13.87**	**94**	**47.0**

Soil Moisture Balance

Fresno, California

Date	ET	Effective Rain	Irrigate	Moisture Balance
1/1/2006	0.01	0.75	0.00	0.75
1/2/2006	0.02	0.75	0.00	0.75
1/3/2006	0.03	0.00	0.00	0.72
1/4/2006	0.04	0.00	0.00	0.68
1/5/2006	0.05	0.00	0.00	0.63
1/6/2006	0.05	0.02	0.00	0.60
1/7/2006	0.05	0.00	0.00	0.55
1/8/2006	0.02	0.00	0.00	0.53
1/9/2006	0.03	0.00	0.00	0.50
1/10/2006	0.05	0.01	0.00	0.46
1/11/2006	0.02	0.00	0.00	0.44
1/12/2006	0.01	0.01	0.00	0.44
1/13/2006	0.07	0.01	0.00	0.38
1/14/2006	0.06	0.28	0.00	0.60
1/15/2006	0.07	0.01	0.00	0.54
1/16/2006	0.05	0.00	0.00	0.49
1/17/2006	0.04	0.00	0.00	0.45
1/18/2006	0.02	0.28	0.00	0.71
1/19/2006	0.05	0.00	0.00	0.66
1/20/2006	0.05	0.00	0.00	0.61
1/21/2006	0.04	0.01	0.00	0.58
1/22/2006	0.02	0.00	0.00	0.56
1/23/2006	0.03	0.01	0.00	0.54
1/24/2006	0.06	0.00	0.00	0.48
1/25/2006	0.07	0.00	0.00	0.41
1/26/2006	0.05	0.00	0.00	0.36
1/27/2006	0.06	0.00	0.00	0.30
1/28/2006	0.03	0.00	0.00	0.27
1/29/2006	0.04	0.00	0.00	0.23
1/30/2006	0.05	0.12	0.00	0.30
1/31/2006	0.04	0.00	0.00	0.26
2/1/2006	0.06	0.00	0.00	0.20
2/2/2006	0.06	0.00	0.00	0.14
2/3/2006	0.05	0.01	0.00	0.10
2/4/2006	0.04	0.01	0.00	0.07
2/5/2006	0.06	0.00	0.00	0.01
2/6/2006	0.07	0.00	0.50	0.44
2/7/2006	0.09	0.01	0.00	0.36
2/8/2006	0.08	0.00	0.00	0.28
2/9/2006	0.09	0.01	0.00	0.20
2/10/2006	0.09	0.01	0.00	0.12
2/11/2006	0.09	0.00	0.00	0.03
2/12/2006	0.07	0.01	0.50	0.47
2/13/2006	0.08	0.00	0.00	0.39
2/14/2006	0.09	0.00	0.00	0.30
2/15/2006	0.09	0.00	0.00	0.21
2/16/2006	0.09	0.00	0.00	0.12
2/17/2006	0.04	0.13	0.00	0.21
2/18/2006	0.08	0.01	0.00	0.14
2/19/2006	0.05	0.17	0.00	0.26
2/20/2006	0.09	0.00	0.00	0.17
2/21/2006	0.09	0.00	0.00	0.08
2/22/2006	0.09	0.00	0.50	0.49
2/23/2006	0.10	0.00	0.00	0.39
2/24/2006	0.10	0.00	0.00	0.29
2/25/2006	0.12	0.00	0.00	0.17
2/26/2006	0.05	0.04	0.00	0.16
2/27/2006	0.07	0.13	0.00	0.22
2/28/2006	0.11	0.00	0.00	0.11

Date	ET	Effective Rain	Irrigate	Moisture Balance
3/1/2006	0.11	0.00	0.50	0.50
3/2/2006	0.09	0.03	0.00	0.44
3/3/2006	0.04	0.59	0.00	0.75
3/4/2006	0.08	0.00	0.00	0.67
3/5/2006	0.10	0.00	0.00	0.57
3/6/2006	0.04	0.32	0.00	0.75
3/7/2006	0.06	0.27	0.00	0.75
3/8/2006	0.08	0.01	0.00	0.68
3/9/2006	0.09	0.06	0.00	0.65
3/10/2006	0.05	0.06	0.00	0.66
3/11/2006	0.03	0.07	0.00	0.70
3/12/2006	0.07	0.04	0.00	0.67
3/13/2006	0.12	0.00	0.00	0.55
3/14/2006	0.02	0.42	0.00	0.75
3/15/2006	0.10	0.01	0.00	0.66
3/16/2006	0.06	0.00	0.00	0.60
3/17/2006	0.02	0.29	0.00	0.75
3/18/2006	0.08	0.01	0.00	0.68
3/19/2006	0.11	0.00	0.00	0.57
3/20/2006	0.06	0.28	0.00	0.75
3/21/2006	0.11	0.00	0.00	0.64
3/22/2006	0.12	0.00	0.00	0.52
3/23/2006	0.14	0.00	0.00	0.38
3/24/2006	0.12	0.00	0.00	0.26
3/25/2006	0.03	0.43	0.00	0.66
3/26/2006	0.11	0.00	0.00	0.55
3/27/2006	0.09	0.48	0.00	0.75
3/28/2006	0.03	0.70	0.00	0.75
3/29/2006	0.11	0.01	0.00	0.65
3/30/2006	0.11	0.00	0.00	0.54
3/31/2006	0.08	0.50	0.00	0.75
4/1/2006	0.15	0.05	0.00	0.65
4/2/2006	0.11	0.23	0.00	0.75
4/3/2006	0.05	0.68	0.00	0.75
4/4/2006	0.08	0.75	0.00	0.75
4/5/2006	0.06	0.12	0.00	0.75
4/6/2006	0.13	0.00	0.00	0.62
4/7/2006	0.18	0.02	0.00	0.46
4/8/2006	0.14	0.00	0.00	0.32
4/9/2006	0.11	0.00	0.00	0.21
4/10/2006	0.08	0.03	0.00	0.16
4/11/2006	0.11	0.05	0.00	0.10
4/12/2006	0.17	0.00	0.50	0.43
4/13/2006	0.18	0.00	0.00	0.25
4/14/2006	0.05	0.21	0.00	0.41
4/15/2006	0.11	0.00	0.00	0.30
4/16/2006	0.09	0.18	0.00	0.39
4/17/2006	0.19	0.00	0.00	0.20
4/18/2006	0.17	0.00	0.00	0.03
4/19/2006	0.19	0.00	0.50	0.34
4/20/2006	0.18	0.00	0.00	0.16
4/21/2006	0.17	0.00	0.50	0.49
4/22/2006	0.06	0.01	0.00	0.44
4/23/2006	0.02	0.52	0.00	0.75
4/24/2006	0.13	0.00	0.00	0.62
4/25/2006	0.12	0.02	0.00	0.52
4/26/2006	0.09	0.03	0.00	0.46
4/27/2006	0.12	0.00	0.00	0.34
4/28/2006	0.20	0.00	0.00	0.14
4/29/2006	0.20	0.00	0.50	0.44
4/30/2006	0.20	0.00	0.00	0.24

Soil Moisture Balance

Fresno, California

Date	ET	Effective Rain	Irrigate	Moisture Balance	Date	ET	Effective Rain	Irrigate	Moisture Balance
5/1/2006	0.23	0.00	0.00	0.01	7/1/2006	0.30	0.00	0.00	0.18
5/2/2006	0.23	0.00	0.50	0.28	7/2/2006	0.31	0.00	0.50	0.37
5/3/2006	0.20	0.00	0.00	0.08	7/3/2006	0.32	0.00	0.00	0.05
5/4/2006	0.14	0.00	0.50	0.44	7/4/2006	0.32	0.00	0.50	0.23
5/5/2006	0.20	0.00	0.00	0.24	7/5/2006	0.32	0.00	0.50	0.41
5/6/2006	0.23	0.00	0.00	0.01	7/6/2006	0.31	0.00	0.00	0.10
5/7/2006	0.22	0.00	0.50	0.29	7/7/2006	0.29	0.00	0.50	0.31
5/8/2006	0.26	0.00	0.00	0.03	7/8/2006	0.29	0.00	0.00	0.02
5/9/2006	0.24	0.00	0.50	0.29	7/9/2006	0.31	0.00	0.50	0.21
5/10/2006	0.23	0.00	0.00	0.06	7/10/2006	0.33	0.00	0.50	0.38
5/11/2006	0.24	0.00	0.50	0.32	7/11/2006	0.31	0.00	0.00	0.07
5/12/2006	0.26	0.00	0.00	0.06	7/12/2006	0.30	0.00	0.50	0.27
5/13/2006	0.28	0.00	0.50	0.28	7/13/2006	0.28	0.00	0.50	0.49
5/14/2006	0.23	0.00	0.00	0.05	7/14/2006	0.29	0.00	0.00	0.20
5/15/2006	0.22	0.00	0.50	0.33	7/15/2006	0.30	0.00	0.50	0.40
5/16/2006	0.26	0.00	0.00	0.07	7/16/2006	0.30	0.00	0.00	0.10
5/17/2006	0.25	0.00	0.50	0.32	7/17/2006	0.30	0.00	0.50	0.30
5/18/2006	0.28	0.00	0.00	0.04	7/18/2006	0.20	0.00	0.00	0.10
5/19/2006	0.20	0.00	0.50	0.34	7/19/2006	0.30	0.00	0.50	0.30
5/20/2006	0.24	0.00	0.00	0.10	7/20/2006	0.30	0.00	0.00	0.00
5/21/2006	0.05	0.28	0.00	0.33	7/21/2006	0.23	0.00	0.50	0.27
5/22/2006	0.15	0.09	0.00	0.27	7/22/2006	0.29	0.00	0.50	0.48
5/23/2006	0.22	0.00	0.00	0.05	7/23/2006	0.30	0.00	0.00	0.18
5/24/2006	0.25	0.00	0.50	0.30	7/24/2006	0.31	0.00	0.50	0.37
5/25/2006	0.27	0.00	0.00	0.03	7/25/2006	0.31	0.00	0.00	0.06
5/26/2006	0.26	0.00	0.50	0.27	7/26/2006	0.31	0.00	0.50	0.25
5/27/2006	0.26	0.00	0.00	0.01	7/27/2006	0.29	0.00	0.50	0.46
5/28/2006	0.25	0.00	0.50	0.26	7/28/2006	0.28	0.00	0.00	0.18
5/29/2006	0.27	0.00	0.50	0.49	7/29/2006	0.28	0.00	0.50	0.40
5/30/2006	0.27	0.00	0.00	0.22	7/30/2006	0.29	0.00	0.00	0.11
5/31/2006	0.28	0.00	0.50	0.44	7/31/2006	0.33	0.00	0.50	0.28
6/1/2006	0.28	0.00	0.00	0.16	8/1/2006	0.27	0.00	0.00	0.01
6/2/2006	0.29	0.00	0.50	0.37	8/2/2006	0.27	0.00	0.50	0.24
6/3/2006	0.30	0.00	0.00	0.07	8/3/2006	0.27	0.00	0.50	0.47
6/4/2006	0.31	0.00	0.50	0.26	8/4/2006	0.27	0.00	0.00	0.20
6/5/2006	0.30	0.00	0.50	0.46	8/5/2006	0.25	0.00	0.50	0.45
6/6/2006	0.24	0.00	0.00	0.22	8/6/2006	0.26	0.00	0.00	0.19
6/7/2006	0.29	0.00	0.50	0.43	8/7/2006	0.25	0.00	0.50	0.44
6/8/2006	0.28	0.00	0.00	0.15	8/8/2006	0.25	0.00	0.00	0.19
6/9/2006	0.27	0.00	0.50	0.38	8/9/2006	0.25	0.00	0.50	0.44
6/10/2006	0.26	0.00	0.00	0.12	8/10/2006	0.28	0.00	0.00	0.16
6/11/2006	0.25	0.00	0.50	0.37	8/11/2006	0.29	0.00	0.50	0.37
6/12/2006	0.25	0.00	0.00	0.12	8/12/2006	0.25	0.00	0.00	0.12
6/13/2006	0.24	0.00	0.50	0.38	8/13/2006	0.25	0.00	0.50	0.37
6/14/2006	0.27	0.00	0.00	0.11	8/14/2006	0.25	0.00	0.00	0.12
6/15/2006	0.29	0.00	0.50	0.32	8/15/2006	0.25	0.00	0.50	0.37
6/16/2006	0.27	0.00	0.00	0.05	8/16/2006	0.25	0.00	0.00	0.12
6/17/2006	0.29	0.00	0.50	0.26	8/17/2006	0.25	0.00	0.50	0.37
6/18/2006	0.31	0.00	0.50	0.45	8/18/2006	0.25	0.00	0.00	0.12
6/19/2006	0.30	0.00	0.00	0.15	8/19/2006	0.26	0.00	0.50	0.36
6/20/2006	0.29	0.00	0.50	0.36	8/20/2006	0.26	0.00	0.00	0.10
6/21/2006	0.29	0.00	0.00	0.07	8/21/2006	0.24	0.00	0.50	0.36
6/22/2006	0.29	0.00	0.50	0.28	8/22/2006	0.21	0.00	0.00	0.15
6/23/2006	0.30	0.00	0.50	0.48	8/23/2006	0.25	0.00	0.50	0.40
6/24/2006	0.29	0.00	0.00	0.19	8/24/2006	0.25	0.00	0.00	0.15
6/25/2006	0.28	0.00	0.50	0.41	8/25/2006	0.25	0.00	0.50	0.40
6/26/2006	0.24	0.00	0.00	0.17	8/26/2006	0.23	0.00	0.00	0.17
6/27/2006	0.23	0.00	0.50	0.44	8/27/2006	0.24	0.00	0.50	0.43
6/28/2006	0.30	0.00	0.00	0.14	8/28/2006	0.25	0.00	0.00	0.18
6/29/2006	0.33	0.00	0.50	0.31	8/29/2006	0.24	0.00	0.50	0.44
6/30/2006	0.33	0.00	0.50	0.48	8/30/2006	0.23	0.00	0.00	0.21
					8/31/2006	0.22	0.00	0.50	0.49

Soil Moisture Balance

Fresno, California

Date	ET	Effective Rain	Irrigate	Moisture Balance	Date	ET	Effective Rain	Irrigate	Moisture Balance
9/1/2006	0.23	0.01	0.00	0.27	11/1/2006	0.08	0.00	0.00	0.34
9/2/2006	0.23	0.00	0.00	0.04	11/2/2006	0.09	0.00	0.00	0.25
9/3/2006	0.23	0.00	0.50	0.31	11/3/2006	0.08	0.00	0.00	0.17
9/4/2006	0.23	0.00	0.00	0.08	11/4/2006	0.03	0.01	0.00	0.15
9/5/2006	0.22	0.00	0.50	0.36	11/5/2006	0.05	0.01	0.00	0.11
9/6/2006	0.23	0.00	0.00	0.13	11/6/2006	0.07	0.00	0.00	0.04
9/7/2006	0.22	0.00	0.50	0.41	11/7/2006	0.08	0.00	0.50	0.46
9/8/2006	0.22	0.00	0.00	0.19	11/8/2006	0.10	0.00	0.00	0.36
9/9/2006	0.19	0.00	0.50	0.50	11/9/2006	0.11	0.00	0.00	0.25
9/10/2006	0.19	0.00	0.00	0.31	11/10/2006	0.08	0.00	0.00	0.17
9/11/2006	0.20	0.00	0.00	0.11	11/11/2006	0.04	0.02	0.00	0.15
9/12/2006	0.19	0.00	0.50	0.42	11/12/2006	0.04	0.00	0.00	0.11
9/13/2006	0.21	0.00	0.00	0.21	11/13/2006	0.04	0.17	0.00	0.24
9/14/2006	0.21	0.00	0.50	0.50	11/14/2006	0.07	0.06	0.00	0.23
9/15/2006	0.20	0.00	0.00	0.30	11/15/2006	0.06	0.01	0.00	0.18
9/16/2006	0.18	0.00	0.00	0.12	11/16/2006	0.07	0.00	0.00	0.11
9/17/2006	0.18	0.00	0.50	0.44	11/17/2006	0.07	0.01	0.00	0.05
9/18/2006	0.17	0.00	0.00	0.27	11/18/2006	0.02	0.01	0.00	0.04
9/19/2006	0.20	0.00	0.00	0.07	11/19/2006	0.02	0.01	0.00	0.03
9/20/2006	0.18	0.00	0.50	0.39	11/20/2006	0.01	0.00	0.00	0.02
9/21/2006	0.19	0.00	0.00	0.20	11/21/2006	0.03	0.00	0.50	0.49
9/22/2006	0.17	0.00	0.00	0.03	11/22/2006	0.02	0.00	0.00	0.47
9/23/2006	0.17	0.00	0.50	0.36	11/23/2006	0.08	0.00	0.00	0.39
9/24/2006	0.18	0.00	0.00	0.18	11/24/2006	0.06	0.00	0.00	0.33
9/25/2006	0.19	0.00	0.50	0.49	11/25/2006	0.06	0.00	0.00	0.27
9/26/2006	0.18	0.00	0.00	0.31	11/26/2006	0.05	0.06	0.00	0.28
9/27/2006	0.16	0.00	0.00	0.15	11/27/2006	0.03	0.04	0.00	0.29
9/28/2006	0.15	0.00	0.50	0.50	11/28/2006	0.07	0.00	0.00	0.22
9/29/2006	0.14	0.00	0.00	0.36	11/29/2006	0.05	0.00	0.00	0.17
9/30/2006	0.11	0.00	0.00	0.25	11/30/2006	0.06	0.00	0.00	0.11
10/1/2006	0.04	0.02	0.00	0.23	12/1/2006	0.06	0.00	0.00	0.05
10/2/2006	0.07	0.00	0.00	0.16	12/2/2006	0.06	0.00	0.50	0.49
10/3/2006	0.09	0.00	0.00	0.07	12/3/2006	0.07	0.00	0.00	0.42
10/4/2006	0.13	0.00	0.50	0.44	12/4/2006	0.06	0.00	0.00	0.36
10/5/2006	0.08	0.08	0.00	0.44	12/5/2006	0.06	0.00	0.00	0.30
10/6/2006	0.10	0.00	0.00	0.34	12/6/2006	0.06	0.00	0.00	0.24
10/7/2006	0.13	0.00	0.00	0.21	12/7/2006	0.06	0.00	0.00	0.18
10/8/2006	0.13	0.00	0.00	0.08	12/8/2006	0.11	0.00	0.00	0.07
10/9/2006	0.14	0.00	0.50	0.44	12/9/2006	0.08	0.24	0.00	0.23
10/10/2006	0.12	0.00	0.00	0.32	12/10/2006	0.01	0.10	0.00	0.32
10/11/2006	0.14	0.00	0.00	0.18	12/11/2006	0.03	0.00	0.00	0.29
10/12/2006	0.15	0.00	0.00	0.03	12/12/2006	0.01	0.17	0.00	0.45
10/13/2006	0.08	0.00	0.50	0.45	12/13/2006	0.05	0.01	0.00	0.41
10/14/2006	0.09	0.00	0.00	0.36	12/14/2006	0.03	0.00	0.00	0.38
10/15/2006	0.11	0.00	0.00	0.25	12/15/2006	0.03	0.01	0.00	0.36
10/16/2006	0.11	0.00	0.00	0.14	12/16/2006	0.02	0.00	0.00	0.34
10/17/2006	0.12	0.00	0.00	0.02	12/17/2006	0.05	0.00	0.00	0.29
10/18/2006	0.12	0.00	0.50	0.40	12/18/2006	0.05	0.00	0.00	0.24
10/19/2006	0.12	0.00	0.00	0.28	12/19/2006	0.05	0.00	0.00	0.19
10/20/2006	0.13	0.00	0.00	0.15	12/20/2006	0.05	0.00	0.00	0.14
10/21/2006	0.12	0.00	0.00	0.03	12/21/2006	0.02	0.36	0.00	0.48
10/22/2006	0.12	0.00	0.50	0.41	12/22/2006	0.01	0.06	0.00	0.53
10/23/2006	0.11	0.00	0.00	0.30	12/23/2006	0.02	0.00	0.00	0.51
10/24/2006	0.12	0.00	0.00	0.18	12/24/2006	0.02	0.00	0.00	0.49
10/25/2006	0.13	0.00	0.00	0.05	12/25/2006	0.04	0.00	0.00	0.45
10/26/2006	0.11	0.00	0.50	0.44	12/26/2006	0.05	0.16	0.00	0.56
10/27/2006	0.12	0.00	0.00	0.32	12/27/2006	0.03	0.18	0.00	0.71
10/28/2006	0.11	0.00	0.00	0.21	12/28/2006	0.05	0.00	0.00	0.66
10/29/2006	0.11	0.00	0.00	0.10	12/29/2006	0.04	0.01	0.00	0.63
10/30/2006	0.10	0.00	0.50	0.50	12/30/2006	0.05	0.00	0.00	0.58
10/31/2006	0.08	0.00	0.00	0.42	12/31/2006	0.05	0.00	0.00	0.53

A Differentially-Irrigated, Xeric Plant Demonstration Garden in Northwestern New Mexico

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Abstract

Outdoor watering restrictions, which are increasingly being imposed by municipalities to conserve finite water resources, may limit the selection of species that can be practically maintained in semi-arid urban landscapes. To assist in the process of selecting suitable species, a xeric plant demonstration garden was established in northwestern New Mexico to serve as an exhibit of more than 90 drought tolerant, potential urban landscape plant species watered at four different drip-irrigation levels: 0, 20%, 40%, and 60% of reference evapotranspiration (ET_{rs}). In 2006, irrigation volumes ranged from precipitation only (8.8 in.) to 160 gallons per plant (plus precipitation) at the 60% ET_{rs} treatment. Most plants exhibited acceptable growth and quality at between 20% and 40% ET_{rs} per square foot of canopy area. Observations from this demonstration suggest that a well designed xeriscape can be maintained with less than 25% of the water needed to maintain an acceptable quality cool season turfgrass lawn at this same site.

Introduction

The American Intermountain West is facing a water crisis. Staggering increases in human population are placing ever increasing demands on the limited water resources of the region. On the Colorado Plateau, for instance, the population has increased more than six-fold since 1900 and has more than doubled since 1960 (Grahame and Sisk, 2002). Meanwhile, water remains scarce on the semiarid Plateau. Average annual precipitation is less than 10 inches and water from the Colorado River, the primary drainage of the Plateau has been fully allocated for decades (Folk-Williams, et. al. 1985). While the vast majority of Colorado River water is used by agriculture, expanding urban areas both on and off the Plateau (i.e. Las Vegas, Phoenix, Albuquerque, southern California) rely, in part, on Colorado River water for continued growth and development. To help conserve these dwindling water resources, many western cities (Albuquerque, Santa Fe, Las Vegas, Denver, Salt Lake, etc.) are imposing restrictions on landscape water use which, during the summer months, accounts for about 50% of total domestic water use in these urban areas (Vickers, 2001). Additional incentives (water rate structures based on usage, rebates for removal of turfgrass, etc.) have also been implemented to help reduce urban and residential outdoor water use.

Surveys (Schultz, R.D. no date) and studies (Sovocool, et. al. 2005a, Sovocool, et. al. 2005b, Smeal, et. al. 2006) suggest that more than 70% of the water now used to irrigate landscapes could potentially be saved by replacing traditional ornamental plants (i.e. imported cool season turfgrasses and non-native flowers and trees) with native species or plants more suited to a semi-arid environment (i.e. xeric adapted species). Water savings are not achieved through plant selection alone. Irrigation efficiencies must be maximized (through system modification and maintenance) and irrigation schedules must be modified to compensate for the variable water requirements of the selected species. To accomplish this, the irrigator must know the output of his irrigation system and the water requirements of the plants in the landscape.

Many drought tolerant plants native to the Intermountain West have potential for use in urban landscapes of the region and there are native plant exhibits in cities, such as Albuquerque, Flagstaff, Colorado Springs, Salt Lake, and Denver that serve to educate the public on some of the available options. The actual water requirements of these plants when maintained in an urban landscape (Xeriscape), however, have not been accurately quantified.

This demonstration/research project was implemented to exhibit drought tolerant plant species that may be suitable for U.S. Intermountain Region landscapes and to quantify the water requirements of these species.

Objectives

- Establish and maintain a xeric plant demonstration/research garden to serve as an educational exhibit of various drought tolerant plant species that may be suitable for landscapes in the Intermountain West.
- Evaluate the growth and quality of xeric plant species at various levels of microirrigation and quantify the levels of water required to maintain satisfactory aesthetic quality of each species.
- Develop irrigation scheduling recommendations for xeric landscapes based on plant quality/irrigation relationships observed for various species in a xeric plant demonstration/research garden.

Materials and Methods

This demonstration/research garden was established at New Mexico State University's Agricultural Science Center at Farmington in northwestern New Mexico. The center is located on the eastern side of the Colorado Plateau (Lat. 36º 41' N, Long. 180º 18' W), at an elevation of 5640 ft. Average annual precipitation at the semiarid site is 8.2 in. The mean monthly maximum and minimum temperatures, respectively, range from 40 and 19 ºF in January to 91 and 60 ºF in July. The average frost-free period is 163 days from May 4 to October 14 (Smeal, et. al. 2006). The site is located in USDA Plant Hardiness Zone 6b (annual extreme minimum temperature between 0 and -5^{O} F). The soil type at the garden site is a Kinnear very fine sandy loam (Typic Camborthid, fine loamy, mixed, calcareous, mesic family) having a pH of about 8.0, an organic matter content of less than 1%, and an approximate water-holding capacity in the top 2 feet of about 12% (1.5 in/ft) (Anderson, 1970).

A plot area 160 ft long by 80 ft wide (12,800 ft^2 or 0.3 ac) was prepared for planting in early spring, 2002. The plot area was disked, spring tooth harrowed, rototilled, and spike-tooth harrowed in mid-April. A suitable plant list was compiled after consulting various native plant and xeriscaping references (Schultz, [no date]; Proctor, 1996; Busco and Morin, 2003; Phillips, 1998; Knopf, 1991; Mielke, 1993). Plants were obtained from various New Mexico native plant sources and were planted on various dates between April 25 and September 5, 2002. The plot area was split into four equal quadrants of 40 ft by 80 ft prior to the initial plantings of April 25, 2002. A minimum of four specimens of each cultivar was obtained and at least one individual of each species was planted in each of the four quadrants (Fig.1). The plants were arranged randomly around an elliptical path within each quadrant.

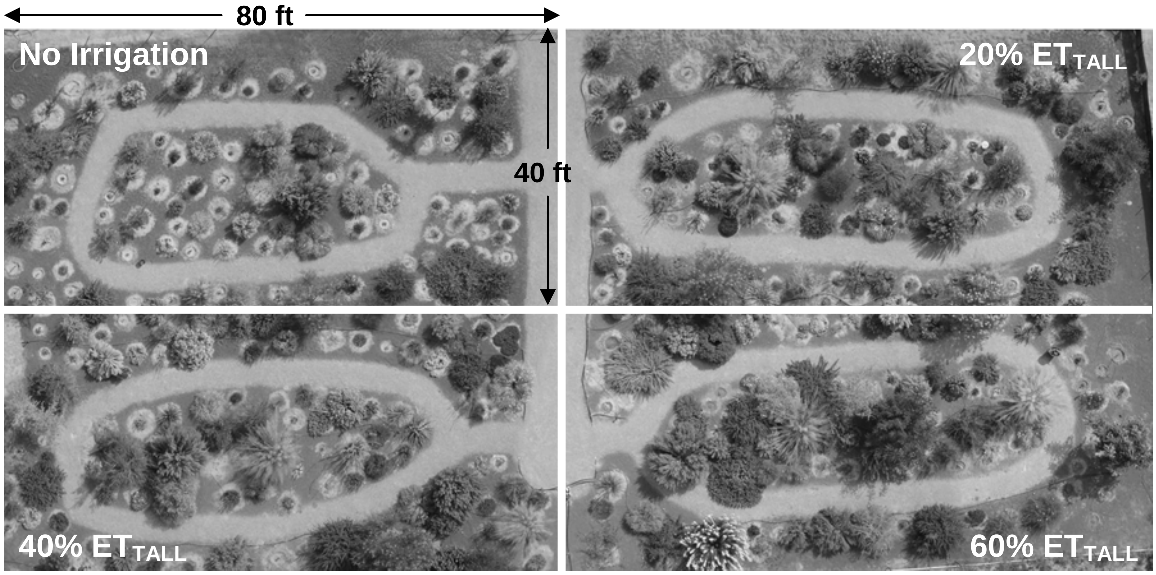

Figure 1. Overhead view of the xeric plant demonstration garden on September 19, 2005 showing general layout and pathways in the four different irrigation zones.

Holes, at least four times the volume of the pots containing the plants, were dug and filled with water and allowed to drain prior to planting. The removed soil was pulverized before backfilling the hole and then lightly tamped around the transplants. No soil amendments were used. After planting, a circular dike was built around each plant to form a water-holding basin. These basins were filled with water after planting and at weekly intervals during 2002 and most of 2003 using a garden hose connected to an irrigation line (see irrigation information below for amounts).

A 3-zone, drip irrigation system was installed in the garden during the summer of 2003 and was used during 2004, 2005, 2006, and 2007 to provide different irrigation treatments to three of the quadrants (zones). The fourth zone received no supplemental irrigation during these four years (Fig. 1). Drip irrigation components in each zone consisted of a main shut off (ball) valve, a main pressure regulator, an in-line main filter, a 1-in poly pipe main line, 0.5-in poly pipe laterals (Fig. 2, left), Xeribird-8 multi-outlet, pressure-compensating emitter manifolds (Fig. 2, right), 1-gph emitters, and 0.25-in vinyl distribution tubing. During 2003, elliptical, 3-ft wide pathways were also formed in each garden quadrant using gray crusher fines over weed barrier. A 10-ft wide, gray crusher-fine pathway separated the north and south halves of the garden (Fig. 1). In February and March 2004, red, crushed lava rock was spread to a depth of about 2 inches in the open areas between plants but outside of the plant basin dikes to provide mulch.

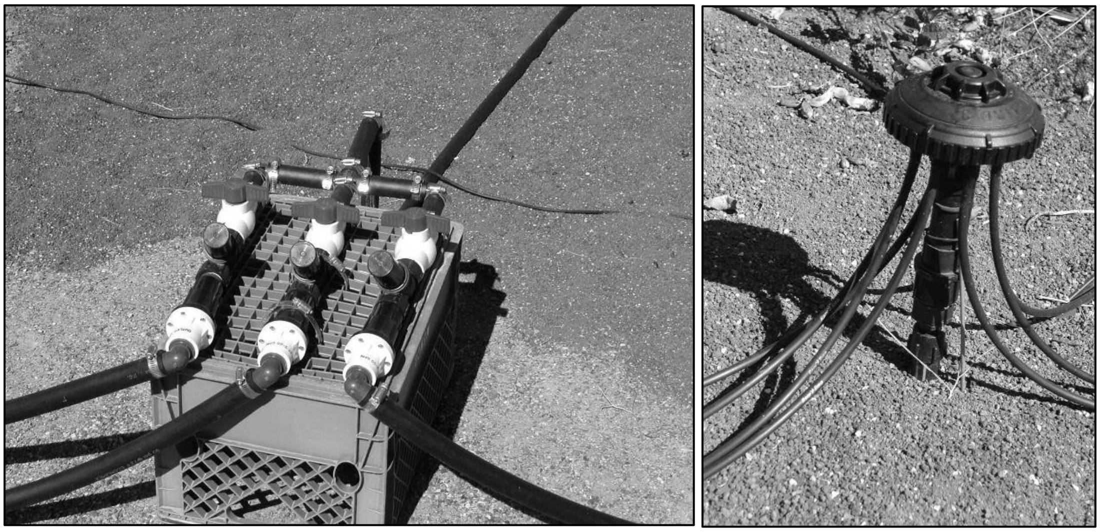

Figure 2. Photos of the ball valves, filters, pressure regulators, and 1-in mainline (left) and the 8-outlet distribution manifolds (right) used for irrigating the xeric plant demonstration garden.

Weed Control

Weeds within the garden were controlled by hand-hoeing or spot treating with a spray bottle containing a 2% glyphosate solution.

Irrigations

During establishment (2002 and early 2003) the plants were irrigated through a garden hose with between 1 and 3 gallons of water per week dependent upon plant size, age, and atmospheric demand. During the first few weeks, newly planted specimens from 2-in to 3-in pots were irrigated every other day with about 0.25 gal of water per application. As the plants became established and new growth was evident, irrigation frequency was reduced to once or twice per week and irrigation volume increased to between 1 and 3 gals per application.

Beginning in late 2003, irrigations were scheduled in the respective irrigation treatments to replace 0, 20, 40, and 60% of reference evapotranspiration (ET_{rs}) about every 7 to 10 days. The following formula was used to convert inches of ET_{rs} to gallons of water for irrigation:

$$I = ET_{rs} \times K_L \times 0.623 \times A_C \qquad \text{[EQ. 1]}$$

Where:

I = irrigation (gals per application period)

ET_{rs} = Penman-Monteith alfalfa-based (tall) reference ET (in per period)

K_L = Landscape coefficient or treatment factor (0.0, 0.2, 0.4, or 0.6)

0.623 = gallons of water to cover 1 ft^2 to a depth of 1 in

A_C = plant canopy area (ft^2)

Daily weather data from a New Mexico Climate Center (NMCC) weather station located less than 100 feet from the center of the garden were used to calculate ET_{rs}. These data and ET_{rs} values are available (as ET_{TALL}) at the NMCC web page (http://weather.nmsu.edu) and the method used to calculate ET_{rs} is presented by Snyder and Paw U (2007).

Since all plants within each quadrant received the same amount of water, a gross average canopy area, representing the mean of all plants within the quadrant, was used for irrigation scheduling. Since the canopy shape of most plants was roughly circular, canopy area in square feet (A_C) was calculated using diameter measurements and Equation 2.

$A_C = D^2 \times 0.785$ [EQ. 2]

Where:

A_C = canopy area (ft^2)

D = canopy diameter (ft)

Irrigation runtimes were adjusted to apply the appropriate irrigation treatment volume to each quadrant using Equation 3.

$T = I \times Q \times 60$ [EQ. 3]

Where:

T = runtime (mins)

I = irrigation volume (gals per application period)

Q = flow rate of emitter (all were 1 gph)

60 = mins/hr

Plant growth, flowering, overall shape and appearance, quality and aesthetic appeal of the plants were observed throughout the growing season. Several photographs were also taken for archiving and to assist in the evaluations. Aerial photos were taken to evaluate the relationship between canopy area and irrigation.

Results and Discussion

Average daily ET_{rs} (ET_{TALL}) during 2003 through 2007 increased from about 0.08 in/day during December and January when the plants were dormant to a peak of slightly less than 0.4 in/day in June and July (Figure 13).

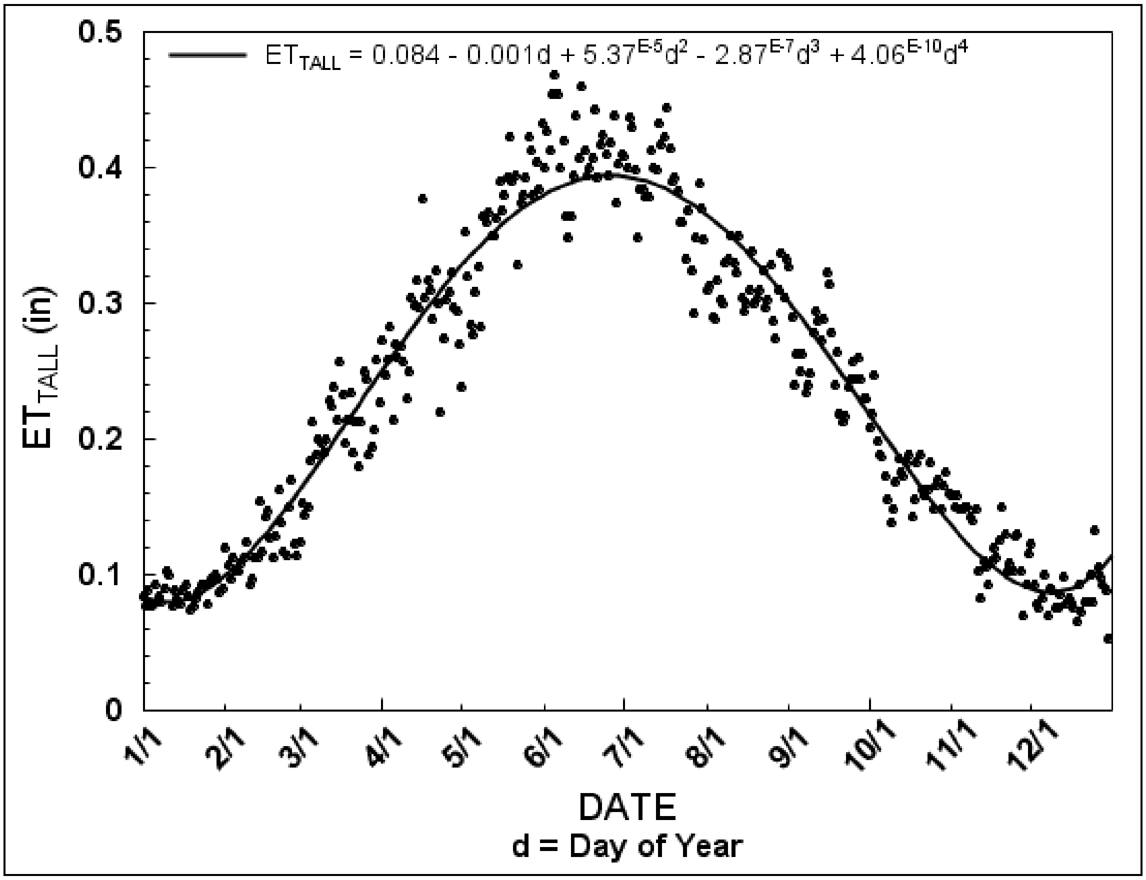

Figure 1. Average daily reference evapotranspiration (ET_{TALL}) during the years from 2003 through 2007. NMSU Agricultural Science Center, Farmington, NM.

Estimates of mean plant canopy area during this 5-year period ranged from a low of 0.2 ft^2 (D = 0.5 ft) early in the establishment year (2003) to more than 16 ft^2 (D = 4.5 ft) in August 2007 (Table 1). In some years, average live canopy area decreased from August to October due to leaf senescence or selective pruning.

Table 1. Plant diameter estimates used to calculate canopy area for scheduling irrigation treatments in the xeric plant demonstration garden from 2003 to 2007.

	Average Plant Diameter (feet)						
Year	**April**	**May**	**June**	**July**	**August**	**September**	**October**
2003	0.5	1.0	1.0	1.0	1.0	1.0	1.0
2004	1.5	2.0	2.3	2.5	3.0	2.5	2.3
2005	1.5	2.0	2.8	3.5	3.5	3.5	3.5
2006	2.5	2.5	3.0	3.0	4.3	4.3	4.0
2007	2.5	2.9	4.2	4.6	4.8	4.5	3.8

Total cumulative ET_{rs} during the active growing seasons (April 1 through October 31) of years 2003 through 2006 averaged 68 inches (Table 2). Total seasonal irrigation (not including the zero irrigation plot) ranged from a low of 39 gals/plant/year in the low (0.2 K_L) irrigation zone in 2004 to a high of 241 gals/plant/year in the high (0.6 K_L) irrigation zone in 2007. Total annual and seasonal precipitation from 2003 through 2006 averaged 8.1 and 5.4 inches, respectively (Table 2). Complete weather and irrigation data for October 2007 are not yet available, so they are not included in the calculation totals or means.

Table 2. Total seasonal (April 1 through October 31) reference ET (ET_{rs}), precipitation, and irrigation per plant applied to four irrigation treatments (0, 20, 40, and 60% of ET_{rs}) from 2003 to 2007 in the xeric plant demonstration garden.

	ET_{rs}	Irrigation (gallons per plant)				Precipitation (inches)	
Year	**inches**	**60%**	**40%**	**20%**	**0%**	**7 Month Season**	**Total Annual**
2003†	72.3	25-40	25-40	25-40	25-40	3.1	6.3
2004	67.8	109	74	39	0	6.3	8.7
2005	67.3	150	102	55	0	5.3	8.7
2006	64.6	159	121	67	0	6.9	8.8
2007‡	58.9	241	174	100	0	4.4	7.1
Mean‡‡	**68.0**	-	-	-	-	**5.4**	**8.1**

†Irrigation amounts during 2003 were not specifically quantified but fell within the ranges reported.
‡Totals in this row are from April 1 through October 8, 2007.
‡‡Does not include 2007 data.

A complete listing of the species in the xeric plant demonstration garden, along with suggested K_L values (based on subjective quality ratings), are shown in Table 3. Most of the plants listed survived, and many exhibited potentially acceptable quality, at lower levels of irrigation than suggested by the K_L value shown. The suggested K_L values are based on factors, such as increased flowering, less wilting during excessive heat, color, shape, etc., that may have been exhibited at the higher irrigation levels. In many other cases, higher irrigation levels resulted in poorer plant quality due to scraggly or rangy appearance, falling down of foliage, root rot, yellowing of foliage, etc.

Several species specifically native to the Four Corners area (i.e. *Amelanchier utahensis*, *Artemisia tridentata*, *Artiplex canescens*, *Chrysothamnus nauseosus Fallugia paradoxa*, *Foresteria neomexicana*, *Penstemon ambiguus*, *Juniperus scopulorum*, *Rhus trilobata*, *Yucca baccata*) and other regions of New Mexico (i.e. *Berlandiera lyrata*, *Chilopsis linearis*, *Yucca elata*), once established, did not exhibit appreciable better quality when irrigated than when non-irrigated (Table 3). Contrastingly, other species, including the Four Corners natives, *Helianthus maximilianii and Ribes aureum* and southern U.S. natives *Artemisia abrotanum*, *Oenothera missouriensis*, and *Echinacea purpurea*, exhibited best quality at relatively high levels of irrigation ($K_L > 0.5$). Overall, most plants exhibited acceptable quality at either the low ($K_L = 0.2$) or medium ($K_L = 0.4$) irrigation treatment.

Table 3. List of species in the xeric plant demonstration garden with estimated landscape coefficients (K_L) based on plant quality and size observations from 2004 through 2007.

Species	Common Name	Landscape Coefficient (K_L)†
Achillea millefolium	Common white yarrow	NEI (0,4)
Agastache foeniculum	Blue giant hyssop	0.4
Agastache ruprestris	Licorice hyssop	0.4
Agave utahensis	Utah agave	0.5
Agropyron smithii	Western wheatgrass	0.3
Amelanchier utahensis	Utah serviceberry	0-0.2
Anemopsis californica	Yerba mansa	NEI (0.6)
Armeria maritima	Seathrift	NEI
Artemisia abrotanum	Southernwood	0.6
Artemisia frigida	Fringed sagewort	0.3
Artemisia ludoviciana	Prairie sagewort	0.3
Artemisia nova	Black sage	0.5
Artemisia tridentata	Big sagebrush	0
Artiplex canescens	Fourwing saltbush	0
Atriplex confertifolia	Shadscale saltbush	NEI
Asclepias tuberosa	Butterfly weed	0.4
Berberis fremontii	Fremont barberry	0.2
Berlandiera lyrata	Chocolate flower	0

Species	Common Name	Landscape Coefficient (K_L)[†]
Brickellia californica	California bricklebush	0.5
Buddleia davidii	Butterfly bush	0.3
Caesalpinia gilliesii	Bird of paradise	0.3
Callirhoe involucrata	Wine cups	0.5
Calylophus berlandieri	Berlandieri sundrops	0.5
Campsis radicans	Trumpet vine	0.5
Caragana arborescens	Siberian peashrub	0.3
Caryopteris clandonensis	Blue mist spirea	0.4
Centranthus ruber	Jupiter’s beard	0.3
Cerastium tomentosum	Snow in summer	0.5
Cercocarpus ledifolius	Curl-leaf mountain mahogany	0.2
Cercocarpus montanus	True mountain mahogany	0.2
Chamaebatiaria millefolium	Fernbush	0.2
Chilopsis linearis	Desert willow	0-0.2
Chrysanthemum sp.	Crete white chrysanthemum	0.3
Chrysothamnus nauseosus	Rubber rabbitbrush	0-0.2
Coreopsis lanceolata	Lanceleaf coreopsis	0.5
Cowania (Purshia) mexicana	Cliffrose	0.2
Datura metaloides	Sacred datura	0.4
Delosperma cooperi	Purple iceplant	0.5
Delosperma nubigenum	Yellow iceplant	NEI
Echinacea purpurea	Purple coneflower	0.6
Ephedra viridis	Mormon tea	0-0.2
Eriogonum jamesii	James’ buckwheat	0.2
Euphorbia myrsinites	Myrtle (yellow) euphorbia	0.3
Fallugia paradoxa	Apache plume	0
Festuca glauca	Blue fescue	NEI
Foresteria neomexicana	New Mexico olive	0-0.2
Gaillardia aristata	Blanket flower	0.4
Gaura lindheimeri	Gaura	0.5
Helianthemum nummularium	Sunrose	0.5
Helianthus maximilianii	Maximilian sunflower	0.6
Helichrysum angustifolium	Curry plant	0.4
Hesperaloe parviflora	Red yucca	0.3
Heuchera sanguinea	Coral bells	0.5
Ipomopsis aggregata	Scarlet gilia	NEI
Juniperus scopulorum	Rocky Mountain juniper	0-0.2
Kniphofia uvaria	Red-hot poker	0.5
Koelreuteria paniculata	Goldenrain tree	0.5
Krascheninnikovia lanata	Winterfat	0.3
Liatris punctata	Dotted gayfeather	0.4
Linum perenne	Perennial blueflax	0.4
Lychnis chalcedonica	Maltese cross	NEI
Lycium pallidum	Pale wolfberry	0.5

Species	Common Name	Landscape Coefficient (K_L)[†]
Malus sp.	Flowering crabapple	NEI
Melampodium leucanthum	Blackfoot daisy	NEI
Mirabilis multiflora	Giant four o'clock,	0.2
Nassella tennuissima	Threadgrass	0.4
Nolina microcarpa	Beargrass	NEI
Oenothera caespitosa	Tufted evening primrose	NEI (0.3)
Oenothera missouriensis	Ozark sundrops	0.6
Oenothera organensis	Organ Mtn. evening primrose	0.3
Oenothera speciosa	Mexican evening primrose	0.5
Opuntia imbricata	Tree cholla	0
Oryzopsis hymenoides	Indian ricegrass	0.3
Parthenium incanum	Mariola	0-0.2
Penstemon abuelitas	Abuelita penstemon	0-0.2
Penstemon ambiguus	Bush penstemon	0
Penstemon angustifolia	Narrow leaf penstemon	0.2
Penstemon barbatus	Scarlet Buglar penstemon	0.4
Penstemon eatonii	Firecracker penstemon	NEI (0.4)
Penstemon palmeri	Palmer penstemon	0.4
Penstemon pinifolius	Pineleaf penstemon	0.4
Penstemon pseudospectabilis	Desert penstemon	0.2
Penstemon strictus	Rocky Mtn. penstemon	0.3
Peraphyllum ramosissimum	Squaw apple	0.3
Perovskia atriplicifolia	Russian sage	0.3
Pinus nigra	Black pine	0-0.2
Potentilla fruticosa	Native potentilla	0.4
Potentilla thurberii	Red cinquefoil	0.5
Prosopis pubescens	Screwbean mesquite	0-0.2
Prunus besseyi	Western sandcherry	0.2
Prunus domestica 'Stanley'	Stanley dwarf prune	NEI
Ratibida columnifera	Prairie coneflower	0.3
Rhus trilobata	Three-leaf sumac	0-0.2
Rhus trilobata var. pilosissima	Pubescent squawbush	0.0.2
Ribes aureum	Golden currant	0.6
Robinia neomexicana	New Mexico locust	0.1
Rosmarinus officianalis	Upright rosemary	0.5
Salvia greggii	Cherry sage	0.5
Salvia greggii	Navajo Dark Purple Salvia	NEI
Salvia pinguifolia	Rock sage	0.3
Sedum spurium	Dragon's blood sedum	0.4
Sedum telephium	Autumn joy sedum	0.3
Silene lanciniata	Cardinal catchfly	NEI
Spartium junceum	Spanish broom	0.2
Sphaeralcea ambigua	Desert globemallow	0.2
Sporobolus wrightii	Giant sacaton	0.2

Species	Common Name	Landscape Coefficient (K_L)†
Stachys byzantina	Lamb's ear	0.5
Stanleya pinnata	Prince's plume	NEI
Teucrium arogrium	Greek germander	0.3
Verbena macdougalii	Western spike verbena	NEI
Yucca baccata	Banana yucca	0-0.2
Yucca elata	Soaptree yucca	0
Zauschneria californica	Hummingbird plant (trumpet)	0.3
Zinnia grandiflora	Desert zinnia	0.2

†NEI = not enough information. K_L in parentheses is an approximation based on surviving individuals.

Table 4 provides suggested weekly, per plant irrigation volumes at various K_L values and plant canopy diameters for xeric landscapes in the U.S. Intermountain region using the observations of this five-year project. While the volumes are presented on a weekly basis for convenience, they are not indicative of the actual recommended irrigation frequency. For example, plants that are small and not yet established might require every-other day watering while large, well established native plants may exhibit acceptable growth and quality with deep, infrequent (i.e., bi-weekly or monthly) waterings. Irrigation recommendations are presented on a weekly basis for the convenience of homeowners, landscapers, etc. who may be replacing sprinkler-irrigated turf, that use automatic irrigation controllers, with xeric, drip-irrigated landscapes. In most cases, the existing irrigation system mainlines, sub-mains, timers, etc. can be retrofitted for xeric landscapes but many controllers cannot be programmed for irrigation frequencies of less than once per week.

Table 4. **Suggested weekly irrigation (gallons per plant) during the growing season for xeric landscape plants having differing landscape coefficients and canopy diameters in northwestern New Mexico.**

		DATE								
		April 16-30	May 1-15	May 16-31	June	July	August	Sept. 1-15	Sept. 16-30	Oct. 1-15
		Average Daily Reference ET (inches)								
K_L	D	0.30	0.32	0.39	0.41	0.39	0.31	0.27	0.25	0.19
	feet	Irrigation Per Plant Per Week (gallons)								
0.6	1	0.6	0.7	0.8	0.8	0.8	0.6	0.6	0.5	0.4
	2	2.5	2.6	3.2	3.4	3.2	2.6	2.2	2.1	1.5
	3	5.6	5.9	7.2	7.6	7.2	5.8	5.0	4.7	3.4
	4	9.9	10.5	12.8	13.5	12.7	10.3	9.0	8.3	6.1
	5	15.5	16.5	19.9	21.2	19.9	16.1	14.0	12.9	9.6
0.4	1	0.4	0.4	0.5	0.6	0.5	0.4	0.4	0.3	0.3
	2	1.7	1.8	2.1	2.3	2.1	1.7	1.5	1.4	1.0
	3	3.7	4.0	4.8	5.1	4.8	3.9	3.4	3.1	2.3
	4	6.6	7.0	8.5	9.0	8.5	6.9	6.0	5.5	4.1
	5	10.3	11.0	13.3	14.1	13.3	10.7	9.3	8.6	6.4
0.2	1	0.2	0.2	0.3	0.3	0.3	0.2	0.2	0.2	0.1
	2	0.8	0.9	1.1	1.1	1.1	0.9	0.7	0.7	0.5
	3	1.9	2.0	2.4	2.5	2.4	1.9	1.7	1.6	1.1
	4	3.3	3.5	4.3	4.5	4.2	3.4	3.0	2.8	2.0
	5	5.2	5.5	6.6	7.1	6.6	5.4	4.7	4.3	3.2

Plant size or canopy area and reference ET are not the only criteria that should be considered in estimating the water requirements of xeric landscapes. Actual seasonal evapotranspiration varies widely between plant species due to differences in leaf area, plant morphology, phenology, physiology, etc. For example, while all species in the xeric plant demonstration garden are perennials, many are herbaceous and die back to the ground each year, reemerging from the roots in spring. These plants are relatively small, reaching a maximum canopy area of perhaps 7 to 12 ft^2 (3-ft to 4-ft diameter). Larger woody species on the other hand may have maximum live canopy areas greater than 20 ft^2 (5 ft diameter). In some cases, where the K_L of the larger species is much lower than that of the smaller species, the total water requirements for acceptable quality of these different plants may not be appreciably different.

Figure 4 illustrates the average daily irrigation requirement that should provide acceptable growth and quality for a typical xeric herbaceous perennial (i.e. *Penstemon strictus*) and tree or shrub (i.e. *Chilopsis linearis*) in northern New Mexico based on our observations. Total seasonal volume of irrigation water required per square foot of final canopy area would be 4.4

gals (7.0 in depth) for *Chilopsis linearis* (K_L = 0.2) and 7.1 gals (11.4 in depth) for *Penstemon strictus* (K_L = 0.3). This compares to a total seasonal irrigation requirement of 19 gals/ft^2 (31 in) for cool season turf and 12 gals/ft^2 (20 in) for warm season turf, not including an average growing season precipitation depth of about 5.5 in (Smeal, et. al., 2001).

Summary

This Xeric Plant Demonstration/Research Garden has served to exhibit several drought tolerant plants that can be used in water conserving landscape in the U.S. Intermountain Region. While not a rigorous scientific research study due to the lack of recognized or accepted statistical randomization and replication techniques, the differentially irrigated aspect of the garden has provided an indication of irrigation requirements for several plant species and of landscape crop coefficients that can be used to effectively schedule irrigations on these species.

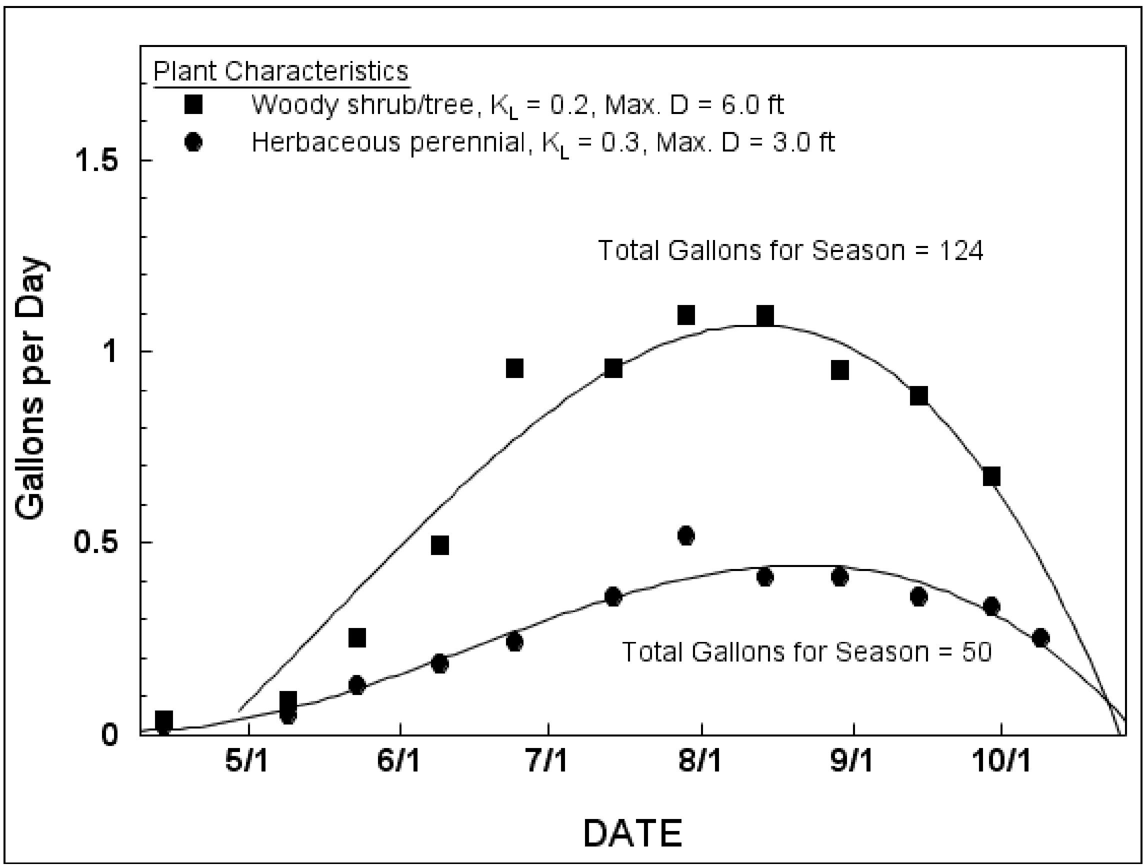

Figure 4. Estimated irrigation requirements of two typical xeric species; a herbaceous perennial (i.e. *Penstemon* sp.) having a K_L of 0.3 and a live canopy area ranging from 0.35 ft^2 (D = 0.75 ft) in mid-April to 7.1 ft^2 (D = 3 ft) from mid-July through mid-October, and a woody shrub or tree (i.e. *Chilopsis linearis*) having a K_L of 0.2 and a live canopy area ranging from 0.8 ft^2 (D = 1.0 ft) in early-May to 28.3 ft^2 (D = 6.0 ft) from August 1 through mid-October.

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Monitoring Spatial Variability in Soil Properties and Turfgrass Stress: Applications and Protocols

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Precision Turfgrass Management (PTM)

Spatial and temporal variability of soil, climatic, plant, and irrigation application aspects are challenges for traditional agriculture and turfgrass/landscape sites. Precision Agriculture (PA) evolved as a means to facilitate site-specific management in contrast to uniform whole-field management for the purposes of: a) efficiently targeting application of inputs where, when, and at the appropriate rate in a site-specific manner; b) environmental stewardship via control of non-point source pollutant movement of fertilizers, pesticides, and salts; c) to assess and sustain soil quality, and d) to enhance crop performance (Corwin and Lesch, 2005a, 2005b). These same purposes will stimulate traditional turfgrass management toward a Precision Turfgrass Management (PTM) approach that supports sustainable practices (PTRI, 2007).

Site-specific management requires site-specific information – i.e., information from the site to make management decisions. Similar to PA, PTM must obtain accurate and timely information by integration of sensor and electronic technologies, including: global positioning systems (GPS), geographic information systems (GIS), and plant, soil, and/or climatic sensors via mobile platforms, in-place, or combinations (Johnson et al., 2003). However, there are considerable differences between PA and PTM. First, turfgrass systems allow easier access to sites, including data acquisition during dry-downs from irrigation or rainfall events; and for periodic monitoring over a season. Second, site access allows plant stress monitoring to evaluate turfgrass performance with mobile spectral units as a useful substitute for end of year crop yield (Jiang and Carrow, 2007; Bell et al., 2002). Third, specific sensor arrays or technological approaches may differ from PA. One example is the wide-spread use in PA of electromagnetic induction (EM) to determine apparent soil electrical conductivity (ECa), which provides spatial information on soil texture, moisture, and salinity depending on whether the soil is saline or non-saline (Corwin and Lesch, 2005a, 2005b). Turfgrass sites allow use of electrical resistivity (ER) with the 4-wenner array probe arrangement to determine ECa since turf does not have a dry, fallow surface and irrigated turfgrass allows ER probe contacts with little canopy penetration (Rhoades et al., 1999). Also, time-domain reflectrometry (TDR) for direct determination of volumetric water content in the surface zone is easier with a turfgrass surface than an agriculture field that may have a dry zone at the surface.

For progress to be made in PTM, it is necessary to define key, specific applications and then to develop systematic protocols to address each application, similar to the approach of Lesch and Corwin (2005a, 2005b) and Yan et al. (2007) in PA. While a number of applications of spatial mapping are possible within PTM, we will focus on three major issues, namely: water-use efficiency/conservation, soil salinity, and soil compaction.

Applications

Water-Use Efficiency/Conservation. Water-use efficiency/conservation is a dominant environmental issue confronting the turfgrass and irrigation industries (Kenna and Beard, 2007). Mobile spatial mapping of site conditions has potential for PTM, especially for enhancing water-use efficiency and conservation on complex sites with a high degree of spatial and temporal variability. To achieve progress in this area, we identified six specific field applications for spatial mapping that would significantly improve water management. Initially, the emphasis may be on golf courses or other complex sites since they exhibit a high degree of soil, plant, environmental, and irrigation-based variability and success in this arena would allow application to other less challenging sites. The six related but specific field applications are:

1. Use of mapping information to identify relatively easy-to-correct changes in irrigation design and/or scheduling for uniformity of water application or soil status;
2. Defining site-specific management units (SSMU) on non-saline sites – SSMU information is essential to achieve the purposes of PTM stated earlier as well as to assist irrigation scheduling, aid in evaluating efficiency of the irrigation system, and correct in-place sensor placement.
3. For current irrigation systems, evaluation of system design across the whole site for degree of uniformity of water application (distribution uniformity, DU) based on soil moisture distribution rather than the traditional catch-can approach to determine if the system is efficient – i.e. the core of a *New WaterAudit approach* that would entail integrating field applications 1, 2, 3, and 5.
4. For newly installed irrigation systems, use the New WaterAudit approach for assessment of design for uniformity (i.e. incentive for better design) a few weeks after turf establishment; and as a tool to aid turf managers in irrigation scheduling and to maximize the use of their new system in the least amount of time after installation;
5. Determining the best locations (key indicator sites) for placement of in-situ sensor arrays within representative SSMU areas. Carefully selected sites for in-place sensors would allow real-time and more robust on-going data with the least number of sensor locations.
6. Use of the mobile spectral mapping during routine mowing to assess system problems from either equipment malfunction or scheduling.

By focusing on individual issues/problems (i.e., field applications) for spatial and temporal mapping of turfgrass sites, this aids in formulating appropriate procedural protocols for each application. Protocols can differ somewhat depending on the objectives for each specific field application and will be discussed later.

Salinity. Salinity is an increasing issue on turfgrass sites due to use of irrigation water sources that are often more saline than in the past, development of more salt-tolerant turfgrasses such as *Paspalum vaginatum* (seashore paspalum), and golf courses established on coastal sites (Duncan and Carrow, 1999; Carrow and Duncan, 1998). Important field applications of spatial and temporal mapping for saline sites are:

- All of the field applications noted in the water conservation section are just as important for salinity management since efficient and effective leaching is the key management strategy for saline sites (Carrow et al., 2000). Irrigation system design for uniformity and flexibility coupled with efficient scheduling are essential necessary for good leaching.
- However, prior to leaching, it is important to determine spatial distribution of soluble salts across the landscape and within the soil profile (Cassel S., 2007). Additionally, mapping over time can determine temporal changes in salt distribution patterns. Mobile salinity mapping assists in identifying where to leach, how much water to apply (minimal leaching requirement), and whether leaching is effective. This is a *New SaltAudit* approach.

Soil Compaction. On recreational sites soil compaction is a primary management problem that affects water and salinity movement and retention (Carrow and Petrovic, 1992). Mobile platforms to spatially map soil compaction could aid in site-specific cultivation and where irrigation scheduling may need to be altered.

Protocols

In 2003, a USDA-ARS sponsored workshop on Precision Agriculture concluded that "protocols for conducting geo-referenced field-scale ECa surveys and guidelines for interpreting the ECa measurements are needed to insure reliability, consistency, and compatibility of data" (Corwin and Lesch, 2005a). Based on this need, a survey protocol for the ECa approach in PA to determine soil spatial variability and define SSMUs was developed by Corwin and Lesch (2005a) along with a case study (Corwin and Lesch, 2005b). The term "protocol" was used in a very broad sense to refer to all aspects necessary to achieve detailed site assessment information. The PA protocol categories are applicable to PTM and provide a grid for focusing research efforts. With some change to reflect a PTM situation, the procedural protocols are:

- Mobilized Measurement Equipment.
- Site Description/Goals and Geo-Referenced Data Collection with the mobile units.
- Soil Sampling Design, Sampling, and Soil Core Analysis for validation of SSMU areas and to determine SSMU soil chemical and physical characteristics.
- GIS Database Development and Graphic Display
- Descriptive and Spatial Statistical Protocols
- Display, Reporting, and Interpretation Protocols for Information Packaging directed to the end-user in a concise, accurate fashion.
- Information Transfer System Protocols.

Protocol details will differ for PTM compared to PA, and protocols will also differ to some extent for each field application. As with any new technology or approach, it is necessary to focus onto real-world problems – i.e., field applications. Therefore, we would suggest systematic development of detailed protocols and case studies for each field situation within the various applications (water conservation, salinity, soil compaction)

The first step toward rapid spatial mapping of large, complex turfgrass areas is development of mobile platform equipment. We have developed two mobile devices each with GPS units. The first device is for use on non-saline sites with capability for: a) rapid measurement of surface zone volumetric water content (VWC). VWC data can be used to map spatial VWC, evapotranspiration (ET) patterns, and determination of Coefficient of Uniformity (CU) for VWC (Dukes et al., 2006); b) turf performance or stress by NDVI (normalized differential vegetative) using spectral reflectance; and c) penetrometer resistance (PR) for soil compaction mapping. A second device has the capability for: a) determination of apparent soil conductivity (ECa) using ER and 4-wenner probe array for multiple soil depths, and b) turf performance by NDVI by spectral reflectance. Within PA and PTM, ECa can be used to estimate soil texture and soil moisture on non-saline sites, and salinity on saline sites.

This equipment or similar spatial and temporal mapping devices developed by other scientists will provide the means to rapidly obtain spatial data on turfgrass sites and address the remaining protocols for the specific field applications previously noted in the water conservation, salinity, and soil compaction areas. Combining systematic protocols with real-world case studies for each of these field applications will be major steps toward implementation of the PTM approach for water, salinity, and soil compaction management.

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Reducing irrigation of turfgrass areas by detecting stress early and using wetting agents.

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Key words: localized dry spot, reduced irrigation, reflectance, surfactant, water stress

ABSTRACT

In order to optimize irrigation reduction and conserve water resources, ways to increase water use efficiency and early plant responses to water stress need to be identified. This experiment was conducted to determine if frequent surfactant applications in couple with identifying water stress early can reduce the need for irrigation while maintaining turfgrass quality. Three consecutive trials were conducted in which bermudagrass was subjected to either (*i*) no irrigation, (*ii*) irrigated daily or, (*iii*) initially treated with a surfactant over a dry-down period. Turfgrass quality and localized dry spot (LDS) symptoms from surfactant-treated turfgrass was similar or better than irrigated turfgrass, with both showing greater quality and less LDS symptoms than observed from the non-irrigated, non-treated turfgrass. On some dates, the sensor determined water stress before stress was visually apparent. Applying a surfactant decreased irrigation requirements up to 71% while maintaining similar quality as bermudagrass that is not water stressed.

INTRODUCTION

Ensuring a high quality water supply for human consumption and for the preservation of natural resources is a priority within an increasing number of State legislatures. Thus regulations are either currently in place or are expected for non-essential uses of fresh water such as irrigation of large turfgrass landscapes (i.e. golf courses, sports fields, parks and residential lawns). Compliance of these restrictions while continuing to maintain quality turfgrass will require proper methods to be identified for altering management practices.

Turfgrass managers already utilize many water saving management options: scheduling irrigations during early morning hours to maximize distribution uniformity by reducing applied water to wind drift and evaporation; incorporate additions from rainfall into irrigation scheduling; promote uniform wetting fronts by applying surfactants; and irrigating infrequently but deeply to discourage growth of disease pathogens, but encourage deep rooting., Turfgrass managers are hesitant to further curtail irrigation since increasing the period time between irrigations can cause the soil to dry out. These wetting and drying cycles promote subcritical soil water repellency to develop causing the soil profile to be difficult to rehydrate and alleviate visual LDS symptoms (Wilkinson and Miller, 1978). As it is, these wetting and drying cycles already occur in South Florida during the transition of the dry season to the wet season (end of April to the end of May) when rainfall is infrequent and higher temperatures, longer day lengths and increased wind speeds result in greater evapotranspiration (ET) demand. During this time, soil water repellency symptoms can develop quickly. Subsequently, preferential flow patterns develop causing non-uniform soil wetting fronts decreasing infiltration and soil moisture, and increasing ponding and subsequent losses by evaporation and runoff (Dekker et al., 2001). Turfgrass quality declines and the occurrence of localized dry spot (LDS) increase (Snyder et al., 1984; Wallis et al., 1989; Snyder and Cisar, 2004).

Management of water repellent soils includes both non-favorable and favorable methods for water conservation. For example, increasing irrigation frequency and quantity to make sure the turfgrass does not dry out (Snyder et al., 1984; Cisar et al., 2000; McCarty and Miller, 2002) may increase the amount of water used for irrigation. In comparison, improving soil physical characteristics by frequent aerification and topdressing, and vertical mowing, will help to ameliorate water repellency (Karnock and Tucker, 1999) and increase water movement into and throughout the soil.

Since further irrigation curtailment is not conducive to maintaining quality turfgrass, managers must implement alternative management strategies that maximize the water they have available to them in order to meet future water restrictions without compromising turfgrass quality. This includes maximizing the delivery of applied water (timing and amount of water entering the root zone), and maintaining water within the rootzone for availability to the turfgrass (Carrow et al., 2005; Kostka et al., 2007).

Surfactants can promote a uniform moist soil profile and rewetting of the soil, less water stress and LDS, as well as continued turfgrass quality in bermudagrass maintained on sandy soils (Park et al., 2004, Karnok and Tucker, 2001; Cisar et al., 2000; Miller and Kostka, 1998; York and Baldwin, 1992; Wilkinson and Miller, 1978). If surfactants increase water infiltration (Letey et al., 1969), promote uniform soil wetting fronts (Kostka, 2000), and increase plant available water (Leinauer et al., 2001), perhaps they can also assist in increasing water use efficiency (WUE) for non water-repellent soils as well.

Another management strategy may be to detect water stress at early stages in order for quick intervention and potential reduction in management inputs (irrigation). While traditional methods for determining water stress have relied on visual observations of wilted turfgrass, monitoring the spectral reflectance has proven as way to document less obvious differences in turfgrass stands (Narra et al., 2004; Nutter et al., 1993; Shepard et al., 1990). Perhaps this is because spectral reflectance allows not only for monitoring the visible part of the spectrum, but also the near-infrared range, which is not perceivable by the human eye (Lemon, 1966).

In order to maintain quality bermudagrass and comply with water regulations, proper methods need to be identified for altering management practices to maximize water applications to the root zone. This experiment examines if turfgrass quality can be maintained when less irrigation is applied if (a) a surfactant is integrated into an irrigation schedule, and (b) early signs of stress are monitoring for.

METHODS AND MATERIALS

This experiment was conducted during April and May 2004, when high ET demand, and low precipitation was conducive to LDS symptom development. The experiment consisted of three trials, each consisting of a dry-down period (April 30-May02, May 05-06, and May 16-18 for trials 1, 2, and 3, respectively) and was conducted at the Fort Lauderdale Research and Education Center in Fort Lauderdale, Florida. Sixteen meter^2 *Cynodon dactylon* X *Cynodon transvaalensis* 'Tifdwarf' bermudagrass plots were grown in on a Margate fine sand [Siliceous, hyperthermic Mollic Psamnaquent]. For each trial, each plot was subjected to one of three treatments in a randomized complete block design: (*i*) irrigated daily to replace daily potential ET (IIRD); (*ii*) application of a surfactant (APG-EO/PO block copolymer surfactant blend, currently commercialized as patented Dispatch) at a rate of 89ml ha^{-1} upon initiation of each trial (SURF); or (*iii*) no irrigation and no surfactant (NINS). The surfactant was injected into an irrigation system and applied with irrigation equaling to the current days potential ET. No further irrigation was applied to the surfactant treated plots for the remainder of each trial. Treatments were replicated four times for a total of twelve test plots. Treatments were applied to the same plots for each of the three trials. Rainbird 1800 quarter circle pop up irrigation sprinklers were located at the four corners of each plot to evenly distributed irrigation water and/ or the surfactant over the bermudagrass. Each plot had an irrigation shut off valve to control irrigation for individual plots. Each trial was initiated when bermudagrass showed no visual water stress symptoms (acceptable visual quality and minimal LDS symptoms).

An experimental active turf quality sensor (LI-COR, Lincoln NE) measuring reflectance within two narrow wavebands within the red (400-700 nm) and near-infrared (715-950 nm) was used to monitor water stress. Due to proprietary reasons, specific wavelengths will be released at a later date. The sensor was mounted on a tripod looking down on a 0.6 meter diameter circular area (LI-COR, Lincoln NE). The sensor's circuitry was designed to reject all external light (natural and artificial), and only to detect reflected light originating from the instrument. Twice daily (at 0800 and 1500 hrs), reflectance at the two wavelengths was measured in each plot four times and averaged for each observation period. Turf quality was assessed by monitoring the wavelengths and calculating the near-IR/Red ratio. Visual turf quality (rated on a 1-10 scale with 1= dead turf, 6= minimally acceptable, and 10=dark green turf) and % LDS symptoms were rated at the same time as the 1500 hr sensor measurements were collected. Each trial ended when wilting was visually observed at which time clippings were removed from a 1m^2 area to determine growth. Clippings were dried at 60 ^{o}C and then weighed. Immediately after clippings were removed, the turfgrass was irrigated to replace daily potential ET and turfgrass was allowed to recover. Water use efficiency was determined by dividing the clipping yields by the total amount of water applied for each treatment.

Data from the three trials were pooled after the variances were determined similar by Levene's test for homogeneity, and thus results are discussed as pooled trial averages. Pooled treatment means were statistically tested using an ANOVA, with significant treatment differences identified by the Duncan's Multiple Range Test (SAS Institute, 1990). Rainfall, ET and air temperature were obtained from the Florida Automated Weather Network via a weather station located approximately 100 meters from the experimental site.

RESULTS AND DISCUSSION

Optimum drought conditions persisted during the experimental period, characterized by low rainfall (one rain event = 23 mm) with high ET demand (May ET=188mm) and high temperatures (average May daily temperature=26^{o}C). Visual ratings and sensor assessment of quality document that SURF bermudagrass had similar quality as IRRD bermudagrass, with both treatments having greater quality than the NINS bermudagrass (Table 1). A similar trend was evident when comparing the percentage of LDS, with over three times as much LDS observed on NINS bermudagrass than the other treatments (Table 1).

The average irrigation applied to all turfgrass at trial initiation was 4.3mm. Although the IRRD bermudagrass was irrigated for the remainder of each trial, the fact that SURF bermudagrass and IRRD bermudagrass showed similar quality and physiological condition as measured by the reflectance ratio suggests that they had similar soil water available to them. Yet the SURF bermudagrass received a mean of 63 % less irrigation than the irrigated turfgrass. This is also indicated by the SURF bermudagrass having a greater WUE than the IRRD and NINS bermudagrass (Table 1).

Mean near-IR/Red reflectance ratios revealed diurnal patterns with higher AM ratios compared to PM ratios. Perhaps this is because these wavebands monitor for morphology differences due rehydration of the turfgrass from the surrounding available soil water overnight, and mid-day water stress due to high evaporative demands.

When slopes are determined from daily PM reflectance ratios, SURF bermudagrass and IRRD bermudagrass resulted in average slopes of 0.05 (R^2 = 0.99) and 0.06 (R^2 = 0.95), respectively compared to a slope much closer to a slope much closer to 0 for the NINS bermudagrass (0.005 and R^2 = 0.45). The PM positive slopes found in the SURF and IRRD bermudagrass document growth, suggesting that soil water was not a limiting factor. The NINS slope much closer to zero maybe due to the combination of reduced growth rate and intensified mid-day water stress as by not having sufficient plant available water.

CONCLUSIONS

This experiment demonstrated that WUE for minimally irrigated turf can be increased by integrating a surfactant within the irrigation schedule, to the point of better WUE than if the turf had been irrigated daily to replace ETp. While visual quality treatment differences were observed, this was only during the PM. Visual quality as a means to asses water stress is difficult during morning hours because of overnight plant rehydration from the surrounding soil, presence of dew, and the angle of the sun. Monitoring AM NIR/Red reflectance ratios compensated for the inability to visually monitor quality in the morning. Both utilizing a surfactant with irrigation and monitoring NIR/Red reflectance ratios can be used as best management practices for water conservation.

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Table 1. Significance (and LSD) of treatment effect on pooled trial mean visual quality ratings, %LDS, NIR/Red reflectance ratios, and WUE (g cm^{-2}).

	Quality	%LDS	AM NIR/Red reflectance ratios	PM NIR/Red reflectance ratios	WUE
NINS	6.3b∫	35a	0.915b	0.838b	12.5b
SURF	7.4a	11b	1.035a	0.978a	20.0a
IRRD	7.6a	8b	1.037a	0.983a	8.4b
Significance†	***	***	***	***	***
LSD‡	0.4	7.3	0.049	0.050	4.7

∫Means with the same letter within a column are not significantly different according to Duncan's Multiple Range Test at P=0.05.
†*** = P<0.001 respectively.
‡LSD: Least significant difference

Recycled Water for Landscapes

in the Middle East

by
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Abstract. Recycled water (treated sewage effluent) is in common use throughout the Middle East. This paper focuses on observations made in 2006 as the authors became involved in a rapid assessment of the City of Jeddah's current and future use of recycled water for landscapes. The City irrigates streetscapes, parks, and large open spaces with recycled water.

Observations were made during a site visit conducted at the request of the municipality and insights were obtained as to historic practices, maintenance concerns, operational issues, automation, and equipment selection. The use of recycled water is likely to continue in this water short region and future systems can be improved even considering the local constraints that are prevalent.

Pumps, filtration, automation, and other equipment will be described as well as design, hydraulics, and maintenance practices. Design, construction, and maintenance all play an important role in the future system expansion and upgrades if they are to be successful.

Introduction

The City of Jeddah, with a population of approximately 2.5 million people, is located in the western part of Saudi Arabia on the Red Sea. Generally speaking, the climate is quite hot and humid in the summer months and mild and humid in the winter.

The City of Jeddah enjoys an extensive network of roadways and streets. Roadways tend to be boulevards with landscaped medians and often landscape and plantings can be found on the sides as well.

Landscape plant materials tend to thrive when properly irrigated. Many planted areas have been established 10 or more years ago and mature palms or deciduous trees are well established

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along roadways. In addition to street plantings, there are numerous gardens. Gardens are actively used by the public and typically consist of turf areas, trees and shrubs, playground equipment and benches or picnic tables.

The City of Jeddah in Saudi Arabia is not unique in the Middle East with the prevalent use of recycled water for landscape irrigation. The overall operational concept is not difficult to understand. Water from the Red Sea is desalinated, treated, and hauled by tanker truck to individual potable water tanks for each residence and business. Most often these potable water tanks are found on the roof of buildings and are quite notable as one looks around the community. No potable water is used to irrigate plants in the landscape. Potable water is used for culinary and sanitary needs.

Sewage is collected in subterranean tanks and then periodically pumped back into tanker trucks for trucking to sewage treatment plants outside of Jeddah proper. Treated sewage effluent or recycled water is then trucked back into the community and delivered to subterranean concrete tanks. Water is the pumped and filtered and used for landscape irrigation – parks, streetscapes, and large open spaces. Sprinkler and drip irrigation are fairly common but bubbler irrigation is most prevalent.

The result of many years of irrigation in this way has resulted in a wide disparity in implementation, equipment, maintenance practices, operational practices, repairs, and overall quality of the operating irrigation system. In December 2006, the authors were privileged to be asked to conduct a rapid assessment of the irrigation systems within the City of Jeddah, and this paper reports on many observations made during the project.

Recycled Water Storage, Pumping, and Filtration

After treatment at the sewage treatment plant, recycled water is hauled to subterranean storage tanks having a capacity of 100 cubic meters. There are more than 400 individual storage tanks spread throughout the City of Jeddah.

Centrifugal pumps with a foot valve on the intake are used to pressurize the system. Element filters are located downstream of the pump. In a few cases, a water meter is found downstream of the pump station.

See Figures 3, 4, 5, 11, and 15.

When filter elements become clogged, the landscape maintenance workers may remove the element and leave it out of the filter housing so that a greater flow and pressure can be attained. Irrigation equipment then is likely to become clogged and emission devices are then often removed by maintenance workers as a response. In many cases the irrigation lateral has become, in effect, a means of flood irrigating medians or other landscaped areas that are bordered by a curb which contains the water inside the landscaped areas.

The issue of one problem leading to another and hence another has a cascading effect. A root cause of these problems is water quality. If recycled water was of greater quality and a predictable quality, then some core maintenance issues could be resolved. Worker response can most likely be resolved by implementing training programs.

Irrigation Equipment

Examples of sprinkler, drip, and bubbler irrigation can all be found depending on the age of the irrigation system and who designed the system. Bubbler irrigation is most prevalent and this would likely be related to the greater orifice sizes found in bubbler irrigation and therefore the greater reliability of bubbler irrigation systems. Most bubblers were not pressure compensating.

Figure 16 shows an example of maintenance worker response in the field. The bubblers have been removed and placed to the side so that a greater flow of water can be attained. These bubblers will likely be replaced after the median is sufficiently irrigated in the workers' view. This system is being controlled manually at the remote control valve. This is another example of cascading problems that can be corrected.

Control

Independent irrigation controllers are in use although some are set in the "off" position and the system is operated manually by the landscape maintenance workers assigned to that site.

Other sites are centrally controlled and the storage tank water surface elevation is monitored. See Figure 13. A weather station is integrated with the central control.

Operation and Maintenance

Imagine 400 sites supplied by water by tanker trucks. Imagine 400 parks and streetscapes spread throughout any large city and the demands of mowing, pruning, planting, trash removal, irrigation operations, and irrigation repairs. Imagine 400 individual and independent irrigation systems. The magnitude of the effort is enormous and demanding and never ending.

Workers are supplied by landscape contractors. Maintenance practices and results vary widely throughout the City.

The Future

The City of Jeddah is in the process of studying the benefits and costs of implementing piped deliveries of recycled water to the 400 landscaped sites in the community. This approach is recommended in the future to improve delivery consistency, improve monitoring of water quality, and decrease delivery costs.

Acknowledgements

The author would like to acknowledge the staff of Khatib and Alami in Jeddah who were wonderful and hospitable. In particular, we would like to acknowledge the hospitality and assistance of Dr. Bahget of the Plantation and Landscaping Department, Municipality of Jeddah.

Figure 1. Tanker trucks are filled at the sewage treatment plant and recycled water is hauled to subterranean tanks throughout the community. Water is used for landscape irrigation.

Figure 2. Some landscapes are surface or flood irrigated directly from tanker trucks as shown here.

Figure 3. Some pump enclosures were also used for storage of other landscape maintenance equipment as well as personal items of workers.

Figure 4. Pumps and filters are housed in expanded metal enclosures with a metal roof. The concrete tank holding 100 cubic meters of recycled water can be seen in the foreground. This site is centrally controlled and the antenna for the control system is set in the concrete block seen in the foreground.

Figure 5. Filter elements are often removed by workers to increase flow and pressure downstream of the pump station. This, of course, aggravates plugging of emitters and orifices in other water emission equipment.

Figure 6. Pressures were measured to document dynamic pressures in the irrigation system. Low pressures were sometimes due to multiple laterals opened manually and simultaneously, thereby causing the pump to run out on the pump curve and produce inadequate pressures.

Figure 7. Bubbler irrigation is prevalent. Some bubblers are imported from the U.S. but bubblers are also manufactured in the Middle East.

Figure 8. This operating sprinkler is clearly operating well below minimum acceptable pressures.

Figure 9. Roundabout landscapes are often quite colorful and a significant contribution to the beauty of the City of Jeddah.

Figure 10. Palm trees in roadway medians dominate the landscape but often with an understory of groundcover or flowers.

Figure11. The pump, filter, and control system housed in this enclosure are exemplary of the newest construction.

Figure 12. Workers shown here are installing bubblers that will be used to irrigation trees as well as understory groundcover.

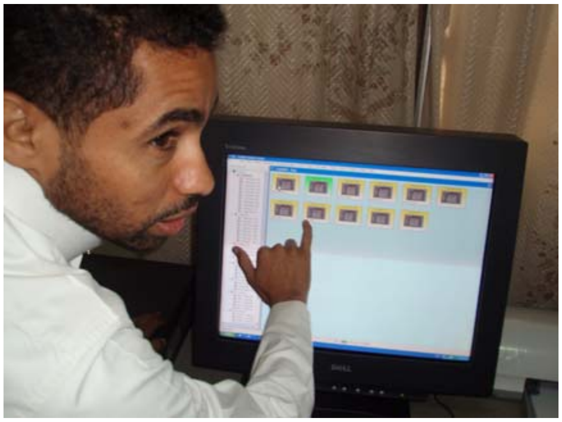

Figure 13. A portion of the landscape irrigation systems in the City of Jeddah are controlled using a central control system tied directly with a local weather station to monitor day-to-day evapotranspiration rates.

Figure 14. This irrigation controller is an independent controller not compatible with the central control system. Only a small portion of the 400 landscape irrigation sites are on the central system.

Figure 15. In the photo on the left above, the filters were disassembled to show that no filter elements were installed at the time of this site visit. In the photo on the right, the clogged filter element can be seen. This filter element was sitting off to the side -- uncleaned and unused.

Figure 16. The “fountains” in the median are the result of the maintenance crew removing the bubblers from the risers during sprinkler operation. The bubblers are the black caps to the left of the fountains. It is assumed that the caps are then replaced at the end of the irrigation cycle, although several areas were observed with missing bubblers. This adapted approach to bubbler irrigation is the result of “cascading” operation and maintenance issues.

Monday, December 10, 2007
IA07-1055

Reclaimed Irrigation Practices to Move Salts Out of the Root Zone for Turf

Jenny Fifita, City of Westminster (Colorado), 4800 W 92nd Ave, Westminster, CO 80031
The application of reclaimed water to urban landscapes can cause salt build up in the turf root zone. Preliminary results will be provided on a study designed to develop a method for applying reclaimed water that will include 'flushing cycles.' Flushing cycles are periods where water is applied in excess (of plant needs) to push the wetting front deeper in the soil profile and facilitate the redistribution of salts below the turf root zone. The primary equipment used in the study is an irrigation controller that gathers data from a soil moisture and conductivity sensors located at different levels in the soil profile in order to monitor the movement of salts and water. This information is used to schedule irrigation and flushing cycles. During the study, turf quality will be evaluated and correlated with conductivity in the root zone.

This presentation will be of interest to anyone using reclaimed water or other water sources with higher salinity levels for irrigation.

See more of Turf/Landscape: Climate-based Irrigation Scheduling
See more of The 28th Annual International Irrigation Show (December 9-11, 2007)

Managing Soil Moisture on Golf Greens Using a Portable Wave Reflectometer.

Douglas L. Kieffer[1], T. Sean O'Connor[2]

Paper presented at the 28th Annual Irrigation Show
San Diego, CA
December 9-11, 2007

Abstract

The agronomic needs of grass and the demands of the contemporary golfer pose many challenges to managing irrigation on golf greens. The turf must be kept as dry and firm as possible without allowing it to die. Greens have a high degree of spatial variability, including hot spots that can rapidly become critically low in available water. Currently, core samples are taken across the green and moisture content assessed by feel. This is time consuming, destructive, and subjective. A portable, electronic wave reflectometer uses time domain technology to give fast, accurate, and objective measurements of local soil moisture content. In general, it takes about 2 weeks to identify the desirable soil moisture ranges for the course. A determination can then be made on what greens require hand-watering or whether a complete irrigation cycle is needed. If the green is grid sampled, distribution uniformities similar to those computed with catch cans can easily be computed. Soil-moisture based uniformity coefficients suggest that reductions in irrigation amounts could be merited.

Introduction

The agronomic needs of grass and the demands of the contemporary golfer pose many challenges to managing irrigation on golf greens. The majority of golf courses are currently designed with sand-based greens. Low mowing heights and the desire for firm, fast surfaces mean that the turf must be managed very carefully and intensively. The turf must be kept as dry and firm as possible without allowing it to die. Sand has a low water-holding capacity so the greens are always at risk of drought stress, especially during the hot and dry weather of mid-summer. The inability of the sand to hold water also makes it difficult to maintain proper fertility because nutrients are easily leached. Greens have a high degree of spatial variability, including localized dry spots that can rapidly become critically low in available water. Conversely, if the turf receives too much water, either from rain or excessive irrigation, there is the risk of anaerobic soil conditions and the warm, moist environment is conducive to the spread of fungal diseases. Further, too much water leads to a poor putting surface with foot printing and excessive ball marks. The cost of water and energy means that the conservation of water is not just a matter of environmental stewardship, but is also important to a superintendent's bottom line. Additionally, local municipalities are passing legislation that restricts the amount of water available for commercial and residential irrigation.

Regular monitoring and maintenance of irrigation hardware is needed to reduce water wasted from damaged or mis-aligned sprinkler components. Common remediation

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techniques for improving the infiltration of water into the turf's root zone include aeration, de-thatching, top-dressing with sand and the application of surfactants. Localized dry spots are often hand-watered on an as-needed basis. Fungicides and algaecides are used to combat the effects of disease pressure.

The two most common methods of assessing the amount of moisture in the soil and/or making irrigation decisions are by visual observation of the turf or pulling a soil sample with a probe and determining moisture content by feel. Visual ratings are subjective and can be influenced by light levels and the consistency of the person doing the rating. Errors are also introduced when different people do assessments on different days. However, by the time symptoms of moisture stress are visible to the naked eye, irreversible damage may already have occurred. Moisture-by-feel assessments are also subjective and result in slight damage to the green where the core is taken.

Sprinkler Uniformity

One way for evaluating the performance of an irrigation system is with an irrigation audit. The Irrigation Association has published guidelines for performing irrigation audits (IA, 2007). Catch cans are placed in a grid pattern prior to running the irrigation system for that zone. The amount of water collected in each can is measured and recorded. Two recognized irrigation uniformity coefficients are Christiansen's coefficient of uniformity (CU) and the lower quartile distribution uniformity, DU_{lq}.

Christiansen (1941) developed a coefficient of uniformity that accounts for irrigation amounts above and below the overall average. It is calculated as:

$$CU = 1 - \frac{\sum_{i=1}^{n} | V_i - \overline{V}_{total} |}{\sum_{i=1}^{n} | V_i |}$$

Where:

V_i = The volume captured in a given catch can.

$\overline{V}_{total}$ = Average of all catch can volumes or soil moisture of all readings.

This coefficient treats over-watering and under-watering the same. This coefficient was developed for agriculture and has not gained acceptance in turf where visual quality must be maintained across the entire site (IA, 2003).

DU_{lq}, is calculated as the ratio of the average from the 25% of cans that collected smallest amount of water to the average across all cans.

$$DU_{lq} = \frac{\overline{V}_{lq}}{\overline{V}_{total}}$$

Where:

$\overline{V}_{lq}$ = Average of the lowest 25% of catch can volumes (or soil moisture readings).

$\overline{V}_{total}$ = Average of all catch can volumes (or soil moisture of all readings).

The Center for Irrigation Technology (C.I.T.) has developed a visual tool to depict how sprinklers will distribute water across an irrigated area. The densogram produces a chart that uses a dot matrix to display water distribution on color scale from dark to light with dark being the heaviest concentration and light being no water at all (Zoldoske et al., 1994). This gives visual indications of the size and location of wet and dry areas. This can be done with theoretical sprinkler distribution patterns or catch can data.

Solomon and Kissinger (2005) created a water conservation diagram for turf and landscape irrigation. It is a graphical depiction of how water is applied to an irrigated area. It combines the effect of distribution uniformity and irrigation scheduling decisions into an educational tool that explains the benefits of irrigation improvements.

Irrigation Scheduling

There are 3 common methods for adjusting the run-time based on irrigation audit data.

1. The least conservative adjustment is to correct the run-time so the driest area gets the minimum amount of required water. The scheduling coefficient (SC) is computed as the ratio of the overall catch can average to the average in the driest contiguous percent. The most commonly used portion of total area is one to five percent (Zoldoske, 2003; Connelan, 2004) or even as high as 10 percent (IA, 2003; Zoldoske et al., 1994). The scheduling coefficient is usually calculated with computer software such as the Sprinkler Profile and Coverage Evaluation (S.P.A.C.E.) program from the C.I.T. A rough version can also be calculated by dividing the overall average by the volume of the single driest catch can (Kopec, 1994).

$$SC = \frac{\overline{V}_{total}}{V_{driest}}$$

2. The DU_{lq} can be used to compute a run-time multiplier (RTM) which can then be used to compute an irrigation water requirement:

$$RTM_{lq} = \frac{1}{DU_{lq}}$$

3. An adjustment based on the lower-half distribution uniformity (DU_{lh}) has been found to be a better basis for irrigation scheduling (Dukes et al., 2006). DU_{lh} is similar to DU_{lq} except the numerator is the average of the 50% of cans that collected the smallest amount of water. The run-time multiplier (RTM) is calculated as.

$$RTM_{lh} = \frac{1}{DU_{lh}}$$

In all cases, it is assumed there is a minimum plant water requirement that must be applied to the driest area of the green. In the simplest application, the irrigation water requirement (IWR) is then calculated by multiplying plant water requirement by the run-time adjustment factor. In more sophisticated applications, factors such as weather, soil type, and the maximum desired soil moisture depletion amount are also considered. In any case, this results in some areas receiving more water than necessary. So, there is an advantage to selecting the lowest factor that still maintains acceptable turf quality.

The catch can audit works well for finding flaws in the water delivery system (Mecham, 2001). This includes leaks, damaged heads and misaligned sprinklers. Some drawbacks of the traditional irrigation audit are 1) It is time consuming to set up the cans, run the irrigation system and measure the collected volumes, 2) It is not easy to repeat if modifications are made to the system, 3) It is usually performed for a fee by an outside agent, and 4) It only yields information on how well the water has reached the surface but gives no information on how the water is distributed in the soil. This last point is especially important when irrigation recommendations use the distribution uniformity to set the run time so a minimum amount of water is delivered to the entire irrigation zone. This is because redistribution of water through the turf canopy and within the root zone smoothes out some of the non-uniformity in applied water. Deeper in the soil profile, soil moisture variability is less sensitive to the impact of sprinkler uniformity (Dukes et al., 2006).

Portable Wave Reflectometer

A portable wave reflectometer (PWR) uses time domain technology to give fast, accurate, and objective measurements of local soil moisture content. This gives superintendents the ability to quickly take readings on their greens. Typically, it takes about 2 weeks to ascertain what the threshold water content ranges are for each green. A determination can then be made on what greens require hand-watering or whether a complete irrigation cycle is needed. Soil moisture data collected with such a meter can also be used in place of catch-can volumes to calculate distribution uniformities based on soil moisture content rather than water applied to the surface.

This paper outlines the typical process for integrating a portable wave reflectometer into a turf irrigation program. A comparison of a traditional catch-can and soil moisture based audit is also presented.

Materials and Methods

On the morning of September 6, 2007, an irrigation audit was performed on the putting green for hole 18 at Forest Akers Golf Course in E. Lansing, MI. Wind speed was not measured but was noted to be very low. Hole 18 is a pushup green with approximately 80% Annual Bluegrass. The remaining 20% is Penncross Bentgrass. The shape of the green is a slightly oblong circle with an east-west dimension of 24.7 m and north-south dimension of 25.3 m. This green has relatively poor drainage. The green is irrigated by 4 sprinklers on 18.3 m centers located in the NW, SW, NE, and SE corners of the green (fig. 1). The sprinklers had a throw distance of 18.3 m and rotated in a full circle to water both the greens and the surrounds. A total of 37 plastic cereal bowls were laid out in a grid pattern with a spacing of 0.4 m (fig. 1). The bowls had a diameter of 15.5 cm and a height of 6.7 cm. Before operating the sprinklers, volumetric water content measurements were made with a Field Scout TDR 300 portable wave reflectometer (Spectrum Technologies, Plainfield, IL). Readings were taken to a depth of 12 cm for an estimated sampling volume of 300 cm^3. The probe was inserted directly adjacent to each bowl. The soil moisture readings were geo-referenced with a Garmin 72 (Garmin International, Olathe, KS) hand-held GPS receiver connected to the TDR 300. The sprinkler was then set to run for 20 minutes (fig. 2). The volume of water captured by each bowl was measured and recorded. Approximately 20 minutes after the sprinklers were shut off, the green was again sampled with the reflectometer.

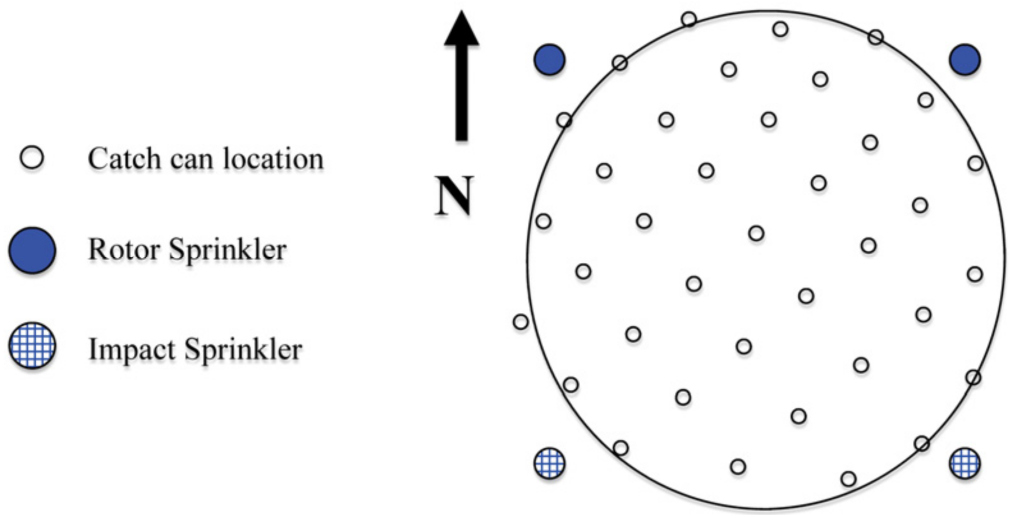

Figure 1. Layout of sprinklers and catch cans on Hole 18.

Figure 2. Sprinklers in operation during audit

Lower quartile and lower half distribution uniformities (DU_{lq}) were calculated for each of three data sets. 2 dimensional color plots of soil moisture and catch can data were created using the SpecMaps mapping utility (Spectrum Technologies, Plainfield, IL).

Discussion

Getting Familiar with the Reflectometer

Although a portable wave reflectometer (PWR) can be a powerful instrument for evaluating soil moisture variability on a golf course green, it must be emphasized that it is only a tool. A PWR is not intended to make a *water/don't water* determination. The superintendent must use the measurements from the PWR, along with information about environmental conditions, the weather forecast, and visual assessments to make decisions about whether and how much water to apply. Accompanying the general guidelines is a review of how a PWR was incorporated into the water management program of Forest Akers Golf Club in E. Lansing, MI.

Initial evaluation

The first, and most important step, is to determine the soil moisture threshold values for each management area. The superintendent should pick out a handful of representative greens and sample them extensively with the PWR. Readings should be taken at known wet and dry areas. When these readings are taken, some other subjective assessment should be done simultaneously. This could by visual assessment of the turf and/or by pulling soil cores. This initial step gives the superintendent a sense of what range of soil moisture values can be expected on the course as well as "ground truths" these numerical soil moisture values with the current evaluation method. Stowell (2006) suggests a moisture content of 15-25% as a threshold value for optimum greens firmness. For any given green, this number will be close to the optimal value. It is best not to do the initial sampling if the ground is very wet from rain or a recent irrigation. If possible, the initial evaluation should be done in the spring because the turf is under less stress.

At Forest Akers, all greens were sampled both at known localized dry spots and at areas that have historically been the last to suffer wilt. Numerical readings from the PWR were compared to visual ratings. Sampling was repeated every day over a two week period. This 2-week period included a light rain and several days of dry weather. After examining the data, it was determined that a value of 18% would be appropriate for the spring. It was concluded that there were 7 greens that could be used to predict the worst-case wilt conditions for the rest of the greens on the course. In other words, if these greens were found to have sufficient soil moisture reserves, the remaining greens would be in a similar state. Only when the representative greens gave low readings would other greens need to be inspected for possible irrigation.

Modifying the criterion

Although the initial evaluation is essential so the PWR can be used to guide irrigation decisions, the interpretation of the readings will necessarily evolve as the season progresses into summer. In the summer, the stress of hot, dry days applies increasing evapotranspirative demand on the grass. Elevated soil temperatures shrink the average root depth down to 2.5cm. USGA greens are especially vulnerable to wilt in these extreme conditions. Therefore, the minimum water content necessary to sustain a playable surface increases until the peak demand period of July and August. During this time, the soil moisture level necessary to maintain healthy turf should be re-evaluated. At Forest Akers, the minimum acceptable soil moisture threshold was raised from 18 to 21% during the summer to account for the increased stress. Summer also brings greater variability in the soil moisture across the greens. Another factor to consider is that the summer is also a time when golf courses will schedule tournaments that can last up to 3 or 4 days. Opportunities to irrigate are more limited and must be timed more precisely than during other times in the season. Under these conditions, the combined information garnered from weather data, visual assessments as well as the PWR provide the superintendent with the information necessary to make informed irrigation decisions.

At Forest Akers, during the summer, water needed to be applied to most of the course just as often as in past years. However, the PWR allowed for the fine-tuning of the amount of water added. Although it was obvious that the localized dry spots would need daily hand watering, the PWR revealed that irrigation could be delayed on some of the areas less prone to stress. Another novel use of the PWR was the use of the 12 cm rods on the pushup greens. In general, the rooting depth of turf on a putting green extends not much more than 7.5 cm. And in the summer this number can be reduced significantly. But, a unique characteristic of older pushup greens is that, because of repeated topdressing, a significant layer of sand builds up above the mineral soil. Therefore, although the root zone may be very dry in the sandy soil near the surface, sufficient moisture can still be stored in the in the mineral soil below. This moisture will be detected if the 12 cm rods are used. The superintendent discovered that the PWR readings, combined with visual inspection of the green, helped determine whether a full irrigation cycle was required, or only a shorter run-time sufficient to replenish the near-surface portion.

At Forest Akers, it was estimated that about two-thirds of the time, the PWR came to the same conclusion as a visual inspection. But, for the other times, the PWR provided information about the soil moisture status that could not easily obtained in other ways.

<u>Audit Results</u>
The raw data from the audit is shown in table 2. 2-dimensional contour plots of soil moisture and catch-can data sets from green 18 are shown in figure 3.

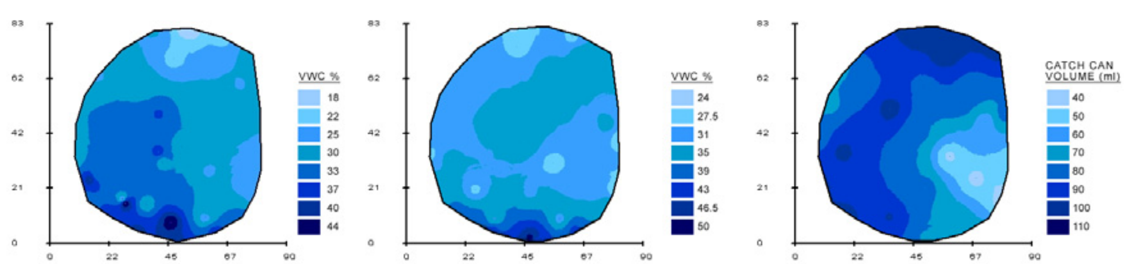

Figure 3. Contour plots of pre-irrigation soil moisture, post-irrigation soil moisture, and catch-can data.

In both soil moisture charts, a wet area is evident in the southwest portion of the green. The driest areas are seen near the northern and southeast edges. The overall average soil moisture increased from 29.0% before irrigation to 32.5% after irrigation. One effect of the irrigation is that the variability of soil moisture is slightly decreased. This is seen both in the plots and in a slight increase in distribution uniformity (table 1). The plot of the catch can data shows that the least amount of water is applied to the southeast and northwest corners while the greatest amount of water is going to the northeast section. It appears that the irrigation pattern is heaviest in a diagonal band that stretches from the northeast to the southwest corners. The volume of water applied then decreases gradually in curved bands that are centered at the sprinkler heads in the southeast and northwest corners. One feature of these figures that stands out immediately is the discrepancy in the northeast corner. This area receives more irrigation water than any other but it is also one of the driest areas - even 20 minutes after the irrigation. This part of the green has historically been susceptible to wilt and this was confirmed by visual inspection before the audit (fig. 4).

Figure 4. Portion of green 18 that received the largest amount of water during the catch-can audit. This area however does not have the highest soil moisture values and is susceptible to wilt.

Lower quartile and lower half distribution uniformity (DU_{lq} and DU_{lh}) and run-time multipliers are shown in table 1. Consistent with earlier findings (Dukes et al. 2006, Mecham, 2001), soil moisture based uniformity is significantly higher than that calculated from the catch can data. Distribution uniformity before and after the irrigation event is very similar. The run-time multiplier based on a lower quartile computation is 33% lower for a soil-moisture based uniformity coefficient. Even for the more conservative calculation based on a lower half computation, the multiplier is on the order of 9% lower. The comparison of uniformity coefficients before and after irrigation agrees with Li et al. (2005) who found that a soil moisture-based coefficient of uniformity before irrigation was found to approximate uniformity after irrigation.

Table 1: Coefficients of uniformity and run-time adjustment factors for 3 audit types.

Audit Type	DU_{lq}	DU_{lh}	RTM_{lq}	RTM_{lh}
CC	64.0	80.2	1.6	1.2
TDR1	81.5	86.7	1.2	1.1
TDR2	83.1	88.5	1.2	1.1

DU, distribution uniformity; RTM, run-time mulitplier LQ, lower quartile; LH, lower half; CC, results from catch-can audit; TDR1, results from first soil moisture audit; TDR2, results from second soil moisture audit.

Conclusions

The ability to capture site-specific soil moisture information is a valuable asset for managing irrigation on golf course greens. While it is not a black box that can definitively say whether or not to apply water, a portable wave reflectometer gives the superintendent immediate assessments of the range and geographic scope of water deficiencies within the green. A superintendent should expect to spend approximately 2 weeks ground truthing the readings from the reflectometer to the conditions on the course. It is advisable to periodically adjust the soil moisture threshold values to account for the increasing demands of the summer. The portable nature of such a meter also allows for the geo-referencing of the data. This data can then be used to create 2-dimensional plots which highlight the spatial variability of soil moisture across the green. Finally, because several data points can be taken essentially simultaneously, soil moisture data can be used to calculate uniformity coefficients that have traditionally been computed using catch-can data. Soil moisture based uniformity, in general, will be higher than that calculated based on water applied to the surface. This leads to shorter predicted irrigated run times without sacrificing turf quality.

Table 2: Volumetric water content and catch can volume data from green 18.

Location	Catch Can volume (ml)	TDR1 (%VWC)	TDR2 (%VWC)	Location	Catch Can volume (ml)	TDR1 (%VWC)	TDR2 (%VWC)
1	92	31.9	41.3	**20**	94	29.7	34.8
2	92	39.1	44.9	**21**	74	31.5	30.1
3	80	44.2	50.3	**22**	61	26.8	30.8
4	68	43.8	48.1	**23**	85	29	31.5
5	89	25.4	31.1	**24**	83	27.9	31.1
3	81	22.1	26.4	**25**	74	33.3	32.6
7	91	29.7	32.6	**26**	75	26.4	31.9
8	74	25.7	28.6	**27**	54	24.6	29
9	54	29.3	30.1	**28**	44	23.9	27.5
10	66	31.5	30.4	**29**	44	25.4	25.4
11	88	32.2	31.1	**30**	72	25.7	29.7
12	72	27.5	31.1	**31**	73	26.4	33.7
13	73	29.3	30.8	**32**	75	26.4	31.5
14	65	22.8	30.4	**33**	94	27.5	34
15	77	38	40.2	**34**	98	19.9	25.7
16	30	27.2	33.3	**35**	101	23.9	26.4
17	37	27.5	27.9	**36**	97	24.6	32.6
18	38	29	25.7	**37**	108	27.9	33.3
19	71	34.8	34.8				

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