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Irrigation practices during long-term drought in the Southeast

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Abstract

Georgia, like much of the Southeast, experienced prolonged drought between summer 1998, and fall, 2002. During this time, UGA scientists and researchers had a program in place to monitor monthly irrigation practices on 800 randomly selected permitted irrigation systems. The coincidence of the monitoring program, called Ag Water Pumping, and the drought gave us the opportunity to see what strategies and how much water farmers would use to survive the drought. On average farmers in Southwest Georgia used 9.5 in./y while those in the Coastal Zone used 7.7 in./y. Those who had to rely upon streams or ponds used 2 to 4 in./y less than those who had well water supplies. Many farmers reported that their surface supplies dried up during the drought. Individual use varied broadly with up to 25 in. or more applied to some crops, but the distribution was skewed toward those who used lesser amounts. When compared with deficits between ET and rainfall, mean monthly applications closely mirrored that deficit.

Introduction

Agricultural irrigation systems used on Georgia farms, orchards, nurseries, and certain golf courses are supplied with water from ground and surface water resources that fall under permitting requirements of the Georgia Environmental Protection Division (EPD). Most of the wells, surface water pumping stations and ponds used in these systems were built and purchased by individual land owners. Each individual water source usually supplies only one or two of the estimated 16,500 irrigation systems in the State. In the 1988 statutes that required permits for agricultural withdrawals, these privately owned pumping and delivery systems were specifically exempted from water metering, record keeping, and reporting to EPD. Consequently, Georgia water planners have lacked systematic enumeration of water quantities used in agricultural production. In 1998, EPD requested that the Georgia Cooperative Extension Service (CES) establish a statewide system for measurement of water use by farmers and conduct a multi-year study of those water withdrawals.

During the course of the measurement program, Georgia experienced a prolonged hydrologic drought that had begun by mid-1998 and that continued through fall 2002. Considered one of the worst droughts in Georgia's history, farmers and other water users across the state had to adjust their water use in response to increased water demand and limited water supplies.

Georgia had few tools to regulate water use by farmers. Permits placed no restriction on seasonal or annual amounts used as long as pumping rates and irrigated areas did not increase. A newly created drought management program in the Flint River basin[2] was used to idle 30,000 to 40,000 acres (2 to 3%) of potentially irrigated land during 2001 and 2002. Permitting for new agricultural water withdrawals was also suspended in the Flint River basin and along the coast. Other areas of the state were allowed to obtain new withdrawal permits throughout the drought period.

With independent water supplies for most irrigation systems, farmers had to make independent decisions on how to manage their irrigation during the drought. Squeezed between low prices for many of their crop commodities and rising prices for fuel needed for pumps, farmers had to manage water and other inputs

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[2] Flint River Drought Protection Act of 2000. Official Code of Ga. 12-5-540. Defined in Chapter 391-3-28 of the Ga. Dept. of Natural Resources EPD.

carefully to achieve profitability and repay production loans. This paper summarizes the observations of irrigation on farms in Georgia during three consecutive drought years.

Methodology

Engineers, researchers and statisticians at the University of Georgia (UGA) designed a statewide irrigation monitoring program that met the dual needs of rapid startup and modest budget. The basic design included repeated monthly visits to selected irrigation sites by UGA personnel. Water use was calculated from equipment use time and calibrated flow rates for most irrigation systems. Electric timers were installed on irrigation application equipment when possible or on pumps or generators that supplied unique irrigation systems and had uniform flow rates. When flow rates varied over time, flow meters were used. At each monthly visit, crops that were in the irrigated fields were noted, and the proportion of water that was used on each was estimated.

A stratified, random sampling was used to identify potential participants for a voluntary monitoring program. A statewide 2% random sample was taken of the Agricultural Water Withdrawal Permits issued by EPD between 1988 and 1998. The sample was stratified to assure proportionality of sampling by county and water source. A secondary stratification was made in an attempt to represent types of irrigation systems and choices of crops as identified by separate CES surveys. The randomly selected permit holders were asked to participate in the monitoring program that became known as Ag Water Pumping (AWP). A large majority of farmers agreed. When a farmer could not or would not participate, a potential replacement was randomly selected from among others who used the selected water source type in that county.

Once a withdrawal site was selected, all wells, surface water sources, pumps and irrigation systems connected to that site were characterized. Multiple water sources and multiple irrigation systems were common. Flow points in the system that supplied fixed “wetted” field areas with water were selected as metering sites. Flow rates were measured with the pumps and application system operating under normal conditions and under control of the farmer. Portable “strap-on” digital flow meters provided flow rates. These did not require modification of the irrigation system for the measurement and follow-up flow checks could easily be made. A systematic follow-up of flow rates was made during the 2001 to evaluate changes in farmers systems over time.

The state was divided into four reporting areas based on special water planning needs (Fig. 1). The 24-county Coastal Zone had been previously identified by EPD as a special area based on salt water intrusion concerns for the Upper Floridan aquifer. Similarly, a 26-county area in Southwest Georgia had been described because of agriculture’s unique role in water use in the tri-state water planning talks. Setup and monitoring of AWP sites was initiated during 1999 for both of these reporting regions. On average, 93 irrigation systems were monitored in the Coastal zone; 221 in Southwest Georgia. The 34 remaining Coastal Plain counties were grouped into a third reporting area. Likewise all 75 counties that lay north of the fall line were grouped into a fourth. Setup and monitoring of AWP sites was initiated in 2000 for these last two regions. On average, 249 irrigation systems were monitored in the central Coastal Plain, while 15 were monitored in north Georgia. A total of approximately 43,000 acres of irrigated land was included in these sampled systems statewide. Monthly monitoring was continued through 2004. This report details water use for the period 2000 to 2003.

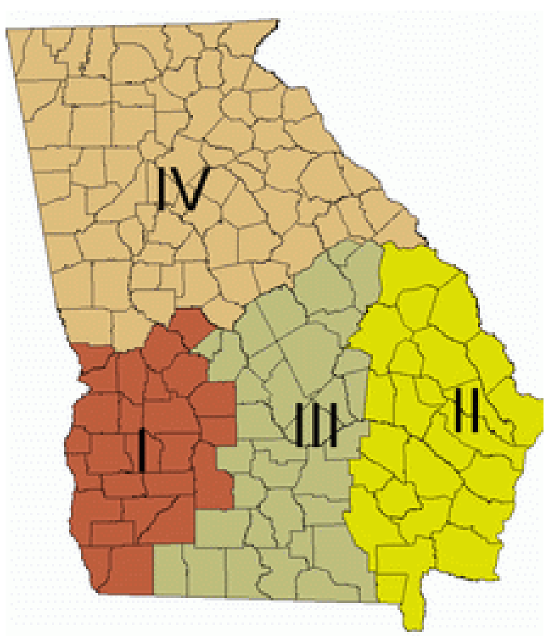

Fig. 1. Irrigation reporting regions in Georgia - I = Southwest or Flint Basin; II = Coastal Zone; III = Central Coastal Plain; IV = North GA.

Results

Statewide mean annual application depths were 9.4, 7.8, and 8.7 in. for the 2000, 2001, and 2002 drought years. Irrigation depths were weighted by field sizes to minimize the influence of small fields of specialty crops that received high irrigation depths. When applied on a statewide basis, area weighting made little difference among the 585 monitoring sites. Weighted mean annual application depths were 9.6, 7.5, and 8.4 in. for 2000 through 2002, respectively. However, when weighting was applied to smaller areas or when comparing irrigation among water sources or system types, it provides for a more reasonable value for use in water use planning. Withdrawal amounts could be computed directly from area weighted means, and this value will be used in the remaining comparisons in this summary.

In each year, farmers at some of the metered systems made the decision not to irrigate. These varied from 5 to 7% of metered systems during the drought years and increased to 17% during 2003. At times the decision to withhold irrigation was based upon limited water supplies; at others it reflected rotation of more valuable crops among a farmer's irrigation systems.

Farmers who used ground-water sources for irrigation used more water than those who relied upon surface water sources. Statewide mean application was 11.4 in. when irrigation was from ground-water sources, and 7.2 when it was from surface water sources in 2000. Similarly comparisons for 2001 and 2002 were 8.6 vs. 6.1 and 9.9 vs. 7.1 in., respectively. Explaining these differences presents a "chicken vs. egg" dilemma. Farmers who produce higher value, more water intensive crops might drill wells to obtain a reliable water source; farmers with wells might choose to grow higher value crops. During the 1998 through 2002 drought, farmers often found that their surface water supplies had dried up. While they might have planned to use more water, dry ponds and streams prevented that. Since this was a significant drought period, their surface water supply may have been adequate in most other years. In still other explanations from farmers in our study, surface water supplies were often connected to irrigation systems like travelers that are used less frequently because of increased labor requirements. Thus for a variety of reasons, surface water users applied less irrigation during our study.

Faced with inadequate runoff to refill ponds just when it was needed for irrigation, many farmers drilled wells adjacent to the ponds to supplement them during peak use periods. In some cases, the choice of a well-to-pond system was made because wells of sufficient pumping capacity to directly supply the irrigation system were too expensive or impossible given the local geology. Wells of smaller capacity could be drilled and run longer, while water would be pumped out at higher rates with separate pumps while the irrigation system was used. In other cases the choice of well to refill the pond was only to provide insurance in times of inadequate runoff and stream flow to maintain pond water levels. The higher costs associated with pumping from ground-water and again from the pond made this a less desired option than using surface water whenever it was available.

EPD issued permits by water source and recognized well-to-pond systems as a separate category in its permitting. It was included among our random selections in proportion to those permits and counties. On a statewide basis, mean annual application depths for well-to-pond systems were 8.7, 7.3, and 6.9 in. for 2000 to 2002, respectively. These values were in between amounts used with ground-water and surface supplies.

Farmers differed in their irrigation practices creating a wide distribution in annual application amounts, and those distributions differed by regions (Figs. 2 and 3). Differences among individual users could be attributed to many factors – rainfall differences among individual fields, type and value of crop, length and specific period of the crop's growing season, different yield expectations, reliability and capacity of water source, capacity and type of irrigation system, scheduling automation, and farmer's risk aversion.

Means for irrigation depths are useful in planning for water withdrawals, but it is important to recognize that means were computed from fields whose individual application depths varied from 0 to over 300 in./y. In drought years, these application depths were normally distributed over much of the range of observed irrigations. However, irrigation application depths that exceeded 20 in./y occurred with a greater frequency than would be expected for a normally distributed population.

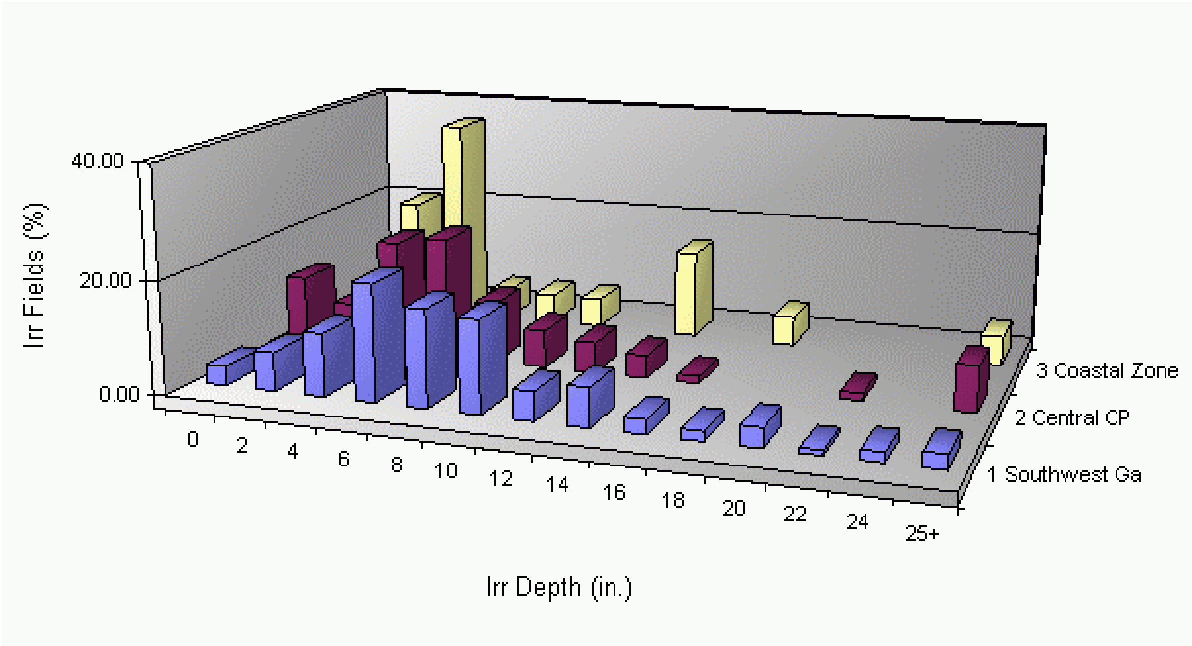

Fig. 2. Distribution (as a % of all users) of annual irrigation amounts for ground-water users during 2001. There were no ground-water users among monitored fields in North Georgia.

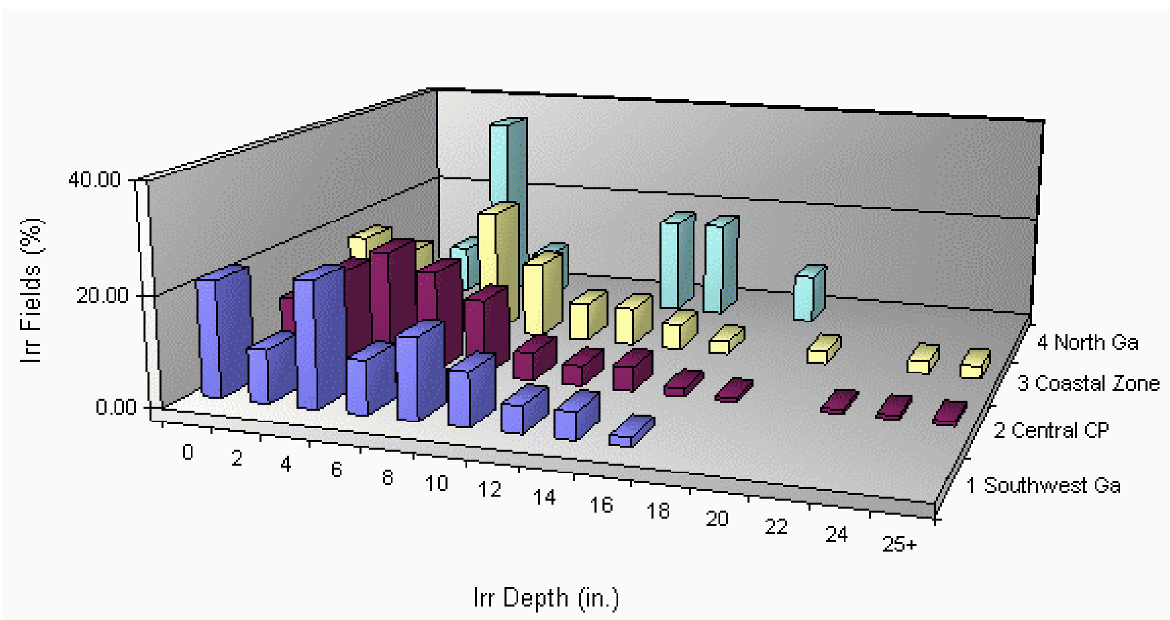

Fig. 3. Distribution (as a % of all users) of annual irrigation amounts for surface water users during 2001.

When the full range of observations were ranked, application depths associated with the 50th (median), 75th, 90th and 95th percentiles were determined. Median irrigation application depth was 8.3, 6.2, and 6.7 in. for 2000, 2001, and 2002, respectively. Less than 25% of farmers used more than 12 in./y; only 10 percent used more than 16 in./y, and 5 percent more than 20 in./y between 2000 and 2002.

When averaged over all users, more water was applied to fields in Southwest Georgia than in other regions in each of the drought years. For ground-water users, these area-weighted mean application depths varied from 9.1 to 12.0 in. in Southwest Ga., 6.8 to 8.4 in. in the Coastal Zone, and 9.0 to 10.6 in. in the central Coastal Plain. For surface water users, they varied from 5.2 to 7.3 in. in Southwest Ga., 5.6 to 6.8 in. in the Coastal Zone, 6.0 to 7.3 in. in the central Coastal Plain, and 7.2 to 7.6 in. in North Ga. Few irrigators in North Georgia have access to adequate ground-water for irrigation, and none were included in our randomly selected sample.

Irrigation systems in Georgia include center pivots, traveler systems like hose reel and cable tow, solid set sprinklers, and micro-irrigation including surface drip, drip under plastic and subsurface drip. Irrigation depths for center pivot systems were very close to overall statewide means. This was expected since 80% of the state's systems were center pivots. Of these 40% were supplied by ground-water. Almost 97% of these were in use in each year. In contrast, only 6% of systems were travelers, and of those only 9% used ground-water. Even during drought only 40 to 75% were in use. Irrigation depths with travelers were generally less than 4 in./y.

Farmers used solid set systems primarily for pecan and other orchards, nurseries, and athletic fields. These uses resulted in mean annual application depths of 29 to 57 in./y between 2000 and 2003 when supplied from ground-water. When supplied from surface sources, solid set systems had much lower annual application depths, 7.5 to 11.2 in./y.

Drip systems were also in use on specialty crops, including pecan orchards and vegetables. About 87% of these were supplied with ground-water. Mean annual application depths varied from 8.0 to 13.7 in./y in this period. These drip systems were almost always used each year.

Irrigation does not occur uniformly throughout the year. Farmers apply water in response to plant needs, and those plants have different growing periods. Patterns of monthly withdrawals were prepared for each region and source, but common to all were peak use periods of May through September (Figs. 4 and 5). In the Southwest region, little water was applied outside of this peak use area. In the Coastal Zone and central Coastal Plain, a diversity of vegetables and pastures resulted in proportionally higher application depths in winter months than seen in the Southwest Georgia region.

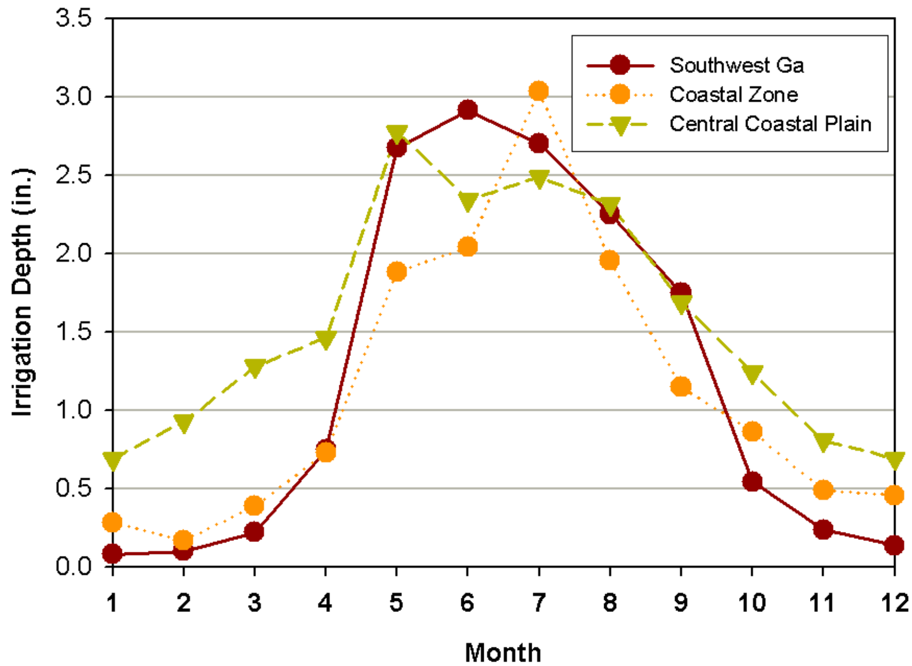

Fig. 4. Maximum of mean monthly application depths applied during the drought years 2000 to 2002 by ground-water users in three areas of Georgia.

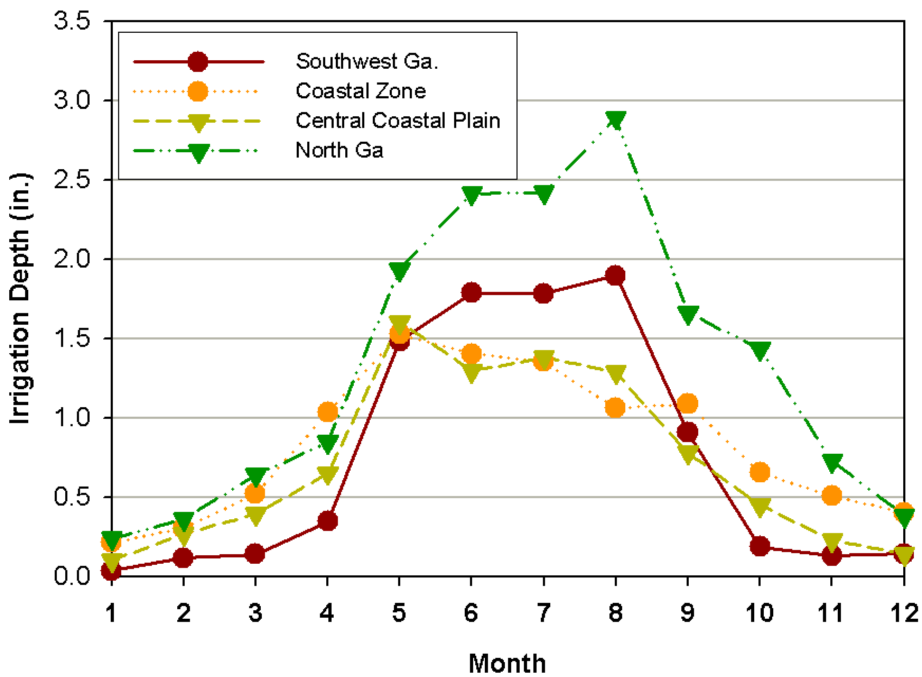

Fig. 5. Maximum of mean monthly application depths applied during the drought years 2000 to 2002 by surface water users in four areas of Georgia.

Irrigation demand is also related to net difference between evapotranspiration and effective rainfall. In effect farmers in the humid region are using irrigation to fill the gaps between effective rainfall and crop ET. Because most of the soils in Georgia's crop production region are sandy, soil water storage provides little of a crop's seasonal water needs, and it is ineffective in storing significant quantities of irrigation water. It is largely for this reason that very few surface application systems are found in the state. In Fig. 6, an example of rainfall and predicted ET is shown for the Southwest region. Total rainfall is shown rather than effective rainfall, so differences between ETp and rainfall are actually greater indicated.

When the monthly deficit was plotted with the mean monthly irrigation, the relationship between deficits and irrigation became more evident (Figs. 7 to 9). An April deficit occurred each year, but at that time a significant portion of Southwest Georgia's irrigated acreage had not been planted. Many of those who irrigate field corn and sweet corn in the region initiated their irrigation in April as initial soil water supplies failed. By May, the deficit grew in these drought years. Irrigation was needed to supply most of that month's water for spring crops, and in some cases was needed to establish stands of peanut and cotton, the region's primary crops by irrigated area. From June through August, water use mirrored the monthly deficits. September irrigation exceeded the deficit, although most of the rainfall in September came in tropical storms after irrigation that completed maturation of peanut and cotton.

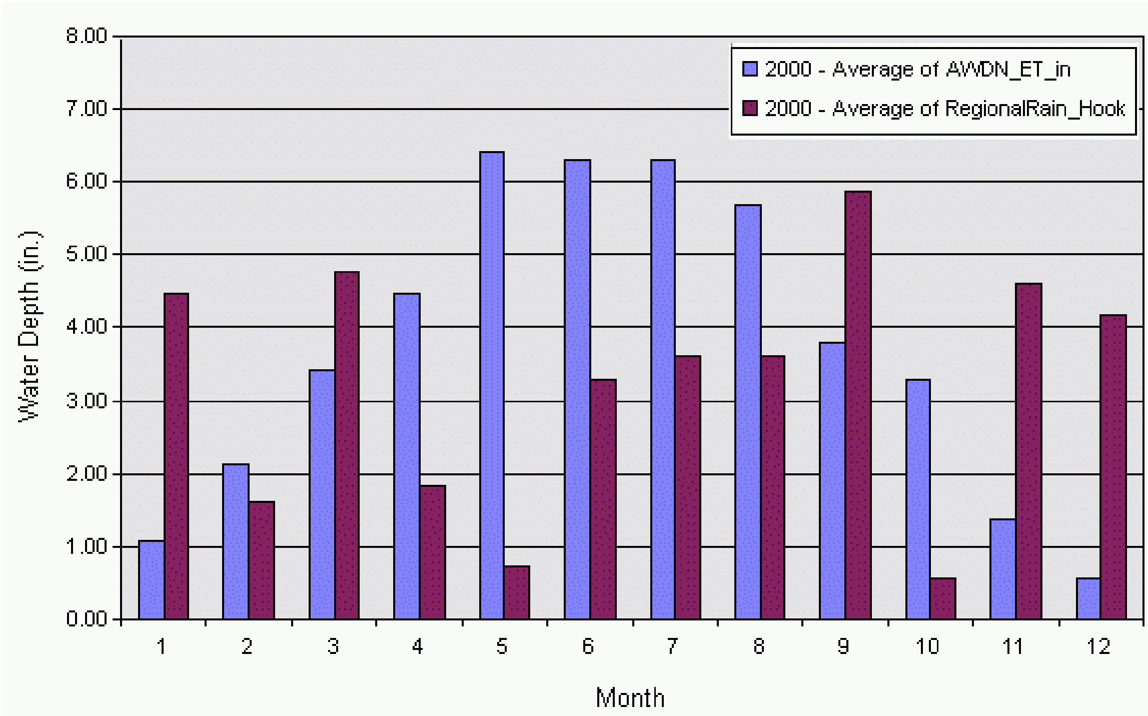

Fig. 6. Regional mean rainfall and predicted evapotranspiration (ETp) derived from Georgia's Automated Weather Data Network (AWDN) for sites in and around the Southwest Ga. region during 2000.

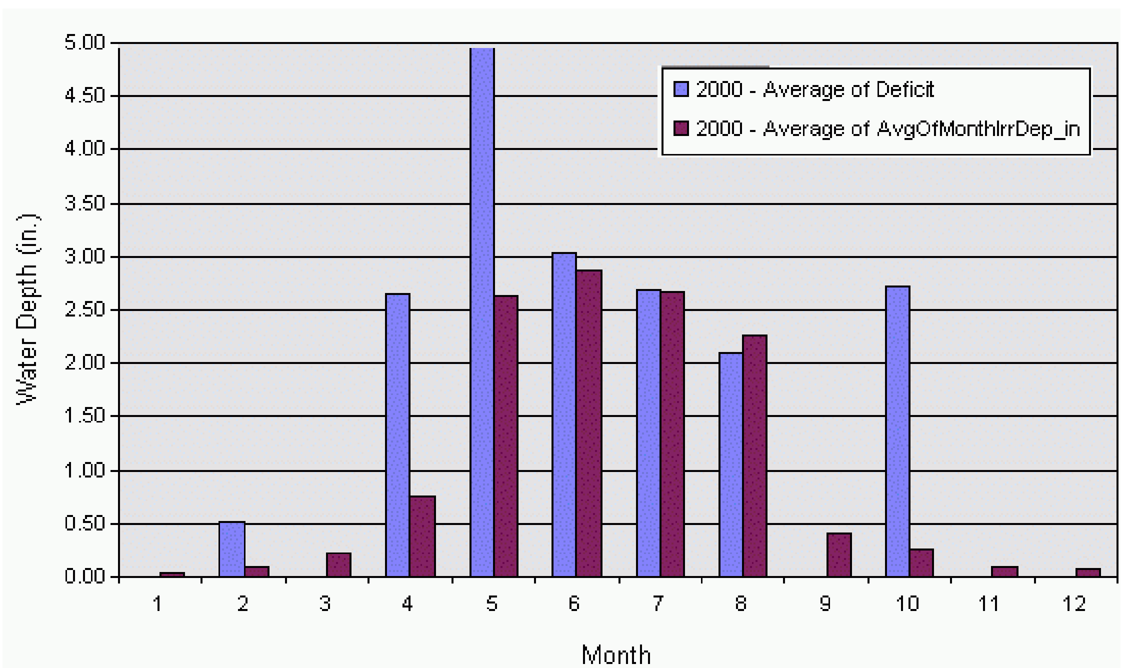

Fig. 7. Regional deficit (ETp - rain) and area-weighted mean monthly irrigation depths for ground-water users in Southwest Ga. in 2000.

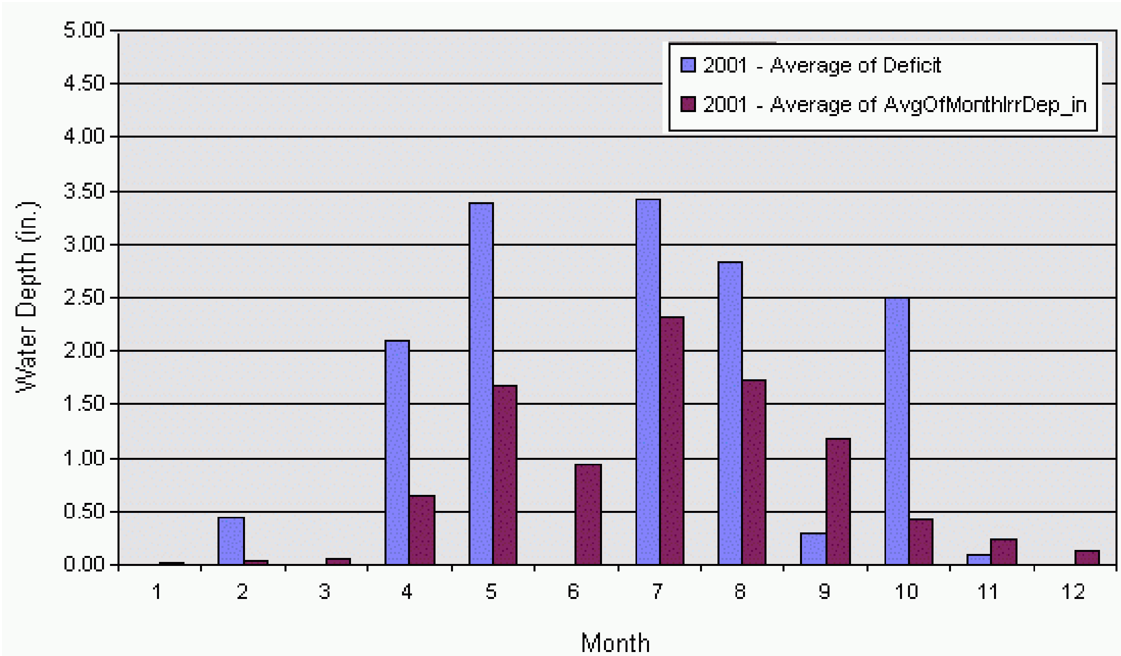

Fig. 8. Regional deficit (ETp - rain) and area-weighted mean monthly irrigation depths for ground-water users in Southwest Ga. in 2001.

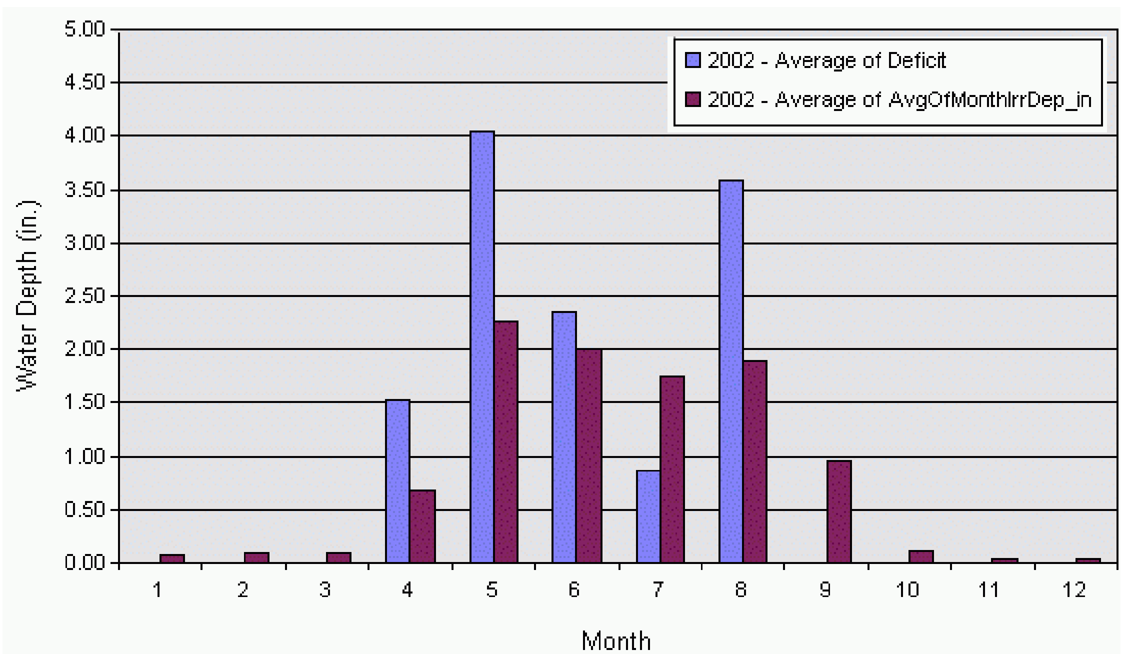

Fig. 9. Regional deficit (ETp - rain) and area-weighted mean monthly irrigation depths for ground-water users in Southwest Ga. in 2002.

Summary

The Agricultural Water Pumping program provided Georgia with a comprehensive examination of water use amounts by Georgia farmers during the severe drought years of 2000 to 2002. Irrigation amounts were seen to vary by year, region, water source, irrigation system, and month of the year. Many of these variations were related to the type of crop produced with various systems and water sources. On average, farmers used less than 12 in./y even in these drought years.

Irrigation Requirements of Container-grown Woody Plants

submitted by
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Abstract:

Up to eighty percent of the 1.3 billion woody plants produced by U.S. nurseries each year are grown in containers. However, limited research has been done to determine how much irrigation water is required by these plants. A university study was completed at The Ohio State University during the 2003 growing season and then corroborated nationally during the 2004 growing season to help establish BMP for irrigating container-grown woody plants.

Based upon this controlled testing, the adjusted irrigation rate required for “Heritage” riverbirch was found to be only 1.08 liters per cm of trunk caliper per unit ET per hour and 0.71 liters per cm of trunk caliper per unit ET per hour for pin oak. Thus, during peak Evapo-Transpiration conditions, a 1.5 inch caliper pin oak uses only 1.29 liters of water over the course of a day while commercial U.S. nurseries typically apply over 15 liters a day, or 10.6 times more than is required.

Background:

According to the July 2004 USDA survey of nursery production, approximately 1.3 billion single stem woody plants are being grown in the U.S. It was also been estimated by Brooker, Hinson, and Turner in 2000 that approximately 80% of these plants are grown in containers in the largest horticulture production states. Furthermore, the trend in the industry is toward growing in Pot N Pot containers larger than #10 rather than in the field. This leads to a conservative estimate of 138 million plants being grown nationally in large containers.

Introduction

It is noted that very few controlled research studies have been conducted to determine the actual irrigation requirements for these 138 million containerized plants. Thus the question of how much water is really needed by the plant was largely unanswered. The purpose of this study was to determine season long evaporation transpiration rates (adjusted for tree caliper, unit ET and unit time) and thus a value for the actual required irrigation volumes for typical woody plants grown in #15 (15 gallon) containers irrigated when delivered at low delivery rates.

Materials and Methods

Two species, “Heritage” riverbirch (*Betula nigra* “Heritage “) and pin oak (*Quercus palustris*), were grown in #15 sized containers at the Department of Horticulture and Crop Science, The Ohio State University, Columbus, Ohio during the 2003 growing season. The #15 sized containers were filled to within 2.5 cm of the container rim, resulting in a total filled volume of approximately 41 liters. Two different growing medium were used. Haydite:Comtil (3:1 by vol) medium was used so that roots could be separated from the medium when harvested.

Another group of plants were grown in Pine bark:Comtil (3:1 by vol). The pine bark medium had 67% total pore space and 48% water filled pore space at field capacity, resulting in an estimated 19.7 liters of water. The Haydite medium had 47% total pore space and 41% water filled pore space at field capacity, resulting in an estimated 16.8 liters of water. (Comtil is a composted municipal sewage sludge produced by the City of Columbus). Four foot tall, 1/2" to 5/8" caliper, container-grown whips were transplanted into the #15 sized containers in late April 2003 and placed outdoors without any form of protection.

Two irrigation methods were used to provide daily moisture directly to the containers: TOh Products ContainerTenders[tm] (Model number 1721C, 0.1 to 0.5 gallons per hour [GPH]) and Roberts Spot Spitters[tm] (Model No. 030.001005, 3.0 to 3.6 GPH). The Container Tenders[tm] (Figure 1) were operated under 12 PSI for an estimated rate of 0.99 liters per hour (LPH). The Container Tenders[tm] were run for 120 minutes per day thus applying 1.98 liters of water per day per container. In comparison, two Spot Spitters[tm] were used per container at pressures ranging from 20 to 25 PSI per container and delivered a total of 22.8 to 27.4 LPH. The Spot Spitters[tm] ran for 40 minutes per day thus delivering 15.3 to 18.3 liters per day per container. A standard 150 mesh screen filter was used for all irrigation water. The filter was cleaned monthly.

All plants were fertigated with 100 ppm N from 21-7-7 Peters water soluble fertilizer (O. M.Scotts and Sons, Maryville, OH). At this concentration, Container Tenders[tm] delivered 198 mg N per day while the Spot Spitters[tm] delivered 1672 mg N per day (when using a mean irrigation volume of 16.72 liters at 22.5 PSI).

Periodically, the actual water used by the plants was estimated by weight differences: initial saturated container-medium-plant weight minus container-medium-plant weight after a given time interval. The procedure was as follows: sample containers were saturated early in the morning (900 hours), allowed to drain for one hour and then weighed. This weight was used as the saturated weight and represents the maximum water holding capacity of the container-plant system. After approximately five hours of exposure to central Ohio sunlight, the containers were re-weighed (1500 hours). The weight difference was attributed to evapo-transpiration. This procedure was repeated for each of the next two days. Total Haydite Pin Oak container weights were between 47 and 51 kg in the morning and 45 and 49 kg, five hours later.

After determining the saturated container weight, an initial morning reading on an ET gauge was recorded (Model A Evapo-transpiration simulator, [Ben Meadows.com] fitted with a ceramic alfalfa leaf standard). Upon weighing the containers after 8 hours, the ET gauges water level was again recorded. The difference between the initial and final ET readings was the daily ET value based on the alfalfa leaf standard. Evapo-transporation was expressed as liters of water per unit trunk caliper per ET per unit time. Because ET was estimated between 900 and 1500 hours on sunny days, it represents the maximum daily ET value and thus reflects the maximum irrigation rate actually required by these species using these delivery modalities.

Three randomly selected plants per media, irrigation system, and species were harvested following the third day of weighing. Harvesting was done in June, July, August and October. Total plant fresh weight, caliper, height, total leaf area and root and leaf dry weight were recorded (Table 1).

Table 1. 2003 Water Use Data

Species	Irrigation system	Caliper (mm)	Height (cm)	Total leaf area (cm^2)
Pin Oak	Container Tender	37[a]	251	16631
	Spot Spitter	34	246	15066
'Heritage'	Container Tender	39	313	18738
	Spot Spitter	41	348	28000
P-values	Pin oak	0.411	0.827	0.740
	Heritage' Riverbirch	0.441	0.173	0.004

[a] Each value is the mean of 12, single plant replications.

Follow up studies are being conducted around the country during the 2004 growing season to corroborate these results. (Ohio State University, Oklahoma State University, Oregon State University, Virginia Tech Hampton Roads AREC, Cornell Cooperative Extension).

Results and Discussion

Season long evaporation transpiration rates:

Based upon the 2003 study, the average adjusted water use for "Heritage" riverbirch grown in #15 sized containers was found to be 1.08 liters per unit ET per hour between 900 and 1500 hours. The average adjusted water use for pin oak grown in 15 gallon containers was found to be 0.71 liters per unit ET per hour between 900 and 1500 hours (Column 1 of Table 2).

Initial results from the national 2004 study reflect that there is some slight differences in the average adjusted water use for a given species grown around the country (Table 2). The reasons for these difference are being investigated as additional data comes in from the test sites.

These adjusted water use values can be used as a starting point when designing optimum irrigation systems and the required application rates to containers. For Example: A quick calculation yields that a 3.8cm (1.5inch) caliper pin oak requires an average of only 1.29 liters (0.3 gallons) of water over the course of a day. Similarly, a 3.8 cm (1.5 inch) caliper "Heritage" riverbirch requires an average of only 1.78 liters (0.26 gallons) of water over the course of a day.

It is noted that some commercial U.S. nurseries typically apply 15 to 18 liters a day or more with spray stakes. (10.6 times more than the average required). Comparing these numbers suggest that current irrigation and fertility programs typically used in American nurseries for containers are inefficient.

A word of caution....the wide range of values for the data summarized in Table 2 suggests the need for some additional analysis. This analysis is currently taking place with the cooperating professors and the participating companies. The full paper and follow-on results from the 2004 growing season will be available soon obtained at: www.containertender.com

Plant Growth:

There were few statistical differences in end-of-season growth between plants grown with Container Tenders[tm] or Spot Spitters[tm] (Table 1) even though 88% less water and fertilizer was delivered to the Container Tender[tm]plants.

For "Heritage" riverbirch, plants grown under Container Tenders[tm] had less leaf area (18,738 vs 28,000 averaged cm_2).

There were no significant differences in pin oak growth when grown under either irrigation method, or in either media. The largest pin oak plants were grown under a combination of Haydite medium and Container Tender[tm] irrigation system.

Irrigation Scheduling for Optimum Plant Water and Nutrient uptake

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Abstract

Effective and efficient water resource management is undoubtedly one of the most important policy issues facing agriculture in Hawaii in the years ahead. A successful irrigation water management program optimizes water availability, ensures the best crop yield and quality while minimizes production costs and nutrient losses below the rootzone. The objective of the current work is to establish an irrigation scheduling program for a tomato crop to optimize plant water and nutrient uptake. A tomato variety trial was conducted at the University of Hawaii Poamoho research station on a Wahiawa silty clay soil. Irrigation setting points were determined based on root system growth and soil water release curves established from soil cores taken within and below the rootzone. Rain, irrigation and real-time soil water content were monitored throughout the soil profile. Plant water uptake and excess losses below the rootzone were calculated using a water balance approach and field data.

Introduction

Irrigated agriculture is the leading water user around the world. In Hawaii, declines in plantation agriculture resulted in a drastic reduction of agriculture water use. However, Hawaii agriculture is still required to optimize its water use for two main reasons: to optimize crop production in order to compete with the import markets and to minimize environmental impacts from erosion or nutrient leaching into aquifers.

Demands on our limited water supplies in Hawaii are increasingly competitive, especially as we experience more cycles of drought and dynamic changes in land use. Growth of a diversified agriculture in Hawaii is dependent on its ability to compete with imported products. In order to have a competitive advantage, Hawaiian agricultural production efficiency is becoming necessary for producers to maintain or increase their net returns in an increasingly global market. Increase in net returns could be realized by increasing crop yield per unit area and/or minimizing crop production costs. Several crop water production functions, describing the relationship between crop yields and evapotranspiration, have been developed for different crops under different management practices. In addition to their cost, excess water losses ensuing from poor irrigation scheduling carry with them dissolved fertilizers and pesticides beyond their targeted area resulting in substantial increases in production costs. Hence, optimum irrigation water management is critical in any effort to increase Hawaiian diversified agriculture net returns.

Yield and dry matter production of many plants are linearly related to total evapotranspiration (ET). The relationship between ET and available soil water in the rootzone is generally linear but becomes curvilinear when soil water content is close to saturation. The curved portion of the line reflects low efficiency of irrigation water use, primarily due to excessive water leaching below the rootzone. Moreover, such leaching removes nutrients and pesticides away from their intended application zones resulting in higher crop production costs and water quality impairment. Ample research findings in the literature show that efficient irrigation practices reduce production costs, improve crop yield, limits erosion and sediment-loading, and enhance environmental quality.

There are several candidate crops for irrigation studies in a new and a more diversified Hawaiian agriculture. Tomato is a good representative of an economically diversified agriculture in Hawaii. Water management of these crops is mainly based either on the growers' best judgment and experience of trial and error. To date, little information is available for the highly weathered, well-structured tropical soils that prevail in the agricultural lands of Hawaii.

The purpose of prudent irrigation scheduling is to determine when and how much to irrigate to meet crop demands. Several irrigation scheduling methods have been used for different crops. Check-books, pan evaporation and soil water monitoring devices, i.e., tensiometers and neutron probes have been successfully used as irrigation scheduling tool for several decades. However, recent electronic advances resulted in the development of real-time soil water monitoring devices such as time domain reflectometry and capacitance sensors. These devices have been used extensively for efficient irrigation and nutrient management in different crops, i.e. citrus (Fares and Alva, 2000; Fares and Alva, 1999). Since capacitance sensors monitor water content at multiple depths and at different locations in real-time; they can be used along with tensiometers to determine important soil physical properties such as soil water release curves, hydraulic conductivities and soil water holding capacities. Fares and Alva (2000, 1999) used this approach in addition to irrigation and rainfall data to calculate daily plant water use and excess water losses below the rootzone.

A sound irrigation management program requires knowledge of the soil water holding capacity, root zone depth and the ability to determine or estimate the available soil water at any time during the growing season. This information, in turn, allows for the methodical determination of the timing and amount of irrigation water to be applied (Fares et al., 2000).

Materials and Methods

The study was conducted at the University of Hawaii-Manoa Poamoho research station, Waialua, Oahu, HI. This study was part of a tomato variety trial (*Lycopersicon esculentum*) grown under drip irrigation on a Wahiawa silty clay. A typical soil profile for a Wahiawa silty clay consists of Ap1 (0-6 inch), Ap2 (6-12 inch), B21 (12-16 inch), B22 (16-33 inch), B23 (33-45 inch), and B24 (45-60 inch) horizons (National Cooperative Soil Survey, 1978). Bulk densities range from 1.10 – 1.30 g/cm^3 for 0-14 inch depths, permeability ranges from 0.6-2.0 in/hr for depths of 0-2 inch and 0.2-0.6 in/hr for depths of 2-14 inch. Soil water release curve data for a typical Wahiawa silt clay loam soil as reported by Gavenda, et al. (1996) are presented in Fig. 2.

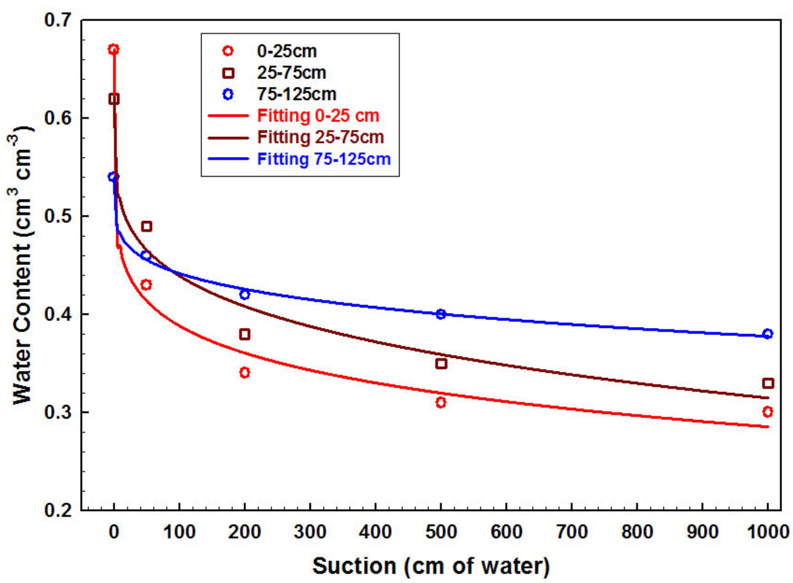

Figure 1. Soil water release curves for a Wahiawa soil (Gavenda, et al., 1996).

The mean annual rainfall is 1270 mm and mean annual temperature is 22º C, however, this year there was 1230 mm (Fig. 2) in only four months of the dry season.

Description of Field Experiment

Four tomato plants, each representing a variety (FI 68-5, HA-3816, F1 #5, and BHN555), were selected for soil water monitoring and measurements. Three ECH$_2$O® capacitance sensors (Decagon Devices, Inc.) and one EasyAg® (Sentek Sensor Technologies) capacitance sensor, one per plant, were installed to measure soil moisture content in real-time within a root zone of 0-

25cm. Sensors measured soil moisture content every 10 to 30 minutes and data were recorded using a Campbell Scientific data logger. In this paper, we are reporting the EasyAg data only. A rain gage equipped with a data logger was used to monitor both irrigation and rainfall events. Daily and cumulative rainfall during the study period are shown in Fig.2.

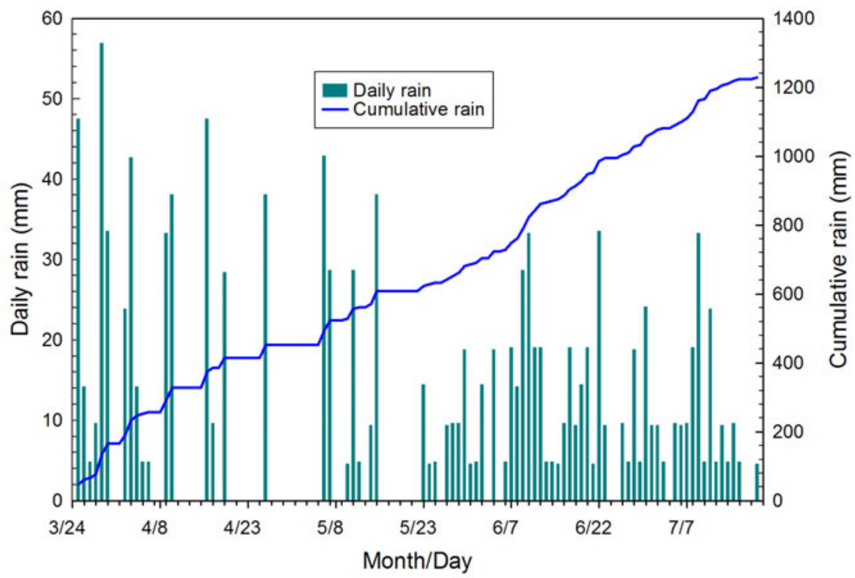

Figure 2. Daily and cumulative rain for the research site.

Results and Discussion

The data presented in Fig. 3 show the daily rain data (C), and the water content at 10, 20 (A), 30 (B) and 50 (C) cm below the root zone. In an average year, summer months are dry; however, this year over 600 mm of rain was received during three summer months (June - August). A calibration experiment was conducted on the same site to calibrate the EasyAg to these tropical soils. Results of this work are not presented here; however the calibration equations developed for each depth were used to process the raw data collected by the capacitance sensors. Soil water content data presented here were converted using these new calibration equations and not the manufacturer default calibration equation.

The water content in the top 10 cm showed more wetting and drying cycles as compared to all the other depths. The water content at that depth varied between 0.26 and 0.40 $cm^3\ cm^{-3}$ as a result of water inputs (rain and irrigation), and water losses through soil evaporation, and plant water uptake through evapotranspiration, and excess water losses below the rootzone and occasional runoff under intense rainfall events.

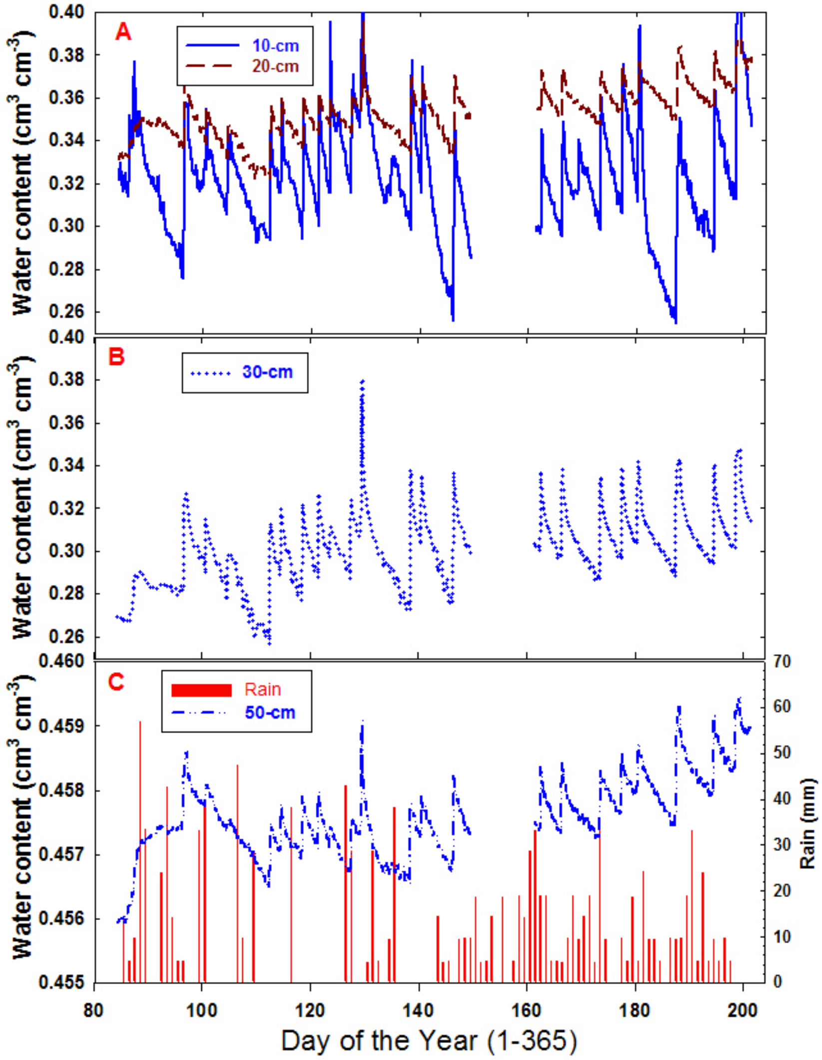

Figure 3. The daily rain (C), and the water content at 10, 20 (A), 30 (B), and 50 cm below the soil surface.

The water content in the 20-cm depth showed similar variation as of that in the 10-cm depth; however, the amplitude of this variability was lower, it varied between 0.33 and 0.38 $cm^3\ cm^{-3}$.

The water content in the 30-cm depth showed similar dynamics as the water content in the top two levels. The range of this variability is more similar to that in the 10-cm depth than to that in the 20-cm depth. It varied between 0.26 – 0.34 $cm^3\ cm^{-3}$. The water content at the 50-cm depth showed less than 1% variability over the entire period (Fig. 3 C). At the finer scale, the water content variations are similar to those shown in upper sensors.

The water content data at the four depths, 10, 20, 30 and 40 cm were used to calculate the water content in the rootzone and below it. It was assumed that the majority of the tomato roots are in the top 45 cm; thus the water content data from the top three sensors were multiplied by 15, 10 and 20 cm, respectively, to determine the total water stored in the rootzone (Fig. 4 A). The "Full Point" and "Wilting Point" were defined as the water storage in the rootzone, top 45 cm, corresponding to field capacity and permanent wilting point, respectively. Optimum irrigation management practices should ensure that the storage water in the rootzone should vary between those upper and lower boundaries. The sensor at the 50-cm depth was used to represent the water content below the rootzone in the zone between 45 and 55 cm below the rootzone. Data for this sensor are plotted in Fig. 4 B. These data show that excess water reached the 50-cm depth as a result of the rainfall events shown in Fig. 2.

The stored water below the rootzone followed a similar pattern as that in the rootzone; however, the amplitudes of the variation of the latter were relatively small; this could be attributed to the low hydraulic conductivity of this soil. The variations of the stored water in the rootzone are the results of water input from the rain and occasional irrigation and water output that include evapotranspiration through the soil surface and plant transpiration, excess water losses below the rootzone and potential surface runoff.

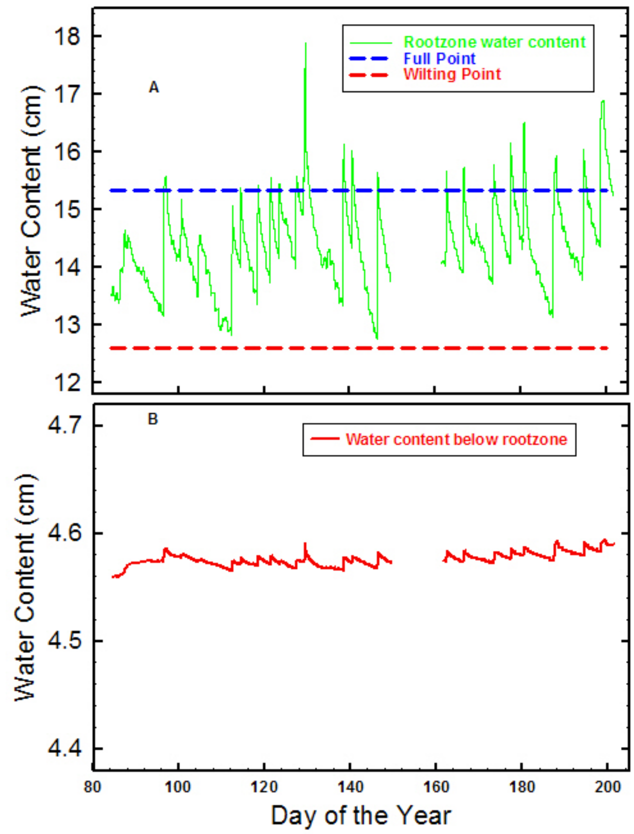

Figure 4. cumulative water in the rootzone (A) and blow it (B) with the upper and lower limits.

Summary and conclusions

As a major water user, irrigated agriculture is expected to make substantial changes to optimize its water use. Optimum water management should be based on understanding soil water holding capacity and crop water use through the growing season. Water content within and below the rootzone in a tomato trial was monitored for several months. Soil samples were taken for a laboratory determination of soil water release curve at four different depths, 10, 20, 30 and 40 cm. Real-time soil water content monitoring within and below the rootzone showed substantial variations as a result of water input through irrigation and rainfall and also the as a result of water output through evapotranspiration and deep percolations. Future field work should include at least three soil moisture sensors per treatment, on site weather data collection and field determination of soil physical properties. These data will be necessary to determine the different water budget components for a tomato crop grown under Hawaii leeward conditions.

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Status of Georgia's Irrigation System Infrastructure

Kerry A. Harrison and James Hook[1]

Introduction

For many years, the Georgia Cooperative Extension Service (CES) has worked to track Georgia's irrigation infrastructure so that it could provide education, service and research programs for farmers who irrigate. The Georgia Irrigation Survey has been conducted at intervals of one to three years since 1970, most recently in 2000. The Extension unit of the Biological & Agricultural Engineering Department sends this survey to the Extension agent in each of Georgia's 159 counties who is responsible for agriculture and natural resources programs. This individual fills out the survey form based on his knowledge of agricultural practices in his/her county. The forms are then returned to the Extension engineering unit where the data is compiled and distributed. Basic information from the survey has included irrigated area and irrigation amounts for each major crop in the latest year. Types of irrigation systems, water sources, and pumping plant power sources have also been enumerated, but little to no information was collected about repairs, changes, or upgrades made to the irrigation systems. Summaries of these surveys have been shared with the irrigation industry by means of the Irrigation Journal's annual survey of irrigation in each state.

A new opportunity to define the state's irrigation systems was created when the state began to regulate water withdrawals for irrigation. In 1988 Georgia's Groundwater Protection Act and Surface Water Quality Control Act were amended to require those who made withdrawals for agricultural irrigation to obtain permits from the Georgia Environmental Protection Division (EPD). During the next 10 years nearly 20,000 permits were issued. Farmers were asked to supply information about their pumps and wells, but they were not asked to describe their application systems. Unlike municipal and industrial users, agricultural users were exempt from water metering and reporting. This left EPD with names of permitted irrigators, general locations of their withdrawals but little to no information about how and when the water was used. They did stipulate limits on pumping rates (described in gallons per minute) and maximum irrigated area (acres), but no field verification was conducted. As water planning issues grew in importance, EPD turned to the CES for assistance in obtaining more specific answers to the questions "How much, when, and with what equipment?"

A statewide irrigation monitoring program was established for Georgia by UGA scientists and CES. A two percent sample of existing EPD-issued irrigation permits were randomly selected for monitoring of agricultural irrigation withdrawals. That total number was based upon estimates of monitoring costs versus available resources, but in a large population a 2% randomly selected sample would not be considered unreasonable. Selected participants were asked to participate voluntarily and most agreed. The monitoring program was conducted over a 6-year period (1999-2004) to make certain that drought years would be encountered and that crop rotation would also be "cycled through the sample population".

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The approach for the monitoring program, which became known as Ag Water Pumping (AWP), included monthly field visits to each of more than 800 irrigated fields. Project personnel recorded crops grown, systems in use, and accumulated hours of operation. Since flow rates were measured on each system under normal operating conditions, they were able to determine volumes of water removed from surface and ground-water sources. This timer approach eliminated the need for expensive up-front meter installation and allowed AWP to get accurate answers in a short time period. Current water use was recorded by type of irrigation system, source of water, type of crop and time of year in both severe drought years and in moderately wet years. Using the random sample of existing water users in combination with the survey information should allow projections for future water needs to be made with computer models. In addition to water use data, wells, pumps, and irrigation systems were documented. These descriptions detail the status of irrigation system infrastructure in Georgia - the subject of this paper.

CES Survey of Irrigation Systems

Georgia is among the top ten states nationally in area under irrigation by sprinkler systems (Table 1). Triennial CES surveys in Georgia show the total irrigated area in the state has gone through two growth periods (Fig. 1). From 1975 to 1980, there was a very rapid increase in irrigation as high commodity prices and competition led to a rapid increase in irrigation even though the period was not marked with significant droughts. The ability to install center pivots that required little field labor encouraged this trend. In the early 1980, farm prices collapsed, and little new irrigation was installed. By the mid 1980's summer droughts became more common and more serious. Bankers began to demand better protection for crop loans, and labor became less available in rural areas of the state. Since that time a second, steady annual increase in irrigated area has occurred in Georgia.

Table 1. Sprinkler-irrigated area in those U.S. states with the greatest sprinkler area.

State	Irrigated Area (ac)*
Nebraska	5,150,000
Texas	4,050,000
California	2,792,000
Idaho	2,584,300
Kansas	2,402,287
Washington	1,625,000
Georgia	1,362,835
Colorado	1,351,000
Montana	1,215,500
Missouri	671,400
Florida	667,000

* Irrigation Journal, January/February 2001

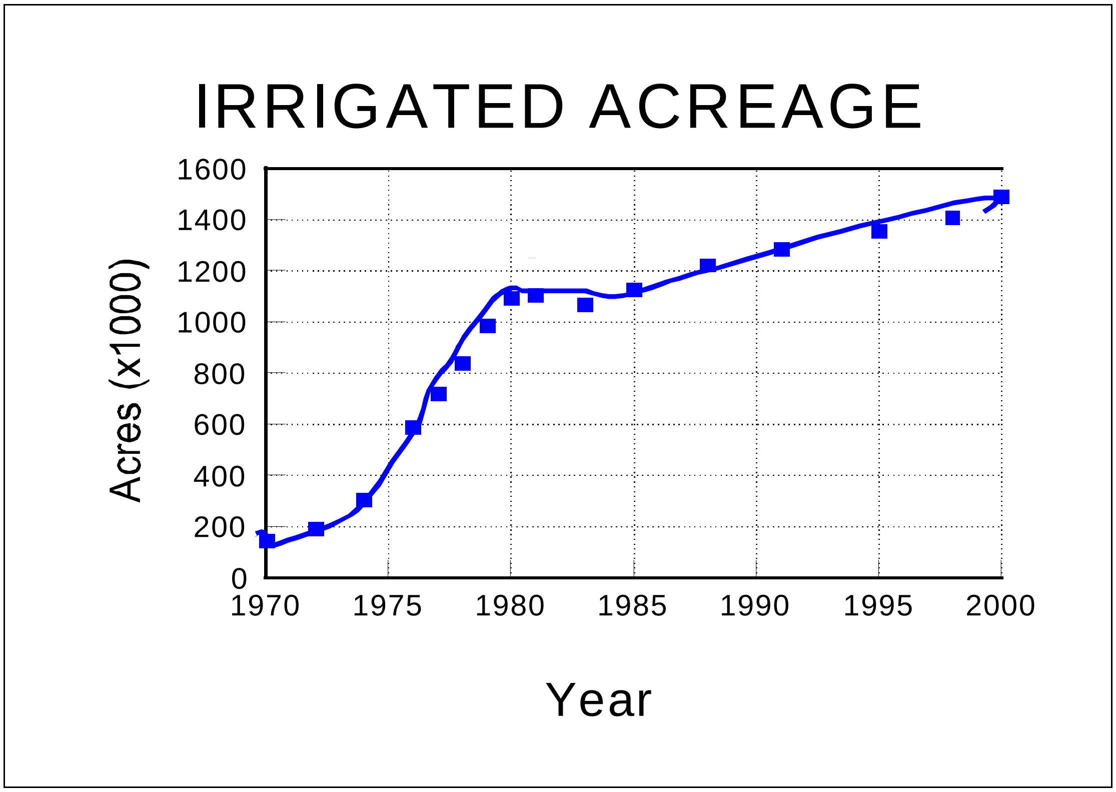

Fig. 1. Total irrigated area in Georgia as reported in CES Irrigation Surveys. Figures include drip and microirrigation, as well as sprinkler irrigation.

The CES surveys have also documented shifts over time in the preferred irrigation systems (Fig. 2). During the rapid growth period of the late 1970's both center pivots and travelers were being purchased. Since the 1980's relatively few travelers have been purchased, most of those as replacements. These systems required too much time and labor to set up, and labor has remained scarce on Georgia farms. As we observed during the Ag Water Pumping study, many of those traveler systems remained unused much of the time. Center pivot systems, however, continued to increase in numbers. Solid set systems made up the remainder of Georgia's sprinkler-irrigated land. Most were used in pecans and other permanent orchard crops or in athletic fields and golf courses that are considered agricultural water use by EPD in most of the state.

Besides the sprinkler systems, a slow and continuing growth has occurred in drip and other micro-irrigation systems. Many of the drip systems have been installed as alternatives to solid-set sprinklers in pecans; others are new vegetable production systems with drip under plastic mulch. In recent years, we've observed drip irrigation being installed under center pivot systems or in replacement for them as vegetable production continued to increase in South Georgia. Maintaining the center pivot in these fields may permit growers to rotate among non-vegetable crops in order to suppress weed and disease problems, or farmers may be hedging their bets and maintaining future options as they retire the units in favor of drip irrigation.

The CES Survey showed that by 2000 about 75% of the irrigated area in Georgia (1,120,000 ac) was being irrigated by 10,100 center pivots. Other sprinkler irrigated acres (methods) included 3,350 travelers irrigating 242,000 ac and 460 solid set systems providing irrigation on 31,000 acres.

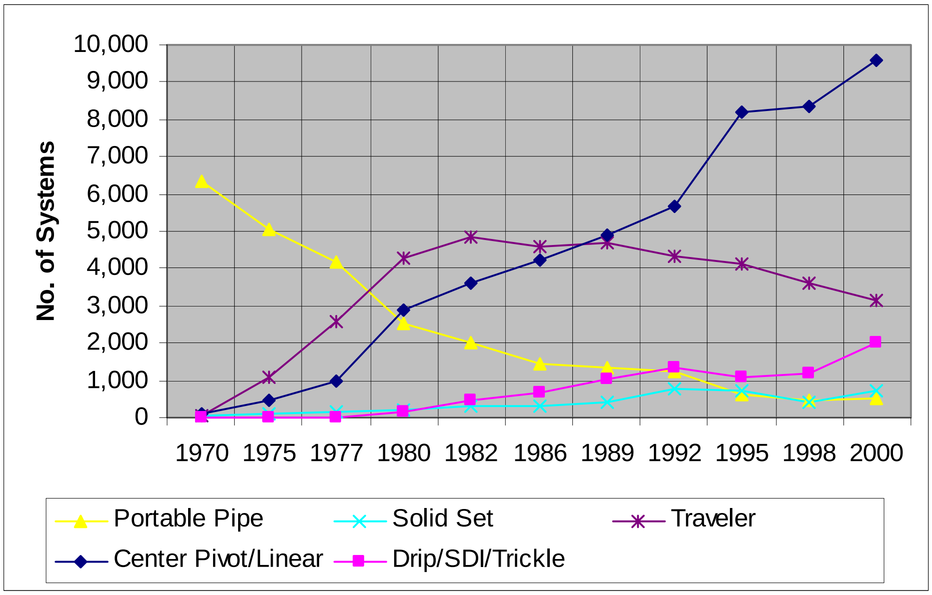

Fig. 2. Number of irrigation systems by type as reported in CES Surveys.

AWP Monitored Irrigation Systems

While the CES surveys provided valuable insight to the irrigation infrastructure, the Georgia EPD wanted detailed information on annual water use from a selection of its agriculture permit holders. In the process of selecting and describing the irrigation systems used with these permits and in our monthly return visits to each system over the past 5 to 6 years, we have gained considerable understanding of Georgia's irrigation infrastructure. The infrastructure is both complex and dynamic.

<u>Center Pivot Systems</u>

As noted in the CES survey, the vast majority of irrigation systems in the state were center pivots (Table 2). Of the 604 systems connected to 448 permitted withdrawal points, 86% were permanent or towable center pivots.

Table 2. Average number of irrigation systems by type in the random sample monitored during statewide sampling 2001 to 2003, and the percent of those monitored systems or fields that were not used during each year.

Irrigation System Type	Ave. No. in sample	2000	2001	2002	2003
		%	%	%	%
Permanent Center Pivot	474	2	4	8	11
Towable Center Pivot	48	11	9	6	19
Traveler	38	25	54	60	75
Surface & Subsurface Drip	18	0	11	16	20
Solid Set Sprinklers	26	6	4	3	13

Market share among sampled pivots in Georgia was as follows: Valley, 44.7%; Lindsay (Zimmatic), 30.5%; Lockwood, 10%; Reinke, 8.0%; Rainbow, 2.3%; Gifford Hill, 1.4%; TL, 1.2%; Raincat, Pierce, and unknown made up 2.1%. Georgia's center pivots are aging. Almost 45% are 15 years or older; 32% more than 20 years; 17% are over 25 years old. Almost all of these systems were operated each year (Table 2), indicating the remarkable durability of the pivots and their ability to be maintained and upgraded. About 10% of the pivots were (still) towable units at the time that the statewide sampling was started. Because of work involved in moving the units, there was a greater tendency not to use some of the fields irrigated by towable pivots each year (Table 2). In some cases the pivots themselves were not used at all in some years.

Throughout the 6 years of the study, farmers continued to modify and upgrade their irrigation systems. When permanent center pivots were replaced, it was usually in conjunction with property changes, land clearing, or smaller pivots being replaced by large units. Towable pivots were also changing. Usually a farmer chose one of the multiple riser points and permanently locked down the towable pivot. A new pivot was installed for the other riser point.

Despite the added aggravation for operation of part-circle center pivots and the higher per acre cost of these systems, 34% of Georgia's pivots could not be operated full circle. Additionally, 23% of towable pivots could not operate in full circle on at least one riser point. Fence rows, property boundaries, ponds, wetlands, utility poles, roads and buildings, as well as other pivots, created obstructions that prevented the full circle operation. Forests were also common in the non-irrigated section, but usually they were in conjunction with some other obstacle. Clearing of forests and sometimes riparian areas and drainage ways were common in pivot areas, even when these could not be planted with crops.

About 12% of systems were still equipped with high pressure, high angle impact sprinklers. Of these, almost a third have been installed on systems younger than 15 years. Low pressure, low angle nozzles are more common; 34% of pivots were equipped with them. About 38% of systems in our sample were equipped with sprays on top, while only 16% were equipped with sprays on drops.

Water Application Information

The interaction of the type of irrigation system and its water source on irrigation amounts must be understood if future water demands are estimated. Throughout the period of this study, irrigation systems were changed. Traveler-irrigated fields were reconfigured and drip systems were installed as vegetable production began on previous row-crop fields. Towable center pivots were locked in one position and a new permanent center pivot was added at the second riser. Older, often smaller, pivots were replaced by new pivots, and wooded borders were cleared to expand the coverage of pivots that had been operated in a part circle mode previously. In one case a center pivot was idled and drip irrigation installed in its field. The tendency of these changes was to increase water use by shifting to systems that have higher average water use or to increase areas irrigated by the monitored withdrawal source.

A comparison of the water amounts obtained is shown in Table 3 for crops grown in Georgia. Not all crops were statistically represented by the monitoring project in 2000. The amounts are in agreement for most crops that had representation in the monitoring project.

Table 3: Water Applied in 2000

Crop	Inches Applied* (# sites)	Inches Applied**
Corn	13.6 (33)	14.1
Cotton	8.6 (148)	11.6
Peanuts	8.6 (104)	11.2
Tobacco		7.4
Soybeans	6.2 (24)	6.0
Small Grains		4.4
Vegetables - Sprinkler		10.5
- Drip	***	12.6
Pastures		7.5
Apples		6.0
Blueberries		8.9
Peaches	***	7.2
Pecan - Sprinkler	12.4 (9)	13.8
- Drip	4.2 (11)	12.8
Field Nursery	***	35.5
Vineyards	***	13.0
Turfgrass		18.3
Greenhouses	***	14.2
Golf Courses	***	31.6
Athletic Fields		
All Other Crops		7.6
Statewide Average	9.4 (385)	9.7

* Information was obtained from Ag Water Pumping program sample monitoring on 32,416 acres.

**Information was compiled from estimates supplied by county Extension agents.

***Not listed since small sample size would reveal individual data.

Summary Discussion

Even though Georgia receives a relatively abundant amount of annual rainfall, the patterns of rainfall are very inconsistent, particularly during the summer growing season. Consequently, irrigation is increasingly being viewed as a necessary input for profitable agricultural production in Georgia.

Irrigated acreage in the state has increased more than ten-fold since 1970, but indications are (Fig. 1) that future growth will occur at a much slower pace. Increasingly, farmers are using more efficient methods of irrigation which should help improve the effectiveness of the irrigation water applied.

The amount of irrigation water applied will vary tremendously from year to year and from crop to crop depending on the amount of rain received in the agricultural areas during the growing season. Estimates of yearly average water applications agree with monitored results and indicate that annual irrigation water use fluctuates between 100 and 300 billion gallons. Higher irrigation use will generally occur during periods of lower than normal rainfall. Since this typically coincides with periods when water tables are naturally low, this may present an interesting challenge in managing the states water resources. A second problem that arises is the unit of measurement for agricultural water use. In some areas of the nation agricultural water use is expressed in area-depth units (i.e. acre-feet) but in Georgia the units of water measurement have traditionally been volume per unit of time (i.e. million gallons per day-MGD). This has slowed communication efforts between agencies and commodity groups but should improve in time. Thus far, relatively few conflicts have occurred, and have typically been isolated incidences during extremely dry years.

The project had 644 permits monitored with 854 fields (sites). Or, on average, about 1.33 fields per permit. The total monitored acres were 75,448. These numbers more than satisfy the 2% target stated earlier. The number of center pivots monitored was 726 or 84% of the sites monitored. This number agrees with the survey information presented earlier and gives confidence to the survey information.

Other summary information obtained about the monitored center pivots was:

- The average pivot age is 13 years with 45% older than 15 years.
- Only 66% of those were able to make a full circle.
- 99% of pivots used end guns;
- 40% with operational end gun shut-off.
- 8% of pivots are towed among fields
- **88%** of all pivots had improved energy and application efficiency sprinkler packages.
- **80%** of the old pivots have been converted
- **38%** had spray nozzles on top of pivot
- **16%** had sprays on drop tubes

From the monitored sites we determined that most Georgia pivots have already been converted to low angle impact, low pressure sprays on the pivot pipe, or sprays on drop tubes.

Sprinkler irrigation systems, in particular, center pivots; are aging. Most owners have made improvements related to sprinkler packages but more expensive and in depth changes will be needed in the future as the basic infrastructure (pivot pipe and towers) ages.

Related Literature/Publications

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Table 3. Compilation of Georgia Irrigation Surveys conducted by the Georgia Cooperative Extension Service between 1970 and 2000 (Harrison, 2001).

	1970	1975	1977	1980	1986	1989	1992	1995	1998	2000
Acres of irrigationsystems	144,629.00	307,416	592,088	988,356	1,128,584	1,223,835	1,286,707	1,356,726	1,430,235	1,507,929
Number of irrigation systems	6,572	7,038	8,343	10,599	11,886	13,283	14,159	14,584	12,833	17,428
Irrigated acreage by crop:										
Corn	30,418	76,996	250,227	410,241	341,296	281,135	290,505	143,611	216,496	195,006
Cotton	2,627	1,116	9,270	17,655	69,554	109,868	178,818	543,308	569,507	645,690
Peanuts	38,227	91,334	19,544	271,323	375,160	374,398	365,221	313,064	312,905	305,582
Tobacco	42,402	54,518	46,081	46,522	31,605	33,725	36,926	37,885	33,831	30,890
Soybeans	795	4,725	21,728	133,695	94,349	105,240	63,504	20,637	26,615	21,733
Winter & Small Grains	-	-	-	-	12,758	36,006	21,933	7,283	7,008	32,894
Vegetables - Sprinkler	20,061	26,223	39,727	49,005	97,890	124,737	123,053*	106,563	107,486	108,745
- Drip	-	-	-	-	-	-	9,596*	12,497	13,130	22,452
Pastures	5,440	4,613	10,668	13,991	24,216	18,442	29,617	26,172	34,820	26,267
Apples	-	152	1,100	1,378	677	514	365	54	225	178
Blueberries	-	-	-	-	1,130	1,936	2,201	2,669	3,230	4,644
Peaches	1,542	721	1,995	4,594	5,343	5,083	3,807	5,347	4,186	3,444
Pecan - Sprinkler	485	1,356	4,662	16,266	48,538	69,335	22,269*	22,774	19,823	23,172
- Drip	-	-	-	-	-	-	45,668*	48,213	44,696	57,181
Field Nursery	1,453	424	602	1,115	3,013	4,567	4,307	4,484	5,285	5,369
Vineyards	-	145	240	1,581	517	604	561	665	752	953
Turfgrass	-	1,557	1,764	2,252	5,409	9,195	11,411	15,389	34,007	32,711
All Other Crops	1,179	2,121	7,411	7,665	10,163	5,014	9,507	1,728	3,965	192
Golf Courses	-	-	6,069	7,638	**-	**-	**-	**-	**-	
Athletic Fields	-	-	-	614	6,966	15,111	18,795	21,015	24,649	22,951
Number of irrigation systems by type:								***	***	***
Portable pipe (hand-move)	6,365	5,026	4,179	2,517	1,452	1,352	1,250	599/32	454/37	497/31
Cable-tow	69	1,090	2,585	3,825	3,618	3,554	3,135	2,851/73	2,049/70	1,705/66
Hose Reel (hose pull)	-	-	-	429	955	1,132	1,198	1,276/93	1,608/82	1,642/78
Center Pivot	87	478	983	2,858	4,191	4,855	5,660	8,167/108	8,410/121	10,059/111
Lateral Move (linear)	-	-	-	7	28	29	23	21/120	19/84	27/81
Drip-Trickle	-	-	21	159	687	1,040	1,356	1,083/67	1,167/57	2,014/37
Solid Set Sprinkler	32	122	135	211	288	429	764	709/37	427/68	720/43
Golf Courses	-	291	229	250	257	-	-	-	-	-
Athletic Fields	-	120	175	256	405	892	766	579/37	650/37	748/33
Number of irrigation systems by type of power:										
Gasoline Engine	2,985	2,009	1,936	885	658	617	506	347	254	208
L.P. Gas Engine	1,116	1,377	1,033	822	788	781	876	684	738	553
Diesel Engine	2,292	3,434	4,180	6,794	7,485	7,950	7,769	9,366	7,779	8,076
Electric Motor	179	329	441	919	2,420	3,014	4,206	4,187	5,018	6,653
Undesignated Sources	-	-	-	1,179	5	3	4	-	-	-
Number of systems by source of water:										
Ground water	582	1,118	1,771	3,387	4,628	7,260	7,876	8,391	8,881	10,101
Surface water	5,990	6,258	6,211	6,378	6,666	6,018	6,283	6,165	5,998	6,328
Waste water	-	-	-	-	-	-	11	177	140	197
Number of acres under chemigation:										
Fertilizer	-	-	-	-	136,618	133,285	155,749	106,164	118,725	103,842
Herbicide	-	-	-	-	31,958	20,077	15,810	16,870	13,918	10,200
Fungicide	-	-	-	-	6,617	9,200	12,026	6,975	7,385	1,764
Nematicide	-	-	-	-	1,200	700	1,587	1,500	2,545	402
Insecticide	-	-	-	-	4,819	7,615	4,112	3,003	5,355	1,170

*Drip and Sprinkler acreage separated beginning 1992.
**Golf courses and athletic fields combined for these years.
***Number of systems/average, system size in acres rounded to nearest acre.
This information was compiled from estimates supplied by county Extension agents for educational purposes only.

A Historical Review of Mechanized Irrigation Performance for Wastewater Reuse Projects in Humid Regions

By
Jacob L LaRue, Valmont Irrigation

Summary:
This paper will focus on some select mechanized irrigation wastewater reuse projects in humid regions which were proposed and were not developed, were installed but later abandoned and projects which have been operating for ten years or more successfully. An analysis will be presented of what leads to success and to failure of mechanized irrigation wastewater reuse projects both in the short and long run. From the analysis a list of parameters will be discussed which are considered critical to a project's performance. Municipal, industrial and agricultural projects will be included in the discussion.

Objective:
To discuss what leads to successful waste water reuse projects using mechanical move irrigation, solid set and treatment and discharge and identify critical parameters.

Introduction:
Land application of wastewater with center pivot and linear irrigation equipment has been used for more than thirty years. Since the early 1980's the equipment and techniques for irrigating with fresh water have changed dramatically and many of these changes have been incorporated into mechanized equipment used for land application (Gilley, 1983). While these changes have brought significant improvements, also in today's world we must take into account the issues and public perception of land application systems. Mechanized irrigation, due to their characteristics, are considered to have advantages with regards to applying waste water for reuse, particularly from a lagoon with large amounts of water to handle. Some of these characteristics include limited labor input required, application uniformity, ease in handling large quantities of effluent and particularly the ability to apply to actively growing crops with minimal negative impact to the crop. Pivots can also apply during periods of adverse climatic conditions preventing conventional waste handling mechanisms to be used. Some concerns have been expressed include "Land application of wastes may be imposing in some locations, potentially dangerous conditions relative to environmental quality". (Hegde 1997). Many projects choices are dictated by more than just the equipment being used also critically important is the project meets public scrutiny. Some land application projects are very successful for many years and others are abandoned after a relatively short time (Valmont Industries, 1988).

Discussion:
This paper will focus on some specific projects and their performance. A review of the original choices considered, concerns, project developed, challenges and benefits will be considered.

I. Municipal projects:

1) Project for three small towns in an area of rapidly expanding development. The project was hydraulically limited.
    a. Choices considered were expanded waste treatment plant and discharge, solid set or center pivots
        i. Area needed for land application - 92 acres
    b. Concerns with using center pivot
        i. Operator skill level
        ii. Missed area in corners
        iii. Maintenance
    c. Project developed with center pivots in 1995
        i. Project expanded in 2003 with center pivots
    d. Major challenge
        i. Harvest and removal of biomass
    e. Major benefit
        i. Considered environmentally positive

Project has consistently met and exceeded expectations due to the original design which had the correct area for the flows, the desire of operators to make the project a success and working with local farmer to harvest and remove the biomass. When it was time for expansion, no consideration was given to anything but using center pivots.

2) Project for a small town with rapid growth in housing. The project was hydraulically limited.
    a. Choices considered were solid set or center pivots
        i. Area needed for land application - 62 acres
    b. Concerns with using center pivot
        i. Maintenance
        ii. Appearance of center pivots – too visible
    c. Project developed with solid set in 1996
        i. Project expanded in 2001 with solid set
    d. Major challenge
        i. Harvest and removal of biomass
        ii. Breaking of heads during harvest
    e. Major benefit
        i. No discharge

In the initial phases the center pivots were ruled out early due to their 'appearance' according to the board. Board did not want something that was obvious and readily visible from the roads which went around all sides of the project. Center pivot capital cost and area met all requirements except was too visible. Only solid set was considered when the expansion phase was constructed.

3) Project of two small towns in area of rapid growth. The project was hydraulically limited.
   a. Choices considered were expanded waste treatment plant with discharge, solid set or center pivots
      i. Area needed for land application - 38 acres
   b. Concerns with using center pivot
      i. Operating costs
      ii. Management of crop
   c. Project expanded with additional changes to waste treatment plant in 2001
   d. Major challenge
      i. Cost of hndling sludge
   e. Major benefit
      i. Unknown

During the design phase much concern was expressed about operating cost and crop management. The board did not appear interested in any solution other than treatment and discharge. Land application appeared more expensive due to the costs of land. Little consideration was given to operating cost and sludge handling.

II. Industrial projects:

4) Project for poultry processor. The project was nutrient limited.
   a. Choices considered were expanded solid set or center pivots
      i. Area needed for land application - 185 acres
   b. Concerns with using center pivot
      i. Operator skill level
      ii. Maintenance
   c. Project developed with center pivots in 1998
      i. Project expanded in 2002 with center pivots
   d. Major challenge
      i. Wheel tracks
   e. Major benefit
      i. Revenue from crop production

Time was spent with the plant management to help them understand land application and using center pivots. They were taken to visit other sites with center pivots. Early on a farmer was identified who wanted to use the water and this has helped generate a revenue stream for the operation of the project.

5) Project for power plant. The project was hydraulically limited.
    a. Choices considered were treatment and discharge or center pivots
        i. Area needed for land application - 275 acres
    b. Concerns with using center pivot
        i. Capital investment
        ii. Maintenance
    c. Project developed with treatment and discharge 2003
    d. Major challenge
        i. Cost of disposal of precipitates
    e. Major benefit
        i. Low capital investment

In the design phase were not able to overcome management's concern about the cost of land for the project. They were sold on technology for treatment without significant consideration of the operating cost to dispose of the precipitates. Comments were made after the project was installed indicating the operating costs were far exceeding their expectations.

6) Project for meat packer. The project was hydraulically limited with the potential for salinity projects.
    a. Choices considered were treatment and discharge or center pivots
        i. Area needed for land application - 148 acres
    b. Concerns with using center pivot
        i. Maintenance
        ii. Operation
    c. Project developed center pivots 1991
        i. Project abandoned and converted to treatment and discharge 1998
    d. Major challenge
        i. Odor issues
        ii. Biomass production
    e. Major benefit
        i. None identified

The initial design was undersized given the volume of water and climatic conditions. No consideration was given to management of the land and too many decisions were left to the farmer in the beginning. By the time the project was abandoned, less than 25% of the area had an active crop and there were significant odor problems.

III. Agricultural projects:

7) Project for farrowing operation. Project was hydraulically limited.
    a. Choices considered were direct injection or center pivots
        i. Area needed for land application - 125 acres
    b. Concerns with using center pivot
        i. Maintenance
    c. Project developed with center pivots in 2001
        i. Project expanded in 2003 with center pivots
    d. Major challenge
        i. Crop management
    e. Major benefit
        i. Crop production
        ii. Ability to apply during growing season

Due to previous problems with being able to get into the fields, center pivots were considered the preferred solution. A farmer was identified early on and the design was developed to meet the hog and farm operations.

8) Project for integrated hog production. Project was nutriently limited.
    a. Choices considered were direct injection or center pivots
        i. Area needed for land application - 195 acres
    b. Concerns with using center pivot
        i. Odor
        ii. Maintenance
    c. Project developed with direct injection during 2000
    d. Major challenge
        i. Inability to apply during growing season

The hog operation was convinced center pivots would have the potential for too many odor issues. They did not want to consider some of the advanced design sprinkler packages available. Their vision was limited to impact sprinklers on top of the pipe. In addition little effort was put into identifying a crop producer who might be interested in participating with a center pivot.

Conclusions:

Land application using mechanical move irrigation equipment has proven very beneficial to many reuse projects and can be cost effective over the life of the project. One of the keys to successful projects is an integrated approach to the design combining hardware, agronomic principles and management together with the existing wastewater treatment plant.

An analysis of the projects above would indicate the key parameters to be:

- Land application system should fit with the existing management and/or treatment processes.
- Sufficient land must be available for the expected nutrient and hydraulic load with some allowance for the future.
- Early identification of a potential farmer
- Design must be sensitive to the local concerns about odor, impact on visual landscape other possible concerns.
- Projects must be reviewed periodically to ensure operation is meeting the design basis.
- Continuing education must be kept up for consulting engineering firm’s personnel so they understand the equipment, the concepts and agronomics of a land application water reuse system.

References:

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Application and Economics of Linear Irrigation for Precision Agriculture

By
Jacob L LaRue, Valmont Irrigation

Summary:
The current trend for conversion to more efficient and precise irrigation is dominated by center pivots and some drip irrigation. Commonly overlooked are mechanical move linears. Historically linear irrigation tends to only be considered for large, rectangular fields or very high value crops. This paper will focus on the application and economics of linear irrigation for a variety of sizes and shapes of fields. The analysis will include a look at capital investment, operation and maintenance costs. In addition limitations of linear irrigation will be presented.

Objective:
To present information on the viability of linear irrigation for small, irregular shaped fields

Introduction:
Many people when they think of linear irrigation think primarily of large fields (320ac / 130ha or larger) being irrigated from a canal. For irrigating irregular shaped fields, traveling guns, solid set, SDI, and center pivots, either with corner arms, part circle operation or towable operation are usually the only considered options. Product changes and improvements by mechanized irrigation manufacturers have lead to a variety of cost effective linears for smaller, irregular shaped fields.

Discussion:
Too often linears are not even considered for small irregular shaped fields. Linears can in many cases bring the advantages of center pivots (application efficiency and uniformity, cost effectiveness, and low labor requirements) to these smaller, irregular fields. Linears have been introduced by manufacturers recently allowing for small, two wheel carts which may be towed forward and reverse and/or swung around. These units generally use a maximum of center pivot components and commonly do not use the more complex floating alignment or special carts required for the large field linears. In addition these small, flexible linears commonly pull fairly long hoses and have the ability to reverse without having to move the hose. This overcomes one of the primary disadvantages of linears - labor to handle and move the hose. The following examples will be used to illustrate the potential advantages of a linear. The prices and costs are in relative terms compared to the linear.

Example 1
Water source – well in center of field
Flow – 150gpm
Annual application – 8in per year
Field - 660 x 1320, rectangular shaped field, 20 acres
Power - generator

Irrigation	Traveling Gun	Center pivot Towable	Center pivot Part circle	Linear
Acres irrigated	19.1	18.2	17.9	19.3
Number of sets	3	2	1	1
Annual costs				
Energy	+$ 594	-$ 59	-$ 9	$ 0
Lease (5yr)	-$ 3,959	-$ 3,945	-$ 1,576	$ 0
Labor	+$ 1,680	+$ 840	+$ 0	$ 0
	-$ 1,685	-$ 3,164	-$ 1,585	$ 0
Crop revenue	-$ 1,614	-$ 1,110	-$ 868	$ 0
Net difference	+$ 71	+$ 2,054	+$ 717	$ 0

The energy costs are based on diesel fuel at $ 1.65 per gallon. The lease is for the irrigation equipment only and does not include the cost of the pump or pipeline. Labor is considered to be $35/hour. No cost is assigned to equipment to move the traveler or the towable pivot. Due to the higher horsepower required for the traveling gun, the pump investment would be greater. Also the traveling gun and towable pivot would require additional pipeline.

As shown in example 1 it will cost the operator $71 more per year to use the linear over the traveling gun, $ 2,054 more than for the towable pivot and $ 717 more than for the part circle center pivot. The additional advantages the linear provides which are difficult to put a value on are:

- Farm in straight rows and square blocks
  - No concern about applying too much seed or fertilizer in corners
- Lower average instantaneous application rates
- Higher uniformity of application
- Easy to apply small applications for germination, chemical activation or other reasons.

Example 2
Water source – well in center of field
Flow – 150gpm
Annual application – 12in per year
Field - 660 x 1320, rectangular shaped field, 20 acres
Power - generator

Irrigation	Traveling Gun	Center pivot Towable	Center pivot Part circle	Linear
Acres irrigated	19.1	18.2	17.9	19.3
Number of sets	3	2	1	1
Annual costs				
Energy	+$ 890	-$ 89	-$ 13	$ 0
Lease (5yr)	-$ 3,959	-$ 3,945	-$ 1,576	$ 0
Labor	+$ 2,520	+$ 1,260	+$ 0	$ 0
	-$ 549	-$ 2,596	-$ 1,589	$ 0
Crop revenue	-$ 1,614	-$ 1,110	-$ 868	$ 0
Net difference	-$ 1,065	+$ 1,486	+$ 721	$ 0

As shown in example 2 as labor changes due to more applications per year, this example shows using the linear it will save the operator $ 1,065 per year over a traveling gun and now costs the operator $ 1,486 more than for the towable pivot and $ 721 more than for the part circle center pivot. The assumptions and conditions are the same as in example 1. The additional advantages are similar to Example 1.

Example 3
Water source – well in center of field
Flow – 250gpm
Annual application – 8in per year
Field - 660 x 1980, rectangular shaped field, 30 acres
Power - generator

Irrigation	Traveling Gun	Center pivot Towable	Center pivot Part circle	Linear
Acres irrigated	25.5	27.3	17.9	29.0
Number of sets	6	3	1	1

Annual costs				
Energy	+$ 890	-$ 89	-$ 13	$ 0
Lease (5yr)	-$ 3,959	-$ 3,945	-$ 1,576	$ 0
Labor	+$ 2,520	+$ 1,260	+$ 0	$ 0
	-$ 549	-$ 2,596	-$ 1,589	$ 0
Crop revenue	-$ 4,568	-$ 1,302	-$ 8,360	$ 0
Net difference	-$ 4,019	+$ 1,294	-$ 6,771	$ 0

As shown in this example as the field shape changes and the flow the costs change dramatically. Now the linear will save the operator $ 4,019 over the traveling gun and $ 6,771 over the part circle center pivot due to the combination of labor and lost revenue due to the amount of the field the part circle pivot will miss. The towable pivot would be less expensive as long as the issue of moving it does not become a major burden. The additional advantages besides those previously stated of the linear in example 3 are:

- Minimal amount of labor compared to the traveling gun and towable pivot
- Maximum land utilization particularly when compared to the part circle center pivot

Example 4

Water source – well in center of field
Flow – 250gpm
Annual application – 12in per year
Field - 660 x 1980, rectangular shaped field, 30 acres
Power - generator

Irrigation	Traveling Gun	Center pivot Towable	Center pivot Part circle	Linear
Acres irrigated	27.3	25.5	17.9	29.0
Number of sets	6	3	1	1
Annual costs				
Energy	+$ 1,335	-$ 134	-$ 20	$ 0
Lease (5yr)	-$ 3,959	-$ 3,945	-$ 1,576	$ 0
Labor	+$ 3,780	+$ 1,890	+$ 0	$ 0
	+$ 1,156	-$ 2,189	-$ 1,596	$ 0
Crop revenue	-$ 4,568	-$ 1,302	-$ 8,360	$ 0
Net difference	-$ 5,724	+$ 887	-$ 6,764	$ 0

As shown in this final example as labor changes due to more applications per year, using the linear will save the operator $5,724 per year over a traveling gun and due to the lower revenue will save the operator $ 6,764 over using the part circle pivot. The cost to operate the linear is still more than for the towable pivot ($ 887). If the field conditions require frequent light applications the labor calculations for the towable pivot will be too low. The general conditions remain the same for this example.

Conclusion:
Linear irrigation should not be automatically ruled out without consideration to the overall design. Specific parameters which favor linear irrigation would be labor required, field utilization efficiency and crop value. In many cases when all of these factors are accounted for the linear may provide a positive annual cash flow over other types of irrigation.

Small, linear irrigation units bring a number of advantages which are difficult to apply a value to such as farming with square fields, uniform application and maximization of potential irrigated area. In addition once the unit is paid off in five years (as in the examples above) the net benefit would be significantly greater for the linear systems.

Limitations of linears are:

- Higher degree of management required
- Initial investment is usually higher
- Labor if not properly designed.

The perception that linears have little place in the irrigation of small fields may be in many cases incorrect.

References:
Personal communication with irrigation dealers and manufacturers.

Valmont Linear Design Guide

Spatial and temporal Plant Water Use and Rain Inputs as Affected by Citrus Canopy and Microsprinkler Irrigation System

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Abstract

Citrus root systems are exposed to different hydrologic conditions as a result of tree canopy shading and under-tree microirrigation. The objective of this study was to investigate shading and irrigation effects on spatio-temporal distribution of rain, plant water uptake and water content (WC) under mature Hamlin orange trees grown in a Florida sand soil. Soil WC was monitored every 30 minute in a 3 dimensional-grid system 11 m long by 3 m wide and 1.5 m deep. Weather data were monitored under and outside citrus canopies. Microirrigation, rain and weather data were used to calculate different water balance components, i.e. rain, plant water uptake and deep percolation. Rain was affected by the tree canopy interception which accounted for over 30% of the incoming rain. Plant water uptake was higher under tree canopy than in the row-middle especially during the dry season.

Introduction

In recent decades water resource management within Florida is becoming an important function as a result of increase urban water use and year-to-year variations in rainfall. Florida receives an average of 53 inches of rainfall each year (Geraghty, 1973). Total annual rainfall for Florida may vary considerably from one part of the state to another, from one season of the year to another, and from one year to the next. Seasonal variations in rainfall are evident. Traditionally, summer is the wettest season in Florida, with 70 percent of the annual rainfall occurring during the period from May to October (*Florida's Water: A Shared Resource*, 1977).

Effective rainfall (ER) is defined as useful or utilizable rainfall. Some of the ER may be unavoidably lost due to the combined effect of rainfall intensity, frequency, and amount. Just as total rainfall varies, so does the amount of effective rainfall. The useful portion of rainfall is stored and supplied to the plant for its use.

Before reaching the soil surface, some or all of the rain may be intercepted by the canopy of the citrus tree and/or weed species covering the row middles. This fraction of rain needs to be considered in any rainfall calculation. With ridge soils, most of the water reaching the soil surface infiltrates into the soil without any significant runoff losses. Of the water that infiltrates into the soil, some may be retained and is thus stored in the root zone while the rest may move below the root zone. The water stored in the root zone is utilized for evapotranspiration. Water may be lost beyond the root zone by deep percolation to groundwater storage or a nearby surface water body, i.e., stream or lake. In summary, ER is considered to be that portion of the total rainfall that directly satisfies crop water needs.

Several methods have been used to calculate ER. Technical Release No. 21 (TR-21) has been used worldwide to calculate effective rainfall and predict irrigation requirements. Improvement in real-time soil water monitoring sensors provided a good opportunity to test the accuracy of the TR-21 in estimating ER. Obreza and Pitts (2002) used a spreadsheet to develop an analytical model that implements the TR-21 equation to calculate ER.

Little is known about the different water balance components of a central Florida citrus grove. The main objective of the current work is to use a water balance model and real-time soil water content data to investigate spatial and temporal distribution plant water uptake and effective rainfall. Specific objectives are: i) use a water balance model and real-time soil water content data to calculate and estimate effective rainfall, plant water uptake and excess water losses below the rootzone; and iii) compare the performance of the TR-21 in estimating ER with that calculated using the soil water balance model.

Materials and Methods

Field experiments were conducted under mature Hamlin orange trees grown in a Candler fine sand (hyperthermic, uncoated, Typic Quartzipsamments). Two multiple sensor capacitance probe EnviroSCAN systems were used to monitor the soil water contents under the trees in three directions (North, South, and West of the trunk), at three locations (3, 6, and 10 feet away from the trunk) and at 4, 8, 16, and 32 inches below the soil surface. Rain gauges were installed under and outside the canopy between two adjacent tree rows close to the EnviroSCAN probes.

Results and Discussion

Rainfall, Evapotranspiration, and Water Content Monitoring

This period covers October to December 2001, which is part of the fall-winter dry season. The total rainfall that occurred during this period was 2.2 in (Fig. 1), which represents 4.3% of this year's total rainfall (48.1 in). During the same period, there was 8.2 in of reference evapotranspiration calculated based on weather data collected at this location. If we assume that the citrus tree met this evapotranspiration, the difference between rainfall and evapotranspiration is equal to a deficit of 6 in. This deficit was covered by irrigation only under the tree canopy portion of the grove. Irrigation accounted for 8 in. Cumulative rain and irrigation during this time period is shown in Fig. 1. Individual rainfall and irrigation events are shown in Fig. 1. Cumulative reference ETo and daily ETo are shown in Fig. 1.

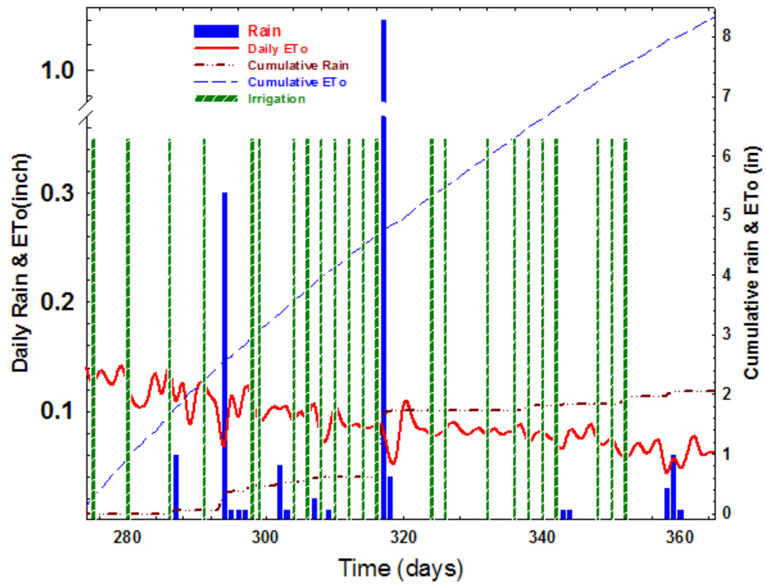

Figure 1

Soil water content in the top 36 inches of the soil profile was measured at three locations (under the canopy, at the canopy drip line, and in the row middle) and is shown in Fig. 2. During this period, water content level in the three different locations was the highest near the trunk under the canopy followed by that at the drip line. However, the row middle had the lowest water content because it did not receive any irrigation water (Fig. 2). The row middle location showed extended dry periods before and after the mid-November rainfall event.

Irrigation events gave a dynamic behavior of the water content under the tree canopy during the dry periods (Fig. 2). The water content for the top 3 feet varied between 2.5 in and slightly over 3.5 in. As the dry period extended, water content was maintained between 2.5 and 3.0 in during the last portion of the month of November and entire month of December.

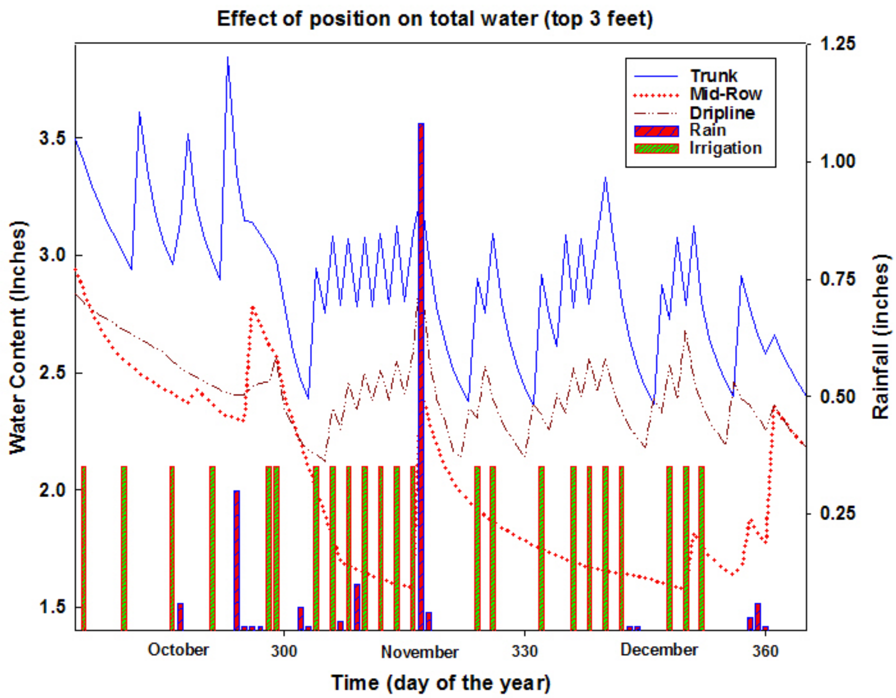

Figure 2

Water Balance Model

Obreza and Pitts (2002) developed the water balance model used in this work. Detailed information about this model can be obtained from their recent publication. The input parameters for the model include: soil water holding capacity, daily irrigation duration and rainfall amount, tree spacing, rooting depth, and crop coefficient. The model calculates effective rainfall for both the irrigated and non-irrigated areas.

The first step in the modeling process was to compare the total water content in the soil profile calculated by the model using TR-21 and that measured in the field using the EnviroSCAN system. The results for the irrigated and non-irrigated portion of the soil profile are shown in Figures 6 and 7, respectively. Overall the model seems to reasonably simulate the measured field data.

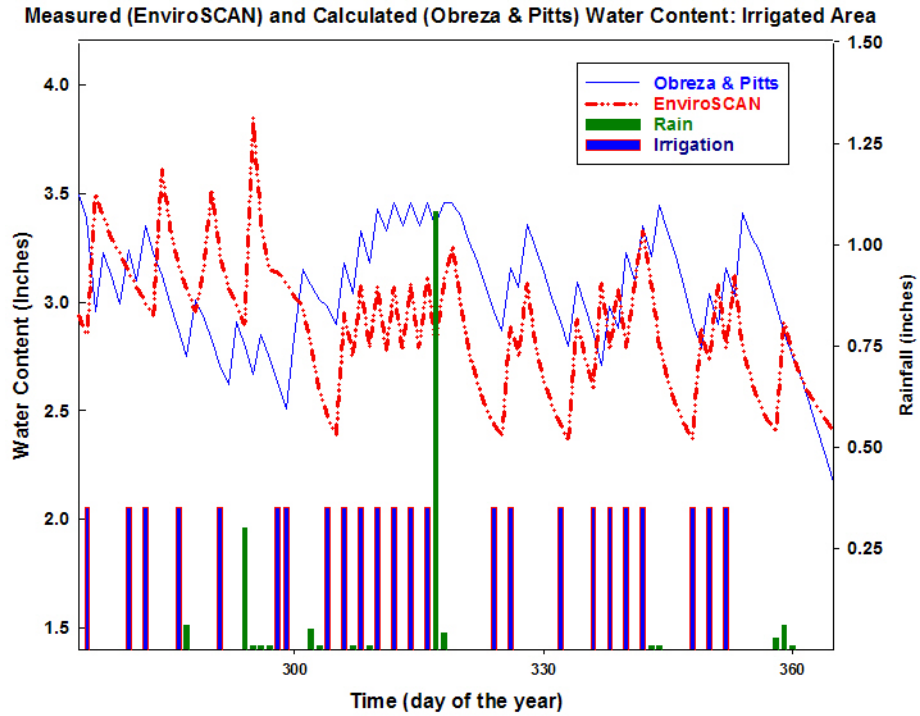

Figure 3

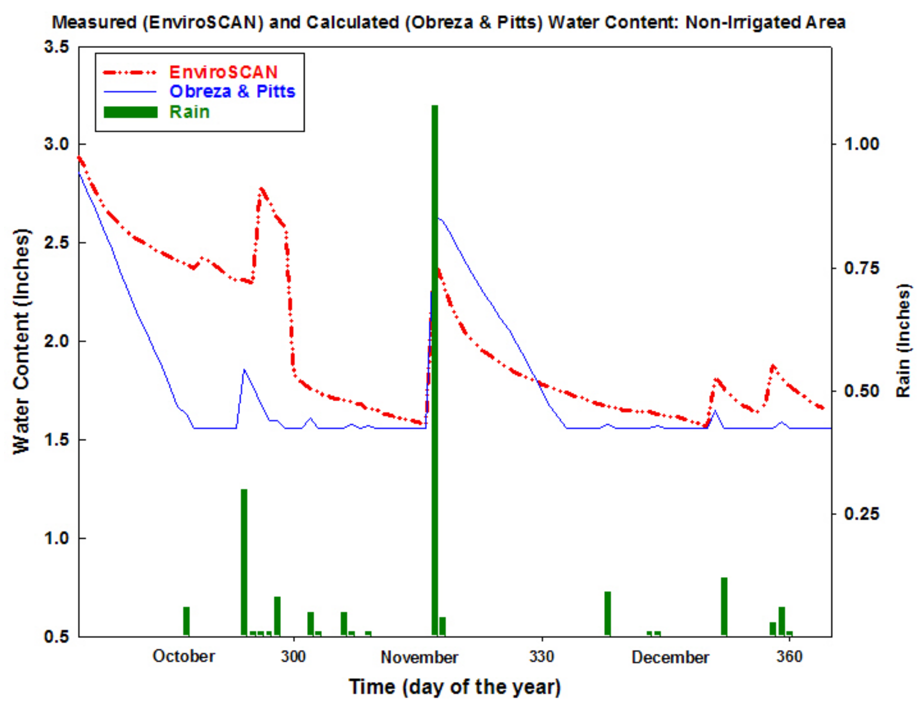

Figure 4

Figure 8 shows the daily and cumulative effective rainfall for the irrigated and non-irrigated areas of the grove. Effective rainfall represented 63 and 100% of the initial rainfall for the irrigated and non-irrigated areas of the grove before it hits any vegetated surface. The major factor that contributes to low effective rainfall in the irrigated area was the higher water content in this zone due to irrigation as compared to the drier row middle portion of the grove. Effective rainfall was also low under the canopy because of two other parameters that are specific to this area: irrigation and canopy interception.

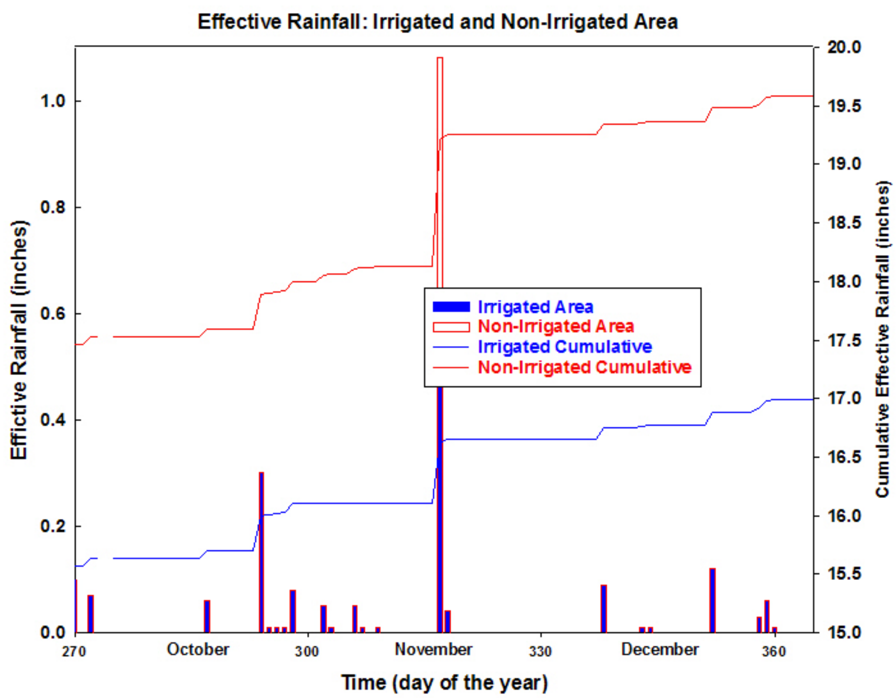

Figure 5

Table 1 summarizes the total monthly (in the row middle and under the canopy) rainfall, effective rainfall, and irrigation for the period of interest. This table shows that 100% of the 2.2 in of rainfall was effective in the row middle; however, it was only 63% under the tree canopy. The composite effective rainfall was 1.66 in or 77% of the total rainfall.

Table 1. Summary of the monthly, rain, irrigation, and effective rainfall (measured and calculated in the irrigated and non-irrigated areas.

Year	Month	Total Rain (inches)	Total Irrigation wtr. appl. (gal/tree)	Monthly Meas. Irrigated Eff. Rain (inches)	Monthly Meas. Non-Irrig Eff. Rain (inches)	Monthly Meas. Comp. Eff. Rain (inches)	Monthly %actual TR-21 Eff. Rain (inches)	Monthly %actual TR-21 Eff. Rain %	Monthly %actual Meas. Eff. Rain %
2001	Oct	0.53	174	0.53	0.53	0.53	0.27	52	100
2001	Nov	1.29	196	0.49	1.29	0.80	0.68	53	62
2001	Dec	0.33	152	0.33	0.33	0.33	0.15	45	100

Summary

Most citrus groves in Florida are irrigated with microsprinklers. These systems do not wet the entire grove floor as did the earlier-used high volume overhead sprinkler systems. Hence, ER in citrus groves with microsprinkler systems is spatially and temporarily variable. The soil water status in both irrigated and nonirrigated zones was monitored in real-time. There were significant differences in water content dynamics between the irrigated and non-irrigated areas of the citrus groves. Results of three months showed that 100% of the 2.2 in of rainfall was effective in the non-irrigated area of the groves; however, only 63% was effective rainfall for the irrigated area under the tree canopy.

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Blockage in Micro Irrigation Systems – Causes and Cures

Main Entry: **blockage**
Pronunciation: 'blä-kij
Function: noun
an act or instance of obstructing : the state of being blocked, :to block, choke, clog, close congest, obstruct, occlude, plug, stop, cork, pack, impedance, impediment, disrupt, hinder, interrupt, cut off, shut off, turn off, to make unsuitable for passage or progress by obstruction, to prevent normal functioning of ,

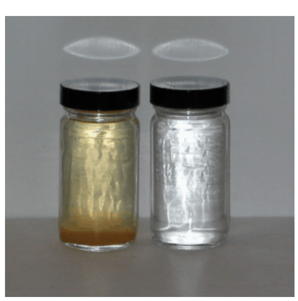
<a blockage in a coronary artery (or micro irrigation system)>

Blockage of emitters is the most serious problem when dealing with micro-irrigation systems. Properly designed and maintained filtration systems generally protect the system from most blockages. Blockages cause poor water distribution, which in turn may damage the crop if emitters are plugged for a long period of time. When the plants show excessive stress, it is generally too late to correct the problem. Therefore, multiple emitters per plant are highly recommended. The main causes of clogging include algae, bacterial slime, precipitates, construction debris, and sediment. In general, adequate filtration, line flushing, and chemical treatment can prevent most blockage.

It's like the old game of Twenty Questions? Is it a Mineral, Vegetable, or Animal? When it comes to blockages, it can be one of the above or all three. Most blockages are a combination of two or more.

Minerals

Pure mineral blockage is the rarest form of plugging. The most common forms of "alleged" blocking results from iron and calcium buildup. It is common to hear a grower say that he or she has 'an iron or calcium problem'. However, iron is not the cause of this plugging. Iron is what is visible, but it doesn't cause blockage by itself. Almost all iron is soluble and remains in solution. Iron precipitates out of solution only after oxidation has occurred. This oxidation process takes 8 to 12 hours on average. Let me give you an example. If you had a 100 gallon aquarium and you filled it with your irrigation water, at that time there would be no visible iron in the water. The iron would remain in solution, and there would be no sign of any iron in the water. However, if you observe the water the next morning, you would see a light orangish brown dust near the bottom of the aquarium. The iron oxidized overnight and became a heavier molecule, falling out of solution.



The iron bacteria converts soluble iron, from a liquid state (Fe^{2+}), to the insoluble form, (tiny rusty flecks), many times referred to as “red water” (ferric iron (Fe^{3+})). Most naturally occurring iron is in the soluble ferrous state. This tells us that the iron will flow through even the smallest emitter, because it is soluble. Something must catch and hold the iron for it to be visible. However, as stated earlier, the problem isn’t actually the iron. Iron may be visible, but it is only a symptom of an underlying problem rather than the cause. Visible iron is usually associated with bacteria, bacterial slimes, or sulfate reducing bacteria. Iron bacteria will be discussed later. Therefore, organisms are the underlying problem associated with iron buildup. The iron buildup is only a symptom of this underlying problem. The organisms are filimentatious, which are long stringy organisms. In the case of bacterial slimes, the organisms appear in the form of a jelly. These organisms begin to lay down a matrix, and as the organisms continue to grow, this matrix becomes deeper and begins to form a cross-linked matrix. This matrix resembles a fine polymer filter. This “filter” then begins trapping even the smallest particles, such as iron or calcium. This gives iron the opportunity to oxidize, and it becomes visible in the form of rust. Therefore, when you open up a blocked emitter, you will see visible signs of rust. What you don’t see is the green, brown, black or red algae, or the bacterial slime that is growing underneath the iron. Filters are normally not fine enough to catch these organisms, they are built primarily for filtering out particulate matter. When the filter begins to plug, colonies of organisms begin to build within the filter. An indication of this is when the pressure rises and flow rate is reduced through the system.

The other mineral of most concern is calcium, which appears as a white crusty deposit. If hardness, a term used to measure calcium and magnesium content in water, creates a blockage, it would take the form of “scale”. Scale is generally formed by the calcium becoming insoluble and falling out of solution. Calcium deposits in micro-irrigation are usually too small to determine constituents via qualitative analysis. However, a simple field test can be performed. If a small amount of acid (such as hydrochloric acid (also called muriatic), phosphoric acid, nitric acid, or vinegar) is dropped onto the deposit, the deposit will dissolve.

Calcium hardness in water is generally determined by the amount of calcium available in the ground. In Florida, shells provide a source of calcium and iron. The discoloration in seashells is caused when the animal takes in the sea water and extracts calcium and iron to form its shell. In places such as Atlanta that have granite as the major substrate, we find that the hardness of water is almost zero due to the fact that granite does not dissolve in water. The quality of this water is excellent, but it is also corrosive. When you reduce water’s hardness (calcium and magnesium), it tends to become corrosive. This explains why installing a water softener in your home often causes problems with copper fittings and elbows. The water leaches the copper out of the pipes. Out West, you are more likely to find more calcium sulfate with moderate amounts of calcium carbonate. Calcium sulfate is less soluble and much more likely to form scale. As a general rule, if you have higher calcium you will have lower corrosion, and lower calcium will mean higher corrosion.

How much calcium is in the water? To put the amount of calcium in the water in perspective, consider how much or little is in the water and what it means. At 200 ppm, that translates to 200 lbs. of calcium for every million lbs. of water. That is 200 lbs. in every 120,000 gallons of water. On a percentage basis this is 0.02%. This is a very small amount and is being spread over a large area. 200 lbs. of calcium can be spread over 40 acres and would form a very thin film. At this concentration, the calcium would not form scale for many years. In order for scale to cause clogging at these levels, the drip tape would have to be several decades old.

A mineral scale will generally not form without heat and pressure, such as you would find in a cooling tower or boiler. It takes heat, an imbalance of alkalinity vs. calcium, or recirculation and evaporation for scale to form.

A very simple formula can be used to determine if the calcium is soluble or insoluble. Take your total alkalinity or M-alkalinity, and multiply by your total hardness (which is the total calcium and magnesium carbonate or calcium and magnesium sulfate).

$$\text{M (or total) Alkalinity} \times \text{Total Hardness} \leq 110{,}000$$

The total M must be less than 110,000. An example, 400 ppm hardness and 225 ppm alkalinity (which is extremely high) only yields 90,000 which is far less than 110,000. The calcium in this example is soluble. If the number is above 110,000 the calcium is going to come out of solution. You would generally add acid to reduce the alkalinity. In this case, you can use sulfuric or n-furic. This will reduce the alkalinity, but it does not affect the calcium. You can use any acid, however sulfuric is generally used for pH control because it is highly concentrated and inexpensive. I have never seen insoluble calcium in agricultural irrigation water. However, I have seen it deposited on organic growths. If you remember the aquarium example, the same rule applies to calcium. However, in this case the calcium is not going to come out of solution even if you let the water sit overnight. The calcium will remain soluble and you will not see calcium on the bottom of the container. It isn't impossible for calcium to fall out of solution, but it's extremely unlikely. Therefore, plugging from hardness in the water is not a major cause of blockage.

Other minerals in the water are found in such small concentrations, (silica, sulfates, chlorides, etc) that the chance of forming scale and blockage is remote. The mineral most likely to cause plugging is silt. Silt is a combination of sand, clays, and other insoluble soils. This is a filtration issue that can be solved by using an effective filter. Coarseness of filters, the costs, etc are all variables involved in choosing the right filter for your system. Generally, the best type of filter is a media filter. The sand can be supplemented with DE (diatomaceous earth) for very fine filtration if necessary.

Plants and Algae

In the most general sense, a plant is a member of the lower or vegetable order of living organized things. Thallophyta are the most lowly organized plants and include a great variety of forms, the vegetative portion of which consists of a single cell or a number of cells forming a more or less branched thallus. They are characterized by the absence of differentiation of the body into root, stem and leaf which is a common feature in higher plants. Both sexual and asexual reproduction occurs in these types of organisms. They can be unicellular or complex organisms, lack mobility, have simple processes for digestion and reproduction, have little defense mechanisms, tend to have thinner cells walls, and can either be aerobic or anaerobic. They can survive and thrive in sunlight, darkness, or a combination of the two. Even if they become substantially dehydrated, these organisms will revive when exposed to water again. Types of these include algae (including Seaweeds) which contain chlorophyll, the Fungi which have no chlorophyll and therefore lead a saprophytic or parasitic mode of life, and the Lichens which are composite organisms consisting of an alga and a fungus living together in a mutual parasitism (symbiosis). A study of phylogeny has suggested twelve classes arranged in the following sequence: (1) Bacteria; (2) Cyanophyceae (Blue-green algae); (3) Flagellatae; (4) Myxomycetes (Slime-fungi); (5) Pendineae; (6) Conjugatae; (7) Diatomaceae (Diatoms); (8) Fleteroconteae; (9) Chlorophyceae (Green Algae); (10) Characeae (Stoneworts); (II) Rhodophyceae (Red Algae); (12) Eumycetes (Fungi);

In Green Algae (the most common algae) the differentiation of cells is comparatively slight. Many forms, even when multicellular, contain identical cells in structure and function, and are therefore physiologically unicellular. The cells are commonly joined end to end in simple or branched tissue filaments. These contain chlorophyll and constitute a self supporting organism. The rhizoid, a certain type that lives on or in the soil, penetrates the ground to absorb food substances (dissolved salts) from the substratum.

The simpler Fungi, like the Green Algae, consist of single cells or simple or branched cell-threads. However, among the higher forms, a massive body is often formed, particularly in connection with the formation of spores, and may exhibit considerable tissue-differentiation. A characteristic feature of the fungal vegetative body (mycelium) is its formation from independent tubes or cell-threads. These organisms branch, and may be packed or interwoven to form a very solid structure, but each grows in length independently of the others and retains its own individuality. Its growth is defined by external conditions and is correlated with that of its neighbors.

Plugging can be caused by the plant that you are growing. Some plants such as watermelons, or peppers have extremely fine hairs which can penetrate into the emitters and cause plugs. A root control agent can be used to remove roots from micro-irrigation systems if handled properly.

If you are using your irrigation system for fertigation, you need to remember that just as the fertilizer makes your plants grow, it will also make algae and slimes grow. So while fertigation is great, you need to remember that you may be making your plugging problem worse. During times of the year when there is a shortage of water, plants and algae will draw it up as much as possible in order to survive.

Plants are much easier to control. Think of the difference between killing a plant and trying to kill a wild boar. The dead cells from plants bio-degrade much easier than that of animals. Plants will scavenge the dead cells for food. Simple plants will consume dead cells with the same DNA readily and but are apprehensive about taking in cells with foreign DNA.

Animals and Bacteria

Any of a kingdom (Animalia) of living things including many-celled organisms and often many of the single-celled ones (as protozoans) that typically differ from plants in having cells without cellulose walls, in lacking chlorophyll and the capacity for photosynthesis, in requiring more complex food materials (as proteins), in being organized to a greater degree of complexity, and in having the capacity for spontaneous movement and rapid motor responses to stimulation. The lack of a rigid cell wall allowed animals to develop a greater diversity of cell types, tissues, and organs. Most animal bodies are made up of organized cells that are specialized to perform a specific task. Other cells are organized into even more specialized organs. Most animals are capable of moving relatively fast, unlike plants. Most animals reproduce sexually. Single-cell animals, and bacteria, typically have some mechanical means of movement. Some bacteria use long external whip-like filaments called flagella. Flagella are rotated by a molecular motor to cause propulsion through water. The larger single-cell animals may use flagella similar to bacteria, or they may have rows of short filaments called cilia, which work like oars. Most ingest food and digest it in an internal cavity. Some one-celled organisms display both plant and animal characteristics.

Some of the lower organisms that affect irrigation are iron bacteria, sulfate reducing bacteria, denitrifying and nitrifying bacteria. Some are beneficial and others can cause severe problems throughout the system.

Iron bacteria [...(1) Leptothrix Ocharacea ...(2) Gallionella Ferruginea ...(3) Spirophyllum Ferrugineum ...(4) Crenothrix Polyspora ...(5) Cladothrix Dichotoma ...(6) Clonothrix Fusca] are bacteria that “feed” on iron. They are a natural part of the environment in most parts of the world. There are several non-disease causing bacteria which grow and multiply in stringy clumps in water and use iron dissolved in water as part of their metabolism. In the presence of the bacteria, the dissolved iron reacts with the oxygen from the air forming rust colored iron oxides. These oxides do not dissolve in water and either settle to the bottom or are stored in the slimy jelly like material that surrounds the iron bacteria’s cells.

Simply because iron is abundant in ground water, iron bacteria is generally more common than sulfur bacteria. Iron bacteria are "oxidizing agents." That is, they combine iron or manganese dissolved in ground water with oxygen. A side effect of this process is a foul smelling brown slime which can coat well screens, pipes, and plumbing fixtures. This slime isn't a health hazard, but it can cause unpleasant odors, corrode plumbing equipment, and clog well screens and pipes. If conditions are right, the bacteria can grow at amazing rates and an entire well system may be rendered virtually useless in just a few months. There are several signs that may indicate an iron bacteria problem. Water may have a yellow, red or orange color. Rusty slime deposits may form in the distribution system. A strange smell resembling fuel oil, cucumbers, or sewage may be noticeable. Sometimes the odor will only be apparent in the morning or after other extended periods of non-use.

Sulfur Bacteria

There are two categories of sulfur bacteria: sulfur oxidizers and sulfur reducers.

Sulfur-oxidizing bacteria

Sulfur-oxidizing bacteria produce effects similar to those of iron bacteria. They convert sulfide into sulfate, producing a dark slime that can clog plumbing.

Sulfur-reducing bacteria

Sulfur-reducing bacteria (SRBs) live in oxygen-deficient environments. They break down sulfur compounds, producing hydrogen sulfide gas in the process. Hydrogen sulfide gas is foul-smelling and highly corrosive.

Of the two types, sulfur-reducing bacteria are the more common. The most obvious sign of a sulfur bacteria problem is the distinctive "rotten egg" odor of hydrogen sulfide gas. As with odors caused by iron bacteria, the sulfur smell may only be noticeable when the water hasn't been run for several hours. In some cases, the odor will only be present when hot water is run; this could indicate that SRBs are building up in the water heater. Blackening of water or dark slime coating the inside of water system may also indicate a sulfur bacteria problem.

Iron bacteria and sulfur bacteria contaminations are often difficult to tell apart because the symptoms are so similar. To complicate matters, SRBs often live in complex symbiotic relationships with iron bacteria, so both types may be present. Fortunately, both types of bacteria can be treated using the same methods.

Virus- Viruses are not alive in the strict sense of the word, but reproduce and have an intimate, if parasitic, relationship with all living organisms. Viruses invade plants and animal cells, but are not part of either kingdom.

Treatments

Chlorine

Chlorine has been tried with limited success and effectiveness. It does kill at high concentrations, but it does not remove cells at lower dosages. The dead cells will remain and become food for future generations. These dead cells allow organisms to grow much more quickly. The growth cycle for these organisms is 7 to 10 days. They grow exponentially: 10^2 to 10^5 power, 100 to 100,000 times growth rate. One of the things to think about with chlorine is that chlorine is adequate for prevention, but it is not good for the removal of organic matter. An example would be a mildewed towel or shirt. It would show signs of mildew as black spots. An initial plan may be to place it in the laundry with some chlorine bleach. You will notice when you remove it from the laundry that the chlorine has in fact faded the spots slightly, however the spots do remain and are now a slightly lighter black color. Therefore, you decide to increase the chlorine dosage and try again. When you do that, you end up with a degraded piece of cloth with holes in it. The stain was removed, but you destroyed the cloth in the process. This same thing would happen in the field. Small doses are usually recommended, up to 5 ppm on plants. At higher dosages you would cause serious damage to the tissue of the plant, just like it caused damage to the cloth in the above example.

Liquid bleach is about 10 percent chlorine. A 20 ppm chlorine shock treatment for an irrigation system with a capacity of 500 gpm would require approximately 6 gallons of chlorine per hour or about one-tenth of a gallon of bleach per minute. One should continuously monitor system performance and adjust the water treatment and maintenance schedule as needed. Chlorine will inhibit growth at the time of treatment, but it readily dissipates and does not remove organic matter at this 20 ppm shock level unless treatment is continuous for 6 to 12 hours.

Acids

A wide variety of acids have been used for treating water. Acids fall into two categories: mineral acids which include sulfuric, hydrochloric (muriatic), nitric, phosphoric, and n-furic, and organic acids such as sulfamic and citric. Various combinations have been tried with mixed results. Acids are usually corrosive to tissue and to metals, and can contribute high levels of chlorides, sulfates, and phosphates which can form compounds that will cause blockages. Acid has no killing power. It will not destroy the cell walls. Another of the effects of using acid in these systems is that acids dehydrate and draw water out of tissue. Acids will even draw the water out of plastic. If you spill acid on your hands, you will see your skin begin to shrivel up. Contrary to popular belief, your skin is not being burned, but rather the acid is drawing the water out of your skin. After contact with acid, Plastic becomes extremely brittle and at times you can touch it and it will shatter. It will dehydrate tissue in a high enough concentration, but if it dehydrates the cell walls of tiny organisms, it will also dehydrate plants.

Industrial water treatment facilities frequently use acid to increase calcium solubility. The acid is added to reduce the alkalinity. The calcium becomes more soluble as the alkalinity decreases. This allows the water to be able to hold more calcium in solution to keep the calcium from forming scale (blockage). In this case, acids are not added to water to remove calcium, but to lower the alkalinity. Almost any acid can be used to reduce alkalinity, but again, as I stated above, generally sulfuric acid is used due to low cost and higher concentration.

Most of the mineral acids will attack and dissolve calcium. Acids are used to remove scale that has formed. In order to remove calcium using an acid, the pH of the water must be below 2.5 and must remain below 2.5 while the calcium is slowly dissolved. Of course, a pH below 2.5 would be extremely toxic to plants. Many acids are used for descaling, including organic acids such as sulfamic, which is frequently used in cooling towers.

Sulfuric and n-furic acid are not used to remove calcium. Neither acid will dissolve acid. Sulphuric and n-furic have no effect on calcium. Many years ago I had a customer who was purchasing drain opener (sulfuric acid) in large quantities. I finally asked them what they were trying to do with all of this drain opener. They explained that an opossum crawled into a sewer pipe and died, and they were trying to dissolve the bones which would be easier than digging up the sewer pipe. They had been using countless gallons of sulfuric acid. We suggested they try hydrochloric acid and in one dose, it dissolved the bones and opened the sewer pipe.

Pour sulfuric acid and hydrochloric acid side by side on concrete. The sulfuric acid won't bubble and fizz as hydrochloric acid does. Looking at the photograph, you can see that the sulfuric acid has no visible effects on the concrete while the hydrochloric acid shows great activity.

Acid treatments have also been tried. Acids first reduce the bicarbonate alkalinity. In order to dissolve calcium, all of the alkalinity must be 100% removed before the acid can attack the calcium. In the water sample we discussed previously, 200 ppm of total alkalinity requires 200 ppm of acid (active). If you are using sulfuric or n-furic acid, the alkalinity can be reduced to 0 ppm, but that's as far as the acid can go. These acids do not attack or dissolve calcium. The pH at which the acid will dehydrate cell walls is below 3.5.

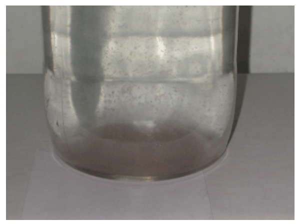
Acids and Chlorine

The idea behind this treatment is that chlorine works best at a lower pH, and the acid will lower the pH. Yes, it is true that the acid will lower the pH and that chlorine does work better at a lower pH. But what happens is that the acid shears the chlorine from the hypochlorite molecule and releases it into the water to form a salt. The caustic nature of the hypochlorite solution neutralizes the acid. They work against each other. And the bad part is that the chlorides are still available to the plant and usually it forms salt (sodium chloride). A simple experiment shows the results. Add 1.3 ozs. (38 grams) of a 10% liquid chlorine solutions to a 5 gallon bucket of water. This will yield a chlorine residual of 2 ppm. Now add the same amount of sulfuric acid to the bucket and stir. Run the chlorine test again, and then check the pH. The chlorine level will be zero and the pH will be around 5.0.

New Technology

The advent of new organic compounds have given us a new compound for treating blockages. A derivative of peracetic acid (or peroxyacetic acid) has proven effective at removing blockages of all types. It removes the organisms from emitters which releases the calcium and the iron deposits. The dosages used are as low as 100 ppm. This compound does not affect the pH, it does not affect plants, it has no taste, it leaves no residue, it is 100% organic, and it is economical to use. It can also be used in weekly dosages to prevent the blockage from ever occurring. It has been used in greenhouses and has been sprayed on orchids at 1500 ppm with no resulting damage. The only effect during this experiment was the removal of lichen moss that was growing near the root of the orchid. This new compound is non-specific in that it removes all organisms including algae, bacteria, viruses, slimes, molds, etc. Using an injector for precise control has yielded superior results in unplugging drip tape, drip lines, micro jets, and other micro irrigation equipment. It is best to inject this compound before the filter as the compound also cleans the filter and thereby removes the greatest source of contaminants within the irrigation system.

Final Results



The only disadvantage of this new material is that it is a corrosive oxidizer. Therefore, it has the potential of causing severe burns and eye damage while in concentrated form and should be handled with caution.

Investing for Profitability: How Water Conserving Irrigation Technology Improves Farm Profitability

By Inge Bisconer, Dean Best and Mark Hewitt, Rain Bird Agri-Products

Growers are increasingly encouraged to conserve water because fresh water is becoming more scarce each day, and because there are social/environmental costs associated with wasting our most precious resource, water. When growers set out to conserve water, they typically expect to spend money on water conserving irrigation equipment, and precious management time, to achieve their goals. It is the subject of this paper to show that in addition to water savings, farm profitability is often increased as a result of decreasing farm costs and/or increasing farm income. In fact, increased profitability is often the primary motivator for adoption of water conserving equipment rather than just water savings. The three examples that follow illustrate that water can be saved and overall profitability increased by adopting modern irrigation technology.

Quady Winery, Madera, CA

The management at Quady Winery knew that the variable soils in their 10-acre home vineyard presented irrigation challenges. When the entire parcel was irrigated manually with a few valves, the sandy soils were often overwatered and/or the heavier soils experienced runoff. Also, the existing drip system was old and needed to be updated. To better manage the vines and irrigate more precisely, in 2003 the system was upgraded with new drip irrigation, additional control valves, soil moisture sensors and a Rain Bird® Cyclik™ wireless control system. Each control valve was placed according to soil type, and the wireless control system allowed individual valves to be easily and inexpensively programmed to apply the right amount of water at the proper frequency. Western Ag and Turf in Madera, CA supplied the design, materials and expertise.

Each soil type on the home vineyard was now irrigated properly and water was saved. For instance, the sandy soils were never irrigated more than an hour at a time, and the heavier soils never were irrigated more than four hours at a time. This cycle and soak irrigation method applied water to the soil in a manner which maximized lateral water movement in the soil profile as opposed to downward water movement. Thus, deep percolation and runoff were avoided, and less water was applied overall. Specifically, irrigation run time was decreased from 65 hours per week down to 36 hours per week, a net savings of 45%. Considering a crop ET of about 2-acre feet per acre, 4.44-acre feet was applied without the upgrade, and only 2.22-acre feet with the upgrade. This amounted to net savings of 22.2-acre feet for the 10-acre vineyard, which is over 7 million gallons of water! But that's not all.

In addition to water savings, other irrigation expenses were significantly reduced. Pumping costs decreased from $187 per acre to $93 per acre, a net savings of $94 per acre. Irrigation labor decreased from $720 per acre (one laborer working on irrigation 12 hours per day about 50 days per year) to $144 per acre, a net savings of $576 per acre.

Naturally, in order to make these gains, an investment was required. Here's how much: the irrigation system improvements cost $805 per acre including $354 for the new drip irrigation, $204 per acre for the valves, controls and sensors, and $247 per acre for labor and misc. pipe and fittings. In addition, management costs increased to $170 per acre due to the ability to monitor the moisture sensors and program the valves with the proper irrigation schedules.

If these investment costs and resulting savings are graphed in the seven-year Rain Bird® Ag Cash Flow analysis shown below, it can be shown that the system upgrade pays for itself after the first year. After seven years, the cumulative cash flow, all conditions remaining equal, amounts to $2,695 additional profit per acre, or $26,950 additional profit on 10 acres. All this in addition to the 7 million gallons of water saved per season on 10 acres!

Other advantages to adopting modern irrigation technology exist but are less easily quantifiable. First, the ability to properly manage irrigation and improved vine health allow the fruit to sugar up and gain maturity more uniformly and with better predictability. Second, precise irrigation control promotes healthy root systems that help the vines fight off disease. Third, pulse irrigation disperses the water laterally in the soil, to spread out the roots and promote a healthier root system. Fourth, managed deficit irrigation before verasion, and maintaining higher soil moisture later in the season, is the best way to obtain the sugar, color, flavor and phenolics for which the winemaker is looking. Bottom line, Quady management believes that in addition to water savings and increased profitability, winegrape quality has improved as a result of better water management.

RAIN BIRD.

Rain Bird Ag Cash Flow Software

Page 4

Grower Name:	Quady California Desert Wines	Date:	20 Sep 04
Field Location:	Madera, CA	No. Acres:	10
Phone #:	559-673-8068	Crop:	Winegrapes
Project Filename:	C:\Rain Bird Ag\Marketing\Cash Flow Software\Sep 04\Quady Winery 24 Sep 04 DB.rcp		

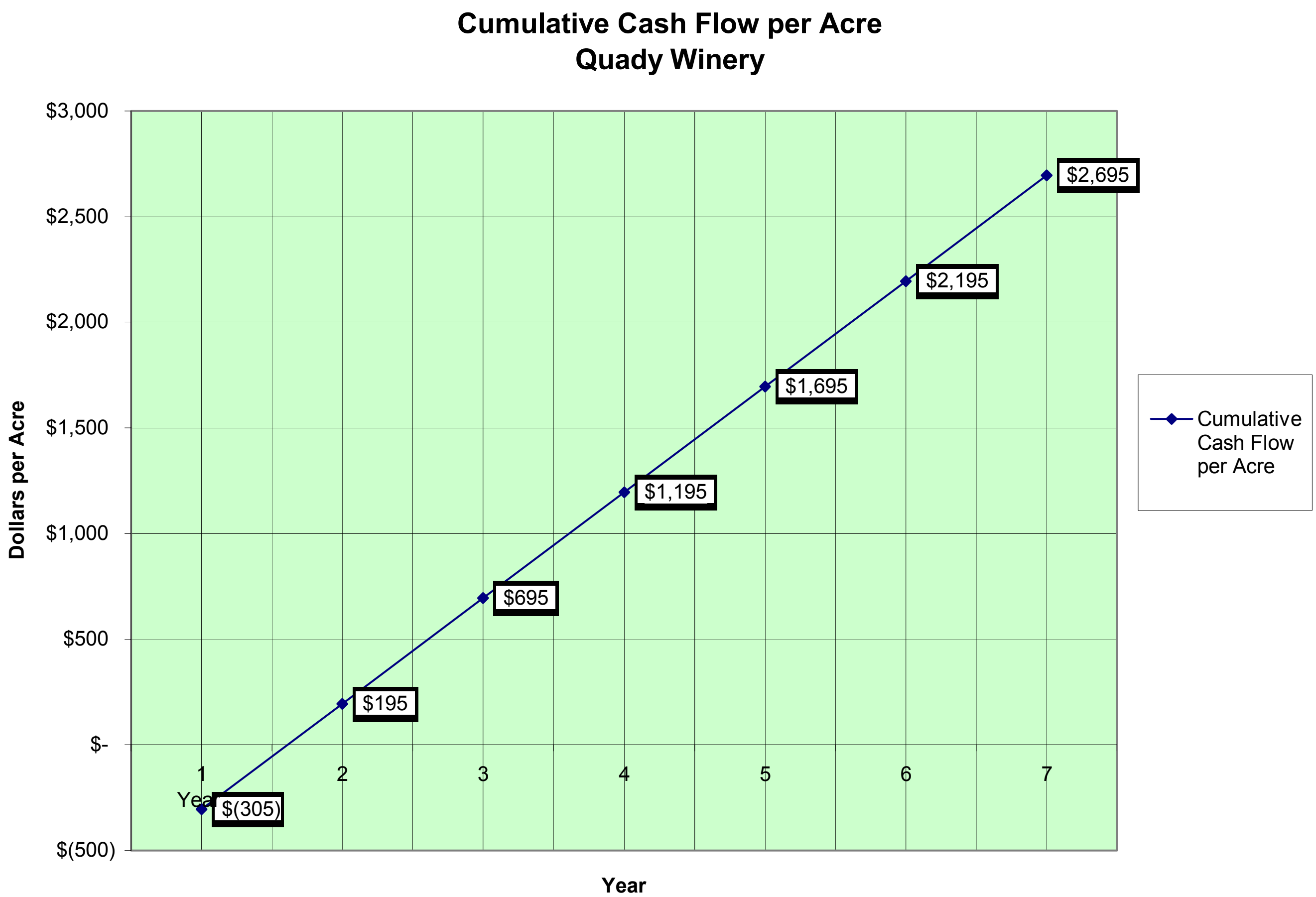
Project Analysis

Project Cost Per Acre:	$ 805
Amount to be Financed:	$ 0
Additional Profit Per Acre:	$ 500

Cash Flow Per Acre

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Project Costs:	$ 805	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
Additional Profits:	$ 500	$ 500	$ 500	$ 500	$ 500	$ 500	$ 500
Cash Flow Each Year:	$ -305	$ 500	$ 500	$ 500	$ 500	$ 500	$ 500
Cumulative Cash Flow:	$ -305	$ 195	$ 695	$ 1,195	$ 1,695	$ 2,195	$ 2,695

It is to be understood that the Rain Bird Ag Cash Flow Software is an estimating tool and does not purport to guarantee any specific results. Individual conditions affecting agricultural results vary widely and are largely unpredictable. Rain Bird does not guarantee or assume responsibility for profits or results attained through the use this planning and estimating tool. It provides the Ag Cash Flow Software solely for your use in planning your farming operations.



Goschie Farms

Gayle Goschie and her brothers just celebrated 100 years of growing hops at their Silverton, Oregon farm. Part of their success is attributed to their ability to continue to incorporate modern farming practices over the years, including irrigation. For decades, Goschie farms irrigated with a large 'gun' sprinkler system which broadcast water widely to the entire crop. The water application efficiencies with sprinklers are considered to be 65% at the farm, and two pumps are required to deliver the water at the proper pressure.

In 2001, a 42-acre drip system using Rain Bird® PC Driplinewas installed to replace the gun sprinkler system. Stettler Supply in Salem, Oregon provided the design, materials and expertise. The improved drip delivery method allowed Goschie management to more accurately adjust the delivery rates and amounts of water for each application, thereby creating more effective water usage. Goschie considers the drip system application efficiency to be 95% which is 30% better than the gun system. Since irrigation in Oregon is supplemental to rainfall, the amount applied through the drip system over the season is only 8"/acre. Thus, on 42 acres, the sprinkler system applies 54-acre feet of water to achieve the 8" desired, whereas the drip system applied only 31-acre feet of water. This is net savings of 23-acre feet on 42 acres, or nearly 7.5 million gallons of water, by using drip irrigation! But of course, that's not all.

Goschie Farms was able to realize other significant cost savings by adopting drip irrigation. First, energy costs were substantially reduced because one booster pump was completely eliminated, and another was turned down from 75 hp to 30 hp. This resulted in net savings of $15 per acre. Irrigation labor was reduced from $30 per acre to $13 per acre as high quantities of low cost labor were replaced with a minimal quantity of medium cost management labor. Cultivation costs were reduced from $60 per acre to $15 per acre because weed growth was reduced under drip, and less mowing was required. Maintenance costs were reduced from $20 per acre to $18 per acre. Chemical costs were reduced from $120 per acre to $80 per acre because of a 20% reduction in fungicide use and a 50% reduction in aphicide use. The reduction in fungal growth and aphid populations is attributed to the reduced humidity associated with drip irrigation.

Perhaps most significantly, yields under drip have increased by 24%, from 6.5 bales per acre with sprinklers to 8.5 bales per acre with drip in 2004. With hops valued at $3.00 per pound, the yield increase alone resulted in a revenue increase of $1,200 per acre! Although more hops were harvested under drip, harvesting costs remained constant since harvesting efficiencies were increased. Fertilization costs also remained constant because the drip system used lower quantities of a higher cost, liquid fed fertilizer compared to the higher quantities of lower cost broadcast fertilizer used with the sprinkler system. Although costs were the same, the drip system provided additional value by allowing for a more precise application of crop nutrients on a weekly basis compared to four applications of granular fertilizer with the gun system.

What did these significant achievements cost? The graphs below illustrate that in addition to water savings, profitability is significantly increased with the adoption of improved irrigation technology. Using Cash Flow, we see that the cost to invest in the drip irrigation system was only $600 per acre, thus the additional profits of $1,308 per year from increased revenue and decreased costs are only offset by $600 per acre the first year. This results in a net gain of $708 per acre the first year, and $8,556 per acre, all things remaining the same, over the course of 7 years. This is an increased profit of nearly $60,000 in seven years on 42 acres in addition to the 7.5 million gallons of water saved the first year! It is likely that with such decisions, Goschie Farms will be farming in another 100 years.

RAIN BIRD.

Rain Bird Ag Cash Flow Software — Page 4

Grower Name: Goschie Farm — Date: 9-24-04
Field Location: Silverton, OR — No. Acres: 42
Phone #: 503-932-8119 — Crop: Hops
Project Filename: C:\Rain Bird Ag\Marketing\Cash Flow Software\Sep 04\Goschie 9-28-04.rcp

Project Analysis

Project Cost Per Acre: $ 600

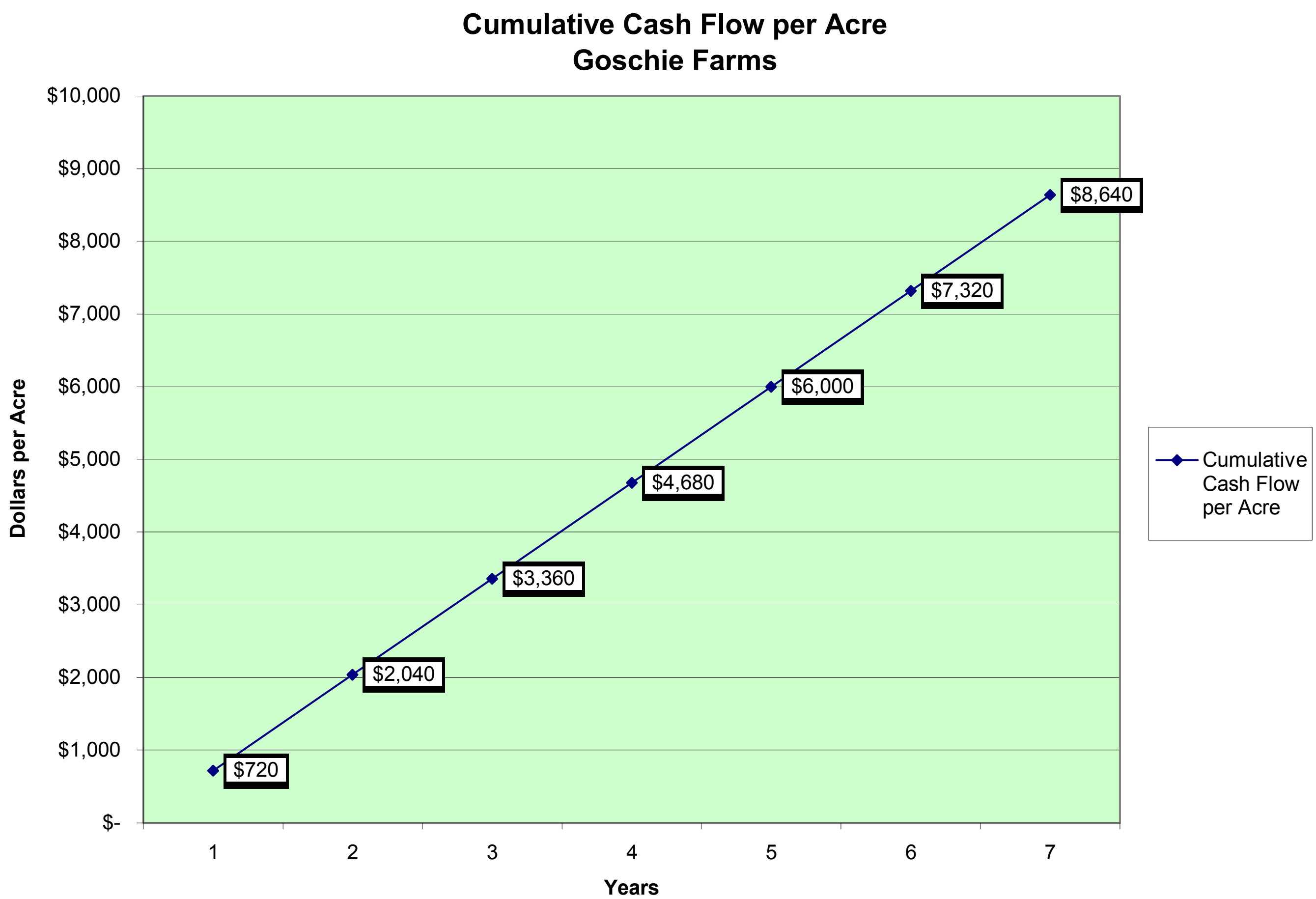
Amount to be Financed: $ 0

Additional Profit Per Acre: $ 1,320

Cash Flow Per Acre

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Project Costs:	$ 600	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
Additional Profits:	$ 1,320	$ 1,320	$ 1,320	$ 1,320	$ 1,320	$ 1,320	$ 1,320
Cash Flow Each Year:	$ 720	$ 1,320	$ 1,320	$ 1,320	$ 1,320	$ 1,320	$ 1,320
Cumulative Cash Flow:	$ 720	$ 2,040	$ 3,360	$ 4,680	$ 6,000	$ 7,320	$ 8,640

It is to be understood that the Rain Bird Ag Cash Flow Software is an estimating tool and does not purport to guarantee any specific results. Individual conditions affecting agricultural results vary widely and are largely unpredictable. Rain Bird does not guarantee or assume responsibility for profits or results attained through the use this planning and estimating tool. It provides the Ag Cash Flow Software solely for your use in planning your farming operations.



Tom Rogers Farm

Tom's family has been growing almonds in Madera for over 20 years. Their 135-acre ranch consists of trees of various ages, but all are highly productive and command premium prices due to quality. Tom is a leader in his community and is interested in doing his part to irrigate properly. Towards that end, he has recently begun several upgrades that have saved him labor and management time, and will ultimately save him water too.

In 2003, Tom invested in Rain Bird® Cast Iron Valves, Cyclik™ controllers and LF1200™ sprinklers. His primary goal was to save labor and management time since, oftentimes, it was he that changed the valves and checked the sprinklers. Tom felt that higher value activities should occupy his time, and that automation was key. Tom first upgraded his sprinklers because "without reliability, I cannot automate." Once the system was reliable, the investment in the wireless control system allowed him to program the valves to come on and off at the right time without extensive support from labor or management. The cost of the upgrade was $452 per acre including $236 per acre for sprinklers, $118 per acre for controls, valves and sensors, and $98 per acre for miscellaneous pipe, fittings and labor. Western Ag and Turf in Madera provided the design, materials and expertise.

This past year, upgrading the system saved Tom significant labor and management time. Specifically, he reduced irrigation labor costs from $36 per acre to $9 per acre, and management time from $358 per acre to $89 per acre. As illustrated in the Cash Flow graphs below, Tom paid for the system within two years, and the investment yielded $1,620 per acre in additional profits over a seven-year time period. On 47 acres this amounts to over $76,000 over seven years!

RAIN BIRD

Rain Bird Ag Cash Flow Software — Page 4

Grower Name: Tom Rogers
Field Location: Madera, CA
Phone #: 559-930-0340
Project Filename: C:\Rain Bird Ag\Marketing\Cash Flow Software\Sep 04\Tom Rogers 26 Sep DB.rcp
Date: 20 Sep 04
No. Acres: 47
Crop: Almonds

Project Analysis

Project Cost Per Acre: $ 452

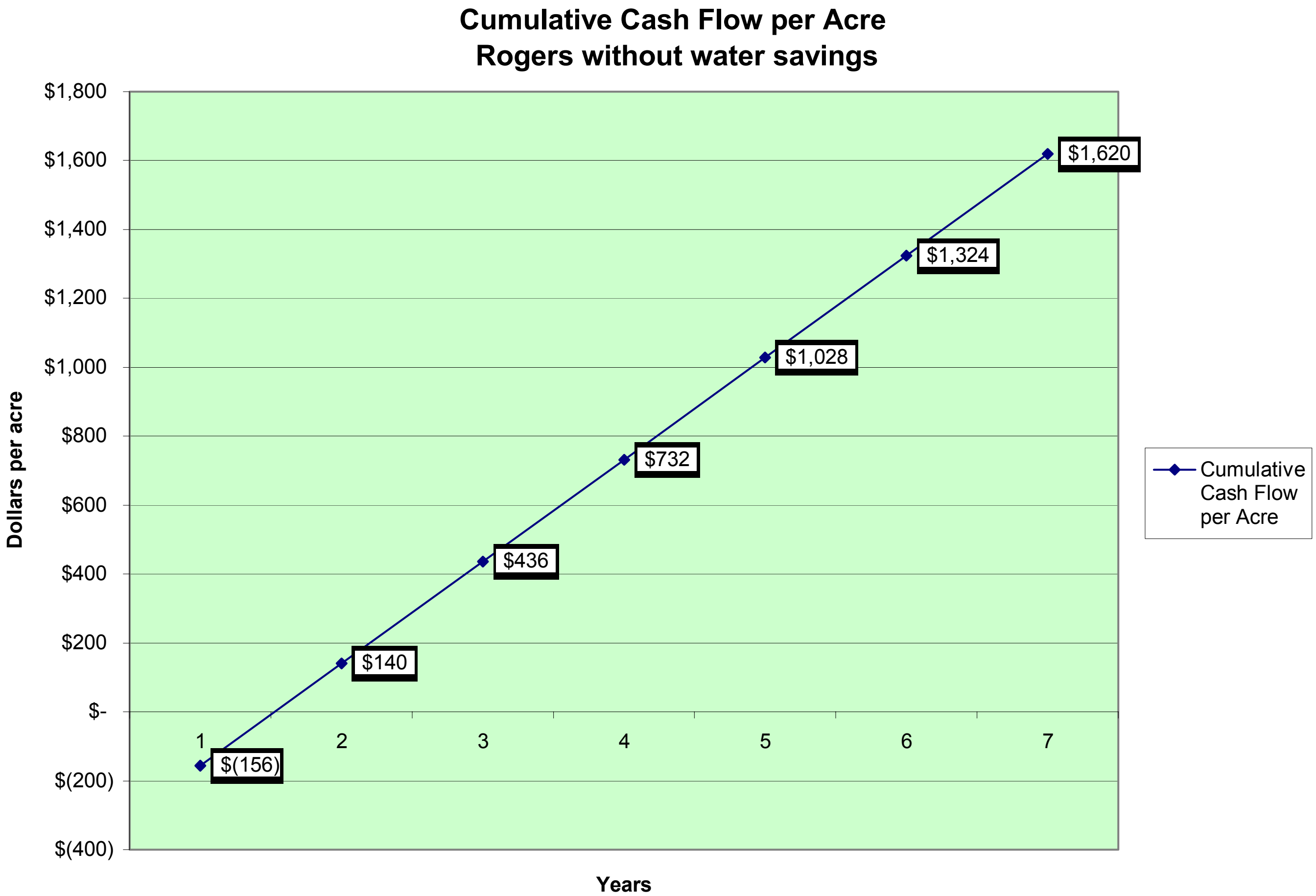
Amount to be Financed: $ 0

Additional Profit Per Acre: $ 296

Cash Flow Per Acre

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Project Costs:	$ 452	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
Additional Profits:	$ 296	$ 296	$ 296	$ 296	$ 296	$ 296	$ 296
Cash Flow Each Year:	$ -156	$ 296	$ 296	$ 296	$ 296	$ 296	$ 296
Cumulative Cash Flow:	$ -156	$ 140	$ 436	$ 732	$ 1,028	$ 1,324	$ 1,620

It is to be understood that the Rain Bird Ag Cash Flow Software is an estimating tool and does not purport to guarantee any specific results. Individual conditions affecting agricultural results vary widely and are largely unpredictable. Rain Bird does not guarantee or assume responsibility for profits or results attained through the use this planning and estimating tool. It provides the Ag Cash Flow Software solely for your use in planning your farming operations.



Although the irrigation system uniformity at Rogers farm was improved approximately 10% with the purchase of new sprinklers, Tom did not take advantage of that feature the first year; he applied 3.75 acre-feet of water to all of his trees regardless of sprinkler uniformity values. If he takes advantage of the higher uniformity performance of the new sprinklers and runs them a shorter duration next year, Tom could save 25-acre feet of water or more on his 47 acres, a saving of over 8 million gallons of water! In addition, the cost of his energy and water could be reduced from approximately $175 per acre to approximately $147 per acre for a net additional saving of approximately $28 per acre. If this potential savings were added to the labor savings already mentioned, Tom could reap an additional $1,816 of profits per acre over seven years. On 47 acres, this amounts to over $85,000 of additional profits over seven years in addition to saving 8 million gallons of water or more each year!

RAIN BIRD

Rain Bird Ag Cash Flow Software

Page 4

Grower Name: Tom Rogers
Field Location: Madera, CA
Phone #: 559-930-0340
Project Filename: C:\Rain Bird Ag\Marketing\Cash Flow Software\Sep 04\Tom Rogers with water savings1.rcp

Date: 20 Sep 04
No. Acres: 47
Crop: Almonds

Project Analysis

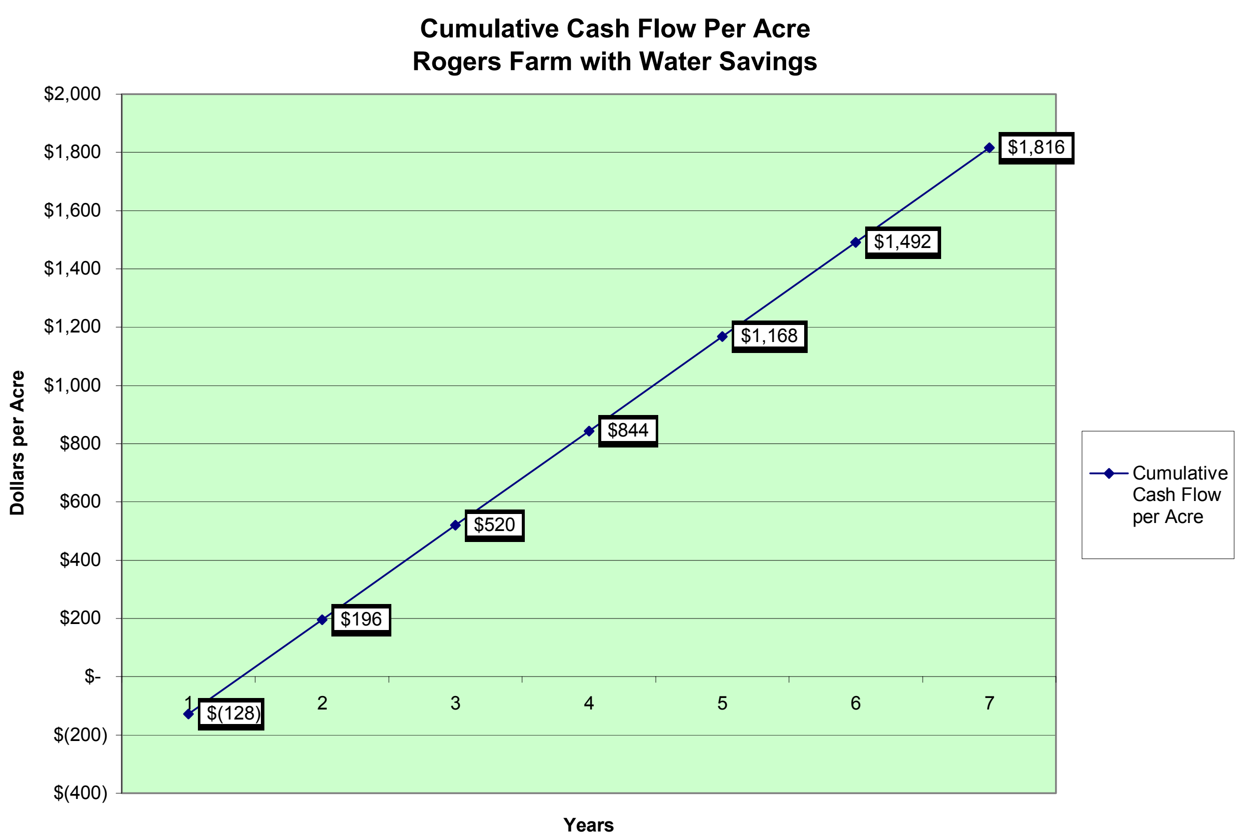
Project Cost Per Acre: $ 452

Amount to be Financed: $ 0

Additional Profit Per Acre: $ 324

Cash Flow Per Acre

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Project Costs:	$ 452	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
Additional Profits:	$ 324	$ 324	$ 324	$ 324	$ 324	$ 324	$ 324
Cash Flow Each Year:	$ -128	$ 324	$ 324	$ 324	$ 324	$ 324	$ 324
Cumulative Cash Flow:	$ -128	$ 196	$ 520	$ 844	$ 1,168	$ 1,492	$ 1,816



Summary

In summary, water conservation is important and warrants investment in irrigation technology because of the substantial amounts of water that can be saved. However, the capabilities inherent in water conservation equipment often reduces farm costs and increases farm income so much that the cost of buying water conservation equipment is usually offset within the first few years after adoption. This makes investing in water conservation equipment a win-win for both growers and the communities where they operate because water is saved and farm profitability is increased.

Paper #1060

Low Pressure Drip Irrigation--Concept and Description

By

Claude J. Phene[1], Dennis Hannaford[2], Claude Phene II[3]
Scott White[4], Thomas L. Thompson[5], Pat Fernandes[6], Mike Illia[7]

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INTRODUCTION

Since its introduction in the 1960's, the availability, quality, management and performance of drip irrigation (DI) and subsurface drip irrigation (SDI) have greatly improved. The uses of DI and SDI have increased significantly as understanding and benefits of real-time irrigation methods increased and plastic materials availability, manufacturing processes, emitter designs and fertilizers improved. However, the perceived high initial cost of DI and SDI systems have slowed down the conversion of gravity irrigation to these systems. The low pressure system (LPS) is a systematic development of a low cost DI system which performs as DI except that the water is applied 3-4 in. (0.08-0.10 m) below the soil surface through discrete emitters, with a wide ranges of discharge rates and spacings. The low pressure capability of LPS (2-3 psi; 0.14-0.21 kg/cm^2) provides an effective low energy and economical upgrade for furrow irrigation. Furthermore, LPS mitigates environmental issues arising from difficult-to-control surface irrigation, non-point source pollution, deep percolation of soluble salts and pesticides, erosion and sedimentation of watersheds. The introduction of LPS provide an alternative initial low cost systems with a multiyear life expectancy displaying a number of advantages associated with permanent DI and SDI systems.

CONCEPT

The major objective of LPS is to provide a one-to-three year life span irrigation system with water and fertilizer application advantages of DI and SDI systems but at a lower initial cost, although the initial LPS cost is dependent on the sophistication level of the LPS. Conceptually, LPS is specifically designed to: (1) help growers use existing infrastructures such as leveled fields, water sources and pumps, (2) minimize front end investment (3) provide fast return on investment, (4) reduce energy cost for pumping and pressurizing, (5) move and reuse equipment easily and (6) provide low system maintenance and management. Two visualized additional advantages of LPS could be: (1) low pressure/low flow design suggests that LPS could operate similarly to furrow irrigation by applying water uniformly over 1/4 mile- (400 m)-long rows and thus could potentially replace large Western furrow irrigated acreage and (2) water discharge rates being lower than most soil infiltration rates would not require the use of rigorous high frequency irrigation scheduling (LPS can stay on for longer periods of time without creating runoff and/or deep percolation). As an example, Figure 6 shows the downstream end of a uniform potato field (800 ft. long; 250 m) irrigated by a LPS in the Arava Valley, Israel. The water distribution and the potato crop canopies are highly uniform across the whole field.

Components of a Typical LPS System

A typical LPS consists of several specific components. Depending on the size of the system, the topography of the site, the soil characteristics, the crop, the water/fertility requirements, the water source, availability and/or quality or the application considered, LPS may vary considerably in physical layout but generally will basically consist of some of the components shown in Figure 1, although LPS will often be as simple as the system shown in Figure 2. The various components of the system can be added as desired and are divided into: (1) connection to water source, (2) control headworks including a fertigation system, (3) field distribution system, (4) dripperline laterals, (5) accessories and installation tools and (6) optional automation and instrumentation. These components will be briefly described and discussed below:

1. Connection to Water Source

a. <u>Alfalfa Valve</u>--Many furrow irrigation systems are using alfalfa valves to deliver irrigation water from an elevated reservoir to gated pipes, head ditches and hand siphons. Assuming that the steady state static pressure from the reservoir is at least 7-8 ft. (2.1-2.5 m), alfalfa valves, fitted with a bell coupling, provide an ideal water supply connection for the LPS.

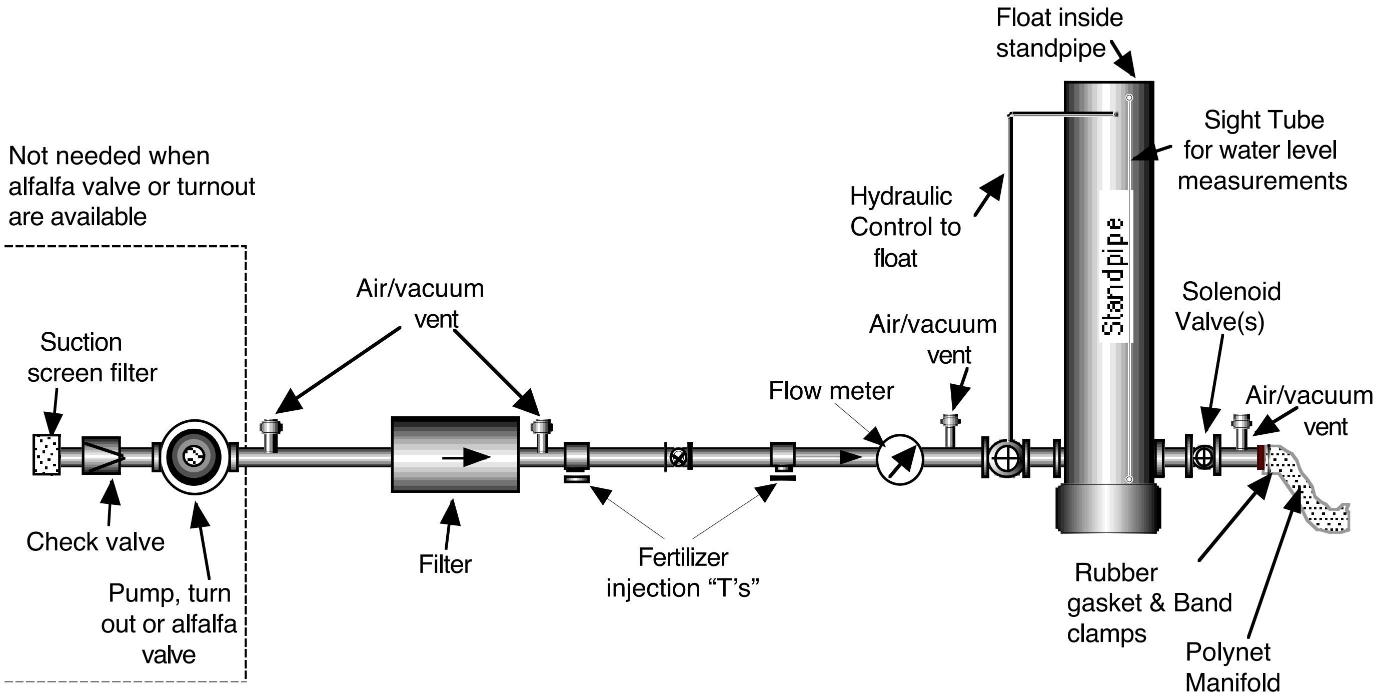


Figure 1. Headworks components for a basic LPS system.

b. Reservoir and Pump--Many farms are storing water in elevated reservoirs to supply water on-demand to their irrigation systems and will not required a pump if the reservoir static pressure is at least 7-8 ft. (2.1-2.5 m). In cases where the static pressure from the reservoirs do not meet this minimum pressure requirement, a pump can be used to supply pressurized water for the LPS.

c. Direct Connection to a Pressurized System--Many Irrigation Districts are supplying pressurized water to on-farm turnouts to supply water on-demand for their irrigation clients. In these cases, a pump may not be required if the static pressure from the turnout is at least 7-8 ft. (2.1-2.5 m). In cases where the static pressure from the irrigation district does not meet this minimum pressure requirement, a pump could be used to increase the water pressure for the LPS. Figure 2 shows a basic example of an on-farm low pressure water turnout supplying water for a LPS via a screen filter and a pressure regulating standpipe.

2. Control Headworks

The headworks of a basic LPS consists of specific components, as shown in Figure 1. Depending on the type of LPS used, the topography of the site, the soil characteristics, the crop, the water/fertility requirements, the water source, availability and/or quality or the application considered, field systems may vary considerably in physical layout but generally will consist of the following or some variations of the following components:

a. Air vents-- Air vents are a critical component of any hydraulic network. In its natural liquid state, water contains 2%-3% of dissolved air. As water temperature rises and/or pressure in the line drops, this dissolved air is released from the water in the form of small bubbles. The air bubbles expand and rise to the top of the pipe and accumulate at elbows and high points in the system. If not released, air pockets are formed, reducing the effective diameter of the pipe. Hence, the use of air relief valves at all high points of the LPS is the most efficient way to control air. There are three major types of air vents: (1) Air/Vacuum Relief Vents, also known as kinetic air valves. These air vents discharge large volumes of air before a pipeline is pressurized, especially at pipe filling. They admit large quantities of air when the pipe drains and at the appearance of water column separation; (2) Air Release Vents are also known as automatic air valves. These vents continue to discharge air, usually in smaller quantities, after the air vacuum valves close, as the line is pressurized and (3) Combination Air Vents, also known as double orifice air valves, fill the functions of the two types of air vents described above.

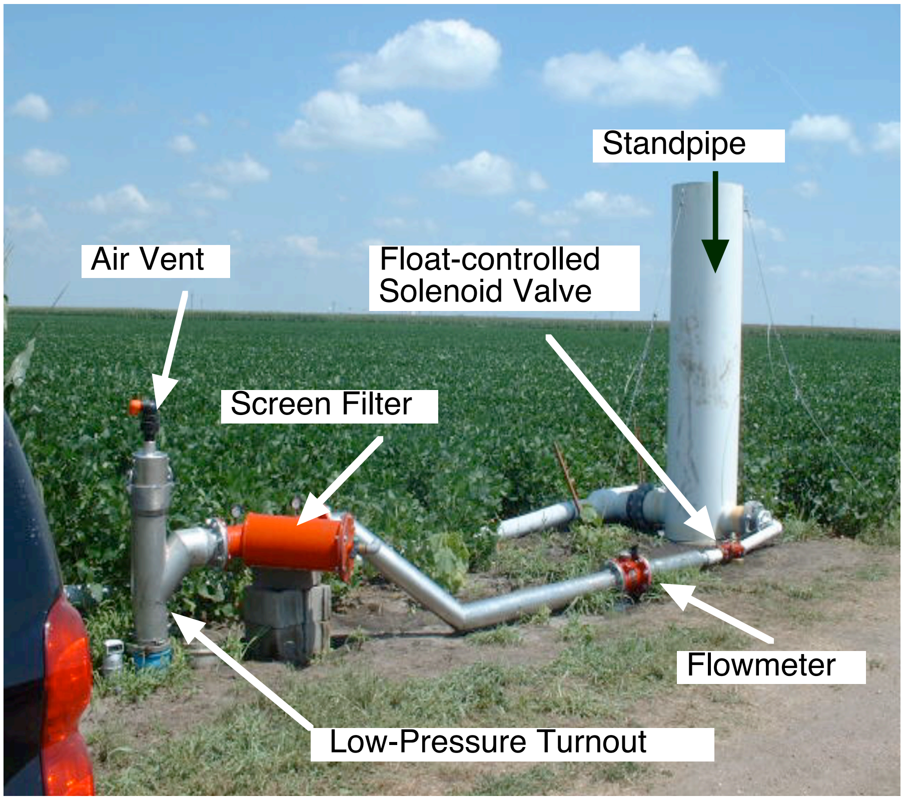


Figure 2. A low pressure turnout and screen filter supplying water to a LPS-irrigated soybean crop at the University of Nebraska, South Central Lab, Clay Center NE.

b. Filter--The main purpose of filtration is to keep mainlines, submains, laterals and emitters clean and working properly. It is critical with LPS because of their low available flushing velocity. Physical, chemical and biological clogging factors can and must be prevented by proper filtration and water treatment.

Many factors affect the selection of a filtration system. Designers should use the correct equipment for a specific farm water source. With LPS, the choice of a filtration system is further limited by the availability of electrical power and hydraulic pressure. Screen filters, such as shown in Figure 2 (raise the LPS required pressure) and gravity filters (low pressure) have been used with LPS.

c. Flowmeter--Knowing how much water and when it is supplied are critical measurements for correctly operating LPS irrigation. Inline flow meters should record total flow and flow rate both visually and electronically. With LPS it is also recommended to use several single lateral electronic flowmeter so that small flow rate changes can be detected and corrected at the onset of the occurrence

d. Float Control Valve--The main solenoid valve is controlled by a float, located in the standpipe at the preset maximum water level. The valve solenoid is hydraulically controlled by the float and opens or closes to maintain a constant water level and head pressure on the downstream LPS system.

e. Standpipe--The main purpose for the standpipe is to accurately control the pressure applied to the LPS dripperlines. Typical standpipes are 10.7 ft. high by 2.25 ft. diameter (3.25 m x 0.69 m) with inlet and outlet flanges. Water level and downstream pressure control are achieved by using a float which activates the float control valve shown upstream of the standpipe in Figure 2. A clear, external water level tube allows the operator to visually determine the water level in the standpipe. Inlet and outlet pipes are connected to the standpipe by bolted flanges. In areas where wind gusts are occurring, the standpipe can be anchored to the ground by three or more steel cable ties.

f. Fertilizer Injector--Fertilizer injection methods range from dripping fertilizers at calculated rates into the standpipe (no available electrical power or necessary pressure) to using fully computerized monitoring and control systems. When electrical power is available, injecting with metering pumps is the most versatile method for injecting chemicals into LPS systems. Automatic time and programmable controllers are usually the best way to control fertilizer injection. When full automation is used, the metering of the fertilizer is programmed for injection during the middle of the irrigation cycle to avoid the line filling time of the irrigation cycle. Injection of chemicals can also be stopped during filter flushing operations. Continuous measurements of pH and EC_w are also recommended to ensure adequate system performance and to control the pump on or off and/or in the case of accidents and malfunctions. Figure 3 shows a recommended design for safely controlling the injection of multiple nutrients and acid.

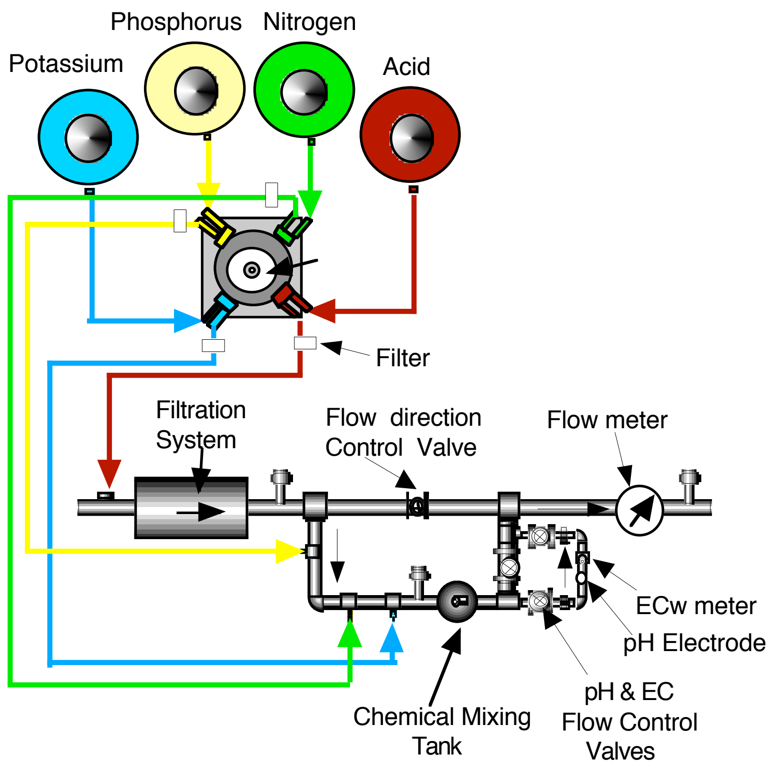


Figure 3. A recommended design for safely controlling the injection of multiple nutrients and acid into a LPS.

g. Pressure gauges/transducers--The sight tube mounted on the standpipe provides a good estimate of the pressure applied to the LPS, although pressure gauges with a range of 0-15 psi can also be used at several points in the headworks. Electronic pressure transducers are also available for input into a controller but are presently relatively expensive.

h. Field Solenoid Valve and Flowmeter/Polynet Submains/Manifolds--
Field solenoid control valves, each with an individual flowmeter and connections to several Polynet submains/manifolds can be set up for a large field application requiring several irrigation sets.

3. Field Distribution System

The field distribution system consists of (1) solenoid or manual valves, (2) Polynet submains/manifolds with its EPDM lateral connectors, (3) air vents and (4) manual clamps. Figure 4 shows a photograph of a manual valve for a distribution manifold (3a), a connection to a Polynet submain/manifold with a flexible PVC header tube (3b), a close-up of Figure 3b with direct connection of the dripperline to the EPDM insert (without the flexible PVC header tube) (3c) and a simple wood or metal clamp that can also be used as a manual feed or flush valve (3d).

4. Laterals

Depending on the type of LPS applications, there are several types of thin-wall dripperlines with emitters integrated within the pipe wall that are available for LPS. The available types of LPS dripperlines are based on life expectancy (1-3 years) and types of tillage application. Emitters with different flow path configurations, discharge rates and operating pressure range are presently tested in LPS dripperlines.

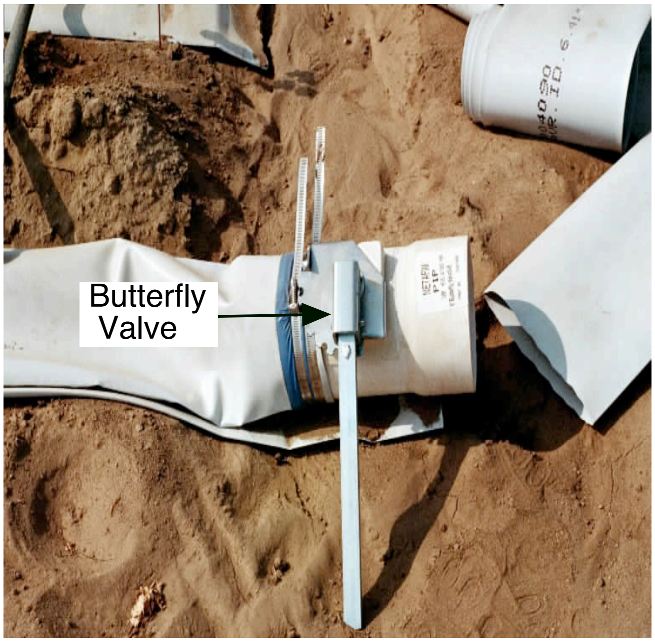
5. Accessories and Installation Tools

a. Tractor and Implements--A standard field tractor with a twin shank injection implement can be used for installation of LPS dripperlines, although larger tractors and implements are also being used.
b. Punch Tools, gaskets and Adjustable Band Clamps, etc...--Necessary hand tools and accessories to install LPS system are now commercially available. They include the hole punch to install LPS EPDM connectors to the Polynet manifold, adjustable band clamps to secure the Polynet manifold to the PVC pipes, rubber gaskets that fit between the Polynet and the PVC pipe and miscellaneous parts to help the LPS perform as specified.

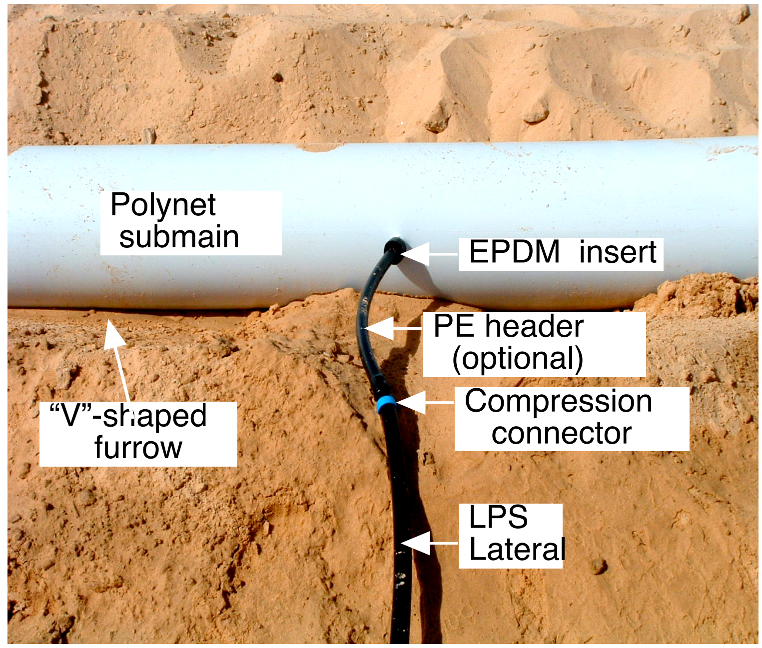
6. Automation and Instrumentation

Full automation of LPS is available, although strictly an option. Because LPS applies water at a rate usually lower than the soil infiltration rate, high frequency irrigation management is not necessary to prevent runoff and/or deep percolation. Hence irrigation scheduling is typically less complicated and intense than for DI and SDI. However, although optional, instrumentation to measure weather and soil water conditions or access to a system that does (State Weather Network) can help meet the rapidly changing evapotranspiration demand of the crop and improve water use efficiency.

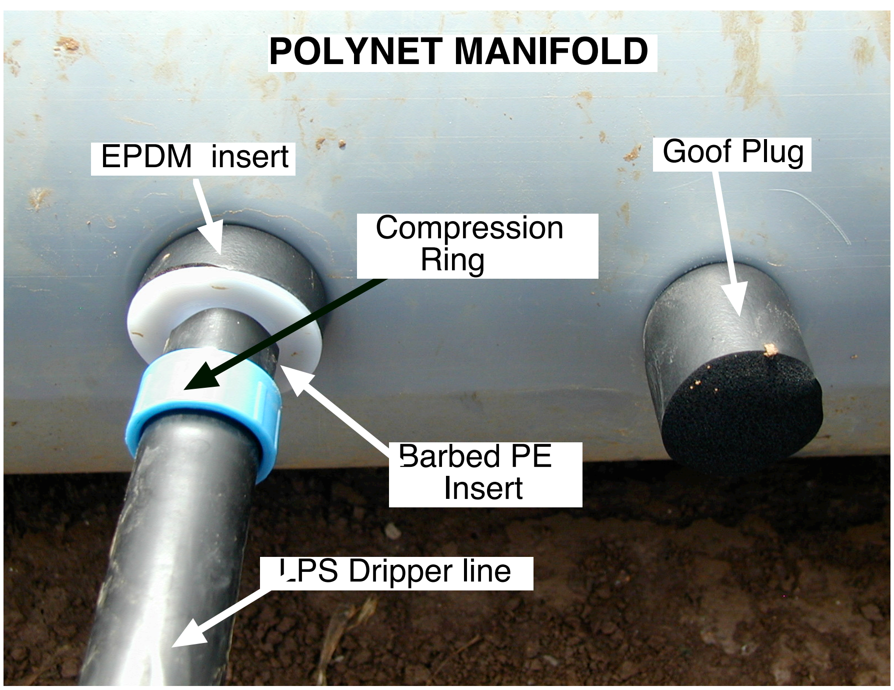
Ensuring adequate LPS operation also benefits from continuous measurements of water flow and pressures to determine water availability, broken lines and/or small changes which might be caused by plugging due to root intrusion, soil accumulation in the flow path of the emitters, biological growth and/or chemical precipitation. Changes in water quality due to source changes and mixing of waters and fertilizers may also require pH, water temperature and EC_w measurements in real time. The logic of an optional automation system capable of performing these functions automatically is available and shown in Figure 5. The typical components for a remotely accessible, real time/feedback automated control system can be added at any time to the LPS.



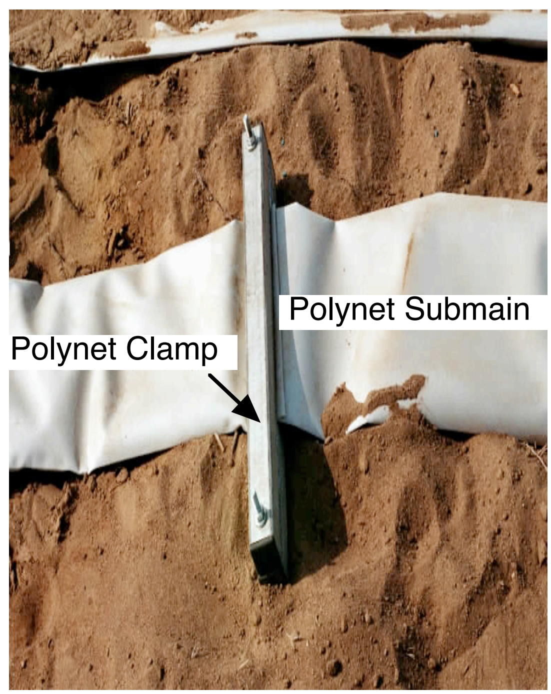
(3a)



(3b)



(3c)



(3d)

Figure 3. Photograph of a manual valve for a distribution manifold (3a), a connection to a Polynet submain/manifold with a flexible PVC header tube(3b), a close-up of Figure 3b with direct connection of the dripperline to the EPDM insert (without the flexible PVC header tube) (3c), and a simple clamp that can be used as a valve (3d).

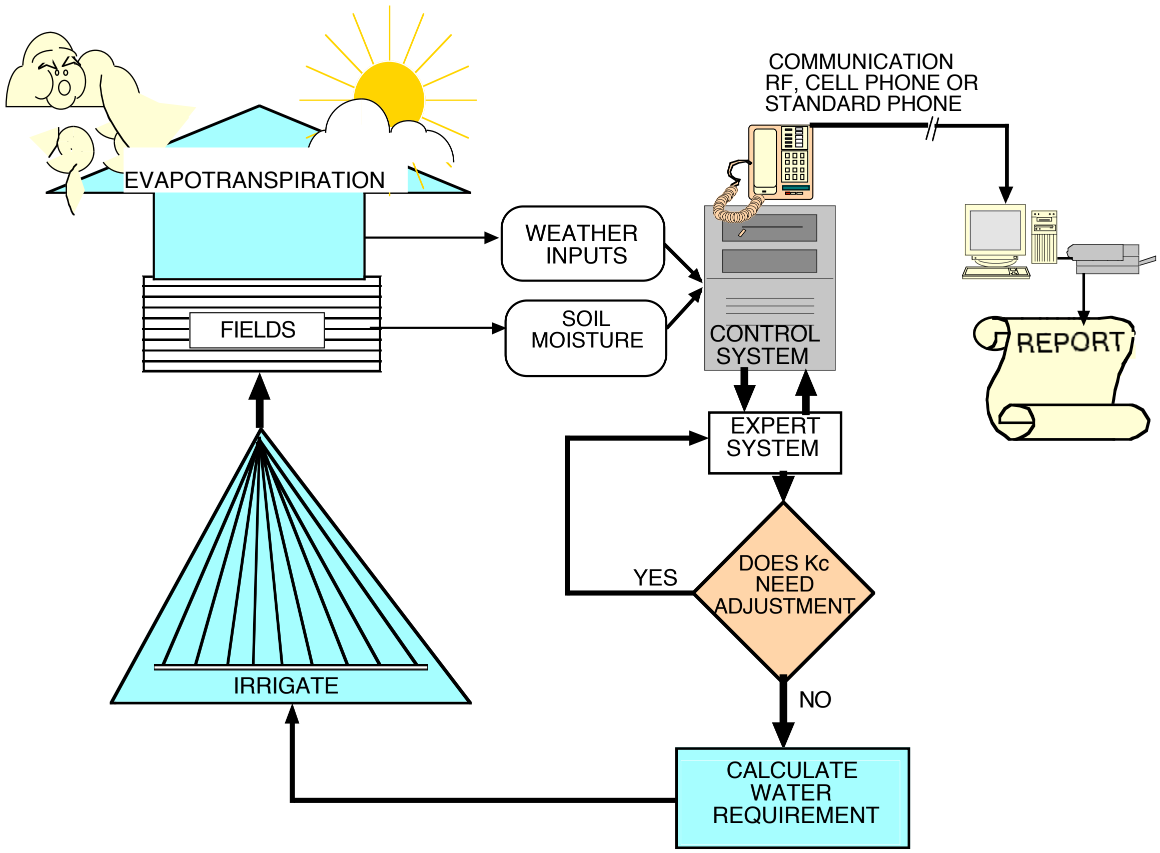


Figure 5. Logic for a remotely accessible and real time/feedback automated control system.

CONCLUSION

Several statistically designed and replicated LPS projects were conducted in cooperation with university extension staffs in Arizona, Arkansas, California (cotton) and Nebraska (soybean). At writing time, although final results are not yet available, preliminary results indicate that LPS can operate and perform as specified. Some final results will be presented at the IA Technical conference. Initial results point out the importance of the management of water quality and volume, dripperline installation and location with respect to the plants and measurements of volume and rate of water application. The management advantages of automation, real time soil moisture monitoring and computerized fertigation were clearly demonstrated in the California project at UC Shafter Cotton Research Center. There, the LPS laterals will remain in the field and minimum tillage practices will be carried out to test the potential of dust reduction. These projects will be repeated for an additional two to three years to validate the life expectancy of the dripperlines and to define the conservation and water use efficiency aspects of the method.

Acknowledgment

The authors wish to acknowledge the contributions to these projects from the following persons and their respective facilities:

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University of Arkansas, Marianna: Leo Espinoza, William C. Robertson and Claude Kennedy.

University of California, Shafter Cotton Research Center : Brian H. Marsh, Robert B. Hutmacher and Francisco Leal.

University of Nebraska, South Central Lab: Suat Irmak, Richard Ferguson and Bill Rathje.

Figure 6. The downstream end of a large potato field (800 ft. long; 250 m) irrigated by LPS in the Arava Valley, Israel .

CONSENSUS BUILDING AS A PRIMARY TOOL TO RESOLVE WATER SUPPLY CONFLICTS

MaryLou M. Smith[1]

ABSTRACT

The allocation of limited supplies of water for multiple uses in the western United States is increasingly difficult. Stakeholders have diverse and seemingly irreconcilable needs, with many deep-rooted opinions on how the water should be allocated. A complex system of water rights and the regulations of multiple government agencies add further complications.

The U.S. Department of the Interior has deemed the issue serious enough to undertake *Water 2025: Preventing Crises and Conflict in the West*, to "speed up the resolution of water supply problems and ensure that the solutions are balanced and durable." How will solutions be found? Are more technological solutions needed, or better application of the technological solutions already available? Or are solutions more likely to be found in the arena of resolution of conflict among stakeholders laying claim to the water? How can the public be brought onboard in a meaningful way, when the issues are so complex? Do models used in the past provide the framework through which resolution can be achieved? Does legislative action and/or public referendums help or hinder?

This paper proposes that those responsible for making decisions about water supply allocation should consider creative consensus building processes their primary tool, not a peripheral one. Such processes should take the place of adversarial debate and litigation which often leads to mediocre results and a discouraged, disenfranchised public. Research dollars should be allocated to explore emerging collaboration techniques and to formulate and test state of the art consensus building technologies. Consensus built solutions should replace 1) adversarial debate on the part of legislative bodies and 2) voting by the public via the referendum process. The State of Colorado's current experience with a statewide water supply initiative following a failed public referendum is discussed as a case study.

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Referendum A—Background and Outcome

Referendum A, a 2003 ballot initiative in Colorado to provide a line of credit for water development projects, was soundly defeated by a 2 to1 margin, despite a period of prolonged drought combined with the state's highest growth rate ever. Voters and water leaders interviewed cited the primary reason for defeat to be the measure's lack of specific projects to be funded. Others, including many in the water industry who favor increased storage, did not see the need for this referendum because they believe the issue is not getting money for water storage, but getting water storage proposals through a complicated series of approvals, primarily environmental, something the measure did not address.

Environmentalists voted against the measure believing that conservation is sufficient to solve the state's water supply problems so further storage is not needed, or because they favor a balanced approach that ties serious, long-term water conservation measures with storage solutions crafted to minimize large disruption of ecosystems. West Slope farmers and politicians voiced concern that east slope needs would, under the terms of the Referendum, take priority over their needs without proper mitigation of the effect on their communities.

In 2002, attempts to move permanent storage forward as a critical solution were launched during two different legislative sessions. The first attempt failed, but the second passed both the House and the Senate after provisions were included to address concerns related to conservation and in-stream flow as well as mitigation of negative effects of water infrastructure projects on west slope communities.
This legislation, because of the funding mechanism required, had to go before the voters in the form of a referendum.

Before the election, Denver Post pollster Floyd Ciruli wrote: "Lawmakers hoped the referendum would prompt interest groups to work together to find a solution, but it could backfire. This is really a political exercise on building for the future. If the referendum fails, it will be self-defeating. It could set back reaching a consensus for many years." Indeed, it appears that the most obvious outcome of Referendum A is that it seems to have further polarized stakeholders.

Water Buffaloes

Some believe Coloradoans voted against Referendum A to avoid a return to the heydays of the state's "water buffaloes--" a handful of giants such as Glenn Saunders, John Fetcher, and Wayne Aspinall who, according to the Denver Post, earlier "worked political deals to snare huge chunks of federal money for large dams and reservoirs." Their foresight and courage is said to have made possible today's Colorado—large expanses of irrigated farms and Front Range cities. No one doubts the contribution of these men, though some, following the logic of writers such as Donald Worster in *Rivers of Empire*, believe the region would have been better left in its natural form. In fact, Worster proposes that large projects by the Bureau of Reclamation were intended more to line the pockets of industrialists with agricultural holdings than to serve the public good.

An April, 2004 feature in the Denver Post pointed out that the days of water buffaloes appear to be over, considering that "not one (large) reservoir or dam has been built in Colorado in 40 years." The Two Forks project proposed for the South Platte River cost taxpayers forty million dollars before it died at the planning table in 1990. The Post article quotes a new generation of water thinkers, such as former assistant state attorney general Melinda Kassen, who says "The kind of projects that get built today are… smaller, faster, cheaper, (with) more conservation, more cooperation."

In his article *The Water Divide in Colorado*, pollster Ciruli summarizes key differences of opinion about Colorado water shortages. He says the issues revolve primarily around out of basin diversions and amount of mitigation required, the efficacy of new storage structures, the potential for reliance on conservation and reuse strategies, and the use of agricultural water for municipal and industrial needs. He talks about a new political environment of water which he calls "post-Two Forks thinking." He says that economic development executives, water policy makers, municipal leaders and others are talking more seriously recently regarding methods to bridge differences of opinion. But, he says "only when actual projects are proposed will it be clear if the willingness to compromise is real."

Where are the visionaries who will champion new solutions with the foresight of the last century's water buffaloes? Where are the movers and shakers who will capitalize on the various needs/values/viewpoints and carve out solutions which are not black, not white, not even gray, but maybe chartreuse or purple?

<u>Statewide Water Supply Initiative</u>

Governor Bill Owens, in his January 2002 state of the state address, directed the Colorado Water Conservation Board (CWCB) to launch a "statewide water supply initiative." SWSI, (pronounced SWAH-zee) was to be a forum for diverse water use interests. The Department of Natural Resources (DWR) hired a consultant, Camp Dresser McKee (CDM), to lead diverse stakeholders in each of the state's eight basins to assess: What water is available? What are the demands? What are potential alternatives for meeting demand? Basin roundtables were established to receive and discuss results of the work of DNR and CDM, and to narrow down possibilities into a set of proposed alternatives for CWCB to present to the legislature.

<u>Colorado Water Congress Panel: What Now, After Referendum A?</u>

Convened by Colorado Water Congress in Denver in January 2004, selected state water leaders were asked "What Now, after Referendum A?" Though almost everyone expressed interest in dialogue, the only mechanism cited for such was SWSI. Here are some representative comments:

Don Ament, Colorado Commissioner of Agriculture, spoke of the need for “a new collaboration and a cooperative effort.”

Peter Binney, Director of Utilities, City of Aurora, alluded to a successful agreement between Aurora and the Arkansas Valley, and said “I suggest that our legislature start thinking about intrastate compacts, whether they be between basins or between users of the past and users of the future.”

Reeves Brown of the West Slope’s Club 20 said : “The biggest lesson we learned from Referendum A was we need to build consensus before we build proposals.” We need to “get beyond the C words of conflict, courtrooms, and condemnation.”

Jo Evans, environmentalist, said “We don’t reach consensus when the people are at the table primarily to see that their ox is not being gored.”

Bob Ewegen, Denver Post: ”I think Referendum A was a constructive dialogue. I supported Referendum A because we need to change the attitude, the dialogue, the way in which water is discussed in this state. We need to at least bring things like win/win solutions to the table.”

Jim Martin, Natural Resources Law Center, CU Law School in Boulder**:** “Referendum A was not a dialogue. It was whatever the opposite of dialogue is. What we need is a very broad based, comprehensive, careful, patient dialogue in this state about water. We have to refrain from the sort of heated rhetoric and blame game we have been guilty of in the past. And we need to think more carefully about the others sides’ perspectives, needs and wants and try to find some sort of way down the middle that really does provide an equitable solution and a vision for a sustainable Colorado. We need to get more serious about finding a way in which we can create a forum in which all the stakeholders are not only invited, but feel comfortable and capable of participating fully and effectively. That’s different than just putting everyone in a room together. Unless we do this, we’re going to continue to spin our wheels on this issue because this is such a difficult and complex issue that goes to the very heart of what most of us hold dear.”

Frank Jaeger, Parker Water and Sanitation District: “I don’t want to see a hundred more bills come across my desk. I’ve got a stack that thick of water bills that don’t mean a hell of a lot to me other than half of them will injure me and the other half will move the fulcrum in my direction. We don’t need a plethora of bills that put power on one side of the table or the other, we need business deals, deals which require that both sides walk away feeling comfortable with what happened.”

Harold Miskel, Colorado Water Conservation Board, introduced a “set of C words we can work toward: cooperation, collaboration, consensus, communication.” He said, “We need to have dialogue that gets to what people are really feeling, what’s at the root of their values. We need to be responsive to the concerns of the people who are impacted by proposed projects. We need to build understanding from the bottom up, understanding of what the needs are, what the resources are, what the concerns and issues are, and then start talking about what the possible options are to take care of these issues and concerns. The only way is for folks to come to the table and talk about these things. That's what the Statewide Water Supply Initiative (SWSI) is all about."

Wally Stealey, Southeast Colorado Water Conservation District, and the most outspoken panel member said, "We're beginning to understand that Harold Miskel's C words have a much greater impact than we thought. But we need real consensus, real compromise, not a definition of compromise that says 'you take, I give.' It must truly be consensus of the citizens of Colorado."

During this panel discussion several stakeholders pointed out that "we need dialogue." But instead, everyone just gave their fifteen minute spiel and participated in a question and answer session afterward. If dialogue is desired, when will it begin? Will Colorado Water Congress convene the next discussion around a consensus building format instead of a panel?

Can SWSI Deliver Dialogue?

At the May, 2004 meeting of the CWCB, DNR staff and CDM consultants reported on completed work related to supply and demand findings, and stated that the next round of basin roundtable activities would focus on generation of alternatives. Alternatives would be proposed by the consultants, and stakeholders would discuss them, presumably coming to consensus about which ones would be presented to the legislature in November.

Also presented were results of an objectives weighting process in which basin roundtable participants had been asked to weigh agreed upon objectives in a forced choice manner. Slides were shown depicting for each basin how different interest groups weighed the various objectives. As one might expect, the results fell along interest lines. Agriculture stakeholders ranked "meeting agriculture demands" the highest, while environmental stakeholders ranked highest "providing for environmental enhancement." CDM said that it planned to track how participants representing different interest groups (stakeholders) score different proposals brought forth as compared to their stance in the objectives weighting process, stating that the process is supposed to lead to a "forum for dialogue and understanding."

One CWCB director, Raymond Wright, expressed discouragement at the findings of the objectives weighting process. Regarding what the weighting process showed in terms of stakeholders weighing objectives according to their own bias, he said, "I don't like this. It implies a high degree of divisiveness." He said that he thinks discussions can be fruitful, however, if they are properly structured and "if stakeholders are encouraged to think win-win."

Part of the SWSI process has been to allow for public input. At the February meeting of the SWSI South Platte Roundtable, environmentalists from more than a dozen organizations took advantage of the public input time to read prepared statements. The result was not dialogue, but simply a series of monologues—an airing of views.

Western Governors on Water Issues Collaboration

One source which would seem to be important to those interested in serious consensus building at the state level is the proceedings of a 2002 conference chaired by then Governor of Oregon, John A. Kitzhaber, M.D. In his forward to *WaterShed Solutions: Collaborative Problem Solving for States and Communities* Kitzhaber asserts that collaborative watershed partnerships cannot replace legal and regulatory tools but they can become the vehicle through which those traditional tools can be more successfully applied. This valuable document outlines important points about collaboration in watershed matters including that collaboration

- reduces conflict and litigation which often results in unsatisfactory, narrow decisions that don't address underlying problems.
- can turn apparently inflexible federal or state mandates into opportunities
- provides an alternative way of approaching problems that avoids the gridlock often associated with traditional governmental approaches

Conferees agreed that states should appropriate funds for collaborative processes, provide high level training to all levels of public officials and private stakeholders in fundamentals of collaboration, develop demonstration projects to showcase collaboration, and request universities to conduct research on collaborative problem solving.

Drought in the West: Can Consensus and Collaboration Make a Difference? is a special report which came out of the 2002 annual meeting of Council of State Governments-West, which provides a platform for regional cooperation among the legislatures of the 13 western states. The report includes points made by representatives from Montana-based Western Consensus Council who talked about "replacing traditional procedures used to resolve conflicts in the public arena with collaborative models for problem solving." Asserting that traditional procedures result in gridlock, impasse, and skyrocketing legal fees, they presented a table of actions that can be taken within a legislative context to foster collaborative procedures, the most radical of which is "by instituting the collaborative process through statute."

Southern Alberta (Canada) Experience

Many who deal with water issues in the west have been fascinated by the recent experience of the Southern Alberta (Canada) Water Users Group in which consensus was reached despite long odds during their drought of 2000. The group has been highly praised and has earned numerous awards as a result of their achievement. When asked what it took to bring water users to the table to develop a win-win solution, two factors rise to the top. The first is that of crisis. Something had to be done or large numbers of irrigators would lose their crops. The second factor appears to be that the largest user and the user with the most power (the St. Mary River Irrigation District) willingly gave up some of their rights to benefit others, so that legalities were overridden for the period of the drought. Does this example have lessons for the rest of us?

<u>What Did Referendum A Tell Us about Voters?</u>

Some believe Referendum A did not pass because the public is not well-educated about water issues. An alternative view could be that the public voted against the measure because they *are* educated and they want a full view of the situation so they can make educated decisions. Is it possible that by voting no to Referendum A and leaving the state without a solution to its significant water supply problems, the public was not being blind to realities, but were basically saying they want meaningful choices, not black and white, pieced-together solutions? Is it possible voters saw the bill as basically a storage solution with environmental and western slope mitigation concessions tacked onto it as an insincere attempt to bring along the "other side?"

Many voters interviewed expressed that they felt disenfranchised by Referendum A. They want a multi-faceted, comprehensive solution to state water supply problems, not just large-scale storage. Referendum A did not give them that choice. Furthermore, the voting process itself further polarized constituents, and moved everyone further away from a rational solution with mutual benefits.

Walter Lippman, writing in his 1920's classic *Public Opinion*, says that people form opinions based not on education but on long-held beliefs and values. But if we believe the public *can* be educated, where do we expect them to receive education about complex issues such as water supply? The media does not educate; it gives us sound bites based on the deeply held beliefs and values of those trying to promote their side of an issue. People hear what they want to hear, based on their own deeply held beliefs and values. What can be done to break down those deeply rutted paths? Would collaborative vs. adversarial approaches pull people together—re-engage them, open them up to new ways of looking at issues?

Some say our adversarial system of power politics supports endless conflict among competing interest groups and leaves little room for open-ended exploration of mutually beneficial solutions. Adversarial politics promotes power hoarding and does not allow for the development of trust and respect which can lead to solutions which take into consideration the interests of various stakeholders. As long as solutions for the common good have to compete in an adversarial environment dominated by vested interests, we are fighting an uphill battle.

<u>What Can We Learn about Consensus Building in the Public Policy Arena?</u>

What can we learn from the social sciences to help us solve water supply conflicts? We have a great deal of research into technological solutions. What we most need is to put more of our resources into social technologies—research into ways to bring together divergent viewpoints. We have only begun to understand the inner workings of deliberative models and their social potential. Often we hear that the social sciences, the so called soft sciences, are really the harder sciences to study and to apply. That is surely true, and the challenge is formidable. But it seems that, under the excuse "you can't change human nature" we have failed to take on the challenge. Are we overlooking the potential for truly globe-changing solutions which could be derived from learning how people can come to understand one another and build consensus? We are in great need of experimental laboratories to try out strategies for using conflict creatively and constructively to generate workable and lasting solutions to conflicts.

Consensus Building Models

In *The Tao of Democracy*, Tom Atlee collects and reports on a variety of methods being used to draw on the wisdom of multiple viewpoints to come up with creative, workable solutions for today's complex issues. He claims we need to look at new ways to "do democracy" because elections, polls, and the numerical adding up of our individual opinions doesn't lead to good decisions which build on our collective wisdom. He believes we need to embrace a more comprehensive view of reality: more view points, approaches, and complexity, so that we can get as good a sense of the whole picture as possible. The premise is that conflict can be a powerful generator of quality problem solving. Atlee cites a number of non-adversarial approaches to conflict which are being used by those he calls social process activists.

Citizen deliberative councils are discussed at length. These councils are typically made up of a group of diverse ordinary citizens. Participants are given extensive education on a given issue and assisted in coming to consensus by a trained facilitator. In Denmark, such citizen councils are convened by the Danish Parliament to study an issue, deliberate with the help of a facilitator, and present findings to parliament. The deliberation process calls for weighing the full range of facts, factors, perspectives, options, and consequences related to the issue and often creates new options in the process. Atlee says "Given a supportive structure and resources, diverse ordinary people can work together to reach common ground, creating wise and deliberate policy that reflects the highest public interest."

U.S. Representative Edward J. Markey speaks of his experience with a citizen deliberative council which undertook an extensive study of telecommunications issues in the Boston area in 1997. Recognizing the political potential of this innovation, he said, "This is a process that I hope will be repeated in other parts of the country and on other issues." Dick Sclove, from the Loka Institute, was the lead organizer of the effort. Of the experience, he said: "These ordinary citizens ended up knowing more about the subject than the average congressperson who voted on the issue, and their behavior conclusively disproved the assertion that government and business officials are the only ones competent and caring enough to be involved in technological decision-making. This lay panel assimilated a broad array of testimony, which they integrated with their own very diverse life experiences, in order to reach a well-reasoned collective judgment grounded in the real needs of everyday people. To me this example demonstrates that democratizing science and technology decision making is not only advisable, but also possible and practical."

Stakeholder dialogues are similar to citizen deliberative councils except that the participants are chosen not from the general citizenry, but from groups who hold various, often opposing views on a given issue, and who have a definite “stake” in the outcome. These dialogues have proven especially effective for “issues that have proven immune to conventional legislative solutions.” An emerging form of stakeholder dialogue called The Consensus Council has been championed by former Montana governor Marc Racicot, who created the Montana Consensus Council. In this form of consensus building, a government agency chooses a representative from each significant interest group with a stake in the issue and helps them come to agreement on recommendations, which are then passed in resolution form to the legislature. Politicians back decisions which come out of stakeholder dialogues because they are supportable by a wide variety of constituents. The success of the Montana Consensus Council and that of a comparable one in South Dakota has led to an effort by a major mediation group, Search for Common Ground, to have Congress establish a national Consensus Council. Former U.S. Secretary of Agriculture Dan Glickman is one of those leading the effort. A United States Consensus Council would “serve the nation by promoting consensus-based solutions to important national legislative policy issues, and would convene the stakeholders on a given issue and seek to build win/win agreements—those that reach the highest common denominator among the parties.”

At root, these approaches accept the premise that emotion and intuition have a legitimate place in decision making, and that healthy relationships are a powerful resource for finding solutions. Such an approach addresses the questions, “What are the fears of participants on all sides of the issue? How can we come up with solutions that address those fears?” Truly understanding others with opposing values stems from a chance for meaningful expression of those values, and from this interpersonal understanding can come the motivation to build consensus.

How might we integrate citizen deliberative councils or stakeholder dialogues into our political process such that they could make a significant difference and even become a central feature of our political system? What if meaningful, facilitated dialogue following comprehensive study of issues were to become the norm for our elected officials? Is it too much to ask that in a democracy our elected officials should mirror the diversity in our populations? Can we even imagine a democracy in which elected officials whose views run the gamut come together amicably, study the issues, and make their decisions not in an adversarial way but through facilitated dialogue? Can we imagine true openness to new solutions instead of dogged insistence on pre-formed positions?

Where is SWSI Now?

The scheduled basin roundtable sessions were completed in September, 2004. At the South Platte Basin Roundtable Technical Session 4, Rick Brown of the Department of Natural Resources and the consultants from Camp Dresser McKee summarized the findings and set the stage for generation of alternatives to be presented to the Colorado Water Conservation Board and subsequently to the state legislature in November. They showed what the basin by basin water needs of the state are projected to be by the year

2030. The amount of water projected to be available to meet those needs was presented, having been catalogued following communication with each basin's water providers about their plans. The resulting "gap" was shown, again basin by basin, and a very preliminary approach to finding "projects and processes" to fill that gap was discussed. Ensuing discussion centered around both the "gap" which SWSI has identified, calculated to be the shortfall of water after considering the plans of water providers, and what this author calls the "GAP"—the shortfall which the providers already have plans to fill.

Water providers' plans include a wide variety of projects and processes, some of which are increased conservation, agricultural transfers for municipal use, existing reservoir enlargement, and the building of new reservoirs. An example of the latter is the Northern Integrated Supply Plan, or NISP, which the Northern Colorado Water Conservancy District is promoting. NISP participants are several northern Colorado water districts who have joined forces in hopes of building two plains reservoirs. The project is in the stage of gathering public comment prior to the preparation of an EIS--Environmental Impact Statement—a lengthy process which is considered by most as a formidable hurdle for any water storage project to clear.

Two distinctive avenues of questioning at this final basin roundtable technical session were, first, "Are some of the water providers' plans overlapping—are they counting on some of the same sources of water?" and second, "How confident are we that the providers will be successful in implementing their plans, especially given the regulatory and public opinion hurdles to be overcome?" As a result of the discussion, plans were made for assessing even more carefully how much of a "fudge factor" should be considered to allow for the uncertainty, and indeed whether some water providers would want to alter their figures to be more conservative.

For purposes of this paper, the more important issue is what will be done, and in some cases is already being done, to build support for the projects and processes which have been or will be proposed. Many of the projects and processes which fall into the GAP category are already in some stage of being developed and/or analyzed by regulatory process, which includes public comment. How will the water providers proceed in building consensus for their plans? In the case of the smaller gap, the ten percent or so which SWSI has uncovered to be the projected statewide need outside what water providers already have plans to provide, how will processes and projects be proposed to fill that gap? As a part of the September roundtables, Rick Brown from the Dvision of Natural Resources and consultants from Camp Dresser McKee presented a couple of rough ideas for potential processes/projects which might be forwarded to the CWCB and eventually to the legislature as a part of the final SWSI report. The point was made that hopefully this will not be a final report, but that the SWSI process will be ongoing in some form. Would this be the ideal time for the SWSI team to propose to the CWCB and the CWCB to the legislature that the roundtable participants now undertake a year of dialogue in which they develop some creative alternatives hammered out among themselves? The roundtable participants were chosen to provide a wide variety of viewpoints, including agricultural, urban, and environmental. Why not now move to a stage in which these folks have the opportunity to create ideas together?

Increasingly, water providers are thinking about public opinion as they develop their plans. But the big questions are: "How can we convince water providers to utilize citizen and stakeholder groups upfront to play an active role in developing plans and proposals rather than simply trying to gain their support for plans and proposals after they have been developed? What would it take to convince those responsible for providing water for Coloradoans between now and the year 2030 to place primary, not peripheral emphasis on the process by which alternatives are to be developed and consensus derived?"

Conclusion

The days of water buffaloes brokering deals in smoke-filled rooms is over. We've come far enough to know we have to involve stakeholders and the public in a cooperative process. But are we putting enough into the process to make it work, and are we serious about working the process? If so, why do we keep seeing band-aid bills come out of the legislature and confusing referendums put in front of the voters?

Who has the right to use the water when available supplies do not meet all the demands? That question will be asked more and more, not just in Colorado but across the nation and even the globe.

This paper proposes that answers to that important question must come from consensus-built public policy. Consensus building as a primary tool must be championed by new visionaries who take the lead to develop and apply soft science technology to bring together stakeholders with conflicting interests. Any consensus building related to water supply problems must help folks on multiple sides of the issue understand deeply where various values and beliefs originate, to fully listen to and gain respect for the roots of the view of the other. In exploring those views, creative solutions with potential for acceptance from all can emerge.

Design of Next Generation Sprinkler Head for Curved Landscapes

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Abstract
With growing population and dwindling water sources throughout the U.S., Cities, Counties and Water Agencies are seeking ways to conserve water and reduce surface runoff. This paper will describe the advantages of using a new proposed sprinkler head developed through a partnership between CSU Fullerton and the Bureau of Reclamation. Depending on the degree of curvature of the landscape, existing sprinkler heads spill water onto hardscapes, thus contributing to water wastage and added surface runoff. The benefits of the new sprinkler head are easily quantifiable and the objective is ultimately to provide landscape professionals and homeowners an easy alternative to save water and reduce urban run-off which is impairing several waterways.

Introduction

The motivation of this work is to design a new sprinkler nozzle with multiple orifice openings that can optimally water curved landscapes. Existing sprinkler heads although perform well for regular landscapes, are far from optimal when used across curved landscapes. Depending on the degree of curvature of the landscape, existing sprinklers spill water onto hardscapes (i.e., sidewalks, driveways, roads etc), thus contributing to, water wastage and added surface runoff. The proposed sprinkler nozzle will have inbuilt mechanism that can take into account the curvature of the landscape and thus optimally water the landscape. It will provide a practical approach for efficiently watering curved landscapes. Additionally, an improved sprinkler system can also open new opportunities for improved landscape design. Since urban lifestyle and good landscaping go hand in hand, an offshoot of this work is an enhanced quality of life. With rising water costs and depleting water sources, the proposed sprinkler can benefit both the end users and water management agencies. The target audience that can be benefit from the proposed sprinkler nozzle are water managers, home owners, city planners/decision makers, landscape designers and architects.

According to the U.S. Geological Survey, of the 26 billion gallons of water consumed daily in the United States[1], approximately 30 percent (i.e., 7.8 billion gallons), is spent on outdoor uses. A significant portion on the water is spent in landscaping. It is estimated

[1] W.B. Solley, R.R. Pierce, and H.A. Perlman. 1998. *Estimated Use of Water in the United States in 1995* (USGS Circular 1200). USGS. Reston, VA. p.27.

that a typical suburban lawn consumes 10,000 gallons of water above and beyond rainwater each year[2]. In the U.S., 25% to 33% of the estimated 101 gallons of water per capita consumed daily in single family residences is used to water plants, lawns and gardens[3]. In arid regions like the southwestern United States, that percentage can be as high as 60% to 90%[3,4]. Existing sprinklers although they perform well in the interior regions of any large landscapes, when used in the vicinity of the borders in a curved landscape, they spill water on to its adjacent hardscape (i.e., sidewalk, driveway, roads, et al.) Although estimating the amount of water that is spilled onto driveways/hardscape is a difficult task, it is safe to say that for curved landscapes a certain amount of water does spill on to the hardscape.

Designing an efficient sprinkler nozzle that can take into account the curvature of landscape can contribute to among others (a) water conservation/efficient efficient water use and (b) reduced urban runoff. Figure 1 is a definition sketch to illustrate the performance details of current and proposed sprinkler nozzle head for curved landscapes.

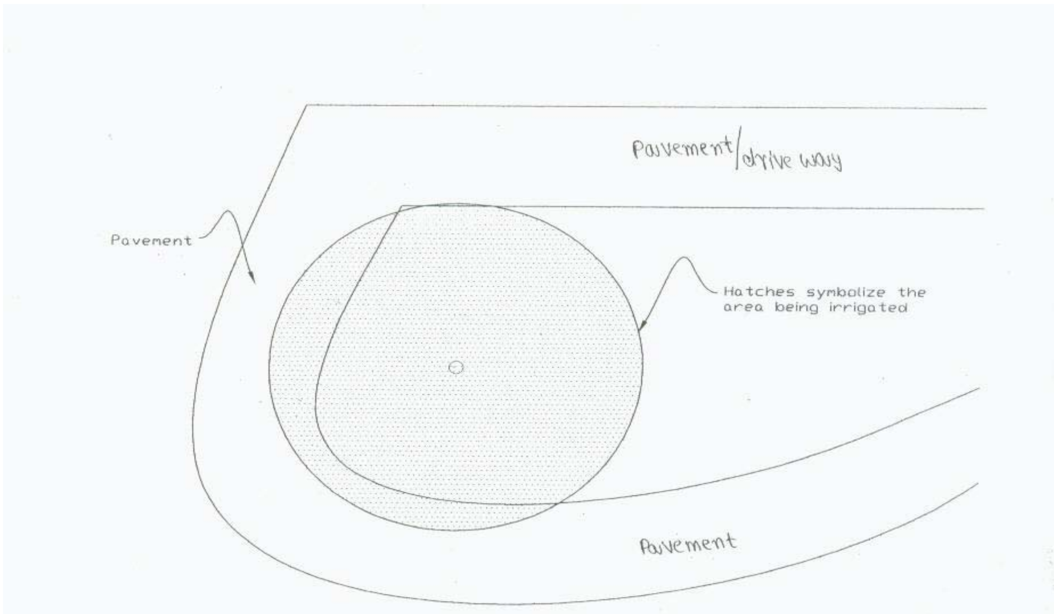
The second order affects of the proposed sprinkler nozzle include

(a) Improved water quality in the water bodies, that otherwise are polluted by the runoff
(b) Enhanced biological integrity and improved ecosystem
(c) Extended life of related infrastructure components

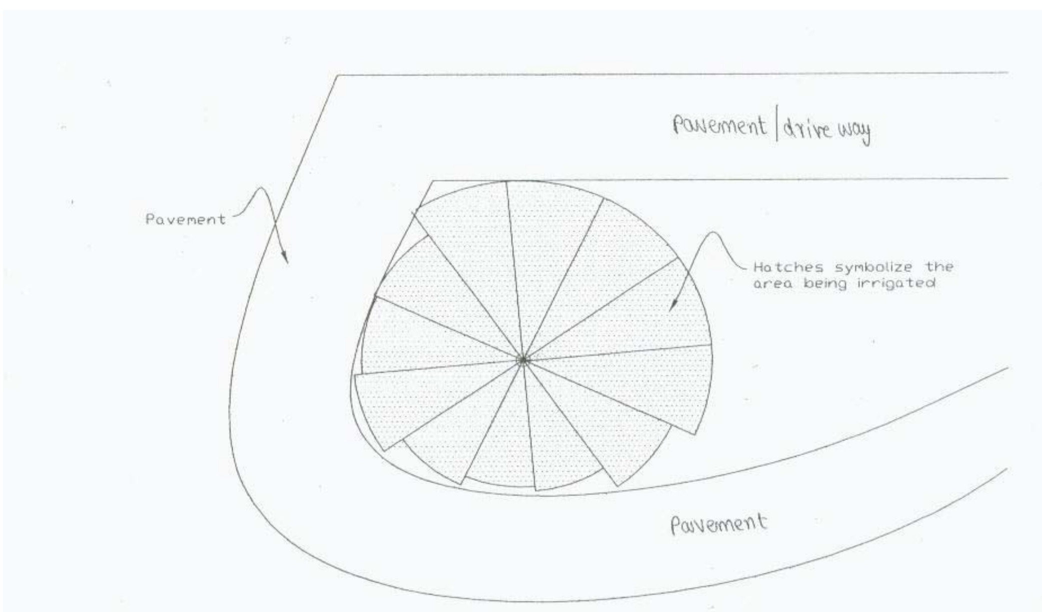
The proposed sprinkler nozzle is a lasting economical solution to an otherwise problem, that has not been addressed satisfactorily until now. With no affective mechanism in place to stop polluted water in storm drains from reaching oceans and other water bodies, the proposed sprinkler can significantly reduce the volume of dry urban runoff.

Performance of Existing Sprinklers for Curved Landscapes
Currently there are many sprinkler heads (both from spray and rotor sprinklers) which can be used for watering regular and irregular landscapes. While the standard spray sprinkler nozzles have many characteristic features, the feature closest to the proposed sprinkler is their ability to water quarter, half and full circle areas, which facilitates directing water to any particular area of interest (i.e., the watering arc can be manipulated from 45^o to 90^o, from 90^o to 180^o etc.). Independent of the degree of water arc, the water spray will still continue to be uniform all across the flow area. Since the flow area will be uniform, the existing sprinklers cannot be optimally used for curved landscapes. Figure 2 illustrates a sample limitation of the existing nozzles.

[2] Amy Vickers. 2001. *Handbook of Water Use and Conservation*. WaterPlow Press. Amherst, MA. p. 140.
[3] Kent A. Sovocool and Janet L. Rosales, A Five-Year Investigation into the Potential Water and Monetary Savings of Residential Xeriscape in the Mojave Desert,[online paper] available from Southern Nevada Water Authority at www.snwa.com/assets/pdf/xeri_study.pdf
[4] Vickers, *Handbook of Water Use and Conservation,* Waterplow Press, ISBN 1-931579-07-5



(a)



(b)

Figure 1. Definition sketch to illustrate the performance details of (a) existing sprinkler head and (b) proposed sprinkler head across curved landscapes (the location of the sprinkler head is identified by o)

An optimal sprinkler for curved/irregular landscape should have a feature in it, by which the radius of flow emanating from each orifice opening can be controlled.

Figure 2. Sample photograph to illustrate the water efficiency wise limitation of standard sprinkler heads for curved and irregular landscapes

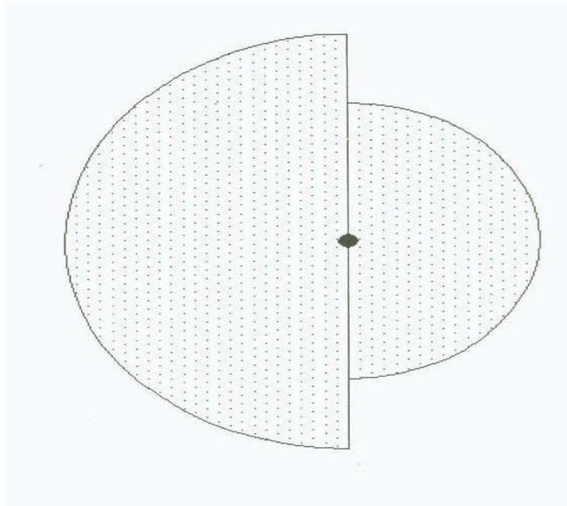
Design Details of the New Sprinkler Nozzle

Since the design aspects of the new nozzle are currently in the process of being patented, the authors are not sharing those particular details in this paper. Interested audience can directly correspond with the authors, so as to get a copy of the drawings.

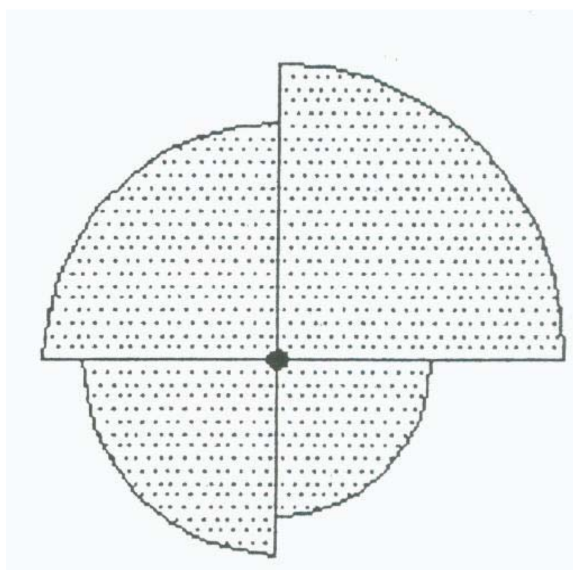
The features in this new sprinkler nozzle are

- The nozzle can have multiple orifices
- The radius of the water arc emanating from each orifice opening can be adjusted
- The spraying pattern from each orifice is uniform, and this is independent of the radius of water arc from that orifice
- For landscapes with steep curvature, a nozzle with multiple orifices can be chosen to water the whole landscape area efficiently
- For using the sprinkler head, no additional learning/training is required from the end user
- No additional investment is needed from the end user to install the new sprinkler head into their landscape
- It can be used for both pop-up style sprinklers and shrub style sprinklers

Sample performance aspects of the nozzles with two and four orifices is shown in Figure 3.



(a)



(b)

Figure 3. (a) Nozzle with two orifices spraying water across two radii (b) Nozzle with four orifices spraying water across four radii

Experimental Test Site for Measuring the Performance Details

The reliability of the newly designed sprinkler head is being tested for a sample landscape, shown in Figure 12. The width of this curved landscape (located in the campus of CSU, Fullerton) varies from 4 ft to 16 ft, across a length of 20 ft. Along the four sides, the landscape is surrounded by walkways which are frequently used by the students. Figure 12 captures the salient details of this test site. Sections AA and BB, at which the performance tests have been illustrated later on are identified in Figure 12. While the width of the landscape at AA is 4 ft, the width at BB is 12 ft. Our idea in choosing this site for testing the sprinkler head is twofold: (a) It closely resembles the curved landscapes in real word and (b) It facilitates in an unbiased testing of the sprinkler heads.

The orifice with two nozzles has been used in these tests. One of the orifice openings was closed and the flow occurred through the other orifice opening. The pipe assembly was placed along the side CC (see Figure 12) and water was allowed to spray through the orifice opening facing the landscape. This nozzle has been tested across 9 sections, the width across which varied from 4ft to 12 ft. The trend of the results at the two end sections (i.e. AA and BB) are presented herein. The idea was to adjust the flow controlling screw of the orifice opening and let water spray to a distance approximately equal to the width of the section. Photographs were taken at the end points for both dry and wet time periods. The dry photographs were used as bench mark data for comparison purposes.

Figure 13 (a) illustrates the profile of the section (section BB in Figure 12), the width of which is equal to 12 ft. On the left side, the pipe assembly is present. Figure 13(b) is the zoom view of the end point, under dry conditions. Figure 13(c) is the zoom view at the same end point, after the sprinkler is switched on. As evident for this water pressure and for flow controlling screw location, the radius of the water is about 13 ft. Figure 13(d) illustrates that the flow pattern is uniform at the orifice opening.

We have then taken the pipe assembly to section BB (see Figure 12), the width of which is equal to 4 ft. Figure 14(a) is a zoom view of the end point under dry conditions. The width of the section is indicated herein. Figure 14(b) is the corresponding view after the sprinkler is switched on. The flow adjustment screw has been adjusted to ensure that the flow through the orifice opening is reduced. This figure indicates, that the radius of water arc is about 4ft. The width of the water arc was observed to be uniform all across its radius.

When Figures 13 and 14 are seen together, the following conclusions can be arrived at:

- By adjusting the position of the flow adjustment screw, the amount of flow and hence the radius of water arc from the orifice opening can be changed.
- The end locations of the flow adjustment screw can either completely shutoff the flow from the orifice or allow a maximum flow rate from the orifice. These end conditions translate to either zero water radius or maximum water radius[5].
- The water spray pattern from the orifice opening is uniform and this is independent on the location of flow adjustment screw.
- The flow adjustment screw facilitates an accurate control of the radius of the water arc.

Table 1 documents the affect of the flow adjustment screw (in terms of the number of revolutions) on the maximum distance over which water can be sprayed for that particular nozzle

[5] The maximum radius of water arc depends on the water pressure in the pipe.

opening. A zero revolution implies that the nozzle opening is completely shutoff. At the end of four revolutions, the discharge in the nozzle opening is maximum and thus the distance of the ??

Table 1. Effect of flow adjustment screw on the maximum distance of the water spray

Number of revolutions	Maximum distance over which water column sprays (in ft)
0	0
0.5	1.6
1	3.6
1.5	5.1
2	7.2
2.5	8.4
3	10.2
3.5	12
4	12.9

(a)

(b)

Figure 12. Test site over which the performance data is being gathered [(a) normal view, (b) zoom view which captures the minimum width of the test site]

(a)

(b)

Figure 13. Performance details of the sprinkler nozzle for the 12 ft width portion of landscape [(a) zoom view of the end point under dry conditions (b) zoom view of the end point under wet conditions]

(a)

(b)

Figure 14. Performance details of the sprinkler nozzle for the 4 ft width portion of landscape [zoom view of the end point under (a) dry conditions (b) wet conditions]

It is expected that this innovative sprinkler nozzle will be a welcomed addition to the options of nozzles, sprinklers and other irrigation hardware available on the market today. Although there are many more advanced irrigation technologies on the market, often it is the low tech options that find its way into consumers' yards. This new sprinkler nozzle will enable those professionals and homeowners concerned with a healthy landscape, save water and reduce non-point source pollution without compromising their aesthetic values.

Impact of Aerated Subsurface Irrigation Water on the Growth and Yield of Crops.

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Abstract

The concept of aerating the irrigation water increases the potential for the air to travel with water movement within the root zone. Physical, chemical, and biological soil characteristics that influence crop growth and yield depend on the relative proportions of the liquid and gas phases within the root zone. The findings of a pilot study conducted in 2000 at the Center for Irrigation Technology in which air was injected into the root zone of bell peppers via the subsurface drip irrigation (SDI) system justified follow-up fieldwork on larger plots approaching commercial scale. We present a review of current research aimed at evaluating the technical and economic feasibility of air injection into a SDI as a best management practice for fresh-market tomato, melon and bell pepper production. Generally, the incorporation of high efficiency venturi injectors in SDI systems increased root zone aeration and can add value to grower investments in SDI.

Introduction

Modification of root zone environments by injecting air has continued to intrigue investigators. The concept of aerating the irrigation water increases the potential for the air to travel with water movement within the root zone more generally and affect crop growth. Physical, chemical, and biological soil characteristics that influence crop growth and yield depend on the relative proportions of the liquid and gas phases within the root zone. For example, a soil that is well aerated will favor increased root respiration and aerobic microbial activity. Conversely, in waterlogged soils typical of poor drainage, anaerobic conditions prevail. Since oxygen is essential for root respiration, then immediately after the roots have been surrounded by water they can no longer respire normally.

Through work in other areas, the Mazzei® Corporation has developed high efficiency venturi injectors capable of aerating water with fine air bubbles. In 2000, a pilot study was conducted at the Center for Irrigation Technology (CIT) in which air was injected into the root zone of bell peppers via the subsurface drip irrigation (SDI) system (Goorahoo et al., 2001a,b). In that study an increase of 33% in bell pepper count, and a 39% increase in bell pepper weight was noted for the aerated plots versus the plots receiving only water. When the roots were examined, there was a significant difference between the root weight to total plant weight ratios for the aerated plants and the non-aerated plants. The findings from the 2000 CSU-Fresno study justified follow-up fieldwork on larger plots approaching commercial scale.

Since the 2000 small scale study, CIT researchers have been funded as part of the *Governor's Buy California's Initiative,* to work with commercial vegetable growers in evaluating the feasibility of the air-injection system in crop production systems utilizing SDI. In addition to our research in the San Joaquin Valley (SJV) in California, similar work is being conducted by scientists in Australia (Bhattarai et al., 2003 and 2004) and Japan (Professor Hitoshi Ogawa, Tamagawa University, Tokyo, Japan, personal communication). Furthermore, a group of scientists at Queensland, Australia, who are in contact with researchers in Germany, have indicated that they are currently compiling a review on the topic of aeration within the root zone (Professor David Midmore, Plant Sciences Group, Central Queensland University- personal communication). Hence, it is obvious that the issue of aeration of subsurface irrigation water is of interest worldwide as growers continue to look for ways to optimize crop production and water use efficiency.

In this paper, we present some of the findings from our current research, being conducted in California, aimed at evaluating the impact of air injection into a SDI as a best management practice for fresh-market tomato, melon and bell pepper production.

Review of Current Research

The major goal of the current research is to evaluate the technical and economic feasibility of injection of ambient air into a subsurface drip tape irrigation system, as a best management practice for crop production. Ideally, the technology should be applied to and tested on as many crops as possible. Realistically, we plan on assessing the practice on as many vegetable and fruit crops commonly grown in the SJV, over the next two years. In this phase of the research, our focus is on three crops: bell peppers, fresh-market tomatoes and melons.

Details on the design and theory of operation of the air injection system employed in the research can be found in Goorahoo et al., (2001a,b). Briefly, the basic principle of the Mazzei® (patented) injector is as follows: as water under pressure enters the injector inlet, it is constricted in the injection chamber (throat) and its velocity increases. The increase in velocity through the injection chamber, according to the Bernoulli equation, can result in a decrease in pressure below atmospheric in the chamber. This drop in pressure enables air to be drawn through the suction port and be entrained into the water stream. As the water stream moves toward the injector outlet, its velocity is reduced and the dynamic energy is reconverted into pressure energy. The aerated water from the injector is supplied to the irrigation system. The fluid mixture delivered to the root zone of the plant is best characterized as an air-water slurry.

The commercial size plots were located in Firebaugh (tomatoes) and Mendota (melons and peppers) in the SJV. The air injection systems used in the melons and pepper project were different from the set-up in the tomatoes project in that in the melon and pepper fields, each drip tape had its own air injector, whereas in the tomato fields there was a single larger injector servicing twenty four drip lines (Figures 1 and 2).

Soils in this region range from sandy loams to clay loams. Some of the measurements performed to date include:

1. Pre-Plant Soil sampling
2. Crop Growth and Irrigation Monitoring
3. Harvest and Yield Data Collection
4. Photosynthesis and transpiration
5. Plant Height and width measurements
6. Root and Shoot Post Harvest
7. Post Harvest Soil Sampling

Significant results and Accomplishments to Date

Much of the data collected to date is still being processed.

Melons

In Fall 2003, we conducted comparative tests between air injection and water only treated melons (honey dews) on 13acres plots with a drip tape run length of over 400m. There was a 14% increase in the number of melons and, a 16% increase in the weight of melons harvested due to air injection. These figures translate into a projected increase of $260 to $350 per acre for the farmer depending on the wholesale price of melons which can range from $3 to $4 per box. Generally, there was a decrease in yield of melons in moving from the South to the North end of the experimental plot (Figures 3 and 4). This trend was for both the air injected and water treated plots. It is noteworthy that the irrigation manifold was at North end (replicate #4) of field, and the vent valve was at South end (replicate #1). With respect to quality, there was no significant difference between the sugar levels measured for the air treated and the water only treated melons. The average Brix level for the air treated and water-only melons were 11.0 and 12.9, respectively.

In Summer 2004, for cantaloupes grown on 20-acre plots, there was a 13% increase in the number of melons and, a 18% increase in the weight of melons harvested due to air injection (Tables 1 and 2). More importantly, the increase in the number and weight of large air–injected melons, which were shipped in 9 per box, exceeded that of the water-only melons by 43% (table 1) and 39% (Table 2), respectively. The larger melons are the most desirable grade for the grower. There was a greater shoot to root dry weight ratio for plants subjected to air injection (mean 80 ±7) than those receiving water only ((mean 67 ±5) (Figure 5).

Tomatoes and Peppers

Most of the tomato and pepper experiment data sets are still being processed.

In the tomato experiment grown on 20 acre plots with drip tape run lengths of approximately 300m, so far we have observed that for the air treated plants there were greater yields from the plants located at the "head" of the drip line versus the plants down at the "tail". Our initial findings seem to indicate that in the case of the tomato crop, there may have been earlier fruit maturity for the air treated plants.

In the 2003 experiment with peppers grown on 40acres with run of over 400m, we observed that although there was a trend of decreasing yield (both numbers and weights) in moving away from the source of the air and water injection, there was still a positive effect of the air injection towards the tail end of the irrigation tape (Table 3).

One constraint of conducting the experiment on the on the commercial farm was that it was not possible to carry out excessive destructive plant sampling during various growth stages in an effort to examine the impact of the air injection on the roots. In 2004, a bell pepper research plot (0.25 acres) was been set up at CIT in which the destructive sampling was carried out. Figure 6 shows the shoot to root ratio along the tape length for peppers in 2004. Generally, there was more root weight per shoot weight for the plants subjected to air injection than those plants receiving only water. For the 2004 experiment, photosynthesis and transpiration rates were also measured using a CIRAS 2 photosynthesis analyzer. This data is currently being processed and will be presented at the meeting.

Conclusions and Future Research

- Recent and on-going research has shown that the incorporation of high efficiency venturi injectors in SDI systems can increase root zone aeration and add value to grower investments in SDI.
- The increase in yields and improvement in soil quality associated with the root zone aeration augers well for the adoption of the SDI-air injection technology primarily as tool for increasing crop productivity.
- The work conducted to date has been aimed at evaluating the SDI-air injection system on traditional farms. However, because the air injection system with the venturi devices uses ambient air, there exists the potential to use this system on organic farms. We intend to evaluate the SDI-air injection system on land designated for transition to organic vegetable production at California State University-Fresno.
- In addition to yield and fruit quality, future studies should focus on the impact of air injection on water use efficiency, soil respiration, insect/pest resistance and rooting characteristics of the various crops.

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Table 1: Comparison of Count for Melons- 2004

Treatment	Large	Medium	Small	Total Harvestable	Non Harvestable
Air	96	203	447	746	696
Water	67	180	411	658	667
Difference	29	23	36	88	29
% increase	43%	13%	9%	13%	4%

Table2 Comparison of Weight for Melons-2004

Treatment	Large	Medium	Small	Total Harvestable Wt.
Air	207.4	331.6	603.0	1142.0
Water	149.31	325.44	491.56	966.3
Difference	58.05	6.13	111.49	175.66
% increase	39%	2%	23%	18%

Table 3: Summary of Pepper yield along the drip lines grown in 2003.

Replicates	No. of Peppers	No. of Peppers	Wt. of Peppers	Wt. of Peppers
	Air	Water	Air	Water
Head (West)	100	57	13	10.72
Middle	80	84	12.26	14.03
Tail (East)	47	45	7.18	7.52
Total	**227**	**186**	**32.44**	**32.27**
Difference	**41**	**0.17**		
% Difference	**22.04%**		**0.53%**	


Figure 1: Single injector for each drip line.


Figure2: Relatively larger injector servicing 24 drip lines.

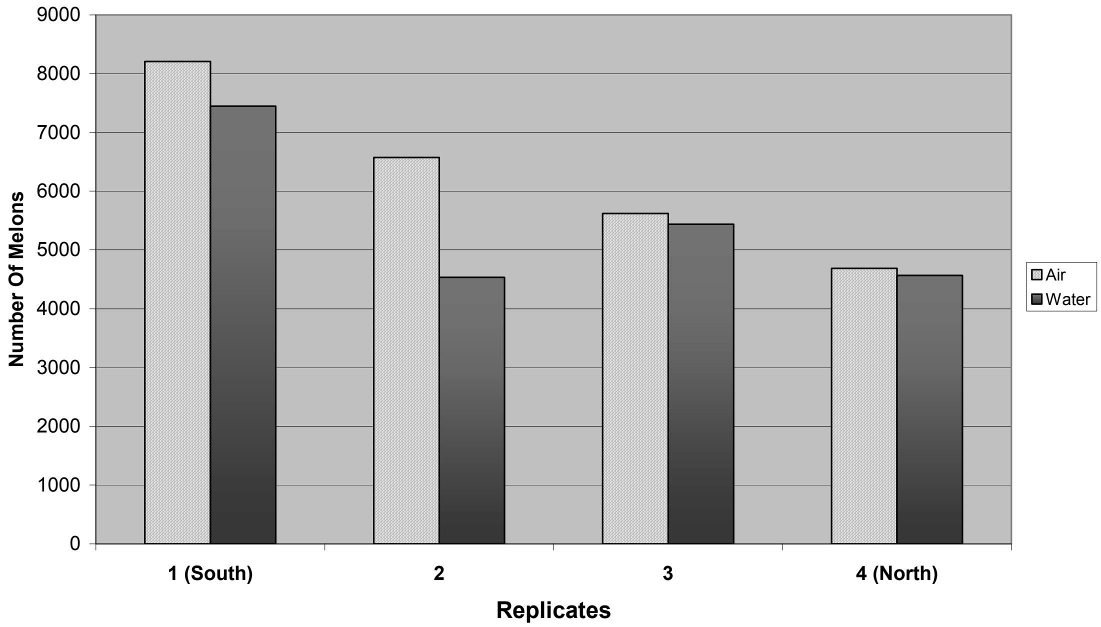

Figure 3: Total Number of Melons in Air versus Water Plots-2003

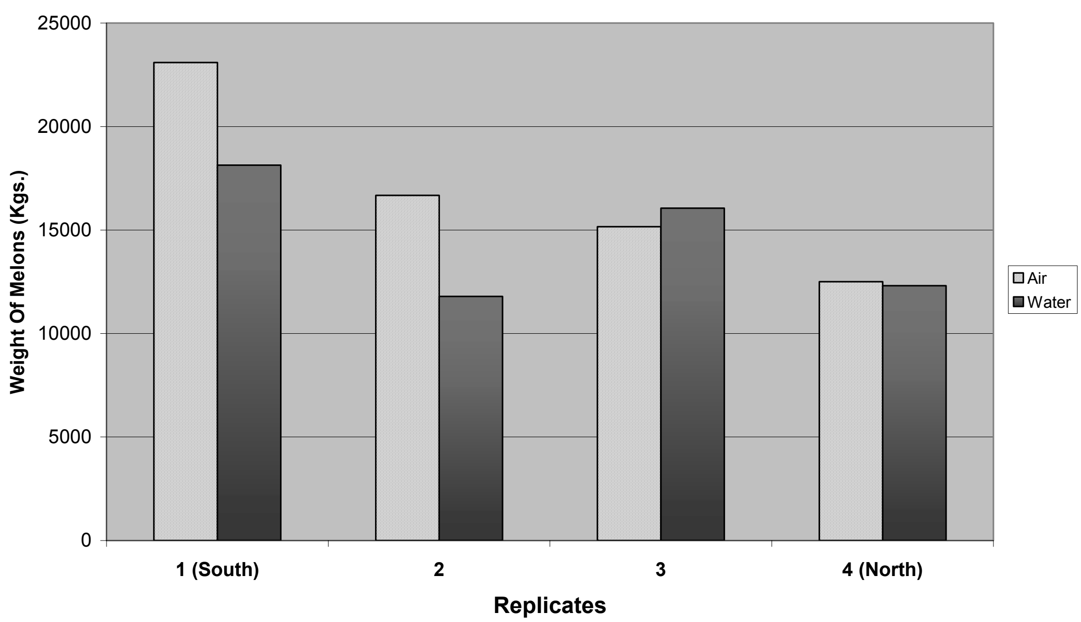

Figure 4: Total Weight of Melons in Air versus Water Plots- 2003

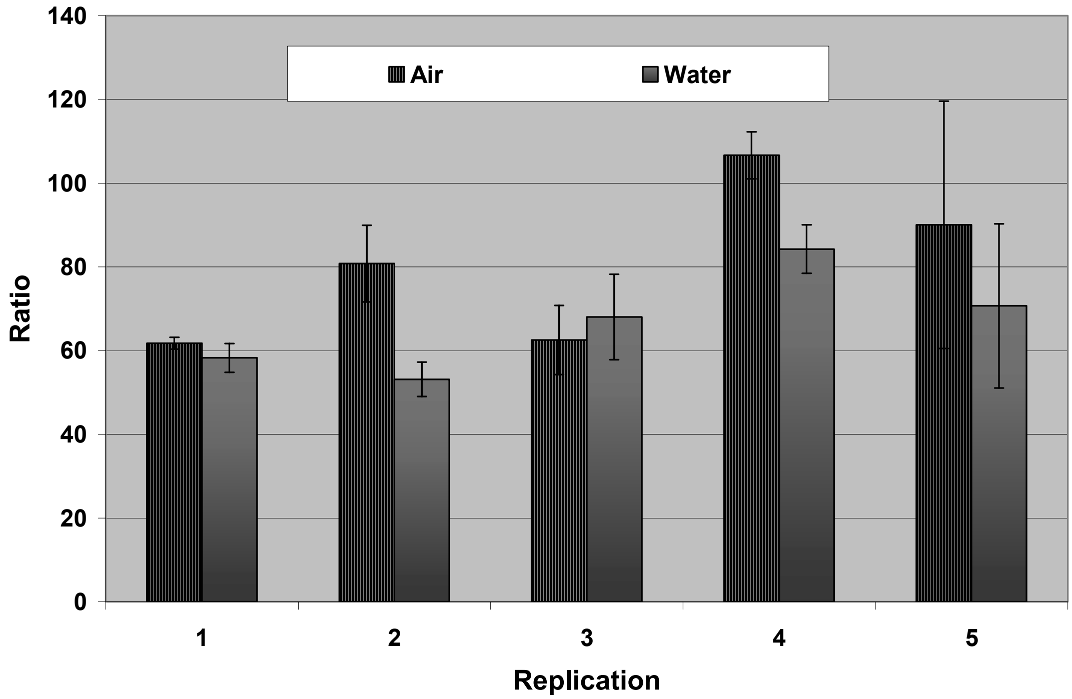

Figure 5: Shoot to root dry weight ratio for melon plants harvested in 2004.

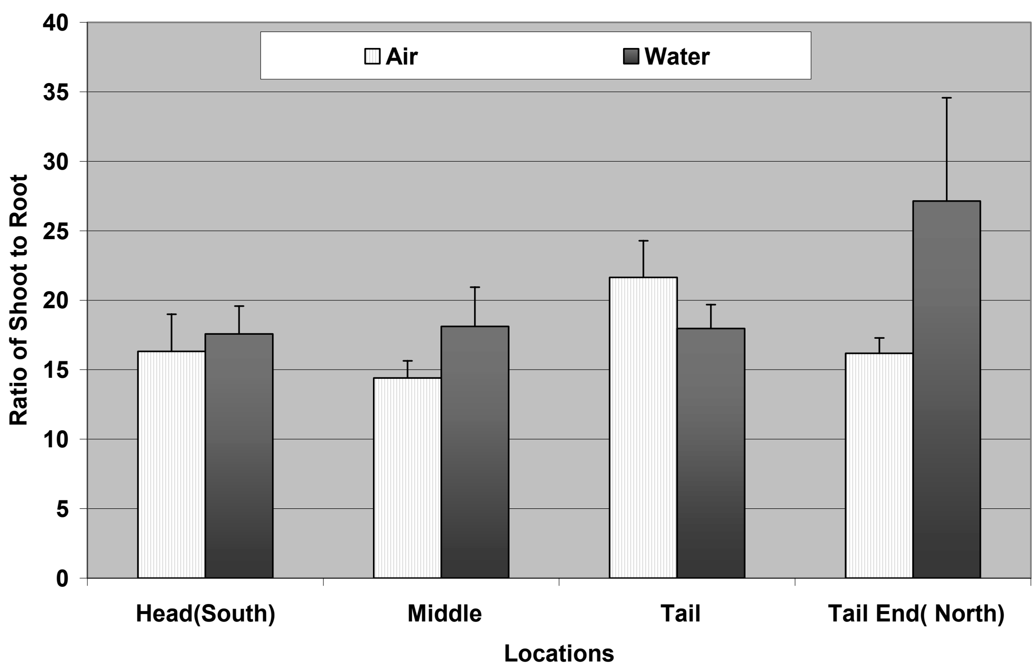

Figure 6: Shoot to Root Ratio along the Tape Length for Peppers in 2004.

Concepts of Ground Water Recharge and Well Augmentation in Northeastern Colorado

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Donald O. Magnuson[3]

ABSTRACT

In northeastern Colorado, severe drought plus recent state court rulings have caused new and increased pressures on water rights. The current drought has been analyzed and is now thought to be a 300-year event based on proxy data obtained from tree rings. The drought factor, dramatic regional growth, transference of water from agriculture to municipal, and the increasing price of water have all put water rights under new and increased pressures.

Tributary wells in the South Platte River Basin, in particular, have been severely impacted because of recent State Supreme Court rulings. In response, several ditch and canal companies have implemented their own ground water recharge programs and well augmentation plans to replace out of priority depletions to the river caused by well pumping. The approaches that several canal companies have used in developing a long term strategy are described. Interestingly, the dynamics of ground water recharge and well augmentation programs also dovetail nicely with canal modernization strategies and SCADA.

In particular, the efforts of the New Cache la Poudre Irrigating Company and the Union Ditch Company are described to include application for new junior water rights, implementation of ground water recharge programs, and filings of augmentation plans for member wells in their respective service areas.

INTRODUCTION

Contentious issues have never been in short supply in the arena of Colorado water rights. That is particularly true today. In recent years, the authority of the State Engineer to approve substitute water supply plans has been successfully challenged and this put a 30-year-old augmentation plan for approximately 4,000 wells in the South Platte River basin in jeopardy. In fact, the Groundwater Appropriators of the South Platte (GASP) is gradually being dissolved. GASP was heavily reliant on leased water to meet timed well depletion obligations. As a result of GASP's demise, many subgroups of the 4,000 wells have formed, some as individual farm well groups, and some as larger groups, often under the auspices of the mutual irrigation companies.

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Mutual irrigation companies logically get involved in well augmentation plans because they typically hold the decree on behalf of the shareholders under the ditch and because many of those shareholders are well owners, recently well owners needful of a suitable augmentation plan.

Although a rather small group of engineers and attorneys has been involved in well augmentation plans in the past, the current situation has provided both opportunity and necessity for additional technical expertise. Also related, Colorado State University has been actively involved and "in the fray" so to speak in providing useful supporting technical models. These models, described further in a later section, allow the engineers to build timed depletion models on a transparent platform for conformity, better understanding of technical minutia, and most importantly, reduced time in both building (for the applicant) and scrutinizing (for the objectors) depletion models to be used in substitute water supply plans, augmentation plans, and ultimately in water court proceedings.

This paper describes some concepts of ground water recharge and well augmentation and comments on the process and the recent experience.

WATER RIGHTS IN COLORADO

Colorado was the first state to develop a system of water rights and laws based on the prior appropriation system. The core of the system is "first in time, first in right." So, if you were the first to divert the water from a stream, then you are the first priority on the river, and so forth. Calls on the river are satisfied according to the priority or priorities enjoyed by the water right holder. This approach, started in the mid-1800s, has worked quite well for Colorado and other western states.

In the late 1960's, a State of Colorado statute legally recognized that tributary ground water is hydrologically connected to surface water[4]. Consequently, both ground water and surface water are administered under Colorado's prior appropriation system. Colorado's water supply can come from either surface or tributary ground water sources, both of which are governed in the same way.

WELL AUGMENTATION

When the State of Colorado determined that tributary ground water and surface water should be administered together, they also determined it necessary to develop well augmentation plans. An augmentation plan is a water court approved plan designed to protect senior water rights, while allowing junior water rights to divert water out of priority (CFWE, 2003). These plans insure that the out-of-priority ground water depletions from junior wells are augmented (replaced) at the proper <u>time, location, and quantity</u> so as not to injure more senior water rights.

[4] When this paper refers to ground water, it is referring to tributary ground water that is hydrologically connected to surface water in streams and rivers. This should not be confused with deep ground water, which is not regulated by the prior appropriation system in Colorado.

Since the late 1960's, over 4,000 well owners in the South Platte Basin have belonged to the GASP well augmenting entity. This entity provided replacement water for well depletions on a year by year basis by primarily leasing surface water. Over the last 30 years, GASP had operated under a temporary augmentation plan (otherwise referred to as substitute water supply plan), which was approved by the State Engineer annually. Compounded in part by drought and recent legislation in the State Supreme Court, these 4,000 wells are now required to file permanent augmentation plans by the end of 2005.

In general, the process behind a well augmentation plan is to: (1) determine ground water depletions caused by wells, (2) analyze replacement water sources needed to insure senior water rights are not injured by the depletions, and (3) administer and account for the operation of the plan.

Over the last year and a half both the Union Ditch Company (Union) and the New Cache la Poudre Irrigating Company (NCLPIC) have been in the process of refining their augmentation plans, which were filed with the water court in 2003. Figure 1 shows the Union Ditch service area, which is located southeast of Greeley. A major component of an augmentation plan is an engineering analysis used to determine the lagged effects of ground water pumping on the river. These depletions must be analyzed in the context of replacement water sources that are needed to insure injury does not occur. This paper will discuss some of the key components of this engineering analysis, with particular reference to the plans submitted by NCLPIC and Union.

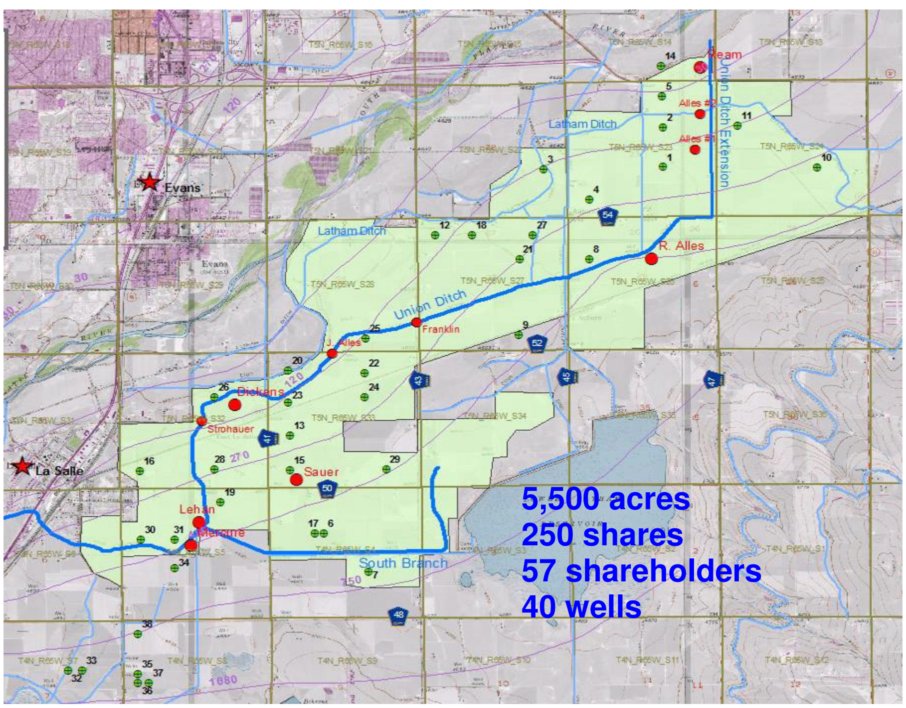

Fig. 1. Union Ditch Company service area.

ENGINEERING TOOLS AND MODELS

The most widely used engineering tools and models used to support augmentation plans in the South Platte Basin have been developed by the Integrated Decision Support (IDS) group at Colorado State University (www.ids.colostate.edu).

The Consumptive Use Model (IDSCU) is used to determine a detailed water budget for farms. Using farm characteristics, surface water supply, and weather data, the model can be used to determine the total water requirement for a farm, the water available from surface water to meet farm water requirements, and the amount of ground water needed to satisfy farm water requirements not met with surface water supplies.

The Stream Depletion Factor Model (SDF View) and the Alluvial Water Accounting System (IDS AWAS) include several methods that can be used to determine the movement of ground water from the river to the well. Conversely, these models can also be used to determine the movement of ground water from recharge ponds to the river.

Simply stated, when a well is pumped there is a depletive effect on the surface water but the impact may not be immediate. Likely the effects of pumping are felt days, weeks, or even years later.

As an example, if the well were very close to the river, even adjacent to the river, the effect would be almost identical to a direct diversion on the river. Colorado law recognizes this in that a well within 100 feet of the river is administered exactly like a headgate. Conversely, if a well is far from the river, the effects of pumping do not reach the river for many days. See Figure 2.

The time delay in Figure 2 is expressed in days and termed the stream depletion factor or SDF. Stream depletion factors are used to determine the lag time from when water is pumped from the aquifer and when the depletion happens in the river -- the larger the SDF, the more delayed the impact on the river (directly proportional to the squared distance from the river).

The USGS completed an extensive mapping of the South Platte in the 1970's and determined SDF values. Maps showing lines of constant SDF were developed and these maps continue to be valid and useful today for those areas mapped at that time. Other areas of the South Platte have never been mapped but additional work is being done by consulting firms in support of their client needs to predict the depletive effects of pumping. The SDF method is one of the most common methods used in these plans to predict stream depletion as well as stream accretion from ground water recharge.

REPLACEMENT WATER SOURCES

Newly formed well augmentation groups are making use of a variety of replacement sources. Because these water sources must replace ground water depletions at the proper time (often throughout the year), location, and quantity, it is necessary for these groups to have a diverse

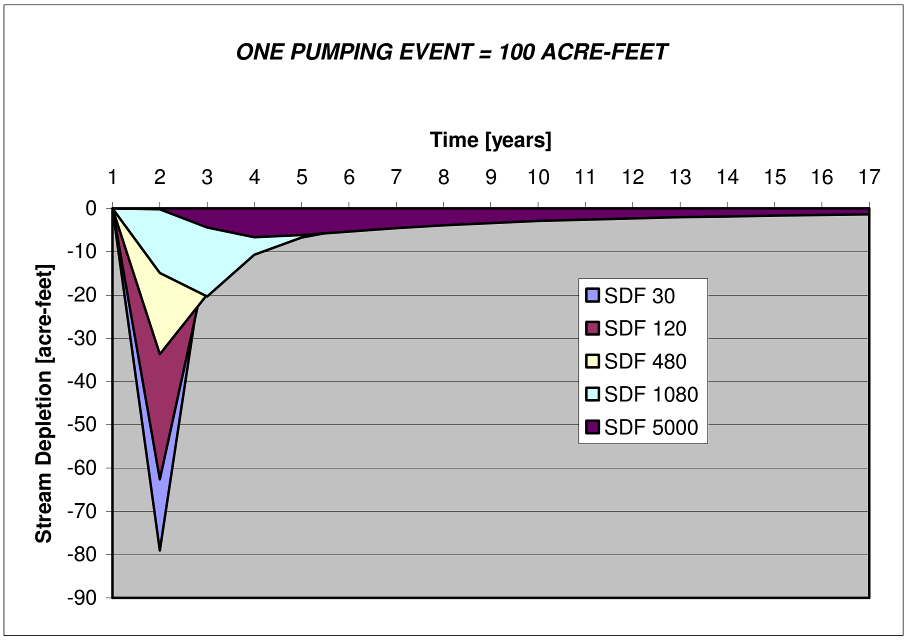

Fig. 2. Assume one pumping event at 100 acre-feet; if the well is located at 120 days from the river, most of its impact on the river will occur in the first two years after the pumping event. If the well is located 5,000 days from the river, the most significant impact on the river will occur 4 years after the pumping event.

water supply portfolio. Some examples of water replacement sources that are used in the basin include:

(1) **Storage Water** - many companies have storage water rights in reservoirs, which may be changed through the water court and used for augmentation purposes. Augmentation sources in storage offer a degree of flexibility over other augmentation sources because they can be released from the reservoir on an as needed basis. For example, Union Ditch Company owns several shares in a local reservoir company which it plans to use for augmentation. Union may request the exact amount of water to be releases at the exact time that water is needed.

(2) **Senior Direct Flow Water –** many companies are in the process of purchasing direct flow water rights from shareholders within their own company or within other companies. Once purchased, these water rights can be changed through the water court and used for augmentation purposes. In order to meet the objectives of the State, it is becoming increasingly important for augmentation groups to actually own, rather than lease their replacement sources. This has real

implications for agriculturalists, who find it difficult to compete with the high market price of water in the region.

(3) **Excess Augmentation Credits** – the water replacement portfolios for each augmentation group differs significantly. As such, there may be times when one group has developed excess augmentation credits that they can lease to other groups that are in need. Union and NCLPIC are two of several groups that have identified each other in their augmentation plans as sources of additional water supply.

(4) **Dry-up of Irrigated Land for Bypass** – it is not known at this time if the temporary dry-up of irrigated land for purposes of bypassing water supplies is an acceptable source of replacement water. The concept is that during times of drought, farms would dry-up all or a portion on their irrigated land. Water previously dedicated for irrigation on this land would bypass the farm and become available for augmentation credit.

(5) **Retiming Wells** – ground water pumped from tributary wells can be a source of replacement water if the well is covered in an augmentation plan. Retiming wells are used to "retime" stream depletions. For example, a well group may pump their retiming well because they need replacement water in the river today, with the hope that they have water in the future to repay the retiming well depletions that are yet to occur in the river. Figure 3 shows a retiming well that is used to pump water into a spillway to the South Platte River. Because retiming wells do not provide a real source of replacement water (it is actually tributary ground water), they aren't a preferred replacement source; however they are commonly used.

RECHARGE PLANS AND RECHARGE STRUCTURES

Another commonly used source of replacement water includes developing a new, junior water right for recharge. Both NCLPIC and Union filed for junior water rights in 2003 with the intent of diverting water from the South Platte River during wet periods and/or during the winter (whenever their new right is in priority). The water will be diverted into newly constructed recharge ponds located at varying distances from the river depending on the desired timing of the accretions. Water placed in the "recharge structure" ponds will be allowed to seep into the ground and will slowly move towards the river, where it will ultimately serve as augmentation credits. The IDS models can be used to determine the strategic location of these ponds to insure that recharge credits hit the river at the time needed to replace well depletions (Figure 4).

PLAN ACCOUNTING

A significant component to the augmentation plan is real-time measurement, recording, and accounting. Plan operations must be reported to the State at least on a monthly basis and must include a daily accounting of well depletions and replacement activities in the river. The most accurate measurement equipment is required for plan monitoring and reporting activities. This degree of accountability is needed to insure other water right holders and the public that well pumping is not unjustly impacting the water supply in the river. Interestingly, the checks, flow measurement structures, gates, and SCADA that may be required for plan monitoring and reporting are also desirable from the standpoint of modernizing the canal system. This is proved to be a factor in both the Union Ditch and the New Cache La Poudre Irrigating Co. situations.

Fig. 3. Retiming well in operation. Water is pumped from the ground and is delivered to the river to cover stream depletions from irrigation well pumping. Sometime in the near future, stream depletions from the retiming well will occur in the river, and must be covered.

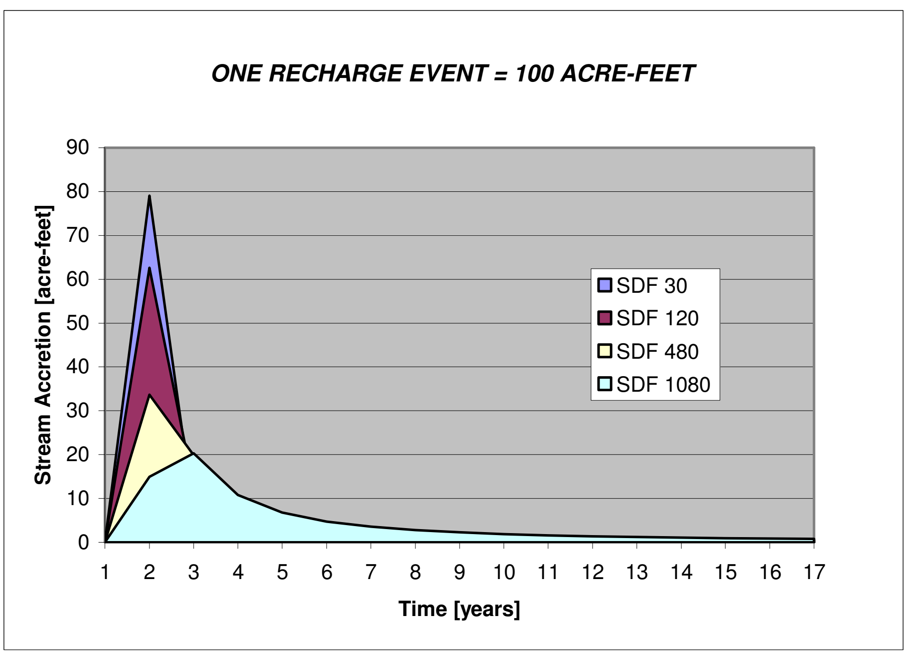

Fig. 4. The concept of ground water recharge is essentially the same as ground water depletion, only in reverse. Recharge ponds can be located so as to strategically time recharge to the river.

SUMMARY

Colorado's water supply is limited and, in many streams, over appropriated. Severe and unprecedented drought has aggravated an already difficult situation. Well pumping in the South Platte River basin has come to the fore as an issue and substitute water supply plans and well augmentation plans are receiving heavy scrutiny from objectors. Water court proceedings over the next few years will likely set law, rules, procedures, and impositions on all types of water rights.

So where is all of this likely to go? Likely future outcomes include:

- Increased scrutiny of all aspects of Colorado water rights.
- Increased reporting and administrative requirements imposed by the Colorado Water Court and the State Engineer's Office.
- Increased need for measurements, including real time measurements.
- Some agricultural wells will not be augmented, which results in all the related consequences and impacts on Colorado's agricultural economy.
- More difficult, time consuming, and expensive water court proceedings and challenges.
- More discord between conflicted interests without implementation of conflict resolution and negotiation elements into the process.

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Saving Fish & Farmers:

A Model for Responding to Environmental Concerns and Endangered Species Criteria by Applying Irrigation Principles and Water Conservation Practices

The Walla Walla Valley is located in the southeast corner of the state of Washington and the northeast corner of the state of Oregon. Agriculture constitutes the primary sustaining source of revenue for the valley, although a moderate industrial presence has developed over the past few decades. The valley is bounded on the north, south and east sides by the Blue Mountains, which contain the headwaters of the Walla Walla and Touchet Rivers. These two river systems comprise the major drainage corridor of the Walla Walla Valley. The stream morphology of the area is unique because the Blue Mountain Range is a relatively young and resistant formation. This condition produces a rapid change in elevation from peak to valley, creating very fast moving, clean, clear creeks and streams in the upper reaches. As the Walla Walla and Touchet rivers move abruptly into the valley, the relief becomes far less pronounced, and in places nearly flat. The river systems transition through a broad, mature floodplain to the north and west before merging and dropping into the Columbia River Basin and the arid deserts of south central Washington.

Historic stream flows in the Walla Walla and Touchet rivers normally fluctuate from flood stage in the spring to static flows in the late summer. A progressive dewatering of the main drainages of the valley for agriculture and other purposes was one of two primary drivers for development of the conservation programs which will be presented here. The second primary driver was the fact that these rivers contain fish species listed as "Threatened" and "Endangered" under Subpart B of the federal Endangered Species Act (ESA). Because traditional irrigation methods often clash with today's stream conservation requirements and an increasing demand for water by growing populations has placed accelerated emphasis upon efficient use, farmers are often caught between ESA mandates and the cost of improving their irrigation systems.

Two programs that were developed in the state of Washington and which have proven successful in addressing this situation are: (1) the Washington Department of Fish and Wildlife's *Cooperative Compliance Review Program* (CCRP); and (2) the Washington State Department of Ecology's *Irrigation Efficiency Program*. The CCRP is better known as the *Fish Screen Program*, or simply the *Screening Program*. Both of these programs began with doubt and skepticism, but through perseverance, communication and commitment by all of the parties involved, the results achieved have been astounding.

Cooperative Compliance Review Program

The underlying concept of the screening program is very simple. First, irrigators may voluntarily identify their equipment or practices as being in noncompliance with state and federal juvenile fish screening criteria – the specifications that determine how an irrigator may withdraw water from an affected water source which precludes the possibility of removing fish in the process. In return for voluntary identification, irrigators may be eligible for amnesty from potential federal or state enforcement actions. Second, eligible irrigators may receive an 85% cost-share benefit toward the installation costs of new, compliant fish screens. Critical to the practical implementation of such a program is a progressive philosophy and a willingness on the part of responsible government agencies to challenge institutionalized discovery and enforcement policies. The notion that a governmental agency would amend its discovery and enforcement policies, even temporarily and for reasonable expectation of exceptional public benefit, is unusually progressive.

The Screening Program was the brainchild of a Washington Department of Fish and Wildlife (WDFW) agent who had worked in valley communities for over 30 years. He recognized that the commonly held regulatory philosophy of *command and control,* or *"find and fine*", was ineffective in terms of cost-benefit. The so-called *sledgehammer* approach to enforcement throughout the state had arguably met with minimal compliance success and had generally resulted in the deterioration of relationships between the regulated community and agency personnel. He felt that, if presented with an alternative method for resolution of specific noncompliance issues that involved a less confrontational and more proactive manner, local irrigators would embrace the effort and the outcome would be much more amenable to everyone. As a member of the local community, he felt personally compelled to pursue a new approach - one of "cooperative" compliance with his agency. After a year of research and discussion, senior WDFW management agreed and *"Cooperative Compliance"* was given the blessing of the agency's director, albeit, in the event that the program did not produce a timely and effective compliance solution, WDFW would then be compelled to return to an expedited and basin-wide inspection and enforcement position.

In October of 2000, and following WDFW's lead, the National Marine Fisheries Service (NMFS), now known as NOAA Fisheries, also agreed in concept and resolved to defer enforcement of certain of their laws with regard to the Endangered Species Act (ESA) for a limited amount of time. The temporary moratorium on enforcement of the ESA 4(d) rules by NOAA Fisheries was also conditionally approved upon achieving effective and timely progress under the new program.

Even with state and federal agencies in accord, the Cooperative Compliance Program lacked the necessary funding and a programmatic/administrative structure in order to proceed. Noting that valley irrigators and the Walla Walla County Conservation District (WWCCD) were concurrently engaged in other projects associated with salmon recovery, and that the irrigation community was closely acquainted with the methods and personnel of the District, WDFW felt that the Cooperative Compliance Program would be given the best opportunity for success if the WWCCD were to play a lead role.

The WDFW subsequently approached the Walla Walla County Conservation District (WWCCD) to ascertain whether the District could seek funding for the program and also act as the lead implementing agency. Under this scenario, technical oversight, funding and program administration would rest with the WWCCD, while the WDFW would be responsible for recruiting valley irrigators to sign up for the program, and to handle the permitting tasks required to facilitate installation of the new screens and equipment. From a programmatic perspective, this type of collaborative arrangement was considered advantageous in that it would remove WDFW personnel and the agency's attendant enforcement obligation from direct involvement in actual field operations and also provides an administrative buffer between state oversight and local implementation.

The Conservation District thereafter agreed to take on the program for the WDFW and in October of 2000 a $700,000 funding package for technical assistance and implementation of the first stages of the program was secured. This funding was made possible by contributions from the Bonneville Power Administration, a federal utility operating the major hydroelectric projects on the Columbia River, and the Salmon Recovery Funding Board (SuRF Board), an entity established to pool and administer fish protection monies from multiple agencies and organizations in the northwest. With initial funding in place, the CCRP staff began to identify potential program participants and formalize the method in which these participants would be brought under the program. Additionally, the identification of a technical entity capable of performing both field assessment and irrigation engineering design would be required. The latter task was of critical importance in that new fish protection screens, piping, power and control equipment would often require custom design or redesign relative to each irrigation application. Hydraulic and mechanical compatibility among existing site irrigation components, design compliance with ESA species protection criteria and cost maintenance would clearly depend upon finding a service provider that could accomplish both assessment and design at a reasonable cost.

Within months WDFW personnel managed to contact and identify over 400 irrigators interested in program assistance in order to achieve compliance with state and federal pumping criteria. Although Conservation District personnel had anticipated a high level of interest, the state and federal agency administrators were amazed with these results. Despite the level of interest, however, there was still some distrust within the irrigation community. Because the ESA establishes a high and widely known potential monetary penalty associated with the death of threatened or endangered species ($25,000 per "take"), fear and skepticism regarding how long NOAA Fisheries would refrain from enforcement action, even given the new program's protection, was nonetheless an undercurrent. In any case, the Fish Screen Program has now been in existence for nearly four years. During this time, and to the admirable credit of both the WDFW and NOAA Fisheries, neither agency has seen fit, within the legal parameters of its charter, to pursue enforcement action against a program participant. With a beginning level of participation assured, the focus eagerly shifted to filling the technical assistance role.

As a matter of assumption, there had existed a general consensus among the agencies that local consultants, engineers, contractors and distributors would be interested in providing a bulk package of technical assistance services. Unfortunately, this assumption was proven false when Conservation District leaders held an initial meeting with 16 local firms to discuss the technical assistance and implementation aspects of the program. Although the engineering groups had shown moderate interest in the design phase work, site assessment and installation tasks were not viewed attractively. A portion of the contracting firms were interested only in the implementation phase and the distributors were singularly interested in providing materials. No one wished to take on a comprehensive role from site assessment through installation. Nevertheless, the Conservation District felt strongly that the site assessment and design work, and to a lesser extent, implementation, should be performed by the same entity based upon the fact that each site would likely be unique and would require a customized design and implementation plan. In short, the Conservation District wanted a full service consultant.

In March of 2001, this obstacle was eliminated when the local WDFW agent and the Executive Director of the Conservation District approached the Walla Walla Community College Irrigation Technology Program (now the Water Management Program) in order to determine whether there was an interest in providing the requisite technical assistance. We (WWCC) were very interested in providing assistance in our field of expertise. Assisting the local community is one of the services a good community college provides and the WWCC administration agreed heartily that the Water Management Program should be involved. Subsequently, and 18 months after the first discussions within WDFW, the programmatic structure of the effort was completed and ready for implementation.

At this juncture two tasks would need to be performed in order for the program's implementation phase to begin. First, a formal assessment of the hundreds of irrigation sites whose owners had signed up for the program had to be completed. Second, a provider of ESA compliant fish screens, or a manufacturer willing to design and provide screens that met the ESA criteria in sizes that accommodated the diversion flows for each site, needed to be identified. Unfortunately another roadblock with potentially fatal consequences then emerged - Water Rights.

The agency responsible for administering and enforcing all water rights issues in the state of Washington is the state Department of Ecology (DOE). In harmony with the other agencies, the DOE was persuaded to defer action on program-related enforcement issues provided all illegal stream diversions identified were eliminated and all water rights involved were verified as legal. In any case, the Conservation District would be required to ensure that all involved water rights were legal in order to support expense of federal and state money to screen these diversions. Because the Conservation District and DOE now required rights verification, this compromised the path to progress and had to precede any design and installation phase work. The verification of water rights proved to be one of the biggest hurdles to final implementation of the Cooperative Compliance Program, largely because the records of water rights for the Walla Walla Valley were archived in the DOE's Spokane, Washington office. The records existed only as paper copies and were filed in apple crates in the basement of the building. It became apparent early on that this process was going to take time.

While waiting for water rights verifications from the DOE, WWCC hired two irrigation technology students for the purpose of contacting each program applicant and, under the guidance of college program instructors, performing an engineering assessment of each site's existing pumping configuration. Categories of relative retrofit difficulty were established in three phases. Phase-1 sites were those sites which could be designed and completed quite easily – generally involving very small diversions, small streams and small acreages. Phase-1 water system usages were to range in size from 1.72 gpm up to 150 gpm. Phase-2 systems constituted those which were likely to require additional information and would require substantial design time. Phase-3 systems were those for which no readily apparent solution could be determined at that time. Once the phase classifications and assessments were in place for review, all parties involved decided that a concerted effort should be placed on the Phase-1 designs and installations in order that WDFW and NOAA Fisheries could realize some immediate results. In concert, DOE concentrated their water right verification efforts on the Phase-1 sites, aided by the WDFW biologist initially tasked with processing the necessary permitting. This realignment of resources streamlined the process but the situation may best serve as a valuable lesson that water rights verifications should be addressed as early in the process as possible to avoid program implementation delays.

A second action, which was pursued at the same time as water rights verification, was the identification of a source of compliant fish screens. As noted earlier, stream flows in the Walla Walla Valley are highly variable and as a matter of necessity, screen designs would need to address the low suction-shallow submersion pumping requirements of small creeks and streams as well as the high flow-deep diversion configurations of larger irrigation projects. This too proved harder to address than originally envisioned. In brief, it was found that no screens were being manufactured at that time which met both the state and federal screening criteria <u>and</u> which would function effectively in shallow waters. All commercial screens were sized for large diversions of 250 gpm and up or were of the active design. Active design screens possess cleaning bars which either spin themselves around the screen or spin the screen around a stationary bar. Because active screens contain moving parts and had proven problematic for irrigators to maintain, program participants wanted nothing to do with this style of filtration. Only after much additional research and assistance from the agencies was a single manufacturer of a passive style screen meeting federal screening criteria identified. Unfortunately, the only screens offered by this manufacturer were 250 gpm and 500 gpm units that required a minimum of 20 inches of water and were over 5 and 10 feet in length respectively.

When asked if something smaller could be designed to match small diversions in the 10-16 gpm range and up, the manufacturer responded by utilizing a CAD program to scale the two existing screen versions by 50% and 75%. NOAA fisheries subsequently agreed that, provided the screens were downsized as a percentage, the engineered effectiveness of the screens would not change and therefore, the compliance certification of the larger screens was granted for the smaller screens. Ultimately, our program designers could choose from a range of NOAA-accepted passive screens in sizes of 15, 30, 65 and 130 gpm. Because the WDFW screening criteria had been adopted verbatim from the federal regulations, the new screens met all Washington state criteria as well. While testing of a prototype screen in July of 2001 exposed some minor manufacturing problems, the first eight compliant fish screens were in place and operational by the end of that summer. Despite the implementation team's perception that this process had been sluggish, agency leadership was taken aback that so much had been overcome in such a short period of time.

Throughout the rest of 2001 and through December of 2002, 370 targeted pumping sites were assessed with 153 of these sites being classified as Phase-1 screens. Of these, 65 designs had been installed. Cooperative Compliance was beginning to catch on and receiving rave reviews from the farming community. Nevertheless, there remained skepticism on the part of some people in the agencies and the environmental community that the program would not fully achieve its goals of total compliance in the absence of enforcement.

In October 2002 the Columbia Conservation District (CCD), Walla Walla's county neighbor to the north, received a grant to begin their own screening program to be modeled after that operating in the Walla Walla Valley. WWCC assessed 60 sites for the CCD from October 2002 to December 2002 with most of these sites being classified as either Phase-2 or Phase-3 in complexity. In total, over 430 sites had been assessed and 160 had been designed, leaving 270 with no immediate solutions.

It became evident, during this initial assessment phase that the number of sites without an immediate solution was going to be of concern. The primary reason for this problem was that within the federal screening criteria, one specification required that passive fish screens could only be used on diversions of less than 1 cfs. Diversions greater than 1 cfs were required to utilize an active-style screen. As noted previously, active screens are drum-style screens. Drum-style screens, under NOAA criteria, were required to be placed within large, deep stream holes. Since streams in the Walla Walla Valley rarely contain large, deep holes, the Conservation District and WWCC made a proposal to the WDFW and NOAA Fisheries in April of 2002 to pilot test a passive-style screen in a worse case scenario. WDFW and NOAA subsequently agreed to the test provided weekly site visits were performed. An existing pump site was identified on the lower Walla Walla River just west of Touchet, Washington and on July 12, 2002 WWCC staff and students installed the pilot screen. A piezometer was built and installed on the screen so that differential pressure between the surface of the screen and the interior of the screen could be monitored. This was done to check plugging of the screen. Also monitored was the depth of water over the screen, the temperature of the water, total river flow, total gallons pumped and general water quality conditions. When the test concluded on November 7, 2002, the data unequivocally demonstrated that a passive screen could perform to the required criteria in worse case scenarios.

Armed with this new data, the previously classified Phase-2 and Phase-3 sites were reevaluated. As a result, nearly all of the 430 sites then assessed in Walla Walla and Columbia Counties possessed a passive screen solution. These solutions, however, were immaterial in the absence of a federal criteria modification which would allow for passive screen diversions up to 3 cfs. In the early spring of 2003, the WDFW took the lead by granting passive screen acceptance up to 3 cfs, thereby allowing the Cooperative

Compliance Program to progress in the design and installation of passive screen solutions for diversions greater than 1cfs of flow. One year later, NOAA Fisheries would recommend the same rule change to the federal screening criteria.

During the remainder of 2003, WWCC and the screen manufacturer continued to develop new screen configurations. The notion of connecting smaller screens together to form one screen assembly (termed “manifolding”), capable of pumping larger quantities of water, was tested. This design proved effective; although, the number of screen elements comprising the full assembly was limited to 4, given velocity restrictions in the manifold. With these assemblies, screening was now available which could divert water flows of greater than 1 cfs while installed in less than 1 foot of water. This breakthrough now provided a multitude of screen design solutions to fit each individual site. It became simply a matter of matching the site to the solution.

From the time WDFW first compiled the program participation lists to the present, new applicants have continued to step forward. Currently, there are approximately 500 people on the program’s self-identification and assistance lists. Of these, over 450 screening solutions have been designed, and 300 or more have been contracted and/or installed; all without the shadow of enforcement or litigation issues. The final push to complete the project and achieve 100% compliance is now underway. This program concept has since been replicated by the North Yakima Conservation District in the state of Washington and the North Fork of the John Day River Watershed Council in north-central Oregon. Without a doubt, Washington’s Cooperative Compliance Program represents a solid model of what can be accomplished if agencies and the regulated community are willing to take mutual responsibility and a single trusting step toward shared goals.

Irrigation Efficiency Program

The Irrigation Efficiency Program was developed by the Washington State Conservation Commission and is funded by the Washington State Department of Ecology. The program allows an existing water user to upgrade an irrigation system to a new, more efficient system with a cost share of as much as 85%, in return for leasing the conserved water back to in-stream flows. To qualify for this program, an irrigator must present proof of the quantity of beneficial water usage being diverted, and be able to demonstrate a quantity of water savings likely to occur within such usage if the applicant were to be provided with a more efficient irrigation system. The calculated savings in water is then placed in trust by the Washington State Department of Ecology. This action provides a legal protection for the conserved portion of the water on behalf of the holder of the water right from potential confiscation as unused or non-beneficial usage of the water under state water law. Such conserved water, of course, remains in the associated stream or aquifer, although the program participant retains a value of the conserved water through the leasing instrument. While this program has shown tremendous potential, progress has been slowed because of issues related to interpretation of Washington state water law- particularly, those related to water rights. In order to provide some perspective, the potential savings identified in an initial assessment within the Walla

Walla and Tucannon river basins alone was as much as 30 cfs and 20 cfs respectively. In most cases the user must be irrigating a large area in a very inefficient manner in order to realize a quantity of savings which justifies the costs associated with converting to a more efficient system. In essence, experience with the program in its current form has demonstrated that irrigators with large acreages and associated large water rights may qualify for this program, while small users (under 1cfs) generally will not qualify. At this time new ideas are being formulated which would allow small pumping operations to qualify for eligibility under a program such as this.

Once an irrigator has been identified as a potential qualifier, the emphasis is placed upon increasing on-farm irrigation efficiency. This is accomplished by utilizing commonly accepted irrigation principles and practices, new equipment, technology and most importantly, educating the user in correct implementation of these new tools.

To illustrate how the program works, approximately 300 acres of hand-line irrigated alfalfa, winter wheat, peas/beans and pasture was converted to new, low pressure, center pivot irrigation in the Tucannon River drainage in southeast Washington. The standard irrigation efficiency numbers allowed by the Natural Resources Conservation Service (NRCS) are 65% for a well-maintained hand-line/wheel line and up to 85% for a low-pressure drop tube center pivot. Of the foregoing crops, the largest consumptive use (C_U) requirement was given for pasture grass. Using the C_U for pasture grass in the Tucannon River basin and associated soils, an irrigation management plan was prepared utilizing the increase in efficiency which saved in excess of 6 cfs. The landowner received new high efficiency pumps, new fish screens (under the Screening Program), and new mainlines, thus increasing the overall water and energy efficiency of the operation. The 6 cfs "returned" to the river does not represent a yearly total, but an instantaneous flow that corresponds to roughly 10% of the instantaneous flow of the Tucannon River during the months of August and September. This quantity of water conserved was leased by the state and placed in trust. The trust was written for a period of 20 years, at which time the saved water will revert back to the landowner's entitlement. The trust serves two purposes: First, to protect the water, as far as the state is concerned, as it moves downstream; and, second, to provide a beneficial use (in this case "in-stream") which serves to protect the individual's water right. One of the state's statutory requirements with regard to water rights mandates that water diverted or pumped pursuant to a water right must be put to beneficial use or the right to unused and/or non-beneficially utilized water may be terminated after a five-year period. This has been termed locally as the *"use it or lose it"* clause. The state trust essentially eliminates this clause from applicability to participating landowners.

An additional example of the Efficiencies Program is the conversion of approximately 300 flood-irrigated pasture acres to low pressure center pivot irrigation. This conversion took place in the lower Walla Walla basin on the Walla Walla River. The same principles were implemented on this project, using NRCS numbers for flood irrigation efficiency at 50% and low pressure center pivot at 85%. This resulted in savings of over 4 cfs. In 2002 the lowest flow reading taken by the USGS gauging station on the lower Walla Walla River was 2 cfs in late August. With one efficiency project we would have doubled the flow of the river for that time period.

At this time two more projects are under contract on the Tucannon River. These projects involved conversion of hand lines to center pivots and have resulted in another savings of approximately 3 cfs, making the total saved on the Tucannon roughly 9 cfs. Another project in the Walla Walla basin resulted in a savings of another 1 cfs. One additional project in the Walla Walla basin is in the final stages of completion and is expected to go to contract before the end of this year. This project adds another 1 cfs of saved water making the total saved water for the Walla Walla River roughly 6 cfs. The foregoing numbers represent the water saved from a legal water rights standpoint and do not consider the actual true savings from use above the documented water right. If the actual true savings amounts were added into the totals, the savings in both basins is substantially greater. The reason the actual saved water cannot be represented is because the use in excess of the actual water right cannot be placed in trust by the state.

Many critics of the program consider the cost extravagant; saying that if the state would simply enforce the existing laws regarding water rights, the conserved water would remain in-stream, thus they are of the opinion that they are paying for something they already own. A second point opponents bring forth is that merely purchasing the water rights back from the users through the water acquisitions program would offer a simpler alternative. While the first statement has some truth to it, not considered is the "good will" developed between an agency whose track record of dealing with the public is poor at best, and the landowners/operators. The argument also fails to recognize the high cost and social consequences of litigation. History is replete with evidence of such litigation in situations where satisfactory progress has not been made. The second statement does not consider the economic and social ramifications of removing viable, productive agricultural acres. If the costs associated with the program are divided by the number of acres and then amortized through the life of the lease, the true costs are \$47.80 per acre-foot/year or \$9,337 per ft^3/sec/year of in-stream flow.

The results of this program are crystal clear. The state of Washington is able to increase stream flows, which contain threatened and/or endangered species, thus increasing water quality. This in turn decreases juvenile fish mortality rates. The state is thereby able to demonstrate progress toward compliance with the ESA provisions-keeping federal regulators at bay, while pleasing the environmental community by increasing in-stream flows. The state may provide funding for up to 85% of the new irrigation equipment, and in return for this investment, efficiency improvements are realized, agricultural land is kept in production and our farmers remain competitive in the world markets. Utilizing standard irrigation principles and practices, technology and education, we are able to increase the efficiency of agricultural production, while decreasing water use, and conserving stream flows…saving fish and farmers!

Irrigation Impact and Trends in Kansas Agricultural[1]

D.H. Rogers, G. A. Clark and M. Alam[2]

Abstract: Total irrigated acreage in Kansas remains at approximately 3 million acres, which is about 15 percent of total annual harvested cropland acres, based on year 2000 data. This acreage represents over 25 percent of the total value of Kansas crop production. However, regional analysis show the impact of irrigation is much more significant and in an example county, exceeded over 90 percent of the value of crop production.

Keywords: Kansas, irrigation trends

Introduction

Irrigated agricultural remains an important segment of the total Kansas economy, but even more important when irrigation impacts are viewed on smaller regional scales.

Kansas Irrigated Acreage, Crop Value System, Crops, and Water Use

Irrigated Acreage and Crop Value

The Kansas irrigated acreage base in 2000 was reported to be almost 3.2 million acres (Table 1, Figure 1) and produced over 25 percent of the total crop value produced of $2.8 billion (Table 2). Irrigated acreage percentage of crop value produced was similar to previous analysis, (Rogers, 2000). The total value of crop production was less in 2000 than previously.

Irrigation Systems

Center pivot irrigation systems increased their acreage dominance in the state and now represent over 80 percent of all irrigated acreage (Table 3, Figure 1). Subsurface Drip Irrigation (SDI) is the newest irrigation system option. While SDI acreage is increasing, SDI still represents less than one percent of all irrigated acres.

Irrigated Crops

Corn remains the most popular irrigated crop, representing 50 percent of all irrigated acreage (Figure 2). Wheat still remains the second most commonly irrigated crop, but its acreage trend continues downward. Alfalfa and soybean have been gaining acreage, while grain sorghum acreage has been decreasing. Alternative crops of cotton, sunflower and dry beans have been increasing in acreage but the number of irrigated acres is not reported separately from dryland production. However, total acreage of irrigated cotton, sunflower and dry bean are still relatively small.

Irrigation Water Use

The total volume of irrigation water reported pumped in 2000 was 3.86 million ac-ft (Table 1) and reflects the largest volume pumped in five years, and reverses a generally downward trend in applied application depth (Figure 3). Region 1 of Figure 2 represents the western third of Kansas, Region 2, the middle third, and Region 3 is eastern Kansas. Most of the irrigated acres are in western Kansas and concentrated in southwest Kansas.
The downward use trend is likely attributed to the continued conversion of irrigated lands from surface flood irrigation to center pivot irrigation and relatively favorable climatic conditions during the late 1990's. Data collected from the Garden City weather station at the Southwest Research and Extension Center shows that annual precipitation and July-August rainfall amounts were above normal during this period (Figure 4). 2000 annual

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precipitation was above normal but 2000 July-August rainfall was less than normal with high crop water use demand as reflected by the pan evaporation. Increases in pan evaporation reflect increases in temperature, solar radiation, and wind that also increase crop water use requirements. Weather data for 2001 and 2002 are also plotted and indicate that high irrigation water use demand is likely for those two years.

Regional Irrigation Impacts

Western Kansas: Irrigated Acres and Value of Production

The western region of Kansas, representing the western 4 or 5 tier of counties (31 of 105 Kansas counties) has 2.1 million irrigated acres or about two-thirds of all Kansas irrigated acres. Within the region, about one-third of all harvested cropland in 2000 was irrigated and produced 61 percent of the total crop value (Table 4).

Southwest Kansas: Irrigated Acres and Value of Production.

The southwest Kansas region represents a 14 county area. In 2000, about 48 percent of all harvested acres were irrigated and produced nearly 73 percent of the total crop production value (Table 5).

Haskell County: Irrigated Acres and Value of Production

Haskell county is the middle county of southwest Kansas and has the second largest irrigated acreage base in Kansas of 206,000 acres (Table 6). Irrigation was applied to 77.4 percent of all harvested acres in 2000 and 92 percent of all crop production value was produced on irrigated acreage.

Summary

Irrigated agriculture makes important contributions to the Kansas economy. These impacts become increasingly significant for heavily irrigated regions.

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Table 1: 2000 Kansas Selected Crop Statistics

Total Cropland (Harvested) Acres*	Total Irrigated Acres +	Irrigation Water Use (AF)
21,656,900	3,183,983	3,885,805
Irrigation Percentage of Total Cropland	14.7 %	

+ 2000 DWR Kansas Irrigation Water Use Report

Table 2: 2000 Kansas Irrigated Crop Production

Crop	Production	Farm Value $	Cost
Alfalfa	1,222,400 Tn *	117,075,000	$95.77/tn
Wheat	22,724,000 bu	60,218,600	$2.65/bu
Grain Sorghum	9,785,000 bu	1,751,515	$1.79/bu
Corn	284,300,000 bu	568,680,000	$2.00/bu
Soybeans	17,150,000 bu	77,175,000	$4.50/bu
Total Farm Value		724,820,115	
Total Farm Value of all Kansas Crops		$2,871,398,000	
Irrigation Percentage of Total Farm Value		25.2 %	

* only includes the 3 western crop reporting districts from 2002 Kansas Farm Facts for alfalfa

Table 3: 2000 Kansas Irrigation System Acreage Estimates+

Surface Irrigation Acres	Center Pivot Acres	Other Sprinkler Acres	SDI Acres
549,946	2,592,244	29,276	12,500
%	%	%	%
17.3	81.4	0.9	0.4

+ 2000 DWR Kansas Irrigation Water Use Reports

Table 4: 2000 Western Kansas Crop Production Statistics for Wheat, Grain Sorghum, Corn, Soybeans, and Alfalfa*

	Irrigated		Dryland	
Crop	**1000's of Acres**	**Crop Value 1000's of $**	**1000's of Acres**	**Crop Value 1000's of $**
Wheat	**455**	**53,720**	**3,210**	**277,423**
Grain Sorghum	**71**	**11,806**	**925**	**82,170**
Corn	**1,215**	**435,700**	**517**	**48,990**
Soybeans	**134**	**25,848**	**25**	**2,165**
Alfalfa	**249**	**117,075**	**---**	**---**
Total	**2,124**	**644,149**	**4,677**	**410,748**
Total of Irrigated and Dryland	**1000's of Acres**	**Total Value 1000's of $**		
	6,801	**1,054,897**		
Irrigation Percentage	**31.2%**	**61.1%**		

* other crops not included are sunflower, cotton, and dry beans.

Table 5: 2000 Southwest Kansas Crop Production Statistics for Wheat, Grain Sorghum, Corn, Soybeans and Alfalfa*

	Irrigated		Dryland	
Crop	**1000's of Acres**	**Crop Value 1000's of $**	**1000's of Acres**	**Crop Value 1000's of $**
Wheat	**349**	**41,716**	**1,101**	**97,223**
Grain Sorghum	**48**	**7,991**	**475**	**39,527**
Corn	**829**	**308,620**	**65**	**5,600**
Soybeans	**82**	**16,907**	**55**	**770**
Alfalfa	**249**	**1,388**	**---**	**---**
Total	**1,557**	**376,622**	**1,696**	**143,120**
Total of Irrigated and Dryland	**1000's of Acres**	**Total Value 1000's of $**		
	3,253	**519,742**		
Irrigation Percentage	**47.9%**	**72.5%**		

* other crops not included are cotton, sunflower, and dry beans.

Table 6: 2000 Haskell County Crop Production Statistics for Wheat, Grain Sorghum, Corn, Soybeans, and Alfalfa *

	Irrigated		Dryland	
Crop	**1000's of Acres**	**Crop Value 1000's of $**	**1000's of Acres**	**Crop Value 1000's of $**
Wheat	**56**	**7,139**	**40**	**3,620**
Grain Sorghum	**4**	**532**	**15**	**1,570**
Corn	**125**	**51,322**	**4**	**430**
Soybeans	**16**	**3,312**	**0.4**	**56**
Alfalfa	**5**	**2,634**	**---**	**---**
Total	**206**	**64,939**	**60**	**5,676**
Total of Irrigated and Dryland	**1000's of Acres**	**Total Value 1000's of $**		
	266	**70,615**		
Irrigation Percentage	**77.4%**	**92.0%**		

* other crops not included are cotton, sunflowers, and dry beans

Figure 1. Irrigated Acres VS. Sprinkler and SDI Irrigated Acres in Kansas- 1970 to 2000

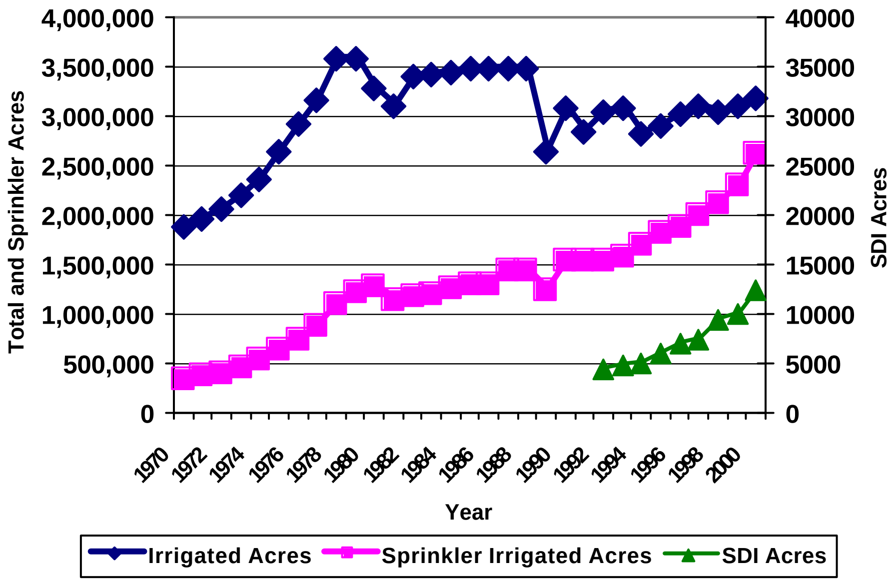


Figure 2. Major Kansas Irrigated Crop Acreage- 1974 to 2000

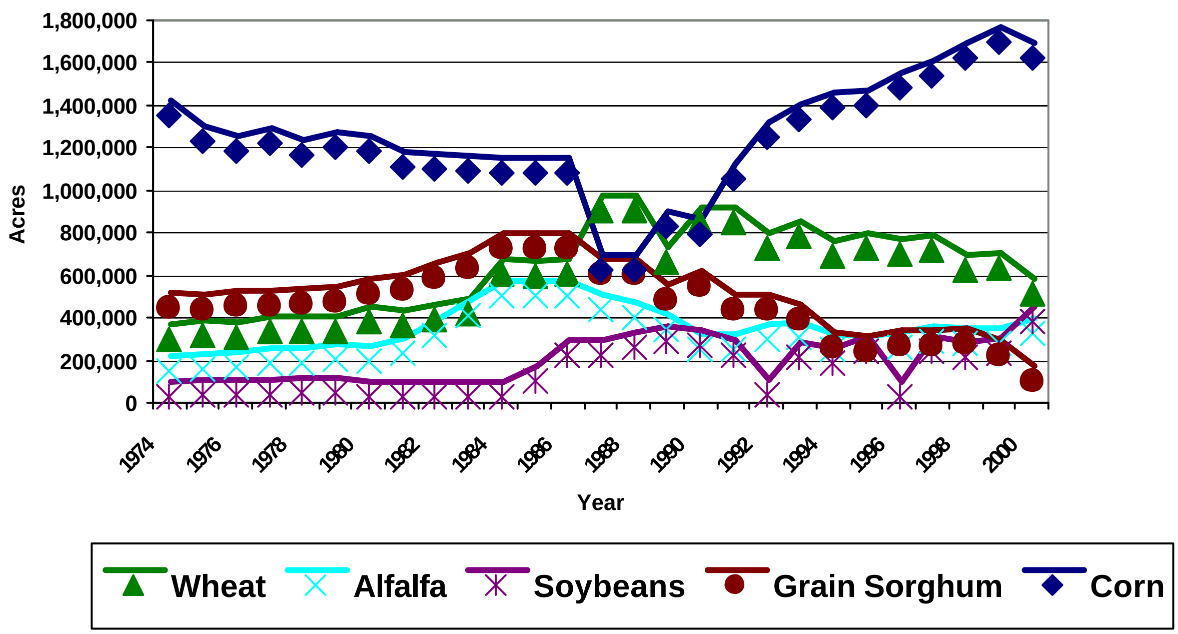


Figure 3. Acre-feet of Water Pumped per Acre by Region for the State of Kansas

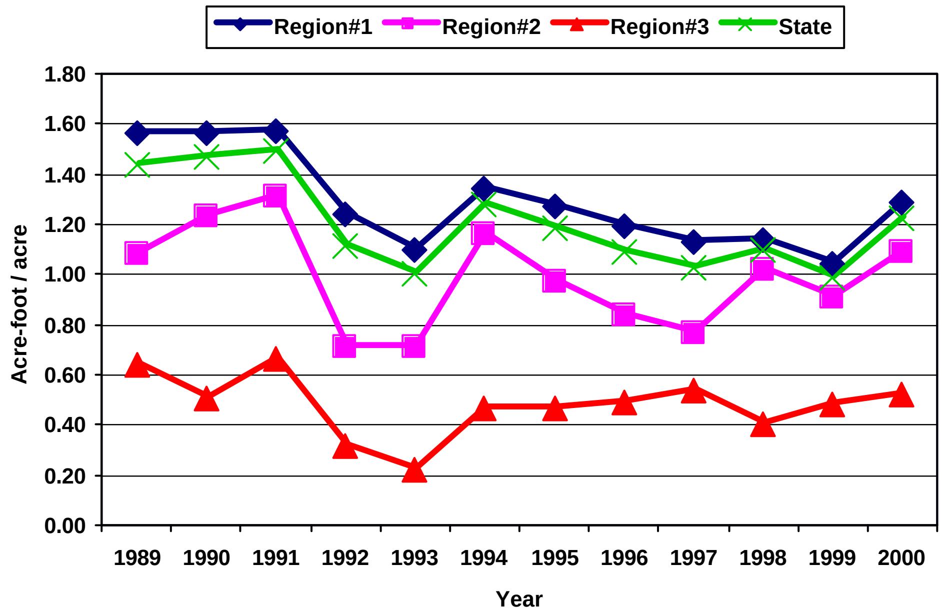
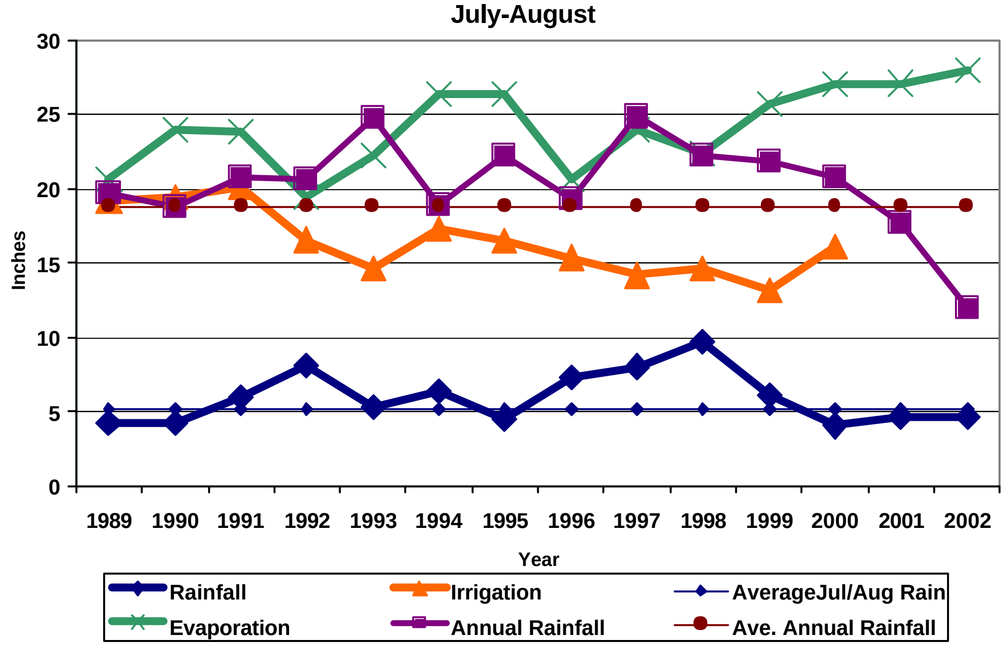


Figure 4. Irrigation, Evaporation, and Rainfall Totals for SW Kansas: July-August



San Antonio
Water
System

San Antonio Water System's

Agriculture Water Conservation Program

Presented by: **Luis Aguirre**
SAWS Water Resources
Water Resources Planner

SAWS' AGRICULTURE WATER CONSERVATION PPROGRAM

INDEX

SAWS HISTORY & CHRONOLOGY

San Antonio has always relied upon the Edwards Aquifer for its water supply. The Edwards feeds the San Pedro and San Antonio springs which, until the middle of the 20th Century, provided the base flow for the San Pedro Creek and the San Antonio River. The springs were the site of Indian encampments centuries ago and were the reason that the Spanish established San Antonio in 1718.

The primary water distribution system in the area was the acequias, or community water ditches. The acequias were supplemented by shallow wells and provided water for both irrigation and consumption. In 1836, the San Pedro Ditch was reserved for drinking and cooking water only; penalties were established for using it for bathing or as a sewer. Although crude, this water and wastewater operation served the City's needs until 1866 when a severe cholera epidemic prompted real efforts to establish a satisfactory water supply system.

Many water development proposals were discussed and subsequently discarded over the years until the City finally entered into a water supply contract with J.B. LaCoste and Associates on April 3, 1877. LaCoste constructed a pumphouse near the headwaters of the San Antonio River in what is now Brackenridge Park. Water pressure operated a pump, which lifted water to a reservoir near the old Austin highway on the present site of the Botanical Gardens. This site was high enough for the water to flow by gravity into the distribution system.

In 1883 a new company, led by George W. Brackenridge, acquired the water system. Recognizing that the source of the springs was possibly a subterranean reservoir under high pressure, Brackenridge proposed that his firm purchase property along the river and drill a well. In 1889, the first artesian well was bored in what later became Brackenridge Park. By 1900, all of the system's water was obtained from artesian wells linked directly to the distribution system.

In 1905, George Brackenridge sold his interests in the water company to George Kobusch of St. Louis. At that time the name was changed to the San Antonio Water Supply Company. Shortly thereafter, Mr. Kobusch sold the business to a Belgian syndicate. The Belgians sold the waterworks to a group of local investors in 1920. Contract and rate disagreements marred the relationship between the City and the new water entity. In 1924, the company demanded a rate increase, and since an agreement could not be reached, the new rates were put into effect and the City was enjoined from interfering. This situation prompted the City to issue seven million dollars in revenue bonds and purchase the system outright. On June 1, 1925, the utility became known as the City Water Board (CWB) and its management was placed under a Board of Trustees appointed by the City Council.

During the Depression and the war years the City Water Board was able to keep pace with increasing demand without much difficulty. However, the post-war building boom and the impact of the 1950's drought significantly taxed the Board's capabilities.

In 1979, a committee established by the City Planning Commission reported to the City Council that San Antonio should pursue the necessary federal and state permits to construct San Antonio's first surface water supply project known as the Applewhite Reservoir. The Water Board received the state permit from the Texas Water Commission in 1982, and the 404 Permit from the U.S. Army Corps of Engineers on August 28, 1989. Construction on the Lake began a few months later. On May 4, 1991, the citizens of San Antonio, by a narrow margin, voted to discontinue the Applewhite Project.

In 1989 the City of San Antonio asked the State Legislature to pass a bill, which would permit the creation of a district devoted to reuse of the municipality's effluent. The Governor signed senate Bill 1667, which established the Alamo Water Conservation and Reuse District, on June 16, 1989. In 1991, the District applied for a permit to divert water from the Leon Creek Plant for reuse purposes.

The controversy brought on by competing water agencies prompted the City Council to vote in December 1991 to establish a single utility responsible for water, wastewater, stormwater, and reuse.

The refinancing of $635 million in water and wastewater bonds made the merger possible. A new entity, The San Antonio Water System (SAWS), became a reality on May 19, 1992.

SAWS was created through the consolidation of the City Water Board (the previous city-owned water supply utility); the City Wastewater Department (a department of the city government responsible for sewage collection and treatment); and the Alamo Water Conservation and Reuse District (an independent city agency created to develop a system for reuse of the city's treated wastewater).

SAWS also owns and operates as a separate utility the former City Water Board's chilled water and steam plant, which is a centralized heating and cooling system for the buildings in and around HemisFair Park.

SAWS was also assigned the responsibility for complying with federal permit requirements for treatment of the city's stormwater runoff. In addition, the water resources planning staff of the City Planning Department was realigned to the new agency, to give it a complete package of related functions.

An important component of SAWS' planning role is the responsibility to protect the purity of the city's water supply from the Edwards Aquifer, including enforcing certain city ordinances related to subdivision development.

EDWARDS AQUIFER GEOLOGY

The Edwards Aquifer is intensely faulted and fractured carbonate limestone that lies within the Balcones fault zone. The dynamics and size of this geologic anomaly make it one of the most wondrous aquifers in the nation, through its storage capacity, flow characteristics, water producing capabilities and efficient recharging ability.

The Edwards aquifer and its catchment area in the San Antonio region is about 8,000 square miles and includes all or part of 13 counties in south-central Texas.

The recharge and artesian areas of the Edwards aquifer underlie the six counties south and east of the Balcones fault escarpment. The aquifer underlies approximately 3,600 square miles, is about 180 miles long from west to east and varies from 5 to 30 miles wide. The Edwards aquifer receives most of its water from the drainage basins located on the Edwards Plateau. The catchment area, about 4,400 square miles, contains the drainage basins of the streams that recharge the Edwards aquifer.

In the San Antonio region, the Edwards limestone attains a thickness of approximately 450 to 500 feet. The water wells supplying SAWS customers' number a total of 92 with an average daily pumpage of 136.50 million gallons per day or 418 acre-feet. From 1934 through 1994 the average recharge to the Edwards aquifer was 676,600 acre-feet.

EDWARDS AQUIFER ZONES

Stretching across portions of ten counties, the Edwards Aquifer is 180 miles long with a width that varies between five and 40 miles. Its primary geologic component is Edwards limestone, and it is one of the most permeable and productive aquifers in the United States. The Edwards Aquifer occurs in three distinct segments: the drainage zone, the recharge zone and artesian zone.

Drainage Area (Contributing Zone)

The area north and west of the aquifer is called the Edwards Plateau or more commonly, the Texas Hill Country. Portions of this area serve as the catchment or drainage zone of the aquifer.

Including all or part of thirteen counties, Edwards, Kinney, Real, Uvalde, Kerr, Bandera, Medina, Gillespie, Kendall, Bexar, Blanco, Comal, and Hays counties. The drainage area is the largest component of the aquifer system, spanning approximately 4,400 square miles. Rain falling in the drainage area soaks into the limestone of the plateau forming spring-fed streams. These streams flow over relatively impermeable older rock formations until they reach the recharge zone.

Recharge Zone

The recharge zone is geologically known as the Balcones Fault Zone. An abundance of Edwards limestone exposed at the surface, with its permeable and porous nature, provides the path for water to reach the artesian zone.

Recharge is water that enters the aquifer through features such as fractures, sinkholes and caves. Streams from the Edwards Plateau flow across the recharge zone, percolating into the ground. Rain falling directly on the recharge zone also percolates into the ground and enters the Edwards Aquifer.

The recharge zone encompasses approximately 1,500 square miles and forms the northern boundary of the artesian zone in Kinney, Uvalde, Medina, Bexar, Comal and Hays counties. Although average precipitation is greater in the eastern counties, the largest amount of recharge to the Edwards Aquifer occurs in the catchment area of the western counties. The Nueces River basin, the Frio-Sabinal River basins and the Seco-Hondo Creek and Medina River basins (located in Kinney, Uvalde and Medina counties) supply about 70 percent of the total recharge to the aquifer. These western basins are characterized by larger catchment areas and larger recharge areas than those in the east.

Artesian Zone

The Edwards Aquifer has great capacity for storing and moving water. The artesian zone is a complex network of interconnecting spaces varying from microscopic pores to open caverns. The artesian zone differs from the recharge zone because it is located between two relatively less permeable layers that confine the water and pressure the system.

The artesian zone underlies all or a portion of the ten counties south and east of the Balcones Fault Zone. Those ten counties are Kinney, Uvalde, Medina, Bexar, Comal, Hays, Atascosa, Guadalupe, Frio and Zavala counties. The artesian zone spans 180 miles from west to east, and varies from less than one to 35 miles wide, underlying about 2,100 square miles. Water cannot seep directly into the artesian zone from the ground surface because of impermeable layers, such as clays, between the surface and the aquifer.

In certain places where there is enough artesian pressure, some of the water is forced to the surface through faults, forming springs. Artesian pressure can also cause some wells to flow without a pump. Water leaving the aquifer is referred to as discharge. Water is discharged from the aquifer through springs or wells.

EDWARDS AQUIFER HISTORY

For centuries, people settled in the Edwards Aquifer region, because of the abundance of fresh, pure spring water. The Edwards Aquifer has supported civilization for more than 12,000 years and today it is the primary source of water for about 1.7 million people.

The southern portion of the Edwards Aquifer is one of the world's unique groundwater resources, extending 180 miles from Brackettville in Kinney County to Kyle in Hays County. While it is our primary source of water, it is the sole-source of water for a unique system of aquatic life, including several threatened and endangered species. Cities, towns, rural communities, and farm and ranch lands all depend on the aquifer's water for household, agricultural, industrial and recreational purposes. The diversity of uses illustrates the importance of the aquifer to the lives and livelihoods of residents in the Edwards Aquifer region.

For years, it was thought the Edwards Aquifer was a never-ending supply of fresh drinkable water. In 1940, the region was pumping 120,000 acre-feet of water or 39 billion gallons, a year. But in the 1950s, a seven-year drought drastically lowered water levels in the aquifer. In the 1980s and 1990s, droughts of shorter duration occurred, requiring heavy pumping from wells. Also, average pumping from Edwards wells has increased dramatically in the last five decades because of population growth and demand. In San Antonio alone, population has increased from about 200,000 people in 1940 to more than one million in 1990. Populations of other communities in the region, such as Uvalde, Hondo, New Braunfels, and San Marcos have also grown. In 1989, regional pumping reached a maximum of 542,000 acre-feet of water per year - more than 175 billion gallons. In the 1990s, the amount of aquifer water pumped ranged from 327,000 acre-feet in 1992, to 493,000 acre-feet in 1996. Average springflow discharge from 1934 to 1999 is 366,700 acre-feet a year.

The Edwards Aquifer will continue to be the primary source of water for the region. Various groups and entities in the Edwards Aquifer region have undertaken the difficult task of addressing present and future water needs. The need for planning is continuous. The need for stewardship is essential. The need for management is critical.

BACKGROUND ON THE EDWARDS AQUIFER AUTHORITY

In 1959, following several years of intense drought, regulation of the Edwards Aquifer began with the creation of the Edwards Underground Water District (EUWD) by the 56th Texas Legislature. The EUWD was given a limited mandate to protect the Edwards Aquifer as a resource, but it was not given regulatory powers to limit withdrawals. The Texas Water Quality Act of 1967 empowered the Texas Water Quality Board to protect underground water quality. Following a short but intense drought in 1984, the counties overlying the Edwards Aquifer began to develop mutually supporting conservation and drought management plans.

During the late 1980s the State Legislature began to seriously consider regulating groundwater withdrawals from the Edwards Aquifer. The EUWD Act was revised in 1987 to require the District to adopt a Drought Management Plan to relieve some of the stress on the Comal and San Marcos Springs. Two years later a proposal to regulate groundwater under an Edwards Aquifer Management Plan failed and a Legislative Committee was appointed to study the Edwards Aquifer.

In 1991, the Sierra Club filed a lawsuit against the U.S. Fish and Wildlife Service of the Department of the Interior alleging violations of the Endangered Species Act at the San Marcos and Comal Springs. The premise of the lawsuit (Sierra Club et al. v. Manual Lujan, Jr.) was that the Fish and Wildlife Service had failed to protect endangered species by allowing Edwards Aquifer users to overdraft the aquifer.

In February 1993, U.S. District Court Judge Lucius Bunton handed down judgment in the case. The judgement identified minimum springflow requirements for Comal and San Marcos springs and "strongly suggested" the Texas Legislature develop a regulatory system to avoid "unlawful takings" of endangered species by May 31,1993.

Senate Bill 1477 was passed by the 73rd Texas Legislature on May 23, 1993, and it was signed by the Governor on June 11, 1993. This Act established the Edwards Aquifer Authority as the successor to the Edwards Underground Water District, effective September 1, 1993. After court challenges, the newly created EAA began operations at the end of June 1996.

REGULATION BY WITHDRAWAL LIMITS

The EAA's general mandate is to protect terrestrial and aquatic life, domestic and municipal water supplies, the operation of existing industries and the economic development of the state by managing the aquifer as a regional resource. Its primary purpose is to regulate groundwater withdrawals from the Edwards Aquifer in order to ensure an adequate supply to the region's historical users and to maintain springflow at Comal and San Marcos Springs.

The EAA is required by its enabling Act to limit withdrawals from the aquifer to 450,000 acre-feet per year and to further reduce withdrawals to 400,000 acre-feet per year by 2008. The Act also provides for increases in these pumping limits if the yield from the aquifer can be increased through recharge enhancement projects or other management technologies to protect springflows. In addition, SB 1477 requires the EAA to implement and enforce water management practices, procedures, and methods to ensure that, by December 31, 2012, continuous minimum springflows at Comal and San Marcos Springs are maintained to protect endangered and threatened species.

The statutory withdrawal limit is being implemented through a groundwater permitting process. Every Edwards aquifer user, with the exception of domestic and livestock well owners using less than 25,000 gallons a day, will be required to obtain a permit with a specified annual limit on aquifer water withdrawal. SAWS' current water use is approximately 170,000 acre-feet per year, and its historic high pumping (the basis for its permit application) was 193,944 acre-feet in 1984. SAWS has recently agreed to a permit of 159,000 acre-feet, which represents the Systems 21-year average.

REGULATION BY CRITICAL PERIOD MANAGEMENT

In addition to the annual withdrawal limits from the aquifer described above, withdrawals will be further reduced during "critical periods" of low rainfall or reduced springflows through further restrictions on water uses and monthly limits on total water use. These reductions are governed by the Critical Period Management Plan originally adopted by the EAA in December of 1996 and amended to the present rules that are in place today. During critical periods, SAWS' withdrawal permits will be reduced from ten to twenty-three percent of the summer demand peak, depending on the severity of the critical period. Prudent planning requires that sufficient supplies be acquired to reduce the impact of these water use restrictions in the future.

SAWS' AGRICULTURE WATER CONSERVATION PPROGRAM

During the last twenty years, 21 to 36 percent of the total Edwards Aquifer water use has been for agriculture use; therefore, agriculture water conservation is an important component in reducing the demands on the Edwards Aquifer. SAWS, as a good neighbor, is supportive of the rural economies. To stretch the use of this limited resource, the SAWS Water Resources Department created in 1999, **the Agriculture Water Conservation Program**.

The AWCP supports research projects in agriculture water conservation. The AWCP has joined other partners in supporting financially, research in brush control, juniper water use, drip irrigation, the development of crop coefficients, and irrigation scheduling. The AWCP supports the creation of the Irrigation Technology Center (ITC) in San Antonio. The ITC is associated with the Texas A & M University System. Some of ITC's duties will be to offer demonstrations in landscape water conservation and certifications for irrigation equipment. We are currently funding agriculture water conservation studies with the following regional partners: Lower Colorado River Authority and Guadalupe-Blanco River Authority in the adjoining basins for future water supply projects. We have made improvements in irrigation efficiency on farms, purchased by SAWS for their Edwards Aquifer water rights. We will finance improvements in irrigation efficiency for farmers that participate in irrigation scheduling projects in exchange for conserved water.

A New Model for Basin Wide Water Use Efficiency

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In the field of irrigation, few concepts seem to inspire as much confusion and controversy as "efficiency". Most proponents of efficient water usage in irrigation fall into one of two camps. The first viewpoint is that of the user, or, in most cases, the farmer. In this viewpoint, efficient use of water means applying the minimum amount of water to a field in order to produce a crop. This viewpoint is important to the farmer because it is directly related to his or her costs to produce and ultimately his or her economic well being.

The second viewpoint is that of the river basin manager, who has the responsibility of assessing the total supply of water available to all the users within the normal drainage of a particular river or stream, and how to best manage the usage of that water. For the basin manager, certain types of inefficiency at the farm field level are not necessarily losses at the basin level, if those inefficient applications of water can be captured and used by others within the basin. The basin manager also needs to be concerned with the timing of availability of water, as well as the suitability of the water for uses that may be down stream. The complexity of the problem faced by the river basin manager has made finding a suitable model of irrigation efficiency difficult.

This paper compares the strengths and weaknesses of several commonly used measures of efficiency. The authors then introduce a qualitative concept that attempts to relate efficient practices at the field level to their impacts at the basin level. This new concept provides a way for the basin manager to assess the impacts of inefficient farm field irrigation practices on the basin's down stream users in terms of quantity, quality, and temporal degradation.

Efficiency, as a concept, has long been applied as a performance measure for machines, systems, and processes. As a concept, efficiency is simple and straightforward. The *American Heritage Dictionary* defines efficiency as – the ratio of the effective or useful output to the total input in any system.

$$\text{Efficiency} = \frac{\text{Effective or Useful Output}}{\text{Total Input}}$$

This basic concept has been applied in different ways by many water-use stakeholders to serve various needs and requirements. This is true for agricultural water use where a number of different efficiency measurements have been developed over the years. These measurements have become both more important and more scrutinized as growing larger quantities of food with less water to feed an ever-growing world population develops into a major global challenge. Many believe that improved water management at the basin and field level can lead to water savings and more productive use of finite water supplies.[1] Others, however, propose that traditional measures of irrigation efficiency fail to account for water reuse within a basin and that basin-wide irrigation efficiencies may be much higher than can be extrapolated from individual field irrigation efficiencies.[2] We will examine these two schools of thought in greater detail later in this paper. First, we offer below some common definitions of irrigation efficiency for the readers benefit:

Application Efficiency (E_a) – Ratio of the average depth of irrigation water infiltrated and stored in the root zone to the average depth of irrigation water applied.[3]

Conveyance Efficiency (E_c) – Ratio of the water delivered, to the total water diverted or pumped into an open channel or pipeline at the upstream end.[4]

Irrigation Efficiency (E_i) – Ratio of the average depth of irrigation water that is beneficially used to the average depth of irrigation water applied.[5]

Project Efficiency (E_p) - is calculated based on farm irrigation efficiency and both on- and off-farm conveyance efficiency, and is adjusted for drainage reuse within the service area. Project efficiency may not consider all runoff and deep percolation a loss since some of the water may be available for reuse within the project.[6]

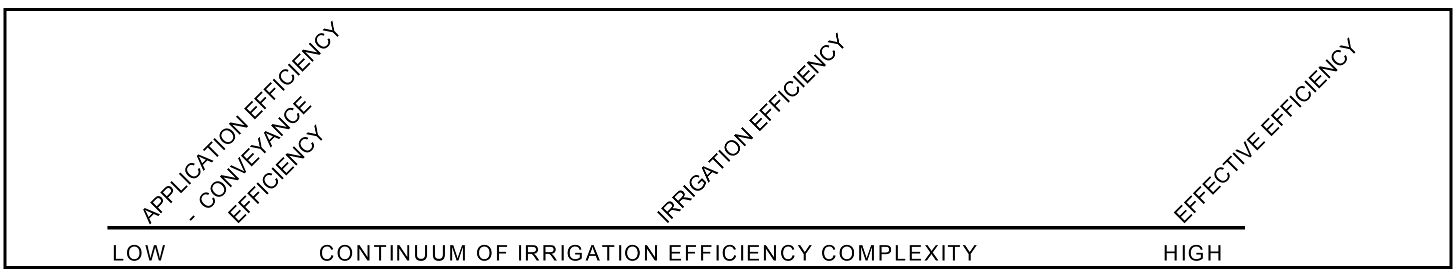
Effective Efficiency (Basin Efficiency) – is the beneficially used water divided by the amount of freshwater consumed during the process of conveying and applying the water.[7]

Water Use Efficiency – The mass of agricultural produce per unit of water consumed.[8]

There are numerous other efficiency measurements related to irrigation and different definitions for the terms defined above, however, we believe that the definitions listed above are reasonable and capture the general concept of each of the terms.

The irrigation efficiency measures listed above can be plotted along a continuum of measurement complexity as shown in Figure 1 below. As can be seen, Application and Conveyance Efficiency are straightforward measures that can be calculated by farmers and researchers with relative ease. In contrast, Effective Efficiency introduces a number of variables that add to the complexity of calculating and understanding this measure.

Figure 1



As stated in our introduction, in this paper we examine the efficiency measurements at each end of the continuum - Application Efficiency and Effective Efficiency. Farmers are typically interested in Application Efficiency both when considering irrigation equipment purchases and when calculating the effectiveness of those systems. Regional water managers and policy makers are more likely to have an interest in Effective Efficiency within the basin. Some tension and confusion can sometimes exist between these two groups and the efficiency measurements they use and espouse. We believe that neither measurement can be used without understanding its limitations; therefore, we will further examine these two efficiency approaches pointing out the limitations of each. In addition, a review and understanding of these measures is appropriate prior to the introduction of our qualitative concept.

Before we move on to further examine these efficiency measures, it is important to note that the actual efficiency of any physical irrigation system is influenced by many factors, including level of management, soil type, crop type, crop-growth stage, climatic factors, and water table considerations.[9] The physical “set-up” of an irrigation system may have theoretical efficiencies higher than those experienced in actual use because of the factors mentioned above.

Application Efficiency

Application Efficiency is the measure typically used in the agricultural community for comparing and contrasting brands, types, and methods of irrigation. Irrigators are interested in measuring, designing for, or estimating Application Efficiency because it takes more water to irrigate inefficiently than it does efficiently, and increased water use translates to higher costs and reduced profitability. Although Application Efficiency is not a perfect measure, it does serve as a common point of reference for irrigation stakeholders. As noted in an Advisory on the web site waterright.org, "The individual farmer should focus on individual, in-field irrigation efficiency because his/her crop development/yield and costs are dependent on this. Basin and project-wide estimates of irrigation efficiency may be useful in political discussions but do not address the individual farm."[10]

If we return to our general definition of efficiency, we see that an output is derived from an input and something is lost to achieve the output. For Application Efficiency, the output is water to the root zone and the input is water applied. The water lost in order to apply water to the root zone comes from evaporation, runoff, and deep percolation. For Application Efficiency, evaporation can occur during sprinkler application before the water reaches the soil or from surface water during flood irrigation. Evaporation can be almost completely mitigated with modern sprinkler designs. Runoff is water applied to the field that is not absorbed into the soil but runs to the end of the field where it cannot be used by the crop. Deep percolation is water applied to the field that seeps into the soil below the root zone and, therefore, is not accessible by the crop. Deep percolation typically occurs when excess water is applied during an irrigation event or when the uniformity of the application is low.

To better understand Application Efficiency we must examine some of the primary components of the definition. Our definition - ratio of the average depth of irrigation water infiltrated and stored in the root zone to the average depth of irrigation water applied - can be examined by its component parts.

One component, the denominator of our formula, is irrigation water applied. The applied water is water leaving the nozzle of a pressurized system, or passing over the sill for border-strip systems.[11] It is the amount of water that exits the irrigation delivery system during an irrigation event.

Another component in the definition of Application Efficiency is the Crop Root Zone which is defined as follows:

> The soil depth from which a mature crop extracts most of the water needed for evapotranspiration. The crop root zone is equal to effective rooting depth and is expressed as a depth in inches or feet. This soil depth may be considered as the rooting depth of a subsequent crop, when accounting for soil moisture storage in efficiency calculations.[12]

Let's take a further look at why Application Efficiency is so widely known and used in agriculture. Farmers understand and use Application Efficiency estimates when making irrigation system purchasing decisions. Different irrigation methods offer vastly different Application Efficiencies. Drip and Mechanical Move irrigation systems can have Application Efficiencies beyond 90% while flood irrigation may be as low as 40% efficient. Farmers know that improved Application

Efficiencies reduce costs and, thus, are interested in the estimated Application Efficiencies of various irrigation methods when purchasing an irrigation system.

Most modern farmers have access to daily evapotranspiration estimates (the estimated crop water requirements) and, as a result, know how much water should be delivered to the root zone. As we now know, farmers typically understand the design application efficiencies of their irrigation equipment and use this information to control irrigation events. For example, a farmer using an irrigation system with an Application Efficiency of 50%, such as flood irrigation, will apply double the estimated need of the crop to meet the water needs of that crop (this is a simplified example and does not account for existing water in the root zone). Thus a key advantage of Application Efficiency is that it is used to measure the performance of a system in the field based on perceived needs of the crop, and, therefore, in comparison with other efficiency measures is much easier to quantify.[13]

Application Efficiency, while simple and widely known, is not without its shortcomings. It does not account for water Distribution Uniformity. Distribution Uniformity is a measure of how evenly water soaks into the ground across a field during an irrigation event.[14] A low uniformity means that water depth varies throughout the field being too little to meet crop water requirements in some places and too much in others which results in water loss through deep percolation. A high Application Efficiency does not ensure that an equal amount of water reaches all parts of a field. Low distribution uniformity can have significant negative impacts on crop yields or could lead to over-watering, which increases costs and could result in water logging and a reduction in yields.

A high Application Efficiency can be achieved without fulfilling the crop water requirement. Theoretically, Application Efficiencies can be high if very little water is applied with conditions being such that little water is lost to evaporation. This means that most of the water applied ends up in the root zone but that the amount of water applied is not enough to meet crop water requirements. Thus, under-watering could result in a high Application Efficiency but low crop yields because of a failure to meet crop water requirements.[15]

Another possible limitation of Application Efficiency is that the measure does not account for all beneficial uses of water such as deep percolation for soil salt leaching.[16] Some volume of water that percolates below the root zone may be beneficial as it takes with it, or leaches, unwanted salts from the soil. This leaching effect is considered beneficial because unwanted salts have a negative impact on crop growth and yields.

Application Efficiency can be over estimated when using simple measurement techniques. For sprinkler irrigation, when measuring Application Efficiency, researchers typically place containers throughout the field where the assumption is made that the average depth of water collected is equal to the average depth that would be stored in the root zone (assuming that the depth collected is not greater than the soil moisture deficit). This ignores the real possibility of evaporation prior to absorption into the soil.[17]

The Basin Model

In this paper we refer to the Basin Model or the Basin Model of Efficiency and use these terms interchangeably with Effective Efficiency as described by Keller, Keller, and Seckler.[18] The Basin Efficiency Model, when applied strictly to irrigation, estimates water used consumptively by crops relative to actual water applied throughout the basin. Consumptive use is primarily evapotranspiration (ET), which is water evaporated or transpired from plant foliage and adjacent soil during crop growth. In its most simple form, the model assumes that water not consumptively used by crops returns to the basin for reuse in the form of surface runoff, seepage, or infiltration.

To better understand the Basin Model we now take a closer look at an idealized version of the model, which is represented in Table 1 below. Our idealized basin begins with an initial diversion of water from some source such as a river, reservoir, or aquifer. This initial diversion is applied as irrigation water to a field.[19] In the example in Table 1 the initial diversion is a volume of 100m^3. We assume that our basic field level irrigation efficiency is 40% which means that 40% of the diverted water is consumed through evapotranspiration. This leaves a remaining volume of water of 60m^3 that flows out of the initial field through runoff or percolation and becomes available for use in a different location in the basin. The process continues with the amount of water not consumed by evapotranspiration ending up in usable form to be used again for irrigation. Eventually, the total volume of water consumed by the crops approaches the amount of the initial diversion. In our example, after just ten cycles, the amount of water consumed, presumably beneficially by crops, is over 99.9m^3. This results in a Basin or Effective Efficiency of 99.9% (the logic for Table 1 was taken from Keller, Keller, and Seckler, 1996).[20]

TABLE 1

Initial Diversion	Return Inflow for Use	Irrigation Consumptive Use	Water Consumed	Outflows	Cumulative Consumption
100m^3	0	40%	40m^3	60m^3	40m^3
	60m^3	40%	24m^3	36m^3	64m^3
	36m^3	40%	14.4m^3	21.6m^3	78.4m^3
	21.6m^3	40%	8.64m^3	12.96m^3	87.04m^3
	12.96m^3	40%	5.184m^3	7.776m^3	92.224m^3
	7.776m^3	40%	3.11m^3	4.666m^3	95.334m^3
	4.666m^3	40%	1.866m^3	2.8m^3	97.2m^3
	2.8m^3	40%	1.12m^3	1.68m^3	98.32m^3
	1.68m^3	40%	.672m^3	1.008m^3	99.328m^3
	1.008m^3	40%	.403m^3	.605m^3	99.933m^3

The contrast between Basin Efficiency and Application Efficiency is now clear. In our example, each irrigation event has an Application Efficiency of about 40%, yet the overall efficiency in the basin approaches 100%. As stated above, the example provided in Table 1 was for an idealized Basin, that is, a theoretical model of a basin where all water applied to a field is either beneficially consumed by the crop or returned to the basin for reuse. In actual practice we know that this is far from reality. A number of different variables influence the amount of water available for reuse in the Basin Model. These variables include salts and pollution, evaporation other than crop evapotranspiration, rainfall, and sinks.[21] Sinks are destinations for water not available for reuse - a common sink for a river basin is a sea or ocean.[22] Any of the variables listed above may impact Basin Efficiency, for instance, a poorly designed irrigation system may result in relatively large amounts of non-beneficial evaporation. In this case, the overall Basin Efficiency is negatively impacted because non-beneficial evaporation is water lost that is unavailable for beneficial use in the basin. In addition, in actual practice, water is often used for leaching salts from soil and this water must also be accounted for in a Basin Model.[23] Adjusting for these variables will generally negatively impact Basin Efficiency.

The Basin Model of Efficiency may be a useful model for planners and politicians, but it, like Application Efficiency, is not without shortcomings. One variable that is not accounted for in the Basin Model is the timing of return flows. Imagine a scenario where water is diverted from a river and applied to a field using an irrigation system with an Application Efficiency of 50%. Let's also assume that 5% of the water evaporates during application and the remaining 45% is lost to this irrigation event through deep percolation. We'll call this deep percolated water W_1. Using the Basin Model we assume that W_1 is available for reuse. If, however, we add the element of time we can see that this is not always the case. In our example let's assume that it takes four months for W_1 to return to the river and during these intervening four months the irrigation season concludes. Further diversions from the river have ceased because crops are no longer being watered. In this simplified scenario, W_1 will not be used but will flow down the river and out of the basin. The actual Basin Efficiency will equal the Application Efficiency of 50%.

Let's return to our example only this time assume that the Application Efficiency is 85% and that 5% of the water is lost to evaporation during the water application. If our other assumptions are unchanged, W_1 in this case equals 10% of the water diverted and is eventually lost from the basin. Because of the higher Application Efficiency, less water will be diverted to put the same amount of water in the root zone. If the water saved at the field level, through higher Application Efficiency, is held upstream in a reservoir, it can be released as needed for irrigation or other water demands down the river.[24] Thus, in actuality reduced water consumption at the field level can be beneficial to water conservation in the entire basin.

What happens if W_1 flows to and is held in an underground aquifer rather than flowing back into a river? This scenario reveals other problems with the Basin Model. If the water in the aquifer is to be accessed for irrigation, additional water must be used to generate the power required to pump the water in the aquifer. The cost of this power is born by the farmer.

The examples above highlight another issue related to the Basin Efficiency Model - the accessibility of return flows. The Basin Model assumes that return flows can be reused through natural and/or engineering processes.[25] Basins are unique, each with distinctive geographical characteristics. So where does the excess water flow? That is a question that must be answered for each diversion, and each field in each basin. This is a highly complex problem that is certainly difficult to model with any degree of accuracy. The conceptually simple approach used in the Basin Model may be insufficient to accurately account for the complexities of individual basins.

Another deficiency of the Basin Model is that while it offers a method for considering the impact of salinity in the water, it is not clear how to account for pollution. The use of chemicals in agriculture has a negative impact on the quality of water infiltrating fields. The severity of this impact is conditional, but it certainly can make excess water unacceptable for reuse. The Basin Model does not provide a clear method to account for the impact of the various forms of pollution in water targeted for reuse.

We have examined some common irrigation efficiency measures for both the field and basin level. We learned that these are useful tools and in some ways complementary; however, we also have seen that both measures have limitations. Neither should be used alone without accounting for some of the deficiencies. Next we offer a new qualitative perspective on irrigation water flows within a basin. We believe that this perspective offers a new and, hopefully, lucid viewpoint for irrigators and other water-use stakeholders.

Thermodynamics, Energy, Entropy, and an Analogy to River Basins

What is Thermodynamics?

Thermodynamics is the study of physical systems and their patterns of energy change.[26] Systems in the thermodynamic sense can range anywhere from individual devices such as a block pulled up an incline, or an internal combustion engine, to extremely complex arrangements such as power plants or even entire planets. Systems can normally be characterized in one of three ways:

1. Isolated with no exchange of matter or energy with the surroundings.
2. Closed with energy exchange but no matter exchange with the surroundings.
3. Open with exchange of both matter and energy with the surroundings.[27]

For the purposes of this analogy, we will be thinking of a river basin as our "system" with water representing the equivalent to "energy" in thermodynamics. The analogy lacks an equivalent to mass transfer across the system boundary, and as a result we will be analyzing the equivalent of an "Open" thermodynamic system. If we imagine a theoretical river basin, water (energy) is flowing into the system in the form of precipitation. Water flows out of the basin through several methods including; evaporation, permanent sinks, and ocean outflow.

In most thermodynamic systems of interest, some of the energy of the system is converted into useful work. In our analogy, the "useful work" of the river basin consists of several items including; crop production through transpiration, water that sustains human life, water that produces industrial production and output, and water that is needed to sustain wildlife and the natural environment.

Excess withdraw of water within the basin can be thought of as the equivalent of "waste heat" generated in thermodynamic systems. Heat is usually a loss in the thermodynamic sense, although techniques exist to recover useful work from waste heat if it is of a useable quality (high temperature), and quantity. There are both theoretical and practical constraints on the use of waste heat. In the real world, cost and effectiveness of recovery heat exchangers, handling systems, and other equipment limit the amount of waste heat recovery possible. Our river basin acts in the same way, returning some of the excess withdraws of water to the system in a lower quality state. That water can still have, in some cases, additional "useful work" extracted from it if it meets the requirements of cleanliness, accessibility, and timeliness required by downstream users as has been pointed out by other authors[28]. As in thermodynamic systems, there are both theoretical and practical constraints in the handling of excess withdraws of water.

In thermodynamic systems, a key focus of analysis and design is to maximize the energy conversion efficiency. An efficient system turns more of the energy input into useful work than an inefficient system. In river basin management, the goal of most managers is to maximize the utilization of water within the basin to produce useful output also.

The First Law of Thermodynamics

The study of thermodynamics is governed by two important laws, both of which will be important to the water basin management analogy. The first law states that the energy of a system is neither created nor lost, but is instead conserved.

To understand this law, imagine an internal combustion engine as our system, complete with its driveshaft, its radiator, and exhaust system. Energy enters the system trapped in the chemical bonds of the fuel and air mixture as it is metered into the engine cylinders. The chemical energy is released as the fuel burns, pushing down the engine piston, and driving the driveshaft. This mechanical rotation is the useful work done by the system. If we measure the mechanical work produced by the engine and divide by the chemical energy that is fed into the cylinders, we would find that the ratio is roughly 32%[29]. Internal combustion engines require significant excess energy input to overcome losses and inefficiencies in their physical designs. Even independent of the losses and inefficiencies, the maximum theoretical efficiency of an ordinary automobile engine is 56%[30]. So where does the excess energy go? Most of it becomes heat generated either from the combustion of the fuel, or from friction in the mechanical system. Most of that heat is rejected to the atmosphere (the surroundings) through the radiator. There is also energy that exits through the exhaust gases. This energy is in the form of heat from the hot gases, and some left over chemical energy from incomplete or imperfect combustion. If our system includes a catalytic converter, much of the remaining chemical energy is converted to heat and also is transferred to the atmosphere. If it was economically feasible, the chemical energy in the exhaust gases could be extracted and burned again in the engine. In principle, the hot exhaust gases or the heat rejected by the radiator could be made to do additional mechanical work by flashing water to steam and turning a turbine. In the real world, however, such schemes that could theoretically increase the energy efficiency of the system are rarely economically justifiable. In the engineering of real world systems using thermodynamic principles, the ultimate task is to determine the degree of efficiency that maximizes the production of useful work and still is economically practical.

In extending the application of the first law to water systems, rather than considering an entire basin with all its complexity, let's draw the system boundary around a single irrigated agricultural field. Water enters the system via a well or canal (or via rainfall, periodically). The useful work of this system is transpiration of the intended crop that ultimately results in the production of some useful economic good (food or fiber). If we divide the evapotranspiration by the water applied, we are measuring the efficiency of irrigation, much like the measure of efficiency in our engine. Unlike most thermodynamic systems, our water system could achieve efficiency of nearly 100% as there are few, if any, theoretical limitations on the system's performance. In the real world, however, there are major and minor sources of loss in our irrigated field. The primary sources of loss include; direct evaporation, run-off, and deep percolation[31]. Much like the engine, these losses represent the "wasted" water in our application, and just as in the engine example, under the right circumstances some of this water can be harnessed for the generation of "useful work" in other applications. The clearest example of this is where run-off water from an irrigation field is collected in a ditch and then used to irrigate an adjacent field. These types of schemes are common in some river systems such as the lower Nile River in Egypt. In these applications, the vast majority of the water can be reused, and hence by including adjacent irrigation fields into the efficiency calculation, the overall application efficiency for the region or the basin is raised. At the other extreme is direct evaporation, which is almost never available for use within the system, atmospheric water vapor being too impractical to collect and utilize. The net basin-wide impact of re-use of waste water has been a subject of great discussion in recent years, as illustrated earlier in this paper. Unlike waste heat, whose utility is defined by its temperature difference compared to the surroundings, “wasted” or over-applied water can be characterized by three quantities; its quality, its accessibility, and its timeliness. Each of these quantities implies the water’s use in a particular process. For example, water that is clean enough for irrigation purposes, may have too much pollution for human consumption or for wildlife. This makes analyzing our basin system more difficult than a thermodynamic system. Fortunately the second law of thermodynamics offers some qualitative insights into how we should think about water management on a basin-wide basis.

The Second Law of Thermodynamics

Understanding the second law of thermodynamics is conceptually more difficult than the first law, and requires first the introduction of a concept called “entropy”. The textbook definition of entropy is something about which mechanical engineering students will spend several weeks developing a mathematical understanding. We will attempt a more conceptual understanding in this paper. Broadly considered, entropy is a measure of the degree of dispersion of energy[32]. For example, imagine a beaker of water that weighs one pound and is at a temperature 200 degrees Fahrenheit above the surrounding environment. This beaker of water would have a lower entropy than a one hundred pound barrel of water at a temperature of two degrees above the surroundings. The same amount of energy is present in each case, but in the latter example, the energy is more dispersed than in the former example. Entropy gives a comparative evaluation of the potential that the energy has to do useful work. The lower the entropy, the more concentrated the energy is, and hence the more likely we are to be able to economically extract useful work from the energy.

With this qualitative understanding of entropy, we are now ready to tackle the second law. The second law simply states that in a closed system that undergoes a process, entropy always increases as a result of the process. The second law is not an experimentally tested law, but is instead the product of extensive observations made of closed systems. The law applies to the entropy of the entire system, not the entropy of any individual parts. In our engine example, it is the process of combustion (and later mechanical friction) that causes the increase in entropy. While the useful work produced by the engine has no entropy, the heat energy from the engine has very high entropy and is of a large quantity. The resultant sum of all entropies of the system is increased by the process.

How can the Second Law Provide Insight into Basin Systems?

The Second Law qualitatively tells us that while energy is conserved, all energies are not created equal. From a practical standpoint, certain types of energy are of greater value than others. For example a small quantity of highly concentrated energy (steam, for example), is more valuable than a large quantity of highly dispersed energy (water near ambient temperature). This observation allows us to draw another analogy to the river basin. Water that is clean, easily accessible near the point of use, and available at the time when we need it, is very useful. Water that is polluted, difficult or expensive to access, or available only at the wrong time, is not very useful. In the theoretical example above, we could say that the former water has a high utility value and the latter a low utility value. To put it in the same terms as entropy (increases in value representing decreases in usefulness), we should probably call the quantity the water “degradation” value. Water “degradation” is at its lowest level when the water is clean, accessible, and timely. We can represent this with the following formula:

$D = f(\text{quality, accessibility, timeliness})$

While the concept of dispersion has been usefully developed into specific formulae for entropy values of various processes and states of energy in thermodynamics, such a framework does not readily exist within river basins. Nevertheless, we can qualitatively describe those quantities that represent quality, accessibility and timeliness to each of the primary stakeholders in river systems:

- Agricultural water users
  - Quality degradation occurs through the introduction of salts and some herbicides at various concentration levels.
  - Accessibility degradation occurs when the water is far from the farm field, deep underground, or at a flow level too small for practical irrigation.
  - Timeliness degradation occurs when the water is available outside of the peak demand periods (usually summer months in North America).
- Municipal water users (including human consumption)
  - Quality degradation occurs through the introduction of any one of many chemicals or elements, some in small trace amounts.
  - Accessibility degradation occurs when the water is far from the users, deep underground, or available at a flow level too small to allow effective distribution.
  - Timeliness degradation occurs when the water is available outside of the peak demand periods, which vary based on location and local practices.
- Industrial water users
  - Quality degradation occurs through the introduction of substances that cause scale, corrosion, or damage the quality of the ultimate product.
  - Accessibility degradation occurs when the water is far from factories, deep underground, or available at a flow level too small to fulfill process needs.
  - Timeliness degradation occurs when the water available does not meet temporal process needs.
- Environmental water users (wildlife and natural systems)
  - Quality degradation occurs through the introduction of salts, trace chemicals, and nutrients in sufficient quantity to cause algae blooms.
  - Accessibility degradation occurs when the water is not in the natural stream, river, or lake system.
  - Timeliness degradation occurs when the water is outside of the natural system during times of need, especially during seasonal low flow periods.

While there are significant differences in the needs of the various basin stakeholders, there are numerous similarities also. In some instances, the increase in degradation for a particular stakeholder may change rapidly only during certain parts of the quality, accessibility, or timeliness scale. One possible approach to dealing with the differences in the needs of various stakeholders is to develop a composite degradation quantity as shown below:

$$D_{Total} = D_{Ag} + D_{Muni} + D_{Ind} + D_{Env}$$

A more practical approach is to recognize that water degradation is occurring from the perspective of at least one of the basin's stakeholders when any one of the following situations occurs:

1. Water is removed from a river, lake, or stream in any quantity in excess of the amount needed to perform constructive output. The degradation increases as

the excess water is further from other points of use or moves significantly downstream, bypassing other potential users.

2. Water comes to rest in an underground aquifer. The deeper the aquifer and the lower the potential pumping rate, the more degradation has occurred.
3. Water returns to a usable point outside the season of peak demand for the basin.
4. Water becomes polluted by any one of a number of pollutants including salts, fertilizers, chemicals, or trace elements such as lead or mercury. The higher the concentration of any of these pollutants, the greater the degradation.

In practice, much like the situation for thermodynamic systems, the real physical environment is a significant factor in determining the amount of degradation. Characteristics such as the geology of the basin, the physical locations of the stakeholders and their relationships to one another, the connection between ground and surface water, the weather patterns, and numerous other factors all have a bearing on the water degradation experienced.

Using the Water Degradation (entropy) Concept for an Irrigated Field

Let's again imagine our irrigated farm field with a system boundary drawn around it. In this case, imagine that the field is irrigated by gravity flow irrigation. Further, let's assume that the water entering the field is pumped from a shallow aquifer and is relatively clean and plentiful and available with good flow even during the time of peak demand. We would say that the water degradation of the flow entering the field is very low. In the process of irrigation, water feeds the roots of the crop and eventually results in transpiration, which produces useful output (work). In addition, and common with most gravity irrigated fields, there is direct evaporation of water from the furrows, run-off that occurs (which includes fertilizers and other farm chemicals that are on the field), and deep percolation. Let's examine the impact of each of these points of exit in terms of water degradation.

Plant transpiration: This is the useful work of the system, analogous to the internal combustion engine's rotating shaft.

Direct evaporation: This water has the largest increase in degradation because it has essentially no future accessibility. In the Basin Model, direct evaporation is considered a loss to the system. In our model, it is simply water with a very high degradation.

Run-off: The degradation of run-off water is certainly higher than that of the incoming stream. The water is of lower quality due to the addition of pollutants. Usefulness of the run-off water depends on the downstream sensitivity of stakeholders to the specific pollutants, the concentration levels of those chemicals, and a dilution effect from combining with other flows. Accessibility is also lower for the run-off water, in that it will require in most cases some form of conveyance to be brought to the next point of use. If our system boundary was larger, then additional degradation considerations would occur in the form of evaporation and deep percolation of the run-off stream, as well as phreatorphytic vegetation consumption (consumption and transpiration of water by non-targeted plants).

Deep Percolation: The degradation of deep percolated water is the most dependent of any type of degradation on local geology and physical location. Deep percolated water is likely to suffer from degradation due to accessibility and timeliness. Where the water goes, and when and how it emerges again is difficult to generalize about. Some deep percolated water finds its way into virtual sinks that have a very high degradation value. Deep percolated water moves slowly in most cases. Its re-emergence during a peak demand time period cannot be counted on, and hence the water suffers degradation. Quality degradation can also become a factor when pollutants concentrate in aquifers. In a broader sense, water that comes to rest in an aquifer causes basin wide degradation because, as we pointed out earlier, it requires pumping power to lift it.

Applicability of the Degradation Model to Basin Management

Unfortunately, the water degradation model, as formulated in this paper, lacks the mathematical precision of the thermodynamic model. This means that calculating water degradation for various usage options and making direct comparisons is not possible. Nevertheless, the degradation model can provide a number of qualitative conclusions concerning basin management. The first of these is a restatement of the objectives of a basin management plan, which is described below:

1. Basin management plans should be developed to meet the needs of each of the four key stakeholders in the basin recognizing that:
    i. Stakeholder needs have varying water quality requirements.
    ii. Stakeholders have different temporal needs; special focus is needed on the peak demand period.
2. Basin management plans should attempt to minimize the overall water degradation of the basin.

There are numerous strategies that can be employed to meet the second of these two objectives within each of the stakeholder sectors. As the theme of this paper is to describe how agricultural irrigation should be managed in light of basin-wide constraints, let's focus our attention in this area. Water degradation in irrigated agriculture can be reduced by any and all of the following actions:

- Reduced direct evaporation due to more effective and efficient water application (in the classic "Application Efficiency" sense).
- Reduced run-off.
- Reduced deep percolation.
- Utilization of soil moisture or other data to improve decision-making and reduce over-application.
- Second order improvements such as:
    i. Reduced phreatophytic vegetation consumption.
    ii. Reduced farm chemical use.
    iii. Utilization of wastewater from industrial, municipal, or animal husbandry operations.

All of these actions will reduce water degradation ultimately allowing a larger quantity of "useful work" to be produced within the basin. On a more integrated basin-wide footing, the management strategy needs to focus on:

- Minimizing evaporation.
- Minimizing pollution.
- Keeping the maximum amount of water possible in reservoirs, rivers, and aquifers.
- Optimizing our storage and conveyance systems to meet peak demand time periods.
- Balancing the needs of all stakeholders.

Complications and Limitations of the Water Degradation Analogy

Unlike thermodynamic systems, where the entropy on a practical level can be referenced back to the potential for matter in a particular energy state to do useful work, with water the analysis is complicated by the implied question of – “Useful for whom?”. In some of the theoretical work done on this subject by Keller, Keller and Seckler (IIMI, 1996) [33], the authors describe the theoretical limitation for reuse of irrigation water based on the salt concentration. In this exploration, the implicit downstream user is another agricultural irrigator, and the maximum allowable degradation is determined to be that point at which a specific crop can not be effectively grown using water of a particular salt concentration. Other downstream stakeholders, however, may have greater or lesser sensitivity to salt, or there may be other pollutants present from agricultural usage that they have greater sensitivity to than salt.

In any real world river basin, labeling return flows as useful implies that the question of “Useful for whom?” is known, can be quantified, and satisfies a real need from a temporal, quality, and proximity standpoint. Knowing the answers to these questions requires intimate knowledge of the geology of the basin, the stakeholders’ needs and sensitivities, and the physical locations of major users. In short, evaluating real world river basins requires extremely sophisticated computer models. Unfortunately, as is frequently true with many real world phenomena, these models still require multiple simplifying assumptions in order to be workable. Despite its own limitations and lack of quantification, the water degradation analogy introduced in this paper represents a method of thinking about basin management that will find many day-to-day uses.

Summary

In this paper we have explored the limitations of classical models for looking at water conservation and water efficiency. When viewed at the project or basin level, it has been demonstrated that the Application Efficiency model may overestimate water savings generated by conversion from flood irrigation to modern technologies by ignoring the use of return flows within the river basin. The Basin Model makes a similar mistake by ignoring the impacts of accessibility, timeliness, and quality and assuming that only evaporative/consumptive losses within the basin are relevant to the question of water conservation. Real river basin systems follow neither of these theoretical models. Recent work by other researchers has recognized that both of these models are vast oversimplifications of complex real world systems that are highly dependent on specific physical characteristics. In this paper, the authors have proposed a framework of thinking about basin wide management, in analogy to thermodynamic systems, which can provide water policy makers, hydrologists, and individual users qualitative guidance on their water management decisions.

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Completing the Connection Between Irrigation Districts and On-Farm Irrigation

C. M. Burt[1]

The Relationship Between Irrigation Districts and Farmers.

Within the western U.S., many farmers receive all or part of their annual irrigation supply from irrigation districts. State laws govern the details of the formation, administrative and legal organization, financial obligations, voting rights, specific titles (e.g., water district vs. irrigation district vs. water storage district) of irrigation districts. In most cases, irrigation districts in the U.S. are operated as public agencies, with a board of directors composed primarily of farmers. The districts either have water rights or purchase water, and are responsible for conveying and finally distributing the water to individual fields. They are financially self-sustaining and non-profit – raising the majority of their funds through the sale of water and/or taxes on land. Of course, there are many variations of this. Privately held mutual water companies are still very common in some areas of the western U.S.

In the U.S., the legal structure of the irrigation districts and the very local nature of them (farmers pay the bills, and farmers are on the boards of directors, and frequent elections are held for board members) tends to stimulate a "can do" attitude. The water gets delivered with a relatively high degree of equity and reliability. The degree of flexibility of those water deliveries, however, varies greatly depending upon the vision of the board members and staff.

Internationally, there are very few irrigation districts, per se. Instead, there tend to be "irrigation projects" that are administered by large government irrigation agencies. In recent years there has been considerable effort to create sustainable "water user associations (WUA)" in international projects. These WUAs come in all shapes and sizes, with a wide range of expectations. There are some instances of success, such as in Colombia (which has a long history of WUAs), northern Mexico (where farmers are completely dependent upon irrigation rather than rain, plus they are accustomed to operating businesses), and in Turkey. WUAs formed in various areas of the Philippines, Thailand, India, middle and southern Mexico, Morocco, and other areas are generally quite weak or only exist on paper. In many cases, they are declared to exist by legislation and the irrigation authorities, with the hope that the farmers will somehow collect money and pay the government for water, and the farmers will also take over all the maintenance of their areas.

What Farmers Need from Irrigation Districts

The question of what farmers need from an irrigation district is more complicated than it might first appear. It must be framed within the context of factors such as the following:

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a. The ability of farmers, or a willing agency, to pay for improvements in water delivery service.
b. Potential benefits for farmers, in terms of
   - Reduced pumping costs
   - Reduced labor
   - Higher crop yields
c. Special requirements for specific irrigation methods that are being used, or may be used, in an area.

I have noticed that farmers are, as a group, just like any other group of individuals in many ways. There are educated and uneducated farmers, some who focus on the business aspects and others who focus on agronomic aspects, energetic and lazy farmers, and farmers who expect the government to pay for everything and others who believe that farmers also have obligations. And just like any group, a local "champion" or leader is needed if internally-driven change is to occur quickly and effectively.

There are many puzzling things about why farmers irrigate a particular way. ITRC conducted a survey of farmers in the Delano-Earlimart Irrigation District on the subject of perceptions of drip irrigation on trees and vines. About half of the farmers had a very favorable impression of drip, and made extensive use of it. The other half had a very poor impression of it, and weren't about to adopt drip/micro. Likewise, I have noticed that if water is available with a high degree of flexibility, only some of the farmers take maximum advantage of that flexibility for many years after it becomes available.

My conclusion after working in irrigation for over 30 years is that only a few farmers in an irrigation district generally have the vision to dream about what changes in water delivery service flexibility will be needed by farmers in 10 or 20 years. Farmers will have much to say about the price of water, the annual availability of water volumes, and other such topics – but very few will articulate arguments in favor of improved water delivery flexibility to farms. One only needs to attend irrigation district board meetings, or to attend regional meetings of irrigation districts, to realize that the details of water delivery flexibility rarely surface in conversations and meetings.

Yet the bottom line is that there are very few irrigation districts in the U.S. that can support automated farm irrigation. They simply cannot deliver the water with enough flexibility to support turnout delivery flow rate fluctuations that would accompany on-farm automation. So automated farm irrigation systems, where they do exist, are usually found on farms with well supplies, or on farms that have their own buffer reservoirs between the irrigation district and the supply.

The interesting thing is that historically there has been little or no demand by farmers to have enough flexibility to automate their on-farm irrigation. There is, of course, the question of why anyone would want to automate the on-farm irrigation. Many farmers firmly believe that someone needs to be in the field, anyway, because so many things can go wrong during an irrigation.

But an unusual factor is changing the way farmers think, and it's not a desire to automate their irrigation systems for better agronomic results or for saving water – traditional arguments in favor of irrigation system automation. The driving force in California, at least, is the desire to reduce electricity bills. If farmers can turn off their irrigation pumps between noon and 6 pm (Monday – Friday), their electric bills are decreased substantially. But the irrigation districts must be capable of providing this service.

I think that this is just one example of how external forces (in this case, the price of pumping) are quickly changing the way many U.S. irrigation districts operate. My idea that improved flexibility will need to come from pressure by farmers with a long-term vision may not be correct.

External Pressures on Irrigation Districts

Irrigation district modernization is moving rapidly in the western U.S., and most of that modernization is motivated by external forces – that is, by pressure that originated from a different source than farmers. In addition to the increasing electrical rates mentioned earlier, other such external forces can include:

a. Reduced water availability, such as has happened in the Central Valley Project in California as water has shifted toward endangered species and away from farming. This is also happening on the Colorado River, which may have allocations that exceed water availability.
b. Competition for water. As an example, cities in southern California have looked at irrigation district spills, and farmer tailwater return flows into the Salton Sea and have demanded that those losses be eliminated and the conserved water be used for urban needs. The Klamath Basin in northern California and southern Oregon is in the midst of a huge debate regarding limited water and competing interests of fishermen, Indian tribes, and farmers.
c. Environmental restrictions related to return flows. As an example, in the middle sections of the San Joaquin River, stringent water quality guidelines have been proposed by regulatory agencies. The only way that such guidelines can be met may be to eliminate all surface return flows from irrigation districts. As another example. major irrigation modernization funding in the Yakima (Washington) River basin has come from efforts to improve the water quality for fish in the Yakima River.
d. Requirements that farmers must pay for water on a volumetric basis. This is a favorite topic with donor agencies such as the World Bank and the Food and Agriculture Organization of the United Nations. It has also been a favorite topic here in the U.S. with the US Bureau of Reclamation. In US irrigation districts that receive federal water, there are now requirements that water deliveries be measured volumetrically.

ASSESSING IRRIGATION DISTRICTS FOR MODERNIZATION

ITRC works on irrigation district modernization in almost all of the western states either directly for irrigation districts, or on behalf of agencies such as the US Bureau of Reclamation. We typically become involved in the first stages of modernization, when strategies and overall modernization plans are being developed.

Prior to making recommendations for modernization, each district receives a Rapid Appraisal Process (RAP) by conducted by senior ITRC engineers with a solid background in modernization. An RAP provides an understanding of the operation procedures, and includes a step-by-step tour of the district to learn how water is controlled and conveyed from the source to the individual fields.

ITRC does not use a formal checklist for the U.S. RAPs. However, we have conducted a number of formal evaluations of irrigation district flexibility and characteristics. Reports on the process and results can be found http://www.itrc.org/reports/reportsindex.html

Evaluation of Irrigation Projects in Less Developed Countries

A formalized RAP was developed by Burt and Styles (1999) in response to the need for a standardized procedure for evaluating international irrigation projects. In addition to improving a wide range of external indicators (e.g., Relative Irrigation Supply and Relative Water Supply), they also developed 31 internal indicators that quantify various aspects of water delivery service at all layers within an irrigation projects. Some of the internal indicators quantify the suitability or impact of various factors that influence the degree of service that is provided

ITRC has conducted evaluation training for irrigation district modernization throughout the world, including Uzbekistan, Mexico, Thailand, Nepal, the Philippines, Vietnam, and Pakistan. We have worked closely with the World Bank and FAO to institutionalize the importance of conducting appropriate RAPS before projects are modernized, and to evaluate modernization proposals based on the ITRC RAP principles.

TYPICAL IRRIGATION DISTRICT MODERNIZATION EFFORTS - USA

Within the U.S., modernization efforts have focused on improving the flexibility of water delivery while simultaneously improving the irrigation efficiency of the district (including conveyance efficiency and on-farm irrigation efficiency). Typical actions include modification of check structures to improve water level control, extensive usage of recirculation systems, improved water ordering procedures and software, incorporation of hand-held dataloggers, improved flow measurement and control at all levels, and wide acceptance of SCADA (Supervisory Control and Data Acquisition) systems. Most SCADA systems first emphasize remote monitoring, followed later by remote manual control. Some districts move directly to automation with associated SCADA systems – but the automation is rarely centralized.

In the U.S., most large-scale irrigation automation projects failed until the late 1990's. There are many reasons for these failures, including the lack of understanding of control algorithms, improper SCADA design, poor sensors, inappropriate control applied to canals, poor PLC hardware, etc. But more than anything else, perhaps the failures were caused by the lack of attention to detail. In irrigation automation, the devil is in the details.

ITRC has now developed detailed flow charts for the complete automation process, and we have learned that automation is much more expensive and time consuming than we had earlier thought – if it is to work successfully for a long time. We now have excellent unsteady simulation models, superb control algorithms, an understanding of all the PLC programming steps in addition to programming the algorithms, and knowledge of required PLC, sensor, and SCADA specifications, and good hardware (PLC, sensors, radios, VFD controllers, etc.). We have worked slowly and meticulously to "knock off" each of the traditional stumbling blocks to irrigation district automation.

This work has been possible only with super interactions with a few irrigation district personnel, integrators, and state and federal government agency professionals.

The final hurdle for us has been the relationship with the integrator – the company that does the final installation and programming of the PLC and the Human-Machine-Interface (HMI). We have had tremendous difficulties on this aspect – we think primarily because most integrators actually have very little experience in sophisticated automation. We have recently (within the last 6 months) decided to utilize a universal programming language that is acceptable by all of the major PLC (Programmable Logic Controller) manufacturers, and we will do all of the control logic ourselves. Trying to communicate with integrators about control logic programming has taken more time than if we just do the programming ourselves – which is what we have been forced to do on several projects. This is not to say that we can do without the integrator. The integrator is still needed to do the on-site installation of sensors, PLCs, radios, HMI software in the office, etc. The integrator is also responsible for calibrating sensors and much of the up-front programming that checks for voltages, sensor activity, availability of power to gates, etc.

TYPICAL IRRIGATION DISTRICT MODERNIZATION EFFORTS - INTERNATIONAL

In international projects, modernization efforts have been much less extensive. In the study by Burt and Styles (1999), it was difficult to find 16 projects that had received even some aspect of modernization. Most "modernization" efforts focus on canal lining and rehabilitation of existing structures, rather than on improvements. Furthermore, there is almost always confusion between employing a single hardware device, versus a comprehensive analysis of modernization to improve service. This inappropriate approach, combined with a frequent but unrealistic hope that some type of centralized computerized management or control equals modernization, almost always yields less-than-spectacular results.

There is also an incorrect perception by persons in major donor agencies such as the World Bank that the ills of international irrigation projects can be solved almost exclusively through "software", sometimes referred to as Irrigation Management Transfer (IMT) or as Participatory Irrigation Management (PIM). One should not forget that IMT – the transfer of responsibilities from the central government to local water user organizations – requires that the newly formed water user associations receive water in a usable, equitable, and reliable manner. Without such security, the water user associations have historically failed.

But perhaps the biggest challenge internationally is a lack of attention to details, combined with improperly selected expert companies and individuals. The automation/modernization is often shoved inside larger rehabilitation projects that can only be administered by large construction firms – who may have little or no true experience in modernization. This is exacerbated by a common requirement that modernization on a complete project be finalized within a couple of years after approval. In the U.S. we could rarely if ever achieve success with such a short timeline. It just takes time for people to "get up to speed".

Over the years I have developed a list of factors, any one of which will almost guarantee failure of modernization programs. Some of these factors include:

a. A desire to model the hydraulics of a complete system. I have never needed to do this. Granted, we do model a canal if gates are to be automated – but we do not model beyond that.
b. The existence of a large gap between what project managers state is occurring in the project, versus what actually exists in the project.
c. Money spent on developing computer models to route flows through an irrigation system – especially when based upon numerous assumptions that will never occur in the field.
d. An inadequate budget for maintenance, spare parts, and long-term support.
e. Dirty offices and bathrooms without good plumbing. This indicates a lack of concern for details, and the lack of motivated staff and management.
f. A staff that has no motivation for working well and hard, and which cannot be fired for poor performance.
g. A modernization plan that does not require many years for implementation, and that does not include very deliberate implementation in the field and adequate training and budget.
h. No local "hero" who lives at the project and who will make certain that things work out.
i. A plan that focuses only on computers and PLC-based automation, and does not put a substantial percentage of the budget into simple structures and recirculation systems.
j. An operation plan that dictates gate movements from the central office.
k. The lack of a "service mentality" at all levels within the irrigation project.

A minimum of 3-5 of the points above pertain to almost all international irrigation projects that I have visited in 25 countries over the years.

A POSITIVE SUMMARY

Irrigation districts throughout the western U.S. are very actively involved in modernization efforts that will continue for several decades. The motivation for modernization has largely come from non-agronomic sources. But when modernization is appropriately designed, the water delivery flexibility to farmers is substantially improved while simultaneously responding to external forces.

ITRC has developed a benchmarking procedure to quantify the quality of service that an irrigation district provides, and to identify the appropriate steps needed to modernize an irrigation district. This RAP has been successfully used to assist dozens of irrigation districts throughout the western U.S. It is being adopted by major donor organizations internationally.

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Simple and Inexpensive Lysimeters for Monitoring Reference- and Crop-ET

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Abstract

Weighing lysimeters are standard tools for measuring evapotranspiration (ET). Planted with a grass crop, a weighing lysimeter can be used to verify or calibrate weather-based reference-ET estimates. Planted with an agronomic crop, a weighing lysimeter can be used to measure crop-water use or to develop crop coefficients for use with weather-based ET-estimation methods. Simple and inexpensive weighing lysimeters are being used to help schedule irrigation of cotton in Mississippi. The design, construction, installation, and operation of these instruments are presented.

Keywords. Lysimeter, evapotranspiration, reference ET, crop coefficient

Simple and Inexpensive Lysimeters for Monitoring Reference- and Crop-ET

Weighing lysimeters have been used for many years to measure and study water use for a variety of crops. A weighing lysimeter measures the amount of water used in evaporation and transpiration by a vegetated area.

Knowledge of crop water use is important in irrigation scheduling, optimizing crop production, and modeling evapotranspiration and crop growth. The ability to estimate and predict evapotranspiration and crop water requirements can result in better satisfying the crop's water needs and improving water use efficiency.

Many studies of crop water use have been undertaken for a variety of crops in many different locations and growing environments. Water-use and crop-coefficient curves have been developed from these studies. The results from one environment, however, may not be readily transferable to another (Piccinni et al, 2002). Installing lysimeters and collecting water-use data for local crop varieties and environmental conditions will provide the information needed to develop curves suitable to the local area.

Lysimeters of many different designs, sizes, shapes, and methods of operation have been built. Howell et al. (1991) offer a history of lysimeter development and use. A variety of studies involving lysimeters by various authors can be found in Camp et al. (1996). Many other researchers have designed and constructed lysimeters to meet their specific needs and objectives.

The objective of this paper is to describe simple and inexpensive lysimeters used for measuring reference- and crop-ET. The construction, installation, and operation of the lysimeters is detailed, and data collected during their operation are presented.

Lysimeter Construction

In designing the lysimeters, ease of fabrication, simple installation, low maintenance requirements, and low cost were important considerations. Using readily available materials and components helped keep cost down, and a simple design allowed fabrication using common shop tools.

The lysimeter design was based on that of Allen (Allen and Fisher, 1990). The main components of the lysimeters were an outer tank, an inner tank, loadcell assemblies, and a drain system. The outer and inner tanks consisted of four side walls and a bottom plate. When installed in the field, the inner tank contained the drain system and a volume of soil and vegetation isolated from the field. The loadcell assemblies supported and monitored the weight of the inner tank. The outer tank isolated the inner tank from the field and supported the loadcell assemblies and inner tank.

Two different lysimeters were designed and constructed, the main difference being the dimensions of the lysimeter tanks. One lysimeter was designed for use in monitoring reference (grass) ET, and had surface-area dimensions of 1 m wide x 1 m long. The second lysimeter was designed for use in monitoring the ET from a row crop (mainly cotton). The surface-area dimensions of this lysimeter were 1 m wide x 1.5 m long. The dimension in the direction of the crop row was lengthened to allow more plants to be planted on the lysimeter. Both lysimeter designs had an inner tank that was 1.5 m deep. An assembly drawing with top and side views of the 1 m x 1.5 m surface-area lysimeter is shown in Figure 1.

The lysimeters were constructed of steel plate and steel U-shaped channel stock. The inner and outer tanks consisted of four side walls and a bottom plate made of standard 4.8-mm (3/16-

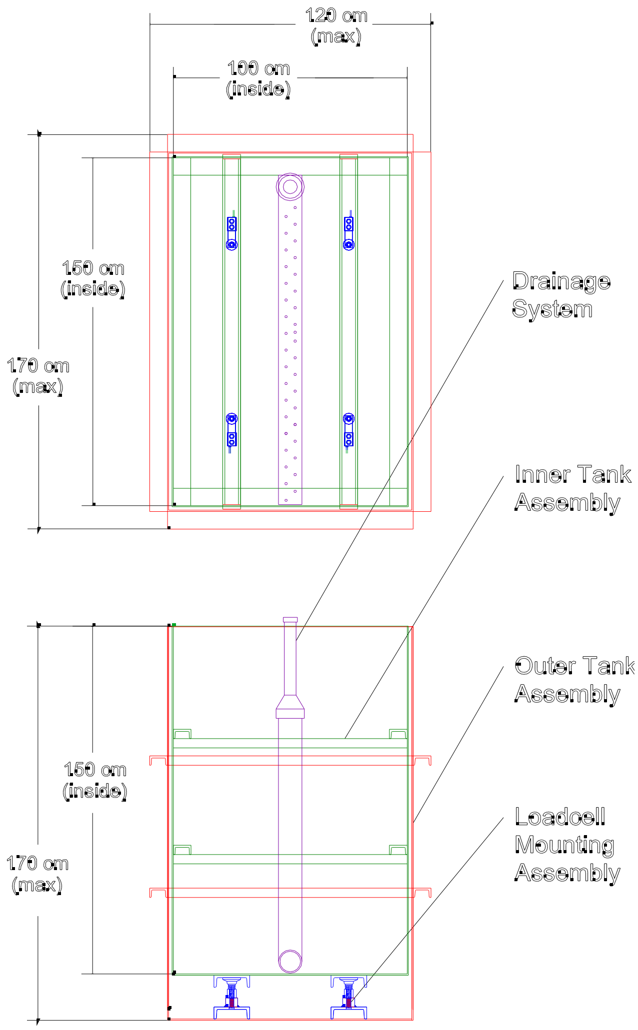

Figure 1. Top- and side-view drawings of the 1 m x 1.5 m surface-area lysimeter.

in) steel plate, and 76-mm (3-in) steel channel support members.

The support channels were welded to the side and bottom plates. The side and bottom plates were then welded together to form each tank. Each completed tank was painted with white enamel paint to protect against rust.

The loadcell assemblies consisted of stainless steel shear-beam loadcells bolted to steel channel supports on the bottom of the outer tanks. The loadcells used for both lysimeters were Sensortronics Single-Ended Shear-Beam, Model 65023[1]. Model 65023 loadcells with a 909-kg (2000-lb) capacity were specified for the 1 m x 1 m lysimeter, while loadcells with a 2272-kg (5000-lb) capacity were used for the 1 m x 1.5 m lysimeter.

The inner tank was supported by the loadcells via stainless steel leveling mounts threaded into the loadcells. The leveling mounts used were LEVEL-IT, Model 9T2LTM for the 1 m x 1 m lysimeter, and Model 19T2LTM for the 1 m x 1.5 m lysimeter, available from J.W. Winco, Inc. The height of the mounts could be adjusted to ensure that the inner tank was level and that there was an even distribution of weight on each loadcell. Views of the loadcell mounting assemblies are shown in Figure 2.

The drain assembly allowed excess water to be removed manually from the lysimeter. The drain assembly consisted of a 15-cm (6-in) diameter perforated PVC pipe connected to a 15-cm (6-in) diameter PVC standpipe. The standpipe was reduced to a 7.6-cm (3-in) diameter pipe near the surface so that it occupied less of the lysimeter's vegetated surface area.

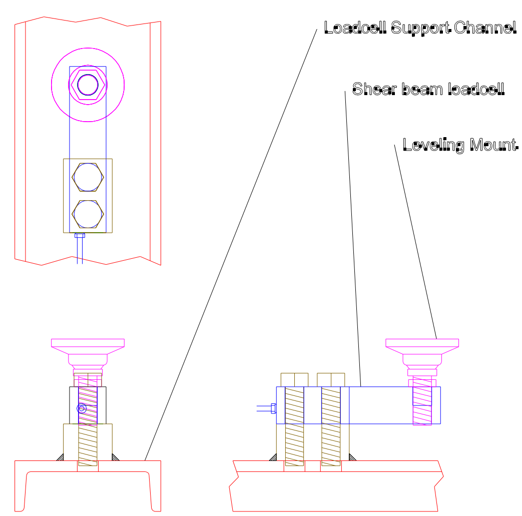

Figure 2. Top-, front-, and side-view drawings of the loadcell mounting assemblies.

[1] The mention of trade or manufacturer names is for information only and does not imply an endorsement, recommendation or exclusion by USDA-Agricultural Research Service.

The cost of the materials needed for each lysimeter, purchased in Mississippi, USA, in 2001, are shown in Table 1. The steel plates for the tank walls and bottoms were cut to size by the steel supplier, with cutting included in the price. The costs shown are for materials and delivery, and do not include labor or material costs of fabrication.

All fabrication was performed in-house by USDA ARS technicians. Fabrication consisted mainly of cutting the steel channels to the proper lengths, welding the plates and channels together, and cutting and assembling the PVC drain assembly. Each lysimeter required the efforts of two people and approximately 40 hours each to assemble and weld the components.

Lysimeter Installation

The lysimeters were installed in pairs in two different locations at the Application and Production Technology Research Unit's Mechanization Farm at the Jamie Whitten Delta States Research Center, Stoneville, Mississippi, USA. Two 1 m x 1.5 m surface-area lysimeters were installed in a field dedicated to row-crop (mainly cotton) research in the summer of 2002. Two 1 m x 1 m surface-area lysimeters were installed in a grass field in the fall of 2002.

Table 1. Cost of materials for each lysimeter

assembly	description	cost
inner tank	3/16-in thick steel plate	$750*
	3-in wide steel channel	
outer tank	3/16-in thick steel plate	
	3-in wide steel channel	
	6-in wide steel channel	
loadcell	2000-lb loadcells (1 m x 1 m lysimeter) 4 req'd	$205 ea
	5000-lb loadcells (1 m x 1.5 m lysimeter) 4 req'd	
	leveling mounts 4 req'd	$25 ea
drain	6-in diameter PVC pipe	$30
	4-in diameter PVC pipe	
total		$1700

*total cost of all steel for inner and outer tank.

Lysimeter installation was accomplished by two people using a backhoe, a forklift, hand shovels, and a few hand tools. Holes for each lysimeter were excavated using the backhoe. The outer and inner tanks were positioned and installed with the forklift. Soil was backfilled around the outer tanks and inside the inner tanks using hand shovels. Each pair of lysimeters required two days of work to complete the installation.

The procedure followed in installing the lysimeters is outlined in the following paragraphs. Photographs taken during and after lysimeter installation are shown in Figures 3 through 12.

1. Choose a location. A location with appropriate conditions for evapotranspiration measurement was chosen. Some factors to consider included; near the center of the field to provide adequate fetch; under healthy, maintained grass surface (for the grass lysimeters); under the center-pivot irrigation system (for the crop lysimeter).

2. Prepare the site. The location to excavate was marked. Plywood sheets were laid out around the area for the grass lysimeter to minimize damage to the existing grass field. This was not a concern in the row-cropped field since the field was tilled each season.

3. Excavate the soil. The soil was excavated in layers, with the soil from each layer placed in a separate pile (Figures 3 and 4). When the proper depth was reached, the bottom of the hole was leveled.

4. Install the outer tank. The outer tank was lowered into and centered in the hole. The tank was checked to ensure that it sat level on the bottom of the hole. Soil was backfilled around the outer tank to stabilize the tank (Figures 5 and 6).

Figure 3. Choose location and begin excavation.

Figure 4. Remove soil and ensure bottom is level.

Figure 5. Install outer tank in hole.

5. Install the loadcell assemblies. The loadcells were bolted to mounts located on the bottom of the outer tank. The leveling mounts

Figure 6. Backfill soil around outer tank.

Figure 7. Install loadcells in outer tank.

were threaded into the loadcells. The loadcell wires were routed to a common corner of the tank, brought out of the tank to the surface, and wired to a datalogger (Figure 7).

6. Install the inner tank. The inner tank was centered in the outer tank and lowered slowly until it rested on the loadcell assemblies. The output from each loadcell was checked to ensure that each loadcell was operating properly and that the weights supported by each loadcell were similar (Figure 8).

7. Install the drain system. The PVC drain system was placed on the bottom of the inner tank. The bottom of the tank and the perforated drain pipe were covered with a layer of gravel. The gravel was then covered with a layer of sand (Figure 9).

8. Backfill the inner tank with soil. The inner tank was backfilled with soil, returning the soil to the depth from which it was excavated. The soil was packed periodically in an attempt to return it to its original bulk density (Figure 10).

Figure 8. Install inner tank.

Figure 9. Install drain assembly, cover with gravel, sand.

Figure 10. Backfill soil in inner tank.

Figure 11. Crop lysimeters prior to planting, 2003.

Figure 12. Lysimeters with cotton crop, 2003.

The row-crop lysimeters after installation are shown in Figures 11 and 12. Figure 11 shows the lysimeters immediately prior to planting. The datalogger enclosure can be seen in between the two lysimeters. Figure 12 shows the same lysimeters with an actively growing cotton crop.

Lysimeter operation

Once installed in the field, the lysimeters were connected to an electronic datalogger (Campbell Scientific, Inc., Model CR21x). Each loadcell was connected to a separate input channel on the datalogger in order to monitor each loadcell independently. Each lysimeter pair was connected to one datalogger, resulting in the monitoring of eight loadcells with each datalogger. Data were stored in a storage module (Campbell Scientific, Inc., Model SM-

192), which provided long-term, non-volatile data backup.

The datalogger was programmed to collect loadcell measurements at 10-minute intervals. Every ten minutes, each loadcell was read 10 times, and the average of the 10 readings was stored. For each lysimeter, the four average loadcell measurements were totaled, and the total weight of the loadcell was recorded.

MAINTENANCE

Routine maintenance involved periodic visits to the lysimeter sites to check the condition of the vegetation on and around the lysimeters, and to check for excess water inside the outer and inner tanks. The grass on the grass lysimeters was periodically trimmed by hand and irrigated to maintain proper height and well-watered "reference ET" conditions. The row-crop lysimeter was occasionally tilled and sprayed by hand if the mechanized field equipment was not able to access the lysimeter.

Excess water inside the lysimeter tanks was removed periodically using a hand suction pump. After heavy rain events, the soil inside the inner tank could become saturated due to deep drainage being restricted by the tank's bottom plate. This water was removed by inserting the flexible tubing on the hand pump's inlet side into the vertical PVC standpipe on the drain system and pumping the water out. On several occasions, the rainfall was heavy enough to cause the inner tank to fill and overflow. The water flowed down between the inner and outer tanks and filled the space underneath the inner tank where the loadcells were located. The loadcells were not damaged, but the data were not usable during these periods. The water was removed by inserting the flexible tubing on the hand pump's inlet side into the space between the inner and outer tanks and pumping the water out.

One problem which resulted in loss of data and recurring problems involved damage to the loadcell wires. Initially, the loadcell wires were connected to the datalogger at a nearby weather station. The loadcell wires were buried in a shallow trench between the lysimeter tank and the weather station, then up alongside a metal pipe to the datalogger. During a visit to the site about six months after installation, the wires were found chewed through by some type of animal. The wires were spliced back together and loadcell measurements resumed. A conduit was then constructed of rigid PVC pipe and elbow fittings, and the loadcell wires were placed inside this to protect them.

LYSIMETER MEASUREMENTS

Lysimeter measurements consist of a time-series of absolute weights of the lysimeter's inner tank and its contents. The weights include the weight of the inner tank and drain system, and the weight of the vegetated soil inside the inner tank, which includes gravel, sand, soil, vegetation, and water.

Lysimeter measurements were collected automatically and continuously at 10-minute intervals. At each measurement interval, a series of 10 weight measurements were collected from each of the four loadcells. The 10 measurements from each loadcell were averaged, and the average weight was stored in the datalogger's memory. The four average weights were then added together to provide a measure of the total weight of the lysimeter.

Evapotranspiration rates and amounts were determined from changes in lysimeter weight which occurred over time. During daylight periods, weight decreases as water evaporates from plant and soil surfaces and transpires through plant tissues. The amount of water evaporated and/or transpired was determined by calculating the difference in weight from one time period to the next. The weight of water removed due to evapotranspiration, in kg, was then converted to an equivalent depth of water, in mm.

The lysimeters were also useful in measuring rainfall and irrigation amounts. Rainfall or irrigation water falling on the lysimeter caused an increase in lysimeter weight. Calculating the increase in weight from one time period to the next resulted in accurate determinations of rainfall and irrigation rates and amounts.

Examples of lysimeter weight data and calculated evapotranspiration and rainfall amounts are shown in Figures 13 through 15. The figures show absolute weights and calculated changes in weight, converted to equivalent depths of water, for a three-day period in May 2003. Weight measurements were collected at 10-minute intervals, with changes in weight/depth calculated as the difference in consecutive 10-minute weight measurements. The changes in water content are shown as cumulative totals, and were determined by resetting the cumulative total to 0 at midnight (0 hrs) and accumulating consecutive changes throughout the day.

The three-day series in Figures 13 through 15 shows data from the two grass lysimeters during two sunny days and one rainy day. The lysimeters are called E (East) and W (West), and in the figures, the weights and cumulative changes in water content are shown for 24-hr periods from midnight to the following midnight. In Figures 13 and 15, the cumulative change in water content (evapotranspiration) ranged from about 6.5 mm/day to 7.5 mm/day. In Figure 14, a rainfall event occurred around 0900, with approximately 2.5 mm of rain falling on the lysimeter. Evapotranspiration continued after

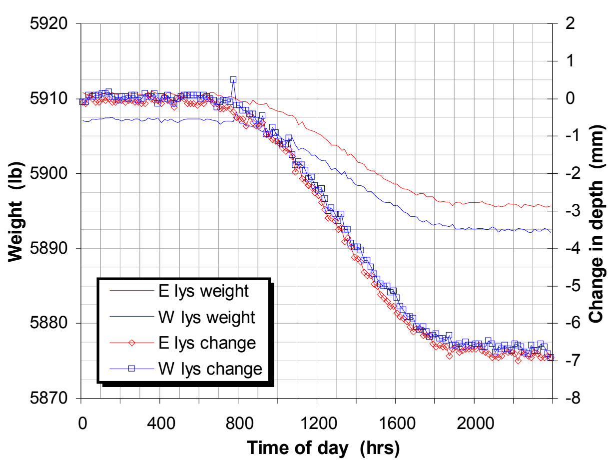

Figure 13. Lysimeter weights and cumulative changes in the depth of water over a 24-hr period, 24 May 2003.

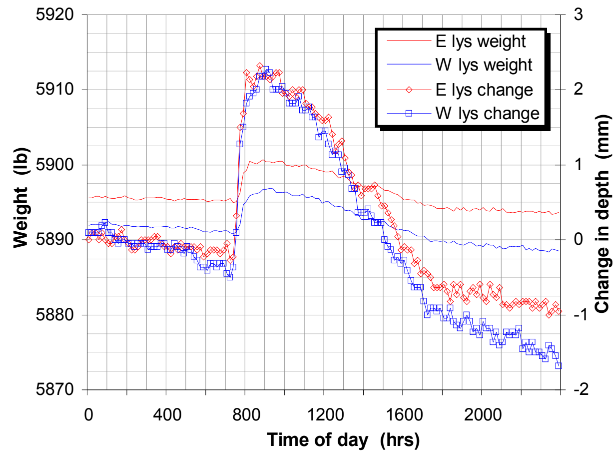

Figure 14. Lysimeter weights and cumulative changes in the depth of water over a 24-hr period, 25 May 2003.

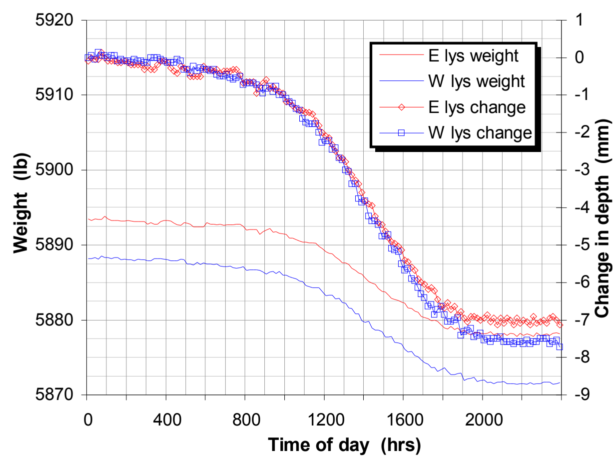

Figure 15. Lysimeter weights and cumulative changes in the depth of water over a 24-hr period, 26 May 2003.

the rain, with a cumulative change in water content of about 3.5 mm for that day. Lysimeter measurements were used to determine evapotranspiration values on a daily basis. The changes in water content from one day to the next were determined by calculating the difference in lysimeter weights at 0700 on consecutive days. The 0700 time period was chosen to coincide with the measurement interval of the weather station at the Stoneville research station.

Daily evapotranspiration values for the grass and crop (cotton) lysimeters for the 2003 growing season (April through September) are shown in Figures 16 and 17. Figure 16 shows grass (reference) ETo values from one lysimeter: the other grass lysimeter values were almost identical. Figure 17 shows crop (cotton) ETc values from one crop lysimeter: the cotton crop on the other lysimeter was noticeably stunted and in poor health throughout the growing season and the ETc values were not deemed representative of a typical cotton crop grown in the region.

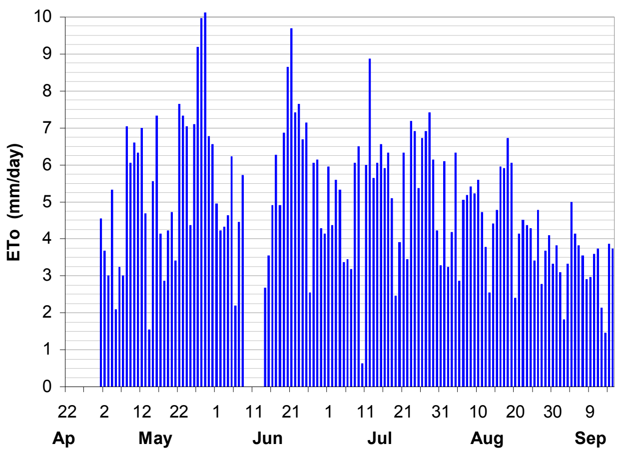

Figure 16. Daily ET values for grass measured during the 2003 growing season.

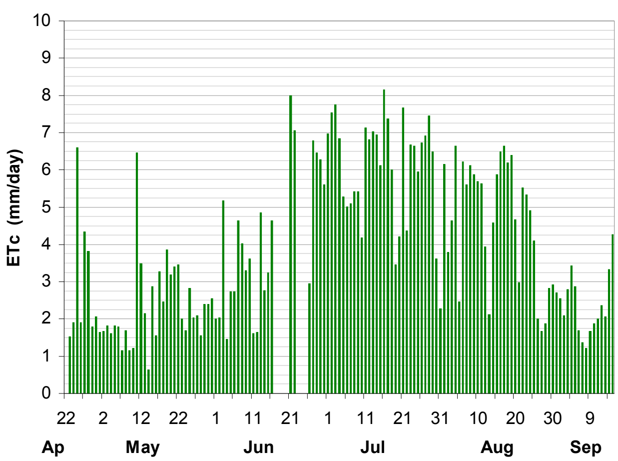

Figure 17. Daily ET values for cotton measured during the 2003 growing season.

Conclusions

Two pairs of electronic weighing lysimeters were constructed and installed. The lysimeter design was simple, consisting mainly of an inner tank, outer tank, and strain-gage loadcells. The cost of each lysimeter was approximately US$1700, excluding labor costs of construction.

Evapotranspiration data are being collected under reference (grass) and crop (cotton) covers on a daily and seasonal basis. The data will be used to quantify water use under local environmental conditions, evaluate weather-based reference-ET estimation methods, and develop crop coefficients.

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The Influence of Geometrical Parameter of Dental Flow Passage of Labyrinth Drippers on Hydraulic and Anti-clogging Performance

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Abstract: The hydraulic performance and anti-clogging ability of emitters with dental flow passage were studied and results are presented in this paper. The orthogonal array was used for experimental design. Tests were conducted on dentation angle (104°, 108°, 112°, 117°), spacing between dentations (1.5, 1.8, 2.1, 2.5mm), dentation height (1, 1.3, 1.6, 1.9mm), and depth of flow passage (0.6, 0.9, 1.2, 1.5mm). Results showed that spacing between dentations had significant influence on the exponential value of flow state and the anti-clogging ability of emitters. The anti-clogging ability of emitters was not linearly correlated with flow rate as commonly believed and was improved nearly linearly with the increase in the width of flow passage. Results also indicated that the chance of emitters being plugged by sand particles was small if the openings of screen filter were selected according to the rule of 1/10th of the size of the width of flow passage.

Key words: emitter; flow passage; hydraulic performance; anti-clogging performance

1. Introduction

Emitters are one of the key parts in trickle irrigation system, and their structure parameters affect corresponding hydraulic performance and anti-clogging ability. According to Gilaad et al. (1974) the hydraulic performance of emitters were determined by the forms, dimension, and the materials of the flow passage [1]. Ozekici and Sneed (1991) studied the hydraulic performance of dental form emitters. Their experimental results showed that most water pressure was lost at the dental structure parts [3]. Avner Adin and Mollie Sacks (1991) investigated the clogging problems in drip-irrigation systems using wastewaters, and the results revealed that the structure forms of flow passage had great influence on the clogging potential [4]. Wang et al. (2000) studied the flow state in labyrinth emitter using Finite Element Method and attained numerical simulation results, and investigated the influence of the Reynolds numbers on flow field [5]. However, the information on the relationship between structure parameters of flow passage and the hydraulic performance and anti-clogging ability of emitters were not specifically addressed and information on these are limited. The study was conducted to evaluate the hydraulic performance and anti-clogging ability of emitters with dental flow path with variation in dentation angle, spacing between dentations, dentation height, and the depth of flow passage. The term dental or dentation is used in this article to define the repeating zigzag or saw-toothed pattern of the emitter pathway.

2. Materials and Methods

2.1 Experimental Design

The structural factors of the emitters and the level of each factor are presented in Table 1. Each factor was evaluated at four different levels for dentation angles, spacing, height, and passage depth.

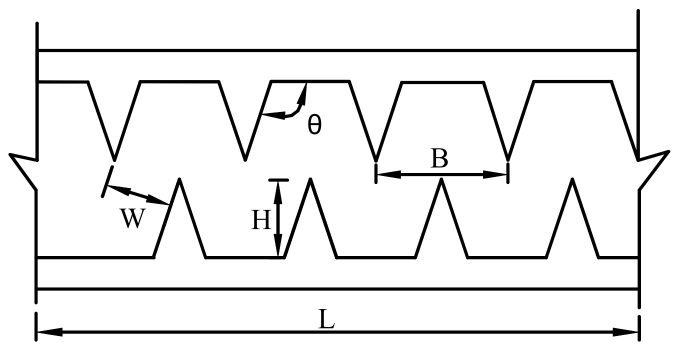
The value of each variable was selected on the basis of the dripper emitters available in the market.

Table 1: Independent variables or factors and values of four levels

Factors	level			
θ, dentation angle	104°	108°	112°	117°
B, dentation spacing	1.5mm	1.8mm	2.1mm	2.5mm
H, dentation height	1.0mm	1.3mm	1.6mm	1.9mm
D, depth	0.6mm	0.9mm	1.2mm	1.5mm

Note: The length of flow passage of all emitters was 19.4mm. Most manufacturers used this length.

A schematic representation of a dental labyrinth emitter is shown in Figure 1.



θ: dentation angle, B: dentation space, H: dentation height,

W: width of flow passage, L: length of flow passage

Figure.1: Dental structure parameters of a labyrinth emitter

The traditional factorial arrangement of all possible combination for four factors at four levels of variation coupled with 8 test phases for 8 mixes of particulate materials would raise the number of tests to an unmanageable level. The aim was to investigate the effects of the individual variables (or factors) and also how the variables interact. Considering the condition, the orthogonal array was adopted for the experimental design [2, 8].

2.2 Materials

The moulds for above 16 kinds of emitters were made and hundreds of emitters were manufactured for every type of emitter combination by extrusion and was installed in 16mm diameter drip tapes by Beijing Luyuan Company. The tests were conducted according to ISO 9261 and ISO/TC 23/SC 18/WG5 N4 [6, 7].

2.2.1 Methods

a) Hydraulic performance test

Hydraulic performance of emitters, that is, the relationship between working pressure and flow rate of emitter is given by the equation,

$$Q = kH^{x}$$

Where, Q = flow rate of emitters (L/h), H is working pressure (m), k is discharge coefficient, x is flow state exponent.

The Hydraulic performance of emitters was tested according to ISO9261 (Emitter-pipe systems—Specification and test methods)[6].

b) Anti-clogging performance test

Anti-clogging performance test methods for emitters were performed according to the "short term clogging test procedure" contained in first working draft of ISO/TC 23/SC 18/WG5 N4 (Clogging test methods for emitters). This method has been developed for testing the capability of emitters to either let pass or prevent entry of solid particles of a given size. The ISO test procedure suggests the use of aluminum oxide [7]. However, considering the fact that the sand acted differently from aluminum oxide in the water condition, we adopted river sand was adopted as a natural clogging material in the experiment.

The test condition and procedures are listed in Table 2, and the number of test phases for each kind of emitter was 8. Cumulated grain size distributions for sands used in different experimental phases are shown in Fig.2. The mix and the concentration of sands employed in the 8 test phases are shown in Table 3.

Table 2: Short term clogging test procedure for emitters

Test sample	25 emitters
Number of test lines	25, horizontal, with valves at both ends, water conserved in line when non pressurized
Test pressure	- nominal pressure of emitters, or - pressure mid-range of regulation range of emitters tolerance +/- 20%
Temperature of water	Ambient
Velocity of water at end of line	1 m/s tolerance +/- 20%
Phase duration	50 min (15 + 30 +5)
Duration 1 of line pressurization within cycles	15 min
Duration of line non-pressurization within cycles	30 min
Duration 2 of line pressurization within cycles	5 min
Number phases	8
Concentration of particles suspended in test water	As specified in Table 3
Grain size distribution	As specified in Figure 2
Measurement of emission rate	Individual (25 measurements taken between min 14 and min 15 of each phase) and the average of those
Detection of clogging	The emitter sample is declared clogged when the average of the 25 measurement of emission rate from test sample does not exceed any more 75% of the value of initial average emission rate of the sample
End of test	End of last phase (8) or whenever the average of the 25 measurement of emission rate from test sample does not exceed any more 20% of the value of initial average emission rate of the sample

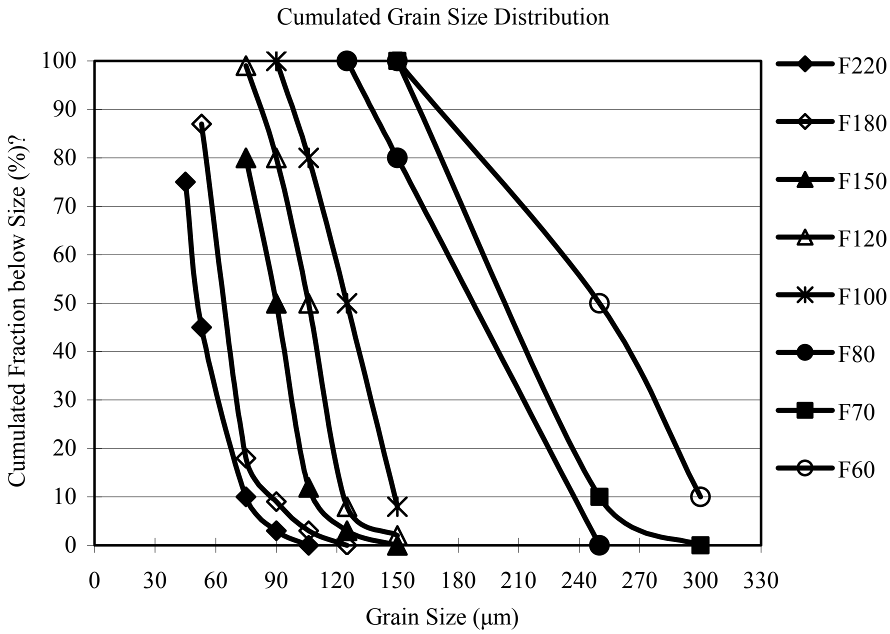


Fig 2: Cumulated grain size distributions curve of Clogging Experiment Stages for sands

Table 3: Specifications for concentration of sands to be employed in the 8 test phases

Sands grain size	F220	F180	F150	F120	F100	F80	F70	F60	Total load Per phase
Phase 1	250ppm								250ppm
Phase 2	250ppm	250ppm							500ppm
Phase 3	250ppm	250ppm	250ppm						750ppm
Phase 4	250ppm	250ppm	250ppm	250ppm					1000ppm
Phase 5	250ppm	250ppm	250ppm	250ppm	250ppm				1250ppm
Phase 6	250ppm	250ppm	250ppm	250ppm	250ppm	250ppm			1500ppm
Phase 7	250ppm	250ppm	250ppm	250ppm	250ppm	250ppm	250ppm		1750ppm
Phase 8	250ppm	250ppm	250ppm	250ppm	250ppm	250ppm	250ppm	250ppm	2000ppm

Data on emitting rates and percentage of clogged drippers for all of the 16 kinds of emitters with time or experimental phase were collected. The clogged drippers percentage at certain phase was calculated dividing the total number of experimental drippers by the clogged drippers. The grain size, which led to initial clogging for a certain kind of emitter, was taken as the index for evaluating the anti-clogging ability. The bigger the grain size, the better anti-clogging ability drippers held.

3 Results and Discussion

The flow passage structure parameters and the flow rate flow state exponent, and flow coefficient and the initial clogging sands size are listed in Table 4.

Table 4: Dripper structure, hydraulic performance, and grain size at initial clogging

Dripper type	θ Dentation angle	B Dentation spacing (mm)	H Dentation height (mm)	D Flow Passage depth (mm)	W Flow passage Width (mm)	A=W•D Cross section area (mm^2)	Q Flow rate at 10m (l/h)	k Discharge coefficient	x Flow state exponent	Grain Size for initial clogging (mm)
1	104°	1.5	1.0	0.6	0.73	0.438	1.49	0.37	0.59	0.09
2	104°	1.8	1.3	0.9	0.87	0.783	2.46	0.88	0.44	0.3
3	104°	2.1	1.6	1.2	1.02	1.224	4.45	1.37	0.51	0.23
4	104°	2.5	1.9	1.5	1.21	1.815	5.85	1.88	0.49	0.35
5	108°	1.5	1.6	1.5	0.71	1.065	3.80	1.09	0.54	0.125
6	108°	1.8	1.9	1.2	0.86	1.032	3.60	1.20	0.48	0.29
7	108°	2.1	1.0	0.9	1.00	0.900	3.57	1.07	0.52	0.28
8	108°	2.5	1.3	0.6	1.20	0.720	2.57	0.86	0.48	0.4
9	112°	1.5	1.9	0.9	0.70	0.630	2.62	0.81	0.51	0.1
10	112°	1.8	1.6	0.6	0.83	0.498	2.10	0.69	0.48	0.12
11	112°	2.1	1.3	1.5	0.97	1.455	6.61	1.96	0.53	0.15
12	112°	2.5	1.0	1.2	1.16	1.392	6.60	2.16	0.48	0.27
13	117°	1.5	1.3	1.2	0.67	0.804	3.54	1.11	0.50	0.095
14	117°	1.8	1.0	1.5	0.80	1.200	4.98	1.71	0.47	0.075
15	117°	2.1	1.9	0.6	0.94	0.564	2.46	0.81	0.49	0.2
16	117°	2.5	1.6	0.9	1.11	0.999	4.21	1.48	0.46	0.25

3.1 Variance Analysis of dental labyrinth drip emitter structure on the flow state exponent x

Statistical analysis for variance was done using SPSS statistical software. The results are shown in Table 5.

Table 5: Variance Analysis results of flow passage parameters on flow state exponent x

Dependent Variable: x

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared
Corrected Model	1.732E-02	12	1.444E-03	2.520	.242	.910
Intercept	3.970	1	3.970	6929.553	.000	1.000
Dentation angle	1.869E-03	3	6.229E-04	1.087	.473	.521
Dentation spacing	1.172E-02	3	3.906E-03	6.818	.075	.872
Dentation height	1.719E-03	3	5.729E-04	1.000	.500	.500
Flow passage Depth	2.019E-03	3	6.729E-04	1.175	.449	.540
Error	1.719E-03	3	5.729E-04			
Total	3.989	16				
Corrected Total	1.904E-02	15				

It is evident that dentation spacing had significant effect on the flow state exponent x at 0.1 levels, Table 5. The significance ranking of flow passage structure parameters on the flow state exponent x is: Dentation space >Depth of flow passage >Dentation angle>Dentation height. The x value at different dentation spacing is shown in Fig.3.

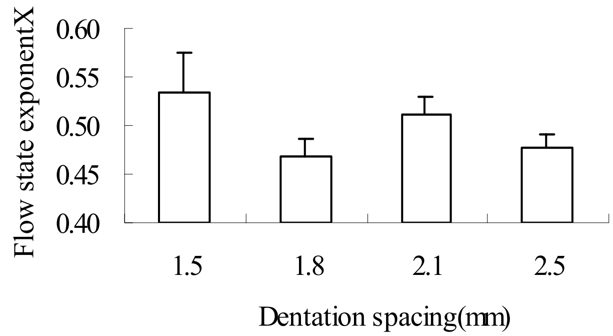


Fig.3 Relationship between dentation spacing and flow state exponent

3.2 Variance Analysis of dental labyrinth drip emitter structure on the flow rate of emitters

Variance analysis results are shown in Table 6.

Table 6: Variance Analysis of flow passage structural parameters on the flow rate of emitters

Dependent Variable: Flow rate Q

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared
Corrected model	36.586	12	3.049	41.982	.005	.994
Intercept	231.877	1	231.877	3192.887	.000	.999
Dentation angle	2.777	3	.926	12.746	.033	.927
Dentation spacing	9.529	3	3.176	43.737	.006	.978
Dentation height	.732	3	.244	3.362	.173	.771
Depth of flow passage	23.548	3	7.849	108.082	.001	.991
Error	.218	3	7.262E-02			
Total	268.681	16				
Corrected Total	36.804	15				

The results obtained show that the depth of flow passage, dentation spacing, and dentation angle had significant effect on the flow rate of emitters at 0.1 levels. The ranking of significance was in the order of depth of flow passage >dentation spacing >dentation angle>dentation height.

3.3 Mathematical regression model

A linear regression model of SPSS software was used to develop relationship of structural parameters of emitters on flow rate. The results are shown in table 7.

Table 7 Linear regression model Summary and regression Coefficients

(a) Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.957	.915	.884	.5324	.915	29.710	4	11	.000

(b) Coefficients

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	-7.510	3.282		-2.288	.043	-14.734	-.286
	Dentation angle	2.250	1.624	.122	1.385	.193	-1.324	5.824
	Dentation interval	2.052	.360	.501	5.703	.000	1.260	2.844
	Dentation height	-.579	.397	-.128	-1.459	.172	-1.453	.294
	Depth of flow passage	3.599	.397	.796	9.070	.000	2.726	4.473

Dependent Variable: Q

The linear model describing the relationship between flow rate, Q, and structural parameters of flow passage under the present condition of flow passage length (19.4mm) and at 10m working pressure,

$$Q = -7.510 + 2.250\theta + 2.052B - 0.579H + 3.599D \qquad (1)$$

Where, Q is flow rate of emitters (L/h), θ is dentation angle (in radian unit), B is dentation spacing (mm), H is dentation height (mm), D is depth of flow passage (mm).

The R^2 value of 0.915 (Table 7, model summary) indicates that this model may be used in assisting the design of emitters.

3.4 The relationship between cross-section area and flow rate Q

The relationship of width of flow passage W with dentation height H, dentation spacing B, and dentation angle θ could be expressed by the following equation (see Fig.4):

$$W = [(\frac{B}{2} + H\text{ctg}\theta)^2 + H^2]^{1/2} \text{Sin}\left(\theta - arc\text{ctg}\frac{B/2 + H\text{ctg}\theta}{H} \right) \qquad (2)$$

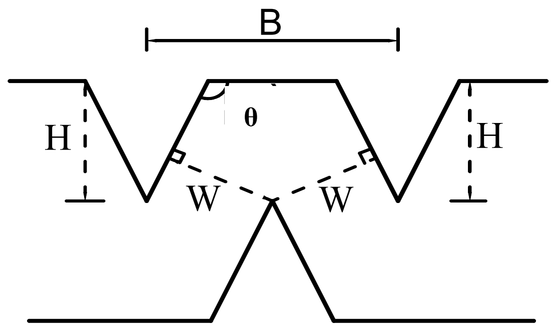


Figure 4: The relationship of flow passage width with dentation height, dentation spacing and dentation angle

Cross-section area of flow passage (A) = Depth of flow passage (D)× width of flow passage (W).

The cross section area of the emitter flow passage and flow rate Q at 10 m pressure are presented in Table 4. Using regression model the relationship between flow rate and cross-section area of flow passage was obtained as,

$$Q = 3.9A \qquad (3)$$

Where, A is cross-section area of flow passage (mm^2)
The plot of regression model is given in Fig. 5. The correlation coefficient R^2 of the equation is 0.91.

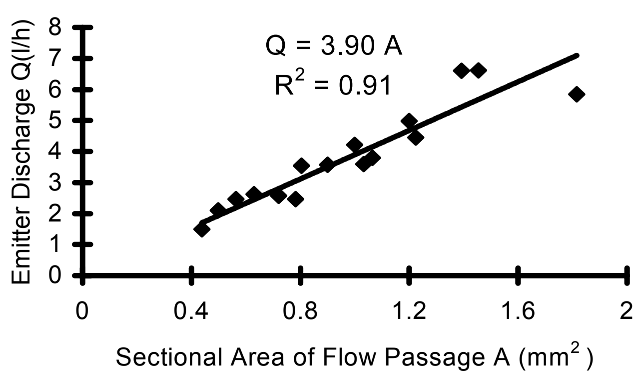


Figure 5: The relationship between cross-section area of passage and flow rate of emitters

3.5 The influence of flow passage structure parameters on the anti-clogging ability of emitters

3.5.1. Progression of emitting rate of drippers and clogged percentage with the increment of experimental phase

Four representative curves to show the progression of flow emitting rate with the increment of experimental phase for dripper 1, 8, 13 and 14 are presented in Fig.6.

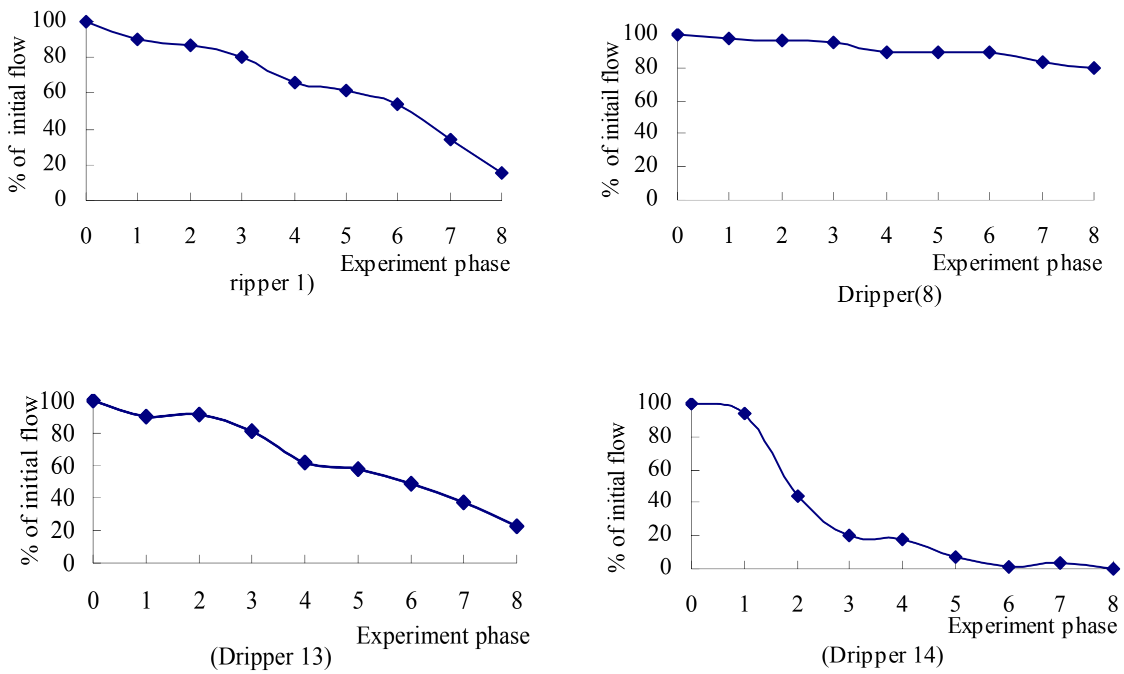


Figure 6: The progression of emitting rate with incremental experiment phase

Representative four curves to show progressive percentage of clogging with the increment of experiment phase are presented in Fig. 7. The emitter sample is declared clogged when the average of the 25 measurements of emission rate from test sample does not exceed any more 75% of the value of initial average emission rate of the sample.

The percentage of clogged drippers at any experimental phase may be calculated by dividing the number of clogged drippers by the total number of each dripper type in the test. Results shown in Fig. 7 indicate that dripper #1 and dripper #13 were gradually getting clogged whereas the dripper #14 was clogged to 60 percent at experiment phase 2. Dripper #8 remained unclogged till the end of experiment and displayed a good ability of anti-clogging.

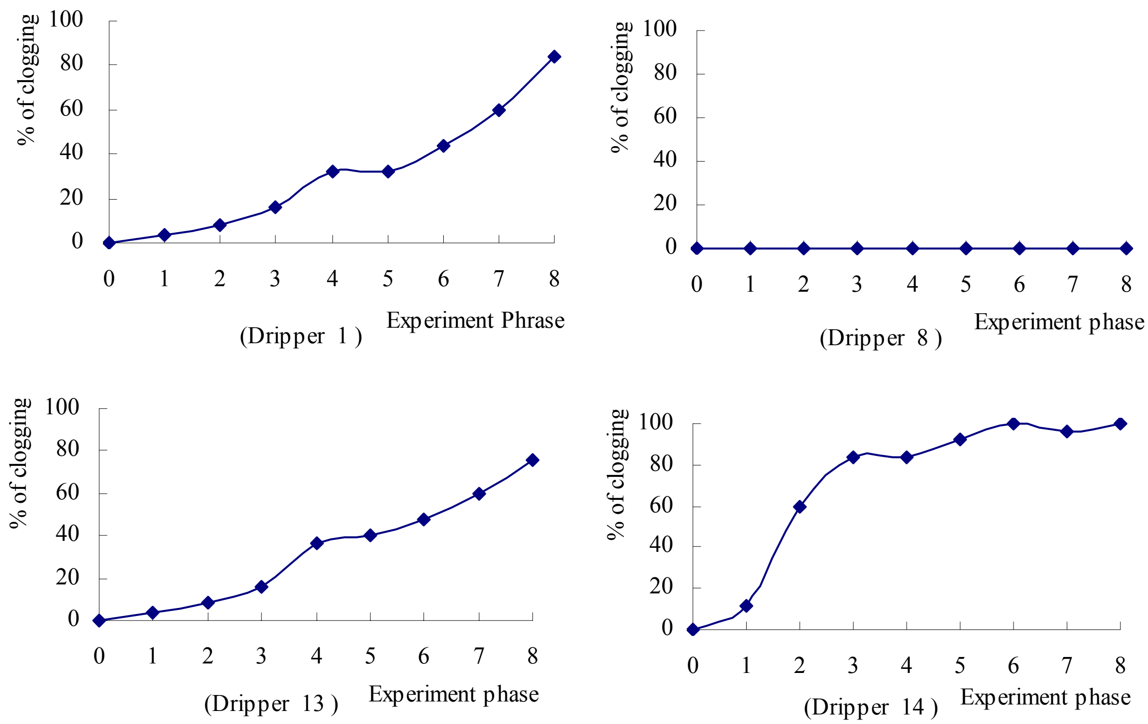


Figure 7: The progression of clogged drippers with experimental phase.

3.5.2 Variance Analysis for particle size interaction with emitter structure parameters

Variance Analysis results for particle size interaction as an indicator for ant-clogging ability of drip emitter is presented in Table 8.

Table 8: Variance Analysis of flow passage structure parameters on sand size for initial clogging

Dependent Variable: sand size for initial clogging

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared
Corrected Model	.156	12	1.298E-02	20.572	.015	.988
Intercept	.691	1	.691	1095.520	.000	.997
Dentation angle	4.250E-02	3	1.417E-02	22.463	.015	.957
Dentation spacing	9.323E-02	3	3.108E-02	49.271	.005	.980
Dentation height	1.239E-02	3	4.131E-03	6.549	.079	.868
Flow passage depth	7.580E-03	3	2.527E-03	4.006	.142	.800
Error	1.892E-03	3	6.307E-04			
Total	.849	16				
Corrected Total	.158	15				

Results from variance analysis (Table 8) indicate that dentation spacing, dentation angle, and dentation height had significant effect on the anti-clogging ability of drippers at levels of 0.1. The significance ranking of flow passage structure parameters on the anti-clogging ability of drippers is: Dentation spacing > Dentation angle > Dentation height > Depth of flow passage.

3.5.3. Relationship between flow rate and anti-clogging ability of drippers

Common perception may be that drippers with higher flow rate have good ability of delivering sands and thus should hold better anti-clogging performance. However, the present experiment results did not fully support the viewpoint. Plotting of the data in Fig. 8 show that the anti-clogging ability of drippers was not fully enhanced with the increase of flow rate. Similarly, results of this study failed to show a linear relationship between cross-section area of flow passage and anti-clogging ability of dental labyrinth turbulent drippers, Fig. 9. This may indicate that the tortuous path geometry is more important than the cross-section area.

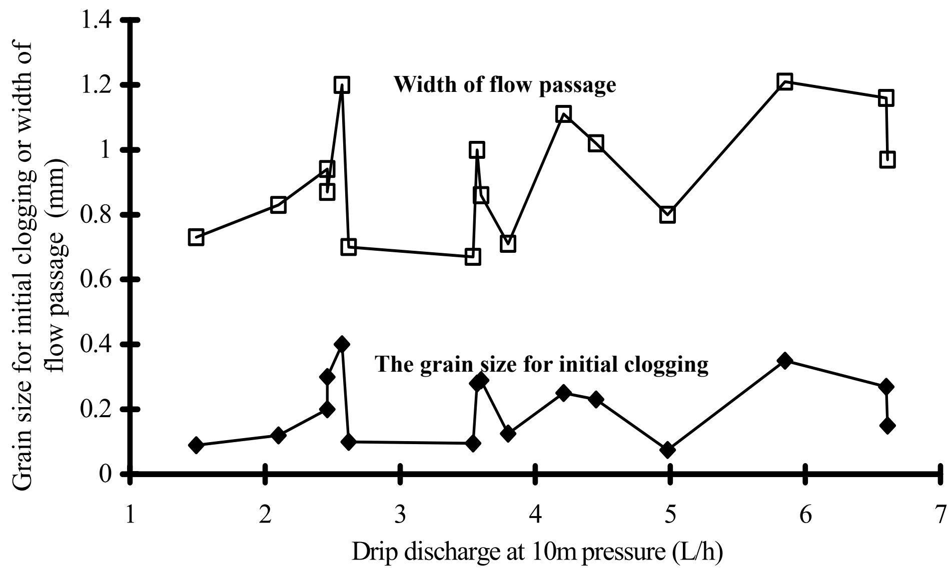


Fig. 8: Relationship of drip flow rate to width of flow passage or grain size for initial clogging

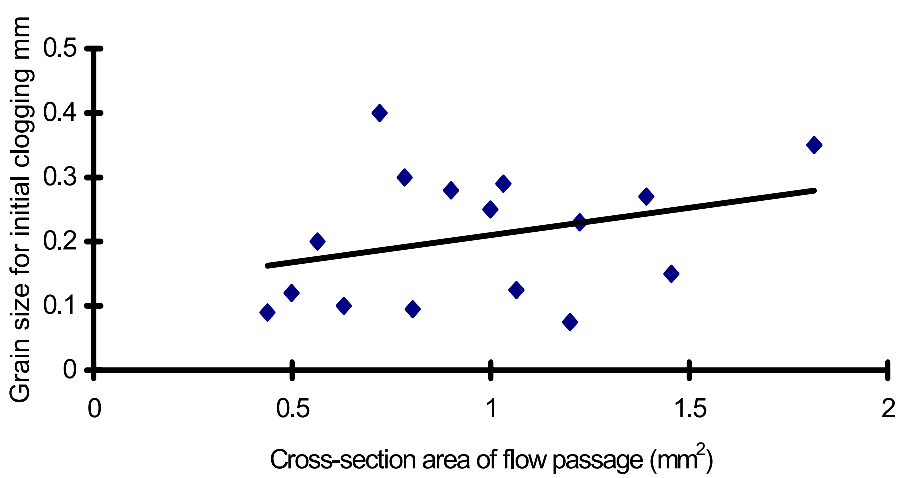


Fig 9: Relationship between cross-section area of flow passage and grain size at initial clogging

3.5.4 Relationship between depth of flow passage and anti-clogging ability of drippers

The experiment results failed to show any clear relationship between the depth of the emitter to grain size for initial clogging, Fig. 10. As mentioned above the labyrinth pathway geometry predominantly determined by dental spacing, angle, width, and dental height may contribute to how the particles move.

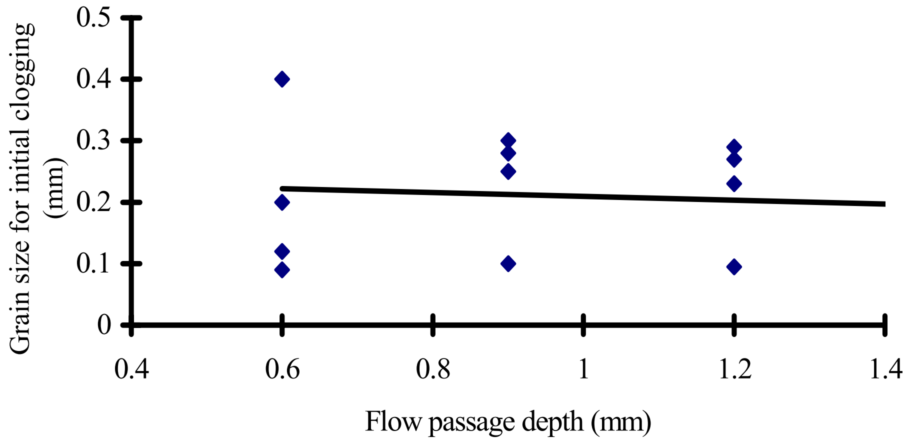


Fig 10: Relationship between flow passage depth to grain size for initial clogging

We observed that the width of all 16 kinds of drippers when plotted against the size of sand grain for initial clogging they produce a mirror image, Fig. 8, indicating a relationship of emitter width to initial grain size for clogging. This relationship is clearer when grain size of initial clogging is plotted against width of flow passage of emitter, Fig. 11. The dashed line in Figure 11 indicates that when the width of flow passage is between 0.6 - 0.8mm, there appears to be very little difference in anti-clogging ability for drippers. However, it changes to a more or less linear relationship as the width of flow passage goes above 0.8 mm.

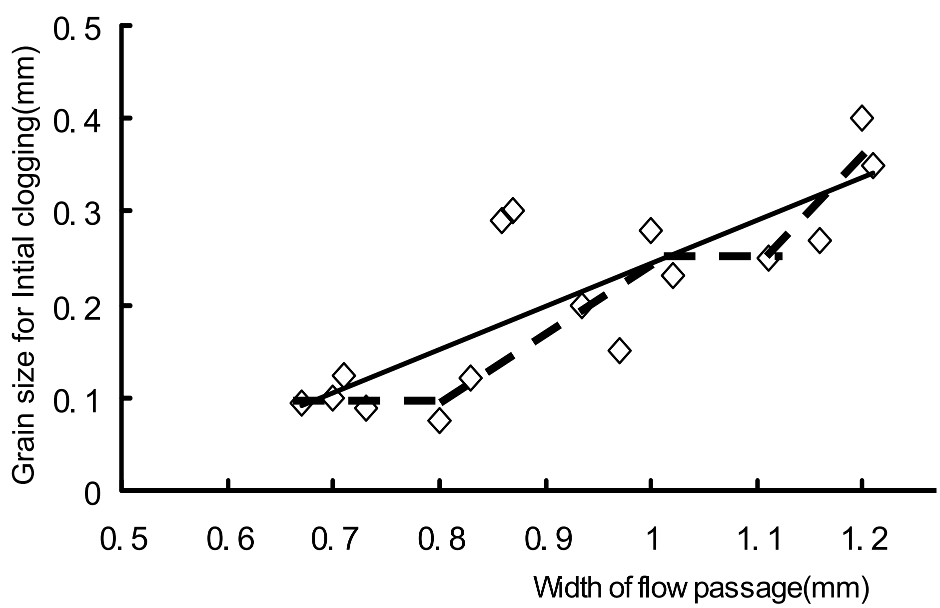


Fig 11 Width of flow passage and grain size for initial clogging

3.5.5 Relationship between the size of flow passage width and the filtering size

Figure 12 shows a graphical plotting of $1/7^{th}$ and $1/10^{th}$ of the width of flow passage opening of filter screen and the grain size that caused initial clogging. Most of the grains that caused initial clogging would be removed before it reaches the emitter.

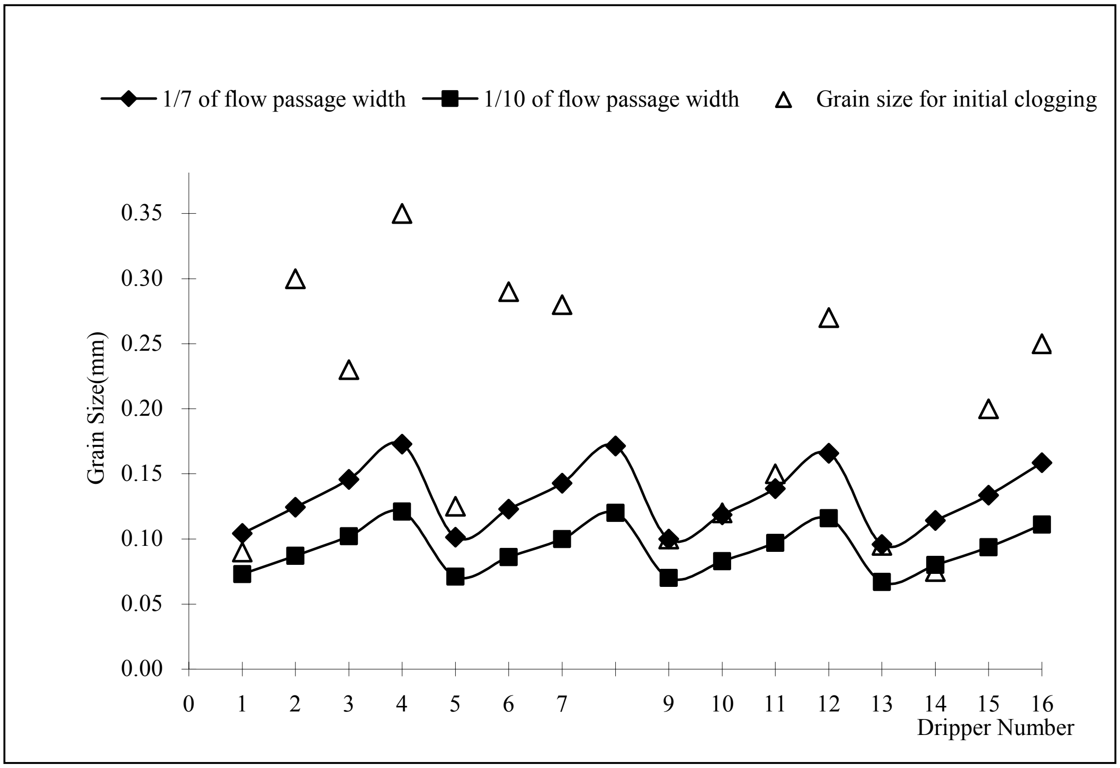


Figure 12 shows a plotting of filter screen opening sizes at $1/7^{th}$ and $1/10^{th}$ of the emitter flow path width and the sizes of the grains that caused for initial clogging

4. Conclusions

1. Dentation spacing of labyrinth pathway of emitter was significant for flow state exponent x. The ranking of significance for the flow state exponent x according to this study is: Dentation spacing >depth of flow passage >dentation angle>dentation height.
2. Depth of flow passage, dentation spacing, and dentation angle had significant effect on the flow rate of emitters.
3. The flow rate of 19.4 mm dental labyrinth drip emitter may be obtained from the linear prediction line, $Q = 3.9 A$, where, Q is in L/H and A is cross sectional area. For the same emitter length the emitter design may be assisted by the equation $Q = -7.51 + 2.25\theta + 2.052B - 0.579H + 3.59D$, where θ = dentation angle, B = dentation space, H = dentation height, and D = flow passage depth.
4. Dentation spacing, dentation angle, dentation height had significant effect on the anti-clogging ability of drippers.
5. The chance of drippers plugged by sand particles was small if the openings of screen filters were selected according to the rule of $1/10^{th}$ of the size of the width of flow passage.
6. More study is needed to evaluate the effect of flow passage depth on anti-clogging property of the emitter.

Acknowledgements:

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Hydraulic and Chemical Properties of Soils Irrigated with Recycled Saline Sodic Drainage Water

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Abstract:

Irrigation with saline-sodic water affects soil physical properties. Knowing the effect of the soil chemical properties on soil water retention and hydraulic conductivity at various depths will lead to better management practices for soils irrigated with recycled drainage water.

Research in San Joaquin Valley (SJV), California, is addressing needs to reduce irrigation volumes and drainage. Fresh water demands have increased and saline irrigation water sources will be used to a greater extent. The objectives of this study are to determine the hydraulic conductivity and soil water characteristics of soils irrigated with recycled saline-sodic drainage water for the eventual use of these parameters in irrigation management models. This study will assist in development of these parameters.

Soils from Red Rock Ranch, west side SJV, were collected from areas with fresh-water and recycled drainage water irrigation to determine saturated conductivity and water retention characteristics. Irrigation water salinity ranges (EC) are < 1 dS/m to ~ 13 dS/m. Soils textures- clay loams. Soil salinity (ECe) was <2.4 dS/m to >50 dS/m and SAR was 8.6 to 85.4. The saturated flow rates (Ks) ranged from 1.02×10^{-3} to 7.58×10^{-7} cm per second.

Introduction:

Saline-sodic irrigation water with ECe > 4.0 dS/m and SAR of 13 or higher can degrade soil structure at pH of 7.8 to 8.5, and thereby reduce the rate at which water enters the soil (infiltration) and percolates through it (hydraulic conductivity). The extent to which soil electrical conductivity (EC) and sodium adsorption ratio (SAR) affects water infiltration into soil, depends on other chemical properties (calcium and organic matter contents), texture, and depth.

Current research conducted in agricultural areas in California, such as in the Imperial and San Joaquin Valley's, are aimed at reducing the volume of irrigation water applied and subsurface drainage by encouraging crop utilization of shallow groundwater, while still maximizing yields in salt affected soils. Soil salinity, shallow saline groundwater, and drainage water disposal all pose major challenges to agriculture on the west side of the San Joaquin Valley (SJV) (San Joaquin Valley Drainage

Implementation Program, 1998 and 1999). These soil constraints reduce yields and profitability, and they limit crop choices. Farmers are looking at management practices that will allow the production of agronomic crops utilizing low quality irrigation waters. The increased demands for fresh water is growing steadily in arid regions and it is likely that saline irrigation water sources will be used to a greater extent. Current infiltration models lack variables that account for different management practices. A study to provide expected infiltration rates for soils as affected by saline-sodic irrigation water management practices would prove valuable to on-going and future research. Refining the management of soils that are being irrigated with saline-sodic water is essential for the sustainability of agriculture on the Westside San Joaquin Valley.

The long-term benefits to alternative irrigation practices are to maintain soil structure and yields, while reducing erosion and the accumulation of salts in the soil. These strategies are needed to feed the growing masses and provide farmers and urban areas plenty of water for sustainability.

Research Objectives:

The objectives of this study are to determine the hydraulic conductivity and soil water characteristics of soils irrigated with recycled saline-sodic drainage water for the eventual use of these parameters in irrigation management models. If a correlation can be found, the results would give researchers and farmers current information on how to best manage their irrigations to optimize irrigation efficiency, maintain adequate soil structure, and reduce the volume of drainage below the crop root zone.

Materials and Methods:

Soils were selected from the west side San Joaquin Valley, California at Red Rock Ranch (RRR) in Five Points (Figure 1). In 1996, an Integrated on-Farm Drainage Management (IFDM) system was developed as a demonstration project at the Red Rock Ranch (RRR) out on the Westside SJV. For the past four years, one focus of our research at the RRR IFDM demonstration project has been the soil characterization of fields at the RRR. The site is a sequential reuse irrigation system with EC and SAR values that steadily increase in each stage. Soils were taken from a fresh-water irrigated area (Stage 1) and from each subsequent area that has been irrigated for seven years with recycled drainage water (Stages 2-4). Irrigation water salinity in Stage 1 is generally less than 1 dS/m and in Stage 4 it averages about 13 to 14 dS/m. Hand augers and a mechanized hydraulic corer, Giddings Rig, were utilized to collect core samples to a 120 cm depth at 30-cm increments.

Texture, pH, EC, and SAR analysis were conducted on samples from all locations and depths. Saturated hydraulic conductivity (Ks), water retention, gravimetric/ volumetric water content, and bulk density were also determined for these samples. Column samples were assessed for saturated hydraulic conductivity using a constant head soil core method (Reynolds and Elrick, 2002). Pressure plate chambers were utilized to simulate the drying out of the soil (de Jong, 1993). Initial readings at saturation were taken as well as readings from field capacity to wilting point.

Results:

Soil textures were mainly clay loams. Soil salinity (ECe) was less than 2.4 dS/m in Stage 1 to greater than 50 dS/m in Stage 4 (Table 1) and SAR was 8.6 and 85.4 for Stages 1 and 4, respectively. The natural process of salts accumulation in irrigated agriculture was evident in Stage 1 at the onset with such high EC and SAR values. Many cash crops can not tolerate these levels and severely hampers crop choice for valley farmers. The saturated flow rates (Ks) varied greatly with values ranging from 1.02 X 10^{-3} in stage 1 to 7.58 X 10^{-7} cm per second in stage 4 (Figure 2). As the soils become increasingly saline/ sodic, the water flow rates slow progressively from Stage 1 to Stage 4. Soil structure is compromised and deflocculating of the colloids occurs to the extent that Stage 4 often has extended periods of ponding and field capacity water levels for several days to weeks after rainy conditions (Buckland et al., 2002).

<u>Conclusions:</u>

Soil water retention and hydraulic conductivity rates vary with time, soil type, texture, rate of application, and the degree to which the soil has salinized and/or become sodic. The sodium cation along with the SAR, are the two factors which largely influence the hydraulic conductivity and degree to which the soil colloids are dispersed (Nielsen, 1986). Increased EC and SAR values in each sequential stage produced decreased hydraulic conductivity and water retention and a correlation needs to be established. Researchers in the past have not clearly defined the degree to which infiltration and hydraulic conductivity may be reduced in saline-sodic soils in the SJV. This is another attempt to add to the accumulation of knowledge on the subject. It is known, however, that variability in infiltration rates in a field will strongly influence the performance and management of surface irrigation systems. Much more must still be done to protect our soil and water resources from the dangers of salt loading and drainage water disposal issues.

For fields irrigated with saline-sodic irrigation water, there exists small scale and localized variability in hydraulic conductivity and hydraulic properties. Characterization of these properties is essential for better understanding of flow and solute transport.

<u>Future Work:</u>

- This data can then be used to determine infiltration rates which in turn, will then be correlated with the soil's physical and chemical characteristics.
- Water retention curve and saturated hydraulic conductivity Ks value may be evaluated to assess water flow and solute transport at the site, RRR.
- Data collected with the pressure plate apparatus will be used to predict the hydraulic parameters for the empirical equations soil water retention curves described by van Genuchten, (1980). For this purpose, we intend to use the non-linear least squares optimization program, RETC, available from the USDA Soil Salinity Laboratory in Riverside, CA.
- SWR curves are then correlated with soil salinity at the varying depths for each of the four fields in the project, e.g. ECe and SAR.
- Complete a regression analysis of established Ks values with those predicted by the same parameters in the RETC program.

Red Rock Ranch IFDM
Sequential Re-use, 4 stages (640 acres, 260 ha)

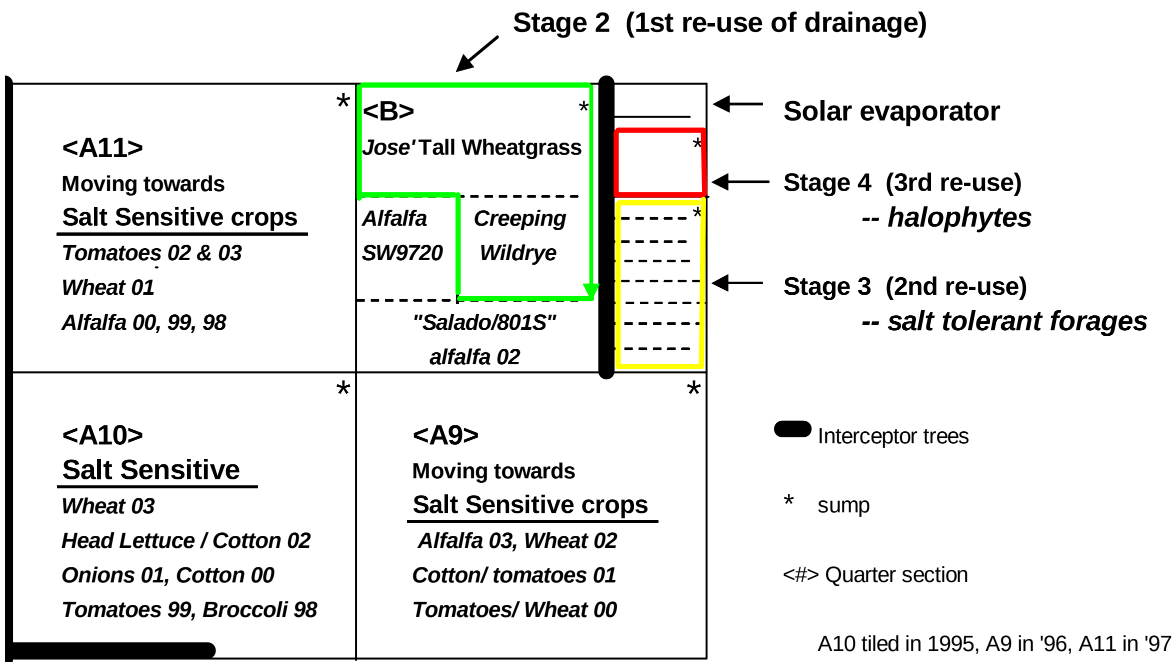

Figure 1. A map of Red Rock Ranch on the Westside of the San Joaquin Valley in Five Points, California. Fields A9, A10 and A11 (Stage 1) receive fresh water irrigation. Tile drains collect the drainage water from each field for its use in each subsequent stage.

Table 1. Average pH, EC and SAR with standard error.

Field Location	Depth (cm)	pH	ECe (ds/m)	SAR
A	30	7.3	3.61	17.98
Stage 1		0.04	1.01	1.64
A	90	7.6	7.05	21.05
Stage 1		0.13	1.88	2.10
B	30	7.4	15.50	26.23
Stage 2		0.13	2.80	5.11
B	90	7.5	18.05	33.38
Stage 2		0.20	0.71	2.79
C	30	7.3	20.34	34.50
Stage 3		0.14	1.41	1.14
C	90	7.2	18.14	29.11
Stage 3		0.13	1.59	4.98
D	30	8.4	35.88	76.10
Stage 4		0.05	4.18	2.51
D	90	8.3	27.88	49.03
Stage 4		0.16	0.79	5.70

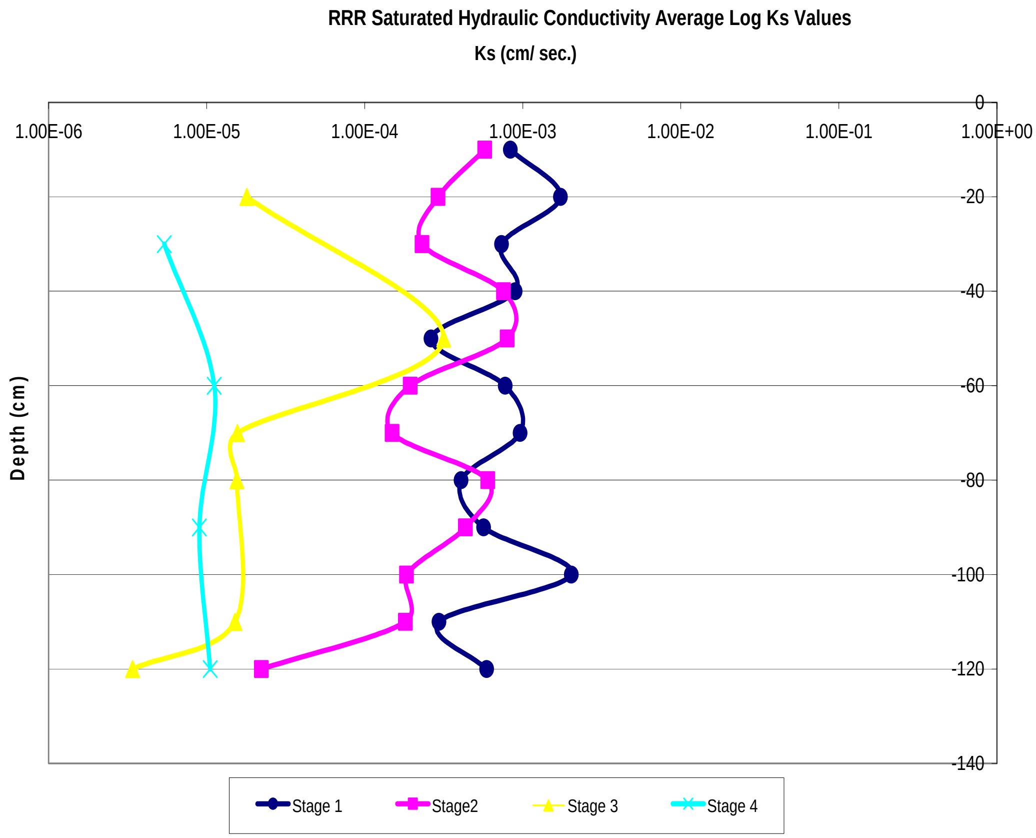

Figure 2. Log Ks changes over all four stages.

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Management Model for Land Application of Wastewater
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Abstract

Applying wastewater to land for remediation has been recommended by the Environmental Protection Agency (EPA) as a method to recycle nutrient and organic matter and conserve water resources. Small communities are selecting primary treatment using a lagoon treatment system and land application as the most cost-effective way of treating municipal wastewater. Managers must balance the irrigation requirements of the vegetation receiving the treated wastewater against the risk of groundwater contamination with nitrogen and against the risk of salinized soils that would effectively kill the biological system. The objective of the research was to develop a water-nitrogen balance irrigation-scheduling model that could be used to schedule irrigation for land application of wastewater from a lagoon treatment system to prevent contamination of the ground water.

The City of Las Cruces constructed a lagoon wastewater treatment plant that has a permit to process 1,500 m^3/d of pretreated industrial wastewater and domestic wastewater from the West Mesa Industrial Park (WMIP). The land application site is a Chahuahuan desert ecosystem where the predominant vegetation consists of winter annuals of flixweed (*Descurainia sophia*)and pinnate tansy mustard (*Descurainia pinnata*), perennials of narrowleaf peppergrass or pepperweed (*Lepidium latifolium*), and shrubs of creosote (*Larrea tridentata*) and mesquite (*Prosopis glandulosa*) The sprinkler system used to apply the wastewater is a fixed system with Senninger #3012-1-3/4 emitters operating at a pressure 310 kPa and a flow 18 l/m. The spacing down the laterals and between laterals is 12 m.

The irrigation scheduling model calculates evapotranspiration (ET) from a volume balance soil water model that reduces potential evapotranspiration by a crop coefficient scaling factor and a soil moisture stress function determined by the plant available water in the soil profile. The model runs on a daily time step. The model predicted 32 kg/ha nitrogen leaching under the creosote plants which occurred in two events where irrigation was over applied. During the rest of the growing season no nitrogen was leach. Nitrogen leaching below the root zone of mesquite was not calculated.
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Introduction

Applying wastewater to land for remediation has been recommended by the Environmental Protection Agency (EPA) as a method to recycle nutrient and organic matter and conserve water resources. The level of treatment prior to land application (LA) can range from primary treatment using a lagoon to tertiary treatment using standard wastewater treatment facilities. Land application systems that utilize the land as a treatment unit and not just as a disposal area are gaining acceptance in many arid regions. Small communities are selecting primary treatment and land application as the most cost-effective way of treating municipal wastewater. In a LA system, wastewater has been applied to crops, rangelands, forests, and recreation areas, including parks and golf courses, and to disturb lands, such as mine spoil sites (Sopper and Kardos, 1973; Sopper et al., 1982; Bastian and Ryan, 1986; Luecke and De La Parra, 1994). These systems are cheaper to construct and can be operated by personnel with familiarity with common irrigation systems.

The soil and plants act as filters that trap and treat, through various mechanisms, contaminants in the wastewater and allow the treated wastewater (effluent) to drain through the soil profile (Watanabe, 1997). The wastewater provides an effective source of nutrients that the vegetation roots assimilate. The net effect is a beneficial system allowing for both the effective remediation of wastes and the recycling of water, nutrients, and carbon via biomass production (Bastian, 1986). However, the effects of continuous irrigation with sewage effluent on soil and leachate water quality need to be evaluated. As the wastewater infiltrates and moves through the soil profile, waste particles are trapped by the soil. Managing the quantity and frequency of waste loading will permit adequate soil drying, thereby avoiding soil clogging, which can result in anaerobosis (Thomas, 1973). The chemical nature of the soil environment is critical to the reactions necessary for waste remediation. Applying organic matter at appropriate, controlled rates, coupled with the proper soil-water-air environment, results in increased microbial activity and subsequent decomposition of compounds found in the wastewater. Even though LA systems are conventional technology approved by the EPA for many communities, there is little information to guide land managers in arid and semi-arid environments where the wastewater may be the only source of supplemental water. Managers must balance the irrigation requirements of the vegetation against the risk of groundwater contamination with nitrogen and against the risk of salinized soils that would effectively kill the biological system. Light, frequent irrigation can increase surface soil salinity that can limit crop production. On the other hand, over-irrigation can carry nitrate-nitrogen to the groundwater.

The objective of the research was to develop a desert ecosystem irrigation scheduling water balance model that could be used to schedule irrigation for land application of wastewater from a lagoon treatment system to prevent contamination of the ground water.

Description of Wastewater Permit

The City of Las Cruces constructed a lagoon wastewater treatment plant that has a permit to process 1,500 m^3/d of pretreated industrial wastewater and domestic wastewater from the West Mesa Industrial Park (WMIP). The facility is located approximately 4 km west of Las Cruces in Section 2, T24S, R1W, and Section 35, T23S, R1W, Dona Ana County. The West Mesa Industrial Park collects and sends the wastewater to one of two treatment trains, each consisting of a manual bar screen and sewage grinder, two synthetically lined mixing basins (in series), and a synthetically lined holding pond. The wastewater is then land applied to 32 ha with a fixed head sprinkler system. Ground water below the site is at a depth of approximately 100 m. The land application site is a Chahuahuan desert ecosystem where the predominant vegetation consists of winter annuals of flixweed (*Descurainia sophia*)and pinnate tansy mustard (*Descurainia pinnata*), perennials of narrowleaf peppergrass or pepperweed (*Lepidium latifolium*), and shrubs of creosote (*Larrea tridentata*) and mesquite (*Prosopis glandulosa*)

The permit for the land application of the wastewater states that the wastewater application will be conducted so that nitrogen loading will not exceed 25% of the maximum amount of nitrogen expected to be taken up by the existing native vegetation.

Theory of wastewater allowable hydraulic loading rate design (English Units)

The yearly wastewater application rate (Lw(p)) needed in the design of the wastewater irrigation system and the amount NO_3^--N loading to groundwater that will occur using this design can be determined based on the yearly water and nitrogen mass balance equations reported in the design approaches outlined by Metcalf and Eddy, Inc (1990) and WCPF (1989).

The hydraulic loading based on water balance equation is:

$$Lw(p) = ET - Pr + Wp \quad \text{[Eq.1]}$$

where:

Lw(p) = Wastewater hydraulic loading rate (m/yr) , the volume of wastewater applied per unit area of land per unit time.

ET = Design evapotranspiration rate (m/yr)

Pr = Design precipitation rate (m/yr)

Wp = Design percolation rate (m/yr).

The wastewater nitrogen loading to ground water based on the nitrogen mass balance equation is:

$$Ln = U + D + 10\ Wp\ Cp \quad \text{[Eq. 2]}$$

where:

Ln = Wastewater nitrogen loading (kg/ha/yr)

U = Crop nitrogen uptake (kg/ha/yr)

D = Denitrification (kg/ha/yr)

Wp = Percolating water (m/yr)

Cp = Percolate nitrogen concentration (mg/L).

The wastewater nitrogen loading (kg/ha/yr) is calculated from:

$$Ln = 10\ Lw\ Cn \quad \text{[Eq.3]}$$

where:

Lw = Wastewater applied (m/yr)

Cn = total nitrogen in applied wastewater (mg/L).

Solve for Wp in Eq. 2 yields:

$$Wp = (Ln - U - D)/\ 10\ Cp.$$

Substitute the Wp term in Eq. 1 yields:

$$Lw = ET - Pr + (Ln - U - D)/10\ Cp \quad \text{[Eq. 4]}$$

The fraction of applied nitrogen removed by nitrification and volatilization (F) can be expressed as:

$$F = D/Ln \quad \text{[Eq. 5]}$$

where:

Ln = Wastewater nitrogen loading (kg/ha/yr)

D= Denitrification (kg/ha/yr).

Solve for D in Eq. 5 and substitute in Eq. 4 yields:

$D = F\ Ln$

$Lw = ET – Pr + (Ln – U – F\ Ln)/10\ Cp$ ………………………….[Eq. 6]

Insert Eq. 3 into Eq. 6 yields

$Lw = ET – Pr + (10\ Lw\ Cn – U – (10\ F\ Lw\ Cn)/10\ Cp$ …………. [Eq. 7]

Simplify Eq. 7:

$Lw = (ET – Pr) + [10\ Lw\ Cn\ (1 – F) – U\ ]/10\ Cp$

$10\ Lw\ Cp = 2.7\ Cp\ (ET – Pr) + 10\ Lw\ Cn\ (1-F) – U$

$10\ Lw\ Cp - 10\ Lw\ Cn\ (1-F) = 10\ Cp\ (ET – Pr) – U$

$10\ Lw\ (Cp - Cn\ (1-F) = 10\ Cp\ (ET – Pr) – U$

$Lw\ (Cp - Cn\ (1-F) = Cp\ (ET – Pr) – U/10$

$Lw\ (Cp - Cn\ (1-F) = Cp\ (ET – Pr) – U/10$

$Lw = [Cp\ (ET – Pr) – U/10] / (Cp – Cn\ (1-F))$…………………….…. [Eq. 8]

Express the unit of Lw in mm/yr and multiply Eq. 8 by '–1' yields:

$Lw = [Cp\ (Pr - ET) + 100\ U] / (Cn\ (1-F)-Cp)$ ………………………[Eq. 9]

The amount of nitrogen taken up by the tree (U) can be expressed in terms of the evapotrnspiration production function and the nitrogen concentration in plant tissues [Cc] in (%):

$U = (a+ b\ ET)\ Cc$ ……………………………………………………[Eq. 10]

Plug Eq. 10 into Eq. 9 yields:

$Lw = [Cp\ (Pr - ET) + (100\ (a+ b\ ET)\ Cc)] / (Cn\ (1-F)-Cp)$ ……….. [Eq. 11]

where:

Lw = allowable hydraulic loading rate (mm/yr)
ET = design ET rate (mm/yr)
Pr = design precipitation rate (mm/yr)
Cp = total nitrogen in percolating water (mg/L)
Cn = total nitrogen in applied wastewater (mg/L)
Cc = nitrogen concentration in plant tissues (%).
a = intercept of the Evapotanspiration production function (kg/ha)
b = slope of the Evapotanspiration production function (kg/ha/mm)
F = fraction of applied total nitrogen removed by denitrification and volatilization. This fraction will be assumed to be 20%.
100 = conversion factor (unitless).

After the irrigation design criteria are determined from Equation 11, then BMPs and operational models should be developed to implement the design criteria on an operational basis. For the original design equation one must know the water production function for the desert species. For the daily operational models, one must know the climate, soils, and vegetation characteristics of the site. The design model assumes that sufficient water is available from the logon treatment system to not limit plant growth and that nitrogen is also not limiting. Consequently, the hydraulic loading always exceeds the ET of the vegetation when solving equation 11, and if sufficient nitrogen is not applied for plant growth by the wastewater then nitrogen is available from the soil nitrogen pool to make up the difference. The design model also assumes that mineralization is not occurring to generate nitrogen for plant uptake or leaching. The operational model does not make these assumptions.

Description of the Irrigation-Scheduling Biomass Model.

A volume balance model served as the water balance component of the irrigation-scheduling model. Et was determined by using climate data to calculate a reference evapotranspiration (Eto) and a crop coefficient (Kc) for each major vegetation type (Sammis 2004). Crop coefficients for each vegetation type were estimated from the literature for mesquite (Levitt et al 1995) and a separate pot experiment for creosote plants (Saucedo et al 2004). The calculated non-stressed Et for each vegetation type was reduced by a water stress function, which was a function of the proportional available water in the root zone (Abdul-Jabbar et al. 1984). The linear water stress function has an intercept of zero and a slope of 2, yielding a water stress factor of 1 obtained at 50% of allowable soil water depletion. Consequently, for a management allowable depletion greater than 50%, the plant will be under water stress.

Other inputs to the model include maximum rooting depth, root growth rate coefficient, and water holding capacity of the soil and a leaf area density function that reduces Et by the percentage change in leaf area index in the field compared to the leaf area index of the non-stressed plants.

The model, which is a one-dimensional model, calculated the total water balance including the deep drainage, and changes in soil moisture due to irrigation and rainfall as inputs and evapotranspiration as output of the soil profile.

Biomass

Daily net dry matter gain per plant (DM) is estimated as the product of Et and water use efficiency (WUE). The allocation of DM is modeled to leaves, then to reproduction, and lastly to branches and the trunk. The leaf area per tree (m^2 $tree^{-1}$) is modeled by multiplying the total leaf biomass per tree by the specific leaf area, SLA (m^2 kg^{-1}). The plant diameter (mm) and height (m) are modeled by converting trunk biomass to volume based on the wood density and then solving for the tree size with the calculated volume of a cone, and tree radius to height ratio specified as an input parameter. Critical growth stages, expressed in terms of thermal time (i.e. cumulative growing degree days), are used to control seasonal growth duration of each organ in the model.

Nitrogen Dynamics

Because plant growth is significantly affected by nitrogen availability, a nitrogen balance component was added to the existing plant model and a nitrogen stress coefficient was used to adjust the WUE and, consequently, daily dry matter gain. Details of the soil temperature and nitrogen dynamics modules are given by Asare (1990). The inputs for the nitrogen object are initial organic nitrogen, ammonia, and nitrate-nitrogen in the top 30 cm of the root zone and the amount of each component in the rest of the root zone. Also, a denitrification rate coefficient is specified. The fraction of nitrogen in the leaves, branches and reproductive organs for nitrate uptake calculations are also specified as input. The nitrogen-nitrate stress function (NS) is a scaling function from 0 to 1 and is described by eq. 12:

NS=IF(N >nstress,1,((N)^nstress/((nstress/2)^12+(N)^nstress))) ……….[Eq.12]

Where N = The average nitrogen level in the soil water in the root zone in mg N/kg H_20

Nstress= Nitrogen level at which nitrogen limited Et and growth mgN/kg H_20. This variable is an input to the model.

This is a sigmoid type function where the nstress level was set to 12 for creosote. Consequently, the nitrogen stress function starts to decrease Et at a N value of 12 mg N/kg H_20 and has a value of less than 0.01 when N reaches 4 mg N/kg H_20.

The nitrogen subroutine was not use in the mesquite runs because mesquite fixes its own nitrogen and so nitrogen was not a limiting factor. Nitrogen will be taken up by mesquite the same as alfalfa until it becomes a limiting factor, and the plant will then generate its own nitrogen by symbiotic nitrogen fixation.

Model Runs

Currently, the model has to be run separately for each major vegetation type. To minimize nitrogen leaching required by the permit, the vegetation type that has the least nitrogen movement below the root should be used to schedule the irrigation during that time period. The yearly water application rate should not exceed that calculated by equation 11. The over all growth for the desert site is the growth of each individual model run weighted by the percent area of the vegetation type for that model run. The same approach is used to get the weighted evapotranspiration from the site.

Material and Methods

The sprinkler system used to apply the wastewater is a fixed system with Senninger #3012-1-3/4 emitters operating at a pressure 310 k Pa and a flow 18 l/m. The spacing down the laterals is 12 m and the spacing between laterals 12 m. The number of sprinklers per line is 18 and the irrigation rate of the sprinklers is 0.75 cm/h. The irrigation controller program operates 1 to 3 lines at once. The research plot is located between sprinkler line 21 and 19. The irrigation controller was programmed to turn on A19, A20, and A21 at the same time when water was available from the wastewater treatment facility.

Before the irrigation-scheduling model was developed, the irrigations were scheduled to apply 5 mm/day during the growing season. Water application was measured using a water meter on the main line. Rain was measured using a tipping bucket rain gage at the site. Weather data and calculated reference evapotranspiration were retrieved from the weather station at the Nation Weather Site and New Mexico state University and the New Mexico Climate Center Web site (NMCC 2003).

The soil type at the site is classified at as Bluepoint loamy sand (0 to 1431 mm and stratified loamy find sand to loamy sand (457 – 1524mm) (Dona Ana County Soil Survey 1980). Nitrogen content of the irrigation water was analyzed by collecting a water sample from the holding pond and analyzing for nitrate-nitrogen and total nitrogen (TKN). Canopy measurements were taken 27 June 2002 using a spherical denisometer (Forest Densiometers Model –A). Four readings (north, south, east and west) were taken on the plot under mesquite and creosote.

Results

Wastewater application

Wastewater application began on February 5, 2002. The treated plot received varied amounts of effluent throughout 2002 and 2003. This was due to temporal fluctuations in tenant-generated wastewater and the high evaporation losses from the wastewater lagoons through the peak summer months (Figure 1).

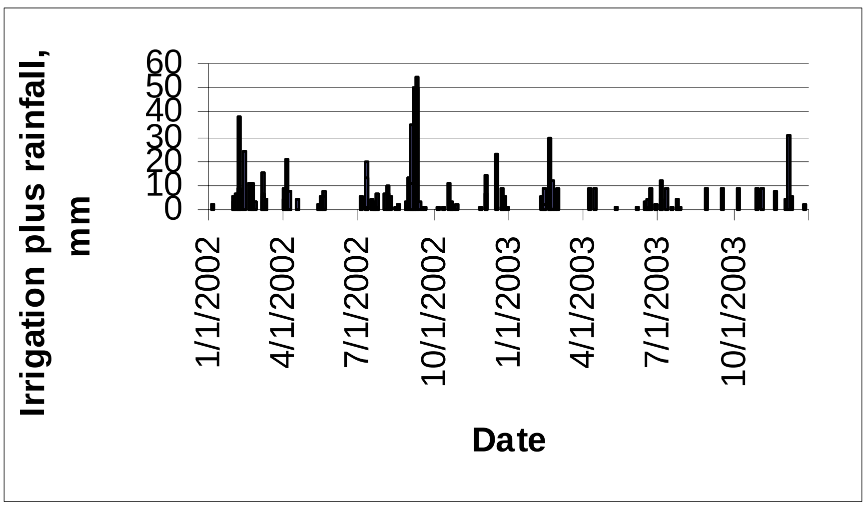

Figure 1. Irrigation plus rainfall applied to the wastewater site.

Generally, the application depth was 10 mm. In late summer, the application of wastewater onto the treated site increased due to one tenant's increase of wastewater discharge. The effluent increased from zero to an average of 50 mm over an 11-day period from August 31 to September 10, 2002. Nitrate nitrogen in the irrigation water for the year averaged less than 0.2 mg/l but the TKN nitrogen averaged 8 mg/l. It was assumed that all this was converted immediately to nitrate nitrogen after entering the soil.

The overhead area occupied by the creosote vegetation canopy was 60% with a standard deviation (SD) of 8% which was slightly larger than the overhead area occupied by the creosote crop coefficient study (50%) used to estimate the crop coefficient. Consequently, the density scaling factor in the irrigation scheduling model was set to one. Mesquite occupied 76% of the area, which would be similar to the overhead area occupied in the pot study to determine the kc for mesquite. (Levitt, et al. 1995).

Because of the low number of creosote and mesquite plants per ground area, the actual project area of the creosote / ground area was 8.7 % and for the mesquite 5.7% base on photographs taken from a airplane in June 2002 and analysised using arceview

Above ground WUE, input into the model was 14 kg/ha/mm. This number was estimated from the crop coefficient pot study and was similar to the slope of the water production function for alfalfa which was 12 kg/ha/mm (Sammis 1981).

Creosote plant model results

The total water applied to the plots was 814 mm in 2002 and 242 mm in 2003, and total Et was 462mm in 2002 and 254 mm in 2003. The non stress Et for the year was 1252 mm in 2002 and 1355 mm in 2004. The steady state design model conditions were not achieved for the two years of operations. Both nitrogen and water were limiting during that time period. Consequently, the design model predicted that under non limiting conditions, the Et would be 1252mm/year and the hydraulic loading could have been 5610mm/year resulting in a nitrogen application of 96 kg/ha/year and a leaching of 23 kg/ha/year of nitrogen.

The daily operation model showed that the creosote plants were under water stress after April 23 2002 when insufficient water was available from the treatment plots to supply enough irrigation water to satisfy the evaporative demands of the plants (Figure 2).

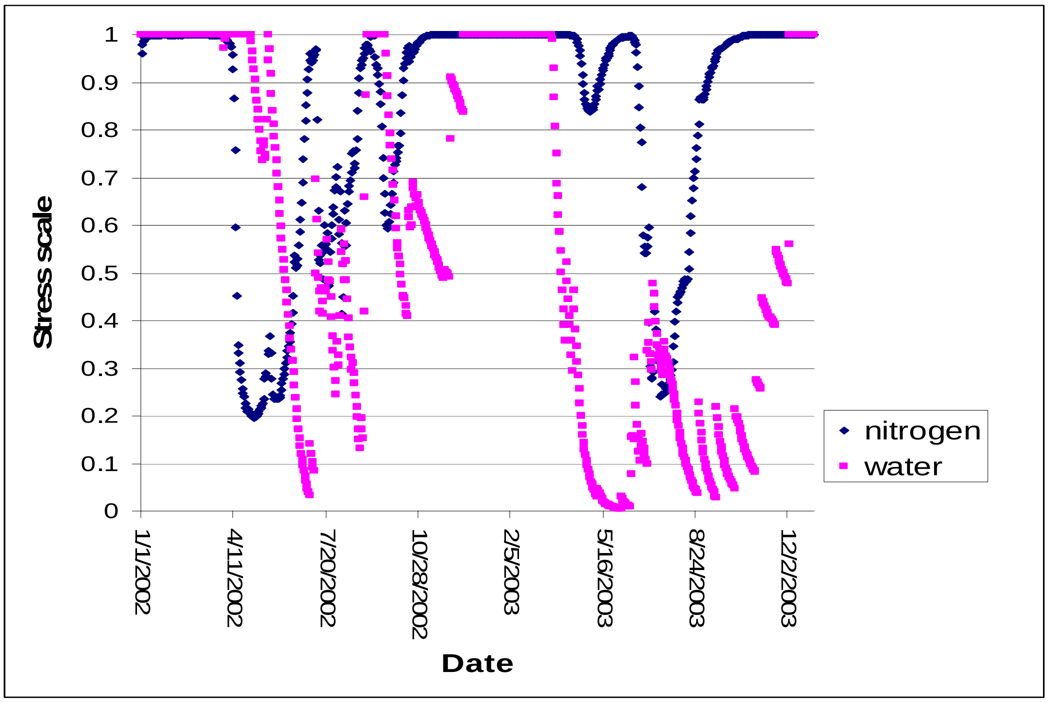

Figure 2. Creosote Nitrogen and Water stress for wastewater irrigated plots.

The assumption in the model was that the soil profile was full at the beginning of the run in January 1, 2002. In 2003 the winter rains filled the root zone but soil water stress again started on March 22. Because the plants were under stress after April 23, 2002 and March 22, 2003, deep drainage was low after those dates except on Sept. 6 –

10, 2002 when the irrigation system was run for 4 straight days when a control valve did not work. Drainage of 11 mm also occurred in Feb 21 2003 (Figure 3).

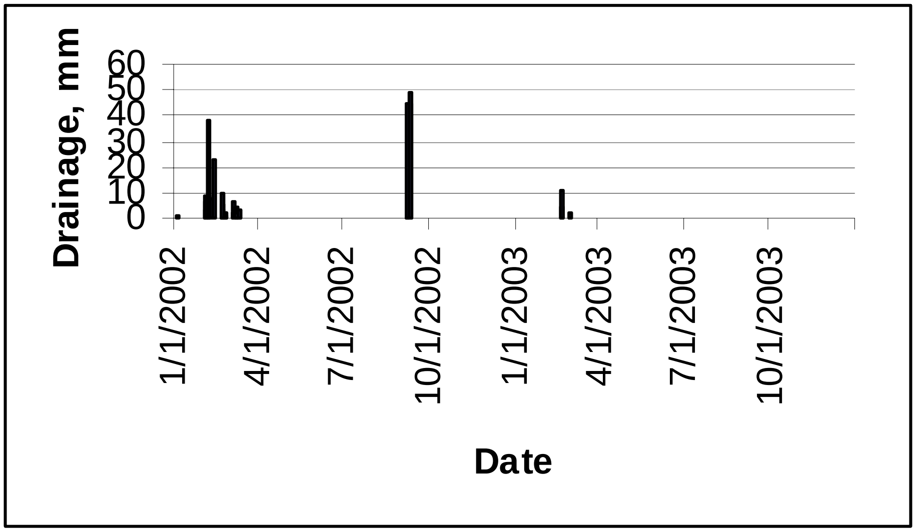

Figure 3. Drainage amount under the creosote plant.

Nitrogen stress also occurred to limited Et and growth because the irrigation wastewater stream had only TKN nitrogen of 8 mg/l. (Figure 2). Generally a logon wastewater treatment plant would have N levels of 40 mg/l which would cause nitrogen to be leached below the root zone (Metcalf and Eddy, Inc, 1990). The logon treatment system receives only industrial waste which accounts for the low nitrogen content. Nitrogen stress generally occurred during the summer months when uptake demand and growth was greatest. Mineralization rates increase during the summer months when temperatures increase, but the mineralization rate was insufficient to supply the nitrogen needed by the creosote plant.

The daily evapotranspiration varied from 3 to 4 mm in/day (Figure 4) during the summer months even though the non stress Et would have been 8 mm/day.

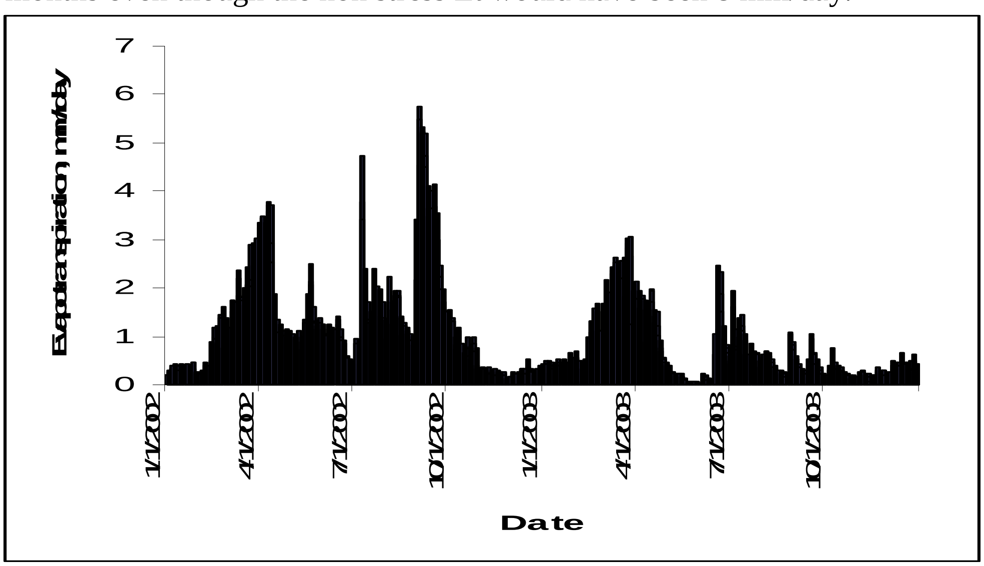

Figure 4. Creosote evapotranspiration rate.

Because nitrogen and water stress existed the amount of nitrogen leached below the root zone was 33 kg/ha for the two years compared to the amount applied of 64 kg/ha. However, all the nitrogen leached occurred on the over irrigation events of Oct 2002 (13 kg/ha) and the end of February 2003 (20 kg/ha). Except when an errors of water application occurs the creosote plant extract all of the available nitrogen in the wastewater stream. Total biomass growth for the 2002 was two 0.64kg/m^2 and 0.35 kg/m^2 in 2003.

Mesquite plant model results

The WUE of the mesquite plant was estimated to be the same as the creosote plant 14 kg/ha/mm**.** The plots received the same amount of water as the creosote plants (Figure 1). The assumption was that nitrogen was not limiting. The mesquite plants were not under water stress until the May in 2002 and 2003 (Figure 5).

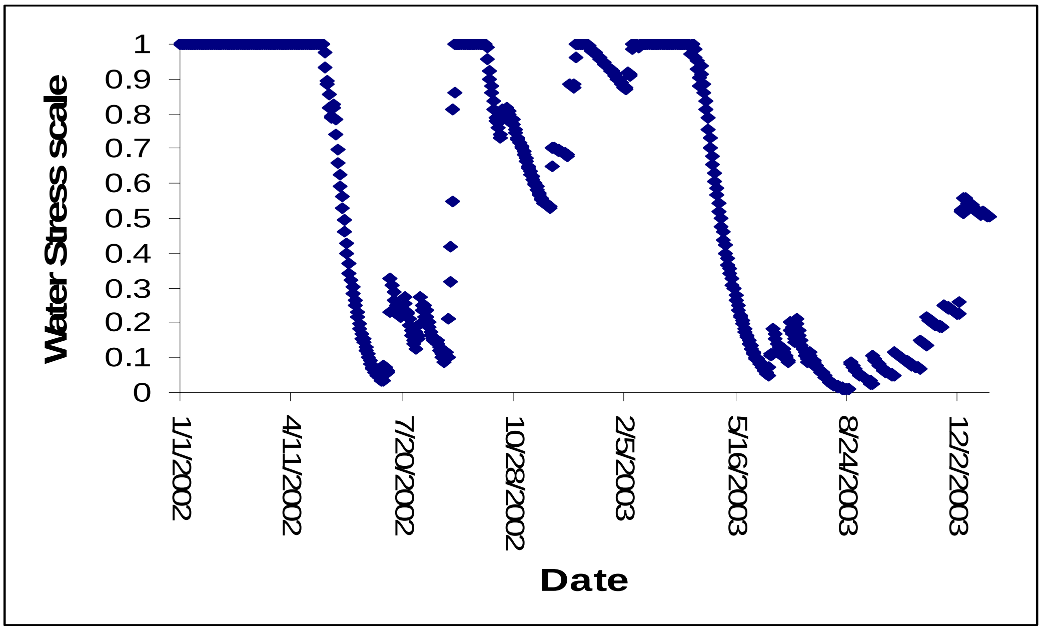

Figure 5. Mesquite water stress for wastewater irrigated plots.

Deep drainage under the mesquite plants was similar to that under the creosote plant (Figure 6). The daily evapotranspiration varied from 5 to 6 mm during the summer higher than the creosote plant because nitrogen was not limiting (Figure 7). The maximum crop coefficient for mesquite under non stress conditions was 1.29 compared to 1.02 for creosote. This also contributed to the slightly higher Et when water was available after a rain or irrigation event. Yearly evapotranspiration calculated by the model was 643 mm in 2002 and 299 mm in 2003 because of the decrease irrigation amounts in 2003 compared to 2002. Consequently, yearly biomass growth was 0.9 kg/m^2 in 2002 and 0.41 kg/m^2 in 2003 greater than the creosote plant growth because the mesquite was not under nitrogen stress. The nitrogen balance for the mesquite plant is still being developed because of its symbiotic ability to produce nitrogen.

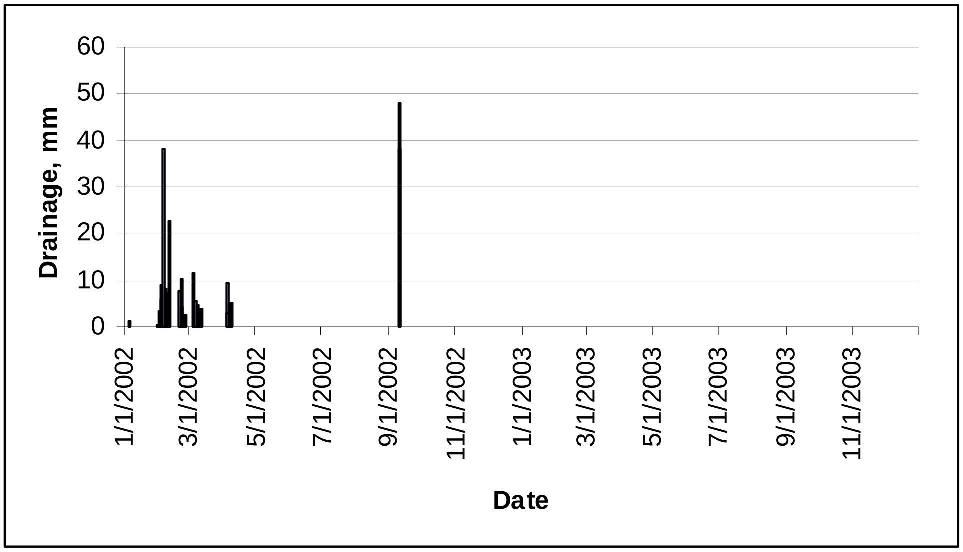

Figure 6. Drainage amount under the mesquite plant.

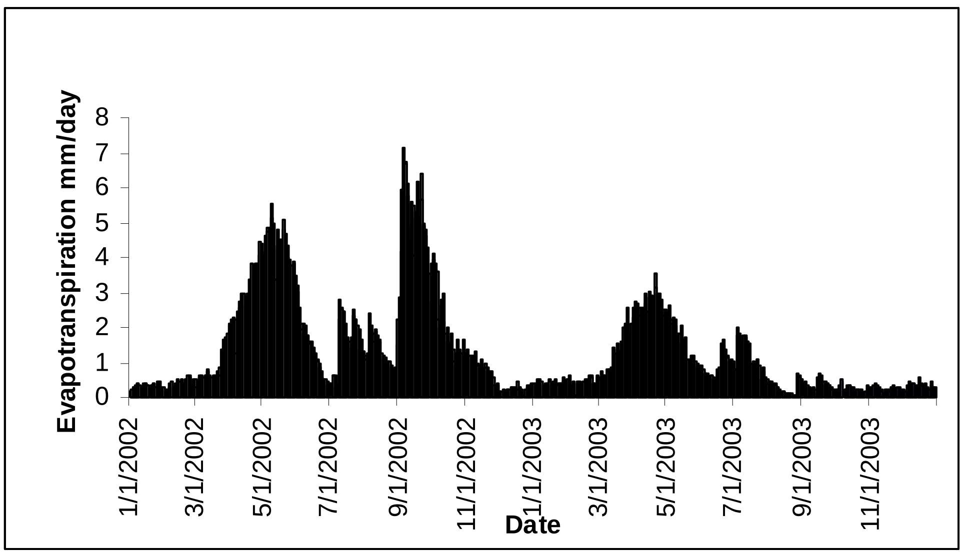

Figure 7. Mesquite evapotranspiration rate.

Conclusion

A preliminary model that simulates the water and nitrogen balance under creosote was developed and a water balance model was developed for mesquite. The model appears to work reasonably well but continued research is underway to verify the growth, nitrogen and water balance components of the models.

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Comparison of Scaled Canopy Temperatures with Measured Results under Center Pivot Irrigation

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Abstract

The remote sensing of crop canopy temperatures using infrared thermometers is being used in conjunction with several new developments in the area of irrigation scheduling and control. These include the time-temperature-threshold (TTT) method of irrigation scheduling, the crop water stress index (CWSI) and the creation of field level canopy temperature maps using infrared temperature sensors mounted on self-propelled irrigation systems. A method of estimating the canopy temperature dynamics throughout the day using only a one time-of-day canopy temperature measurement is useful in the application of many of these technologies to self-propelled irrigation systems such as center pivots or linear moves. Two different algorithms developed by Peters and Evett (2004) for doing this were tested using data collected under center pivot irrigation. These algorithms use the canopy temperature dynamics captured at a stationary location to create a reference curve. Sixteen different infrared thermometers were positioned in stationary locations throughout a field with four different irrigation level treatments; 100%, 66%, and 33% of the irrigation requirements, and a dryland, or a non-irrigated treatment. One time-of-day canopy temperatures measurements were taken from these at various times of day and were scaled using the reference curve to estimate diurnal canopy temperature curves. These curves were then compared with the actual measurements and the errors were analyzed. Errors using measurements early in the day (before 0800 h) and late in the evening (after 2200 h) were unacceptably high. However, the absolute mean errors using measurements taken during the middle of the day were approximately 1° C with a standard deviation of about 1° C. The effects of using a reference curve from plants with different water stress levels were also compared and it was found that the stress level of the reference curve crop did not make a significant difference in the absolute mean errors.

Introduction

The ability to estimate diurnal canopy temperature dynamics from a one time-of-day canopy temperature measurement is useful for many reasons. The crop water stress index (CWSI; Jackson, 1982) requires canopy temperature measurements to be taken close to solar noon on clear cloudless days (U.S. Water Conservation Laboratory, 2004). These measurements could be made more convenient if the solar noon canopy temperature could be approximated using a measurement taken at another time of day. Canopy temperature maps of a field are useful feedback mechanisms to precision irrigation control algorithms for showing water, nutrient, or pest damage stresses in various areas of a field. Creating a canopy temperature map using infrared canopy temperature sensors mounted on self-propelled irrigation systems such as center pivots or linear moves requires a method for correcting for temperature changes due to changing climate conditions over the time it takes the self propelled irrigation system to travel across the field (Sadler et al., 2002). The time temperature threshold (TTT) method of irrigation scheduling requires a diurnal canopy temperature curve to determine if the amount of time that the canopy temperature was above the temperature threshold exceeded the time threshold (Wanjura et al., 1992, 1995; Upchurch et al. 1996). However, sensors mounted on a self-propelled irrigation system only provide a one-time-of-day temperature measurement for each spot in the field as they move over the field. All three of these new developments in irrigation scheduling and control could benefit from a method of estimating the diurnal canopy temperature dynamics using only a one-time-of-day temperature measurement.

Peters and Evett (2004) proposed two different methods for estimating the diurnal canopy temperature curve from a one-time-of-day measurement that using the canopy temperature dynamics as measured in a different part of the field as a reference curve. The objective of this study is to further test these methods using canopy temperature data collected from a center pivot automation study done at Bushland, Texas. In particular it is of interest whether the water stress of reference curve has any effect on the accuracy of the diurnal canopy temperature predictions.

Diurnal Canopy Temperature Determination

Extrapolating a diurnal canopy temperature curve from a one-time-of-day measurement requires an estimation of the canopy temperature dynamics due to changing environmental conditions. Several different models exist that can predict the dynamics of the crop canopy temperature as part of a soil-plant-atmosphere energy balance (e.g. Evett and Lascano, 1993). However, these models require as input detailed weather data as well as knowledge of soil-and plant-specific parameters that are neither readily available nor easy to measure. The most direct and simple way to determine how changing environmental conditions over a day affect canopy temperature dynamics is to measure canopy temperature in one stationary reference location. Peters and Evett (2004) showed that diurnal canopy temperatures in other parts of a field, which may be under different stresses, could be modeled relative to this reference using only a one-time-of-day temperature measurement. Two different methods were proposed; the scaled method and the Gaussian difference method.

<u>Scaled Method</u>

If pre-dawn canopy temperatures throughout the whole field (T_e; *e* for early) are assumed to be the same then:

$$T_{rmt} = T_e + \frac{(T_{rmt,t} - T_e)(T_{ref} - T_e)}{T_{ref,t} - T_e} \qquad (1)$$

as in Figure 1 where:

T_{rmt} = calculated canopy temperature at the remote location (°C)

T_{ref} = canopy temperature from the reference location at the same time interval as T_{rmt} (°C)

$T_{rmt,t}$ = one-time-of-day canopy temperature measurement at the remote location at any daylight time *t* (°C)

$T_{ref,t}$ = measured reference temperature from the time that the remote temperature measurement was taken (*t*).

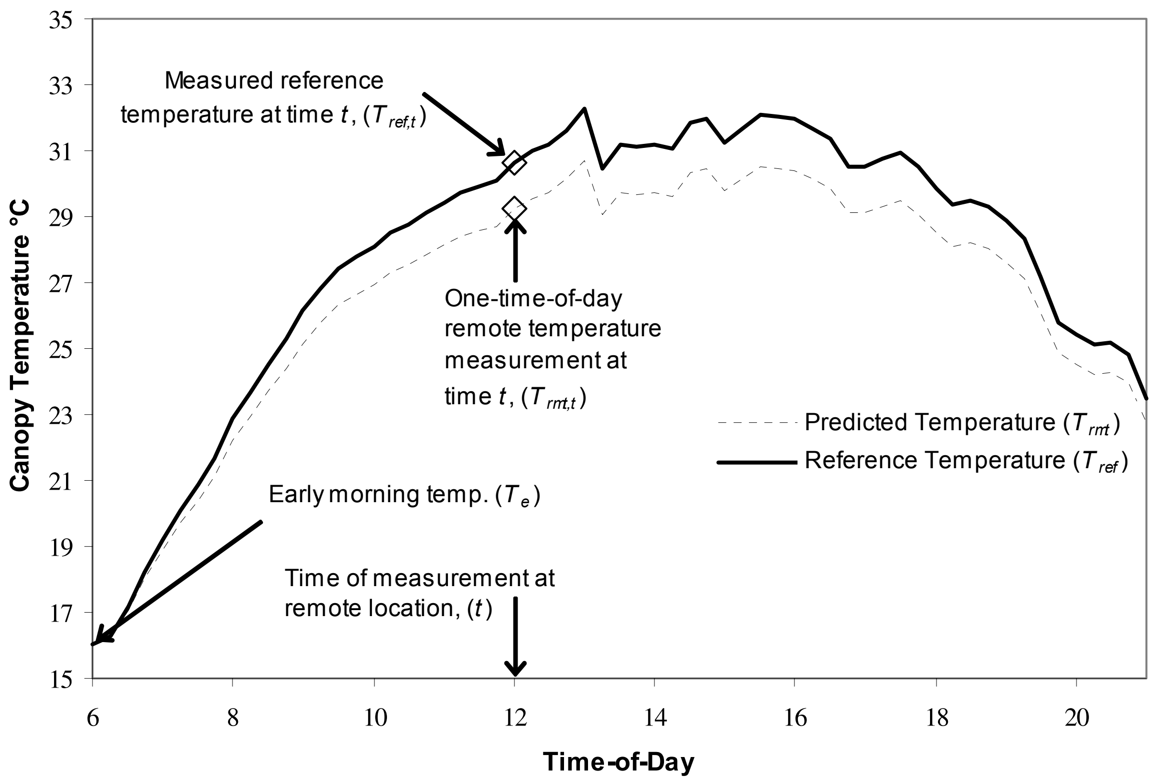

Figure 1. Diagram of the terms used in the scaled method (Eq. 1). Time t might be any daylight time at which a canopy temperature ($T_{rmt,t}$) was measured at a remote location in the field. A contemporaneous temperature ($T_{ref,t}$) from the reference temperature data is then used in equation 1 along with the common pre-dawn minimum temperature (T_e) and each value in the reference temperature data (T_{ref}) to predict corresponding temperatures at the remote location throughout the daylight hours (T_{rmt}).

Gaussian Difference Method

An alternative method was developed and tested that uses the one time-of-day measurement to approximate the diurnal differences between the reference temperature curve and the predicted curve. The diurnal differences were approximated using a three-parameter Gaussian equation:

$$T_d = Ae^{\left[-0.5\left(\frac{t-t_p}{w}\right)^2\right]} \qquad [2]$$

where T_d is the predicted temperature difference ($T_{rmt,t} - T_{ref,t}$) from the reference (°C) at time of day t (h), A is the amplitude of the peak difference (°C), t_p is the hour of day (h) of the peak, and w is a factor that predicts the width of the peak (h).

Peters and Evett (2004) gave constant values for t_p = 14 h and of w = 2.63 h in Eq. [2]. They also stated that the value for t_p will be dependent upon the site longitude in reference to time zone demarcation lines (i.e. solar noon occurs at slightly different times). To use Eq. [2] to predict canopy temperature at a remote location, the measured time (t) and the canopy temperature difference (T_d) are used in Eq. [2] to solve for A. Once A is known, the remainder of the points in the diurnal canopy temperature curve are calculated by computing the temperature difference at each point using Eq. [2] and adding that difference to the reference temperature value.

Materials and Methods

Data from an experiment in center pivot automation based on the time-temperature-threshold (TTT) method of irrigation scheduling were used. The experiment site was a three-tower, 127 m long research center pivot located at the USDA-ARS Conservation and Production Research Laboratory in Bushland, Texas (Figure 2). Only half of the field was used. Soybeans were planted in concentric circles out from the center point. Agronomic practices common in the region for high yields were applied. Four different water level treatments were applied radially out from the center point (100%, 66% and 33% of projected irrigation needs, and a dry-land, or no irrigation treatment). Each drop was pressure regulated to 6 psi. The irrigation level was controlled by nozzle sizes as appropriate. Drops were spaced every other row (1.52 m) and irrigated with low energy precision application (LEPA) drag socks. The furrows were dammed/diked to limit water movement in the furrows. Two replications of each of the irrigation level treatments were applied in a randomized block pattern with the second tower wheel track serving as the block separation line. There were three replications each of an automatically controlled (via the TTT method) treatment, and a treatment that was manually scheduled (using soil water deficiency as determined by neutron probe soil moisture content readings). These treatments were applied in alternate wedge shapes to block for differing soil types underneath the pivot. Two additional rows of soybeans are planted around the outside and inside edges of the pivot to help minimize border effects.

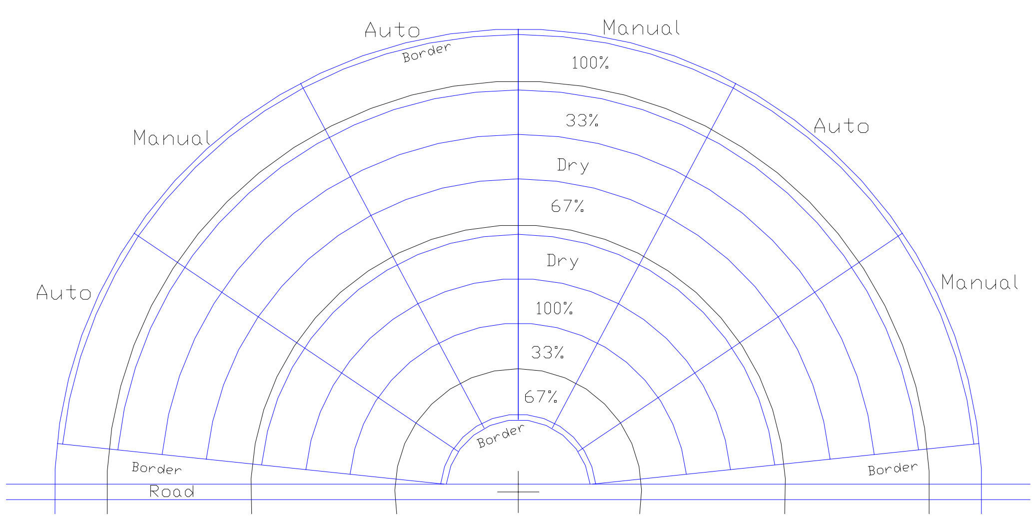

Figure 2. Center pivot automation plot plan.

Sixteen IRTs (model IRt/c.2-T-80, Exergen Corp.)[1] were mounted in stationary locations. One IRT was mounted in each irrigation level of both the automatic and manual treatments in the East end of the field. Each IRT was mounted in the nadir position over the crop row close enough to the canopy so that soil was not included in the field-of-view. These IRTs were adjusted up throughout the season with the changing height of the canopy. They were all connected through a multiplexer (AM25T, Campbell Scientific) and to a datalogger (CR21X, Campbell Scientific). The datalogger logged the five minute averages of each of the IRT readings collected on 10 second intervals. Each IRT was separately calibrated using a black body (Omega Black Point, model BB701) before the season began. A second order polynomial was fitted to the results of the calibration and each IRT was individually corrected after the season was over.

A reference curve was created from the average of the two 100%, manual irrigation treatments. A one-time-of-day temperature measurement from a particular IRT in the field was then used to estimate a diurnal canopy temperature curve using both the scaled (Eq. [1]) and the difference (Eq. [2]) methods and the absolute mean error and the standard deviation of the errors was recorded. This was done for each time of day on five minute intervals from 530 h to 2215 h, for every day of year (DOY) from DOY 99 to DOY 239, and for each of the 16 IRTs individually. This whole process was repeated using a reference curve created from the average of the two 66%, 33%, and dryland manual irrigation treatments to determine if the conditions of the reference curve had a significant effect. Daylight savings time was not applied so that solar noon was near 1300 h during the growing season.

Results and Discussion

The average of the absolute mean errors for every day and across each of 16 different IRTs for both methods (Eq, [1] and [2]) were compared (Figure 3.) The absolute mean error for both methods was close to 1° C during the middle of the day. Temperatures predicted from one-time-of-day measurements taken early in the day (before approximately 0800 h) or late in the evening (after approximately 2200 h) resulted in unacceptably high errors. The Gaussian difference method was slightly more accurate with one-time-of-day measurements taken during the middle of the day (between about 1200 h to 1600 h) than the scaled method. However the scaled showed better accuracy early in the day (between 0800 h and 1000 h) and later in the day (between 1800h and 2000 h). The probability that the differences between these two methods were due to variability is shown in Figure 4. Where the two lines crossed there was no significant difference of course, but significant differences were found during the middle of the day (from about 1300 h to 1400 h) and early (about 0800 h to 1000 h) and late (about 1900 h to 2000 h) in the day. The standard deviations of the absolute mean errors of both methods behaved very similar to the means (Figure 5) with the average being close to 1° C during the middle of the day.

The Gaussian difference method shows quite a bit more stability in predicting accurate diurnal canopy temperature curves than the scaled method (Figure 3). Upon further investigation, the instability in the scaled method was caused by a few points during cool days when the afternoon temperatures were very near the early morning temperatures. This caused the denominator

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

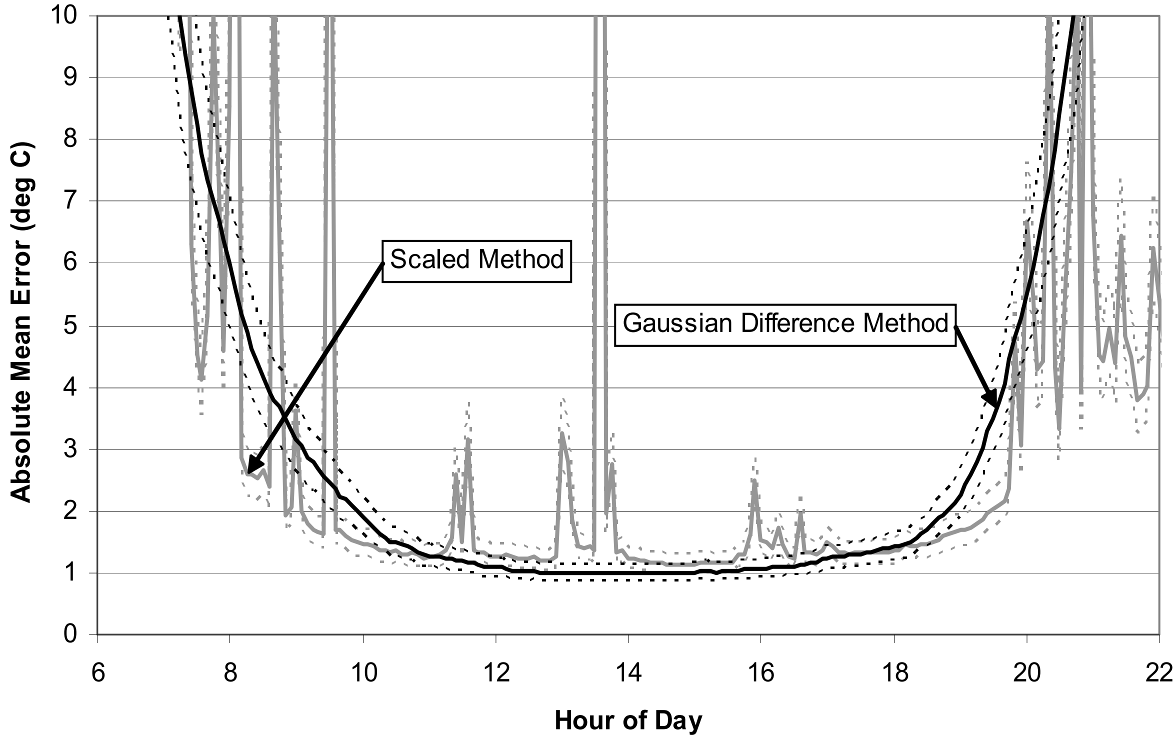

Figure 3. Comparison of the absolute mean error between the scaled and difference methods of determining a diurnal canopy temperature curve using a one time of day measurements from various times (hours) of the day. The 95% confidence interval on each of the means is also shown. The average of the 100%, manual irrigation plots was used as a reference curve.

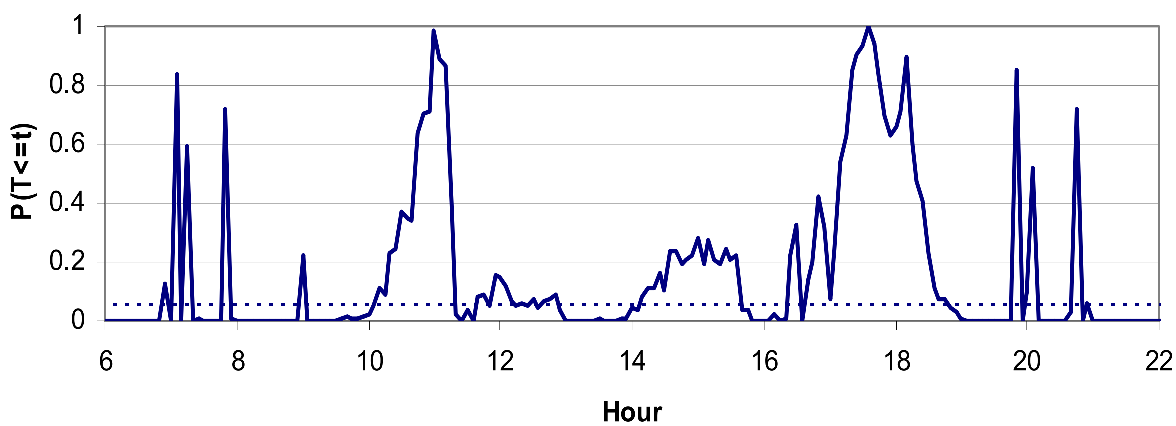

Figure 4. Shows the probability that the measured T statistic is less than the critical t statistic (P(T<=t) for the means (Figure 3 above) at all times of day. This is the probability that the differences between the means is due to variability.

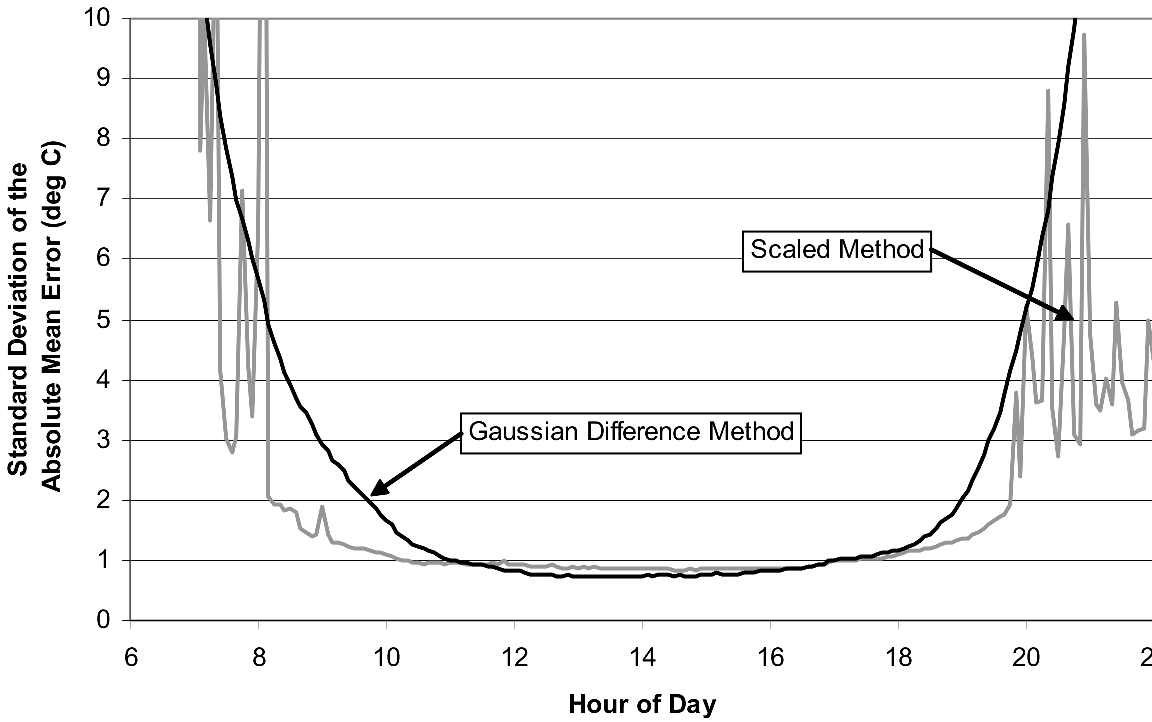

Figure 5. The standard deviation of the absolute mean error between the scaled and difference methods for determining a diurnal canopy temperature curve from a one time-of-day measurement.

($T_{ref,t} - T_e$; the difference between the early morning temperature and the reference temperature at the one-time-of-day measurement) in Eq. [1] to be very small at certain times of day. When this happened the scaled term exploded causing absolute mean error numbers to be many significant digits higher than what was typical. This resulted in error spikes in the curve. These large errors occur only in rare instances when the afternoon temperatures were very near the early morning temperatures and only at those times of day. However the errors using the scaled equation during these instances were very large. This problem may be mitigated programmatically by doing some checking of the method against the Gaussian difference method, or by disallowing the denominator in Eq. [1] to be less than a specified limit, or less than zero. When the few cool days of year with afternoon temperatures near the early morning temperatures were removed these spikes all but disappeared (Figure 6). Many spikes can still be seen during the morning and evening hours when the temperature difference from the early morning temperatures was not very large.

It would be ideal if a reference curve could be measured at any point in the field without having to worry about if water, pest or disease stress of the reference canopy has any negative effects on the accuracy of the diurnal canopy temperature predictions. In order to test this, the same analysis as shown in Figures 3 and 4 was run using reference curves created from the average of the 66%, the 33% and the dryland manual irrigation treatments. Figure 7 shows that the water stress (and therefore the temperature) of the plants chosen for the reference curve had very little effect on the accuracy of the scaled method. Figure 8 shows the same conclusion for the difference method.

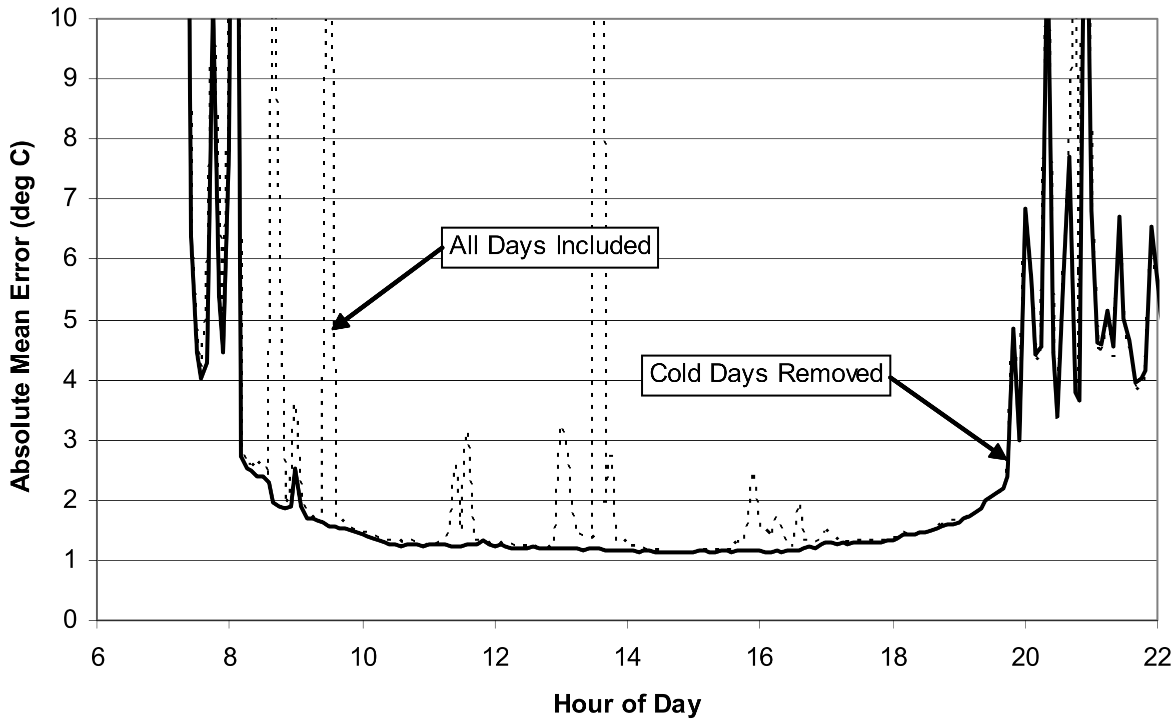

Figure 6. The scaled method with the removal of days when the difference between Tref,t and Te were small (i.e. temperatures near the middle of the day were not significantly warmer than the pre-dawn temperatures.)

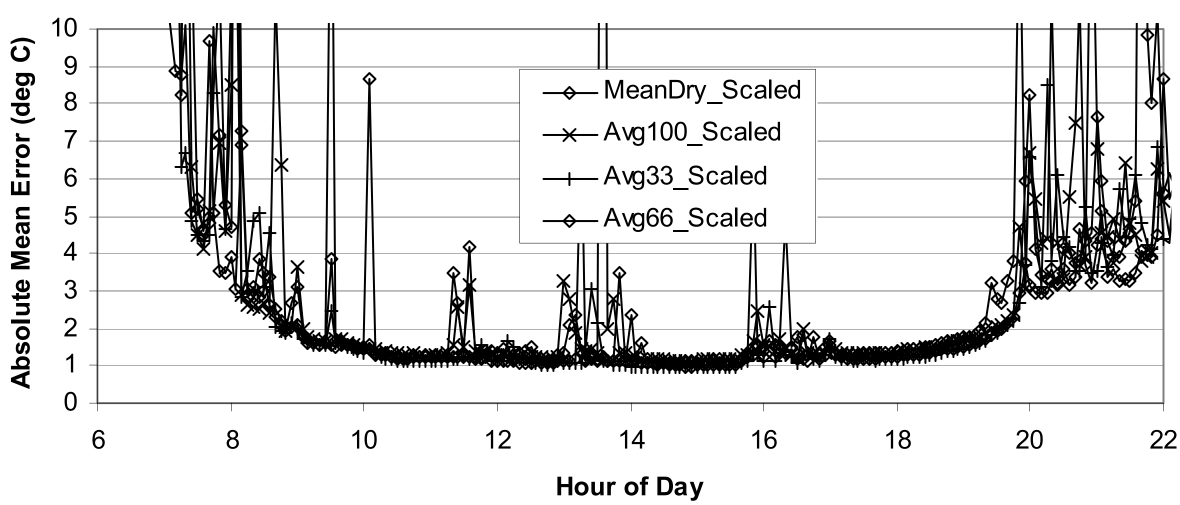

Figure 7. Comparison of the scaled method using each of the four treatments as a reference curve.

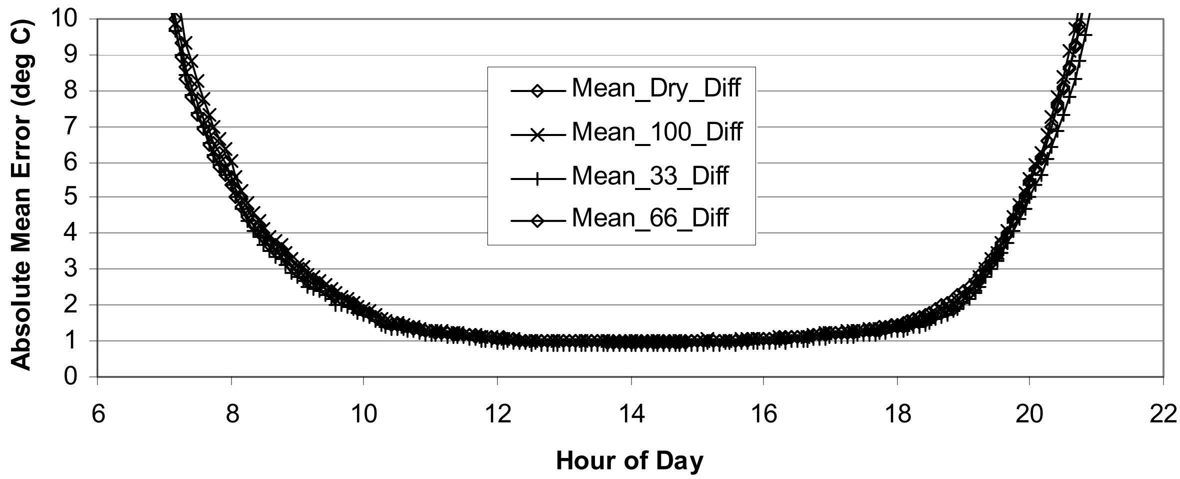

Figure 8. Comparison of the Gaussian "difference" method using each of the four treatments as a reference curve.

Conclusions

These data show that the scaled method (Eq. [1]) and the Gaussian difference method (Eq. [2]) are both viable methods for predicting the diurnal canopy temperature dynamics from a one-time-of-day measurement using a reference temperature during daylight hours. At night, the closest approximation of the canopy temperatures in the remote location is simply the reference temperature. The scaled method is more accurate early in the morning and late at evening while the difference method is more accurate during the middle of the day. Although the difference method is more accurate during the middle of the day, these differences are small and may not be important. The scaled method exhibited instability when the temperature of the reference was near the early morning temperature at the time of the one-time-of-day measurement. The difference method was much more stable. The water stress condition of the reference curve had very little effect on the overall accuracy of the diurnal canopy temperature predictions. When the canopy temperature dynamics are captured at a stationary location to create a reference curve these methods enable the prediction of canopy temperatures at times of day other than when a canopy temperature measurement is taken. These methods simplify the collection of data for the CWSI, enable the creation of canopy temperature maps using infrared thermometers mounted on self-propelled irrigation systems, and also enable the use of the TTT method for irrigation scheduling in fields underneath a self propelled irrigation platform.

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Potential use of a New Forage Grass (*Pennisetum Sp.)* in Best Management Practices Involving Irrigation with Food Processing and Dairy Wastewaters.

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Abstract

Excess nutrients from irrigation of crops with recycled wastewaters from food processing and dairy operations can be a major source of groundwater pollution. Hence, a major component of any Best Management Practice (BMP) should be the inclusion of either an agronomic crop or perennial forage capable of utilizing the nutrients applied in the wastewaters. "Promor A" perennial forage grass (*Pennisetum Sp*.), commonly called Elephant grass, was introduced into California in 1994, and has now been planted in five locations in the State. In this paper we present a summary of research by the Center for Irrigation Technology (CIT) at California State University- Fresno, aimed at investigating the potential use of the Elephant grass to act as a scavenging crop for mitigating contamination of groundwater from fields irrigated with food processing wastewater and dairy effluent. Our findings to date indicate that the Elephant grass is a highly nutritious forage grass exhibiting efficient water use, and is a luxury feeder of nitrogen and phosphorus, thereby implying that the grass has good potential to absorb significant amounts of excess nutrients from dairy effluent and processing wastewater used for irrigation.

Introduction

In California, which is now the number one dairy producing State in the U.S. (CDFA 1999 & 2003), dairy manure is commonly handled as an effluent stream of liquid or slurry by means of a hydraulic flushing - lagoon storage - irrigation system. Major problems associated with the manure management are high solids and nutrient contents of the effluent stream. High solids content causes fast sludge buildup in storage lagoons, thus reducing the available storage volume, and also causes high solids loading to the soil when the wastewater is irrigated, hindering the crop seed germination and growth. High nutrient contents tend to cause overloading of land with nutrients, especially nitrogen and phosphates, causing contamination of surface and ground water resources. The Central San Joaquin Valley of California with its growth of Concentrated Animal Feeding Operations (CAFO) and sprawling urban development is a paramount example of the serious problems in the United States of accommodating population growth in prime agricultural land areas. An intensive study of shallow groundwater wells around diaries in this Valley indicates that within the diaries nitrate-N (nitrogen) levels were 64 mg/l compared to 24 mg/l immediately up-gradient of these dairies (Harter, 2001).

In addition to dairy products, California also leads the nation in grape and wine production (CDFA, 2002). For example, in 2001 California accounted for 91 percent of the nation's grape receipts. Inherent in the production of wines is copious amounts of processing water commonly referred to as winery Stillage. Land application of the process winery stillage allows for the beneficial reuse of nutrients, organic matter, and water, while utilizing the soil profile to treat the process water and prevent degradation of groundwater. However, some constituents may pass through the soil profile and detrimentally impact groundwater.

Excess nutrients from irrigation of crops with recycled wastewaters from the wineries and dairy operations can be a major source of groundwater pollution. Hence, a major component of any Best Management Practice (BMP) should be the inclusion of either an agronomic crop or perennial forage capable of utilizing the nutrients applied in the wastewaters. "Promor A" perennial forage grass (*Pennisetum Sp.*), commonly called Elephant grass, was introduced into California in 1994, and has now been planted in five locations in the State. Elephant grasses are perennials and are grown throughout the tropical world and are one of the most widely used forages for large and small animals. *Pennisetum* grows in clumps or stools having an upright growth habit (Figure 1). Since the introduction of the Elephant grass into the U.S. via official quarantine channels it has been subjected to a series of trials to test its bio-filtering characteristics, forage qualities, agronomic qualities, water use efficiency and its tolerance to insect pests and diseases.

Summary of Research Conducted

In 1995, a three acre plot of the Elephant grass was established at the University of California, Fresno, Center for Irrigation Technology (CIT) in proximity to Fresno University dairy lagoon. The objectives of the trial were to gather initial information on: nutrient absorption and effect of dairy effluent on the growth and condition of the grass; grazing and acceptance of the grass by beef cattle; DM yields and nutritional evolution of the grass with age.

Irrigation water from wells was initially applied by furrow application during the germination period. Subsequent dairy pond waste irrigations were applied on a normal 8-day irrigation interval. Six fenced plots were established in the middle of the planting for sampling of nutrient absorption, yield and forage quality. Fifty mixed breed pregnant beef cows and calves adjusted to and grazed the Elephant grass for daily intervals during two 10-day periods. A second 10-day grazing period occurred after refoliation. A 60-day age of harvest was established to permit 3 harvests from May to October. This trade-off maximized nutrient absorption, and produced quality forage for animal feeding purposes.

In 2002 a grant was obtained through the Agricultural Research Initiative (ARI) California State University System. The Center for Irrigation Technology, Fresno State installed a fully replicated trial with Elephant grass with the following objectives:

- Determine the nitrogen and phosphorus filtering characteristics of the grass
- Determine water consumption of the grass
- Determine possible interactions between bio-filtration and water consumption

A "Nutrient Farm Balance" protocol was established to determine the biofiltration characteristics of the grass (Barry et al, 1993; Goss and Goorahoo, 1995). The irrigation protocol consisted of four treatments replicated four times. Water application was based on the daily evapotranspiration index. The treatments consisted of water applications of 40%, 80%, 120%, and 160% of the daily measured reference evapotranspiration. Water was precisely applied by drip irrigation tubing and an electronic controller timed the daily irrigation interval application.

The soil sampling protocol consisted of 12 sampling sites with one foot intervals to a depth of five feet. The soil was sampled before the experiment was installed, after the first season of harvest, and after the second season. 180 soil samples were taken and analyzed from the 16 plots from a total area of 8600 square feet.

The grass nutrient absorption and forage protocol consisted of harvesting a center section of each plot representing 31% of the area of the plot. The forage was chopped, mixed and two composite 2-kg sub-samples were taken. The chemical fertilization protocol consisted of an initial application in equal amounts to all of the plots of nitrogen, phosphorus and potassium. Subsequent chemical fertilizer applications (in equal amounts to all plots) were made based on the average amounts of N, P, and K absorbed by the grass from the nine separate harvest periods from 2002 to 2003.

Experimental Results

During the 1995 trials, the 60-day age of crop samples averaged the following:

- DM weights of six replicated 1 m^2 plot samples were 2.3 kg.
- Dry Matter (DM) - 17%
- Nitrogen (N) content - 2.0%
- Total N absorption of the crop - 460 kg per hectare
- Protein content ranged between 25.71% at three weeks of age and 15.03% at 10 weeks of age (Table 1)
- Phosphorus (P) content - 0.70%
- Total P absorption of the crop - 161 kg per hectare.

The implications of the data and observations are:

- The grass was highly palatable with no negative effects on the animals (Figure 2)
- Significant amounts of N and P were absorbed by the Elephant grass over the 60 days
- No "burning" or other negative effects on the grass were caused by the wastewater
- Total N accumulation increased from the youngest emerging leaf to the stalk
- Stalk total N accumulation was seven times more than the youngest leaves

- Increasing stalk to leaf mass by aging the grass would increase total N bio-filtration
- The waste application produced forage of significant quality and value for ruminants

For the 2002 experiment, conducted on a sandy loam soil, the average amount of total N extracted by the Elephant grass over the course of the experiment was 1162 kg per hectare compared to the 883 kg of fertilizer N applied per hectare (Tables 2 and 3). However, care must be taken in making any comparison as the total N value reported for the forage includes organic N sources such as proteins, where as the N fertilizer was inorganic nitrogen. Generally, soil nitrate levels within the top five feet of soil were maintained below 8 ppm throughout the duration of the experiment (Figure 3). The only exception was the 16 ppm value measured within the top foot of soil in spring 2003. Soil phosphate levels followed a similar trend as that observed for the soil nitrate (Figures 3 and 4). On average, the grass extracted 230 kg (in 2003) of P per hectare compared to an application rate of 368 kilos of P per hectare in 2002-2003 (Tables 2 and 3). Table 4 contains total dry matter production for years 2002-2003.

The implications of the data from the 2002 funded experiment are the following:

- The Elephant grass has bio-filtering characteristics for filter strip applications
- Treatment 1, the 40% level of water application produced significantly lower dry matter ($P < .01$) than the other treatments
- There was no significance of dry matter production between the 80%, 120%, and 160% treatments
- The evapotranspiration coefficient (water use) of the grass is between 80 and 100% of the referenced daily evapotranspiration
- There was a trend in total nitrogen and phosphorus absorption due to the higher dry matter production of the 80%, 120% and 160% treatments.
- There was no interaction of water level application and N and P absorption. However there seemed to be a trend for higher absorption for the highest water application

Conclusions and Future Research

The information derived from the current research is very important for the agriculture processing and dairy industries as increasingly more strict discharge regulations are being implemented by regulatory agencies. For example, the findings will be useful in providing important information on how different dairy effluent and wastewater discharge regimes affect the loading rates in the field at different growth stages of the elephant grass. Overall, from studies conducted to date, it can be concluded that the Elephant grass appears to have significant potential for scavenging excess soil nitrogen and phosphorus and can be very useful in a bio-filtration system aimed at managing irrigation or recycled water, such as dairy or food processing wastewaters. The stooling growth habit of this grass should provide a secondary benefit through reduction of water velocity and consequent sedimentation of water borne particles when the grass is used as barrier plantings or buffer strips.

The California State Water Resources Control Board has awarded a grant to the Imperial Valley Conservation and Resource Center Committee (IVCRCC), Brawley, California to plant 28 acres of the Elephant grass for a buffer/filter application. The project entitled "Nutrient Control of Agricultural Runoff Water" will use agricultural drain water now running into the Salton Sea to irrigate the grass. The objective of this project is to reduce nitrogen, phosphorus, and sediments, which are causing eutrophication of the Salton Sea. The project will be installed, monitored, and audited by a team of scientists from the Center of irrigation Technology, California State University, Fresno and is scheduled to run for three years.

In another small scale study the use of elephant grass as a scavenging crop for nitrates and organic loading is being compared to Sudan grass on fields which have been subjected to winery Stillage disposal. Soil water quality in the vadose zone will be monitored using suction lysimeters installed at 2 and 4 feet. Vadose zone monitoring at those two depths will be valuable to assess solute movement through the soil profile and determine the role of Elephant grass in reducing water contamination below the root zone. This project is funded by the California State University –Agricultural Research Initiative (CSU-ARI) and is being conducted in collaboration with the City of Fresno Wastewater Treatment Facility.

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Table 1. Nutritional Evolution of the Elephant grass with Age , Irrigated with Dairy pond Liquid Waste (Rothberg, 1995 Internal Report CIT).

Age in weeks	Dry Basis	Protein (DB)	TDN	Acid Detergent Fiber	Neutral Detergent Fiber	Relative Feed Value
3		25.71%	65.20%	30.00%	48.99%	119.0
4		19.72%	62.22%	33.77%	48.99%	119.0
5		21.80%	64.03%	31.48%	49.38%	121.0
6		18.87%	62.67%	33.20%	51.58%	114.0
7		17.16%	61.30%	34.94%	52.68%	109.0
8		15.44%	59.93%	36.68%	53.77%	104.0
9		15.24%	59.94%	36.66%	54.21%	103.5
10		15.03%	59.95%	36.64%	54.64%	103.0
Average		**18.62%**	**61.91%**	**34.17%**	**51.78%**	**111.6**

DB – Dry Basis; TDN- Total Digestible Nutrients; ADF – Acid Detergent Fiber – residue of cellulose, lignin and silica after boiling in acid detergent; NDF – Neutral detergent fiber – remains of cellulose, hemicellulose, lignin, and ash after boiling in a neutral detergent solution; RFV – Relative Feed Value – a ranking index for digestability and intake potential.

Table 2. NITROGEN AND PHOSPHORUS FERTILIZATION

YEAR	N kg/ha	P kg/ha
01 & 02	542	185
2003	341	183
TOTAL	883	368

Table 3. TOTAL N AND P ABSORPTION BY THE GRASS 2001-2003

TREATMENT	N/kg/ha	P/kg/ha*
1	819	178
2	1210	258
3	1208	241
4	1412	241
Average	1162	230

*** P Absorption only in 2003**

Table 4. Total dry matter production in kg/ha 2002-2003

	PERCENT OF WATER APPLICATION/EVAPOTRANSPIRATION INDICE			
	T 1 – 40%	T2 – 80%	T3 - 120%	T4 -160%
DRY MATTER PRODUCTION	52,586	74,774	76,839	78,142

Figure 1: Elephant grasses (*Pennisetum sp)* grows in clumps or stools (Top) and have an upright growth habit as they attain heights of greater than six feet.

Figure 2: Cows grazing Elephant grass irrigated with dairy waste, California State University, Fresno, Center for Irrigation Technology

Figure 3

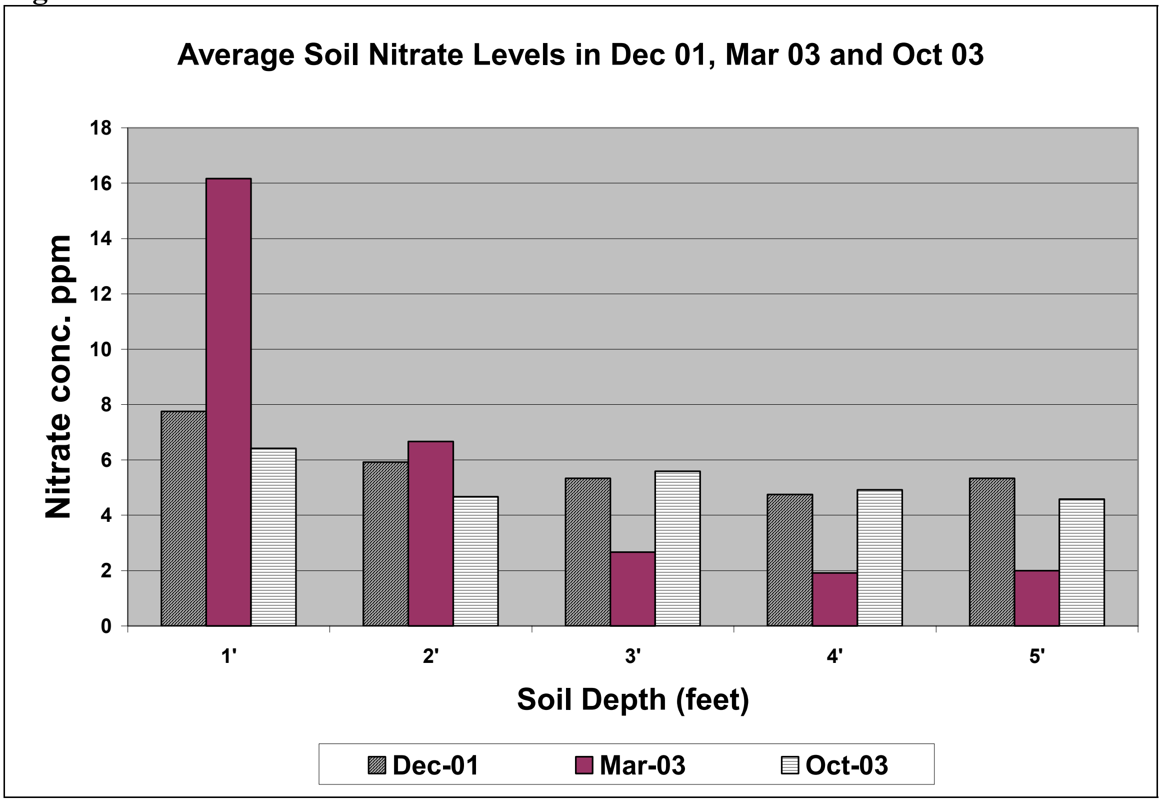
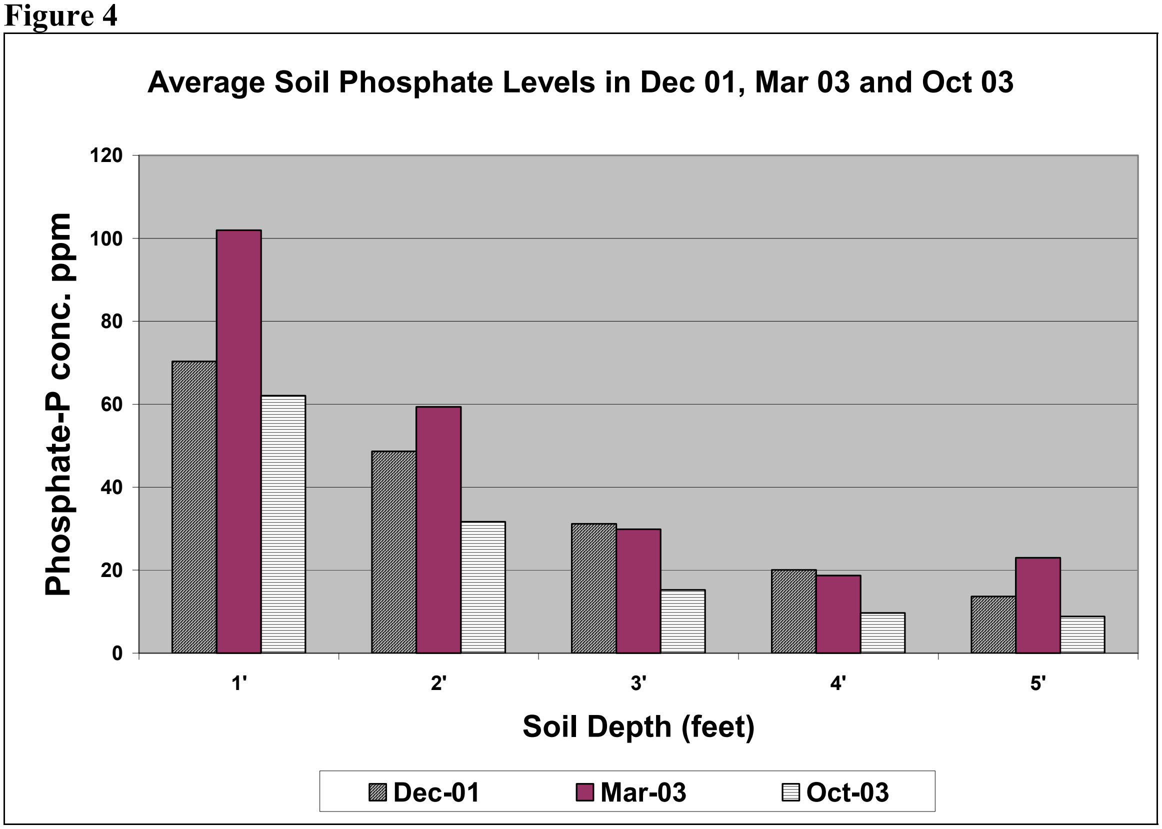


Figure 4



AZSCHED - **A**ri**Z**ona Irrigation **SCHED**uling System

Edward C. Martin[1] Donald C. Slack

ABSTRACT

Water for irrigation is quickly becoming a scare commodity in the western US. This is especially true in Arizona, where the state is in the sixth year of below normal precipitation. An irrigation scheduling program called AZSCHED (**A**ri**Z**ona Irrigation **SCHED**uling) has been developed by researchers at the University of Arizona, Tucson, AZ. The program utilizes real-time weather data from the AZMET (**A**ri**Z**ona **MET**eorological system) system in conjunction with user entered soil, water and crop inputs to recommend irrigation dates and amounts. The program is Windows-based and is can be downloaded from the Internet. Growers in Arizona and surrounding states have used to the program to schedule cotton, wheat, alfalfa and vegetable crops.

INTRODUCTION

As the quantity and quality of irrigation water is reduced in the West, agricultural producers are constantly being pressured to reduce their water use. Although newer, more water efficient irrigation systems can be installed, often these systems are not economical for growers. Thus, growers are looking for ways to better manage their water with the systems already in place. Several options are available including irrigation scheduling.

To help growers increase their water use efficiency, the University of Arizona's Department of Agricultural and Biosystems Engineering developed a computerized irrigation scheduling program called AZSCHED (**A**ri**Z**ona irrigation **SHED**uling) (Fox et al., 1992; Martin, et al., 2003). AZSCHED calculates the crop evapotranspiration (ET_c) as the product of a crop coefficient (K_c) and a reference evapotranspiration (ET_o). ET_o is estimated from real time weather data using the modified Penman equation (Doorenbos and Pruitt, 1977). Crop coefficients are taken from 22 crop curves developed from existing water use data and normalized by heat units to account for climatic variability (Slack et al., 1996; Martin et al., 1996). In this paper, we discuss the use and operation of the AZSCHED system. Originally developed in 1992 by Fox et al., the program is now a Windows-based program available for downloading on the Internet (Martin, et al., 2003).

AZSCHED can only be run under Windows-based operating systems. These systems include Windows NT, Windows 98, or Windows XP. If real time weather is to be used, then an internet connection may be useful. It is recommended that the computer used to run the software have at least 20MB of free hard disk space for the program files and associated Visual Basic .DLL files.

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PROGRAM STRUCTURE

AZSCHED can be downloaded directly form the Internet from **http://ag.arizona.edu/crops/irrigation/irrigation.html.** In addition to the program itself, a Users Guide is downloaded. This handbook is available by clicking "Help" on the first screen of AZSCHED. There are four options on the initial screen: Field Options; Weather Data; Configuration and Exit. Figure 1 shows the initial screen. The following is a brief description of the first three options.

Field Options

This is the portion of the programming where the majority of the user/program interface takes place. Choosing this option, the user is given five additional options plus a "Go Back" button to return to the main menu. A diagram of the screen is shown in Fig. 2.

Field Display

This option will display all of the fields currently being scheduled. The user can choose on how the fields are displays (i.e., according to planting date, crop type, next irrigation or field name). The total number of fields displayed on the screen at one time is determined by the user entered value from the "Configuration" option in the main menu. The fields are displayed in color according to their irrigation needs. Green fields are within the specified soil moisture, yellow fields are closing approaching irrigation or harvesting and red fields are in need of irrigation immediately.

Field Selection

In this option, the user can either select a field to be updated, create a new field, or select a field to be harvested/deleted. Harvested/deleted fields are removed for the field list but the data is saved. Thus, if the user wanted to review data from a field harvested several years ago, it would still be possible to go back and printout a summary/history of that field.

<u>Creating a new field</u>

The creation of a new field requires several inputs from the users and it would be best to gather the information prior to initiating a field. The first screen asks for crop type and soil data format. Crop type is selected from a list. For the soil format, there are two choices: Fixed soil layers – Soil are defined by "fixed" layers of a certain thickness. For example, the soil can be defined every 6 inches… or every 12 inches. Or, the soil format can be defined as Variable soil layers – where each individual layer is defined. Thus, if the soil has about 3 inches of top soil, then 6 inches of clay, then 7 inches of sandy clay, etc., this option will allow the user to define the thickness of each individual layer.

Next, the user needs to input a field ID, planting date, a weather station nearest the field being scheduled, an irrigation efficiency and the maximum allowable deficiency (MAD). The MAD should be in percent and is the threshold of the percent of soil water deficit in the plant rootzone at which the user wants an irrigation to occur. There is also a selection for soil, asking whether the user wants to enter new soil data, use soil data from an existing field or use soil data from a harvested/deleted field. Then the user is given the option to alter the crop's maximum rooting depth.

If the crop to be scheduled is alfalfa, then there are two more entries. One is the Critical MAD and the other is the Field Drying Time. The Critical MAD is a depletion percentage that you never want the field to fall below. Quite often, the cutting date and the scheduled irrigation date conflict. Thus, the program may be calling for irrigation the day before a scheduled cut. In order to avoid this, the program will use the Critical Mad and the Field Drying Time. The default for the Field Drying Time is 7 days. This means that the field can be safely entered with machinery 7 days after an irrigation event. The program will calculate this and may ask for an irrigation earlier than the entered MAD to assure that the hay will be cut and removed before the soil water falls below the Critical MAD. Normally, the Critical MAD is set 5-10% higher than the MAD.

Once this information is entered, the program will automatically check to see if there is weather data available for the field created. If not, a window will now pop up saying that weather data is required. The user can then either download data automatically from the Internet or use default data. The internet data will be automatically downloaded from the AZMET (the University of Arizona's weather station system; Brown, 1998) website and will download data from the weather station the user entered. The second option is to allow the program to use default weather data. The program automatically computes weather data for your station based on the average over many years. This data is not the best to use for scheduling since it uses averages.

<u>Soils Data</u>

When initially setting up the field, the user had the option to either enter soil water data one of three methods: 1) Enter new data; 2) Use data from an existing field; or 3) Use data from a harvested/deleted field. If the user chose to enter new data, a soil screen will appear requesting information of the soil's available water holding capacity and the initial soil water content at planting. If options 2 or 3 were chosen, the user is given a list of existing or harvested/deleted fields to choose from. Once the soils data is entered, the program then predicts the next irrigation.

Field Options

The *Field Options* pull-down menu allows the user to enter data throughout the season on water added to the field. It also allows the user to change certain parameters such as the MAD, irrigation efficiency or field depletion. The user can also get a quick view of the Field Summary and Field Details.

Field Reports

This pull down menu has three options: 1) Print/Save/View irrigation schedule for all fields; 2) Print/Save/View the field report for the field selected; 3) Print the field report for a harvested/deleted field. The irrigation schedule gives a list of all fields presently being scheduled, their present soil water status and the predicted next irrigation date, along with irrigation amount. For alfalfa, the next predicted cutting data is also give.

The field report (Fig 3) contains daily data on the selected field including the following (Text in **bold** is how the data is reported in the field report):

Date
Day (DAP) - days after planting
Avail (in) - available water in inches
Depl (%) – percent available water depletion
GDD (F) – growing degree days in Fahrenheit, for that day
GDD (Cumm) – cumulative growing degree days in Fahrenheit
ETR (in) – Reference Evapotranspiration (ET) for that day, in inches
ETR (Cumm) – cumulative ETR
Kc – crop coefficient
Kd – soil dryness coefficient
ETC (in) – crop ET. It is the ETR times the Kc times the soil dryness factor, in inches
ETC (Cumm) – cumulative ETC
Irr (in) – irrigation amounts
Rain (in) – rainfall amounts
Cut No. – the number of the cut that was taken off a field (for hay only)

The final option is to print a field report of a harvested/delete field. This report is the same as previously described in the last paragraph. However, since these are harvested/deleted fields, only printed copies can be obtained.

Weather Data information section

The "Weather Data" is chosen from the main menu and gives the user several options of adding or viewing weather data. If not previously done, the program will first prompt the user to choose a weather station. Then the user can choose from two pull down menu: 1) Add Weather Data; 2) View Weather Data (Fig. 4).

Add Weather Data

In this section the user can: 1) download data from AZMET; 2) enter/edit weather data; or 3) load default weather data. Downloading AZMET data allows the user to download weather data without having to have a field to schedule. This way, the user can view weather data from any available AZMET station. Option 2, enter or edit weather data, allows the user to enter weather data for any AZMET station. Caution must be used here because the entered data will be saved by the program and used to schedule irrigations. This option should only be used when it is known that the weather data already saved by AZSCHED is incorrect. Loading default weather data can be helpful if there is no Internet connection and the user wants to view historical averages.

View Weather Data

This selection allows the user to view the weather data from the selected station for years that have been downloaded, either directly in the menu or automatically through scheduling. The user also has the option of printing the weather data shown on the screen or printing the entire weather file.

Configuration section

This section allows the user to change the date the program has set as today's date, set units to English or metric, and set field display – which allow the user to change the number of fields that are displayed on your computer screen when the Field Options > Field Displays menu choice is selected. Figure 5 shows an example of the Field Display.

ESTIMATING CROP WATER USE

AZSCHED uses the "water-balance method" to estimate daily crop water use. In this approach, the soil is viewed as a water storage reservoir from which plants extract water. This water is then replaced by either irrigation or precipitation. In using this method, reliable information on the soil available water holding capacity (AWC) is essential. The AWC is generally defined as the amount of water retained in the soil between "field capacity" (FC) and the "permanent wilting point" (PWP).

Crop water use is estimated using a calculated reference crop evapotranspiration (ET_o) data and a crop coefficient. The method used in AZSCHED for estimating ET_o is the FAO Modified Penman equation (Doorenboos and Pruitt, 1977). This equation estimates the ET of a healthy, cool season grass, 8-15 cm in height maintained in a well watered environment. The Modified Penman equation requires daily information on max/min temperatures, max/min relative humidity, net radiation, wind speed and the day/night wind ratio. The equation, often refereed to as the combination equation, has the form:

$$ET_o = c * [W * R_n + (1 - w) * f(u) * (e_a - e_d)] \qquad (1)$$

Where c is an adjustment factor to compensate for the effect of day and night weather conditions; W is a temperature related weighing factor, f(u) is a wind function, R_n is the net radiation equivalent in mm/day and (e_a-e_d) is the vapor pressure deficit.

To estimate actual crop water use, AZSCHED uses the ET_o data with crop coefficient values (K_c), derived from several sources (Erie, et al., 1982; Sammis et al., 1985; Martin, et al., 1996). The crop coefficient is defined as:

$$K_c = \frac{ET_c}{ET_o} \qquad (2)$$

Where ET_c is the actual crop evapotranspiration and ET_o is calculated as previously described.

A unique feature of AZSCHED program is the use of growing degree days (gdd) as the unit of time measurement. Growing degree days (gdd) are often referred to as heat units or thermal time. In its simplest form, gdd are defined as:

$$gdd = T_{mean} - T_{base} \quad (3)$$

Where T_{mean} is the daily mean air temperature and T_{base} is the minimum daily mean air temperature required for crop growth. The value of T_{base} is unique to the crop. Equation 3 is only valid when $T_{base}<T_{mean}<T_{max}$. In areas such as Arizona, where summer temperatures often rise well above 100 °F, an upper threshold temperature similar to T_{base}, and referred to as T_{max} is required. If $T_{mean}>T_{max}$, then formula for computing gdd is:

$$gdd = T_{\max} - T_{base} \quad (4)$$

Where T_{mean} is the daily mean air temperature and T_{max} is the maximum daily mean air temperature that once reached, no additional significant crop growth occurs. Snyder (1985) developed a method for calculating gdd for a variety of temperature scenarios. This method was used in the AZSCHED program to determine daily gdd accumulation.

CONCLUSION

The use of irrigation scheduling and scheduling tools such as soil moisture measuring devices, flow rate measuring devices and knowing crop water requirements have all helped growers in Arizona save water. Reports in the state have shown that growers have reduced or eliminated irrigations due to the implementation of information provided by this program. For example, in 1998, the Pima County, AZ, Active Management Area used AZSCHED in their water management program. They reported that two growers eliminated an irrigation saving almost 400 acre-feet of water and over $13,000. They also reported many growers reduced the amount of irrigation water applied for each irrigation.

More than 200 copies of the new AZSCHED program have been downloaded from the Irrigation website since it became available in June 2003. Additionally, 30 copies have been sent out on CD disks to extension, state and federal personnel (both in and out of state). Personnel from ADWR used AZSCHED to determine crop water needs for state programs that regulate water allocations. They also list irrigation scheduling as one of their acceptable Best Management Practices (BMP) for their water conservation program.

Discussions with growers have helped to reprogram much of the new AZSCHED version. In one case, working with a grower who used a low-flow sprinkler system, the default rooting depth did not fit his field situation. As a result, a new option allowing the user to better define crop-rooting depth was installed.

AZSCHED has also gain acceptance outside the state. In New Mexico, AZSCHED has been used for several years as a recommended scheduling tool. Researchers there have even developed crop data that can be used with AZSCHED. In Iowa, AZSCHED was used to schedule sweet corn (Taber and Smith, 2000) and bell peppers (Taber and Lawson, 2001). A sunflower study in North Dakota (Ashley, et al., 2002) utilized the AZSCHED program to help with irrigation management. In Mexico, the AZSCHED has been presented at conferences and taught in grower workshops as a viable irrigation scheduling tool.

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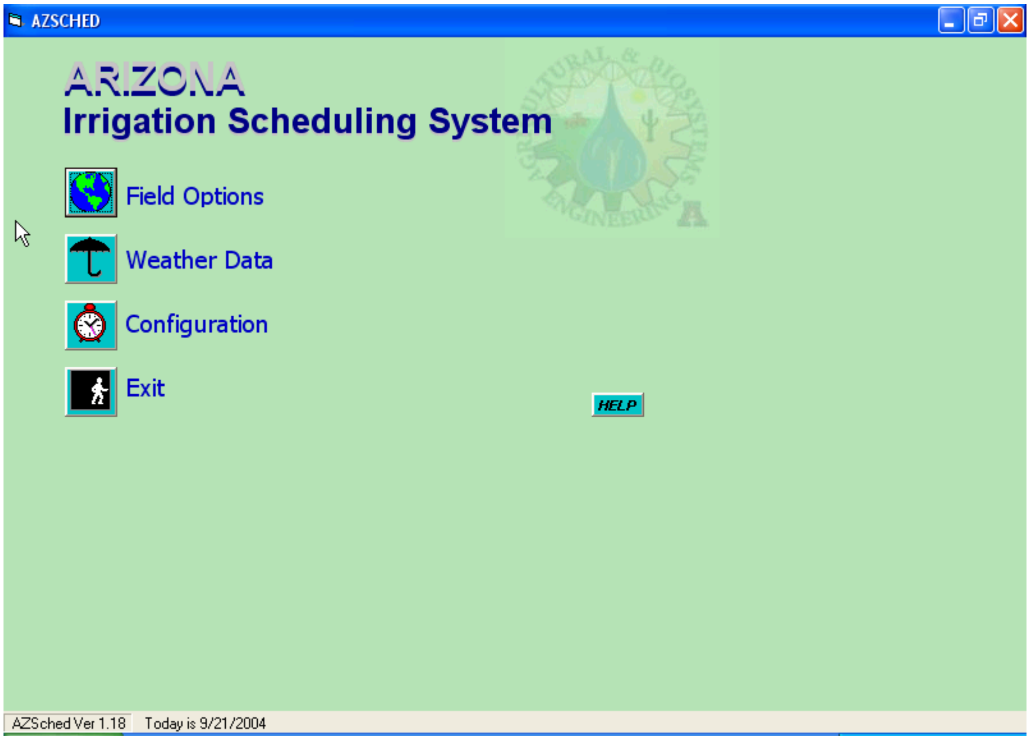
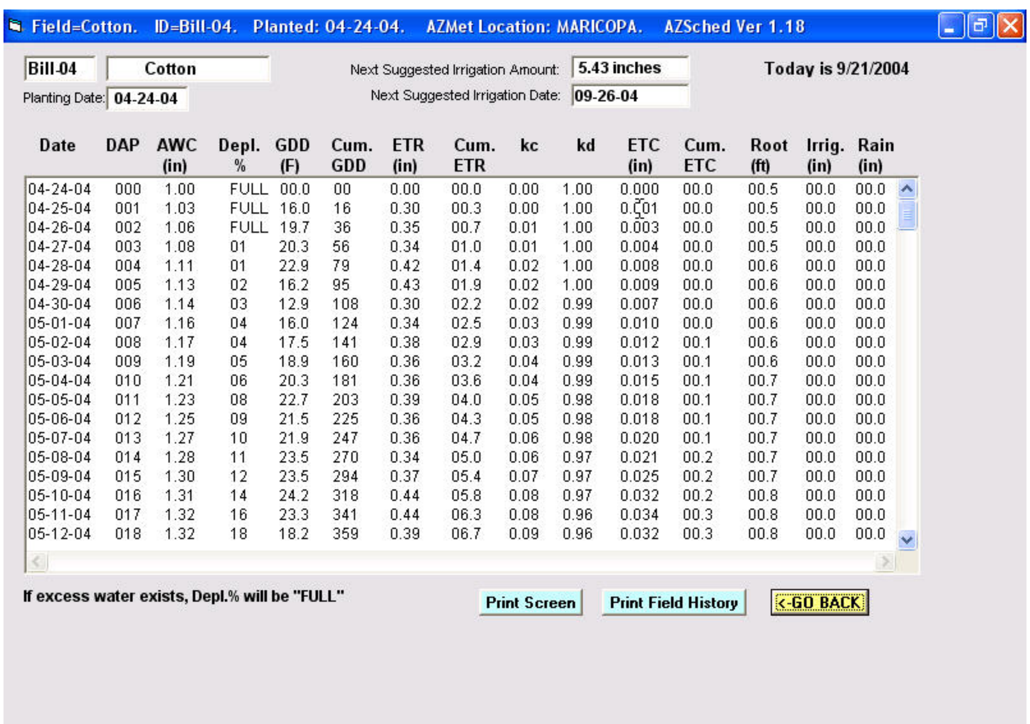


Figure 1. The main menu screen for the AZSCHED program.

Figure 2. The Field Options screen from AZSCHED. This screen shows data from an alfalfa crop planted in late December, 2000.



Date	DAP	AWC (in)	Depl. %	GDD (F)	Cum. GDD	ETR (in)	Cum. ETR	kc	kd	ETC (in)	Cum. ETC	Root (ft)	Irrig. (in)	Rain (in)
04-24-04	000	1.00	FULL	00.0	00	0.00	00.0	0.00	1.00	0.000	00.0	00.5	00.0	00.0
04-25-04	001	1.03	FULL	16.0	16	0.30	00.3	0.00	1.00	0.001	00.0	00.5	00.0	00.0
04-26-04	002	1.06	FULL	19.7	36	0.35	00.7	0.01	1.00	0.003	00.0	00.5	00.0	00.0
04-27-04	003	1.08	01	20.3	56	0.34	01.0	0.01	1.00	0.004	00.0	00.5	00.0	00.0
04-28-04	004	1.11	01	22.9	79	0.42	01.4	0.02	1.00	0.008	00.0	00.6	00.0	00.0
04-29-04	005	1.13	02	16.2	95	0.43	01.9	0.02	1.00	0.009	00.0	00.6	00.0	00.0
04-30-04	006	1.14	03	12.9	108	0.30	02.2	0.02	0.99	0.007	00.0	00.6	00.0	00.0
05-01-04	007	1.16	04	16.0	124	0.34	02.5	0.03	0.99	0.010	00.0	00.6	00.0	00.0
05-02-04	008	1.17	04	17.5	141	0.38	02.9	0.03	0.99	0.012	00.1	00.6	00.0	00.0
05-03-04	009	1.19	05	18.9	160	0.36	03.2	0.04	0.99	0.013	00.1	00.6	00.0	00.0
05-04-04	010	1.21	06	20.3	181	0.36	03.6	0.04	0.99	0.015	00.1	00.7	00.0	00.0
05-05-04	011	1.23	08	22.7	203	0.39	04.0	0.05	0.98	0.018	00.1	00.7	00.0	00.0
05-06-04	012	1.25	09	21.5	225	0.36	04.3	0.05	0.98	0.018	00.1	00.7	00.0	00.0
05-07-04	013	1.27	10	21.9	247	0.36	04.7	0.06	0.98	0.020	00.1	00.7	00.0	00.0
05-08-04	014	1.28	11	23.5	270	0.34	05.0	0.06	0.97	0.021	00.2	00.7	00.0	00.0
05-09-04	015	1.30	12	23.5	294	0.37	05.4	0.07	0.97	0.025	00.2	00.7	00.0	00.0
05-10-04	016	1.31	14	24.2	318	0.44	05.8	0.08	0.97	0.032	00.2	00.8	00.0	00.0
05-11-04	017	1.32	16	23.3	341	0.44	06.3	0.08	0.96	0.034	00.3	00.8	00.0	00.0
05-12-04	018	1.32	18	18.2	359	0.39	06.7	0.09	0.96	0.032	00.3	00.8	00.0	00.0

Figure 3. A sample of the Field Report from AZSCHED.

Figure 4. The Weather Menu from the AZSCHED program.

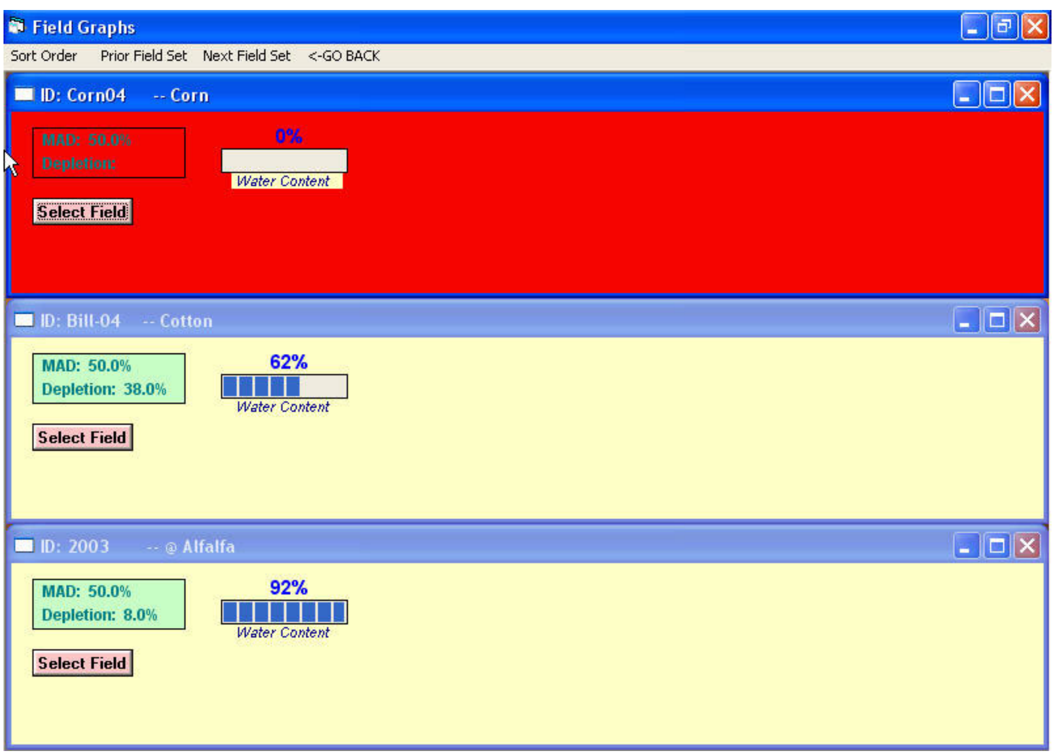


Figure 5. The Field Display screen from AZSCHED.

Modern Electronics for Agriculture

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Abstract

The field of electronics continues to change and evolve rapidly. Electronics are increasingly being used to collect and process all types of data, transfer information, make decisions, and provide automation and control functions. Modern microcontrollers and semiconductor components offer many advantages and ease of use in designing custom measurement and control systems. An array of microcontrollers, sensors, and accessory components are presented and their features, capabilities, and costs are discussed. Several measurement and datalogging circuits were designed for use in irrigation-related research activities. The design, implementation, and performance of these systems are described.

Keywords: electronics, automation, microcontrollers, sensors

MODERN ELECTRONICS FOR AGRICULTURE

The field of electronics continues to change and evolve rapidly. Electronic components and assemblies can be found in a wide variety of industrial and commercial products, and with a wide variety of functions and capabilities. Modern household appliances, toys, and automobiles often contain microprocessors, sensors, displays, and data storage and transfer systems.

Electronics are increasingly being used to collect and process all types of data, transfer information, make decisions, and provide automation and control functions. Electronic components are increasing in their capabilities, while becoming easier to use, smaller in size, and cheaper to buy. Many more specialized components and sensors are available which interface easily and simplify circuit design.

The microcontroller is an important element in modern electronics, and has brought about a change in the way electronic circuits are designed. A microcontroller is a device that interfaces with external components, can input and output information to and from these external components, and can be programmed by the user. It is similar to the central processing unit (CPU) of a personal computer in that it is very flexible and can be programmed to do a wide variety of things.

In the past, significant electronics expertise and experience were required to design a circuit. Now, with a microcontroller, a circuit can be designed much more simply because many of the desired functions can be accomplished in the microcontroller's software. Examples of functions easily accomplished with a microcontroller include; timing (doing something at regular intervals, or measuring elapsed time between events); calibration (converting a raw measurement to a quantity in the desired units); accurate signal measurement (measuring a voltage level or frequency from a sensor); data output (transferring measured data or information to another device, computer, or display).

The number and capabilities of semiconductor sensors and auxiliary components that interface easily with microcontrollers have also increased. Many components, such as sensors, clocks, memory chips, and display units are designed to connect directly to microcontrollers, operate over compatible voltage ranges, and communicate easily with one another. These components usually require minimal external circuitry, have low power requirements, and are controlled in software.

These modern electronic components can be put to use in agriculture as in the many other applications in which they already serve. The availability, compatibility, and ease of use combine to offer many advantages to using microcontrollers and semiconductor components to create measurement and control systems.

The objective of this paper is to present and discuss some of the current, powerful, inexpensive, and easy-to-use electronic components available to and of potential use in agricultural research. The function, operation, and costs of some of these components will be discussed, and a number of examples of their use will be presented.

MATERIALS

Microcontrollers

The number of manufacturers, number and variety of products, and capabilities of the products continue to grow each year. Cravotta (2004) lists 45 manufacturers of microcontroller products, and gives an overview of the target applications, users, and capabilities of each manufacturer's product lines. Rather than discussing the many microcontroller options, capabilities, and differences, however, experiences with two microcontrollers from one manufacturer will be presented.

The PIC microcontrollers from Microchip (Microchip Technology Inc. [1], Chandler, Arizona USA, www.microchip.com) were chosen due to their widespread use and availability, ease of programming, low cost, and advanced features. PIC microcontrollers are among the most popular in use today, and are used in many diverse applications. Much information is available, especially on the Internet, in the form of application notes, project descriptions and documentation, circuit diagrams and schematics, program code, and user forums.

PIC microcontrollers are available in a range of sizes and features. Sizes range from 8 pins to 84 pins. Available features include digital and analog input and output, analog-to-digital (A-D) converters, serial ports, USB capability, varying processor speeds, built-in oscillators, timers, and varying amounts of program memory.

The work presented in this paper was accomplished using two different PIC microcontrollers, the 16F819 and the 16F877. The 16F819 was chosen for its size and features: it has 16 input/output pins, five 10-bit analog-to-digital converters, a built-in oscillator, an adjustable processor speed, serial-port capability, and a large program memory area. The 16F877 has similar capabilities, but with additional input/output pins.

Programming

An additional reason for selecting the PIC microcontrollers was for their ease in programming. A number of programming environments are available for PIC microcontrollers, including assembly language, C compliers, and BASIC compilers. Programming environments are available free of charge, including an assembly-language programming environment provided by Microchip, while others can be purchased. Many code examples and complete programs for these and other programming environments can be found on the Internet.

Among the simplest programming environments are PicBasic and PicBasic Pro (MicroEngineering Labs, Inc., Colorado Springs, Colorado USA). These versions of the BASIC programming language include many functions which greatly simplify the programming of the microcontrollers. Functions are included for using the PICs' analog-to-digital converters, communicating with other digital chips via common protocols (such as I2C and SPI), outputting information to serial ports and LCD displays, measuring frequencies and pulsewidths, outputting analog signals, and enabling interrupts and power-saving features. Once a program has been written, the PicBasic compiler converts the BASIC program to the proper format for downloading to a PIC. While the PicBasic programming environments are not free (PicBasic costs about US$100, PicBasic Pro about US$240), they are much easier to learn and use than assembly language.

A hardware interface is required to download the compiled program to the microcontroller. One such interface, the EPIC programmer (MicroEngineering Labs, Inc.), connects to a computer's parallel port, includes software for editing and downloading a program, is compatible with most PIC microcontrollers, and costs about US$60. Other programmers are available for purchase, and many plans and schematics can be found on the Internet for building simple programmers.

Sensors

Many different sensors are available for measuring a variety of variables. These inexpensive, semiconductor sensors operate in low voltage ranges and interface easily with microcontrollers. Examples of sensors available for measuring parameters of interest in agriculture are discussed in Fisher et al. (2003) and presented herein.

Temperature

Analog temperature sensors are available which output a voltage that is linearly proportional to

[1] **The mention of trade or manufacturer names is for information only and does not imply an endorsement, recommendation or exclusion by USDA-Agricultural Research Service.**

temperature. The LM35 (National Semiconductor), for example, requires an excitation voltage of 5 Vdc, and is calibrated to output a voltage with a 10 mV / °C scale factor. The output voltage is read with an analog-to-digital converter, and the voltage is converted to a temperature reading in the microcontroller's software. The LM35 temperature sensor costs about $2.

Infrared thermometer

In some applications, a non-contact or remote temperature measurement is required. The MX90601 (Melexis) infrared thermometer module was designed for automotive and consumer appliance applications, and provides remote and ambient temperature measurements in analog voltage and digital signal form. The module requires an excitation voltage of 5 Vdc, and the analog output voltage can be read with the microcontroller's A-D converter. The voltage is then converted to temperature in the microcontroller's software using the manufacturer's calibration equation. The MX90601 infrared thermometer module costs about $53.

Pressure

A family of pressure sensors manufactured by Motorola is particularly well-suited for use with microcontrollers. The MPX5xxx sensors are available in a number of pressure ranges: from 0 – 10 kPa (0 - 1.45 psi) with the MPX5010, to 0 – 700 kPa (0 - 101.5 psi) with the MPX5700. The sensors require a 5 Vdc excitation signal and return a signal in the range of 0.2 to 4.7 Vdc. The PIC microcontroller's internal 10-bit A-D converters provide pressure measurements with a resolution of 0.011 kPa (0.0016 psi) with the MPX5010, and 0.76 kPa (0.11 psi) with the MPX5700. The MPX5xxx series of sensors cost about $20 each.

Object detection / distance

Non-contact or remote distance/depth measurements can be made using ultrasonic rangefinders similar to those used in autofocus cameras. The Devontech SRF04 rangefinder is a module that contains an ultrasonic transmitter and a detector, and interfaces easily with a microcontroller. The microcontroller triggers the transmitter, which sends a pulse, and measures the length of time for the pulse to return. The microcontroller then calculates the distance based on the time interval. The SRF04 can measure distances within a range of 3 cm to 3 m, and costs about $35.

Other variables

Additional semiconductor sensors are available for measuring many other variables, and interface easily with microcontrollers. There are sensors for measuring acceleration, humidity, proximity, illumination, location (GPS coordinates), and rotation, for example. Many of the sensors return an analog voltage in the range of 0 to 5 Vdc, a digital signal, or a frequency, and require an excitation voltage of 5 Vdc. Other sensors, such as soil-moisture sensors, strain-gage loadcells, and conductivity sensors, which are often connected to traditional dataloggers, may also be suitable for use with inexpensive microcontrollers.

Auxiliary Components

Additional components are usually required to provide other, necessary functions and complete the measurement system. While the microcontroller provides many of the control and process functions, additional components may be needed for timekeeping, data storage, peripheral equipment control, and data transmission.

Timekeeping

Real-time clocks provide time and date functions very simply. Real-time clocks such as the Dallas Semiconductor DS1307 and DS1337 interface easily to a microcontroller and are accessed by the microcontroller's software. A crystal oscillator connects to the clock chip to provide an accurate timing signal, and a backup battery maintains operation when the microcontroller is in low-power sleep mode or is disconnected from its power source. The DS1307 costs $2, the DS1337 costs $3, and an oscillator costs $0.75.

Storage memory

Most microcontrollers do not normally provide memory for long-term data storage. External memory chips, such as Maxim's 24LCxxx series, are available which can store from 1 kbyte to 512 kbytes of data. The non-volatile memory is accessed via the microcontroller's software, and data can be written and read randomly. The chips cost about $2 each.

Analog-to-digital converters

While many microcontrollers have internal analog-to-digital converters, a variety of external A-D converters are available. External A-D converters can provide higher resolutions, faster measurements, differential voltage measurements, and multiple input channels. The MAX340x series from Maxim, for example, can be programmed to provide variable resolutions ranging from 8- to 16-bits. A lower-resolution setting can be used if less accuracy but a higher sampling rate is needed, while a higher-resolution setting allows for greater accuracy but more time required for each measurement. The MAX340x ADCs cost about $5 each.

LCD displays

Simple and inexpensive LCD displays can be connected for displaying text, while more expensive displays can be used to display graphics. The microcontroller can be programmed to read pushbuttons or keypads to allow users to select options, use menus, or input information to the microcontroller.

RF transmitters and receivers

Radio frequency (RF) transmitters and receivers provide remote sensing, control, and data transmission capabilities. RF transmitters and receivers connect directly to the microcontrollers with no external components, other than an antenna, and operate with simple microcontroller programming. Transmission ranges up to about 300 ft are common, and several frequencies are available which require no FCC licenses for use. One example, the TXS-434 (Laipac), costs about $5.

Example Applications

Collecting agricultural field data can be labor-intensive, time-consuming, and costly. By automating sensor measurements, data can be collected much more frequently and reliably with much less effort. A few examples of data-collection equipment constructed using microcontrollers and semiconductor components are presented in the following sections.

Automated Soil Moisture Monitoring

Moisture sensors (Irrometer, Model 200SS) had been installed at many locations in a number of cotton, corn, and soybean fields at the USDA ARS research station at Stoneville, Mississippi, for use in scheduling irrigations. There were 4 to 18 sensor locations per field, with three sensors installed at different depths in the soil profile at each location. In previous years, sensor readings had been collected periodically by a technician walking to each sensor site, attaching a hand-held electronic meter to each sensor, taking measurements, and recording the readings on a data sheet. Given the number of measurements to be made, the time involved, and other factors, such as inclement weather, weekends and holidays, and other fieldwork, measurements from each sensor were normally collected only once or twice per week.

A circuit board was designed prior to the 2004 growing season to automate the moisture-sensor measurements. Circuit design parameters included the ability to power the moisture sensors, make readings at regular intervals, store the readings, and operate on battery power.

An important consideration in powering the sensors was that the moisture sensors required an AC (alternating current) excitation rather than the DC (direct current) energy supplied by a battery. An AC circuit designed by EME Systems (EME Systems, 2002) was modified and used to provide the proper excitation to the sensors.

The output signal from the sensors was in the form of a frequency which was linearly related to the resistance of the sensor, and ultimately to the water potential of the sensor/soil. A calibration equation was developed to convert frequency to water potential. A series of known resistances was connected to the circuit, and the corresponding frequency from the circuit board was recorded. The known resistances were then connected to the moisture-sensor meter, and the corresponding water potential values were recorded. Correlating these data yielded a calibration equation which provided a water potential value based on output signal frequency.

The main components of the circuit consist of a microcontroller, AC-excitation circuit, multiplexer, real-time clock, memory chip, and batteries. The circuit was etched onto a copper-clad circuit board. Components were then soldered onto the board. Two temperature sensors were added to the circuit, one to measure the temperature of the circuit board, and a second to measure soil temperature. The component-side of the completed circuit board is shown in Figure 1. A list of the main components and their costs is shown in Table 1.

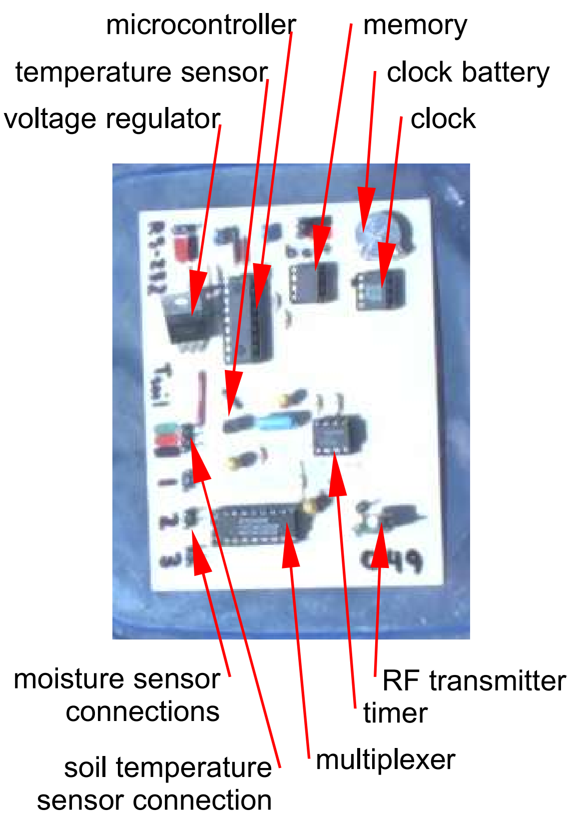

Figure 1. Component side of moisture-sensor circuit board.

Table 1. Parts list and cost of main components on moisture-sensor circuit board

Description *Part number, Manufacturer*	Cost (US$)
Microcontroller	
PIC 16F819, Microchip Technologies	3
Clock	
DS1302, Dallas Semiconductor	3
Memory	
24LC512, Microchip Technologies	3
Multiplexer	
74HC4051, Phillips Semiconductors	1
RF transmitter	
TX-434, Laipac	5
Circuit board	1
Batteries	2
Miscellaneous (resistors, capacitors, pins, timer, voltage regulator)	2
total	$20

The microcontroller was programmed to make and store measurements at 2-hour intervals. The microcontroller continuously monitored the real-time clock, which had a backup battery to maintain the correct time. At the beginning of each measurement interval, the microcontroller activated the AC-excitation circuit and multiplexer chip. The multiplexer selected one sensor at a time, the AC-excitation circuit powered the sensor, and the microcontroller measured the frequency. The microcontroller program applied the calibration routine to convert the frequency to water potential. The program then looped and continued the sensor-measurement process by instructing the multiplexer to select the next sensor, make a measurement, and continue until all sensors had been read. The date, time, and sensor measurements were stored in the memory chip, and the microcontroller then put itself into a low-voltage sleep mode to conserve battery power until the next measurement interval.

The circuit board was also designed to transmit the data out of the field automatically via an on-board RF transmitter. An RF receiver circuit located on one edge of the field would receive the data from all circuit boards within that field, making it quicker and easier to access the data without having to download the data manually from each individual circuit board. The receiver circuit design was not completed by the time the circuit boards needed to be deployed, however, and this feature was not enabled.

Circuit boards were deployed in the 2004 growing season to monitor moisture sensors installed in corn, soybean, and cotton fields. Measurements were made at 3 depths at each sensor location in the field. The three measurements were also averaged.

Sensor readings for two one-month periods are shown in Figures 2 and 3. In Figure 2, measurements collected manually during the 2003 growing season are shown. Nine visits to the field were made during this time period to collect data. Long-term trends are apparent, but conditions immediately after a rainfall or irrigation event are not detected.

Measurements collected automatically during the 2004 growing season are shown in Figure 3. The field was visited normally once per week, to visually inspect crop conditions, collect other data, and download moisture-sensor data. Much less time and labor were required to collect moisture data, and a much more complete picture of the moisture conditions was obtained by automating the measurements.

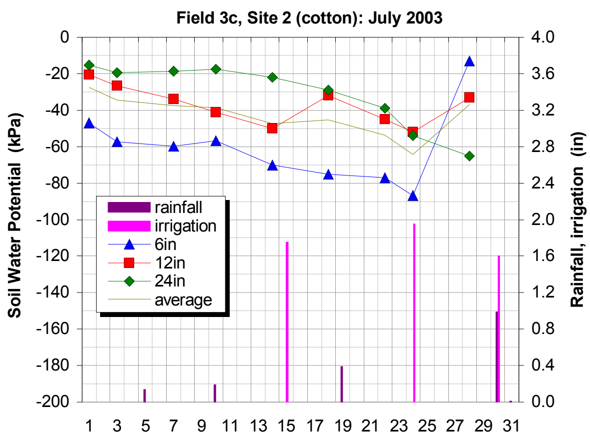

Figure 2. Moisture-sensor measurements collected manually, July 2003.

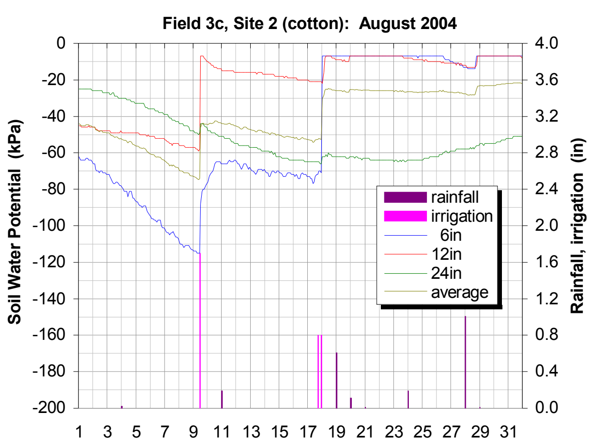

Figure 3. Moisture-sensor measurements collected automatically, August 2004.

Automated Evaporation Pan and Atmometer Measurements

Recent efforts to automate evaporation pan and atmometer readings have been described. Bruton et al. (2000) used a float mechanism to automate evaporation pan readings, but malfunctions in the mechanism and differences between manual and automated readings were noted. Dukes et al. (2004) described a low-cost (US$200) float and pulley datalogger system designed to automate atmometer readings.

An evaporation pan and atmometer were installed at the USDA ARS research station at Stoneville, Mississippi, for use in irrigation scheduling of cotton. Previously, pan and atmometer measurements were made manually, requiring frequent site visits, and recorded on a data sheet.

A circuit board was designed to automate the data-collection process. The metal evaporation pan was first modified by drilling a hole in the side of the pan. A barbed hose fitting was installed in the hole, and a differential pressure sensor was connected to the hose fitting with a short length of plastic tubing. The atmometer was modified in the same way: a hole was drilled in the side and a pressure sensor was attached.

The pressure sensors were used to measure the hydrostatic pressure of the water. The hydrostatic pressure is the pressure caused by the weight of the water, which is a function of its depth. The depth of water, then, could easily be determined by measuring the hydrostatic pressure and calculating the depth based on the pressure vs depth relationship for water.

The main components of the circuit board consist of a microcontroller, connectors for the two pressure sensors, real-time clock, memory chip, and batteries. The circuit was built on a prototype board, shown in Figure 4. The maincomponents of the circuit and their costs are shown in Table 2.

The microcontroller was programmed to make and store measurements at 2-hour intervals. The microcontroller continuously monitored the real-time clock, and when time came to make measurements, provided an excitation voltage to the pressure sensors. The pressure sensors were factory calibrated to provide a voltage signal linearly related to pressure. The microcontroller measured the signal voltages with its built-in analog-to-digital converters. The microcontroller program contained a calibration routine to convert the voltage signals to pressures and then to the depths of water. The

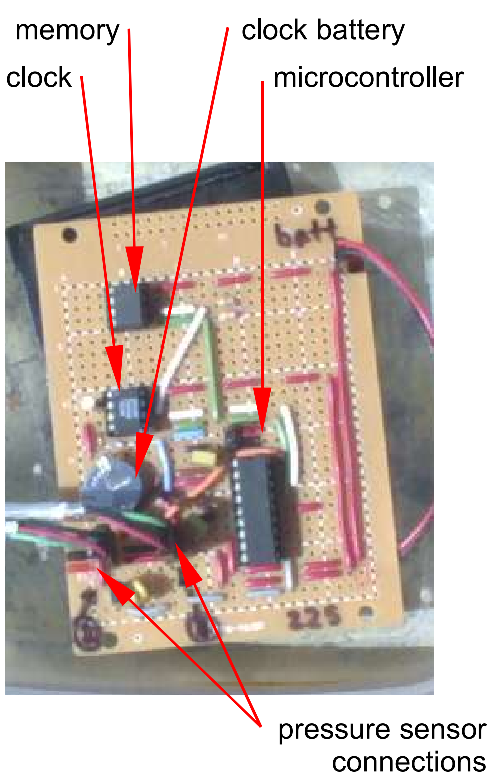

Figure 4. Evaporation-pan and atmometer measurement prototype circuit board.

Table 2. Parts list and cost of main components for evaporation pan/atmometer circuit

Description *Part number, Manufacturer*	Cost (US$)
Microcontroller	
PIC 16F819, Microchip Technologies	3
Clock	
DS1302, Dallas Semiconductor	3
Memory	
24LC512, Microchip Technologies	3
Pressure sensors	
MPX5010D, Motorola	20 ea
Circuit board	1
Batteries	2
Miscellaneous (resistors, capacitors, connector pins, voltage regulator)	2
total	$54

date, time, and water depth data were then stored in the memory chip, and the microcontroller put itself into a low-voltage sleep mode to conserve battery power until the next measurement interval.

To test the accuracy of the automated measurements, manual depth measurements were collected periodically and compared to those made with the circuit board. Manual evaporation-pan measurements were made by reading the metal scale in the evaporation pan. Manual atmometer measurements were made by reading the height of the water column in the clear plastic standpipe on the side of the atmometer. Data from the circuit board were downloaded periodically, and the automated and manual data were input to a spreadsheet for analysis and graphing.

Depth measurements from a 10-day period in September 2004 are shown in Figure 5. Manual measurements were made three times during this period, and compare well with the automated measurements.

Between April and September 2004, 55 manual measurements were made during visits to the site. Measurements were not made at any regular time, rather occurred at various times of the day between 0800 and 1600. The manual measurements were compared to concurrent automated measurements, shown in Figure 6. The automated measurements compared well

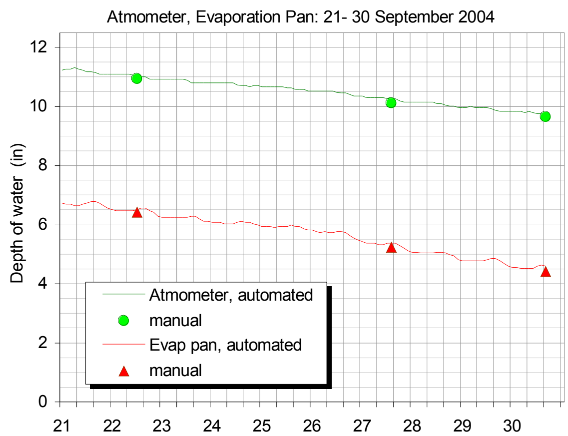

Figure 5. Automated and manual evaporation pan and atmometer measurements during a 10-day period in September 2004.

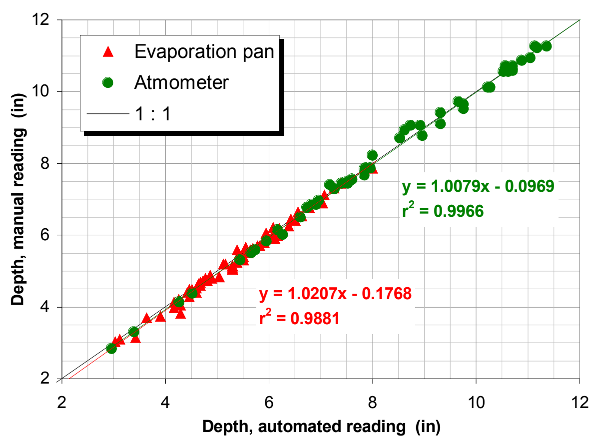

Figure 6. Comparison of automated and manual measurements.

with the manually collected measurements. Standard errors of the automated readings compared to the manual readings were 0.13 in for the evaporation pan and 0.12 in for the atmometer.

Pressure Chamber Controller

An important hydraulic property of a soil is its soil-water retention curve. The soil-water retention curve is the relationship between the soil's water content and water potential. A common laboratory procedure for developing the retention curve is described by Klute (1986), and involves determining the water content of a soil sample over a range of known water potentials.

The equipment used to develop a water retention curve normally consists of a pressure chamber and porous ceramic plate, a source of compressed air, and an air-pressure regulating system. The compressed-air source, usually an electric air compressor, supplies pressurized air to the pressure chamber. The pressure-regulating system maintains the pressure in the pressure chamber at the desired level.

One pressure-chamber system is commercially available (Soilmoisture Equipment Corp., Santa Barbara, California USA). The system consists of mechanical regulator valves, large pressure gages, metal piping, and an industrial-size air compressor. The system has a few potential drawbacks, however. The industrial, high-pressure compressor is noisy, and the equipment takes up considerable space. It is also expensive, and its purchase could be hard to justify for a small project or with a limited budget.

A system was designed to provide an inexpensive, well-regulated source of pressurized air to a pressure chamber for developing water retention curves. The system consisted mainly of an electric air compressor, an air storage tank, an electric solenoid valve, pressure sensors, and a PIC microcontroller circuit board. A sketch of the pressure chamber system is shown in Figure 7. A list of the components and their costs are shown in Table 3.

The system is controlled by a microcontroller which continuously monitors two pressure sensors. One sensor measures the pressure inside the pressure chamber. If this pressure decreases below the desired level, the microcontroller opens the solenoid valve for a fraction of a second. Higher-pressure air upstream of the solenoid valve enters the chamber, increasing the pressure inside the chamber. The second sensor measures the pressure inside the air storage tank, which is maintained at a pressure higher than that desired inside the pressure chamber. If the

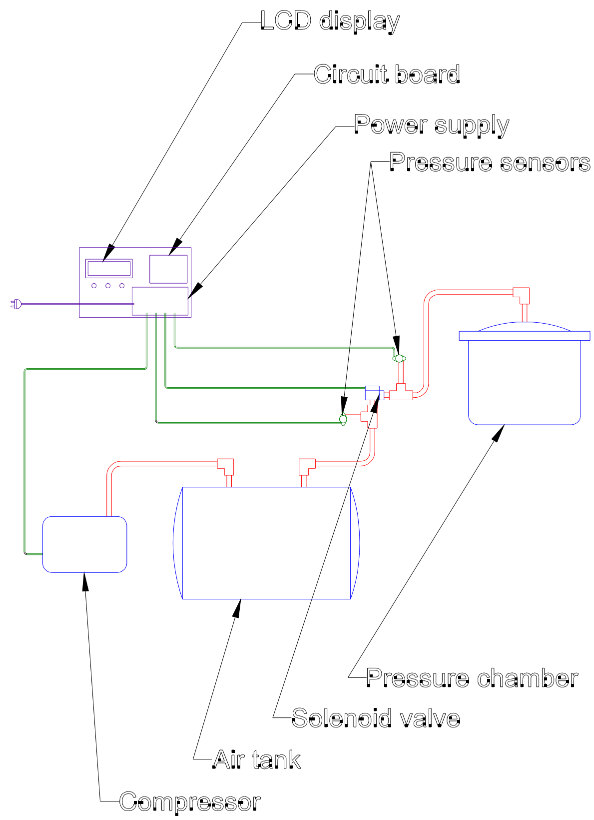

Figure 7. Sketch of components

Table 3. Parts list and cost of main components on pressure chamber controller

Description *Part number, Manufacturer*	Cost (US$)
Microcontroller *PIC 16F877, Microchip Technologies*	7
Pressure sensor *MPX5010D, Motorola*	20
LCD display	10
Circuit board	1
Batteries	2
Miscellaneous (resistors, capacitors, pushbuttons, LEDs, voltage regulator)	3
Power supply *MKS150-12, Astrodyne*	73
Solenoid valve *6011, Burkert*	27
Air compressor *12V Ultra, NuTech*	20
Air storage tank *41712, Central Pneumatics*	20
Plastic tubing, fittings	5
total	$188

storage-tank pressure decreases below a set level, the microcontroller turns on the air compressor. The compressor remains on until the pressure inside the storage tank is recharged. The microcontroller program loops continuously, monitoring the pressure sensors and adjusting the pressures at 1-second intervals.

The control circuitry consists essentially of a power supply, circuit board, and LCD display. The power supply converts the 120 Vac main electrical source to a 12 Vdc supply needed to run the air compressor and the solenoid valve. The 12 Vdc supply provides power to the microcontroller circuit, pressure sensors, and LCD display through a 5-Vdc voltage regulator.

The circuit board consists of a microcontroller, relays, three pushbuttons, and a few resistors, capacitors, and LED lights. Since the compressor and solenoid valve draw more electrical current than the microcontroller can tolerate, each is controlled by the microcontroller via a relay. Pushbuttons enable the user to increase or decrease the desired chamber pressure, and to temporarily pause the system to allow the pressure chamber to be opened and the soil samples accessed. LED lights indicate when the system is operating and when it is paused.

The system has performed well in initial testing. A range of chamber pressures from 10 kPa to 150 kPa have been tested, and the pressure inside the pressure chamber has remained within ±1 kPa of its set pressure.

Non-Contact Water Level Measurements

While pressure sensors are being used to measure water levels (see above), there may be occasions where non-contact measurements are desired. The use of a sensor which does not come into contact with the substance being measured would then be needed.

A circuit was designed for making non-contact depth measurements using an ultrasonic rangefinder. The rangefinder transmits a high-frequency acoustic pulse, which is reflected if it comes into contact with an object. A receiver is activated to detect the reflected signal. The distance of the object from the sensor can be calculated based on the time it takes for the pulse to be reflected and return to the sensor and the speed of sound in air.

The rangefinder was installed above the evaporation pan described previously, and used to measure the depth of water in the pan. Depth measurements were then compared to those made manually and with the pressure-sensor circuit described above.

The main components of the circuit board consist of a microcontroller, real-time clock, memory chip, transistor, connector for the ultrasonic rangefinder, and batteries. The circuit was built on a prototype board, shown in Figure 8. The main components of the circuit and their costs are shown in Table 4.

The microcontroller was programmed to make and store measurements at 2-hour intervals. When time came to make measurements, the microcontroller first energized the transistor, which acted as a switch to turn on power to the ultrasonic rangefinder. The microcontroller

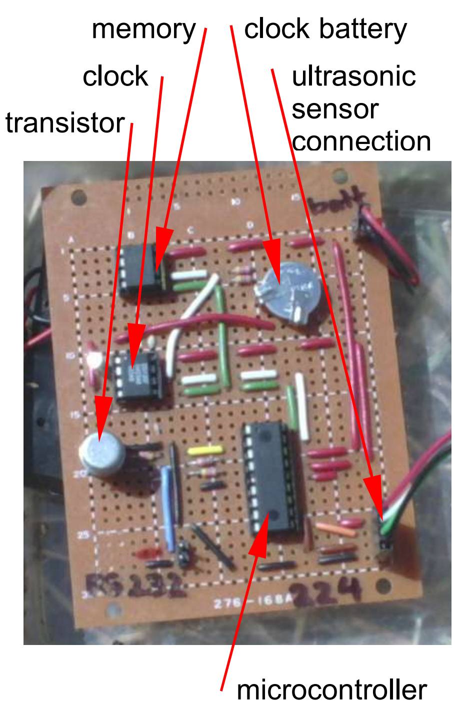

Figure 8. Ultrasonic rangefinder prototype board.

Table 4. Parts list and cost of main components on ultrasonic rangefinder circuit board

Description *Part number, Manufacturer*	Cost (US$)
Microcontroller	
PIC 16F819, Microchip Technologies	3
Clock	
DS1302, Dallas Semiconductor	3
Memory	
24LC512, Microchip Technologies	3
Ultrasonic rangefinder	
SRF04, Devontech	35
Circuit board	1
Batteries	2
Miscellaneous (resistors, capacitors, connector pins, transistor)	2
total	$49

triggered the sensor, which transmitted an acoustic pulse, and initiated a timer. When the sensor's receiver detected the reflected pulse, the timer stopped. The microcontroller program contained a routine to convert the time of travel of the pulse to a distance, and then to a depth of water. The date, time, and water depth data were then stored in the memory chip, and the microcontroller put itself into a low-voltage sleep mode to conserve battery power.

A series of water depth measurements made manually, with the rangefinder, and with the pressure-sensor circuit is shown in Figure 9. In general, the rangefinder showed more variation

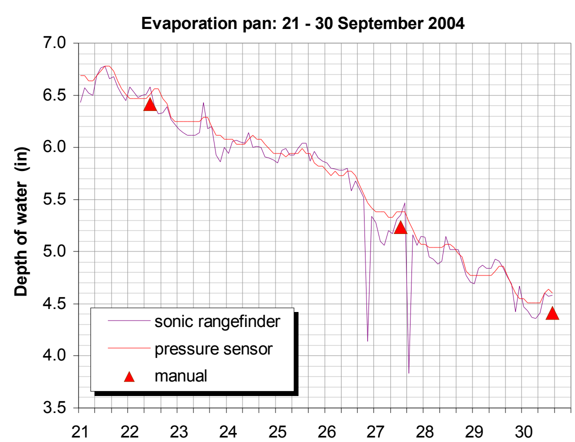

Figure 9. Ultrasonic rangefinder measurements.

in depth than did the pressure sensor. This may have been due in part to the mounting of the rangefinder: the rangefinder was attached to the chicken-wire screen covering the evaporation pan which may have flexed throughout the day. On a few occasions, unrealistic depths were recorded. The cause of these significant random errors is unknown and must be investigated.

Conclusions

The capabilities, prevalence, and ease of use of modern electronic components are increasing rapidly. Electronics are increasingly being used to collect and process all types of data, transfer information, and provide automation and control functions. Many more specialized components and sensors are available which interface easily and simplify circuit design.

These modern electronic components can be put to use in agriculture as in the many other applications in which they already serve. A number of useful, inexpensive, and easy-to-use electronic components were described. Several examples of circuits used in irrigation research were presented and discussed.

Acknowledgements

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Show Me Irrigator, Missouri's Irrigation Scheduling Program

ABSTRACT

A new irrigation scheduling program in spreadsheet format was developed by the University of Missouri and funded by the Missouri Department of Natural Resources. The software, tentatively called ***Show Me Irrigator***, incorporates unique features, such as rainfall run-off estimator, yield prediction, and automatic generation of irrigation aids for local media.

INTRODUCTION

Irrigation scheduling using climatic weather data involves many calculations and thus is ideal for computers. However, there are relatively few computer programs available today. This project was undertaken to develop spreadsheet software that would (a) incorporate the recommended procedures of FAO-56, (b) utilize a run-off module, (c) predict crop yield, and (d) generate graphical irrigation aids for newspapers.

The actual percentage of farms using scientific irrigation scheduling methods (either soil moisture monitoring or computer scheduling) on a national basis is only 9.6 and 2.3%, respectively (Table 1). In some cases, the reason that scheduling is not done is that, like in much of the southwest, water resources are so limited that scheduling becomes a mute point as pumps are kept on continuously as the farmer tries to play " catch up". Depending on rooting depth, soil type and expected rainfall, unless a water resource of about 3.0 to 4.0 gallons per minute per irrigated acre exists, the water supply is marginal for full irrigation, and scheduling would likely remain a mute point. However, for those areas that do have ample water, scheduling should be employed as it is shown to increase yields. Table 2 shows the results of four years of survey data from Missouri farmers where irrigators who used scheduling grossed about $40 per acre more than irrigators who did not schedule.

Table 1. Percentages of farms using irrigation scheduling by either soil moisture monitoring or computer program (USDC, 2001)

State	Soil Moisture Monitoring	Computer Program	State	Soil Moisture Monitoring	Computer Program
Alabama	10.6%	0.8%	Nebraska	6.0%	0.3%
Alaska	17.1%	---	Nevada	3.9%	0.2%
Arizona	8.5%	0.2%	New Hampshire	7.6%	---
Arkansas	9.6%	5.3%	New Jersey	12.7%	0.2%
California	13.7%	1.7%	New Mexico	5.7%	0.3%
Colorado	4.5%	1.5%	New York	13.7%	3.7%
Delaware	12.4%	0.4%	North Carolina	6.5%	0.2%
Florida	16.7%	0.0%	North Dakota	8.7%	3.1%
Georgia	5.3%	2.4%	Ohio	11.0%	
Hawaii	3.5%	0.5%	Oklahoma	6.6%	0.5%
Idaho	4.2%	0.2%	Oregon	5.7%	0.1%
Illinois	7.1%	0.5%	Pennsylvania	7.7%	0.6%
Indiana	8.4%	0.4%	Rhode Island	21.4%	---
Iowa	10.9%	1.0%	South Carolina	9.5%	0.2%
Kansas	10.8%	0.8%	South Dakota	16.3%	0.3%
Kentucky	5.2%	1.7%	Tennessee	4.7%	2.2%
Louisiana	3.4%	0.4%	Texas	9.2%	1.5%
Maine	16.6%	---	Utah	3.3%	0.1%
Maryland	11.9%	0.2%	Vermont	10.9%	---
Massachusetts	20.8%	2.3%	Virginia	7.7%	0.5%
Michigan	11.0%	2.7%	Washington	7.9%	0.8%
Minnesota	14.0%	0.5%	West Virginia	4.0%	---
Mississippi	6.7%	1.4%	Wisconsin	10.6%	1.7%
Missouri	**5.5%**	**1.9%**	Wyoming	2.6%	0.1%
Montana	4.3%	1.8%	**USA**	**9.6%**	**2.3%**

Table 2. Comparison of yields and difference in gross returns for irrigators who scheduled versus those that did not schedule irrigation, SE Missouri, 2000-20003. Sample size in parenthesis (after Henggeler, 2003).			
Crop	**Irrigators Who Scheduled** (bu. [or lbs.] /acre)	**Irrigators Who Did NOT Schedule** (bu. [or lbs.] /acre)	**Gross Return from Scheduling** ($/acre)
Corn	179.5 (49)	168.7 (153)	$26.90
Cotton	954.6 (14)	871.1 (82)	$54.28
Soybeans	45.6 (22)	42.3 (193)	$18.98

SPECIAL FEATURES

The program developed, called ***Show Me Irrigator***, has many features, some of them innovative and not in other irrigation scheduling programs. The program uses EXCEL spreadsheet with Visual Basic macros.

The science behind the scheduling is based on FAO-56 (Allen, et al., 1998). It uses both real-time and historic weather. Reference evapotranspiration (ET_o) is calculated using FAO-56 and the dual crop coefficient (K_{cb}) method, which calculates soil evaporation and crop transpiration separately. When real-time weather is not input, historic data is automatically inserted. Historic weather files exist for 5 locations in Missouri. There is also the option to generate a historic weather file for other locales by inputting monthly mean values of maximum and minimum temperature, wind speed, and minimum relative humidity. This monthly data is used to generate the historic file that includes daily values for the items mentioned above, plus estimated daily ET_o, and daily values for two types of Heat Units (HU) (a corn HU [86ºF maximum and 50ºF base] and regular HU [60ºF base]). The estimated daily ET_o for the historic weather file is based on the Blaney-Criddle calculation method. The Blaney-Criddle values are modified to approximate Penman-Monteith values for Missouri conditions using Equation 1:

$$ET_{o\_PM'} = 0.85\ ET_{o\_BC} - 0.03 \qquad \text{(Eq. 1)}$$

where,

$ET_{o\_PM'}$ = estimated Penman-Monteith ET_o [in]
ET_{o_BC} = Blaney-Criddle ET_o [in]

Future versions of ***Show Me Irrigator*** will use the Hargreaves-Samani calculation method with a correction factor to estimate the Penman-Monteith ET_o values used in the historic weather files. Current investigations indicate this provides a better estimate than the Blaney-Criddle method currently used.

An image of the main worksheet is shown in Figure 1. Some of the features of the program are described below.

Crop Coefficient Curves

The program currently supports corn, soybeans and cotton. The crop coefficient curves (K_c for the single coefficient method [effects of soil evaporation and crop transpiration lumped together] and K_{cb}) were developed specifically for Missouri weather conditions. However, tools to modify the K_c and K_{cb}[1] curves are part of the program.

End-of-season calculations

In most existing irrigation scheduling programs end-of-season water use estimates are very poor. One of the main reasons for this is that, while the beginning of the season (either planting or emergence) is obvious, when the end of the season occurs is less clear. However, having a clear estimate of when a crop will begin to senesce and die is important for two reasons. First, irrigation scheduling programs that call for irrigation water after a crop has terminated will decrease farmers' overall credibility in irrigation scheduling. Second, termination of irrigation too early in the season may be hurting corn and soybean yields in the mid-West (Henggeler, 2004).

[1] Since the program normally uses the dual coefficient method (K_{cb}), the term K_{cb} is used in this paper, but implies both K_{cb} and K_c.

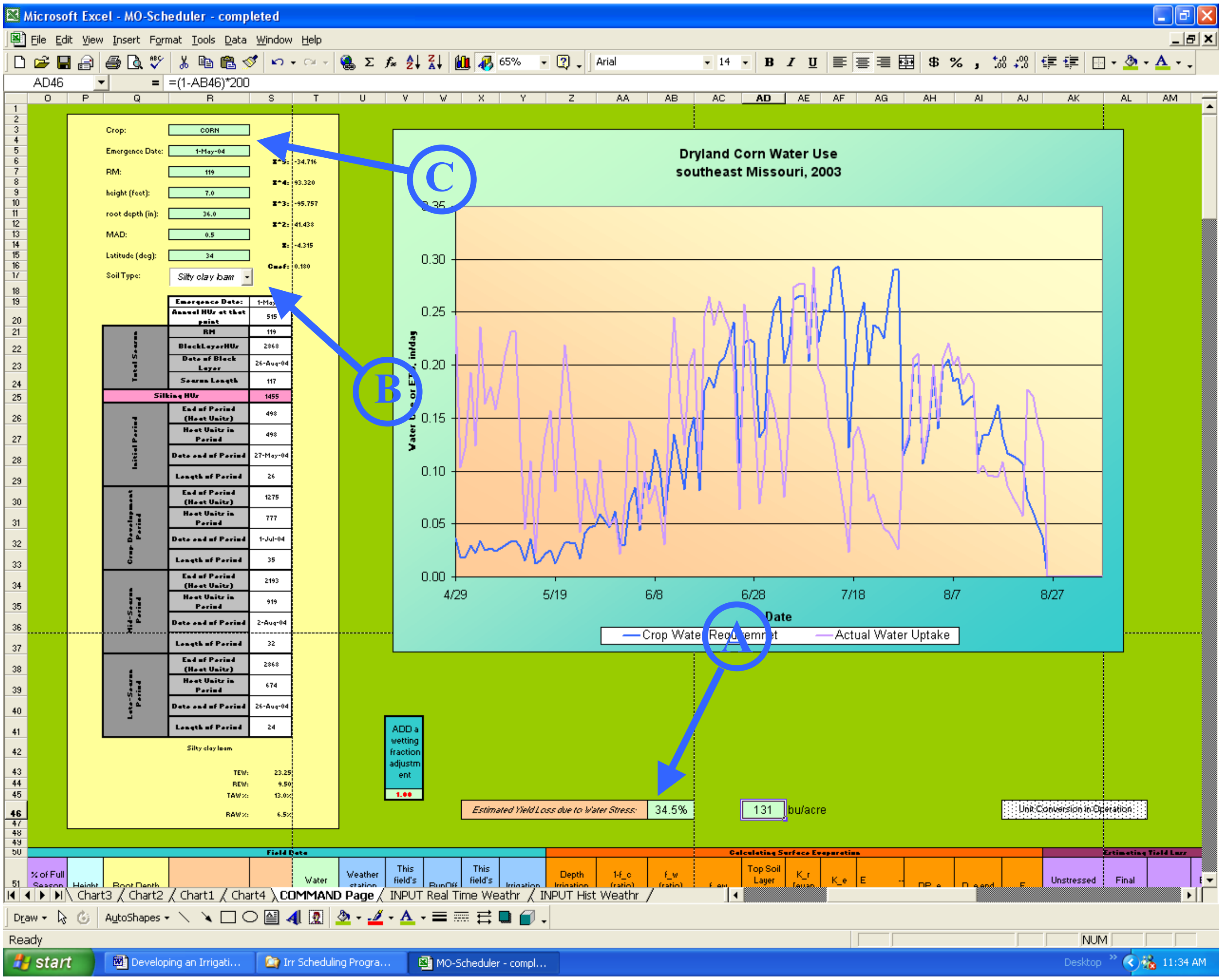


Fig. 1. Main worksheet for *MO-Scheduler*. Item "A" is a yield projector based on crop moisture stressed incurred, item "B" is a pull-down menu with all major soil types, and item "C" is location for input ting data. Providing emergence date and RM is enough to provide breakdown of dates and HUs to major physiological events.

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

Seed companies normally provide data on HUs to black layer (HU_{bl}). In cases where it is not known, the RM value can be used to predict HU_{bl} as seen in Equation 2.

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

where

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

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

The data to create Eq 2 came from many hybrids from three of the major corn seed companies (Pioneer, DeKalb and Micogen). Figure 2 shows a graph of Relative Maturity values versus HUs to reach black layer and silking.

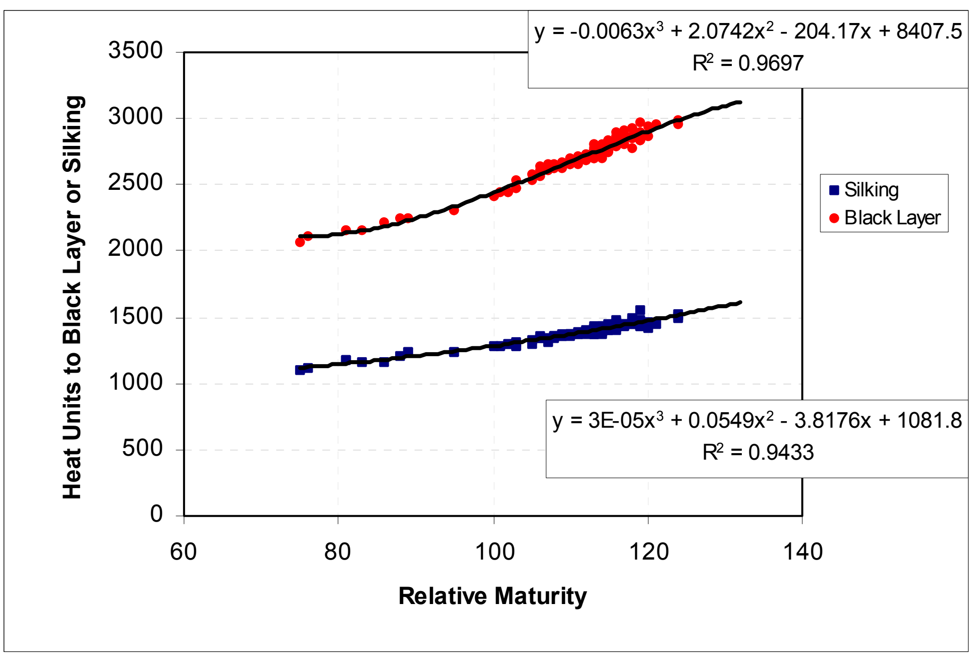


Figure 2- Heat Units to reach silking and black layer for various Relative Maturity ratings of corn.

SOYBEAN. The termination date of soybean is more difficult to determine since most soybeans are day-length sensitive. Based on their normal growing period soybean varieties are categorized by Maturity Groups (MG). The smaller the MG value, the shorter the season. Farmers in Missouri plant varieties with MG values ranging from III to VII. An equation was developed to predict the expected season length of a soybean variety based on its MG, date of planting, and latitude. Data for this model (Eq. 3) was gathered from reported variety tests conducted throughout the Midwest and mid-South that utilized varieties with varying MG values and which reported soybean termination dates for the varieties in the trial.

$$L = -(0.71 \times DOY) + (0.0015 \times DOY^2) + (0.92 \times Lat) + (9.1 \times MG) + 127.6 \qquad \text{(Eq. 3)}$$

where

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

The computer program uses Eqs. 2 and 3 plus the emergence date to determine when, respectively, the corn and soybean will terminate. Thus a reasonable time framework is laid out on which to building the crop coefficient curve.

Coefficient Values

The FAO-56 method (Allen et al., 1998) was used to modify the crop coefficient values and curves. The FAO method takes a minimalist approach, breaking the growing season up into only four periods: Initial (prior to planting to 10% of canopy coverage), crop development (from 10% through about 70-80% coverage [corresponding to a Leaf Area Index of 3.0]), mid-season (70-80% cover until start of maturity when leaves begin to show aging), and late season (maturity to full senescence or crop harvest). FAO-56 provided information on *length in days* for the four periods plus total season length, planting date, plant height, and region of reference for a number of crops, including corn and soybeans. Analyzing the presented data from around the world (6 corn and 4 soybean studies) indicated that the relative length for each physiological period was actually a better method to separate the four periods than number of days. Table 3 shows the relative season length for corn and soybeans for each growth period.

Table 3. Average relative length of each of the four growth periods for corn and soybean

CROP	Initial Period	Crop Development Period	Mid-season Period	Late-season Period
Corn	.174	.271	.320	.235
Soybean	.150	.204	.461	.185

In breaking the season into the 4 parts, just three K_{cb} values (initial, mid-season, and end) are used to describe the entire season. They are referred to as K_{cb_ini}, $K_{cb\_ mid}$, and K_{cb_end}, respectively. Suggested values for these 3 points are provided in FAO-56. However, the placement of these 3 points in the horizontal direction is based on time (or relative season length in our case) of the 4 growth periods. Additionally, the values of $K_{cb\_ mid}$, and K_{cb_end} are based on locales with an average daily minimum Relative Humidity value of 45% and an average daily wind speed of 2 m/s. A procedure is presented in FAO-56 to allow for adjustment. The minimum RH values in SEMO for the periods in question was slightly higher (53%-60%) then the standard RH value and the wind speeds were slightly less (1.12 to 1.45 m/s) and so $K_{cb\_ mid}$, and K_{cb_end} were adjusted accordingly. This coefficient-adjustment tool is a module in the program.

In order to facilitate flexibility, the x-axis value for the crop coefficient curves used in the computer program was based on percentage of the seasonal HUs. Although soybean flower initiation and other factors are not HU-related, early season canopy growth is. The HUs for the time period from emergence to crop termination (determined by either Eq 2 or Eq 3) was calculated based on historical weather data for each site. The final corn and soybean crop coefficient curves, along with the reconstructed FAO-56 minimal curve, are seen in Figs. 3 and 4.

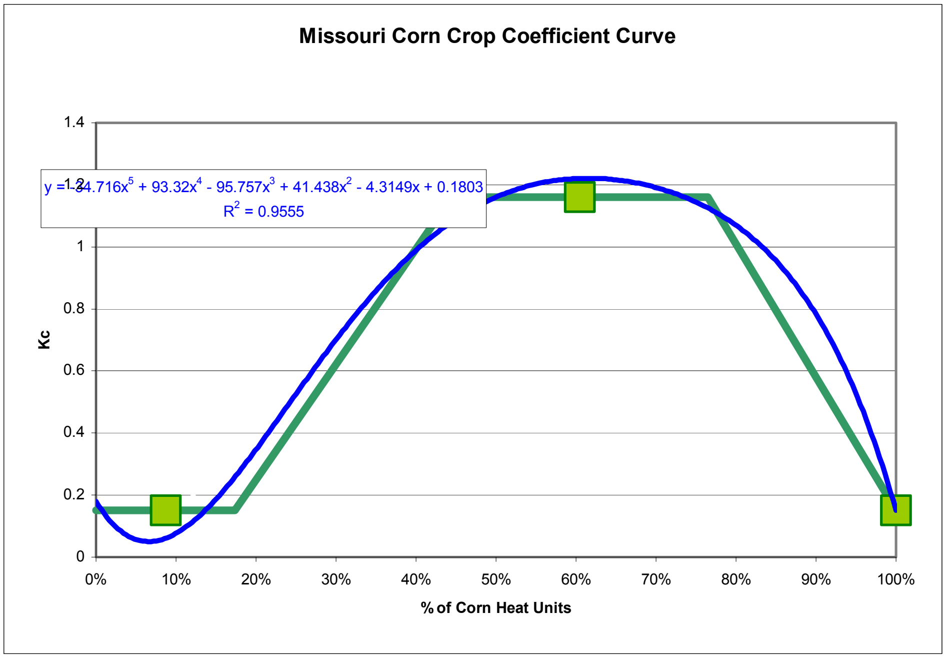


Figure 3- Basal crop coefficient curve for corn in Missouri with a baseline of % of seasonal Heat Units. The FAO-56 4-section curve is shown also.

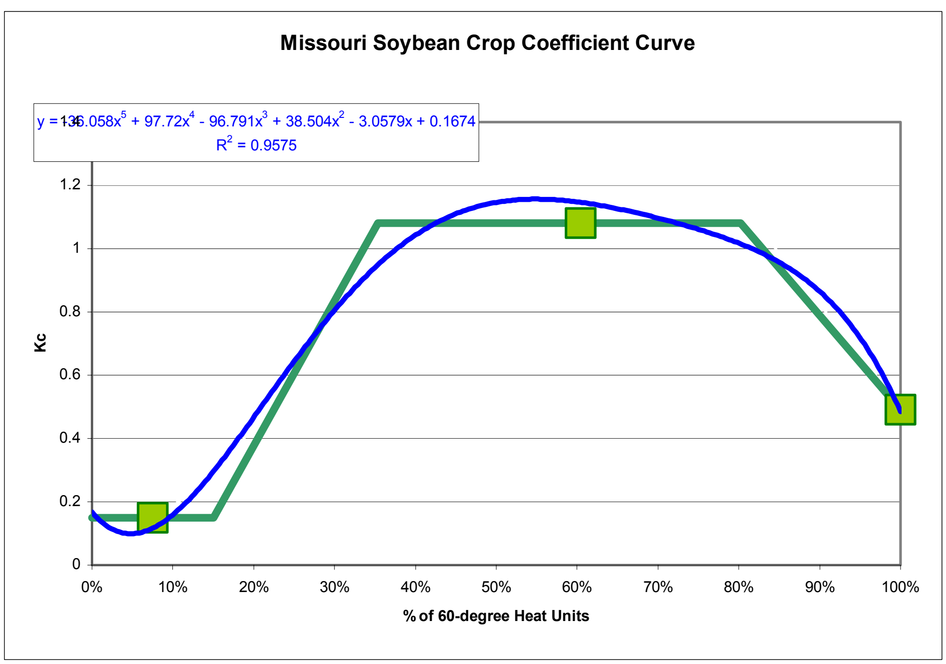


Figure 4- Basal crop coefficient curve for soybean in Missouri with a baseline of % of seasonal Heat Units. The FAO-56 4-section curve is shown also.

Yield Estimates

The program is able to estimate yield based on water stress during the season. The procedure used is based on FAO Irrigation and Drainage Paper No. 33, Yield Response to Water (Doorenbos and Kassam, 1979). One of the main purposes for developing this tool is to help growers who do not have adequate water to fully irrigate all their crops. This is often an occurrence in SEMO where an early-planted corn crop is finishing off about the time late season soybeans begin to need water.

The current estimator is based on season-wide water short falls. FAO-33 actually has more intense methods that allow estimates to be based on the growth stage when the moisture stress occurred. In future releases of the software this procedure will be added.

It is very simple to use the program to develop "what if" scenarios. For example, Fig. 5 shows how relative yield for different emergence dates is affected by rainfall patterns 55 days later. It just took a few moments to gather the data.

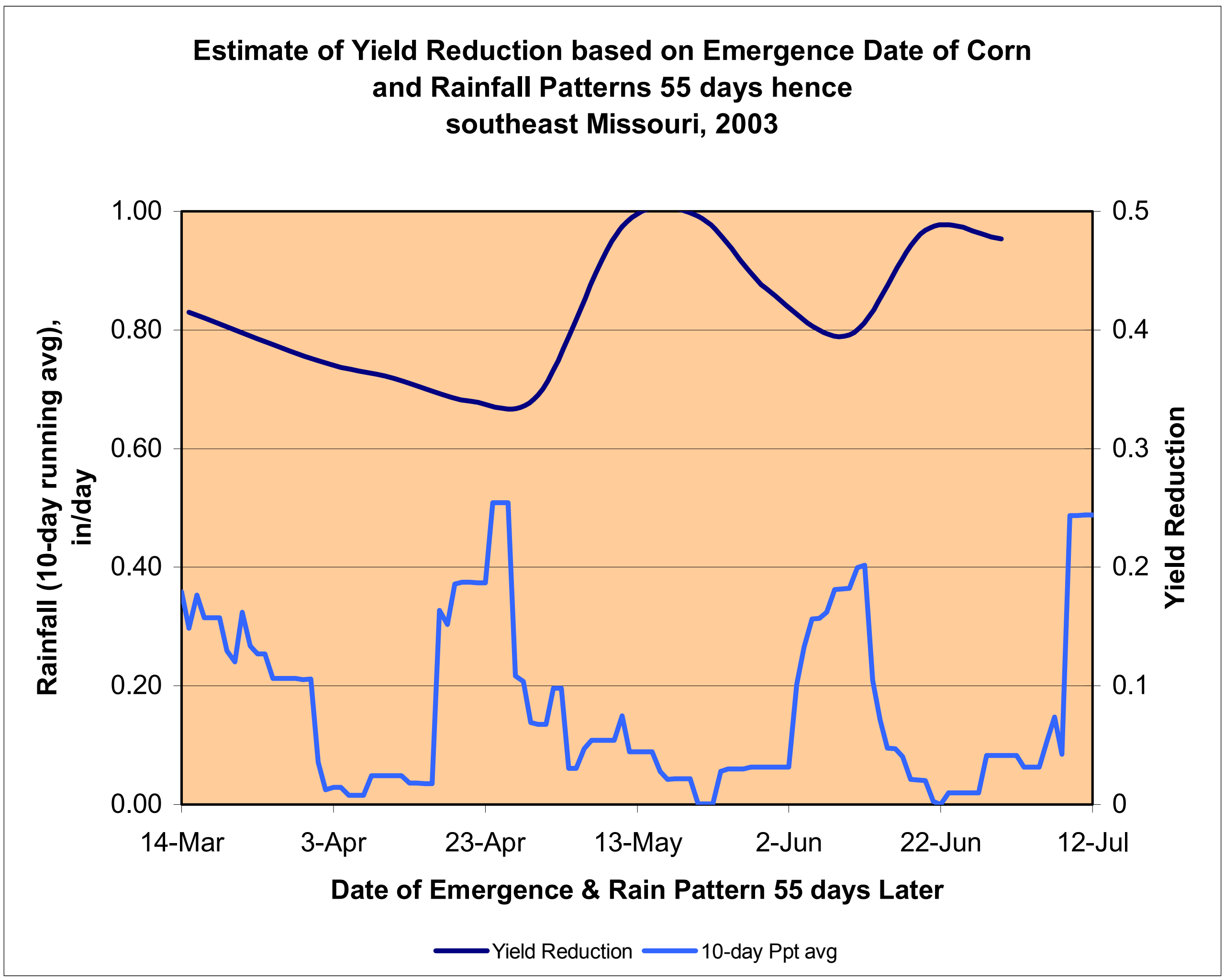
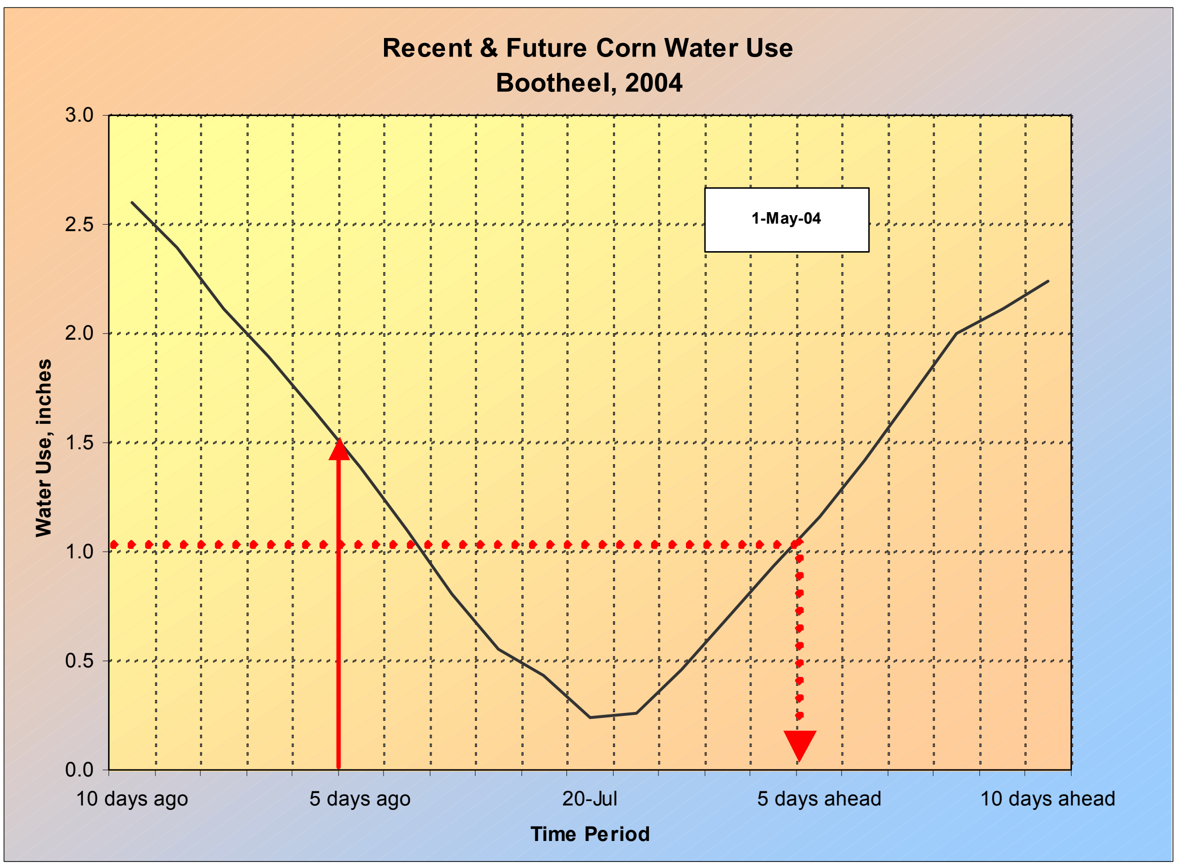


Figure 5- Changes in relative yield reduction based on emergence date overlaid with rainfall patterns (10-day running average) 55 days later. The information was generated with MO-Scheduler.

Generating of Irrigation Scheduling Aids
Current estimates are that only about 15% of Missouri irrigators schedule. Farmers, who are not currently scheduling, could benefit from timely water use updates that might be published in local papers. The program was set up to automatically create irrigation aids like the one in the text box below.

It is very important to use K_c, not the K_{cb}, values to generate public release information since the correct data on rain and past irrigations is not known!

EXAMPLE: This is an automatically generated irrigation aid meant for release to newspapers. It works like this: a farmer wishes to irrigate when 2.5 inches of water of soil moisture storage is used up. He knows that he watered 5 days ago. From that date until now (assuming this is Jul 20), he used up 1.5 inches of water. He needs to use up only 1.0 more inch of water (2.5 – 1.5) before he irrigates again. He goes over to the left axis and moves out at the 1.0-inch mark until he hits the graph line. Then he goes downward to see that we will need to water in 5 days, or Jul 25.



Another educational tool that the program can generate automatically is a tabular representation of water use information. A mock up is shown as Figure 7. We have already contacted newspapers in the irrigated areas of the state concerning the best methods (PDF, spreadsheet, etc.) for getting this information to them.

Water Use Report

(May 9th, 2004)

Sponsored by the University of Missouri and the Missouri Department of Natural Resources

Period		Max Temp (degrees F)	Min Temp (degrees F)	ETo (in/day)	CORN — Date of Emergence: 20-Mar	31-Mar	11-Apr	30-Apr	11-May
					Water Use, inches/day				
Days Ago	10	76.8	52.1	0.21	0.03	0.02	0.01	0.04	0.04
	9	76.5	60.6	0.16	0.03	0.02	0.01	0.03	0.03
	8	77.9	60.9	0.12	0.02	0.01	0.01	0.02	0.02
	7	70.2	49.8	0.11	0.02	0.01	0.01	0.02	0.02
	6	67.3	47.8	0.15	0.03	0.02	0.01	0.02	0.03
	5	62.0	44.7	0.12	0.03	0.02	0.01	0.02	0.02
	4	72.8	47.8	0.19	0.05	0.03	0.02	0.02	0.03
	3	85.5	58.2	0.24	0.06	0.04	0.03	0.02	0.04
	2	86.4	60.9	0.25	0.07	0.04	0.03	0.02	0.05
	1	78.0	56.3	0.15	0.05	0.03	0.02	0.01	0.03
05/09/04		78.3	56.6	0.15	0.05	0.03	0.02	0.01	0.03
Days Ahead	1	78.6	56.9	0.15	0.05	0.03	0.03	0.01	0.03
	2	78.9	57.2	0.15	0.06	0.04	0.03	0.01	0.03
	3	79.2	57.5	0.15	0.06	0.04	0.03	0.01	0.02
	4	79.4	57.8	0.15	0.07	0.05	0.04	0.01	0.02
	5	79.7	58.1	0.15	0.07	0.05	0.04	0.01	0.02
	6	80.3	58.7	0.15	0.07	0.05	0.04	0.01	0.01
	7	80.6	59.0	0.16	0.08	0.06	0.05	0.01	0.01
	8	80.8	59.3	0.16	0.08	0.06	0.05	0.01	0.01
	9	81.1	59.6	0.16	0.09	0.07	0.06	0.01	0.01
	10	81.3	59.8	0.16	0.09	0.07	0.06	0.02	0.01

Team Up!

Figure 6- A tabular representation of local water use data that will be sent to local papers.

Run-off Module

An irrigation scheduling program is only as good as the data being used in the program. While the irrigation community has devoted much effort into determining the most appropriate ET equation, little has been done in recent years in determining run-off from rain, other then a Nebraska University fact sheet (Cahoon et al., 1992). This fact sheet was based on the SCS Runoff Equations numbers developed in the 1950s. Review of the literature shows that this methodology is employed worldwide in determining information on storm events, river flow, etc. Even very complex hydrology models rely on this procedure, which is based on the classification of soils into four run-off categories: A, B, C, and D. Almost all soils in the USA have been so classified. Other main factors include category of crop (e.g., row, pasture, etc.), tillage system, and gross rainfall amount and antecedent moisture conditions. These data are used to generate "CN" values and CN-curves. The solution was traditionally solved graphically.

A module in the program estimates run-off from a rain. The original concept was to have the calculation procedures internally within the program. However, since this entailed that each day of the year in the weather file would need this relatively complicated equation, a compromise solution was to have a single calculator on one of the worksheets within the ***Show Me Irrigator***. In the event of rain, the user can quickly input the information need to determine how much was run-off and how much was effective. Figure 7 shows the screen image of the run-off calculator.

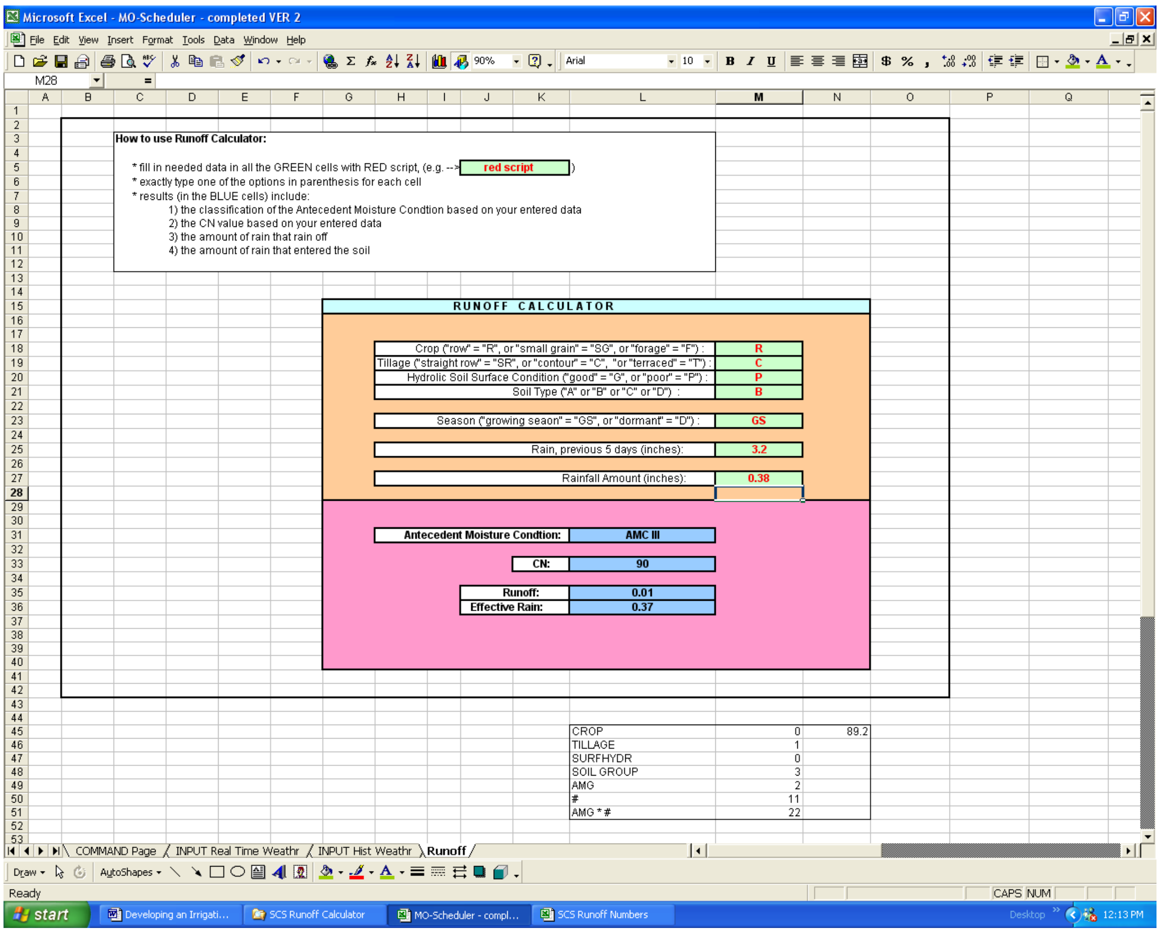


Figure 7- The screen image of the SCS Runoff calculator.

FUTURE WORK

Other features will be hopefully be added to ***Show Me Irrigator*** in future modifications. These include:

- Deep Percolation. Deep percolation is an important factor in safe water-nitrogen management. A graphical display of deep percolation will later be put into the program.

- Enhancing crop yield predictors. Future yield prediction will be based on more intense diagnostic tools that will incorporate the effect of moisture stress based on the growth stage it occurred.

- Soil moisture tension. Values of volumetric moisture content will be converted to soil moisture tension in the program. Several equations for tension versus water content were developed, but were not able to be put into the current version because of time constraints.

- Calculation of the ET_o. Since other software existed to calculate FAO Penman-Monteith reference evapotranspiration values, it was not added to this program. Future version will probably include this capability.

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ESTIMATION OF REFERENCE EVAPOTRANSPIRATION BY A MODIFIED BOWEN METHOD

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SUMMARY: The sustainability of irrigated agriculture depends primarily on efficient water use. Efficient irrigation decisions are function of potential atmospheric demand, which are expressed by reference evapotranspiration (ET_o). In general, all ET_o estimation methods refer to daily values including night evaporation losses, which are only substantial for a few days after rain or irrigation. We propose a method for estimating ET_o, based on the local energy balance from limited meteorological data monitored in an automated weather station throughout daylight periods. To validate the current method, climatic data and lysimetric measurements from Piracicaba, São Paulo, Brazil were used. Regression analyses revealed that a modified Bowen method provided results similar to the Penman-Monteith method and with measurements made by weighing lysimeters. Given the high coefficients of determination and ease of estimation, the method is recommended for assessment of crop water use at other sites.

KEYWORDS: energy balance, modeling, light period.

INTRODUCTION

Until recently, irrigation recommendations were often based on the concept of reference evapotranspiration (ET_o) defined as the water use by a uniform, actively growing, full-cover grass sward or alfalfa canopy with an unrestricted water supply. The daily water requirements of other crops are then estimated by adjusting ET_o via a series of multiplicative crop factors that purport to account for differences between the crop of interest and the reference crop. Differences for arable crops include incomplete ground cover as well as phenological stage of development (DOORENBOS & PRUITT, 1977; CSSRI, 2000 and ALLEN et al., 1994).

Compared to the Penman-Monteith equation, the Priestley-Taylor formula may have operational limits (McANENEY & ITIER, 1996) since it empirically proposes a coefficient of proportionality between evaporation and available energy. Despite this apparent limitation, the Priestley-Taylor equation has substantial experimental support, especially in humid regions (PRIESTLEY & TAYLOR, 1972; PEREIRA et al., 1997).

The estimate of maximum crop evapotranspiration is an important factor to be considered in agricultural planning and has been a research field that has involved studies related to irrigation management and agrometeorology all over the world. The reference or potential evapotranspiration (ET_o) needs to be determined to provide knowledge of crop water requirements. It is desirable to have a method that estimates ET_o with accuracy and from easily obtained meteorological data. Irrigation planning and decision making at a field scale are done based on calculations of crop evapotranspiration (ET_c).

Estimates of ET_o refer to potential evapotranspiration for daily increments. The nocturnal losses of soil evaporation that will be significant for a few days after rainfall or irrigation are taken into account. Usually methods that make use of daily mean values of air temperature, relative humidity, and wind speed do not depict very well the physical reality of evaporative water loss and for the soil surface might mask the actual behavior of the aforementioned meteorological variables. In the current work we have developed an estimation method to calculate the reference evapotranspiration (ET_o) on a diurnal basis throughout the light period, aiming at quantifying only the daytime values of evapotranspiration, which are often more representative of the water vapor transference process to the atmosphere for a given agricultural ecosystem.

THEORETICAL BACKGROUND

The classical theory related to the partition of net radiation (Rn) into the different natural processes presupposes that under natural conditions of water supply a part of Rn might be transformed into latent heat for evaporation and evapotranspiration (λE), part into sensible heat to the atmospheric air (H), and part into energy storage (A), and in compliance with energy conservation principle it is known that:

$$Rn = \lambda E + H + A \quad \text{---} \; (1)$$

By the end of a diurnal cycle we can assume that A is negligible as well as consider that λE and H return from the surface to the atmosphere as transpiration and sensible heat fluxes (heating of humid air). Bowen ratio (BOWEN, 1926) was defined by the following relationship:

$$\beta = H/\lambda E = \gamma/S \text{ --- } (2)$$

In equation 2 the terms signify:

S is the slope of water vapor saturation pressure as a function of mean air temperature ($kPa.^oC^{-1}$); γ is the psychrometric coefficient (= $0.063 kPa.^oC^{-1}$), being determined by means of the following expression:

$$\gamma = \frac{Cp\ P}{0{,}622\ \lambda} \text{ -- } (3)$$

where Cp is the air sensible heat flux (= 1.013 $kJ.kg^{-1}$); P is the local atmospheric pressure (kPa); and λ is the water vaporization latent heat (= 2.45 $MJ.kg^{-1}$).

Substituting (2) in (1) we have:

$$Rn = \lambda E\ (S + \gamma)/S \text{ -- } (4)$$

Defining $\frac{S+\gamma}{S}$ as $\frac{1}{W}$, and substituting it in (4) we will have:

$$E = W\frac{Rn}{\lambda} \text{ --- } (5)$$

In this calculation procedure a method denominated modified Bowen (ET_oBm) is proposed, whose difference from equation 5 refers to the substitution of W value, usually determined at mean air temperature, for the value of W*, obtained as a function of the average between the dry and wet temperatures monitored by a psychrometer, as proposed by MONTEITH (1965), with the adjustment being extremely dependent on air temperature and relative humidity (VILLA NOVA et al., 2002).

The equation that defines the calculation of the potential or reference evapotranspiration by the proposed method and denominated here as modified Bowen will be expressed by:

$$EToBm = \alpha * W * \frac{Rn - G}{\lambda} \text{ --- } (6)$$

where ET_oBm is the potential evapotranspiration estimated by the modified Bowen method throughout light periods ($kg.m^{-2}.day^{-1} = mm.day^{-1}$); Rn is the radiation balance at surface ($MJ.m^{-2}.day^{-1}$); G is the sensible heat flux density in the soil ($MJ.m^{-2}.day^{-1}$); $W^* = S^*/S^*+\gamma$ is a weighing factor for the effect of solar radiation on evapotranspiration that depends on air temperature, relative humidity and psychrometric coefficient; α^* is the adjustment parameter for the proposed method - similar to the Priestley-Taylor parameter (PRIESTLEY & TAYLOR, 1972); and λ defined as above. The term W* is then defined by the relationship:

$$W^* = \frac{S^*}{S^*+\gamma} \text{ --- } (7)$$

where S* is the slope of water vapor saturation pressure as a function of the average temperature between dry and wet bulbs (Tdw). Tabular values of Tdw and S* calculated by VILLA NOVA et al. (2002) were utilized in the calculation of W* as a function of local latitude, air temperature and relative humidity.

The final equation representative of the current method in this study resulting from the substitution of α^*, which assumed the mean value of 1.037, and λ in equation 5 is given by:

$$EToBm = \frac{1.037\, W^* \,(\mathrm{Rn - G})}{\lambda}$$

Or yet, being $\lambda = 2.45$ MJ.kg^{-1}

$$EToBm = 0.423\, W^* \,(Rn - G) \text{ --------------------------------------- (8)}$$

MATERIALS AND METHODS

A set of potential evapotranspiration data was collected by PEREIRA (1998) at Piracicaba, State of São Paulo, Brazil (Latitude 22°42'S, Longitude 47°38'W and Altitude 596m), at the Experiment Station of Escola Superior de Agricultura "Luiz de Queiroz", Universidade de São Paulo - ESALQ/USP throughout the period from 1 August to 24 September 1996, totaling 45 days was used for determination of the mean value of W*. The reference evapotranspiration (ET_o) was obtained in one weighing lysimeter with three load cells (Omega Eng., model LCCA-2K, capacity of 910 kg and accuracy of 0.037%), two drainage lysimeters and two sub-irrigation lysimeters with the same dimensions of load cells-based evapotranspirometer, at 0.65m-depth, 1.20m-long and 0.85m-wide cultivated with bahiagrass sward (*Paspalum notatum* F.) as described by SILVA et al., 1999. A 10m-fetch field adjacent to the lysimeters was managed in such a way to keep the grass sward uniform and actively-growing with a height between 0.08 and 0.15m by means of periodical cuttings. An unrestricted amount of water was continuously supplied by a drip irrigation system to both lysimeter areas and adjacent field so that evapotranspiration occurred at a representative rate, as recommended by DOORENBOS & PRUITT (1977) and ALLEN (1994).

Daily soil water potential readings were made from four digital tensiometers installed in each lysimeter at 15 and 30cm-depth. The soil water suction corresponding to field capacity at the drainage lysimeters was determined directly in the field whenever water drainage within the profile ceased after the soil was saturated.

Throughout the period of data collection, a field calibration procedure on the load cell system was adopted in order to check out its responsiveness. ET_o was calculated and recorded every 30 minutes from data measured each second by a data logger (model CR10, Campbell Scientific, Inc. Logan, Utah) hooked up to three load cells of a weighing lysimeter. The daily mean reference evapotranspiration measured by a weighing lysimeter adopted as a standard for evaluating the performance of other kinds of lysimetres (SILVA, 1999) was used to validate the modified Bowen method.

For validation of the modified Bowen method, sets of data of daily air mean temperature and relative humidity, net radiation, sensible heat flux in the soil monitored by an automatic weather station and lysimetric measurements collected by PEREIRA (1998) throughout the period between September and December 1996 (46 available days of observation), and by MAGGIOTTO (1996) between December 1995 and May 1996 (31 available days of observation) were used. Two comparison criteria were adopted to assess the proposed estimate model performance. A simple linear regression was made between the daily values of ET_o calculated by the modified Bowen method and those measured by weighing lysimeters with load cells. The estimates obtained by the modified Bowen method were also compared to that of the Penman-Monteith method.

RESULTS AND DISCUSSION

Determination of W*

W* values are presented as a function of the observed daily mean values of air temperature (T in degrees Celcius) and relative humidity (RH%) for altitudes from 0 to 1000 meters and from 1000 and 2000 meters, respectively (Tables 1 and 2). Parameter corrections from the average temperature between dry and wet bulbs of a psychrometer, according to MONTEITH (1965), is a function of S* calculated by VILLA NOVA et al. (2002) and is dependent on γ and local atmospheric pressure, as shown above in equation 3.

TABLE 1. Values of W* as a function of the observed daily mean air temperature and relative humidity for altitudes from 0 to 1000 meters.

Altitudes between 0 and 1000 meters									
	Relative Humidity (%)								
Temperature (^oC)	45	50	55	60	65	70	75	80	85
10	0.532	0.535	0.539	0.542	0.545	0.548	0.551	0.554	0.557
11	0.546	0.549	0.552	0.556	0.559	0.562	0.565	0.568	0.571
12	0.560	0.563	0.566	0.569	0.573	0.576	0.579	0.582	0.585
13	0.573	0.576	0.580	0.583	0.586	0.589	0.593	0.596	0.599
14	0.586	0.589	0.593	0.596	0.599	0.603	0.606	0.609	0.613
15	0.599	0.602	0.606	0.609	0.612	0.616	0.619	0.622	0.626
16	0.612	0.615	0.618	0.622	0.625	0.629	0.632	0.635	0.639
17	0.624	0.628	0.631	0.634	0.638	0.641	0.645	0.648	0.651
18	0.636	0.640	0.643	0.647	0.650	0.653	0.657	0.660	0.663
19	0.648	0.652	0.655	0.659	0.662	0.665	0.669	0.672	0.675
20	0.660	0.663	0.667	0.670	0.674	0.677	0.680	0.684	0.687
21	0.671	0.675	0.678	0.682	0.685	0.688	0.692	0.695	0.698
22	0.682	0.686	0.689	0.693	0.696	0.699	0.703	0.706	0.709
23	0.693	0.697	0.700	0.704	0.707	0.710	0.714	0.717	0.720
24	0.704	0.707	0.711	0.714	0.717	0.721	0.724	0.727	0.730
25	0.714	0.717	0.721	0.724	0.728	0.731	0.734	0.737	0.740
26	0.724	0.727	0.731	0.734	0.737	0.741	0.744	0.747	0.750
27	0.734	0.737	0.740	0.744	0.747	0.750	0.753	0.756	0.760
28	0.743	0.746	0.750	0.753	0.756	0.759	0.762	0.766	0.769
29	0.752	0.756	0.759	0.762	0.765	0.768	0.771	0.774	0.777
30	0.761	0.764	0.768	0.771	0.774	0.777	0.780	0.783	0.786

TABLE 2. Values of W* as a function of the observed daily mean air temperature and relative humidity for altitudes from 1000 to 2000 meters.

Altitudes between 1000 and 2000 meters									
	Relative Humidity (%)								
Temperature (^{o}C)	45	50	55	60	65	70	75	80	85
10	0.569	0.572	0.575	0.578	0.582	0.585	0.588	0.591	0.594
11	0.582	0.585	0.589	0.592	0.595	0.599	0.602	0.605	0.608
12	0.595	0.599	0.602	0.605	0.609	0.612	0.615	0.619	0.622
13	0.608	0.612	0.615	0.619	0.622	0.625	0.629	0.632	0.635
14	0.621	0.625	0.628	0.631	0.635	0.638	0.641	0.645	0.648
15	0.634	0.637	0.641	0.644	0.647	0.651	0.654	0.657	0.661
16	0.646	0.649	0.653	0.656	0.660	0.663	0.666	0.670	0.673
17	0.658	0.661	0.665	0.668	0.672	0.675	0.678	0.682	0.685
18	0.670	0.673	0.677	0.680	0.683	0.687	0.690	0.693	0.697
19	0.681	0.685	0.688	0.691	0.695	0.698	0.701	0.705	0.708
20	0.692	0.696	0.699	0.702	0.706	0.709	0.712	0.716	0.719
21	0.703	0.706	0.710	0.713	0.717	0.720	0.723	0.726	0.729
22	0.714	0.717	0.720	0.724	0.727	0.730	0.733	0.737	0.740
23	0.724	0.727	0.731	0.734	0.737	0.740	0.743	0.747	0.750
24	0.734	0.737	0.740	0.744	0.747	0.750	0.753	0.756	0.759
25	0.743	0.747	0.750	0.753	0.756	0.759	0.763	0.766	0.769
26	0.753	0.756	0.759	0.762	0.766	0.769	0.772	0.775	0.778
27	0.762	0.765	0.768	0.771	0.774	0.777	0.780	0.783	0.786
28	0.771	0.774	0.777	0.780	0.783	0.786	0.789	0.792	0.795
29	0.779	0.782	0.785	0.788	0.791	0.794	0.797	0.800	0.803
30	0.787	0.790	0.793	0.796	0.799	0.802	0.805	0.808	0.810

Estimation of the parameter α*

For estimation α* 45 days of lysimetric measurements of ET_o and readings of meteorological elements collected by PEREIRA (1998) during the period comprised between 1 August and 24 September 1996 were taken into consideration. The mean value of α* was 1.037 for the period in question (Table 3).

TABLE 3. Values of Priestley-Taylor parameter modified by the proposed method (α*) obtained by means of equation 5 from data collected by Pereira (1998).

Date	**Rn** *(MJ.m^-2^.d^-1^)*	**G** *(MJ.m^-2^. d^-1^)*	**Rn - G** *(MJ. m^-2^.d^-1^)*	**W***	**ET_o** *(mm.d^-1^)*	α*
August/1	9.91	0.68	9.23	0.678	2.10	0.822
2	10.80	0.73	10.07	0.652	2.10	0.784
3	10.15	0.71	9.44	0.659	2.05	0.807
4	10.92	0.91	10.01	0.675	2.89	1.048
5	10.95	0.74	10.21	0.680	2.99	1.055
6	9.99	0.73	9.26	0.676	2.48	0.971
7	9.54	0.81	8.73	0.693	2.42	0.980
8	9.49	0.81	8.68	0.704	2.68	1.075
9	8.25	0.59	7.66	0.721	2.48	1.100
11	7.60	0.63	6.97	0.674	2.21	1.153
12	9.21	0.76	8.45	0.685	2.26	0.957
13	10.73	0.87	9.86	0.710	2.32	0.812
15	9.91	0.58	9.33	0.680	2.65	1.023
16	12.49	0.43	12.06	0.634	2.85	0.913
17	11.99	0.79	11.20	0.667	3.04	0.997
18	12.00	0.80	11.20	0.672	3.05	0.993
19	12.32	0.78	11.54	0.683	3.10	0.964
21	12.31	0.82	11.49	0.704	3.37	1.021
22	11.42	0.88	10.54	0.714	3.14	1.022
23	11.89	0.86	11.03	0.714	3.45	1.073
24	12.61	0.82	11.79	0.707	3.39	0.996
25	12.69	0.87	11.82	0.711	3.55	1.035
26	12.35	0.89	11.46	0.730	3.74	1.095
27	11.23	0.87	10.36	0.740	3.97	1.269
28	10.06	0.84	9.22	0.722	3.00	1.104
29	10.01	0.62	9.39	0.712	2.61	0.956
30	11.19	0.81	10.38	0.734	3.72	1.196
31	12.47	0.57	11.90	0.739	4.30	1.198

Date	Rn $(MJ.m^{-2}.d^{-1})$	G $(MJ.m^{-2}. d^{-1})$	Rn - G $(MJ. m^{-2}.d^{-1})$	W*	ET_o $(mm.d^{-1})$	α*
September/2	12.50	0.70	11.80	0.704	3.38	0.997
4	8.67	0.53	8.14	0.693	2.72	1.181
7	14.11	0.88	13.23	0.696	3.74	0.995
12	10.38	0.55	9.83	0.677	2.85	1.049
13	13.48	1.06	12.42	0.707	3.18	0.887
14	14.32	0.97	13.35	0.717	4.45	1.139
15	14.49	0.89	13.60	0.714	4.18	1.055
17	10.86	0.38	10.48	0.699	3.52	1.177
18	14.08	0.46	13.62	0.674	3.86	1.030
19	15.03	0.82	14.21	0.698	4.41	1.089
20	14.28	0.92	13.36	0.711	4.14	1.068
22	14.39	0.79	13.60	0.740	5.02	1.222
23	13.54	0.83	12.71	0.748	4.52	1.165
24	12.04	0.65	11.39	0.734	3.72	1.090

Validation of the proposed method

The first validation of the modified Bowen method was a comparison between values of potential evapotranspiration measured by weighing lysimeters with load cells and those estimated by the proposed methodology, taking into account an independent series of data monitored by PEREIRA (1998) at Piracicaba, State of São Paulo, Brazil, throughout the period between 26 September and 9 December 1996, totaling 46 available days of observation. A second validation was performed with the aim of confirming the feasibility of the method through a study of simple linear regression between measured and estimated values of ET_o, taking into consideration lysimetric and radiometric data collected by MAGGIOTTO (1996) at the same site for a span from 23 December 1995 to 16 May 1996, amounting to a total of 31 completely independent observations.

The lysimetric measurements made by PEREIRA (1998) and MAGGIOTTO (1996) and the estimates of ET_o obtained by the modified Bowen and Penman-Monteith methods were closely correlated with coefficients of determination greater than 0.90 (Figures 1 through 6).

ET_o estimated by the modified Bowen method was closely related to the classical Penman-Monteith method, as well as to ET_o measured by weighting lysimeters from experimental data obtained by PEREIRA (1998). The modified Bowen method was accurate given an R^2 value of

0.903 as well as the dispersion of the data from comparison between estimates and measurements around the 1:1 line (Figure 2). The modified Bowen model also shows results very similar to estimates obtained by Penman-Monteith equation (Figure 3). By comparing the performance of the modified Bowen method in study with that one of Penman-Monteith method (Figure 1) it is possible to verify that there is a fairly consistent agreement between methods, statistically confirmed by an R^2 value of 0.961 and by an extremely small dispersion of the data around the 1:1 line. This indicates the feasibility of the modified Bowen method when a larger number of meteorological elements are not available to assess the potential demand at a given site. Given the slopes of the regression line observed in Figures 1 through 3 we may infer that the modified Bowen method corresponded to 96.75% of ET_o calculated by the classical method of Penman-Monteith. Both methods underestimated water use by less than 3%. The modified Bowen method had satisfactory performance at the site in study with a high degree of accuracy.

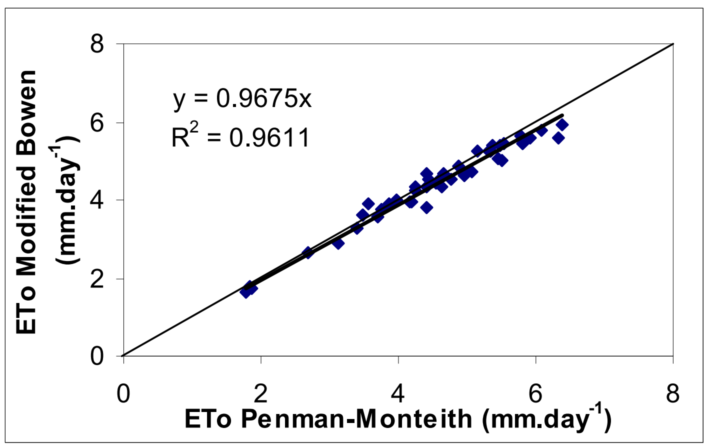

FIGURE 1. Comparison between reference evapotranspiration calculated by the Penman-Monteith method and potential demand estimated by the modified Bowen method for light periods. Experimental data collected by Pereira (1998).

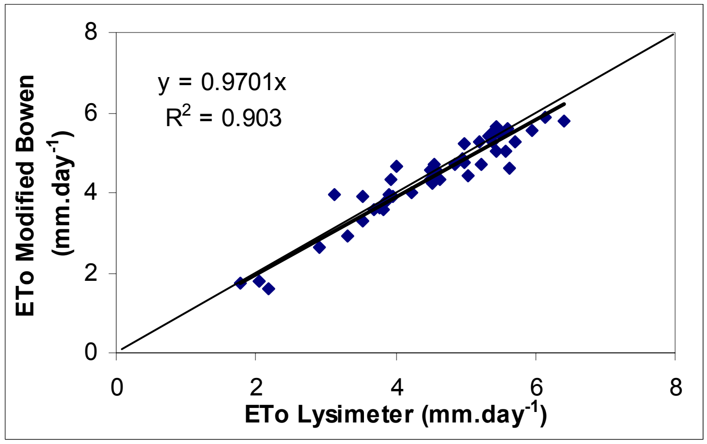

FIGURE 2. Comparison between reference evapotranspiration measured by a weighting lysimeter and potential demand estimated by the modified Bowen method for light periods. Experimental data collected by Pereira (1998).

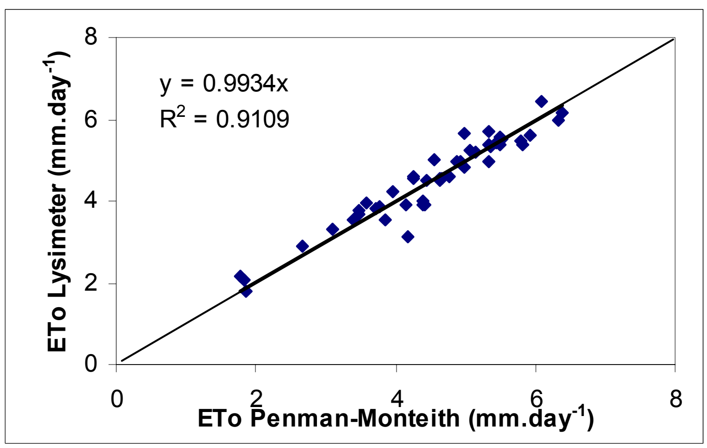

FIGURE 3. Comparison between reference evapotranspiration measured by a weighting lysimeter and potential demand estimated by the Penman-Monteith method for light periods. Experimental data collected by Pereira (1998).

Figures 4 through 6 show the validation of the proposed modified Bowen method from analysis of experimental data obtained by MAGGIOTTO (1996). Figure 4 reveals a pronounced agreement between the considered estimation methods of ET_o, which can be demonstrated by a coefficient of determination of 0.989 and by an evident coincidence degree between the trend line and 1:1 line as the regression line is forced to pass by origin (b = 0.973), standing out once more the feasibility of the proposed method in studies developed to evaluate crop water requirements.

The modified Bowen and Penman-Monteith estimation methods of potential demand were closely related with lysimetric measurements ($R^2 > 0.949$) (Figures 5 and 6). The modified Bowen method tended slightly to overestimate evapotranspiration by about 5%, whereas the Penman-Monteith method underestimated atmospheric demand at a rate close to 7%.

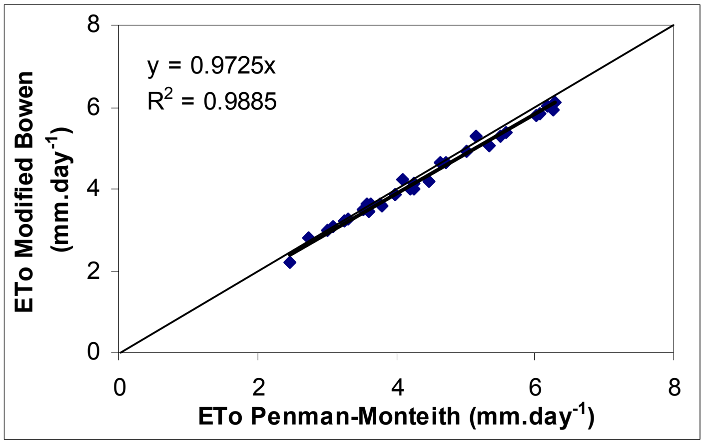

FIGURE 4. Comparison between reference evapotranspiration calculated by the Penman-Monteith method and potential demand estimated by the modified Bowen method for light periods. Experimental data collected by Maggiotto (1996).

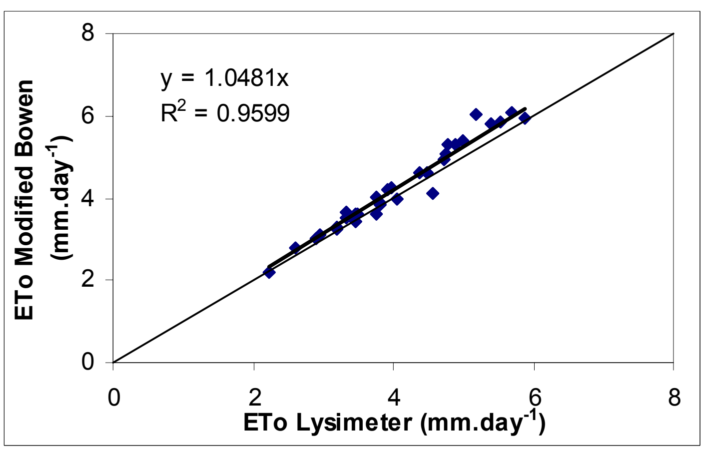

FIGURE 5. Comparison between reference evapotranspiration measured by a weighting lysimeter and potential demand estimated by the modified Bowen method for light periods. Experimental data collected by Maggiotto (1996).

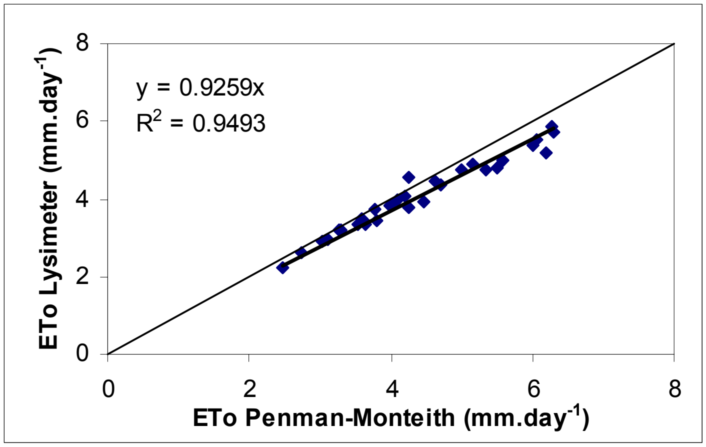

FIGURE 6. Comparison between reference evapotranspiration calculated by the Penman-Monteith method and potential demand measured by a weighting lysimeter for light periods. Experimental data collected by Maggiotto (1996).

Although several states and counties in the USA have a network of computerized weather stations that measure the important environmental variables that govern water loss and predict crop evapotranspiration, in many developing countries there is no such a system to provide the users with information regarding the actual water loss from well-watered grass crop. Thus, the reference evapotranspiration has to be determined in compliance with available climatic elements in a given site, since it has been proven to be very useful in estimating actual crop water needs.

One of the factors that will give one some knowledge for scientific irrigation scheduling is daily estimates of crop water use. The Pacific Northwest AgriMet system uses the 1982 Kimberly-Penman evapotranspiration model combined with locally derived plant growth stage information to produce estimates of daily crop consumptive water use (PALMER, 2004).

All the theoretical background involved in the Penman-Monteith method to calculate ET_o is unquestionable and should be considered by a satellite-based network of automated agricultural weather stations to provide information at farmer levels. However, its limitation is related to a large number of environmental variables that are necessary to determine ET_o, In addition to such a point, the lack of computerized weather station systems available to monitor the atmospheric parameters in many developing localities justifies other alternative methods for determining ET_o as a function of a minor number of input data with a precision compatible to either lysimetric measurements or Penman-Monteith estimates.

CONCLUSIONS

Under local climatic conditions of the experiment, a modified Bowen method (ET_oBm) - gave estimates practically identical to those obtained by the classical Penman-Monteith method. The modified Bowen method had the added advantage of simplifying ET_o calculation, leaving out information related to wind speed, making use of only net radiation, mean air temperature and mean relative humidity in daily basis. For the climatic conditions for the site in this study, the method when compared to potential evapotranspiration measurements obtained by weighing lysimeters showed high statistical accuracy. The modified Bowen method was a feasible alternative to evaluate standard reference evapotranspiration. By means of the theoretical development of the current method, based on equations of net radiation, it might be precisely employed in other climatic regions.

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Capturing Rainwater for Landscape Irrigation in Georgia

By Rose Mary Seymour, Wayne Gardner and Gary Wade

Introduction

There is increasing interest in rain water harvesting as an alternative water supply source particularly for landscape irrigation. Landscape designers and installers are wondering if this could be a new service, product or aspect of design that would be of interest to their customers. In Georgia, from 1998 to 2002, there were five years of excessively dry weather that greatly increased the interest of homeowners in having automated irrigation systems for their homes. At the same time that more irrigation systems were being installed, Georgia was deciding to restrict outdoor water use, the largest use of which is irrigation.

Home owners and high-end commercial locations still want to have green healthy landscapes even during drought when use of potable water may be restricted and would be most needed by landscapes. One possible solution for this landscaping dilemma is to harvest rainfall on site as an irrigation source.

Most studies and development of rain water harvesting guidelines have come from the western US, island countries and developing countries where water supplies are limited. However, harvesting rain water in a humid climate could become a more financially feasible practice due to decreasing water supply availability and increased need for storm water management in urbanized areas particularly. In areas with heavy or increasing urbanization where there are lots of impervious surfaces from which rain water could be harvested, the value of rain water harvest systems may become increase as municipal water becomes more restricted or more expensive to use. A rain harvesting system not only can be an alternative water supply. In humid regions, rain harvesting may also provide some storm water mitigation particularly in urbanized areas.

Rain Harvest – Irrigation System Description

The University of Georgia Griffin Campus (UGA Griffin Campus) installed a rainwater harvesting system for an office building where the harvested rainwater is the supply for a micro-irrigation system. The irrigation system supplies water for the landscape surrounding the building. In addition to rainwater, the condensate from air conditioning in the building was also routed into the harvest system. The rainwater harvest system was retrofitted to the existing building that was over 30 years old on the UGA Griffin Campus without changing any of the building structure. The roof area of the building is approximately

The building that the rainwater is harvested from is a two story building with a roof that slopes slightly to the back of the building. There are 3 gutters located down the back of the building that carry the water off of the roof. To capture the rain water from the roof, the original gutters were routed into new PVC pipes that carry the rainwater to a buried plastic cistern behind the building. The PVC pipe (6 in diameter) was connected to the old gutters about 8 ft. above the grade. A debris trap was set at the connection point between each of the original gutters and the PVC collection pipes. This trap would capture the first flush from the roof and the debris that would be washed off at the beginning of each storm. Then after the first flush of water filled the trap, the rest of the water would flow through the PVC pipes to the cistern storage.

The PVC pipes went from above ground to buried about 3 ft deep. Below ground all three pipes were connected into a pre-fabricated plastic storage cistern. The storage cistern was buried with a 24 in diameter cap that came to the surface for getting into the cistern to clean it out. The cistern holds approximately 2400 gallons of water. The water can exit the cistern in two ways. One exit is for an overflow situation during a storm when the cistern fills to the top. This overflow was a 5 in diameter PVC pipe exiting from the top of the cistern which comes out at the ground surface about 8-10 ft away from the cistern at grade. The other possible exit for the water in the cistern is from a 1 Hp submersible pump suspended in the cistern that pumps the water into a micro-irrigation system that supplies water to the landscaped area surrounding the building.

Water exiting the overflow pipe flows into a landscaped bed that captures much of the overflow. The overflow that stays in the landscaped bed infiltrates into the soil. Surrounding the bed is an expanse of 30 or more feet of established Bermuda grass that slopes gently (less than 2 %) away from the landscape bed. Once the landscaped area which is flat has retained as much rainwater as it can hold the overflowing water will continue to move through the Bermuda grass to an adjacent street. From observation, the heavy stand of Bermuda grass has prevented any erosion and actually holds much of the overflow in place to infiltrate such that virtually none of the overflow makes it to the street.

The landscape that the irrigation system applies water to is a mixture of trees, perennials and woody ornamental plants. In an early design there was going to be small patch of turf that would be watered by drip tape, but the cost of the irrigation equipment for this area was determined to be prohibitive, so the turf area does not receive any irrigation at this time. The total estimated design water requirement for the landscape was about 310 gallons per day. The 1 Hp pump provides much more capacity of flow than is needed for the irrigation system since no zone would need more than 70 gallons per hour. The landscape has 8 zones. The applicators for all zones are 1 GPH pressure compensating drip emitters.

The landscape, irrigation system and rain harvesting system have been in place for about one growing season so far. In this first growing season because it was a wet year, very little irrigation water has been applied, so the rain harvest system has not had a real test so far. It’s benefits will be seen when there is another drought year in Georgia which could happen any time.

Future Plans

The next phase of this project is to implement a monitoring system for the rain harvest system and actually measure how much storm water gets saved and recycled with various weather patterns and whether the cistern can support the area of landscape that it has been designed for or whether it may be possible to extend the irrigation system to cover more landscape in the future with the capacity of the cistern.

The monitoring system consists of a sensor in the cistern that measures the volume of water in the cistern, a flume measuring device that measures any overflow water volume and a inline pipe flow meter measuring the amount of the water that gets used as irrigation water for the landscape. The monitoring equipment is going to be installed this winter so that monitoring can begin in the 2005 growing season.

There are several aspects of the original design that may be able to be improved once the results of the monitoring of the system have been analyzed. For example, the size of the cistern, the size of the pump and the estimate of water use for the landscape may be over-designed for the humid climate of Georgia. If any of these things could be reduced then the cost of the system would be reduced accordingly, and the rain harvest system might be a more feasible addition to the overall landscape design.

Currently, a major deterrent to installation of rain harvesting systems for irrigation is the additional cost to the irrigation system. With the price of municipal potable water increasing, a rain harvesting system for landscape irrigation becomes a more cost effective option. Compared to recycling of treated wastewater, the plumbing costs for retrofitting a building with a rain harvest system are minimal, so in locations where potable water restricted from being used as irrigation water in humid to semi-arid climates, harvesting rain water would seem to be a viable alternative, particularly for smaller landscapes.

Irrigation Scheduling for Optimum Plant Water and Nutrient uptake

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Abstract

Effective and efficient water resource management is undoubtedly one of the most important policy issues facing agriculture in Hawaii in the years ahead. A successful irrigation water management program optimizes water availability, ensures the best crop yield and quality while minimizes production costs and nutrient losses below the rootzone. The objective of the current work is to establish an irrigation scheduling program for a tomato crop to optimize plant water and nutrient uptake. A tomato variety trial was conducted at the University of Hawaii Poamoho research station on a Wahiawa silty clay soil. Irrigation setting points were determined based on root system growth and soil water release curves established from soil cores taken within and below the rootzone. Rain, irrigation and real-time soil water content were monitored throughout the soil profile. Plant water uptake and excess losses below the rootzone were calculated using a water balance approach and field data.

Introduction

Irrigated agriculture is the leading water user around the world. In Hawaii, declines in plantation agriculture resulted in a drastic reduction of agriculture water use. However, Hawaii agriculture is still required to optimize its water use for two main reasons: to optimize crop production in order to compete with the import markets and to minimize environmental impacts from erosion or nutrient leaching into aquifers.

Demands on our limited water supplies in Hawaii are increasingly competitive, especially as we experience more cycles of drought and dynamic changes in land use. Growth of a diversified agriculture in Hawaii is dependent on its ability to compete with imported products. In order to have a competitive advantage, Hawaiian agricultural production efficiency is becoming necessary for producers to maintain or increase their net returns in an increasingly global market. Increase in net returns could be realized by increasing crop yield per unit area and/or minimizing crop production costs. Several crop water production functions, describing the relationship between crop yields and evapotranspiration, have been developed for different crops under different management practices. In addition to their cost, excess water losses ensuing from poor irrigation scheduling carry with them dissolved fertilizers and pesticides beyond their targeted area resulting in substantial increases in production costs. Hence, optimum irrigation water management is critical in any effort to increase Hawaiian diversified agriculture net returns.

Yield and dry matter production of many plants are linearly related to total evapotranspiration (ET). The relationship between ET and available soil water in the rootzone is generally linear but becomes curvilinear when soil water content is close to saturation. The curved portion of the line reflects low efficiency of irrigation water use, primarily due to excessive water leaching below the rootzone. Moreover, such leaching removes nutrients and pesticides away from their intended application zones resulting in higher crop production costs and water quality impairment. Ample research findings in the literature show that efficient irrigation practices reduce production costs, improve crop yield, limits erosion and sediment-loading, and enhance environmental quality.

There are several candidate crops for irrigation studies in a new and a more diversified Hawaiian agriculture. Tomato is a good representative of an economically diversified agriculture in Hawaii. Water management of these crops is mainly based either on the growers' best judgment and experience of trial and error. To date, little information is available for the highly weathered, well-structured tropical soils that prevail in the agricultural lands of Hawaii.

The purpose of prudent irrigation scheduling is to determine when and how much to irrigate to meet crop demands. Several irrigation scheduling methods have been used for different crops. Check-books, pan evaporation and soil water monitoring devices, i.e., tensiometers and neutron probes have been successfully used as irrigation scheduling tool for several decades. However, recent electronic advances resulted in the development of real-time soil water monitoring devices such as time domain reflectometry and capacitance sensors. These devices have been used extensively for efficient irrigation and nutrient management in different crops, i.e. citrus (Fares and Alva, 2000; Fares and Alva, 1999). Since capacitance sensors monitor water content at multiple depths and at different locations in real-time; they can be used along with tensiometers to determine important soil physical properties such as soil water release curves, hydraulic conductivities and soil water holding capacities. Fares and Alva (2000, 1999) used this approach in addition to irrigation and rainfall data to calculate daily plant water use and excess water losses below the rootzone.

A sound irrigation management program requires knowledge of the soil water holding capacity, root zone depth and the ability to determine or estimate the available soil water at any time during the growing season. This information, in turn, allows for the methodical determination of the timing and amount of irrigation water to be applied (Fares et al., 2000).

Materials and Methods

The study was conducted at the University of Hawaii-Manoa Poamoho research station, Waialua, Oahu, HI. This study was part of a tomato variety trial (*Lycopersicon esculentum*) grown under drip irrigation on a Wahiawa silty clay. A typical soil profile for a Wahiawa silty clay consists of Ap1 (0-6 inch), Ap2 (6-12 inch), B21 (12-16 inch), B22 (16-33 inch), B23 (33-45 inch), and B24 (45-60 inch) horizons (National Cooperative Soil Survey, 1978). Bulk densities range from 1.10 – 1.30 g/cm^3 for 0-14 inch depths, permeability ranges from 0.6-2.0 in/hr for depths of 0-2 inch and 0.2-0.6 in/hr for depths of 2-14 inch. Soil water release curve data for a typical Wahiawa silt clay loam soil as reported by Gavenda, et al. (1996) are presented in Fig. 2.

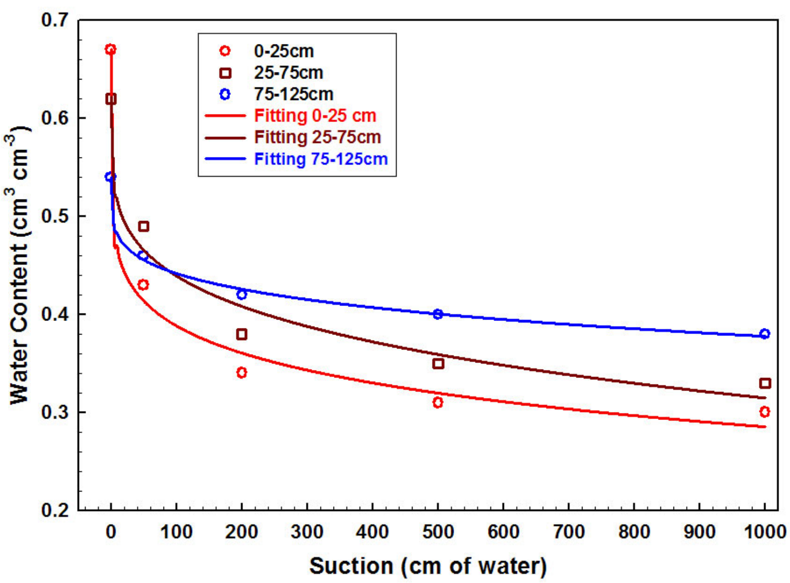

Figure 1. Soil water release curves for a Wahiawa soil (Gavenda, et al., 1996).

The mean annual rainfall is 1270 mm and mean annual temperature is 22º C, however, this year there was 1230 mm (Fig. 2) in only four months of the dry season.

Description of Field Experiment

Four tomato plants, each representing a variety (FI 68-5, HA-3816, F1 #5, and BHN555), were selected for soil water monitoring and measurements. Three ECH$_2$O® capacitance sensors (Decagon Devices, Inc.) and one EasyAg® (Sentek Sensor Technologies) capacitance sensor, one per plant, were installed to measure soil moisture content in real-time within a root zone of 0-

25cm. Sensors measured soil moisture content every 10 to 30 minutes and data were recorded using a Campbell Scientific data logger. In this paper, we are reporting the EasyAg data only. A rain gage equipped with a data logger was used to monitor both irrigation and rainfall events. Daily and cumulative rainfall during the study period are shown in Fig.2.

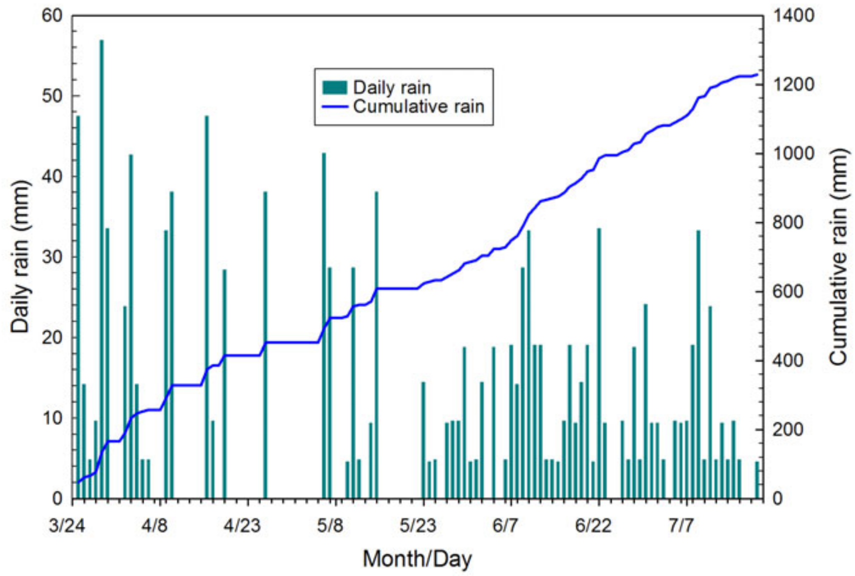

Figure 2. Daily and cumulative rain for the research site.

Results and Discussion

The data presented in Fig. 3 show the daily rain data (C), and the water content at 10, 20 (A), 30 (B) and 50 (C) cm below the root zone. In an average year, summer months are dry; however, this year over 600 mm of rain was received during three summer months (June - August). A calibration experiment was conducted on the same site to calibrate the EasyAg to these tropical soils. Results of this work are not presented here; however the calibration equations developed for each depth were used to process the raw data collected by the capacitance sensors. Soil water content data presented here were converted using these new calibration equations and not the manufacturer default calibration equation.

The water content in the top 10 cm showed more wetting and drying cycles as compared to all the other depths. The water content at that depth varied between 0.26 and 0.40 cm^3 cm^{-3} as a result of water inputs (rain and irrigation), and water losses through soil evaporation, and plant water uptake through evapotranspiration, and excess water losses below the rootzone and occasional runoff under intense rainfall events.

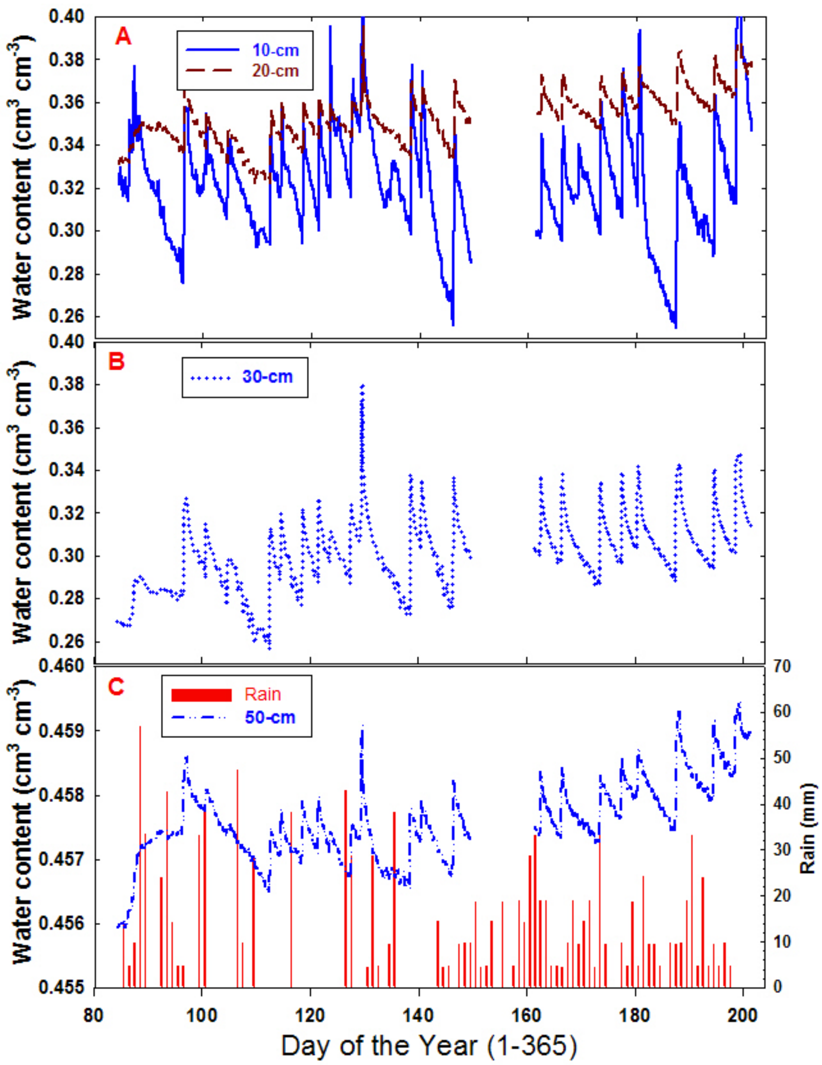

Figure 3. The daily rain (C), and the water content at 10, 20 (A), 30 (B), and 50 cm below the soil surface.

The water content in the 20-cm depth showed similar variation as of that in the 10-cm depth; however, the amplitude of this variability was lower, it varied between 0.33 and 0.38 cm^3 cm^{-3}.

The water content in the 30-cm depth showed similar dynamics as the water content in the top two levels. The range of this variability is more similar to that in the 10-cm depth than to that in the 20-cm depth. It varied between 0.26 – 0.34 $cm^3\ cm^{-3}$. The water content at the 50-cm depth showed less than 1% variability over the entire period (Fig. 3 C). At the finer scale, the water content variations are similar to those shown in upper sensors.

The water content data at the four depths, 10, 20, 30 and 40 cm were used to calculate the water content in the rootzone and below it. It was assumed that the majority of the tomato roots are in the top 45 cm; thus the water content data from the top three sensors were multiplied by 15, 10 and 20 cm, respectively, to determine the total water stored in the rootzone (Fig. 4 A). The "Full Point" and "Wilting Point" were defined as the water storage in the rootzone, top 45 cm, corresponding to field capacity and permanent wilting point, respectively. Optimum irrigation management practices should ensure that the storage water in the rootzone should vary between those upper and lower boundaries. The sensor at the 50-cm depth was used to represent the water content below the rootzone in the zone between 45 and 55 cm below the rootzone. Data for this sensor are plotted in Fig. 4 B. These data show that excess water reached the 50-cm depth as a result of the rainfall events shown in Fig. 2.

The stored water below the rootzone followed a similar pattern as that in the rootzone; however, the amplitudes of the variation of the latter were relatively small; this could be attributed to the low hydraulic conductivity of this soil. The variations of the stored water in the rootzone are the results of water input from the rain and occasional irrigation and water output that include evapotranspiration through the soil surface and plant transpiration, excess water losses below the rootzone and potential surface runoff.

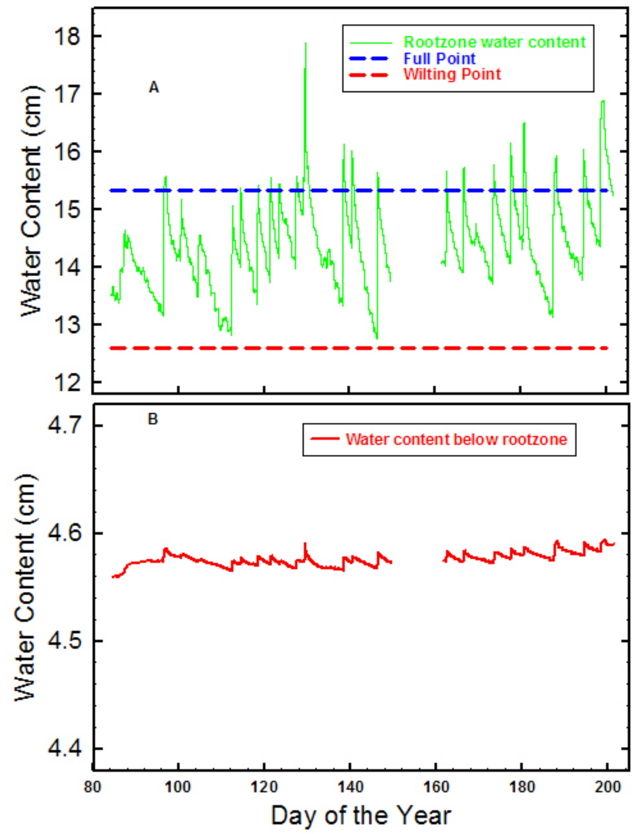

Figure 4. cumulative water in the rootzone (A) and blow it (B) with the upper and lower limits.

Summary and conclusions

As a major water user, irrigated agriculture is expected to make substantial changes to optimize its water use. Optimum water management should be based on understanding soil water holding capacity and crop water use through the growing season. Water content within and below the rootzone in a tomato trial was monitored for several months. Soil samples were taken for a laboratory determination of soil water release curve at four different depths, 10, 20, 30 and 40 cm. Real-time soil water content monitoring within and below the rootzone showed substantial variations as a result of water input through irrigation and rainfall and also the as a result of water output through evapotranspiration and deep percolations. Future field work should include at least three soil moisture sensors per treatment, on site weather data collection and field determination of soil physical properties. These data will be necessary to determine the different water budget components for a tomato crop grown under Hawaii leeward conditions.

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Soybean, Wheat, and Forage Subsurface Drip Irrigation using Treated Swine Effluent

K. C. Stone, P. G. Hunt, and M. H. Johnson[1]

Abstract

Two experimental subsurface drip irrigation (SDI) systems have been initiated to evaluate the use of treated swine effluent on a continuous soybean/wheat crop rotation and on a forage crop. The SDI systems were installed in Duplin County, North Carolina at the location of an innovative swine wastewater treatment system. The effluent from the treatment facility will be applied to both the soybean/wheat and forage crops at agronomic nutrient rates. Treated wastewater application below the soil surface reduces the nutrient loss potential through volatilization and places nutrients in the rooting zone. Preliminary results from the first year of the soybean/wheat rotation and forage operation will be discussed.

Introduction

Animal production has expanded rapidly during the early 1990's in the eastern US. In North Carolina, the number of swine has increased from approximately 2.8 million in 1990 to more than 9 million by 1996 (USDA-NASS, 2004). This rapid expansion of animal production has resulted in greater amounts of concentrated animal waste to be utilized or disposed of in an efficient and environmentally friendly manner. It has exceeded the pace at which new innovative treatment systems have been developed, and it has resulted in the animal production industry aggressively investigating and adapting new alternative wastewater treatment technologies. Additionally, the expansion of animal production has led to fewer, more concentrated operations that are challenged to treat, utilize, and/or dispose of the waste in an environmentally friendly manner. Additional challenges and concerns from these operations are odors, ammonia emissions, and pathogens. Many new and innovative systems still rely on the final land application of treated wastewater which typically use high volume sprinkler irrigation systems.

Subsurface drip irrigation (SDI) systems can help to address some concerns about land application of treated animal effluent. The SDI systems apply effluent below the soil surface and can eliminate spray and drift from land application thereby reducing odors and ammonia volatilization. The SDI systems may also be used during periods of high wind or low temperatures when sprinkler application would not be acceptable.

Subsurface drip irrigation systems have been used in Kansas to apply beef lagoon effluent with successful results (Lamm et al., 2002). In the southeastern Coastal Plains, little research has been conducted using SDI systems for application of wastewater. The objective of this work is to determine the feasibility of and management guidelines for SDI systems applying treated wastewater in the eastern Coastal Plains.

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Methods

Site Description

The study was conducted on a 4-ha site of Autryville loamy sand (Loamy, siliceous, subactive, thermic Arenic Paleudults) in Duplin County, North Carolina. Two subsurface drip irrigation (SDI) systems (forage SDI and soybean/wheat SDI) were installed in the summer of 2003.

Forage SDI: The forage SDI system was approximately 0.53 ha. The system consisted of 36 total plots (9.6 x 9.6 m) with 9 treatments. The treatments were irrigation application amount (75 or 100% of ET), nutrient source (commercial or treated effluent), SDI lateral spacing (0.6 and 1.2 m), and also a non-irrigated treatment.

Soybean/Wheat SDI: The soybean/wheat SDI system was approximately 0.7 ha. The system consisted of 20 total plots (12.8 x 12.8 m) with 5 treatments. The treatments were irrigation application amount (100% of ET or limited application ~1.25 mm/d), SDI lateral spacing (0.6 and 1.2 m), and a non irrigated treatment. The limited irrigation treatment was designed to apply a small daily application to utilize the excess wastewater generated by the treatment system. All nutrients for the soybean/wheat SDI system were supplied with treated effluent.

In both systems, SDI laterals were installed at 0.3 m below the soil surface using two poly-hose injection shanks mounted on a tool bar. The irrigation system for each plot consisted of individual PVC pipe manifolds for both the supply and discharge. Discharge manifolds were flushed back to the adjacent lagoon. Irrigation laterals had in-line, pressure compensating labyrinth emitters spaced 0.6 m apart with each delivering 1.9 L/h.

Control System: The SDI irrigation system was controlled by a 200 GHz Pentium PC running a custom Visual Basic (VB) program. The VB program operated a digital output PCI board, an A/D input board, and a counter/timer board. The digital output board operated supply pumps and solenoid valves. The A/D input board read supply line pressures. The counter/timer board recorded flows. Float switches controlled tank levels.

Each water source had a dedicated pump and supply tank. Selected treatments could receive treated effluent and all treatments could receive well water. Screen filters were used for both water types. A media filter with sand and gravel was used to filter the treated effluent before it reached the screen filter.

Flowmeters were used on each water source as well as each treatment. Supply pressures were monitored using pressure transducers. A pressure transducer was placed before and after the screen filter for each water source.

Weather Station: A tripod mounted weather station was installed at the irrigation site. The station used a CSI data logger to measure relative humidity, air temperature, solar radiation, wind speed, wind direction and rainfall. The data logger tabulated data at 5 minute intervals. The data was downloaded daily to the irrigation control PC via broad spectrum radio.

Irrigation Scheduling: Once the weather data was received from the data logger, potential ET was calculated using a SAS program. The potential ET was then multiplied by a crop coefficient to obtain the daily ET value for the crop. The ET and daily rainfall were accumulated for the previous seven days. When the cumulative ET for the previous days exceeded the accumulated rainfall by greater than 6 mm, an irrigation event was initiated.

Wastewater Treatment System: An innovative swine wastewater treatment system was designed and tested at full-scale on a 4,400-head finishing farm as part of the Agreement between the Attorney General of North Carolina and Smithfield Foods/Premium Standard Farms to replace current anaerobic lagoons with environmentally superior technology (Vanotti, 2004). The treatment system was developed with the objectives 1) to eliminate animal-waste discharge to surface and ground waters, 2) to eliminate contamination of soil and groundwater by nutrients and heavy metals, and 3) to eliminate or greatly reduce the release of ammonia, odor, and pathogens.

The effluent treatment system consisted of three modules. The first module separated solids and liquids. The second module removed nitrogen using a combination of nitrification and denitrification. The third module removed phosphorous in the Phosphorus Separation Module, developed by USDA-ARS (Vanotti et al., 2001), and it recovered the phosphorus as calcium phosphate. This process required only small additions of liquid lime. The alkaline pH with this process reduced ammonia volatilization losses and killed pathogens. Treated wastewater was recycled to clean swine houses and for the SDI systems. The system removed 97.6% of the suspended solids, 99.7% of BOD, 98.5% of TKN, 98.7% of ammonia, and 95% of total P. Average inflow concentrations and system outflow nutrient concentrations are shown in table 1.

Table 1. Treated Effluent Characteristics.

Water Quality Parameter	**Raw Flushed Manure (mg/L)**	**Treated Effluent (mg/L)**
pH	7.6	10.5
TSS	11,051	264
BOD_5	3,132	10
COD	16,138	445
Soluble P	135	8
TP	576	29
TKN	1,584	23
NH_4-N	872	11
NO_3-N+NO_2-N	1	224

Crop Management

Soybean/Wheat: Four soybean varieties were planted on June 25, 2003 using a no-till grain drill. The four varieties were Delta Pine 7220 RR, Northrup S73 Z5 RR, Pioneer 97B52 RR, and Southern States RT6202N RR. The soybeans were harvested on November 18, 2003, using an Almaco plot combine. The soybeans were followed by wheat, which was planted on December 2, 2003. There were four varieties of wheat: Vigor Tribute, Pioneer 26R61, USG 3209, and SS FFR566. The wheat was harvested on June 29, 2004.

Bermuda Grass Forage: Bermuda grass was over sown with SS FFR535 wheat variety using the no-till grain drill on December 2, 2003. The winter cover crop was mowed after heading and bailed on May 27, 2004. Bermuda grass hay was then harvested on July 1, 2004, and August 10, 2004.

Results and Discussion

Soybean: Soybean yields were greatly influenced by the varieties (Table 2). The SDI lateral spacing appeared to have little influence on the soybean yields for most varieties studied. Water application rate had the greatest influence on yield. The 100% ET application rate consistently had higher yields than the limited and non-irrigation treatments. The non-irrigation yields were very similar to the limited irrigation treatments. The limited irrigation treatment was designed to apply a small daily application to utilize the excess wastewater generated by the treatment system. This small application appeared inadequate to move the water laterally and provide water to the soybeans between the laterals.

Table 2. Soybean yields for 2003 season.

Spacing (m)	**Application Rate**	**Delta Pine**	**Northrup**	**Pioneer**	**Southern States**
		(kg/ha)			
1	100% ET	2475	1728	1702	1649
1	Limited	1990	1706	1576	1296
2	100% ET	2663	2099	1876	1982
2	Limited	1754	1584	1548	1290
	Non-Irrigated	1853	1738	1191	1809

Wheat: The wheat crop yields were also dependent on the varieties (Table 3). The variety yields ranged from 52 to 1400 kg/ha with the higher yields resulting from the 100% ET water application treatments. The lateral spacing for the wheat showed more difference than the soybean crop. The 1-m lateral spacing had higher yields for all varieties. The limited irrigation treatment had similar yields for the two lateral spacings and was generally lower than the non-irrigated yields.

Table 3. Wheat yields for 2003-2004 season.

Spacing (m)	Application Rate	Vigoro Tribute	Pioneer 26R61	USG 3209	SS FFR566
		(kg/ha)			
1	ET	233	1397	811	1362
1	Limited	224	852	301	679
2	ET	153	1038	502	752
2	Limited	52	748	366	653
	Non-Irrigated	280	970	665	843

Bermuda Grass Forage: There were two Bermuda grass hay cuttings (Table 4). For this experiment, there were two water application rates, 100% and 75% calculated ET. The first cutting produced yields that appeared to be counter intuitive. The treatments using commercial fertilizer had much lower yields than the treatments with treated wastewater for both lateral spacings and for both application rates. This was partially explained by residual nutrients in the plots that were irrigated with treated wastewater during the wheat season.

Table 4. Bermuda grass hay yields for first two cuttings in 2004.

Spacing (m)	Application Rate	Fertilizer Source	First Cutting kg/ha	Second Cutting kg/ha
0.6	ET	Commercial	3831	6360
0.6	75% ET	Commercial	4195	7114
0.6	ET	Treated	6186	6792
0.6	75% ET	Treated	6229	6158
1.2	ET	Commercial	4140	4820
1.2	75% ET	Commercial	4204	6790
1.2	ET	Treated	6887	6509
1.2	75% ET	Treated	8292	6942
	Non-Irrigated	Commercial	5820	5982

For the second cutting, results for both the commercial and treated waste water treatments were similar. For this cutting, there was little difference between lateral spacing, fertilizer source, and irrigation applications. Generally, irrigated treatment yields were higher than the non-irrigated treatment. The lack of differences between the yields for the different lateral spacing could assist future designs and lower the initial cost of SDI systems by using wider lateral spacings with little yield differences.

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TheHelper, A User-Friendly Irrigation Scheduling Tool In Florida and Hawaii

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Abstract

Efforts are being made to optimize Florida citrus production and minimize non-point source pollution of water resources through best water management practices. A user-friendly irrigation scheduling program, TheHelper, was developed to help different users understand citrus water requirements under different micro-irrigation systems based on historical evapotranspiration data and soil water holding capacities of the major Ridge and Flatwood soils. The user chooses from a menu driven the major input data: soil type, irrigation system specification, irrigation depth and available water depletion level. The program produces several outputs that can be printed including: i) a long-term, annual, irrigation scheduling program with the option of printing it; ii) develop short-term monthly, irrigation scheduling program based on different soil types, depletion levels and irrigation system specifications; and iii) develop a monthly file of the different irrigation events for the different irrigation management units.

Introduction

Water is critical for optimal growth and production of all plant crops. Optimum amounts of water at the right time allow plants to grow and produce at their best. With the exception of arid and semi-arid conditions, rainfall is the main source of water supply for most field crops. However, supplemental irrigation has been proven to increase crop yield even in areas having relatively high annual rainfall. Optimum crop production requires good irrigation scheduling programs. Efficient irrigation scheduling optimizes crop water update and minimizes water losses.

Soils in the rootzone are the reservoir from which crops can obtain their water needs. Soils have different water holding capacities depending on their texture and structure. Usually, fine textured soils have higher water holding capacities than coarser textured soils. Similarly, soils with high organic matter contents have higher water holding capacity than soils with low organic matter.

The depth of the crop roots defines the soil depth that supplies water for the crop. Deep rooted crops usually explore more water than shallow rooted crops under the same conditions. Annual crops explore different rootzone depths as a result of the growth of their root system throughout the growing season. Although during the first few weeks of growth, annual crops use water from the top few inches of soil, at maturity, their roots extend deeper into the profile and their water uptake could reach up to 5 to 6 ft below the soil surface.

Usually, less than 1% of the crop water uptake is assimilated by the plant. The rest of the water is used to cool the crop through the processes of evaporation and transpiration. Combined together, these two processes are called evapotranspiration (ET). Evaporation is the change of water from its liquid form to vapor which requires energy. Under humid conditions, if the leaves of well-watered plants or wet soils are moist, the amount of water evaporating and moving into the air is mainly determined by the energy available from solar radiation known as atmospheric demand. Although it is influenced to a certain extend by air temperature, humidity, and wind speed, ET rate is maily affected by solar radiation. Consequently, ET levels are higher during the summer when daily solar radiation levels and temperatures are high compared with the winter when these two variables are low.

Optimization of crop growth and production requires efficient irrigation scheduling which is the decision-making process used to determine the frequency and amount of irrigation water to meet the needs of the crop. Thus, the goal of irrigation scheduling is to answer two questions: 1) when to irrigate and 2) for how long?

There are several irrigation scheduling methods that have been used for different crops under different edaphic and climatic conditions including visual symptoms, check book, plant water content, plant water stress, soil water content, and computer models using historical ET, soil water holding capacity and crop growth stage. Instrumentation based irrigation scheduling methods are more accurate than the other methods; however, they are usually expensive, require special training and may not be affordable by small growers.

The objectives of this irrigation scheduling method are: i) to collect historical evapotranspiration data and available soil water for different soil types in Florida and Hawaii in addition to calculate a monthly irrigation frequency and irrigation length based on irrigation delivery rates and irrigation depth; ii) use these data to develop a user-friendly visual basic program that can be easily used by growers.

Materials and Methods

The answer to the two main questions in any irrigation scheduling program is when to irrigate and for how long. In order to answer these two questions we have to quantify: i) how much water is available per unit length for a given soil; ii) how much is the daily ET rate? iii) how much of the available water should be depleted before starting the next irrigation? iv) how deep we want to irrigate?

How Much Water is Available for Crop uptake Per Unit Soil Length?

Available water is defined as the amount of water between field capacity and permanent wilting point (PWP). Field capacity is defined as the amount of water that a given soil can hold against gravity one (for a sandy soil) to three (a clay soil) days after its saturation. The permanent wilting point is the water content at which a crop can no longer extract water from the soil and wilt as a result of that; it is usually taken as the water content corresponding to 15-bar suction.

Table 1 shows the depth of the rootzone and the average available water for some of the major soils in Hawaii, Florida flatwood, and Florida ridge locations. These data presented in Tables 1 are used in TheHelper program.

Table 1. Rootzone depth and the average available water for some of the major soils in Hawaii, Florida flatwood, and Florida ridge locations.

	Florida Flatwood Soils						
	Immokalee	Myakka	Bradenton	Pomona	Smyrna	EauGallie	Floridana
Depth (in)	18	18	18	18	18	18	18
AWC (in/in)	0.060	0.060	0.180	0.110	0.200	0.140	0.135
	Florida Ridge Soils						
	Astatula	Archbold	Candler	Tavares	Apopka	Basinger	Zolfo
Depth (in)	36	36	36	36	36	36	36
AWC (in/in)	0.060	0.060	0.060	0.046	0.108	0.124	0.07
	Hawaii Soils						
	Oahu			Big Island	Maui	Kauai	
	Leilehua	Waialua	Hanalei	Waimea	Kula	Puhi	Lihue
Depth (in)	75	60	36	42	54	60	60
AWC (in/in)	0.11	0.12	0.17	0.12	0.15	0.11	0.14

How much is the daily ET rate?

Evapotranspiration is the main process by which available water is depleted from the rootzone of any crop. Evapotranspiration data for different citrus grown under Florida conditions have been calculated and reported in earlier studies (Koo and Sites, 1969; Rogers et al., 1983; Fares and Alva, 1999, 2000). Two daily ET averages throughout the year were computed for citrus grown under Flatwood and Ridge soil conditions (Table 2). Pan evaporation data collected from the leeward and windward locations throughout the main four Hawaiian Islands were used and multiplied by a pan factor of 0.7 to calculate the corresponding daily potential ET are also presented in Table 2.

Table 2. Evapotranspiration data (ETo) for the leeward and windward locations in different islands of Hawaii, and in the ridge and flatwood area of Florida.

Month	Oahu		Kaua'i		Hawai'i		Maui		Florida Citrus	
	WW	LW	WW	LW	WW	LW	WW	LW	Flat-wood	Ridge
	ETo (in)									
Jan	2.44	3.37	3.61	3.35	4.18	3.56	4.17	3.36	2.20	1.97
Feb	2.37	3.58	3.65	3.68	4.34	3.75	3.93	3.54	2.20	1.85
Mar	3.02	4.26	4.61	4.66	4.93	4.70	5.47	4.27	3.19	2.68
Apr	3.02	4.84	4.83	4.93	5.03	4.68	5.71	4.68	3.54	3.31
May	3.25	5.99	5.60	5.22	6.02	5.85	6.61	5.73	4.53	3.07
Jun	3.23	6.64	5.67	5.38	6.23	6.22	6.59	6.28	5.08	4.88
Jul	3.43	6.52	6.10	5.61	6.39	6.14	7.07	6.65	5.00	4.76
Aug	3.47	6.57	5.88	5.58	6.70	5.88	7.03	6.71	4.65	4.45
Sep	3.02	5.33	5.26	5.04	6.10	5.73	6.09	6.38	4.13	4.09
Oct	2.73	4.45	4.64	4.40	5.39	4.73	5.68	5.33	3.66	4.06
Nov	2.48	3.68	3.74	3.61	4.24	4.28	4.56	4.09	2.48	2.32
Dec	2.32	3.23	3.39	3.07	4.34	3.61	3.30	3.43	2.20	1.97

How much of the available water should be depleted before starting irrigation?
Water stress occurs well before the depletion of all available water. Thus, a good irrigation management should prevent yield reducing crop water stress by not depleting all available water but by maintaining the soil water content above the PWP. Optimum citrus production requires maintaining soil water content above the 33% depletion of the available water during the period from February to May to avoid potential adverse effects of water stress on flowering and fruit set (Koo, 1969). However, during the remaining part of the growing season, available water can be allowed to deplete by 67% before replenishment of the soil water back to field capacity. These two depletion levels were implemented in TheHelper; however, we allowed the user of the Hawaii version to choose a depletion level ranging between 10 and 100% of the available water.

How deep we want to irrigate?
The irrigation depth will be used to determine the amount of water available for crop water uptake. The deeper the irrigation depth the longer it takes the crop to deplete the available water and to refill the soil profile up to field capacity during irrigation. Thus, for the same ET rate it will take the crop twice as much to deplete the available water in a two-foot rootzone as compared to a one-foot rootzone. Similarly, the same irrigation system will take twice as long to refill a two-foot rootzone as it does for a one-foot rootzone. The user has the choice to use irrigation depths in quarter foot increments.

Model Description

This computer program was developed Using Microsoft Visual Basic 5.0. It is intended to help the user:

1. Understand citrus water requirements based on historical ET data and soil water holding capacities of the main Ridge and Flatwood soils.
2. Develop a long-term, annual irrigation scheduling program with the option of printing it.
3. Develop short-term, monthly irrigation scheduling program based on different depletion levels and irrigation system specifications.
4. Develop a monthly record-keeping of irrigation events for different irrigation systems and depth of irrigation with the option of saving the data into a file that can be printed or kept in record.

The program consists of six screens including the main screen (Fig. 1). Starting from the main screen, the user has five options:

1. Irrigation Records
2. Annual Schedule
3. Short-Term Scheduling
4. Print
5. Cancel

Each of these options can be activated by clicking on its corresponding TAB. Below is a brief description of each of these options.

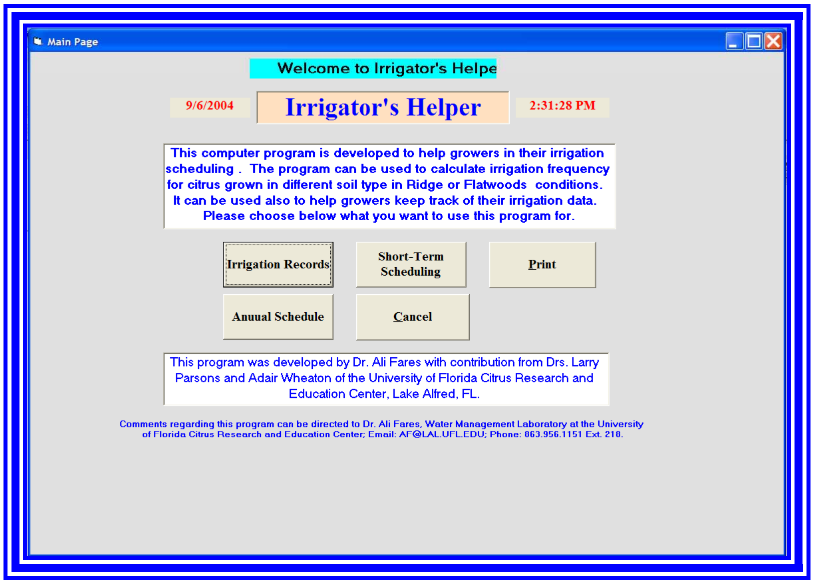

Figure 1. This is the starting page of the TheHelper software.

1. Irrigation Records:

This option intends to help growers keep record of their irrigation events. It involves four main steps:

- First step is for the user to choose the characteristics of her/his irrigation system :
  - Wetting pattern: full circle (360 ^{o}), three quarters of a circle (270 ^{o}), half a circle (180 ^{o}) or quarter of a circle (90^{o}).
  - Delivery volume: the number of gallons delivered per emitter per hour GPH.
  - Wetting diameter: the user has to choose for a range between 10 – 20 ft?.
  - Tree spacing: the user enters the in row and between row tree spacing in feet. The user clicks on the Irrigation Rate (in/h) Tab to get the equivalent irrigation depth applied by his irrigation system on the wet part of his grove. It is assumed that this irrigation system has 85% irrigation efficiency.
- Second step is where the user chooses the month of the year for which she/he is developing the irrigation record keeping.
- Third step: the user has a daily numbered table, i.e., Day 1. The user enters the number of hours of irrigation for every irrigation day for that particular month.
- Step four, the user has several options:
  - Accept Data. By pressing this Tab the user is sending the data that she/he entered to a Microsoft-Word file type called "Report.Doc".
  - Next month option clears the screen and allows the user to start fresh pages. The data of the irrigation system are not altered.
  - Exit option will terminate the program.
  - Back to MainPage returns the program to the main page.

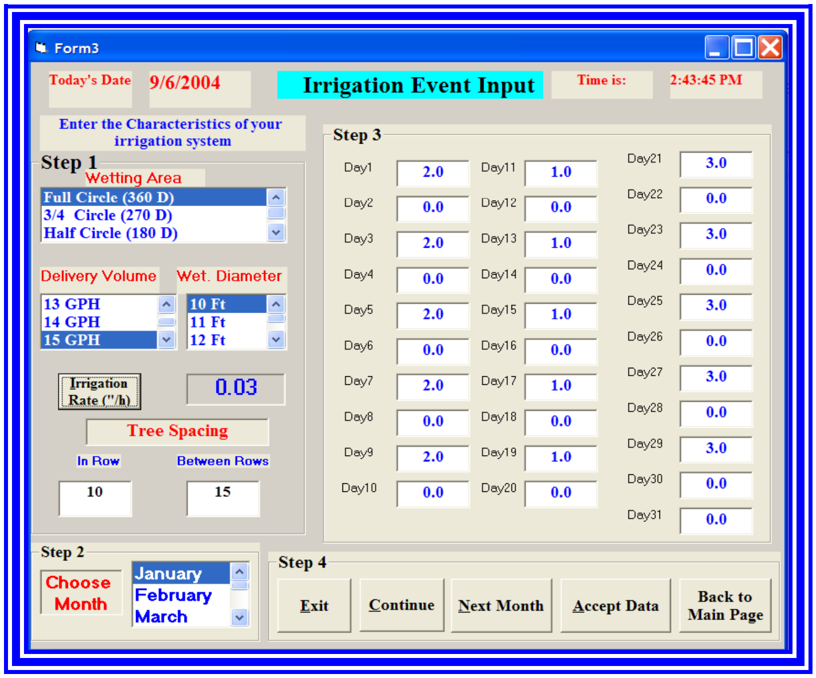

Figure 2. This is the page were the users can enter their irrigation events that will be printed into a monthly report generated by the program.

2. Annual Schedule

This part of the program is intended to calculate an annual irrigation schedule that will result in a printable table where the user will have answer to two questions: How often to irrigate and for how long? As soon as you press the TAB of "Annual Schedule" a new screen opens that involves two main steps and a series of option TABs.

- Step 1. During this step the user chooses:
  - Soil type from two main categories:
    - Ridge and
    - Flatwood
  - Irrigation depth: the range to choose from starts with 0.5 to 4.0 feet with a half-foot increment.
- Step 2. The user chooses the characteristics of her/his irrigation system mainly:
  - Wetting pattern: full circle (360 ^{o}), three quarters of a circle (270 ^{o}), half a circle (180 ^{o}) or quarter of a circle (90^{o}).
  - Delivery volume: the number of gallons delivered per emitter per hour GPH.
  - Wetting diameter: the user has to choose for a range between 10 – 20 ft?.
- Step 3. The user has several options:
  - Annual irrigation schedule TAB. By pressing this TAB the user is instructing the program to calculate an annual irrigation schedule. This will display a form that has two main parts
    - Part 1 has the input parameters that were used to generate the annual irrigation schedule:
      - Irrigation system characteristics:
        - Wetting areas (360 – 90)
        - Delivery volume (GPH) and
        - Wetting diameter.

- Soil type from the Ridge and Flatwood data base.

▪ Part 2 includes the output of the program. It is mainly a three column table:
  - First column includes the months of the year
  - Second column is irrigation duration in hours
  - Third column is irrigation frequency in days.

    You have three options:
    - Print the form by pressing "Print Form" TAB.
    - Return to previous screen "Back to the Annual Input Form"
    - Return to the main page "Back to MainPage".

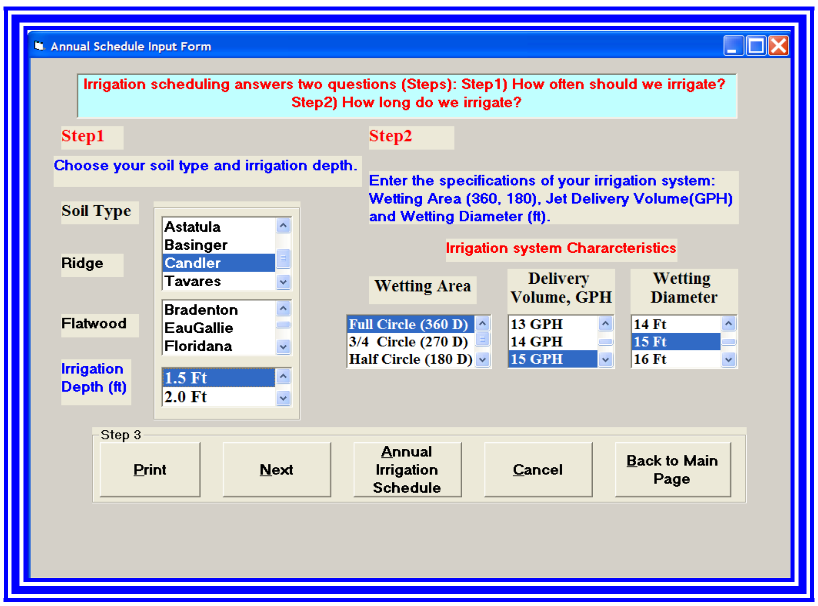

Figure 3. This is the input page for the long-term irrigation scheduling option of the program.

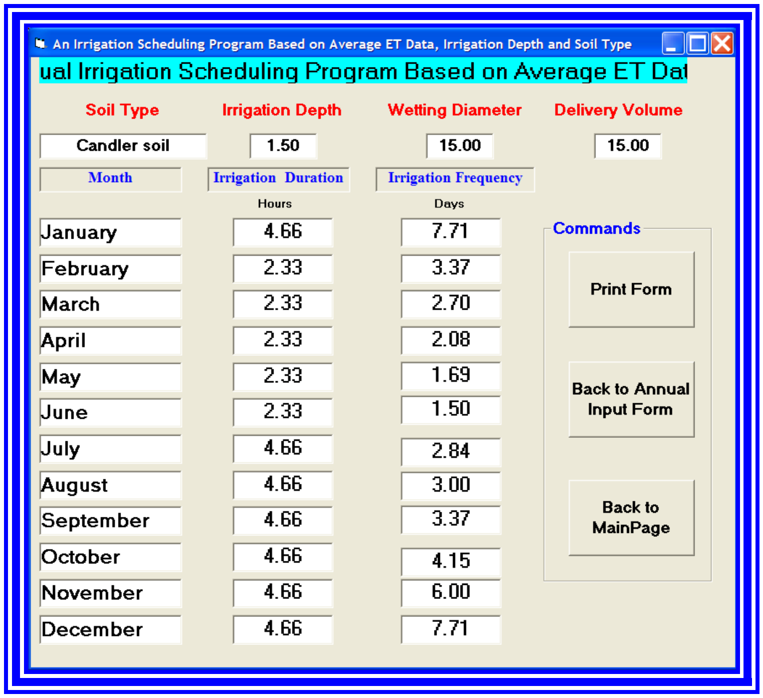

Figure 4. This is output page of the long-term irrigation scheduling option of the program.

3. Short-Term Scheduling

This option involves two screens.

a) By pressing the Short-Term Scheduling TAB, the program loads screen 1. This screen involves three steps:
   - o Step1. The user chooses:
     - ▪ Soil type from two categories:
       - Ridge
       - Flatwood
     - ▪ Evapotranspiration (ET) from levels:
       - Ridge
       - Flatwood
   - o Step 2. The user should enter two parameters:
     - ▪ The first parameter is the number of days since last 1” rainfall or long irrigation events to get an estimate on the initial water content available in the irrigation depth.
     - ▪ The Second parameter is the depth of irrigation. Usually this corresponds to the depth at which most of the roots are.
   - o Step 3.
     - ▪ The user goes to the commands section and chooses the “Deficit Calculation”. After pressing this TAB the program calculates and displays the percentage of depletion level.
     - ▪ To go to the next step in this process, the user should press the “Next” TAB that will load the second screen of this section.
     - ▪ The user has the options:
       - to return to the main page
       - to print this page
       - to cancel the program

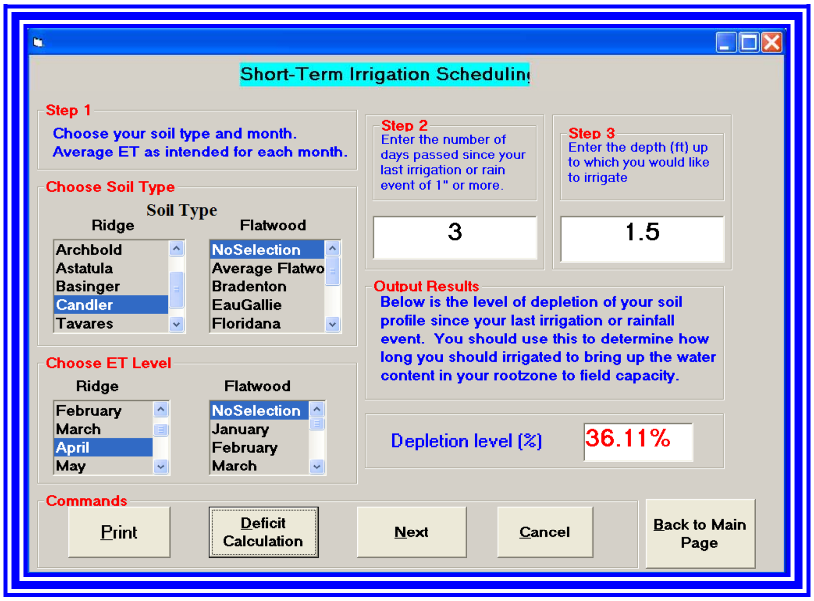

Figure 5. The input part of the short-term irrigation scheduling portion of the program.

b) Screen 2. After pressing the "Next" TAB in screen 1, screen 2 appears. This screen involves the following steps:

- Step 1. The user has the option of:
  - Either use the deficit level that was calculated in Screen 1
  - Or type in the deficit level as a function of depth in the crop parameters section of the form.
- Step 2. This step is used only when you choose NO in Step1. You need to have deficit level (%) as a function of depth (ft).
- Step 3. In this step, you choose the parameters of the irrigation system:
  - Delivery volume in GPH
  - Wetting diameter in feet
  - Irrigation efficiency in %
- Step 4, the command section.
  - Once you are satisfied with the input parameters just press the "Calculate" TAB to get the result of your input parameters in the "Output Results" section of the screen.
  - You can clear the input parameters and start a new calculation.
  - You can print this screen before or after the calculation.
  - You can go back to the first page or to the main page.
  - You can exit the program by pressing the "Exit" TAB.

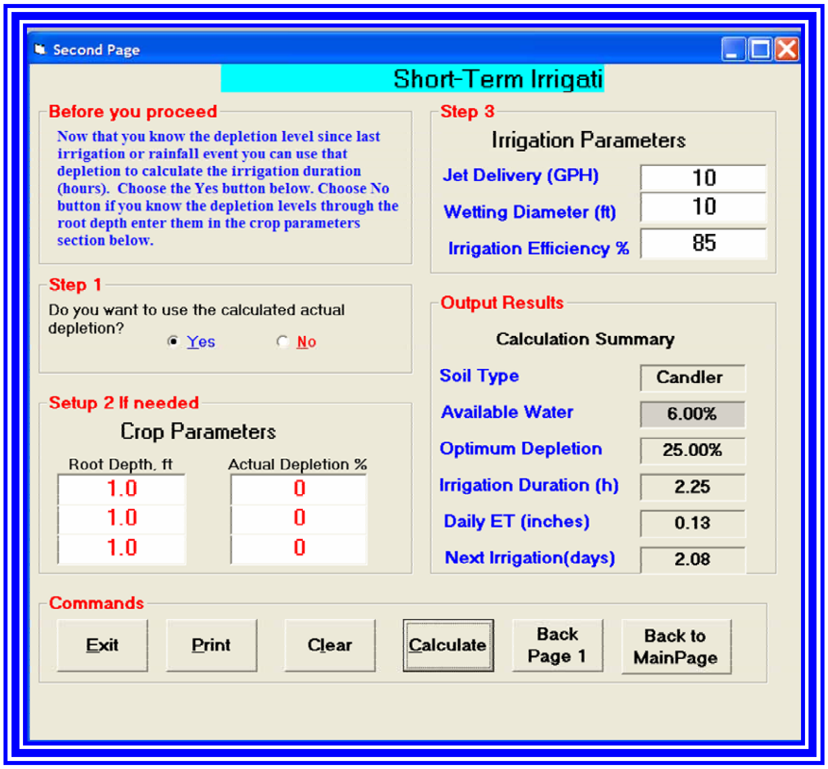

Figure 6. The output part of the short-term irrigation scheduling portion of the program

4. Print

- You can print this form by pressing the "Print" TAB.

5. Cancel

- You can cancel this program by pressing the "Cancel" TAB.

Summary

Improved irrigation scheduling enables growers first to minimize the effects of water stress on crop growth and production, second to avoid excess use of water which could increase production cost and result in increased leaching losses of nutrients and soil applied agrichemicals below the rootzone. There are different irrigation scheduling methods with different degrees of accuracy and cost. Computer programs based on historical weather data, soil physical properties and crop rootzone depths have been used as irrigation scheduling methods that have advantages and disadvantages. They can be used as teaching tools for growers about the benefits of irrigation scheduling; they are a preferred method for low value crops where sophisticated and high cost irrigation scheduling methods are not economically viable. TheHelper offers citrus growers in Florida a tool that can be used to understand citrus water requirements on flatwood and ridge soils. The short- and long-term irrigation schedules could be used as general guidelines for citrus irrigation. Evaluation of this tool by growers, production managers and extension specialists could result in some adjustments.

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Water Temperature Effects on the Discharge Rate of Collapsible Emitting Hose[1]

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Abstract

Lab studies were conducted to measure the effects of water operating temperature on the discharge rate of emitters from thin-walled drip tape (collapsible emitting hose) products. Two different product types (Robert's Ro-Drip, RD; and T-Tape, TT) each with two wall thicknesses were evaluated. The RD product included wall thicknesses of 8 mil (RD08) and 15 mil (RD15) while the TT product included wall thicknesses of 10 mil (TT10) and 15 mil (TT15). Increases in water operating temperature from 69 to 137 ºF doubled the emitter discharge (approximately 0.3 gph) from the RD08 product at both 10 and 12 psi. Emitter discharge rate changes in the RD15 product were not as great (0.03 gph; 10-12% increase) for similar water temperature changes. Effects of water temperature on the discharge rate from the TT products were quite different than the RD products. Emitter discharge rate increased slightly with water temperature at the 8 psi level, but decreased at the 12 psi level. However, decreased flows were less than 0.03 gph or 10% of the original flow rate.

Introduction

The designer of microirrigation systems needs to know how specific products will perform under conditions experienced in the field. Because substantial operating pressure variations can occur in a field system due to elevation changes and friction associated with system hydraulics, most design concerns focus on the operating pressure / emitter discharge relationships of the emitters. The goal is to design a system that will have a hydraulic balance such that a subunit within the system has a known and uniform emitter discharge.

Parchomchuk (1976) measured lateral line temperature increases from 78 to 107 ºF on a bright sunny day for surface positioned polyethylene pipe laterals. Buried laterals (6-in. deep) had a peak measured temperature of 89 ºF. Similar results were reported by Nakayama and Bucks (1985) for 14.5 mm black polyethylene lines in Phoenix, Arizona. Peak water temperatures for surface positioned laterals were measured at 108 ºF in May while empty lines had a peak temperature of 118 ºF. Furthermore, higher temperatures can exist under black polyethylene mulch. Bell and Laemmlen (1991) reported that under clear polyethylene mulch, diurnal temperatures ranged from 75 to 150 ºF at a depth of 2 cm while at a soil depth of 15 cm temperatures ranged from 73 to 127 ºF. Abu-Gharbieh (1997) reported soil temperatures of 122 ºF at 10-15 cm deep and 100 ºF at a depth of 30 cm. Even under these conditions, buried drip irrigation laterals can act as a heat exchanger and absorb heat from the soil thereby increasing the temperature of the water and emitter chambers.

The objectives of this work were to evaluate the discharge rate performance of thin-walled drip tape (collapsible emitting hose) emitters under elevated water temperatures.

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Methods and Materials

Performance tests were conducted on thin-walled drip tape (collapsible emitting hose). Four different products were tested (Tab.1). All products came from the manufacturer on standard rolls. Each drip tape had a reported inside diameter of 0.625 inches. Performance tests focused on the response of drip emitter discharge to water temperature. However, other tests included an elongation test and a standard operating pressure / emitter discharge response test. These latter two tests were used to help characterize the base conditions of the tubing. All tests were conducted in the hydraulic lab in the Department of Biological and Agricultural Engineering at Kansas State University and followed procedures as outlined in ASAE Standard S553 (2001).

Table 1. Drip tape products tested.

Product Code	Manufacturer[§]	Wall Thickness (mil)	Emitter Spacing (in.)	Rated Emitter Discharge[£] (gph)
RD08	Roberts Irrigation, Inc	8	12	0.24
RD15	Roberts Irrigation, Inc.	15	8	0.27
TT10	T-Systems International	10	16	0.27
TT15	T-Systems International	15	8	0.27

[§] Mention of specific products or manufacturers does not imply endorsement by the authors or by Kansas State University.
[£] Discharge at nominal pressure of 8 psi.

Tubing Elongation Tests.

These tests followed procedures in section 8.7 of ASAE Standard S553 (ASAE 2003). Three 60-inch samples of drip tape were cut from the stock roll. A mid-sample section of 40 inches was marked. The upper end of a sample was secured around a pipe for support and a bucket was attached to the lower end to hold water that was added to increase applied weight. The upper end pipe support was hung from anchors attached to a vertical support column in the hydraulics lab. Water was added to the bucket in 4.5 lb increments. After each addition of weight, the tubing was allowed to stabilize for 2 minutes. Elongation was then measured between the originally marked points by using a tape measure. Weight was added until a sample ruptured or elongated more than 25% of the original length. Each test was repeated for 3 samples of each tubing type

Standard Operating Pressure / Emitter Discharge Tests

These tests followed procedures in section 8.3 of ASAE Standard S553 (ASAE 2001) and included five drip tape lateral lines that each had five emitters (Fig. 1). Each lateral was attached to an inlet and distal manifold system. All drip tapes were suspended on a support rack made of 1-inch (nominal) PVC pipe. Emitters from each drip lateral were aligned so that a collection cup rack could be used to simultaneously collect emitter discharge. Small strings (kite string) attached to the drip tape at each emitter extended approximately 6 inches below the drip tape, were saturated during the conditioning periods, and wicked water into the collection cups. Supply water was provided by a 50-gallon reservoir (Fig.1, item 1) that had a small pump used to pressurize the water. Water temperature during these tests was maintained at 73.4 F (±3.6 F). Adjustable pressure regulating valves (Fig.1, item 3) were used to adjust operating pressure. Water operating pressures were incrementally increased between discharge tests from a minimum pressure of 4 psi up to 16 psi in 4 psi increments. Water pressure was measured using a series (0-15, 0-30, and 0-60 psi) of precision Bourdon Tube pressure gauges (Fig. 1, item 2) that were on an adjustable rack so that the gauge level could be consistent with the drip tubing level. Water temperature was measured during each test sequence using both a bimetallic temperature sensor and an electronic thermistor connected to a data logger. Both temperature sensors were inserted into the applied water stream using modified PVC pipe fittings (Fig. 1, item 4). A small nozzle was also attached to the discharge manifold to discharge approximately 0.5 gpm of water. This nozzle discharge was used to maintain flow through the suspended drip tapes and minimize slow internal flow velocities and entrapped air.

During the first test sequence, all drip tapes were conditioned for 15 min at the minimum pressure setting (4 psi). Water discharge amounts from all emitters were collected into small plastic cups over a six-minute collection period. On queue, the collection cup racks were slid under the dripping strings. Then again on queue, collection cups were slid out from under the dripping strings. Collected water volumes were weighed on an electronic balance and converted to volumetric units. Collected amounts typically weighed between 90 and 120 g and the balance had an accuracy of ±0.1 g. All cups were emptied and shaken dry between tests. The water pressure level was adjusted to the next level and drip tubes were then conditioned for 3 minutes at each successive pressure setting prior to collecting discharge volumes.

Drip Tubing Temperature Response

These tests followed procedures in section 8.4 of ASAE Standard S553 (ASAE 2001). Three drip tape lateral lines with five emitters each were tested at each temperature and pressure setting using the previously discussed lab setup (Fig. 1). This test was conducted on each of four different products (Tab. 1). The first sequence of tests evaluated each product at the nominal operating pressure of 8 psi with five water temperature settings (68, 84, 100, 118, and 126°F). Two subsequent series of tests were conducted using operating pressures of 10 and 12 psi and six water temperatures (68, 84, 100, 118, 126, 138°F). New sections of drip tape were used for each operating pressure setting. Operating pressures were established and measured using previously describe procedures.

The water temperature values were target levels. Actual water temperature levels were measured and recorded during each test. The lab tap water temperature ranged between 66 and 70°F. This temperature level was used as the starting point (T_{min}) in all tests. For the first temperature setting in all tests the 50-gallon reservoir was filled with the lab tap water. Temperature sensors were positioned in the reservoir, in the supply pipe to the test manifold, and on the discharge manifold of the testing system. Water temperature readings were digitally and manually recorded during each test to ensure consistent levels throughout the drip tape laterals. For the elevated water temperature tests, water was heated in a standard electric water heater and approximately 20 gallons was added to the 50-gallon reservoir. Cooler tap water and heated water were then added and stirred to obtain a water temperature value close to the next higher target level. Because each water temperature test sequence lasted for less than 30 minutes, the thermal mass of the water in the supply reservoir was sufficient to maintain the elevated water temperature setting during the test sequence.

During a temperature sequence of tests, drip tapes were initially conditioned at the specified pressure setting (8, 10, or 12 psi) and T_{min} (~68°F) for at least one hour. During the test, pressure was maintained at the treatment level. After each test run, the water temperature was increased to the next level as described above, and tubing was conditioned at that temperature level for fifteen minutes. Water discharge amounts from all emitters were collected into small plastic cups over a six-minute collection period using procedures as previously described.

Results

Tubing Elongation Tests

While all elongation responses (Fig. 2) followed a similar trend, product wall thickness and material composition affected the linear elongation response. A load of 35 lbs resulted in a 25% elongation of the RD08 (8 mil) product while 54 lbs was required for a 25% elongation of the RD-15 (15 mil) product. However, while the TT-10 product (10 mil) is thinner than the RD-15 product (15 mil), a load of 58 lbs was required to reach 25% elongation. This demonstrates the difference associated with product composition. The TT-15 product (15 mil) was the stiffest requiring 72 lbs of load to elongate by 25%.

Standard Operating Pressure / Emitter Discharge Tests

Emitter discharge / pressure relationships for the RD (Fig. 3) and TT (Fig. 4) products fit a standard power function that take the form:

$$q_e = kP^x$$

where q_e is the emitter discharge (gph), P is the operating pressure (psi), x is the emitter discharge coefficient, and k is a constant of proportionality. Values of "k" and "x" are summarized for the four products of this study (Tab. 2). These power function regression relationships all had very high R^2-values (>97%). Nominal emitter discharge rates (Tab. 2) were calculated using the respective values of "k" and "x" for each product (Tab. 1).

Table 2. Summary of "k" and "x" values for the drip tape products used in this study. The nominal emitter discharge rate was calculated for each product using the respective values of "k" and "x" at the nominal pressure of 8 psi.

Product	"k"	"x"	R^2	q_{nom} (gph)
RD-08	0.0683	0.66	1.000	0.27
RD-15	0.1186	0.42	0.999	0.28
TT-10	0.0865	0.58	0.976	0.29
TT-15	0.0881	0.56	0.990	0.28

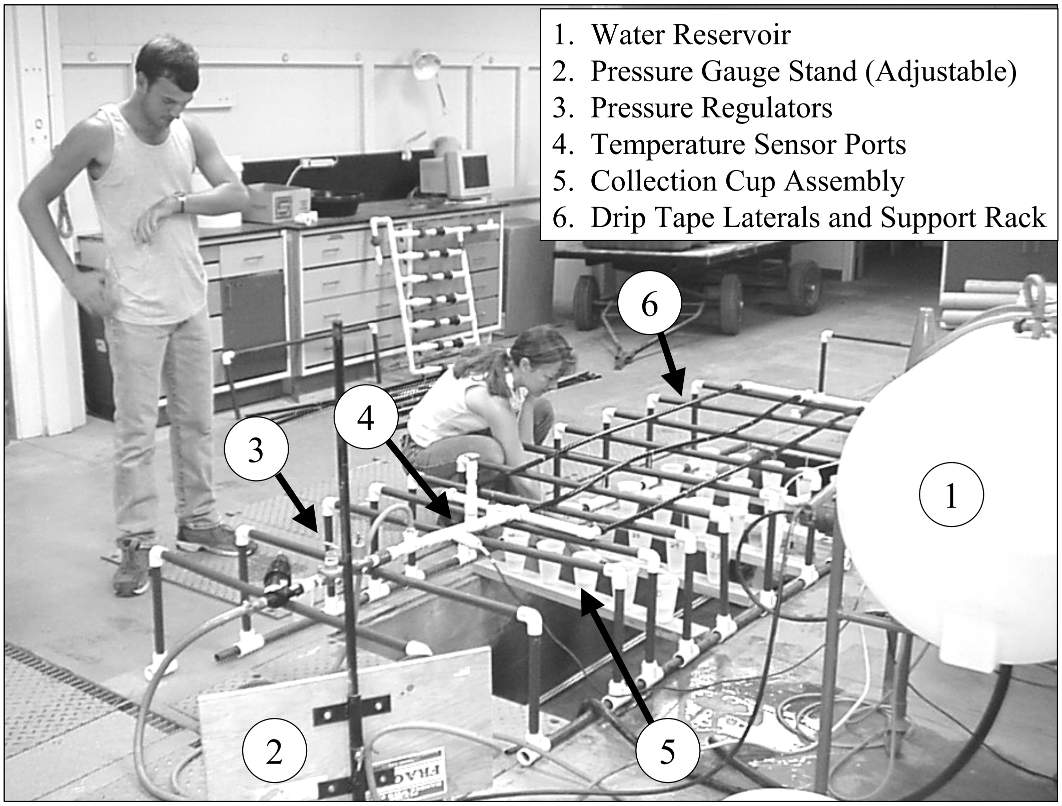


Figure 1. Lab setup to measure drip tape emitter discharge rates.

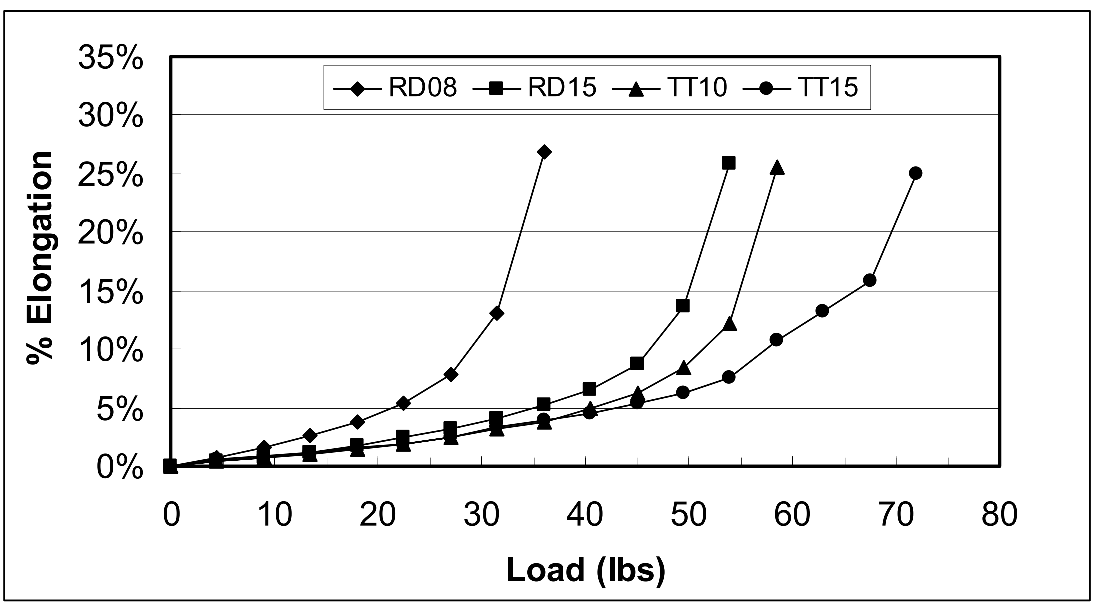


Figure 2. Percentage of tape elongation with respect to applied load (lbs) for the four drip tape products.

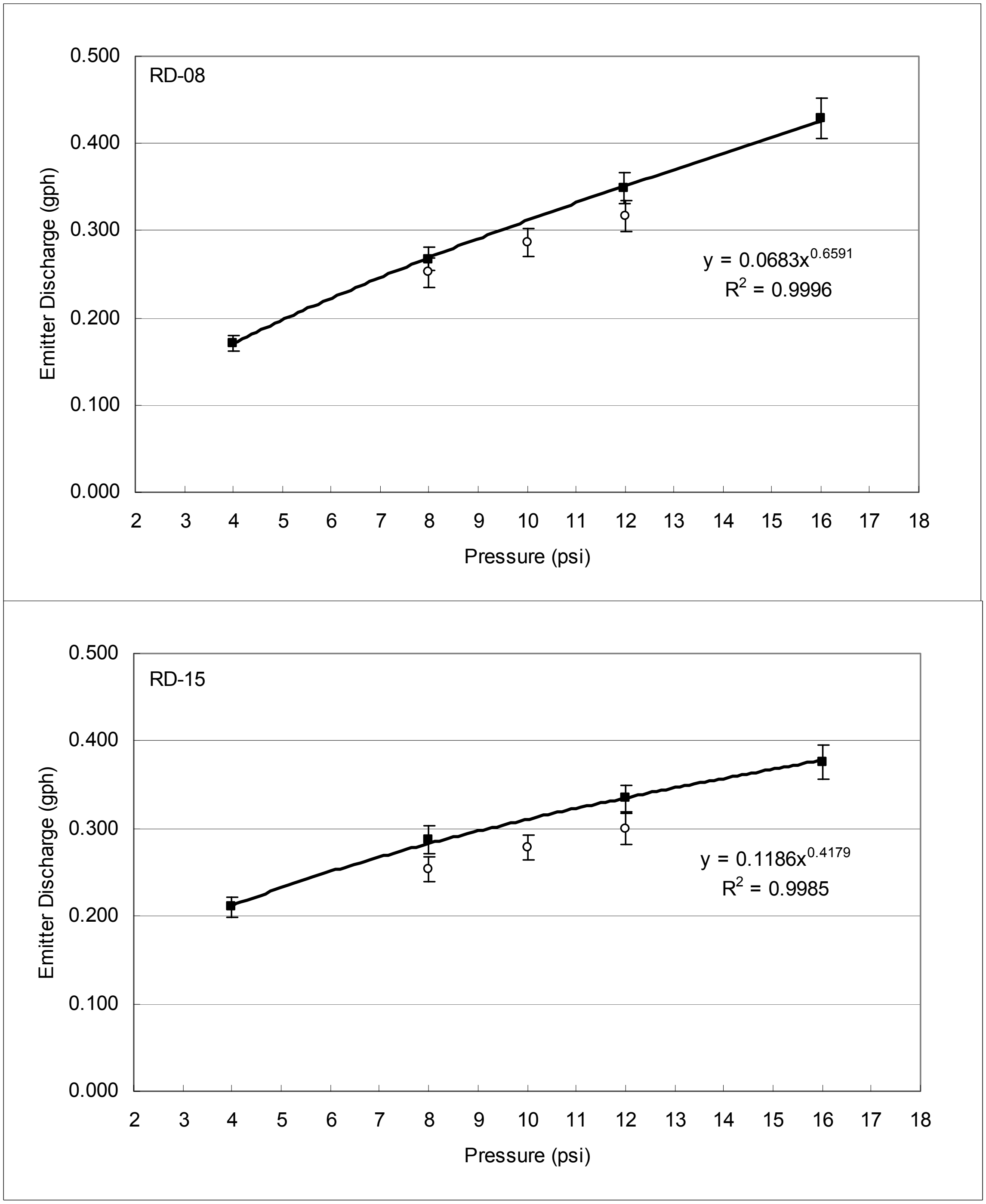
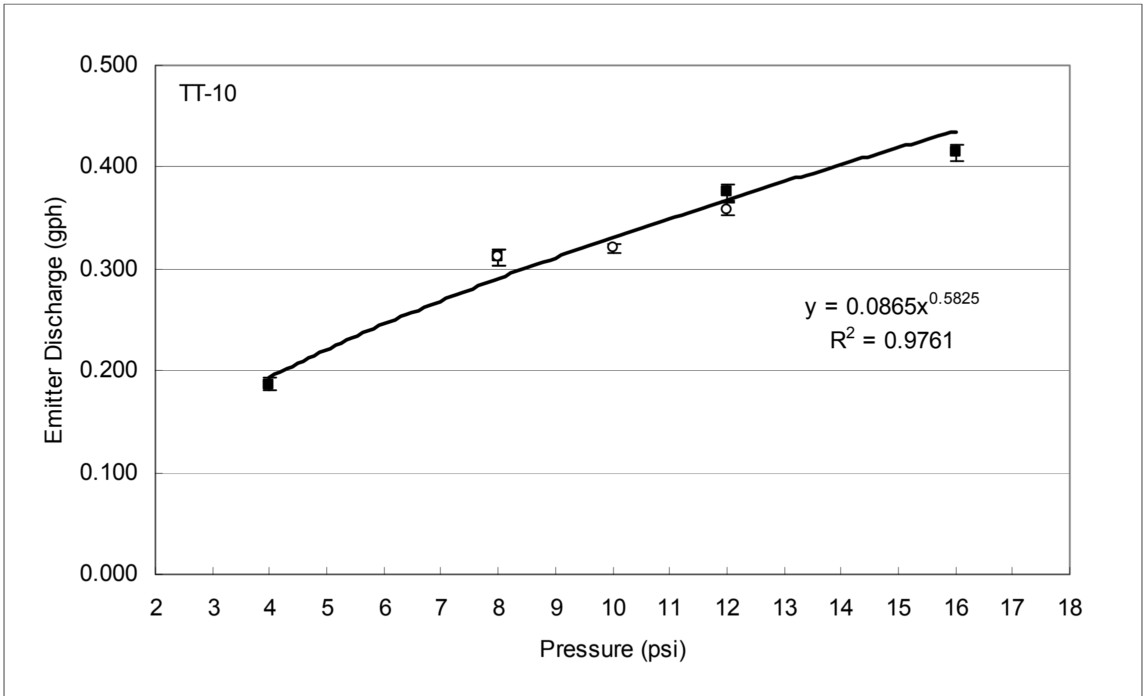


Figure 3. Emitter discharge / pressure relationships for the RD-08 product (upper) and RD-15 product (lower). The original discharge / pressure test data are displayed as solid squares with error bars (± 1 std dev); the power function regression of those data is displayed as a solid line (regression function shown on graph); and baseline emitter discharge data from the water temperature study are displayed as open circles with error bars (± 1 std dev).



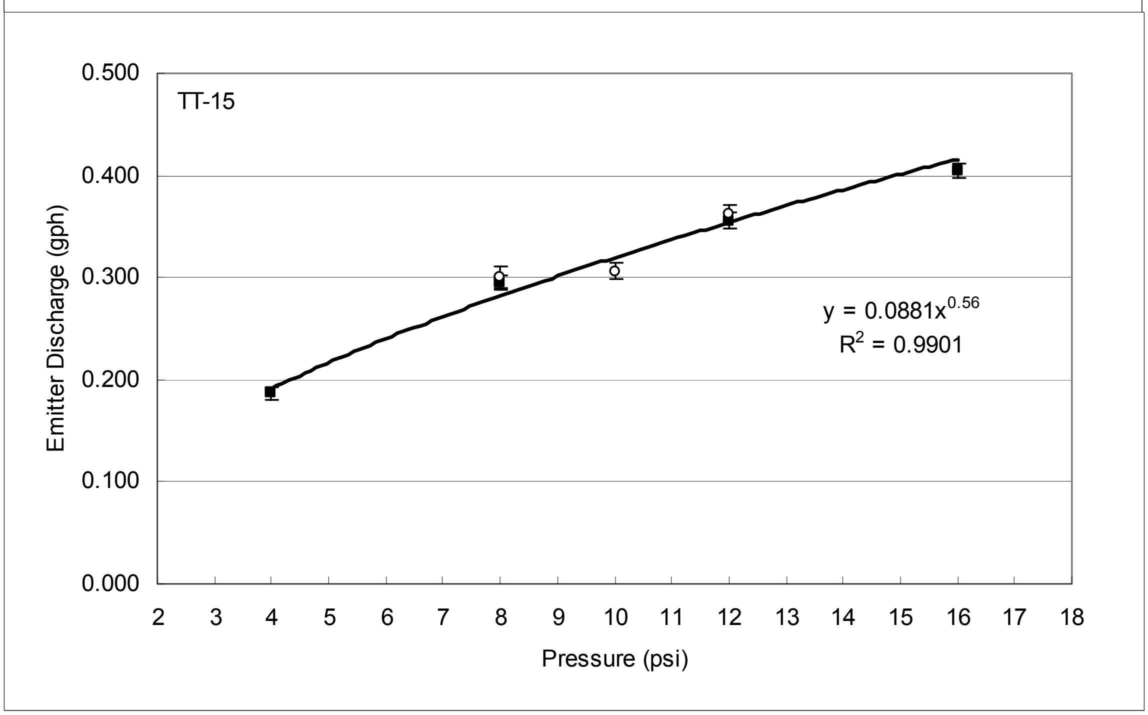


Figure 4. Emitter discharge / pressure relationships for the TT-10 product (upper) and TT-15 product (lower). The original discharge / pressure test data are displayed as solid squares with error bars (± 1 std dev); the power function regression of those data is displayed as a solid line (regression function shown on graph); and baseline emitter discharge data from the water temperature study are displayed as open circles with error bars (± 1 std dev).

The baseline water temperature emitter discharge data for the RD products (Fig. 3) were slightly lower than the previously measured discharge / pressure data. However, the TT product data (Fig. 4) had very good agreement with the discharge / pressure data.

Drip Tubing Temperature Response

Emitter discharge values are presented for each water temperature level at each pressure setting along with the coefficient of variation (cv) of the measured data and the percent change from the baseline water temperature data (Tab. 3, 4, 5, and 6). The RD-08 product had the greatest change in emitter discharge rate with increased water temperature (Tab. 3). At an operating pressure of 8 psi, emitter discharge rate showed little change (1.5%) as water temperature increased from 66 to 83 ºF (26% change). However, these trends were not linear and emitter discharge increased from 0.252 gph to 0.298 gph (18% change) with a water temperature increase from 66 to 125 ºF (89%change). As operating pressure was increased, the effects of increased water temperature on emitter discharge rate were more substantial. At 10 psi, the baseline emitter discharge was 0.287 gph while at a water temperature of 118 ºF the emitter discharge rate was 0.372 gph (+ 29.7%) and at 137 ºF the emitter discharge rate was 0.550 gph, an increase of 91.8%.

Changes in emitter discharge with water temperature for the RD 15 product (Tab. 4) were not as substantial as with the RD08 product. The greatest percentage changes occurred with the 8 psi operating pressure with a 12% increase in discharge rate (0.029 gph) as water temperature increased from 68 to 114 ºF. The stiffer properties of this product (Fig. 2) appear to buffer the effects of increased water temperature

Emitter discharge rate changes in the TT products (Tab. 5 and 6) were quite different from the RD products (Tab. 3 & 4). The TT10 product (Tab.. 4) had a slight increase in emitter discharge (0.015 gph or +4.6%) with a temperature rise from 69 to 125 ºF at an operating pressure of 8 psi. However, emitter discharge rate decreased with increased water temperature at operating pressures of 10 and 12 psi. Decreasing emitter discharge rate results were also measured by Parchumchuk (1976) on vortex type emitters. The greatest decrease occurred at 12 psi with a reduction in emitter discharge of 0.031 gph (-8.8%) as water temperature increased from 67 to 139 ºF. An increase in wall thickness of this product (TT15) reduced the effects of water temperature on emitter discharge (Tab. 4). Emitter discharge changes at pressures of 8 and 10 psi were minimal while at 12 psi emitter discharge rate decreased by 0.022 gph (-6.1%) with a water temperature change from 70 to 138 ºF.

Some variation in emitter response from the RD08 product was measured with coefficient of variation (cv) values ranging from 0.065 to 0.078, 0.047 to 0.055, and 0.053 to 0.069 at the 8-, 10- and 12-psi pressure levels, respectively (Tab. 3). While measured emitter variation with the RD15 product was similar to the RD08 product (Tab. 4), both TT products (TT10 and TT15) had lower cv values (0.014 to 0.036) indicating higher consistency among emitters (Tab. 5 and 6). None of the products showed any trend or substantial change in emitter discharge variation with temperature or pressure.

Table 3. Emitter discharge relationships for the RD08 product at elevated water temperatures for three operating pressures. Data include the operating temperature of the water, the emitter discharge rate (gph), the coefficient of variation of measured flows and the percentage of change from the T_{min} values.

Operating Pressure	Water Temperature (ºF)	Emitter Discharge (gph)	Coefficient of Variation	%Change (from T_{min})
8 psi	66	0.252	0.069	0.0%
	83	0.256	0.065	1.5%
	98	0.266	0.071	5.5%
	114	0.281	0.078	11.6%
	125	0.298	0.076	18.3%
10 psi	71	0.287	0.055	0.0%
	85	0.303	0.053	5.6%
	99	0.323	0.053	12.7%
	118	0.372	0.048	29.7%
	123	0.413	0.053	44.0%
	137	0.550	0.047	91.8%
12 psi	69	0.316	0.056	0.0%
	84	0.337	0.054	6.5%
	103	0.390	0.053	23.2%
	117	0.515	0.069	63.0%
	122	0.624	0.065	97.3%
	139	0.531	0.068	68.1%

Table 4. Emitter discharge relationships for the RD15 product at elevated water temperatures for three operating pressures. Data include the operating temperature of the water, the emitter discharge rate (gph), the coefficient of variation of measured flows and the percentage of change from the T_{min} values.

Operating Pressure	Water Temperature (ºF)	Emitter Discharge (gph)	Coefficient of Variation	%Change
8 psi	68	0.253	0.056	0.0%
	87	0.274	0.055	8.1%
	103	0.282	0.058	11.3%
	114	0.284	0.062	12.1%
	120	0.284	0.063	12.0%
10 psi	67	0.279	0.052	0.0%
	86	0.289	0.073	3.6%
	101	0.286	0.057	2.7%
	118	0.294	0.056	5.5%
	126	0.296	0.063	6.1%
	139	0.306	0.051	9.8%
12 psi	69	0.300	0.058	0.0%
	84	0.309	0.055	3.0%
	99	0.313	0.055	4.3%
	117	0.321	0.053	6.9%
	127	0.330	0.050	10.2%
	131	0.335	0.048	11.6%

Table 5. Emitter discharge relationships for the TT10 product at elevated water temperatures for three operating pressures. Data include the operating temperature of the water, the emitter discharge rate (gph), the coefficient of variation of measured flows and the percentage of change from the T_{min} values.

Operating Pressure	Water Temperature (ºF)	Emitter Discharge (gph)	Coefficient of Variation	%Change
8 psi	69	0.311	0.026	0.0%
	84	0.317	0.025	1.8%
	100	0.322	0.029	3.5%
	117	0.325	0.025	4.2%
	125	0.326	0.023	4.6%
10 psi	67	0.321	0.015	0.0%
	84	0.315	0.017	-1.6%
	101	0.315	0.018	-1.7%
	119	0.312	0.014	-2.6%
	126	0.307	0.015	-4.3%
	138	0.304	0.019	-5.2%
12 psi	67	0.358	0.018	0.0%
	85	0.344	0.017	-4.0%
	101	0.339	0.016	-5.5%
	118	0.333	0.018	-7.0%
	126	0.333	0.016	-7.1%
	139	0.327	0.017	-8.8%

Table 6. Emitter discharge relationships for the TT15 product at elevated water temperatures for three operating pressures. Data include the operating temperature of the water, the emitter discharge rate (gph), the coefficient of variation of measured flows and the percentage of change from the T_{min} values.

Operating Pressure	Water Temperature (ºF)	Emitter Discharge (gph)	Coefficient of Variation	%Change
8 psi	67	0.300	0.036	0.0%
	82	0.300	0.029	0.1%
	96	0.301	0.033	0.4%
	112	0.301	0.032	0.3%
	122	0.302	0.028	0.6%
10 psi	69	0.306	0.024	0.0%
	85	0.313	0.019	2.1%
	99	0.313	0.025	2.1%
	116	0.313	0.020	2.3%
	124	0.309	0.018	0.9%
	135	0.305	0.017	-0.5%
12 psi	70	0.363	0.020	0.0%
	85	0.357	0.020	-1.8%
	101	0.353	0.018	-2.7%
	116	0.346	0.017	-4.7%
	126	0.343	0.016	-5.6%
	138	0.341	0.016	-6.1%

Summary and Conclusions

Lab studies were conducted to measure the effects of water operating temperature on the discharge rate of emitters from thin-walled drip tape (collapsible emitting hose) products. Two different product types (Robert's Ro-Drip, RD; and T-Tape, TT) each with two wall thicknesses were evaluated. The RD product included wall thicknesses of 8 mil (RD08) and 15 mil (RD15) while the TT product included wall thicknesses of 10 mil (TT10) and 15 mil (TT15). These two product types were made of different plastic materials and had different material properties. The RD product was more elastic than the TT product. The load required to provide a 25% increase in length was 35, 54, 58, and 72 lbs for the RD08, RD15, TT10, and TT15 products, respectively.

Increases in water operating temperature from 69 to 137 ºF doubled the emitter discharge (approximately 0.3 gph) from the RD08 product at both 10 and 12 psi. Emitter discharge rate changes in the RD15 product were not as great (0.03 gph; 10-12% increase) for similar water temperature changes. Thus, wall thickness appears to have buffered the water temperature effects.

The effects of water temperature on the discharge rate from the TT products were quite different than the RD products. Emitter discharge rate increased slightly with water temperature at the 8 psi level, but decreased at the 12 psi level. However, decreased flows were less than 0.03 gph or 10% of the original flow rate.

Results of these studies clearly indicate the need to know the effects of water temperature on the emitter discharge relationships of thin-walled drip tape products. Substantial discharge differences associated with water (or soil) temperature can affect the "as-built" characteristics of the system design, pump output, system / subunit uniformity, and/or pressure distribution. Temperature measurements and associated corrections may also be necessary during field performance evaluations of these systems.

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AUTOMATIC COLLECTION, RADIO TRANSMISSION, AND USE OF SOIL WATER DATA

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Abstract

Precise scheduling of drip irrigation has become very important to help assure optimum drip-irrigated crop yield and quality. Soil moisture sensors have often been adopted to assure irrigation management. Integrated systems for using soil moisture data could enhance widespread applicability. An ideal system would include the equipment to monitor field conditions, radios to transmit the information from the field because wires impede cultivation and can complicate cultural practices, interpretation of soil water status, and the equipment to automatically control irrigation systems.
Key words**:** automation, irrigation scheduling, onion, *Allium cepa*

Introduction

Onions (*Allium cepa*) require frequent irrigations to maintain high soil moisture. Drip irrigation has become popular for onion production because a higher soil moisture can be maintained without the negative effects associated with furrow irrigation. Drip irrigation can also be automated. Automated drip irrigation of onions has been used for irrigation management research at the Malheur Experiment Station since 1995 (Feibert et al., 1996; Shock et al., 1996, 2002). In addition the extensive wiring impedes cultivation and can complicate cultural practices. Several companies manufacture automated irrigation systems designed for commercial use that use radio telemetry, reducing the need for wiring. This trial tested three commercial soil moisture monitoring systems and compared their irrigation on onion performance to the research system based on Campbell Scientific (Logan, UT) components currently used (Shock et al., 2002).

Material and Methods

The onions were grown at the Malheur Experiment Station, Ontario, OR on an Owyhee silt loam previously planted to wheat. Onion (cv. Vaquero, Nunhems, Parma, ID) was planted in 2 double rows, spaced 22 inches apart (center of double row to center of double row) on 44-in beds on March 17, 2004. The two rows in the double row were spaced 3 inches apart. Onion was planted at 150,000 seeds/acre. Drip tape (T-tape, T-systems international, San Diego, CA) was laid at 4-in depth between the two double onion rows at the same time as planting. The distance between the tape and the center of the double row was 11 inches. The drip tape had emitters spaced 12 inches apart and a flow rate of 0.22 gal. per min. per 100 feet.

Onion emergence started on April 2. The trial was irrigated with a minisprinkler system (R10 Turbo Rotator, Nelson Irrigation Corp., Walla Walla, WA) for even stand establishment. Risers were spaced 25 ft apart along the flexible polyethylene hose laterals which were spaced 30 ft apart.

Weed and insect control practices were similar to typical crop production standards and fertilizer applications were similar to common practices and followed the recommendations of Sullivan et al. (2001).

The experimental design was a randomized complete block with three replicates. Each irrigation system was tested in three zones that were 16 rows by 50 feet long. There were four automated irrigation systems tested. Each integrated system contained several distinctive parts, some automated and some requiring human input: soil moisture monitoring, data transmission from the field, collection of the data, interpretation of the date, decisions to irrigate, and control of the irrigation. Additionally, all data was downloaded for evaluation of the system.

Campbell Scientific. The system currently used for research at the Malheur Experiment Station uses a Campbell Scientific Inc. (Logan UT) datalogger (CR10X). Each zone had four granular matrix sensors (GMS, Watermark Soil Moisture Sensor Model 200SS, Irrometer Co. Inc., Riverside, CA) used to measure soil water potential (Shock, 2003). The GMS from all three zones were connected to a AM416 multiplexer (Campbell Scientific) which in turn was connected to the datalogger at the field edge. The soil temperature was also monitored and was used to correct the soil water potential calibrations (Shock et al., 1998). The datalogger was programmed to monitor the soil moisture and controlled the irrigations for each zone individually. The Campbell Scientific datalogger was programmed to make irrigation decisions every 12 hours: zones were irrigated for eight hours if the soil water potential threshold was exceeded. The Campbell Scientific datalogger used an average soil water potential at 8-inch depth of -20 kPa or less as the irrigation threshold. The datalogger controlled the irrigations using a SDM16 controller (Campbell Scientific) to which the solenoid valves at each zone were connected. Data was downloaded from the datalogger with a laptop computer or with a SM192 Storage Module (Campbell Scientific) and a CR10KD keyboard display (Campbell Scientific). The datalogger was powered by a solar panel and the controller was powered by 24 V AC. The Campbell Scientific system was started on May 15.

Automata. Automata, Inc. (Nevada City, CA) manufactures dataloggers, controllers, and software for data acquisition and process control. Each one of the three zones had four GMS connected to a datalogger (Mini Field Station, Automata). The dataloggers at each zone were connected to a controller (Mini-P Field Station, Automata) at the field edge by an internal radio. The controllers (Mini-P Field Station, Automata) at the field edge were connected to a base station (Mini-P Base Station, Automata) in the office by radio. The base station was connected to a desktop computer. Each zone was irrigated individually using a solenoid valve. The solenoid valves were connected to and controlled by the controller. The desktop computer ran the software that monitored the soil moisture in each zone and made the irrigation decisions every 12 hours: zones were irrigated for eight hours if the soil water potential threshold was exceeded. The irrigation threshold was the average soil water potential at 8-inch depth of -20 kPa or less. The Mini Field stations were powered by solar panels and the Mini-P Field station was powered by 120 V AC. The Automata system was started on June 24.

Watermark Monitor. Irrometer manufactures the Watermark Monitor datalogger which can record data from seven GMS and one temperature probe. The soil temperature is used to correct the soil water potential calibrations. Each of the three Watermark Monitor zones each had seven GMS connected to a Watermark Monitor. Data was downloaded from the Watermark Monitor with a laptop computer. The Watermark Monitors were powered by solar panels. Irrigation decisions were made daily by reading the GMS at each Watermark Monitor. When the soil water potential reached -20 kPa the zone was irrigated manually for eight hours. The Watermark Monitors were started on May 15.

Acclima. Acclima (Meridian, ID) manufactures a Digital TDT™ that measures volumetric soil moisture content. Each zone had one TDT sensor and four GMS. The TDT sensors were connected to a model CS3500 controller (Acclima) at the field edge. The controller monitored the soil moisture and controlled the irrigations for each zone separately using solenoid valves. The controller was powered by 120 V AC. Data was downloaded from the controller using a laptop computer. For comparison and calibration, the GMS were connected to the Campbell Scientific datalogger which monitored the soil water potential as described above. The Acclima system was started on May 16. The CS3500 controller was programmed to irrigate the zone when the volumetric soil water content was equal to or lower than 27%. The soil water potential data was compared to the volumetric soil water content data to adjust the CS3500 controller to irrigate each zone in a manner equivalent to the irrigation scheduling using the GMS. Due to excessive soil moisture, on June 11 the lower threshold at which irrigations were started was changed from 27% to 19%, and 21% for Acclima zones one and two, respectively, to correspond to -20 kPa soil water potential. When installed, due to a software constraints, the controller could only water a maximum of four hours at each irrigation. On July 21 the software was upgraded allowing irrigation durations to be increased to 8 hours. Given the flow rate of the drip tape, 8 hour irrigations applied 0.48 inches of water. Previous research indicates that the ideal amount of water to apply at each irrigation is 0.5 inches (Shock et al., 2004).

All soil moisture sensors in every zone of the four systems were installed at 8-inch depth in the center of the double onion row. The GMS were calibrated to SWP (Shock et al. 1998). The Campbell Scientific, Acclima, and Automata controllers were programmed to make irrigation decisions every 12 hours: zones were irrigated for eight hours if the soil moisture threshold was exceeded. The Campbell Scientific and Automata dataloggers used an average soil water potential at 8-inch depth of -20 kPa or less as the irrigation threshold. The Irrometer zones also had a threshold of -20 kPa. The amount of water applied to each plot was recorded daily at 8:00 a.m. from a water meter installed downstream of the solenoid valve. The total amount of water applied included sprinkler irrigations applied after emergence and water applied with the drip irrigation system from emergence through the final irrigation.

Onion evapotranspiration (ET_c) was calculated with a modified Penman equation (Wright 1982) using data collected at the Malheur Experiment Station by an AgriMet weather station (U.S. Bureau of Reclamation, Boise, Idaho). Onion Et_c was estimated and recorded from crop emergence until the final irrigation on September 2.

On September 24 the onions were lifted to field cure. On September 27, onions in the central 40 ft of the middle four double rows in each zone were topped and bagged. On September 28 the onions were graded. Bulbs were separated according to quality: bulbs without blemishes (No. 1s), double bulbs (No. 2s), neck rot (bulbs infected with the fungus *Botrytis allii* in the neck or side), plate rot (bulbs infected with the fungus *Fusarium oxysporum*), and black mold (bulbs infected with the fungus *Aspergillus niger*). The No. 1 bulbs were graded according to diameter: small (< 2¼ inch), medium (2¼ to 3 inch), jumbo (3 to 4 inch), colossal (4 to 4¼ inch), and supercolossal (>4¼ inch). Bulb counts per 50 lb of supercolossal onions were determined for each zone of every variety by weighing and counting all supercolossal bulbs during grading.

Differences in onion performance and water application among irrigation systems were determined by protected least significant differences at the 95 percent confidence level using analysis of variance (NCSS 97, Statistical System for Windows, Hintze, 2000).

Results and Discussion

Marketable onion yield was excellent, averaging 1041 cwt/acre (116.6 Mg/ha) over the four drip irrigation systems (Table 1). The average onion bulb yield in the Treasure Valley was 625 cwt/acre (70.0 Mg/ha) in 2000, 630 cwt/acre (70.6 Mg/ha) in 2001, and 645 cwt/acre (72.2 Mg/ha) in 2002 (USDA, 2003). The excellent onion performance with all the systems used was consistent with the maintenance of soil water potential within the narrow range required by onion (Shock et al., 1998, 2000).

A comparison of the systems in terms of onion yield and grade is not completely justified, because the systems were started at different times. In addition, the Acclima and Automata systems required adjustments and modifications after the start of operation.

The Acclima system resulted in among the lowest marketable yield and yield of colossal bulbs. The Acclima system maintained the soil very wet at the beginning of the season due to our lack of knowledge of the appropriate volumetric soil water content that corresponded to ideal soil water potential (Figures 1 and 2). After changes were made to the irrigation threshold for each Acclima zone separately, the soil volumetric water content (Figure 2) was very stable with some seasonal deviations from the target soil water potential of -20 kPa (Figure 1). Due to initial software limitations the Acclima system had irrigation durations of 4 hours until July 21. After July 21 the software was upgraded and the irrigation durations were increased to 8 hours. Irrigation durations of less than 8 hours have been shown to reduce onion yield (Shock et al., 2004). Also early heavy irrigation could have leached nitrate needed for optimal onion growth.

The Campbell Scientific and Automata maintained the soil water potential relatively constant and close to the target of -20 kPa (Figures 3 and 4). The Irrometer Watermark Monitors maintained the soil water potential on target, but with larger oscillations than the other systems, due to the human collection of the SWP and human control of irrigation onset and duration (Figure 5).

Water applications over time followed ET_c during the season (Figure 6). The total water applied plus precipitation from emergence to the end of irrigation on September 2 was 31.5, 40.0, 43.9, and 36.2 inches (800, 1016, 1115, and 919 mm) for the Campbell Scientific, Irrometer, Automata, and Acclima systems, respectively. Precipitation from onion emergence until irrigation ended on September 2 was 3.88 inches (99 mm). Onion evapotranspiration for the season totaled 30.9 inches (785 mm) from emergence to the last irrigation. The Automata system used a new version of their software that had initial bugs to work out. The Acclima system over applied water when first installed until the irrigation thresholds were adjusted downwards.

Conclusions

All the systems tested performed well in this preliminary evaluation. Onion yield, grade, and quality were excellent. Any small shortcomings in precise irrigation may have been due to our unfamiliarity and inexperience using these systems.

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Table 1. Onion yield and grade for a drip irrigated onion field irrigated automatically by four systems. Oregon State University Malheur Experiment Station, Ontario, OR 2004.

System	Total yield	Marketable yield by grade					Super colossal counts	Nonmarketable yield		
		Total	>4¼ in	4-4¼ in	3-4 in	2¼-3 in		Total rot	No. 2s	Small
	------------------------ cwt/acre -------------------------						#/50 lb	% of total yield	-- cwt/acre --	
Campbell Sci.	1035.9	1026.1	21.4	258.5	727.4	18.8	42.6	0.5	1.3	3.1
Irrometer	1081.4	1076.1	36.2	337.2	685.6	17.1	39.5	0.2	0.0	3.4
Automata	1072.4	1064.0	18.2	306.0	724.6	15.2	41.8	0.4	1.5	2.2
Acclima	1008.4	997.9	15.7	215.2	746.4	20.6	47.9	0.3	3.7	4.2
Average	1049.5	1041.0	22.9	279.2	721.0	17.9	43.0	0.3	1.6	3.2
LSD (0.05)	51.2	52.0	NS	86.5	NS	NS	NS	NS	NS	NS
	------------------------ Mg/ha -------------------------						#/50 lb	% of total yield	-- Mg/ha --	
Campbell Sci.	116.0	114.9	2.4	29.0	81.5	2.1	42.6	0.5	0.2	0.4
Irrometer	121.1	120.5	4.1	37.8	76.8	1.9	39.5	0.2	0.0	0.4
Automata	120.1	119.2	2.0	34.3	81.2	1.7	41.8	0.4	0.2	0.3
Acclima	112.9	111.8	1.8	24.1	83.6	2.3	47.9	0.3	0.4	0.5
Average	117.5	116.6	2.6	31.3	80.8	2.0	43.0	0.3	0.2	0.4
LSD (0.05)	5.7	5.8	NS	9.7	NS	NS	NS	NS	NS	NS

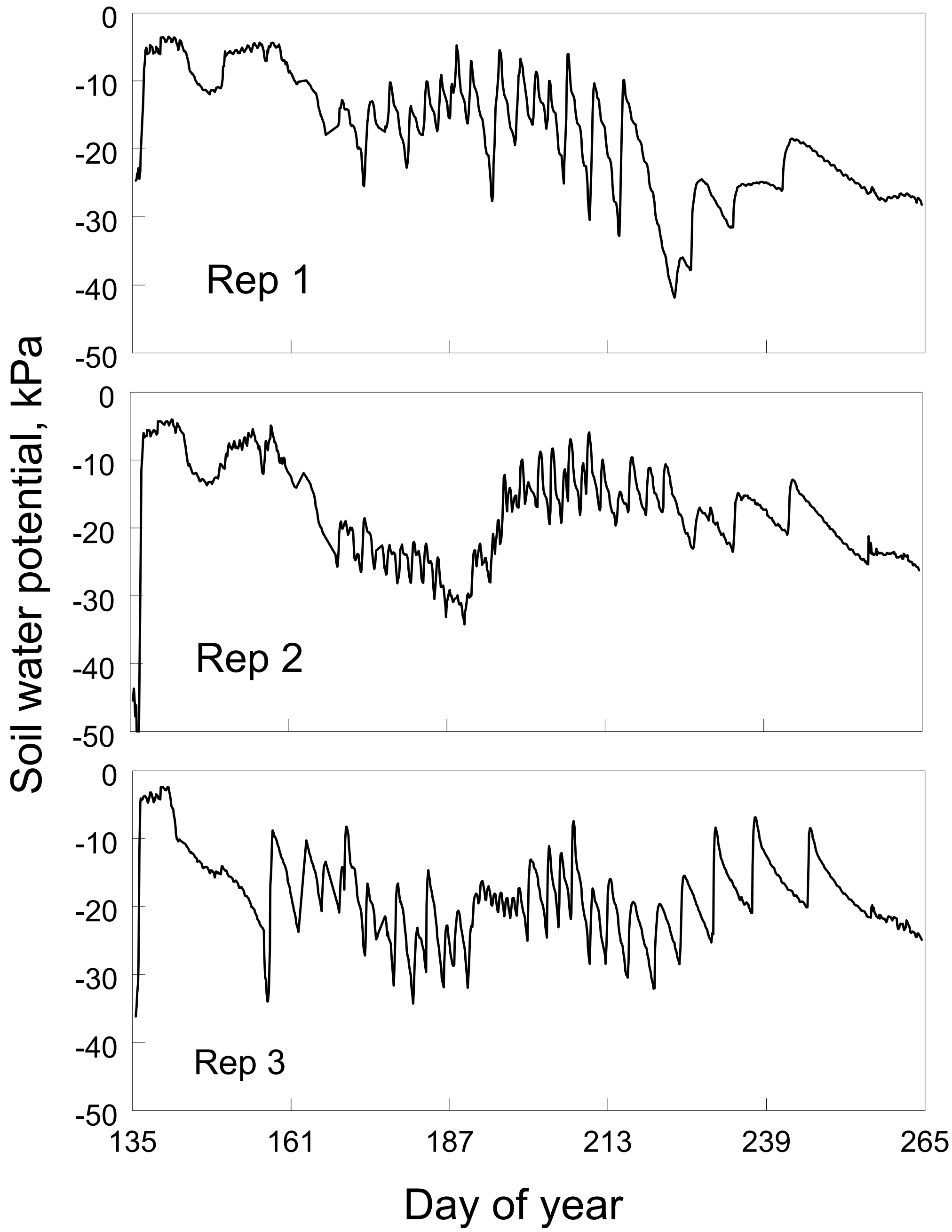

Figure 1. Soil water potential at 8-inch depth for a drip-irrigated onion field using the Acclima automated irrigation system with three irrigation thresholds. Oregon State University Malheur Experiment Station, Ontario, OR 2004.

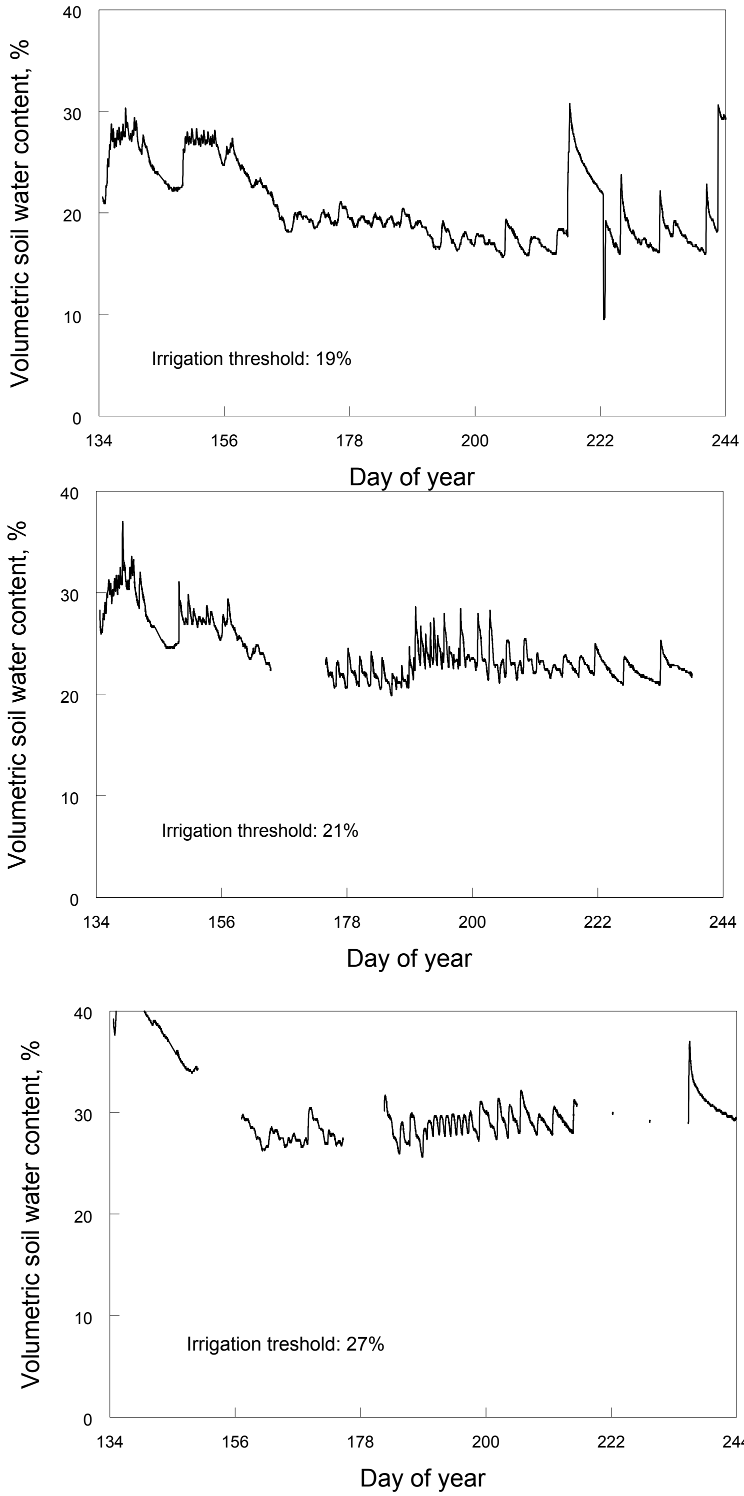

Figure 2. Volumetric soil water content at 8-inch depth for a drip-irrigated onion field using the Acclima irrigation system with three soil water content irrigation thresholds (19, 21, and 27%). Oregon State Univ., Malheur Experiment Station, Ontario, OR 2004.

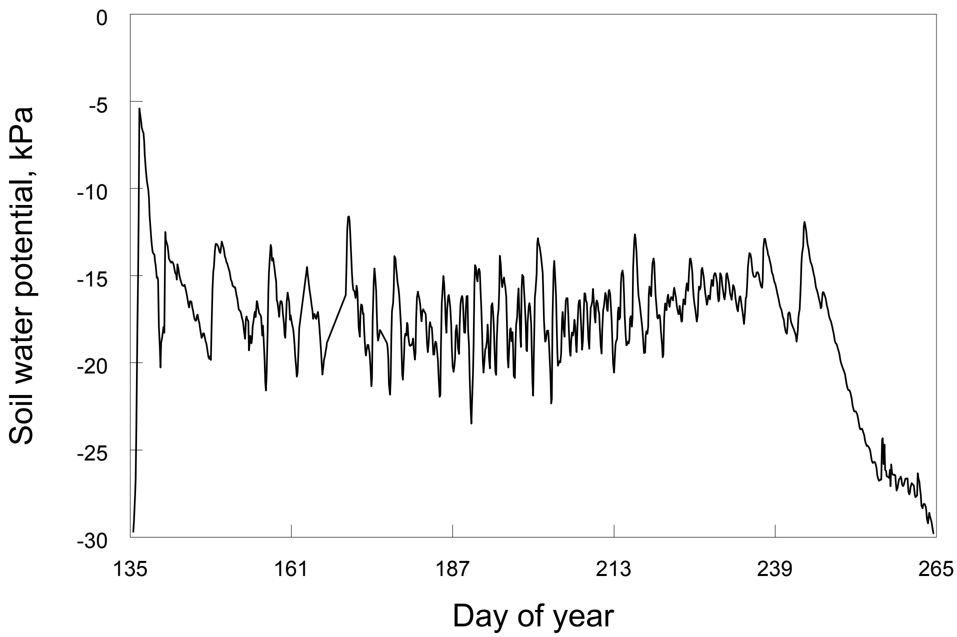

Figure 3. Soil water potential at 8-inch depth for a drip-irrigated onion field using the Campbell Scientific automated irrigation system. Oregon State University Malheur Experiment Station, Ontario, OR 2004.

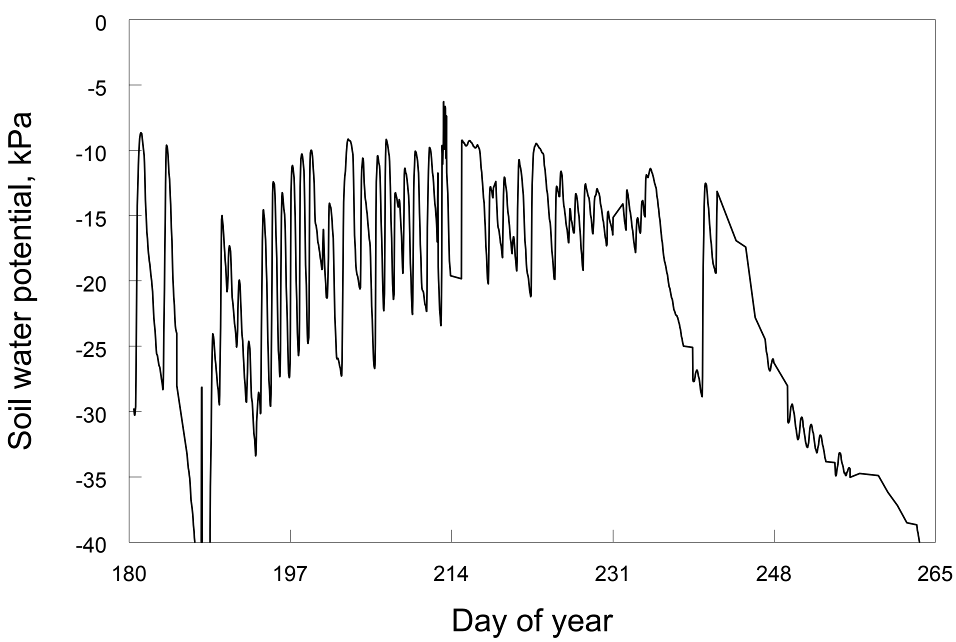

Figure 4. Soil water potential at 8-inch depth for a drip-irrigated onion field using the Automata automated irrigation system. Oregon State University Malheur Experiment Station, Ontario, OR 2004.

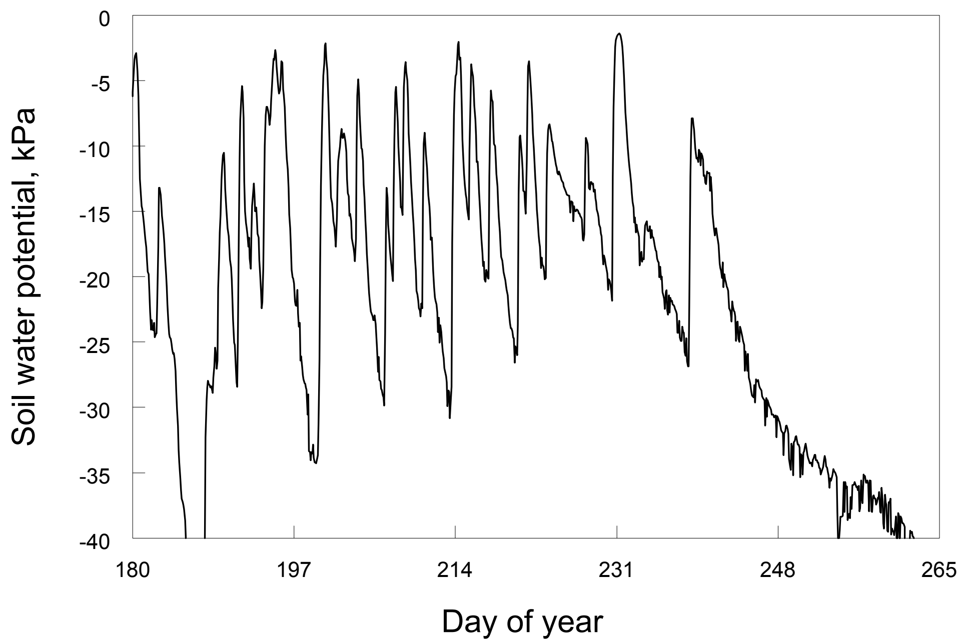

Figure 5. Soil water potential at 8-inch depth for a drip-irrigated onion field using the Irrometer Monitor. Oregon State University Malheur Experiment Station, Ontario, OR 2004.

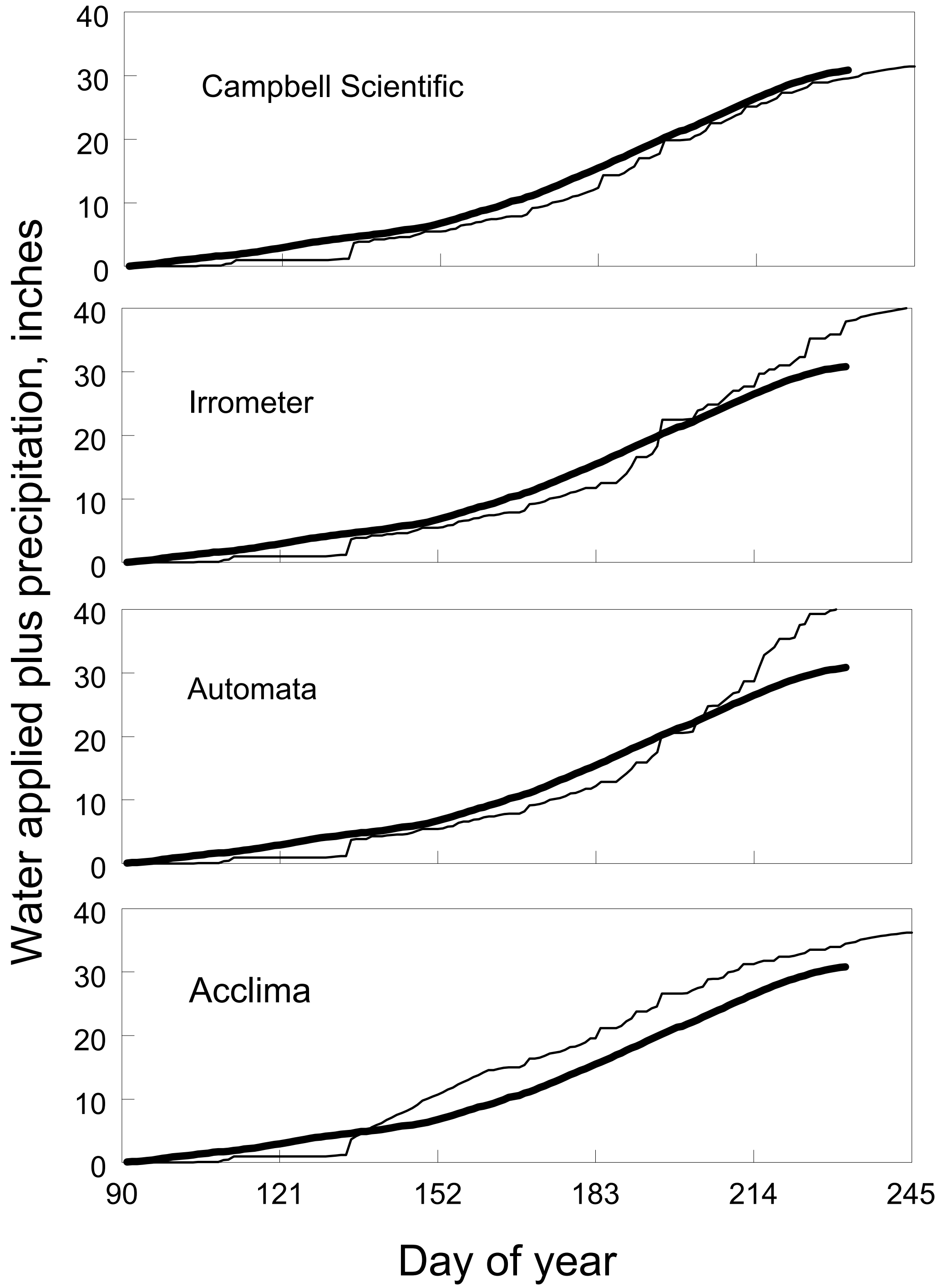

Figure 6. Water applied plus precipitation over time for drip-irrigated onions with four automated irrigation systems. Thin line is water applied and thick line is ET_c. Oregon State University Malheur Experiment Station, Ontario, OR 2004.

Evaluation of a Low Cost Capacitance ECH_2O Soil Moisture Sensor for Citrus in a Sandy Soil

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ABSTRACT

Most citrus in central Florida is grown on sandy soils that have very low water holding capacities. A small change in soil volumetric water content can greatly affect available water. The purpose of this study was to determine if a moderately low cost sensor (ECH_2O probe) can perform well in this sandy soil. Three water stress treatments (irrigated, non-irrigated, and non-irrigated with rain exclusion) were imposed on Valencia orange trees in the fall and winter (2003-2004) to determine the effects of stress on sugar accumulation in the fruit. Five ECH_2O probes were installed in each treatment plot at depths ranging from 10 to 90 cm. Sensors were calibrated in the laboratory. Real time probe responses due to irrigation, rainfall, and water uptake by the plants were collected and analyzed. These probes were able to detect small changes in soil water content at the lower end of the soil water regime and performed well in this soil.

INTRODUCTION

Designing an efficient irrigation scheduling system is problematic in a sandy soil with low water holding capacity and high percolation rate. Sandy soil requires small but frequent water applications to keep the root zone at optimum moisture content. A small change in soil water content can greatly affect plant-available water. Thus, accurate measurement of water is very important in a sandy soil. Currently, some Florida citrus growers use the EasyAG, Diviner, and EnviroSCAN devices manufactured by Sentek (Sentek Sensor Technologies, Adelaide South Australia) and C-probe (AgWise, Agrilink Florida Inc. FL). These sensors are reasonably accurate and easily adapted to reading by either remote communication or dedicated data logging. However, a major factor influencing purchase decision is price. The cost of the single portable unit (e.g.

Diviner) is more than $2000, and a permanent setup with several sensors can range from $4,000 to $15,000. In this study, we investigated a lower cost alternative. The aim of this research was to identify more affordable yet reasonably reliable soil moisture sensors for citrus growers.

The ECH_2O probe is a relatively low cost (<$1000 for five probes, data logger and software) soil water probe manufactured by Decagon (ECH_2O probes, Decagon Devices Inc., Pullman, WA) that has recently become available for scientific and agricultural use. This probe is easy to install, data can be stored in a data logger for manual down load, or data can be radioed to a remote location. However, little information concerning the performance of the ECH_2O probe is available for the fine sandy soils of central Florida. Our objectives were to: (i) to develop a soil-specific calibration model (equation) for a fine sand soil in a water content range commonly found on the central Florida ridge (0.02 to 0.10 $cm^3\ cm^{-3}$), (ii) to test the performance of ECH_2O probes for real time monitoring of volumetric water content (θ_v) under different irrigation treatments, and (iii) to compare the performance of ECH_2O probes with the more expensive C-probes for real time monitoring of θ_v using laboratory calibration models.

Materials and Methods

Study Area

This study was conducted at the University of Florida's Citrus Research and Education Center (CREC), Lake Alfred, Florida. Average annual rainfall there is approximately 1270 mm (Anonymous, 2002), with 60 % of the precipitation occurring in the summer. The soil at the study site was a Candler fine sand (hyperthermic, uncoated Typic Quartzipsamments) that contains > 95% sand, <3% clay, <1% organic matter and has a low water holding capacity (available water = approx. 6%).

Probe Description

The ECH_2O is a capacitance based probe that measures the dielectric constant of the surrounding soil. The probe is 25.4 cm long, 3.17 cm wide and 0.15 cm thick. The probe requires an excitation voltage of 2.5 or 5.0 VDC and outputs a voltage proportional to the dielectric properties of the soil. Claimed accuracies were ± 3% without or ± 1% with soil-specific calibration. The manufacturer indicated that the output is influenced by soil temperature, texture and salinity (Decagon Devices, Inc. Pullman, WA). The standard calibration equation (factory calibration) supplied by the manufacturer for the ECH_2O probe is:

$$\theta_v = 0.000695mV - 0.29 \quad (1)$$

where mV is the probe output in millivolts with a 2.5 V excitation, and θ_v is the volumetric water content.

Probe Calibration, Installation, and Data Acquisition

The standard procedure for calibrating capacitance probes outlined by Starr and Paltineanu (2002) and Campbell (2004) was followed. Details of ECH_2O calibration in the laboratory were described by Borhan and Parsons (2004a). The experiment was conducted in a citrus (Valencia orange) grove where three treatments were imposed: 1) irrigated with rain, 2) non-irrigated with rain, and 3) non-irrigated with rain exclusion. In spring 2003, 15 ECH_2O capacitance probes were permanently installed in three pre-selected treatment plots. Five ECH_2O probes were installed 90 cm from the tree trunk at five depths (10, 20, 30, 50, and 90 cm) from the soil surface that matched the depth of sensors in the C-probe at each plot. A data logger was programmed to collect data hourly. Later on, ECH_2O data were manually downloaded from the data logger and exported to a spreadsheet for further processing.

Two calibration models were developed and evaluated to determine the θ_v of sandy soil. The entire dataset consisted of 48 (6 moisture levels×8 probes) observations used for calibration. Each model was validated using the "leave-one-out" procedure (Borhan et al., 2004). In this procedure, one set of data (6 observations) from a probe was left out and the remaining 42 observations from 7 probes were used to validate the model. This process continued until none of the data sets were left. Models for determining θ_v from ECH_2O probe responses are described below (Borhan and Parsons, 2004a).

Model 1. This is a linear regression of volumetric water content (θ_v) with the corresponding probe's output as millivolt (*mV*) in the laboratory.

$$\theta_v = \beta_1 * mV + \alpha_1 \qquad (2)$$

Model 2. This is a linear regression of θ_v with the corresponding probe's normalized output values (Equation 3). In this model, probe output in *mV* was normalized with respect to two extreme conditions of the soil moisture content (air and water).

$$\theta_v = \beta_2 * \eta_{air-water} + \alpha_2 \qquad (3)$$

$$\eta_{air-water} = \frac{X_i - X_{air-j}}{X_{water-j} - X_{air-j}} \qquad (4)$$

where $\eta_{air-water}$ is the normalized *mV* with minimum (air) and maximum (water); X_i, X_{air-j}, $X_{water-j}$, were the sensor reading in soil, air, and water, for i=1,2,3,…N and j=1,2,3,….K. N and K are the number of observations and sensors, respectively, under measurement. β_1 and β_2 are slopes, and α_1 and α_2 are the intercepts of the regression lines.

Model 3. This is a linear regression between θ_v and the corresponding probe's output as millivolt (*mV*) in the factory (Equation 1).

Statistics of mean error or bias (ME), root mean square error (RMSE), average prediction accuracy (APA), standard error of prediction (SEP), and correlation coefficient (R) were used as evaluation criteria to measure performance of the above two models best approximate measured values. The ME and RMSE, APA, and SEP were calculated based on the following equation (Kramer, 1998; Borhan et al., 2004).

$$ME = \frac{\sum (y_i - \hat{y}_i)}{N} \tag{5}$$

$$RMSE = \sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{N}} \tag{6}$$

$$\text{APA (\%)} = \frac{1}{N}\sum_{1}^{N}\left[1 - \left(\frac{|y_i - \hat{y}_i|}{y_i}\right)\right] \times 100 \tag{7}$$

$$\text{SEP} = \sqrt{\frac{\sum \left((y_i - \hat{y}_i) - \bar{y}\right)^2}{N - 1}} \tag{8}$$

where y_i and $\hat{y}_i$ are the actual and predicted values, respectively, for i = 1, 2, 3, …N; $\bar{y}$ is the mean difference between actual and predicted values; and N is the total number of observations (data points).

Real time Monitoring of Soil Water Status and Performance Comparison

Real time soil water status in three irrigation treatment plots were monitored with ECH_2O probes from 1 January 2004 to 31 January 2004. In addition, the performance of ECH_2O probes for real time monitoring of soil moisture status was also compared with the more expensive C-probe. Real time probe responses due to irrigation and rainfall were collected from 1 November 2003 to 30 November 2003. The data logger was programmed to collect responses (*mV*) from ECH_2O probes every hour. The responses from both probes were converted into volumetric water content using calibration equations (Borhan and Parsons, 2004b; Agrilink Florida Inc.).

Results and Discussion

Development of Calibration Models

In the laboratory, six pre-selected levels (0.0133, 0.0267, 0.04, 0.0533, 0.08, and 0.10 cm^3 cm^{-3}) of moisture content were maintained and corresponding probe outputs in mV were downloaded from the data logger. Statistical analysis showed that mean responses at different moisture levels were significantly different (α=0.05) (Table 1). Thus, ECH_2O probes were found to be capable of differentiating small changes in moisture content in the Candler soil. The regression analysis between probe responses (mV and normalized mV values) and measured volumetric water content (θ_v) resulted in the following equations (Borhan and Parsons, 2004b):

Model 1: $$\theta_v = 0.000964 * mV - 0.3481 \quad (9)$$

Model 2: $$\theta_v = 0.6667 * \eta_{air-water} - 0.10394 \quad (10)$$

No significant differences were observed between these two models in the calibration phase. Observed R^2 for both the models was 0.98 (Table 2). Average prediction accuracy was about 89%. However, minimum and maximum accuracies varied from 45 to 47% and 99.93 to 99.99%, respectively. Calculated SEP and RMSE varied from 0.0038 to 0.004 cm^3 cm^{-3} and 0.0037 to 0.004 cm^3 cm^{-3}, respectively. Similar performances were observed with both models in the validation phase. Observed R^2 was 0.98 and RMSEs were found to be 0.0043 and 0.0041 cm^3 cm^{-3} for model 1 and model 2, respectively. The correlation between actual and predicted soil water content showed a strong relation (Figure 1). The slope and intercept of the correlation line was close to 1 (0.98) and 0 (0.0009), respectively. Thus, this research revealed that ECH_2O probes are able to detect small changes in soil water at the lower end of soil water regime. However, validation of the factory calibration model (Equation 1) resulted in a very low average prediction accuracy, which showed under-prediction of soil water content in a sandy soil (Figure 2). Thus, this result reflected the importance of using the soil specific calibration model.

Real time Monitoring of Soil Moisture Status at Three Treatments Plots

Figure 3 shows a comparison of real time soil moisture status measured by ECH_2O probe at the 20 cm depth in the irrigation treatment plots during January 2004. In the irrigated treatment, a sharp and rapid increase in soil water content was observed after each irrigation event. Then, a gradual decrease in soil water content with time occurred due to drainage and evapotranspiration (ET). ECH_2O probes in the non-irrigated plot responded similarly to rainfall. It was also observed from the real time moisture curve (Figure 3) that probes installed in non-irrigated with rain exclusion treatment did not respond at all during each irrigation and rain event. ECH_2O probes responded fairly well in these three different irrigation treatments. Thus, this research reflects the suitability of ECH_2O probes for real time monitoring of water content in a sandy soil.

Performance Comparison with C-probe

Figure 4 shows the real time soil moisture status of ECH_2O and C-probes at 20 cm depths during November 2003. A sharp and rapid increase in soil water content was observed after each irrigation and a gradual decrease in soil water content with time was also observed when the soil began to dry out due to drainage and ET. For both probes, the overall trends in soil water content were similar and consistent with respect to irrigation and rainfall. ECH_2O probes showed higher soil water content at each depth on irrigation days compared with the C-probes (Figure 4, shows 20 cm depth only for clarity). In general, the probe predicted slightly different soil moisture content, perhaps due to the variations in sensor placement, installation method, root zone depth and distribution, and sprinkler wetting pattern that existed in the field. We do not know which probe produced the most accurate results at this point, but detailed calibration of the C-probe has not been done yet on this type of soil. It should be noted that the accuracy of probes for predicting soil water content might not be very important to the grower. In this situation, growers could correlate the relative position of the probe response curve with current soil moisture status of the grove to trigger an irrigation.

SUMMARY AND CONCLUSIONS

Accurate measurement of soil water is a prerequisite for devising an efficient irrigation scheduling system in sandy soil. A relatively low cost ECH_2O capacitance-based soil moisture probe was calibrated and evaluated for monitoring soil water status in different irrigation treatments in the field. The performance of the ECH_2O probe was compared with the more expensive C-probe for real time monitoring of soil water status in a central Florida sandy soil. The goal of this research was to determine the capability of the ECH_2O probe to monitor small changes in water content across a narrow moisture range. Two models were developed in this study. Observed R^2, average prediction accuracy, standard error of prediction, and root mean square errors were about 0.98, 88%, 0.0042 $cm^3\ cm^{-3}$ and 0.0041 $cm^3\ cm^{-3}$, respectively, in the validation phase. Real time moisture curves showed that ECH_2O probes responded fairly well to three different irrigation treatments. The overall trends in soil water content of ECH_2O probes appeared to be similar and consistent with respect to irrigation, rainfall, drainage, water use by the plants and ET when compared with the C-probe. Thus, the relatively low cost ECH_2O probes appear to be suitable for real time monitoring of water in a sandy soil.

ACKNOWLEDGMENT

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Table 1. Statistics describing measurement variability of ECH_2O probe (mV) response.

Measured Moisture (cm^3 cm^{-3})	Probe responses at different moisture levels						
	Mean (mV)	Minimum (mV)	Maximum (mV)	Range (mV)	STD (mV)	CV (%)	STDER (mV)
0.0133	379.57 [a]	377.59	382.47	4.88	1.62	0.43	0.57
0.0267	385.06 [b]	381.86	388.57	6.71	2.25	1.59	0.80
0.0400	403.74 [c]	401.38	406.26	4.88	1.80	0.45	0.64
0.0533	413.96 [d]	411.14	417.24	6.10	2.19	0.53	0.77
0.0800	442.55 [e]	438.59	452.01	13.42	4.52	1.02	1.60
0.1000	467.26 [f]	459.33	480.07	20.74	6.25	1.34	2.21

Mean values with same letter are not significantly different at $\alpha = 0.05$.
STD is standard deviation; STDER is standard error; CV is coefficient of variation.

Table 2. Performance of calibration models in predicting soil moisture in the laboratory (Borhan and Parsons, 2004a).

Performance with calibration dataset						
Model Types	Calibration accuracies (%)			R^2	SEP (cm^3 cm^{-3})	RMSE (cm^3 cm^{-3})
	Min	Max	Average			
Model 1	45.18	99.99	89.30	0.98	0.0038	0.0037
Model 2	47.43	99.93	88.91	0.98	0.004	0.004
Performance with validation dataset						
Model Types	Prediction accuracies (%)			r	SEP (cm^3 cm^{-3})	RMSE (cm^3 cm^{-3})
	Min	Max	Average			
Model 1	41.02	99.58	88.44	0.98	0.0043	0.0043
Model 2	45.87	99.67	88.76	0.98	0.0042	0.0041
Model 3	-207.33[a]	43.65	-41.98[b]	0.98	0.0090	0.0543

Model 1 used probe responses in *mV*; Model 2 used normalized responses (*mV*); Model 3 used probe response in mV and factory calibration equation; R^2 is the coefficient of determination SEP is the standard error of prediction; RMSE is the root means square error; r is the coefficient of correlation between actual and measured moisture content; and [a] and [b] indicates predicted values are about 3 and 0.41 times lower than actual values, respectively.

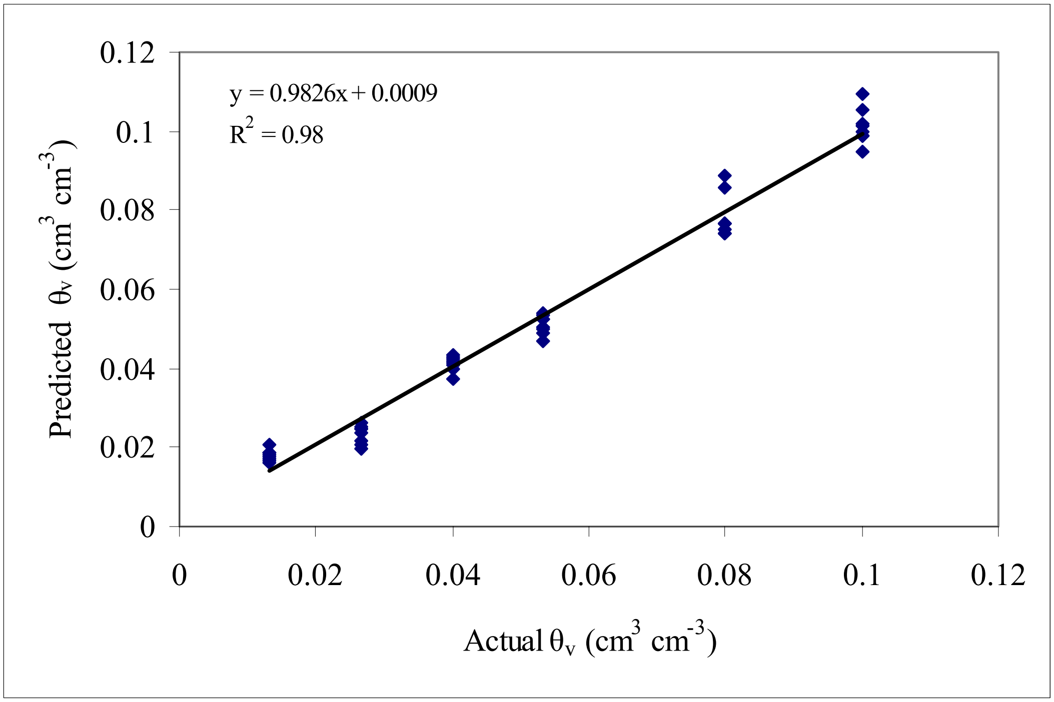

Figure 1. Relation between actual and predicted soil moisture content in validation phase (using Model 2) (Borhan and Parsons, 2004b).

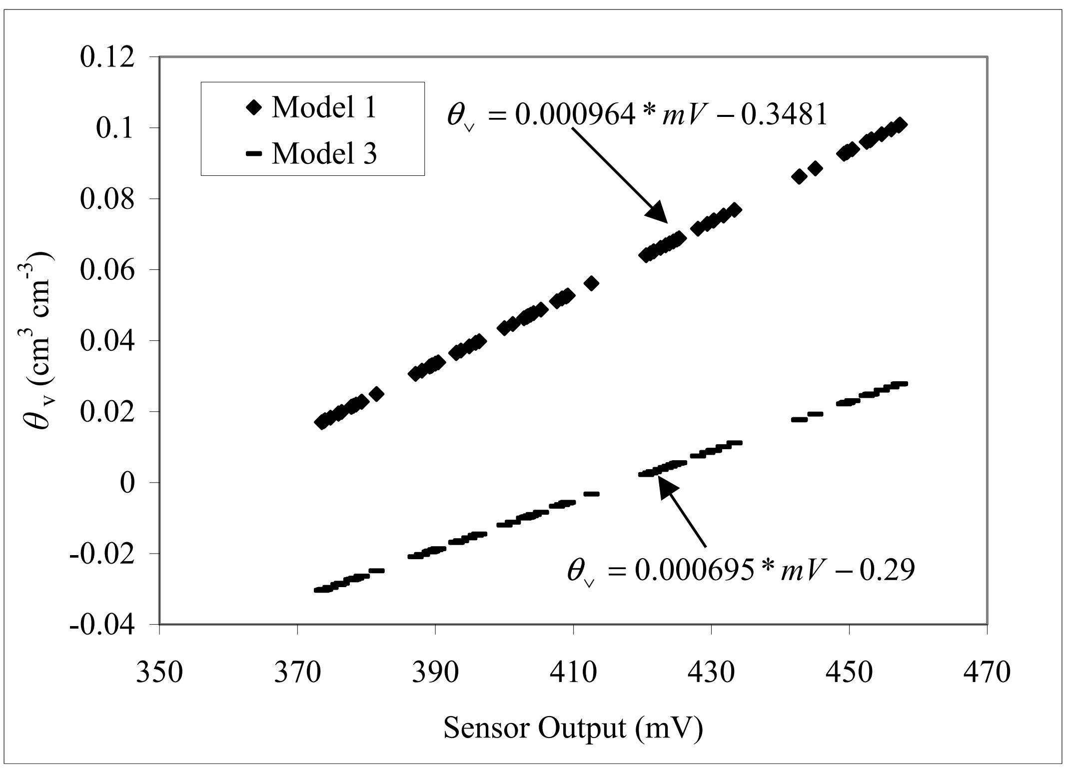

Figure 2. Comparison of Model 1 (Equation 2) and Model 3 (factory calibration model, Equation 1) using validation dataset (Borhan and Parsons, 2004a).

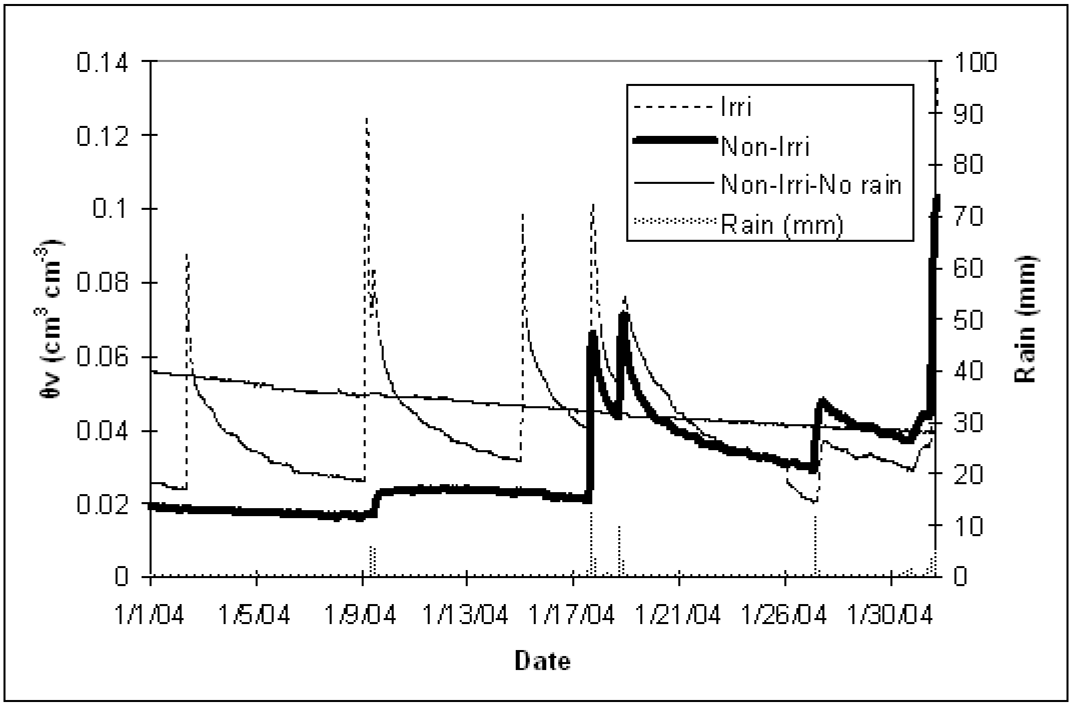

Figure 3. Comparison of real time soil moisture status measured by ECH_2O probe at 20 cm depth in three irrigation treatments plots.

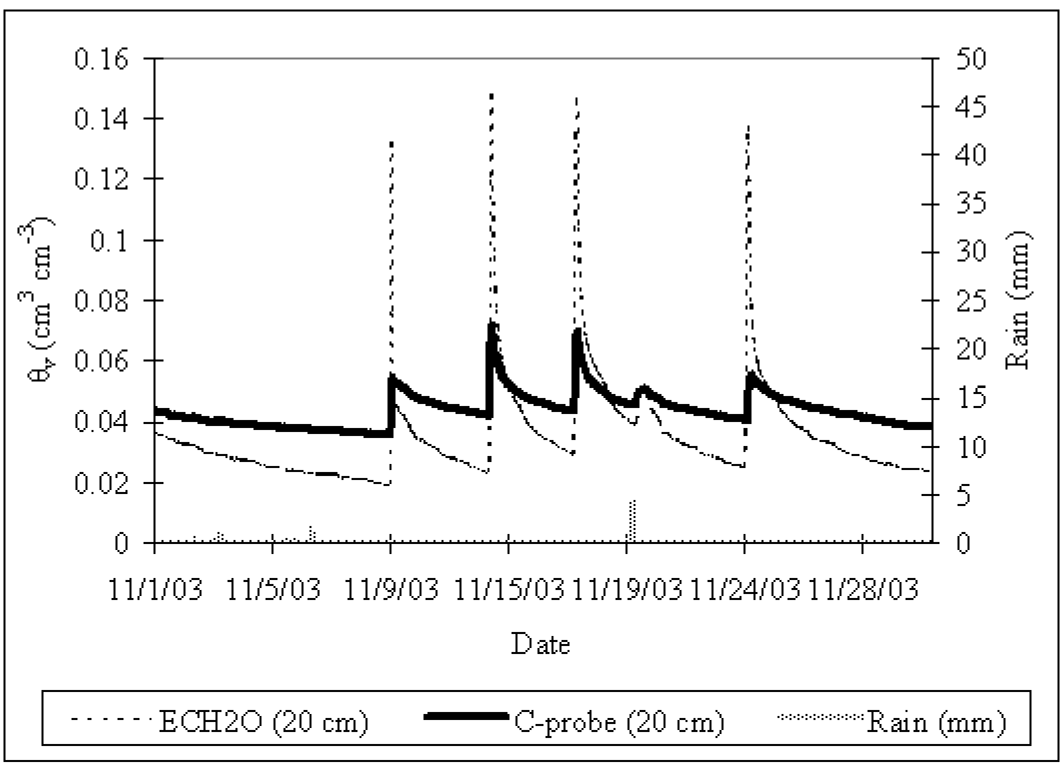

Figure 4. Comparison of real time soil moisture status measured by ECH_2O probe and C-probe at 20 cm depth (Borhan and Parsons, 2004b).

Comparison of SDI, LEPA, and spray irrigation performance for cotton in the North Texas High Plains[1]

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Abstract

Producers in the North Texas High Plains (Amarillo and north) are considering cotton as an alternative crop to corn because cotton has a similar profit potential for about one-half the irrigation requirement. However, limited heat units pose some risk for cotton production. We hypothesized that cotton under subsurface drip irrigation (SDI) would undergo less evaporative cooling following an irrigation event compared with low energy precision applicators (LEPA) or spray irrigation and, therefore, would increase heat unit accumulation and lead to earlier maturation. We did not observe any differences in cotton maturity between irrigation methods in 2003; however, preliminary data in 2004 showed that soil temperatures were greater for SDI than LEPA or spay following an irrigation event. In the 2003 season, lint yield and water use efficiency were greater with SDI under low irrigation capacities (25% and 50% of full irrigation), but were greater with LEPA and spray under full irrigation. Fiber quality, as indicated by total discount, was greater with SDI for all capacities except full irrigation. We are continuing this experiment for two more seasons.

Introduction

Producers in the Northern Texas High Plains (Amarillo and north) have recently shown renewed interest in cotton. This region is adjacent to one of the largest cotton producing areas in the United States, centered approximately at Lubbock (190 km south), where approximately 4 million bales are produced annually (USDA-NASS, 2004; TDA-TASS, 2004). This renewed interest stems from, among other factors, lower water requirements relative to corn, which is presently more widely produced in the northern area and has a similar revenue potential (Howell et al., 1997; 2004). The primary limitation to cotton production in the Northern High Plains is the lack of heat units (Peng et al., 1989; Morrow and Krieg, 1990) and the lack of an industry infrastructure (gins, custom harvesters, etc.). The other main limitation is of course water, specifically the declining availability of irrigation water from the Ogallala aquifer, insufficient and sporadic in-season rainfall, and high evaporative demand. Despite these limitations, Howell et al. (2004) showed that cotton production in this area is feasible, with lint yields and water use efficiencies comparable to those in more ideal climates (Zwart and Bastiaanssen, 2004).

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Pressurized irrigation systems such as mechanically moved and microirrigation can enhance cotton lint yield and water use efficiency compared to furrow (gravity) irrigation or dryland regimes, provided the pressurized system is properly designed and managed. Mechanically moved systems have numerous variants of applicator packages, with the more common configurations being mid- and low-elevation spray application (MESA and LESA, respectively) and LEPA (Low Energy Precision Applicator; Lyle and Bordovsky, 1983; Bordovsky et al., 1992). Microirrigation, usually in the form of subsurface drip irrigation (SDI), has been widely adopted by commercial cotton producers throughout the South Plains and Trans Pecos regions of Texas beginning in the early 1980s (Henggeler, 1995; 1997; Enciso et al., 2003). Although SDI has significantly greater initial costs than spray or LEPA systems (O'Brien et al., 1998; Segarra et al., 1999), it has been documented to slightly outperform LEPA and spray in terms of lint yield, lint quality (as reflected by loan prices), and water use efficiency (Segarra et al., 1999; Bordovsky and Porter, 2003). Similar trends have been reported for surface drip where laterals were placed in alternate furrows (Yazar et al., 2002) and each planted row (Cetin and Bilgel, 2002). Nonetheless, Segarra et al. (1999) analyzed four years of cotton data at Halfway, Texas and concluded that SDI may not always provide as high economic returns as LEPA, but this largely depended on system life, installation costs, pumping lift requirements, and hail damage that commonly occurs in West Texas. Also, Howell et al. (1987) found no differences in lint yield of narrow row (0.5 m) cotton between surface drip and furrow irrigation systems that were designed and managed to minimize soil water deficits, although soil water evaporative losses were less for surface drip.

There is a general perception by some cotton producers that SDI also enhances seedling emergence and plant maturity due to reduced evaporative cooling compared to LEPA or spray, which is a critical consideration in a thermally limited environment and is seldom considered in economic analyses. There is, however, limited data in direct support of this view, as soil water depletion in the root zone is most responsible for inducing earliness (Guinn et al., 1981; Mateos et al., 1991; Orgaz et al., 1992). Nonetheless, a few studies may indirectly support the premise that SDI can enhance cotton maturity and are briefly described here. Wang et al. (2000) reported that mean soil temperatures were 4.4 °C greater for plots irrigated with surface drip laterals than stationary rotating sprinklers, and they observed greater emergence rates and seedling development of soybeans. They noted, however, that their results may have been influenced by the solar heating of water as it passed through the black plastic drip laterals rather than the greater evaporating surface area of the sprinkler plots. Tolk et al. (1995) showed that corn transpiration rates, canopy temperature, and vapor pressure deficits were significantly reduced for several hours following irrigation by overhead impact sprinklers, but not greatly changed following irrigation by LEPA in alternate furrows. The reduced evaporative cooling thought to be associated with SDI, on the other hand, may be countered by the greater cooling effect of increased irrigation frequency (Wanjura et al., 1996). Constable and Hodgson (1990) reported that cotton under SDI matured several days later than cotton under furrow irrigation.

The objectives of this study are to compare cotton yield and quality for spray, LEPA, and SDI under full and deficit irrigation in the Northern Texas High Plains, which is a marginal climate for cotton production. This paper presents the results of the first (2003) season of data, and some preliminary soil temperature data from the second (2004) season.

Procedures

An experiment was conducted during the 2003 and 2004 growing seasons using MESA, LESA, LEPA, and SDI to irrigate cotton at the USDA Conservation and Production Research Laboratory in Bushland, Texas (35° 11′ N lat., 102° 06′ W long., 1070 m elevation MSL). As of this writing, only the 2003 season is complete, so most data presented here reflects a single season. The climate is semi-arid with a high evaporative demand of about 2,600 mm per year (Class A pan evaporation) and low precipitation averaging 470 mm per year. Most of the evaporative demand and precipitation occur during the growing season (May to October) and average 1,550 mm and 320 mm, respectively. Cumulative heat units for cotton average 1,050°C during the growing season (mean daily air temperature minus base temperature of 15.6 °C); however, Peng et al. (1989) state that about 1,450°C is required for full maturity cotton in the region to our south centered around Lubbock, TX. The climate is also characterized by strong regional advection from the South and Southwest, where average daily wind runs at 2 m height can exceed 460 km especially during the early part of the growing season. The soil is a Pullman clay loam (fine, mixed, thermic torrertic Paleustoll; Unger and Pringle, 1981; Taylor et al., 1963), with slow permeability due to a dense B21t layer that is 0.15 to 0.40 m below the surface and a calcic horizon that begins about 1.2 to 1.5 m below the surface.

Agronomic practices were similar to those practiced for high lint yield in the High Plains region of Texas. Cotton (*Gossypium hirsutum* L., Paymaster[3] 2280 BG RR) was planted on 21 May 2003, and disked and replanted on 10 June 2003 (following severe hail damage to seedlings) at 17.3 plants m^{-2}, on east-west oriented raised beds spaced 0.76 m. The same variety was planted on 20 May 2004 at 19.0 plants m^{-2}. Furrow dikes were installed after crop establishment to control runoff (Schneider and Howell, 2000). In 2003, preplant fertilizer containing nitrogen (N) and phosphorous (P) (10-34-0) was incorporated into the raised beds, at rates resulting in 31 and 107 kg ha^{-1} of N and P, respectively, which were based on a soil fertility analysis. In 2004, similar rates of preplant fertilizer were applied (34 and 114 kg ha^{-1} of N and P, respectively). Additional N (32-0-0) was injected into the irrigation water from first square to early bloom, resulting in a total N application of 48 kg ha^{-1} in both seasons for the full irrigation treatment while deficit irrigation treatments received proportionately less. Treflan was applied at one time before planting at 2.3 L ha^{-1} to control broadleaf weeds in both seasons. No other in-season chemical inputs were required in either year, and no post harvest chemical inputs were required in 2003.

The experimental design consisted of four irrigation methods (MESA, LESA, LEPA, SDI, described in more detail shortly), and five irrigation levels (I_0, I_{25}, I_{50}, I_{75}, and I_{100}). The I_{100} level was sufficient to prevent yield-limiting soil water deficits from developing, based on crop evapotranspiration (ET_c) estimates from the North Plains ET Network (NPET, Howell et al., 1998), and the subscripts are the percentage of irrigation applied relative to the full irrigation amount. The different irrigation levels were used to estimate production functions, and to simulate the range of irrigation capacities one might encounter in the region. The I_0 level received sufficient irrigation for emergence only and to settle and firm the furrow dikes and

[3] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

represents dryland production. The experiment was a variant of the split-block design (Little and Hills, 1978), where irrigation methods were in the direction of travel of a three-span lateral move system, and irrigation levels were perpendicular to the direction of travel. This sacrificed the precision of comparing different irrigation levels, but was necessary to facilitate operation of the lateral-move system using applicators common in the Southern High Plains. Each span of the linear move system constituted a complete block (i.e., replicated three times), and irrigation methods were randomized within each block. Plots were 25 m long by 9 m wide with 12 rows each, and 5 m planted borders separated irrigation level strips.

Spray and LEPA irrigations were applied with a hose-fed Valmont (Valmont Irrigation, Valley, NE) Model 6000 lateral move irrigation system. Drop hoses were located over every other furrow at 1.52 m spacing. Applicators were manufactured by Senninger (Senninger Irrigation Inc., Orlando, FL) and were equipped with 69 kPa pressure regulators and #17 plastic nozzles, giving a flow rate of 0.41 L s^{-1}. The MESA and LESA spray heads were positioned 1.5 and 0.3 m above the furrow, respectively. A double-ended drag sock (A. E. Quest and Sons, Lubbock, TX) was used with LEPA. The SDI consisted of Netafim (Netafim USA, Fresno, CA) Typhoon dripline that was shank injected in 1999 under alternate furrows at 0.3 m depth below the surface (before bedding). Irrigation treatment levels were controlled by varying the speed of the lateral-move system for the spray and LEPA methods, and by different emitter flow and spacing for the SDI method. All treatments were irrigated uniformly with MESA at the I_{100} level until furrow dikes were installed to ensure crop establishment.

Soil water was measured gravimetrically near the center of each plot prior to planting and just after harvest in the 1.8 m profile in 0.3 m increments, oven dried, and converted to volumetric contents using known soil bulk densities by profile layer. During the season, soil water was measured volumetrically near the center of each plot on a weekly basis by neutron attenuation in the 2.4 m profile in 0.2 m increments according to procedures described in Evett and Steiner (1995) and Evett et al. (2003). The gravimetric samples were used to compute seasonal water use (irrigation + rainfall + change in soil water), and the neutron measurements were to verify that irrigation was sufficient so that no water deficits developed in the I_{100} treatment.

Soil temperature was measured in 2004 at the I_{50} and I_{100} irrigation levels in the LESA, LEPA, and SDI plots using thermocouples made from 20 AWG Type-T thermocouple wire (Omega Engineering, Stamford, CN). The plots had a set of three (LESA and SDI) or four (LEPA) thermocouples at one bed location per plot, where thermocouples were buried in the sides of the bed (approximately 6 cm from the center) at 5 and 10 cm depths. In the LESA and SDI plots, two thermocouples were buried at the 5 cm depth on each side of the bed, and one thermocouple was buried at the 10 cm depth on the north side of the bed (adjacent to the irrigated furrow). In the LEPA plots, thermocouples were buried in each side of the bed both at the 5 and 10 cm depths. The fourth channel in the LESA and SDI plots was used for an infrared thermometer to measure canopy temperature. The thermocouples and infrared thermometers were not operational until 27 July 2004, when the crop height was approximately 0.75 m or greater, and the canopy width was 0.30 to 0.40 m.

Plants were mapped both seasons in all plots on a weekly basis beginning with 1st square, which included data on height, width, nodes, and number and position of fruit forms. In 2003, hand samples of bolls were collected from each plot on 19 Nov from a 10 m^2 area that was sequestered from other activity during the season. Samples were weighed, ginned, and analyzed for micronaire, strength, color grade, and uniformity at the International Textile Center, Lubbock, Texas. Seed cotton was harvested on 21 November with a commercial cotton stripper. Cotton stalks were shredded on 8 December and rotary-tilled into the beds on 10 December. The same sampling, harvest, and fiber analysis procedure is anticipated for the 2004 season.

Lint yield, seasonal water use (estimated from total irrigation + in season rainfall + change in soil water content in the 1.8 m profile), micronaire, strength, uniformity, water use efficiency (WUE), and irrigation water use efficiency (IWUE), total discount, and total return were tested for differences for each irrigation method using the SAS mixed model (PROC MIXED, Littell et al., 1996). In PROC MIXED, fixed and random effects are specified separately. Random effects were block replicates, block by irrigation level, and block by irrigation method, and the fixed effect was irrigation method. Differences of fixed effects were tested using least square means ($\alpha \leq 0.05$) within each irrigation level. WUE is defined as the ratio of economic yield (i.e., lint yield, LY) to seasonal water use (WU) or $WUE = LY\ WU^{-1}$. Seasonal water use includes evapotranspiration, deep percolation (if any), and runoff minus run on (if any). IWUE is defined as the increase in irrigated yield (Y_i) over dryland yield (Y_d) due to irrigation (IR), or $IWUE = (Y_i - Y_d)\ IR^{-1}$ (Bos, 1980). Further details of experimental design, procedures, and equipment can be found in Colaizzi et al. (2004).

Results and Discussion

The 2003 growing season had much less rainfall and greater temperatures than average, and some record highs were set during the fall (16 September to 23 October). Total rainfall from planting to harvest (10 June to 21 November) was 167 mm, whereas the 65-year average for this period is 280 mm (fig. 1). There was 64 mm of rainfall between 10 and 30 June, which allowed in-season irrigations to be delayed until 8 July as there was sufficient water stored in the soil profile. No significant rainfall occurred again until 29 August, and the last irrigation was on 20 August. Preseason irrigations (100 to 200 mm) are not shown. Crop water use (ET_c) shown here was computed by the North Plains ET Network based on short-season cotton (Howell et al., 1998). The irrigation + rainfall totals for the I_{100} treatment tracked ET_c fairly well until irrigations were terminated (just after maximum bloom), indicating irrigation timing and amounts were appropriate. Additional water for consumptive use after 20 August was provided by water stored in the soil profile.

The record heat from 16 September to 23 October was probably fortuitous in that it compensated for a late start (recall hail damage required replanting on 10 June). The first open boll was not observed until 22 September, but nearly all bolls were open by 20 October, and the first frost occurred on 26 October. Additional frost events defoliated all remaining vegetative matter so that chemical defoliant was not required by harvest (21 November). The crop reached full maturity with only 1076 °C-days (growing degree days based on a 15.6°C base temperature). This was considerably less than the 1450 °C-days thought to be required for full maturity cotton in the Southern High Plains (Peng et al., 1989), but only slightly less than that reported by

Howell et al. (2004) for the 2000 and 2001 cotton seasons at our location, and was at the minimal range of growing degree days reported by Wanjura et al. (2002) for 12 years of data at Lubbock, TX.

No differences in maturity rates (open harvestable bolls) were noted for any irrigation method. Differences in maturity rates appeared to vary primarily with irrigation level, beginning with dryland (I_0), which had the greatest soil water depletion, and proceeding through each subsequent level, in agreement with Guinn et al. (1981), Mateos et al. (1991), and Orgaz et al. (1992).

Overall, SDI tended to perform best at the I_{25} and I_{50} irrigation levels, followed by LEPA. At the I_{75} level, LEPA outperformed the other methods, and at the I_{100} level, MESA performed best (table 1). Most parameter differences within a given irrigation level were not significant. Fully irrigated MESA (I_{100}) had the highest lint yield (1,229 kg ha^{-1}), premium (\$0.0950 kg^{-1}), and gross return (\$1,515.96 ha^{-1}) of all treatments in this study, but these were not significantly greater than other irrigation methods at I_{100} (except for LESA, which had significantly less premium at \$0.0466 kg^{-1}). SDI had the highest premiums at all levels except I_{100}, which suggests SDI generally results in higher fiber quality. Similar trends were observed with grain sorghum yield in a previous study using the same experimental design (Colaizzi et al., 2004).

The greatest values of lint yield, seasonal water use, WUE, premium, and gross return occurred at the I_{100} level among irrigation methods (table 1, irrigation level averages). However, the greatest IWUE and most optimal fiber quality parameters (except fiber length) occurred at the I_{75} level. Note that WUE at I_{50} and I_{100} were more than doubled and almost quadrupled, respectively, compared to dryland (I_0). The lint yield, seasonal water use, and WUE were generally within the range of values reported by Howell et al. (2004) for the 2000 and 2001 cotton seasons under MESA irrigation at our location; however, total irrigation applied (including pre-season irrigation) in the present study was somewhat less due to both a shorter growing season and slightly greater pre- and early season precipitation. Lint yields were almost as high as those reported by Wanjura et al. (2002) for their 1992 season, which only had 1092 °C-days, and they found that lint yield was more correlated to growing degree days than irrigation applied over their 12 years of data. For irrigation methods among levels (table 1, irrigation method averages), SDI had the greatest lint yield, seasonal water use, WUE, IWUE, premium, and gross return, followed by LEPA. Irrigation levels tended to result in parameter differences that were statistically significant, whereas for irrigation methods, parameter differences tended to be merely numerical.

The relationship between lint yield and seasonal water use was highly significant ($P < 0.001$) following linear regression (fig. 2). This relationship was not significantly different from those for individual irrigation methods, not surprising since lint yield showed greater variability with irrigation levels than for irrigation methods (table 1). Note that this relationship represents a single season, and different responses should be expected for different years (Wanjura et al., 2002; Howell et al., 2004). The X-axis intercept was significantly different from zero ($P < 0.001$), where 400 mm of water was required for minimum lint yield. This was double that reported by Howell et al. (2004) for the 2000 and 2001 seasons at our location. WUE was highly responsive to irrigation level through lint yield, with maximum WUE achieved at maximum lint yield (fig. 3). Both linear and quadratic regressions were significant ($P < 0.001$) with zero intercepts (intercepts were not significantly different from zero, and should not be by definition of WUE).

Finally, although the irrigation method did not appear to influence cotton earliness for this experiment in 2003, there is some evidence that the irrigation method can nonetheless influence small differences in soil temperatures. We measured soil temperature for several weeks beginning in 27 July 2004. Measurements included the final irrigation event of the season on 5 August, when 37 mm of irrigation water was applied to the I_{100} plots (fig. 4). Almost immediately, there was a sudden decrease in soil temperature at the 5 cm depth for each irrigation method (fig. 4a). During the next 24 hours, the soil temperature in the SDI plots was greater than LEPA and LESA at both the 5 and 10 cm depths, until 7 mm of rain fell just before 18:00 the following day. After the rain event, there were little differences, and it is uncertain whether this was from the rain event or a redistribution of soil water following the irrigation event. Soil temperatures at a given depth were nearly identical for each irrigation method before the irrigation event (data not shown).

During the three-day period following the irrigation event, we computed heat units based on both air and soil temperature on an hourly basis (i.e., hourly temperature above the 15.6 °C base temperature, divided by 24) (table 2). The hourly basis is thought to be more physiologically accurate than using daily mean temperature for computing heat units, especially for short time periods (Fry, 1983). The accumulated heat units using air temperature was 20.4 °C, but heat units using soil temperature was a few degrees greater and varied both by irrigation level (I_{50} and I_{100}) and irrigation method (LESA, LEPA, and SDI). The greatest difference was observed in the I_{100} plots at the 5 cm depth, where SDI accumulated 1.8 °C more than LESA.

The lack of differences in cotton earliness by irrigation method may be related to our current procedure of not initiating the different irrigation methods until the crop is established, (i.e., we used MESA for all the plots to ensure uniform germination). Soil evaporation may be sufficient to cool the seed bed and the small seedlings so that any heat unit advantage to SDI may be eliminated early in the season. This hypothesis, along with the soil temperature data, prompted us to redesign this experiment to make better use of SDI for crop germination. Thus, the same irrigation method will be used throughout the year for a given treatment, and SDI plots will no longer be subject to possible evaporative cooling by MESA early in the season. We will also concentrate the soil thermocouples in several beds within a single plot to help facilitate soil temperature measurement during the entire season.

Conclusion

Relative response of cotton to spray, LEPA, and SDI varied with irrigation capacity. At lower irrigation system capacity (I_{25} and I_{50}), SDI outperformed (either numerically or significantly) both spray and LEPA; whereas at full irrigation system capacity (I_{100}), spray outperformed both LEPA and SDI but only on a numerical basis. At the I_{75} level, LEPA numerically outperformed SDI, and SDI numerically outperformed spray. Cotton response had greater variation between irrigation capacities than irrigation methods, and highly significant relationships were observed between lint yield and seasonal water use, and water use efficiency and lint yield. Nonetheless, SDI had slightly greater premiums than other methods, suggesting SDI may enhance fiber quality. No differences in cotton maturity were observed among irrigation methods; however, preliminary data in 2004 clearly showed that soil temperature for SDI was greater during and after an irrigation event than that for LEPA or LESA. We believe the lack of differences in cotton maturity may have been related to using MESA for all plots until the crop is established to ensure uniform germination. Therefore, this experiment has been redesigned to make better use of SDI to germinate the crop, to avoid the possible early-season evaporative cooling associated with using MESA in the SDI plots.

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Table 1. Yield, water use, fiber quality, and return parameters as affected by irrigation levels and methods. Numbers followed by the same letter are not significantly different (α ≤ 0.05).

Irrigation Level [a]	Irrigation Method	Lint Yield (kg ha^{-1})	Seasonal Water Use (mm)	WUE (kg m^{-3})	IWUE (kg m^{-3})	Micronaire value	Fiber strength (g tex^{-1})	Fiber length (mm)	Fiber Uniformity (%)	Total Discount or Premium ($ kg^{-1})	Gross Return ($ ha^{-1}) [b]
I_0 (25 mm)	---	196	437	0.046	---	5.17	28.8	0.76	79.1	-$0.1575	$192.71
I_{25} (71 mm)	MESA	213b	477b	0.045b	0.024c	5.20a	28.4b	0.75b	78.9b	$-0.1646b	$208.19b
	LESA	288ab	495ab	0.058b	0.130bc	5.13a	29.4ab	0.79a	80.2ab	$-0.1386b	$288.55ab
	LEPA	362ab	494ab	0.072ab	0.234ab	4.50b	30.1a	0.79a	80.4a	$-0.0810a	$379.56ab
	SDI	491a	530a	0.092a	0.416a	4.70b	29.9a	0.80a	80.9a	$-0.0396a	$540.88a
I_{50} (117 mm)	MESA	536b	604ab	0.089b	0.288b	5.07a	30.2ab	0.83ab	81.3a	$-0.0810b	$567.16b
	LESA	575b	582b	0.098b	0.321b	5.07a	29.2b	0.81b	81.2a	$-0.1111b	$591.89b
	LEPA	685ab	629a	0.109ab	0.415ab	4.77ab	31.3a	0.84ab	81.8a	$0.0150a	$797.32ab
	SDI	844a	627a	0.135a	0.549a	4.40b	30.3ab	0.85a	82.2a	$0.0587a	$1010.08a
I_{75} (165 mm)	MESA	1001a	705a	0.142a	0.491a	4.53a	31.3a	0.86a	82.3a	$0.0623a	$1201.93a
	LESA	984a	685a	0.143a	0.480a	4.40ab	30.8a	0.86a	82.3a	$0.0605a	$1179.55a
	LEPA	1149a	701a	0.164a	0.581a	4.07bc	31.1a	0.87a	81.7a	$0.0500a	$1368.85a
	SDI	1082a	714a	0.152a	0.540a	3.80c	31.6a	0.87a	82.4a	$0.0829a	$1322.12a
I_{100} (211 mm)	MESA	1229a	752a	0.164a	0.492a	4.07a	31.4a	0.88a	82.5a	$0.0950a	$1515.96a
	LESA	1208a	754a	0.160a	0.482a	3.57b	30.9a	0.87a	81.7a	$0.0466b	$1429.41a
	LEPA	1153a	727a	0.158a	0.456a	3.53b	30.9a	0.88a	82.2a	$0.0557ab	$1375.79a
	SDI	1150a	725a	0.159a	0.454a	3.67b	30.4a	0.88a	81.9a	$0.0818ab	$1402.89a
Irrigation Level Averages											
I_0 (25 mm)	---	196d	437e	0.046c	---	5.17a	28.8c	0.76c	79.1b	$-0.1575c	$192.71d
I_{25} (71 mm)	---	339d	499d	0.067c	0.201c	4.88a	29.4c	0.79c	80.1b	$-0.1060c	$354.3d
I_{50} (117 mm)	---	660c	610c	0.108b	0.393b	4.83a	30.2b	0.83b	81.6a	$-0.0300b	$741.62c
I_{75} (165 mm)	---	1054b	701b	0.150a	0.523a	4.20b	31.2a	0.87a	82.2a	$0.0638a	$1268.12b
I_{100} (211 mm)	---	1185a	739a	0.160a	0.471ab	3.71c	30.9a	0.88a	82.0a	$0.0697a	$1431.02a
Irrigation Method Averages											
---	MESA	745a	635a	0.110a	0.324a	4.72a	30.3ab	0.83a	81.3a	$-0.0220bc	$873.29a
---	LESA	764a	629a	0.115a	0.353a	4.54a	30.0b	0.83a	81.4a	$-0.0356c	$872.35a
---	LEPA	837a	638a	0.126a	0.421a	4.22b	30.8a	0.85a	81.5a	$0.0100ab	$980.39a
---	SDI	892a	649a	0.134a	0.490a	4.14b	30.6ab	0.85a	81.8a	$0.0460a	$1068.99a

[a] Numbers in parentheses are in-season (planting to harvest) irrigation totals and do not include 100 to 200 mm of preplant irrigation.
[b] Based on a base loan value of $1.1352 kg^{-1}.

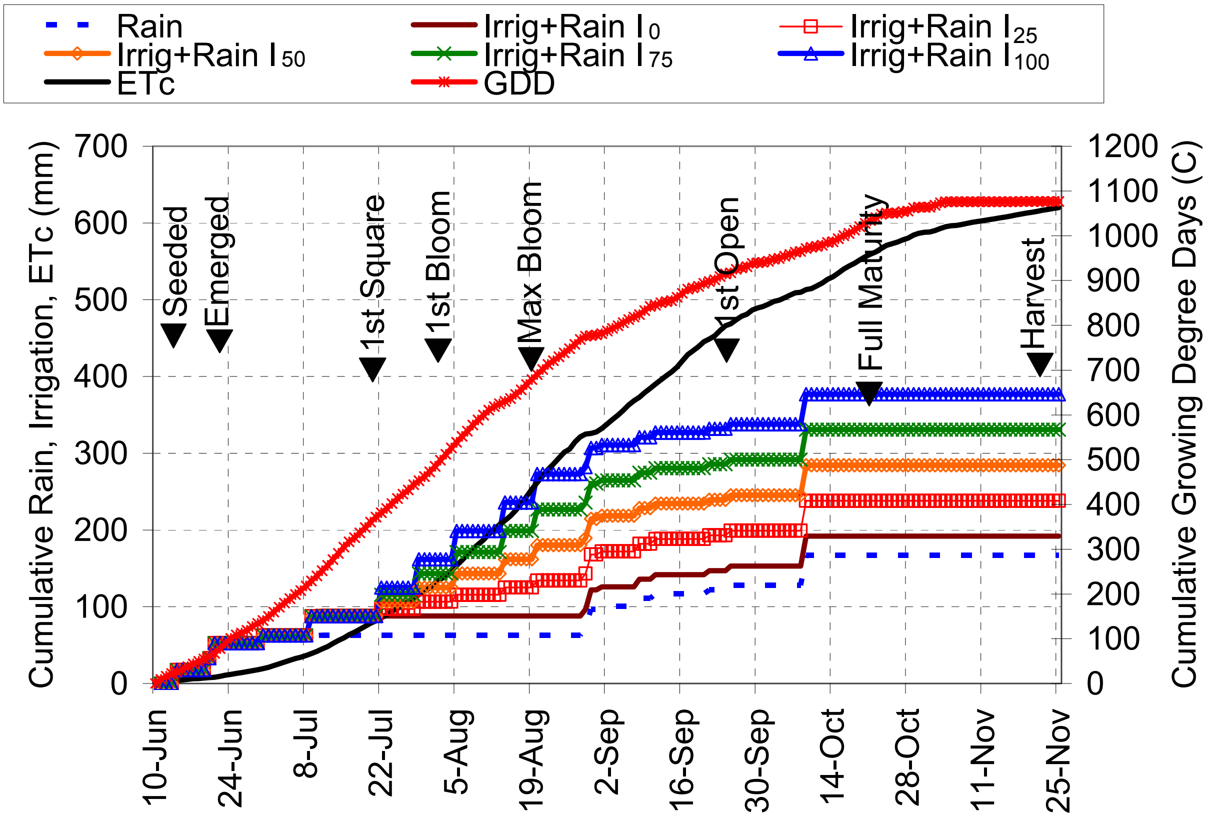

Figure 1. Seasonal rainfall, irrigation + rainfall for each LEVEL treatment, NPET-computed crop water use (ET_c), and growing degree days (°C, based on 15.9 °C base temperature), and growth stages for 2003 cotton season.

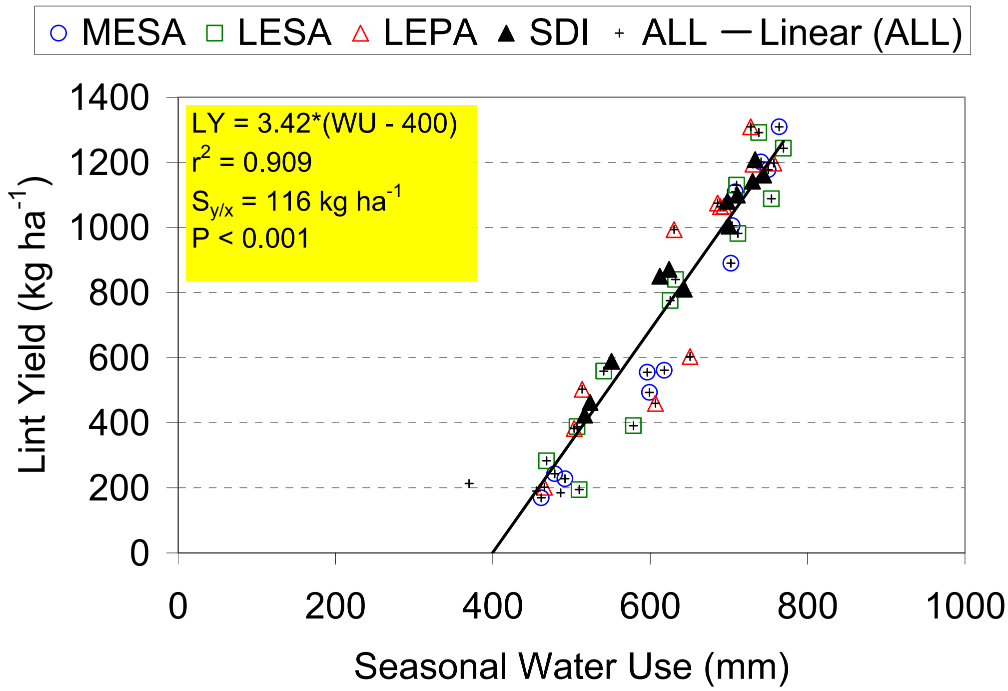

Figure 2. Cotton lint yield response (LY) to seasonal water use (WU) for the 2003 season, and coefficient of determination (r^2), standard error of the estimate ($S_{y/x}$), and significance (P).

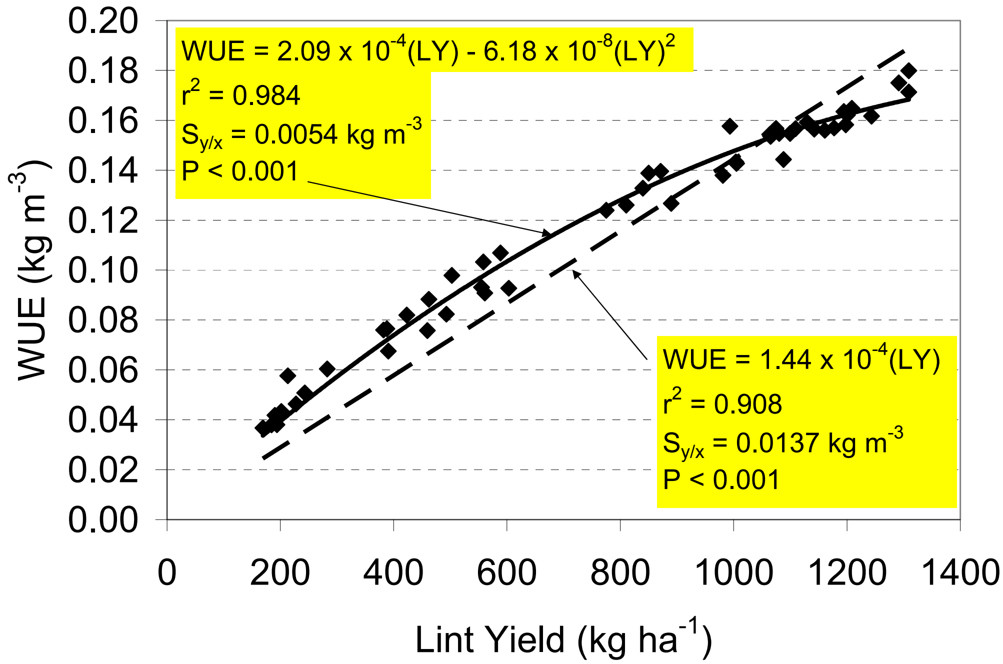

Figure 3. Water use efficiency (WUE) response to lint yield (LY) for the 2003 season, and coefficient of determination (r^2), standard error of the estimate ($S_{y/x}$), and significance (P).

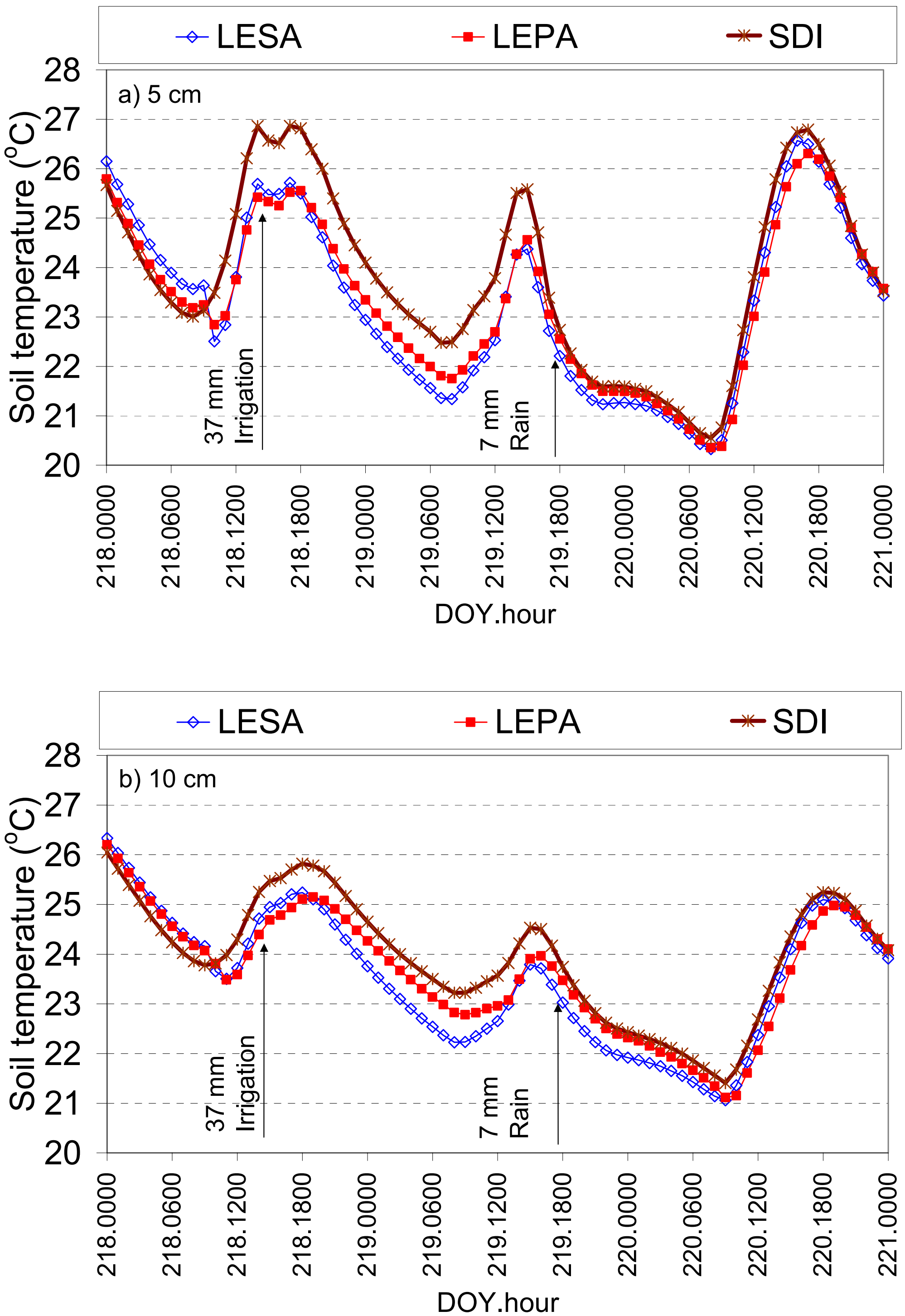

Figure 4. Soil temperature during August 5, 6, and 7, 2004 (DOY 218, 219, and 220) for I_{100} plots at (a) 5 cm, and (b) 10 cm below the surface.

Table 2. Accumulated heat units during August 5, 6, and 7, 2004 (DOY 218, 219, and 220) based on soil temperatures using a base temperature of 15.6 °C. The accumulated heat units based on air temperature was 20.4 °C for this period.

Irrigation Level	Irrigation Method	Soil temp 5 cm °C	Soil temp 10 cm °C
I_{50}	LESA	24.2	25.1
I_{50}	LEPA	24.8	25.3
I_{50}	SDI	25.2	25.9
I_{100}	LESA	23.0	23.7
I_{100}	LEPA	23.2	24.1
I_{100}	SDI	24.8	25.1

COMPARISON OF SDI AND SIMULATED LEPA SPRINKLER IRRIGATION FOR CORN

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ABSTRACT

A seven-year field study (1998-2004) was conducted to compare simulated low energy precision application (LEPA) with sprinkler irrigation to subsurface drip irrigation (SDI) for field corn production on the deep silt loam soils of western Kansas. Averaged over the seven-year period there was very little difference in corn grain yields between system type (235 and 233 bushels/acre for LEPA and SDI, respectively) across all comparable irrigation capacities. However, LEPA had higher grain yields for 4 extreme drought years (approximately 15 bushels/acre) and SDI had higher yields in 3 normal to wetter years (approximately 15 bushels/acre). Higher LEPA yields were associated with higher kernels/ear as compared to SDI (534 vs. 493 kernels/ear in dry years). Higher SDI yields were associated with higher kernel weight at harvest as compared to LEPA (34.7 vs. 33.2 grams/100 kernels in normal to wetter years). Seasonal water use was approximately 4% higher with LEPA than SDI and was associated with the period from anthesis to physiological maturity.

INTRODUCTION

LEPA and other in-canopy center pivot sprinkler irrigation systems have been in use in Kansas since the 1980s. Adoption and successfulness of these systems is somewhat dependant on soils, topography and management. The potential for the widespread usage of SDI for corn production in Kansas remains a debatable topic. Yet, there is a large amount of interest in its potential in western Kansas, where water resources are declining. It is estimated there is 12000 to 15000 SDI acres in western Kansas. No statistically valid, scientific data exists that directly compares corn production under LEPA center pivot sprinkler and SDI systems. The scale and operating logistics of these systems make replicated studies difficult and/or expensive to conduct. This paper describes research where the LEPA application is closely simulated on an SDI study site to help provide statistically valid data.

PROCEDURES

This experiment was conducted at the Kansas State University Northwest Research-Extension Center at Colby, Kansas, USA during the period 1998-2004.

The deep Keith silt loam soil can supply about 17.5 inches of available soil water for an 8 foot soil profile. The climate can be described as semi-arid with a summer precipitation pattern with an annual rainfall of approximately 19 inches. Average precipitation is approximately 12 inches during the 120-day corn growing season.

The seven treatments were simulated LEPA sprinkler irrigation with capacities of 1 inch every 4, 6 or 8 days and subsurface drip irrigation (SDI) with capacities 0.25, 0.17, 0.13 or 0.10 inch/day. Each treatment was replicated three times in a complete randomized block design in the North to South direction. Total plot length was 289 ft with the LEPA sprinkler irrigation being simulated in the first 81 ft of the plot length. All plot cultural practices, sampling, and data collection for both the LEPA and SDI plots were conducted in this 81 ft segment with the remaining length serving as a buffer from south winds. Plot width was eight corn rows spaced 2.5 ft apart (20 ft).

The study utilized an SDI system installed in 1989. The dual-chamber thin-walled collapsible dripline was installed at a depth of approximately 16-18 inches with a 5-ft. spacing between dripline laterals. Emitter spacing was 12 inches and the dripline flowrate was 0.25 gpm/100 ft. The corn was planted so that each dripline lateral was centered between two corn rows (Figure 1). Each plot was instrumented with a municipal-type flowmeter to record total accumulated flow. Mainline pressure entering the driplines was first standardized to 20 psi with a pressure regulator and then further reduced with a throttling valve to the nominal flowrate of 2.89 gpm/plot, coinciding with an operating pressure of approximately 10 psi.

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

The SDI system was disconnected for the plots associated LEPA treatments during the season to prevent any water application by SDI. The simulated LEPA treatments were accomplished by setting up a surface PVC pipe down the 81 ft length with pressure regulated flow dividers for each 30 ft increment. Each flow divider (Figure 2) had 9 equal length supply tubes (0.25 inches ID) delivering water to 9 individual furrow basins. Furrow basins were approximately 9 ft in length and were constructed in the furrows. The amount of water necessary to apply the one-inch application to the LEPA plots was calculated from the number of flow dividers and supply tubes in relation to the land area covered (3 flow dividers with 9 tubes each covering 81 ft of plots and 15 ft of width [3 furrow basins]). The application rate of the simulated LEPA irrigation treatments was approximately 1.5 in/hour which would nearly match the application rate of typical LEPA irrigation in the region. Furrow basins were used to retain applied water until it could infiltrate into the soil. Furrow basins are an integral part of the LEPA system and practices.

Figure 2. Flow divider used to supply water to 9 individual furrow basins for the purpose of simulating LEPA sprinkler irrigation.

Irrigation was scheduled for the studies using a water budget to calculate the root zone depletion with precipitation and irrigation water amounts as deposits and calculated daily water use by corn as a withdrawal. Irrigation was scheduled when the calculated root-zone depletion was in the range of 1 to 1.5 inches. However, irrigation was limited to the capacities imposed by the irrigation treatments. Irrigation amounts were fixed for the LEPA treatments at 1 inch and thus frequency of irrigation treatments varied with the irrigation capacity. Irrigation frequency for the SDI treatments was fixed at a daily interval and thus the irrigation capacity fixed the amount of irrigation. Soil water amounts were monitored with a neutron probe in 12 inch increments to a depth of 8 ft approximately once a week during each crop season, but were not used to update the irrigation schedule.

A ridge-till system was used in corn production with two corn rows, 30 inches apart on a 5 ft. bed. The corn was grown with the conventional production practices for each location. Tractor traffic was confined to the furrows. Pioneer hybrid 3162 seed corn was used in 1998 -2003 and Pioneer hybrid 32B33 in 2004. These hybrids are full season hybrid for the region with an approximately 118 day comparative relative maturity requirement. Pest (weeds and insects) control was accomplished with standard practices for the region. In the years 1999-2001 nitrogen fertilizer was applied to the study area with approximately 180-200 lbs N/acre in an early preplant application. In 2002, the nitrogen fertilization scheme was changed to apply 75 lbs N/acre early preplant and an additional 100 lbs N/acre through fertigation in late June or early July each year. A starter fertilizer application at planting banded an additional 30 lbs N/acre and 45 lbs P_20_5/acre. These fertilizer rates can be described as non-limiting for high corn yields. Agronomic practices are summarized in Table 1.

Table 1. Agronomic information from a LEPA-SDI study for corn.
KSU Northwest Research-Extension Center, Colby, Kansas, 1998-2004.

	Year						
Agronomic parameter	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Corn hybrid (Pioneer brand no.)	3162	3162	3162	3162	3162	3162	32B33
Seeding plant population (p/a)	32000	32000	28000	34000	34000	34000	36000
Planting date	30-Apr	9-May	27-Apr	30-Apr	30-Apr	30-Apr	28-Apr
Emergence date	15-May	21-May	8-May	13-May	13-May	13-May	10-May
N-Source was UAN 32-0-0 and AP 10-34-0							
P-Source was AP 10-34-0							
Preplant N fertilizer (lb/a)	200	200	180	200	75	75	75
Banded N at planting (lb/a)	30	30	30	30	30	30	30
Banded P at planting (lb/a)	45	45	45	45	45	45	45
Inseason N fertigation (lb/a)	-	-	-	-	100	100	100
Fertigation date	-	-	-	-	27-Jun & 10-Jul	23-Jun	28-Jun
Initial soil water measurement date	22-May	13-May	8-May	14-May	13-May	13-May	11-May
Final soil water measurement date	29-Sep	30-Sep	18-Sep	27-Sep	30-Sep	17-Sep	24-Sep
Hand-harvest date at physiological maturity	29-Sep	11-Oct	18-Sep	27-Sep	30-Sep	18-Sep	24-Sep

Corn production data collected during the growing season included irrigation and precipitation amounts, weather data, yield components (yield, harvest plant population, ears/plant, kernels/ear, mass/100 kernels), and periodic soil water content. Weather data were collected with an automated weather station approximately 0.5 mile from the research site. Values calculated after final data collection included seasonal water use and water use efficiency. Water use was calculated as the change in soil water between the initial and final dates, plus any irrigation and rainfall. Calculation of water use in this way can include deep percolation if it exists and also runoff and runon. In this region, deep percolation losses usually occur only in the early part of the season when cumulative precipitation exceeds evapotranspiration. Furrow basins and the low land slope (<0.5%) reduced the chances for runoff and runon.

RESULTS AND DISCUSSION

Weather Conditions

Briefly, the weather conditions can be specified as normal to wetter than normal in 1998, 1999, and 2004 and excessively dry in 2000-2003. Precipitation during the cropping season was 12.71, 17.60, 6.18, 9.26, 9.61, 9.12 and 12.65 inches for the respective years, 1998-2004. Calculated evapotranspiration for a standard 120-day period May 15-September 11) was slightly below normal in 1998 and 1999 (21.26 and 21.64 inches), above normal at 27.48, 26.28, 27.68 and 25.96 inches for the years 2000-2003, respectively, and about normal in 2004 (23.08 inches). The years 2000-2003 can be considered extreme drought years and summer dryland crops in the region generally failed.

Corn Grain Yield

Corn yields were generally high in all seven years ranging from 196 to 278 bushels for the highest irrigation capacities (1 inch/4 days or 0.25 inches/day) (Table 2.) There were significant yield differences due to irrigation capacity in each of the drought years (2000-2004) and there were smaller numerical differences in yields in the wetter years (1998, 1999, and 2003) with higher capacities resulting in higher grain yields. Averaged over the seven year period there were no statistically significant differences in yields between LEPA and SDI for equivalent irrigation capacities. However there were statistical differences and/or numerical trends that varied by system type across years. In general, the SDI treatments had higher numerical yields in the normal and wetter years and the LEPA had higher statistical yields in the extreme drought years. A statistical analysis of the 3 normal and wet years separately showed an approximately 14 bushels/acre advantage for SDI over LEPA irrigation. The same analysis procedure for the 4 extreme drought years gave LEPA a 15 bushel/acre advantage. The difference in system types between years was unanticipated and remains unexplained. In the course of conducting this experiment it became apparent that system type was affecting grain yields particularly in the extreme drought years. It was hypothesized that the surface-applied nitrogen fertilizer was becoming positionally unavailable for the SDI treatments. Indeed there were some informal visual observations of N-stress in some of the SDI plots in 2000 and 2001. In 2002, the fertilization scheme was adjusted to apply both a preplant surface amount and an inseason fertigation amount (Table 1). This adjustment did not remove the yield differences between irrigation system types in the continuing drought years of 2002 and 2003.

Table 2. Summary of corn yield components and water use data from LEPA-SDI study. KSU Northwest Research-Extension Center, Colby, Kansas, 1998-2004.

System type and Irrigation capacity	*Corn plant population at harvest, 1000 plants/acre* 1998	1999	2000	2001	2002	2003	2004	All years	Wet years[1]	Dry years[2]
LEPA, 1in/4 days	31.7	30.2	27.0	34.4	33.4	34.0	36.3	32.4	32.7	32.2
LEPA, 1in/6 days	32.2	30.5	27.7	35.1	33.8	33.4	36.0	32.7	32.9	32.5
LEPA, 1in/8 days	31.1	31.1	26.7	33.8	32.2	34.0	36.0	32.1	32.7	31.7
SDI, 0.25 in/day	32.2	31.1	27.0	34.0	33.5	34.6	35.7	32.6	33.0	32.3
SDI, 0.17 in/day	31.9	30.8	27.3	33.4	33.5	34.0	36.9	32.5	33.2	32.1
SDI, 0.13 in/day	32.5	32.5	27.3	33.7	33.5	34.0	35.7	32.8	33.6	32.1
SDI, 0.10 in/day	31.9	32.2	27.6	33.1	32.5	33.4	36.3	32.4	33.5	31.7
Mean	31.9	31.2	27.2	33.9	33.2	33.9	36.1	32.5	33.1	32.1
$LSD_{0.05}$	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

System type and Irrigation capacity	*Corn ears/plant* 1998	1999	2000	2001	2002	2003	2004	All years	Wet years	Dry years
LEPA, 1in/4 days	0.99	1.00	1.01	0.98	0.98	1.00	0.98	0.99 a	0.99	0.99
LEPA, 1in/6 days	1.00	0.98	0.99	0.99	0.96	1.00	0.98	0.99 a	0.99	0.99
LEPA, 1in/8 days	0.99	0.99	1.00	0.97	0.96	0.98	0.98	0.98 ab	0.99	0.98
SDI, 0.25 in/day	0.98	1.00	1.00	0.99	0.98	0.99	0.99	0.99 a	0.99	0.99
SDI, 0.17 in/day	0.98	1.01	1.00	0.99	0.97	1.00	0.97	0.99 a	0.99	0.99
SDI, 0.13 in/day	0.98	0.99	1.01	0.97	0.95	0.95	0.97	0.97 b	0.98	0.97
SDI, 0.10 in/day	0.99	0.98	0.99	0.97	0.93	0.94	0.99	0.97 b	0.99	0.96
Mean	0.99	0.99	1.00	0.98	0.96	0.98	0.98	0.98 ab	0.99	0.98
$LSD_{0.05}$	NS	NS	NS	NS	NS	NS	NS	0.01	NS	NS

System type and Irrigation capacity	*Corn kernels/ear* 1998	1999	2000	2001	2002	2003	2004	All years	Wet years	Dry years
LEPA, 1in/4 days	568	630 a	539 a	594 a	493 a	629 a	569	575 a	589	564 a
LEPA, 1in/6 days	566	612 a	541 a	540 b	475 a	558 b	565	551 b	581	529 b
LEPA, 1in/8 days	621	612 a	536 a	528 b	445 ab	521 b	576	548 b	603	508 bc
SDI, 0.25 in/day	590	601 ab	542 a	541 b	453 ab	579 a	579	555 ab	590	529 b
SDI, 0.17 in/day	580	632 a	486 b	526 b	415 ab	545 b	584	538 b	599	493 c
SDI, 0.13 in/day	606	559 bc	470 b	474 c	385 b	501 b	585	511 c	583	458 d
SDI, 0.10 in/day	612	544 c	469 bc	449 c	336 b	394 c	542	478 d	566	412 e
Mean	592	599	512	521	429	532	571	537	587	499
$LSD_{0.05}$	NS	43	42	45	86	84	NS	22	NS	35

System type and Irrigation capacity	*100 Corn kernel weight, grams* 1998	1999	2000	2001	2002	2003	2004	All years	Wet years	Dry years
LEPA, 1in/4 days	35.1 bc	34.8	41.5 a	34.9	36.9	26.2 bc	30.7	34.3 b	33.5 bc	34.9
LEPA, 1in/6 days	34.8 bc	35.1	39.1 ab	33.7	36.2	29.3 a	30.5	34.1 bc	33.5 bc	34.6
LEPA, 1in/8 days	33.5 c	34.3	36.7 b	34.6	36.1	26.6 bc	30.3	33.2 bc	32.7 c	33.5
SDI, 0.25 in/day	37.8 a	35.8	42.1 a	34.7	38.1	25.1 c	33.9	35.4 a	35.9 a	35.0
SDI, 0.17 in/day	36.4 b	34.0	42.1 a	34.3	37.5	26.5 bc	32.2	34.7 a	34.2 b	35.1
SDI, 0.13 in/day	35.3 b	36.1	40.5 a	33.9	36.3	26.5 bc	30.1	34.1 bc	33.9 b	34.3
SDI, 0.10 in/day	35.6 b	34.1	36.3 b	33.3	35.5	27.0 bc	30.0	33.1 c	33.2 bc	33.0
Mean	35.5 b	34.9	39.7	34.2	36.6	26.7	31.1	34.1	33.8	34.3
$LSD_{0.05}$	1.8	NS	3.7	NS	NS	2.0	NS	1.1	1.2	NS

System type and Irrigation capacity	***Corn grain yield, bushels/acre*** **1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**All years**	**Wet years**	**Dry years**
LEPA, 1in/4 days	246	260	239 a	275 a	234 a	221 a	246	246 a	251 bc	242 a
LEPA, 1in/6 days	250	252	230 ab	249 b	219 a	215 a	239	236 b	247 bc	228 b
LEPA, 1in/8 days	252	254	206 c	235 b	194 b	182 ab	242	224 c	249 bc	204 c
SDI, 0.25 in/day	278	263	242 a	248 b	222 a	196 ab	274	246 a	272 a	227 b
SDI, 0.17 in/day	261	263	219 bc	235 b	198 b	194 ab	265	234 b	263 a	212 c
SDI, 0.13 in/day	268	256	206 c	207 c	176 b	172 b	240	218 c	255 bc	190 d
SDI, 0.10 in/day	271	231	184 d	190 c	140 c	132 c	229	197 d	244 c	161 e
Mean	261	254	218	234	197	187	248	229	254	209
LSD $_{0.05}$	NS	NS	17	22	25	41	NS	8	12	12

System type and Irrigation capacity	***Total seasonal irrigation amount, inches*** **1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**All years**	**Wet years**	**Dry years**
LEPA, 1in/4 days	11.0	12.0	18.0	19.0	18.0	17.0	12.0	15.3	11.7	18.0
LEPA, 1in/6 days	10.0	9.0	15.0	14.0	14.0	13.0	10.0	12.1	9.7	14.0
LEPA, 1in/8 days	9.0	8.0	12.0	11.0	11.0	10.0	8.0	9.9	8.3	11.0
SDI, 0.25 in/day	11.0	10.3	18.0	18.5	18.0	17.0	12.0	15.0	11.1	17.9
SDI, 0.17 in/day	8.8	8.3	15.5	13.9	13.8	12.9	10.0	11.9	9.1	14.0
SDI, 0.13 in/day	7.2	6.5	11.8	10.9	10.5	9.9	8.1	9.3	7.2	10.8
SDI, 0.10 in/day	5.6	5.1	9.1	8.4	8.1	7.6	6.2	7.2	5.6	8.3
Mean	8.9	8.5	14.2	13.7	13.3	12.5	9.5	11.5	9.0	13.4

System type and Irrigation capacity	***Total seasonal water use, inches*** **1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**All years**	**Wet years**	**Dry years**
LEPA, 1in/4 days	28.5 a	32.4 a	28.2 a	32.6 a	31.6 a	29.3 a	28.3 a	30.1 a	29.7 a	30.4 a
LEPA, 1in/6 days	26.8 bc	29.9 bc	26.2 b	29.4 c	29.0 b	28.3 ab	27.1 a	28.1 bc	27.9 b	28.2 b
LEPA, 1in/8 days	26.4 bc	30.0 bc	24.0 cd	28.5 c	26.4 d	25.4 c	25.6 bc	26.6 d	27.3 bc	26.1 d
SDI, 0.25 in/day	27.0 b	31.0 b	25.7 bc	30.9 b	29.9 b	28.6 ab	27.0 ab	28.6 b	28.3 b	28.7 b
SDI, 0.17 in/day	25.6 cd	29.4 cd	25.2 b	28.8 c	27.9 c	27.6 b	26.2 bc	27.3 c	27.1 c	27.4 c
SDI, 0.13 in/day	24.8 d	28.4 d	23.6 d	27.1 d	25.6 d	25.4 c	24.9 c	25.7 e	26.0 d	25.4 e
SDI, 0.10 in/day	23.3 e	29.0 cd	20.3 e	24.3 e	23.8 e	23.9 c	23.1 d	24.0 f	25.1 e	23.1 f
Mean	26.1	30.0	24.7	28.8	27.7	26.9	26.0	27.2	27.4	27.1
LSD $_{0.05}$	1.3	1.1	1.6	1.2	1.1	1.7	1.7	0.6	0.8	0.6

System type and Irrigation capacity	***Seasonal water use until anthesis, inches*** **1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**All years**	**Wet years**	**Dry years**
LEPA, 1in/4 days	13.0 a	14.5 a	10.1 a	14.9 a	15.0 a	15.9	11.4	13.5 a	13.0 a	14.0 a
LEPA, 1in/6 days	12.1 bc	13.1 b	8.9 b	14.3 ab	14.2 a	16.0	11.1	12.8 b	12.1 b	13.4 b
LEPA, 1in/8 days	12.2 abc	13.5 ab	9.1 ab	14.6 a	13.0 c	15.3	10.5	12.6 b	12.0 b	13.0 b
SDI, 0.25 in/day	12.9 a	14.6 a	10.0 a	14.1 ab	14.0 b	16.1	11.3	13.3 a	12.9 a	13.5 ab
SDI, 0.17 in/day	12.4 ab	13.7 a	9.0 ab	13.4 bc	14.1 a	16.2	10.7	12.8 b	12.3 b	13.2 b
SDI, 0.13 in/day	11.5 c	12.8 b	8.5 bc	13.4 bc	12.3 c	15.1	10.5	12.0 c	11.6 c	12.3 c
SDI, 0.10 in/day	11.3 c	13.8 a	7.6 c	12.9 c	12.6 c	15.0	10.2	11.9 c	11.7 bc	12.0 c
Mean	12.2	13.7	9.0	14.0	13.6	15.6	10.8	12.7	12.2	13.1
LSD $_{0.05}$	0.9	1.1	1.2	1.2	1.0	NS	NS	0.5	0.7	0.6

System type and Irrigation capacity	***Seasonal water use after anthesis, inches*** 1998	1999	2000	2001	2002	2003	2004	**All years**	**Wet years**	**Dry years**
LEPA, 1in/4 days	15.5 a	17.9 a	18.1 a	17.8 a	16.6 a	13.4 a	16.8 a	16.6 a	16.8 a	16.5 a
LEPA, 1in/6 days	14.7 b	16.7 b	17.4 a	15.1 c	14.8 b	12.3 ab	16.0 a	15.3 b	15.8 b	14.9 bc
LEPA, 1in/8 days	14.3 b	16.6 b	14.9 c	13.9 d	13.4 bc	10.1 cd	15.1 b	14.0 cd	15.3 c	13.1 d
SDI, 0.25 in/day	14.1 b	16.4 b	15.7 bc	16.7 b	15.8 a	12.5 ab	15.7 ab	15.3 b	15.4 bc	15.2 b
SDI, 0.17 in/day	13.3 c	15.7 c	16.3 b	15.4 c	13.8 bc	11.4 bc	15.5 ab	14.5 c	14.8 d	14.2 c
SDI, 0.13 in/day	13.4 c	15.6 c	15.1 c	13.6 d	13.2 c	10.3 cd	14.5 b	13.7 d	14.5 d	13.1 d
SDI, 0.10 in/day	12.0 d	15.3 c	12.7 d	11.4 e	11.2 d	8.8 d	12.9 c	12.0 e	13.4 e	11.0 e
Mean	13.9	16.3	15.7	14.8	14.1	11.3	15.2	14.5	15.1	14.0
$LSD_{0.05}$	0.7	0.7	1.1	0.8	1.6	1.7	1.5	0.6	0.5	0.8

System type and Irrigation capacity	***Seasonal water use efficiency, lbs./acre-inch*** 1998	1999	2000	2001	2002	2003	2004	**All years**	**Wet years**	**Dry years**
LEPA, 1in/4 days	484 d	451	474	472	414 a	422	488	458	474 c	446 a
LEPA, 1in/6 days	523 cd	475	490	475	423 a	425	494	472	497 bc	453 a
LEPA, 1in/8 days	534 cd	474	484	462	413 a	403	530	471	513 b	441 ab
SDI, 0.25 in/day	577 bc	476	527	450	416 a	384	569	486	541 ab	444 a
SDI, 0.17 in/day	570 bc	502	488	456	398 a	393	566	482	546 a	434 ab
SDI, 0.13 in/day	606 ab	507	488	427	385 a	373	539	475	551 a	418 b
SDI, 0.10 in/day	651 a	446	506	437	330 b	309	558	462	552 a	396 b
Mean	564	476	494	454	397	387	535	472	525	433
$LSD_{0.05}$	59	NS	NS	NS	51	NS	NS	NS	33	25

System type and Irrigation capacity	***Available soil water at anthesis, inches/8 ft profile*** 1998	1999	2000	2001	2002	2003	2004	**All years**	**Wet years**	**Dry years**
LEPA, 1in/4 days	12.9	12.1 a	10.7 a	9.1 ab	8.7 ab	9.4	10.5	10.5 a	11.8 a	9.5 a
LEPA, 1in/6 days	12.6	12.9 a	9.9 a	8.2 bc	6.3 cd	8.2	10.3	9.8 a	11.9 a	8.2 b
LEPA, 1in/8 days	11.6	12.3 a	8.1 bc	6.6 d	6.6 cd	7.1	10.9	9.0 c	11.6 a	7.1 cd
SDI, 0.25 in/day	11.8	11.7 a	10.3 ab	9.7 a	9.2 a	9.2	11.0	10.4 a	11.5 a	9.6 a
SDI, 0.17 in/day	11.8	12.2 a	10.3 ab	8.1 bc	7.4 bc	7.5	9.9	9.6 bc	11.3 a	8.3 b
SDI, 0.13 in/day	11.8	12.0 a	9.0 b	7.8 cd	7.2 c	7.7	10.1	9.4 bc	11.3 a	7.9 bc
SDI, 0.10 in/day	11.1	9.6 b	7.2 c	6.6 d	5.2 d	6.6	9.6	8.0 d	10.1 b	6.4 d
Mean	11.9	11.8	9.3	8.0	7.2	8.0	10.3	9.5	11.4	8.1
$LSD_{0.05}$	NS	1.4	1.5	1.3	1.5	NS	NS	0.8	1.0	1.0

System type and Irrigation capacity	***Available soil water at maturity, inches/8 ft profile*** 1998	1999	2000	2001	2002	2003	2004	All years	Wet years	Dry years
LEPA, 1in/4 days	8.6	9.4 a	6.4 bc	9.6 b	6.7 b	10.0 a	7.8 a	8.3 b	8.6 a	8.2 b
LEPA, 1in/6 days	10.1	9.4 a	5.4 c	8.3 bc	5.1 cd	6.9 b	7.4 a	7.5 cd	9.0 a	6.4 c
LEPA, 1in/8 days	8.7	7.9 b	4.0 cd	5.9 d	4.8 cd	6.0 b	6.9 b	6.3 e	7.8 bc	5.2 d
SDI, 0.25 in/day	9.7	9.5 a	8.9 a	11.1 a	7.9 a	10.7 a	9.4 a	9.6 a	9.5 a	9.7 a
SDI, 0.17 in/day	9.5	9.9 a	7.4 b	8.4 bc	6.8 b	7.6 b	7.5 a	8.2 bc	9.0 a	7.6 b
SDI, 0.13 in/day	8.7	8.7 ab	5.0 cd	7.9 c	5.4 c	6.9 b	7.2 b	7.1 d	8.2 b	6.3 c
SDI, 0.10 in/day	8.4	5.6 c	3.9 d	7.4 c	4.1 d	5.8 b	6.8 b	6.0 e	6.9 c	5.3 d
Mean	9.1	8.6	5.9	8.4	5.8	7.7	7.6	7.6	8.4	6.9
$LSD_{0.05}$	NS	1.3	1.5	1.5	1.1	2.0	2.2	0.8	1.2	0.8

[1] *Normal to wetter years were 1998, 1999 and 2004.*

[2] *Dry years were extreme drought years from 2000 to 2003.*

These yield differences in performance of system type across years and weather conditions (Figure 3) are important to note because it may be possible to adjust irrigation management to remove the differences. Subsequent discussion that follows below will indicate some of the possible reasons for the yield differences.

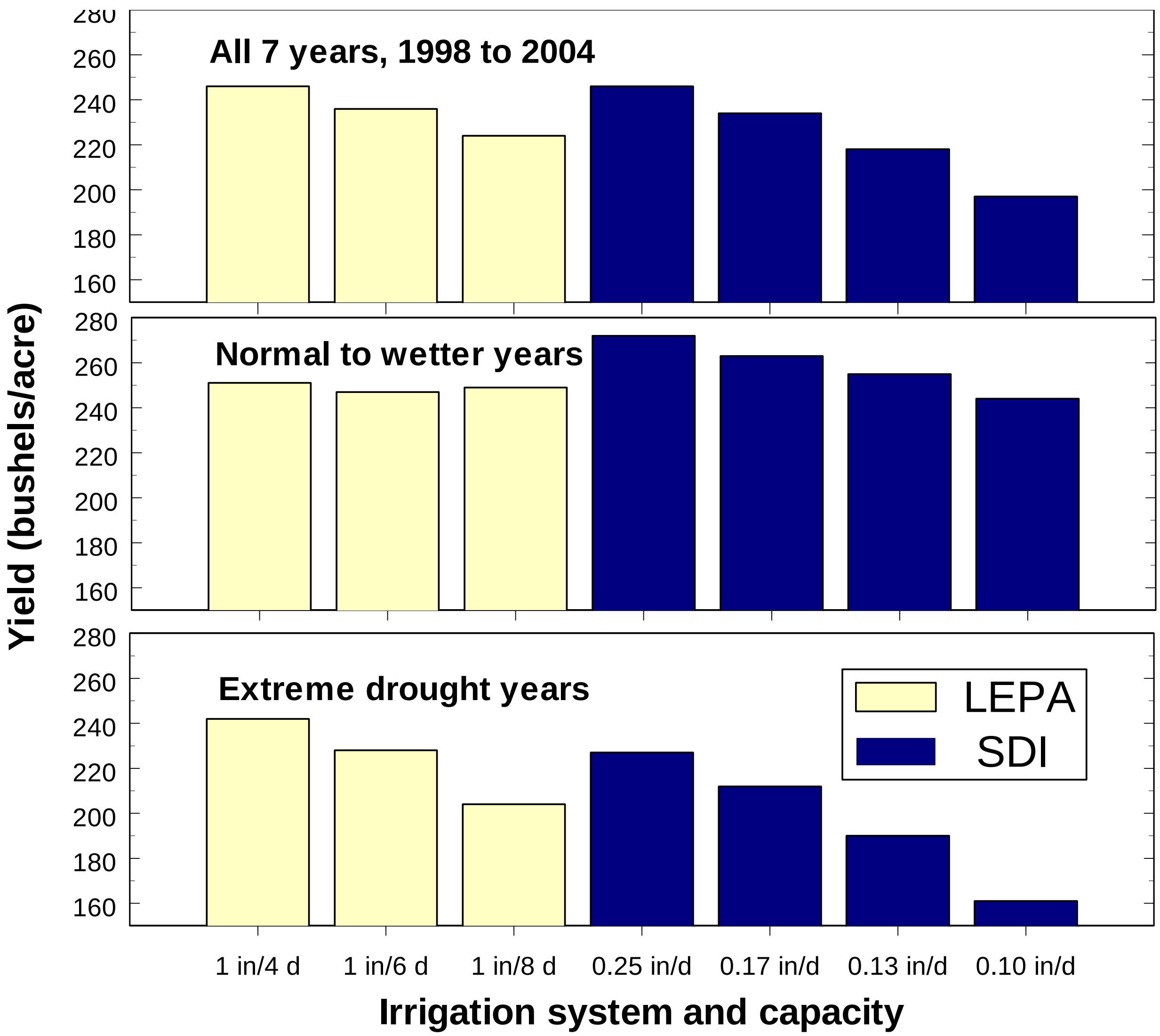

Figure 3. Variation in corn yields across years and weather conditions as affected by irrigation system type and capacity, KSU Northwest Research-Extension Center, Colby Kansas.

Corn Yield Components

Although plant population varied between years from approximately 27000 to 36000 plants/acre (Table 1 and 2) there were no significant differences in harvest plant population within a given year related to treatment. This would be as anticipated. Similarly there was very little difference in the number of ears/plant across years averaging approximately 0.98 ears/plant (Table 2). When averaged across all 7 years, there was a slight decrease from 0.99 to 0.97 ears/plant as irrigation capacity decreased.

There were generally statistical differences or numerical trends in the number of kernels/ear related to irrigation system type and capacity (Table 2). In the normal and wetter years there was generally no statistical difference in the kernels/ear with decreases occurring only with decreases in irrigation capacity in 1999. However, in the extreme drought years, for a given irrigation capacity, LEPA had an approximately 41 kernels/ear advantage. Although the potential number of kernels/ear is determined by hybrid genetics and early growth before anthesis, the actual number of kernels is usually set in a 2-3 week period centering around anthesis. Water and nitrogen availability and hormonal signals are key factors in determining the actual number of kernels/ear. The adjustment of splitting the fertilizer applications to both preplant and inseason in 2002 did not remove the differences in kernels/ear between irrigation system types. Soil water and water use differences will be discussed in a latter section. Hormonal signals sent by the roots may have been different for the SDI treatments in the drought years because SDI may have had a more limited root system.

Kernel weight was statistically higher for higher irrigation capacity in 3 of the 7 years and was numerically higher in additional years. Averaged over the 7 years, for a given irrigation capacity, SDI generally had higher kernel weight and in the normal and wetter years this higher kernel weight was approximately 1.5 grams/100 kernels which resulted in the approximately 14 bushels/acre yield advantage. The number of kernels/ear was not statistically different during these normal and wetter years, so this higher kernel weight for SDI must be reflecting better grain filling conditions for this system type. Grain filling is regulated by general water availability and weather conditions favoring good photosynthesis, so it is somewhat surprising that irrigation system type had an effect in the normal and wetter years but not much effect in the dry years.

Water Use and Water Use Efficiency

Irrigation amount varied with irrigation capacity (Table 2), so it is not surprising to see that total seasonal water use was statistically different with irrigation capacity in all 7 years. There were also statistical differences in total seasonal water use between LEPA and SDI in most years with LEPA using higher amounts. It was initially thought that these differences might be related to higher irrigation efficiencies with SDI compared to LEPA, since total seasonal irrigation amounts were relatively similar. However, when examined in light of the grain yield differences, it appears the differences might be more related to an unexplained reduced transpiration from the SDI plots. This might be further supported by the similarity in water use efficiencies (WUE) for the higher two irrigation capacities in the drought years. Although grain yields were higher for LEPA in these years, the similarity in WUE suggests that SDI obtained the same yield for a given amount of water use. Water use efficiency was seldom affected by irrigation system type in the 7 years but was affected by irrigation capacity in two years. In 1998, a wetter year, WUE was lowered by irrigation capacity and in 2002, an extreme drought year, higher irrigation capacity increased WUE. A partitioning of the corn water use into the periods of emergence to anthesis and anthesis to physiological maturity sheds more light on the irrigation system differences. Prior to anthesis, the results indicate the differences in water use are related only to irrigation capacity (Table 2), but after anthesis, the SDI treatments are utilizing less water. After anthesis, full crop canopies drastically limit the amount of soil evaporation, high crop water use limits the amount of deep percolation for well managed irrigation treatments and runoff from rainfall can be considered negligible with the furrow basins. Differences in water use by irrigation system type after anthesis were unanticipated and unexplained. The list of possible reasons would include smaller crop canopies with SDI which were not visually observed, smaller root systems with SDI that reduced transpiration, and possibly some hormonal adjustments that affected the stomatal control of transpiration.

Soil Water at Anthesis and Physiological Maturity

Water availability at anthesis can affect the actual number of kernels/ear. However, there were no statistical differences in soil water in the 8 foot profile at anthesis as related to irrigation system type (Table 2). An analysis of soil water data in the upper 3 foot of the profile did not indicate any system type differences either (data not shown). However, it should be noted that soil water measurements with the neutron attenuation method do not have a great amount of resolution of minute differences in the near surface layers. Additionally there could have been horizontal soil water distribution differences not revealed by the neutron attenuation method.

Soil water at maturity was statistically higher with SDI than LEPA (Table 2), once again reflecting the differences in water use that occurred during the period from anthesis to physiological maturity. It is possible that this higher level of soil water may have allowed better grain fill in the normal and wetter years, but a counter argument might be that grain fill was not affected by system type in the drier years though soil water still differed at maturity.

CONCLUSIONS

Corn yields were generally high under both simulated LEPA sprinkler irrigation and SDI. Both systems can be managed to give a high level of production and efficient water use.

There were consistent differences in corn production under the two system types as related to the climatic conditions. LEPA performed better in 4 extreme drought years primarily due to higher numbers of corn kernels/ear and SDI performed better in normal to wetter years primarily due to higher kernel weight at harvest. The reasons for these differences were unanticipated and remain unexplained. Further study is required that can hopefully explain the differences. It is possible, once the reasons for the differences are understood that appropriate managements strategies can be developed to optimize production under both system types. The severity of the drought might lead some to assume that SDI might have higher yields than LEPA under average conditions and the data could be used to suggest that. However, it would seem more important to gain an understanding of the reasons between the shifting of the yield components (kernels/ear and kernel weight) between systems as climatic conditions vary.

Water use was higher with LEPA systems in all years as calculated from changes in seasonal soil water amounts plus irrigation and rainfall. These differences were primarily during the period from anthesis to physiological maturity. This period under these study conditions (good irrigation management, good soils and low land slope) would not be typically associated with losses from non-benificial sources, such as deep percolation, soil evaporation and runoff and runon. This suggests that transpiration was less for the SDI during this period for some unknown reason.

[1] *Mention of tradenames is for informational purposes and does not constitute endorsement of the product by the authors or Kansas State University.*

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A New Method of Characterizing Sprinkler Distribution Patterns

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Procedures for characterizing sprinkler irrigation overlap patterns have progressed very little since J.E. Christiansen first formulated the uniformity coefficient (CU) in 1942. The fundamental weakness lies in the fact that the proposed evaluation parameters lack understandable physical significance. This leaves the quality of coverage to be judged by arbitrary standards defining what is acceptable or unacceptable. A serious consequence of this arbitrary evaluation procedure is that sprinklers are not sold on their actual ability to save water.

Any good sales representative knows all the arguments for selling against arbitrarily set uniformity coefficient standards. These arguments range from the effects of wind on a distribution pattern to how water is redistributed in thatch and the root zone. The issue may quickly become so confusing that the customer can no longer follow the logic. Unfortunately this can lead to products being sold on perception, price and minor features. Marketing efforts will use carefully chosen verbiage to develop the perception of improved uniformity. There is little incentive for a manufacturer to develop a product that truly has an ability to spread water more efficiently, particularly if it is more expensive.

What would be beneficial is a non-arbitrary evaluation procedure that is grounded in science and, most importantly, is easily understood. The framework for this proposed procedure is presented in this paper and in Figures 1 through 5. This effort was inspired by the author's work in developing of the testing protocol for "Climatologically-Based Controllers." This protocol requires the use of a run time multiplier and knowledge of sprinkler application efficiencies. Unfortunately, there is currently no hard science providing data on these two parameters. This paper then is a proposed method for filling that need.

Figure 1 is a plot of the overlapped distribution pattern for a representative pop-up spray head on 14 ft X 14 ft spacing. The experimental data can reasonably be represented by a straight line function (Y=1.454 - .00893 X, R^2 = 0.979). The d/mean values shown on the ordinate are dimensionless. The d is simply the amount of deposition in the catchment device (catch can). The mean is the average of all catchment values. The quality of the pattern is determined by quantifying its adequacy and efficiency. In this case, if the effective application is assumed to be the mean application, 11% of the root zone will be in deficit and the pattern loss will also be 11%. It is probable that leaving 11% of the root zone in deficit will have a noticeable effect on turf quality. Christiansen's uniformity coefficient for this pattern would be approximately 70%.

Figure 2 shows the pattern with the effective application reduced to 83% of the mean. This has the effect of reducing the deficit to 5% and increasing the pattern loss to 22%. The suggested 5% deficit value needs to be verified by field studies. However, if some general agreement is reached on this value, the pop-up's uniformity performance is effectively characterized by the resulting pattern loss of 22%.

Figure 3 is a plot of root zone deficit as a function of d/mean. The graph is useful in determining the d/mean value after the allowable deficit has been determined.

Figure 4 is a plot of pattern loss as a function of d/mean. Note particularly that if the deficit was eliminated, the pattern loss for this sprinkler would be 45%. For comparison purposes, the low quarter d/mean value for this pattern is 0.67 and the pattern loss is 34%. The low half d/mean value is 0.78 and the pattern loss is 25%. The deficits are 0.7% and 3.6% respectively.

Figure 5 is a plot of the overlapped distribution pattern for a representative pop-up spray head equipped with a Nelson MP 2000 Rotator on 14 ft X 14 ft spacing. Contrast Figure 1 to Figure 5 to get a sense of the value of uniformity. Using a d/mean value of 1.0 results in a deficit of only 1.8% (vs. 11%) and a pattern loss of 1.8% (vs. 11%). For practical purposes the pattern in Figure 5 is uniform.

The purpose of this paper is to demonstrate an analytical procedure that quantifies the effectiveness and efficiency of sprinkling devices. The patterns shown are real but for illustrative purposes only. With some general agreement on the allowable deficit, the sprinkling devices effectiveness is characterized by the pattern loss value. This characterization does not however address questions of operational and spray losses.

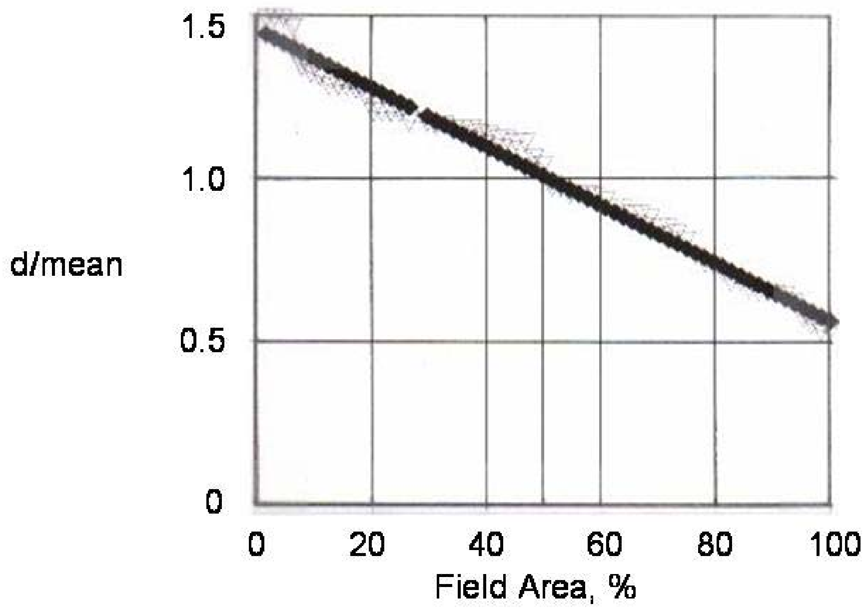

Figure 1. Overlapped distribution pattern for a popup spray head with a 15F (360°) nozzle at 30 psi (3.60 gpm) spaced 14 ft x 14 ft

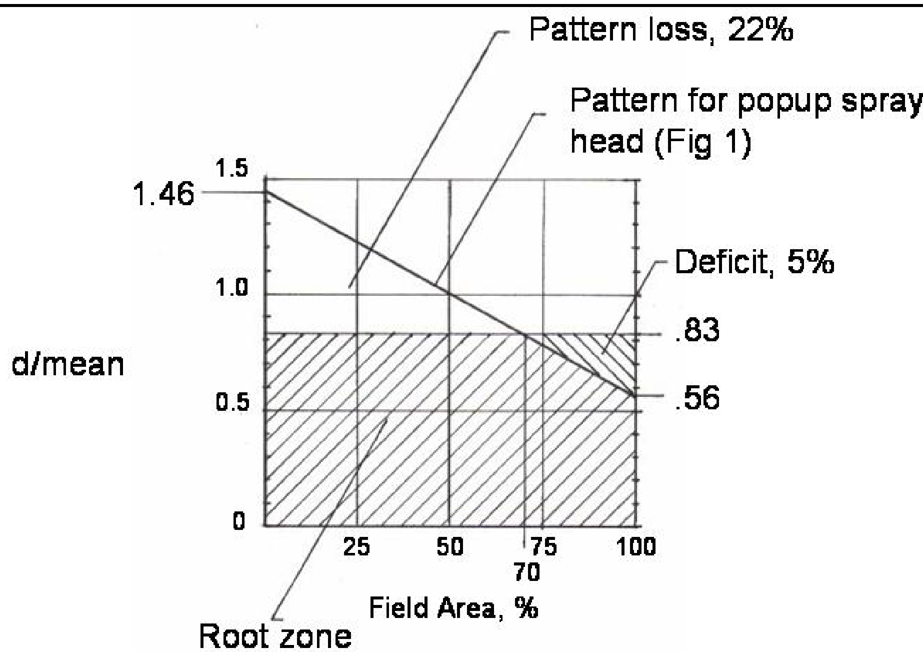

Figure 2. Definitions of proposed evaluation parameters

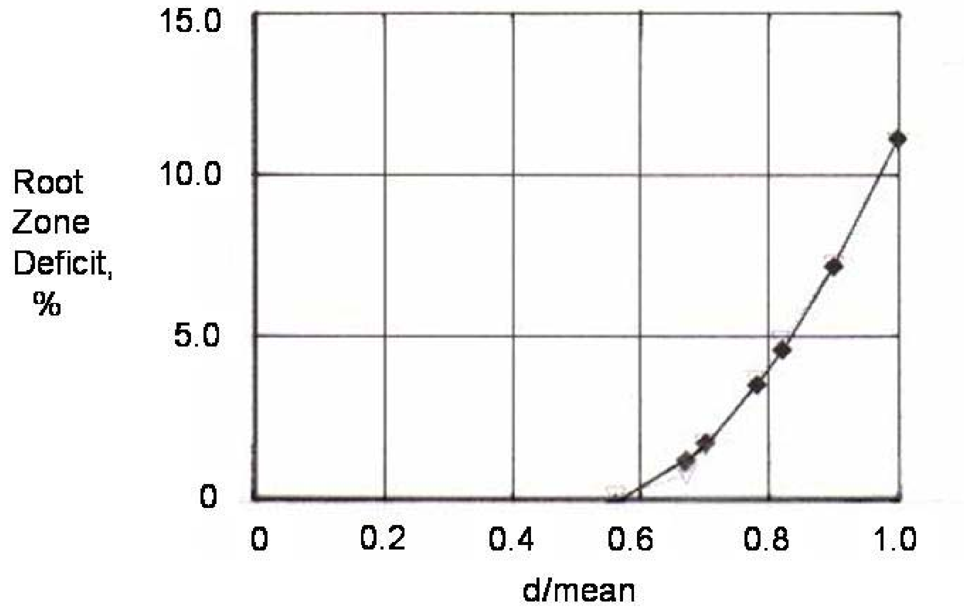

Figure 3. Root zone deficit as a function of d/mean

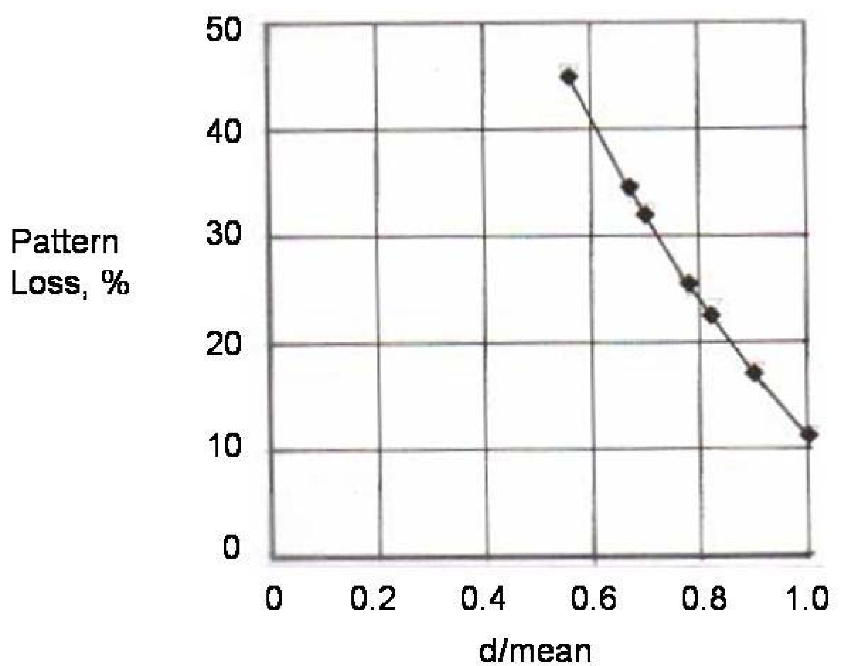

Figure 4. Pattern loss as a function of d/mean

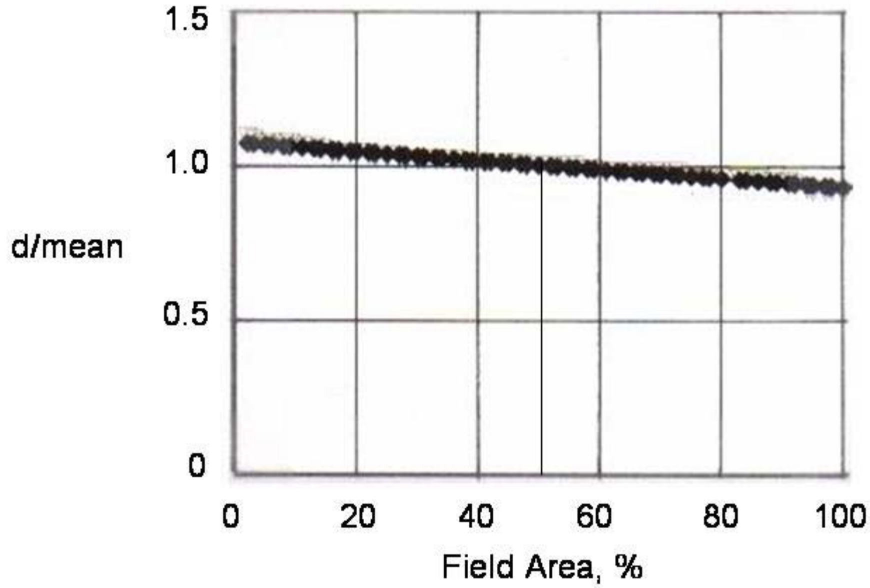

Figure 5. Overlapped distribution pattern for a popup spray head with a rotator (360°) at 30 psi (1.31 gpm) spaced 14 ft x 14 ft

Using Relative Humidity as a Control Parameter for Programming Supplemental Irrigation

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September, 2004

ABSTRACT:
The applicability of using relative humidity (RH) as a parameter for controlling supplemental irrigation of landscaping turf is explored. This economical water-saving technique is intended primarily for the small-plot irrigator. For the many western sites studied, the RH-controlled system is shown to be effective. For these sites internet databases often can provide the detailed weather information required for determining both the potential and the limitations of this irrigation-control approach. Strong correlation is demonstrated between accessed portions of the continuous RH trace and the daily evapotranspiration data that is generally accepted as the best indicator of plant-watering needs. Management of water application includes the quantity of water applied, the daily timing of the irrigation sequence, the length of the total irrigation cycle, the ideal time of day for measuring RH for the control parameter, and the differences of climatological zone types and local soil conditions. Different zone types may require different control strategies.

Using Relative Humidity as a Control Parameter for Supplemental Irrigation

Major Findings

Foremost, this study is based on the applicability of evapotranspiration (ET) data for determining supplemental irrigation requirements. A unique use of relative humidity (RH) as a control parameter for regulating scheduled supplemental irrigation produces the following results. The bases for these conclusions constitute the text of this report.

- **RH-controlled interruption of regular application of supplemental irrigation water significantly reduces excess watering for periods of low need while yet satisfying the extended dryer periods.**
- **RH control systems measure the ambient RH and compare it to a set value (RH set-point) above which normally scheduled irrigation is curtailed for that particular period (e.g. daily).**
- **Combining a matrix of ET data with selected weather parameters (RH and precipitation) for a moderately lengthy period provides a minimal database for evaluating the applicability of RH-controlled irrigation interruption.**
- **Year to year, dry-period ET values are more consistent (predictable) than "average" monthly rainfall.**
- **Most large western cities have local or nearby sites that provide the required ET and weather data for establishing RH-based control parameters.**
- **Generally predictable diurnal (24-hour) RH variation shows that the more stable periods over time for measuring RH are early morning (~maximum RH) and early afternoon (~minimum RH).**
- **For effective irrigation control, the selected RH parameter (e.g., maximum or minimum RH) must strongly correlate with the daily changes in ET and precipitation values, and also must have enough variability to serve as a control parameter.**
- **From the generated database for a selected geographical region, the optimum time of day for making the RH-control measurement (RH set-point) is determinable.**
- **Control of irrigation by selecting an instantaneous RH set-pointvalue from a 24-hr period suggests:**
    - **a) Arid, high-altitude regions could use maximum RH.**
    - **b) Semiarid and moist regions make better use of minimum RH.**
- **For many days at all sites, because of regular diurnal temperature variation the maximum and minimum RH levels usually occur near 0600 hours and 1800 hours respectively.**
- **Fixed time-of-day RH measurements are a simple and economic means of effecting irrigation control for the small-plot user.**
- **For arid and semiarid regions, summer rainfall timing and to a lesser degree the geographical movement of weather systems, upset the diurnal regularity of the RH trace — especially the timing of the maximum RH. Maximum RH often occurs in rainy afternoon periods, and assumed sinusoidal regularity of the diurnal RH trace may lead to erroneous results.**
- **Agricultural ET databases generally include raw data from which effectiveness of irrigation control using RH measured at a fixed time of day can be closely assessed.**
- **Small-plot irrigators for whom the ambient RH normally changes little over a brief total irrigation cycle (a few hours) can use real-time RH-control. "Real-time" implies that ambient RH is continuously being compared to the RH set-point during the irrigation cycle.**
- **Large-area irrigators considerably improve irrigation efficiency by "locking in" the optimal RH set-point control parameter (maximum, minimum, or fixed-time RH) for the entire irrigation cycle.**
- **With morning irrigation usually advised for turf health and water savings, small-plot users also may opt to lock in an evening (~minimum) RH measurement for scheduling irrigation the following morning.**

Hardware and methods described in this report are protected by U.S. Patent No. 6,145.755.

Background and Introduction

The agricultural-industry-accepted standard that indicates plant-watering needs is evapotranspiration (ET), a calculated empirical parameter that accumulates the effects of solar radiation, wind, temperature, and relative humidity (RH). The units of ET are inches (or mm) of water per selected time period. For predicting the monthly needs of a particular region, the daily ET values for the same month over many years are simply summed for each year and the results averaged. Likewise, for each month, the precipitation is summed and combined with the calculated monthly ET value to advise the "normal" amount of supplemental irrigation for that month for the general area. Ideally, the applied irrigation water makes up the difference between the monthly accumulations of ET and precipitation, and shows little variation from year to year. Although most small-plot irrigators are advised to use projected monthly averages for setting the amount of applied water, year to year variations in both monthly rainfall and ET accumulations often cause over-watering or, less frequently, under-watering. The examples and arguments included in this paper validate the use of RH-controlled irrigation. Controlling irrigation with measured RH effects automatic daily water-application adjustments that can offset these varying weather-parameter distributions. The approaches and results presented herein are based on my full acceptance of ET as the best indicator of continually varying plant-watering needs. The main thrust of the paper is to show a strong correlation between the daily varying values of ET and a selected portion of the continuous RH trace. While I do not claim global applicability for these results, my studies show that most arid and semiarid regions can benefit considerably by using the proposed irrigation-control systems. Such sites are typically those for which supplemental irrigation constitutes an appreciable fraction of the turf water needs, i.e., sites for which potential savings from improving irrigation efficiency are appreciable.

The varying requirements for supplemental water needed over the irrigation season typically are represented by bell-shaped curves that for most sites peak during the June-July period. Adjustments to the applied-water needs based on such curves attempt to accommodate historically predictable seasonal changes, but do not address daily ET fluctuations periodically caused by intermittent rain or high humidity. Unfortunately, year-to-year variations that illustrate dramatic regional departures of rainfall from annual norms are commonplace. Any system or method that purports to economize the application of irrigation water must be able to sense and accommodate both seasonal and daily excursions of precipitation and ET from historical norms. The proposed RH-controlled irrigation system is shown to do precisely that for several different climatological zones of the western United States. The full potential and limitations of an RH-controlled irrigation system will be realized only when similar ET/RH correlation studies include all areas that routinely require supplemental irrigation.

Control of irrigation by sensed atmospheric RH initiated with the introduction of the Weathermiser in the late 1900s[1]. For arid, high-altitude sites such as Tucson and Albuquerque that require relatively brief (a few hours) early morning watering, this simple device has proved very effective for reducing excess watering. While being a simple and reliable device however, it functions only as a "real-time" controller which limits its widespread applicability. These limitations involve regions where the RH correlation with ET is different from that of arid, high-altitude sites. They also concern irrigation systems for which lengthy watering cycles (greater than a few hours) are required. For such applications, the ambient RH variations that naturally occur during the irrigation cycle may force an uneven application of water — some irrigation stations at the site will be watered while others won't. Because of the generally consistent diurnal RH variation, this irregularity likely will be repeated, i.e., the same stations may be shorted the following day(s). Another significant disadvantage is that "real-time" control, by definitation, is not compatible with sites for which the RH control parameter is to be measured at a

[1] The Weathermiser is an irrigation-system adjunct that in real time senses RH for overriding (interrupting) the normally scheduled irrigation sequence. It was patented by Al Caprio of Albuquerque, NM on December 1998 and holds U.S. Patent 5,853,122. It includes an adjustable RH set-point such that if the sensed (ambient) RH is above the set-point, the electrical circuit to the irrigation valve(s) is interrupted, thus preventing irrigation until such time that the ambient RH again drops below the set-point during a scheduled irrigation cycle.

time other than during actual irrigation period. The ideal time for measuring the RH for most climatological regions is not during the typically recommended early morning watering period.
My improved control system likewise uses RH as the control parameter that similarly directs the interruption of the time-scheduled supplemental irrigation. But the new system also includes a time-delay option such that the optimal RH control signal is preserved and remains effective until the entire irrigation cycle is completed. This system modification greatly expands the geographical regions for which RH can be used as an effective parameter for conserving irrigation water. My studies show that for most arid or semiarid climatological regions that benefit from regular summer thunderstorms, minimum RH shows much better correlation with daily ET variations than maximum RH. This conclusion implies that for all such regions, a "real-time" control system based on ambient RH measurements requires irrigation in the hot afternoons (during which time minimum RH usually occurs) rather than the usually recommended cooler morning period.

Discussions that involve natural phenomena such as weather-related topics are necessarily complex and invariably incomplete. I assume moderate proficiency of the reader in the topics presented. The technical discussions are directed toward researchers, professional irrigators and consultants, as well as knowledgeable private users. However, I attempt to maintain sufficient simplicity in the technical discussions so that anyone with moderate scientific acumen can follow the logic. Accordingly, I must briefly define several concepts and parameters that will be "old hat" for irrigation professionals. To shorten the body of the report, highlighted words in the following text will have definitions and/or expanded discussions in appendices.

How Irrigation Needs are Determined

Most states with agricultural bases that substantially contribute to their economy provide seasonal real-time weather data to growers so that they can efficiently schedule the irrigation of commercial crops. Some regions provide this information only to fee-paying members, but many others provide free access to such data. Generally this information is in the form of tabulated daily weather parameters and reference evapotranspiration (ETo) calculations. These empirical ET values constitute the industry-accepted standard for establishing crop-irrigation requirements. The ET calculations typically integrate weather conditions over a specified period of time and involve four continuously recorded parameters: temperature, RH, solar radiation, and wind. These parameters are forwarded to a central computing station from a network of automated recording sites dispersed throughout the growing region. Sometimes, the nearest recording station of the agricultural network is close enough to a metropolitan area to accurately model its ET behavior. For example Ft. Lupton, CO information (from CoAgMet[2]) approximates the behavior of Denver; and Spencer, OK information (from the Oklahoma Cooperative Extension Service) approximates the behavior of Oklahoma City. Both of these weather-recording sites are about 15 miles from the city cores.

For assessing plant-watering needs, a single value (reference ET or ETo) is calculated on a daily basis for each field site. The user (or service provider) then adjusts this value by a crop factor (Tc) for the specific crop of interest. For the purposes of this paper the crop is cool-season turf grass that has a Tc of 0.8 to be applied to the ETo. For warmer regions, warm-season turf grass with a crop factor of 0.6 often is preferred[3] because of the 25% lower water usage. Increasingly, more populous states and some metropolitan areas such as Denver also provide local ET data for urban users during the turf irrigation season. I use urban data for local site-behavior comparisons, but the data-set completeness (e.g., including ETo and daily maximum and/or minimum RH together with continuous or hourly RH values) required for optimizing the RH-set-point selection usually is available from only the agricultural sites. I urge non-agricultural users to access these ET/weather data sets. They are generally understandable and straightforward in their applicability for home use. At the very least they

[2] Colorado Agricultural Meteorological Network.
[3] Various sources recommend slightly different crop factors for the same crop. They also may base the ET calculation on different crops and different algorithms. I am not promoting any particular ET value or crop factor; for the purposes of this study they are all very similar and result in the same overall conclusions.

should be used as the basis upon which irrigation scheduling (timing and water-application quantity) is initially set up and seasonally adjusted. They also provide the data sets for establishing the RH set-point values for controlling supplemental irrigation in the examples included herein.

Estimates of annual supplemental water for "normal years" combine the historical turf needs (ET) with historical precipitation records on a month-by-month basis for the irrigation season. Supplemental water needs for turf grass vary widely from region to region depending on the four parameters cited for calculating the ETo as well as the seasonal rainfall timing and quantity, and local topography and soil conditions. Ideally, local annual "monsoons" coincide with the irrigation season, but this is not always the case. In addition, individual rainfalls during the irrigation season may not be totally effective in reducing the supplemental irrigation because they are too intense to be absorbed, or because saturated soil or a sloped surface contributes to high runoff. In a natural process called the water budget method soil can "bank" several days of needed moisture. Turf-watering needs estimated for a specific local region include some or all of these factors. Table 1 projects annual applied water needs of cool-season grasses for selected western cities.[4, 5] The applied-water values of Table 1 sometimes are termed "water deficit."

Table 1. Applied-water requirements for cool-season grasses (inches/yr.)

Flagstaff, AZ	31.2	Reno, NV	36.4
Phoenix, AZ	76.7	Las Vegas, NV	55.9
Tucson, AZ	71.5	Santa Fe, NM	31.2
Sacramento, CA	39.0	Albuquerque, NM	39.0
San Francisco, CA	27.3	Bismark, ND	19.5
Los Angeles, CA	62.4	Oklahoma City, OK	26.0
Denver, CO	28.6	Portland, OR	24.7
Boise, ID	35.1	Sioux Falls, SD	24.7
Kansas City, KS	23.4	Dallas, TX	37.7
St Louis, MO	23.4	San Antonio, TX	49.4
Missoula, MT	20.8	Houston, TX	28.6
Omaha, NB	26.0	Salt Lake City, UT	31.2

Note in Table 1 that the turf irrigation requirements for arid, high-desert Albuquerque approximate those of both Sacramento and Dallas, both lower and much more humid regions. The supplemental needs are similar despite the fact that the average annual rainfall accumulations of these three cities are about 8.9 inches, 17.5 inches, and 33.7 inches respectively. The major climatological difference between Albuquerque and Sacramento is the timing of the rainfall; Albuquerque's rain occurs mostly in the summer while Sacramento's occurs in the winter (non-irrigation) period. The Dallas disparity has a different basis. Dallas average temperatures are consistently higher than those of Albuquerque, and ET values are particularly sensitive to high temperature. However considerably more rainfall and higher humidity reduces Dallas's applied water needs by either offsetting or lowering the ET values.

The annual and monthly ET calculations together with historical rainfall data constitute the database for initially programming irrigation schedules. However, historical weather-data averages are inadequate for scheduling application of agricultural crop water because occasional annual rainfall variations of more than 50% are not uncommon. Additional irrigation adjustments are imperative. The same must hold for turf irrigation. The major factor affecting differing annual water requirements for a selected site is the variation

[4]Because of the more readily available gratis meteorological/ET data in the west, I restrict the scope of my initial studies to western states. However, the overall conclusions likely are applicable to most eastern areas.
[5] A more complete list of U.S. cities is accessed on web site: www.waterwiser.org. This site is a valuable resource for information concerning water conservation.

and timing of precipitation. If the irrigation-control system can accommodate this unpredictable variation it approaches the balance needed to assure acceptable turf health together with irrigation economy.

Creating an irrigation schedule

Creating an irrigation schedule starts with the examination of ETo and precipitation data for the selected region. Turf-referenced ETo values represent the moisture that the turf can absorb for maximum growth. Averaged monthly data are represented by the typically bell-shaped curves shown in Figure 1 for several cities. This figure also includes single-year data: 1997 for Denver, and 1998 for Albuquerque. These two single-year inclusions clearly depart from the typically smooth, symmetrical, bell-shaped curves and demonstrate the need for irrigation control beyond the predicted average seasonal requirements. ETo data, of itself, is not sufficient for irrigation-scheduling purposes. ETo needs to be offset by effective rainfall. Effective rainfall is the rainfall accumulated during the irrigation season less the amount lost to runoff and deep-soil percolation. For most well-grassed sites, percolation is usually low. For level turf plots, a stand of healthy grass reduces runoff for all but exceptionally heavy downpours. The Table 1 list of annual applied-water requirements considers these factors, i.e., on a monthly basis ETo is first adjusted for the crop factor (0.8 for cool-season turf grass), and then offset for historical normal effective rainfall. The monthly needs are accumulated to produce the tabulated ETo-referenced turf water-usage requirements in Table 1.

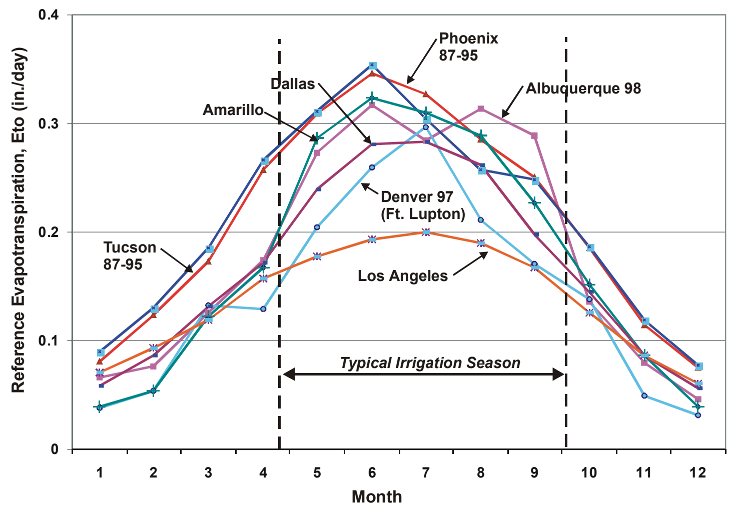

Figure 1. Monthly evapotranspiration (ETo) for several western cities

The calculated monthly ETo values of Figure 1 are not used unaltered by irrigation schedulers. A single ETo value[6] may be used for many different agricultural crops. A turf crop factor (Tc) modifies the calculated ETo value as mentioned earlier (Tc = 0.8 for cool-season grass). The individual curves of Figure 1 are modified for actual crop needs similar to the example shown in Figure 2. ETo values are first adjusted by crop factor into ET values applicable to turf grass. The reduced ETo value (ET) represents the total amount of water that healthy cool-season turf grass with a height of about 4 inches and a well-developed root system can absorb to produce maximum growth. The graphed data[7] of Figure 2 combine ET and rainfall values for each month of an averaged 30-year span for College Station, Texas. The author of this data assumes an across-the-board

[6] Since historically, ETo values were calculated for agricultural crops, ET data are not necessarily based on our reference crop of cool-season grass. The reader is advised to closely examine information from the various ET sources. The reference crop usually will be specified.
[7] Extracted from Richard L. Duble, "Water Management of Turfgrass," Texas A & M University (TAMU). This excellent comprehensive discussion paper is available in the TAMU website.

25% loss of precipitation to runoff[8]. Thus for his model, effective rainfall is only 75% of the actual. The monthly difference between ET and effective rainfall values represents the water deficit (green curve), the supplemental water to be applied on a monthly basis. The averaging of many years of such data produces the generally smooth bell-shaped ET curves of Figure 1. However, as noted earlier, single-year ET traces can exhibit dramatic excursions from the usual smooth curves.

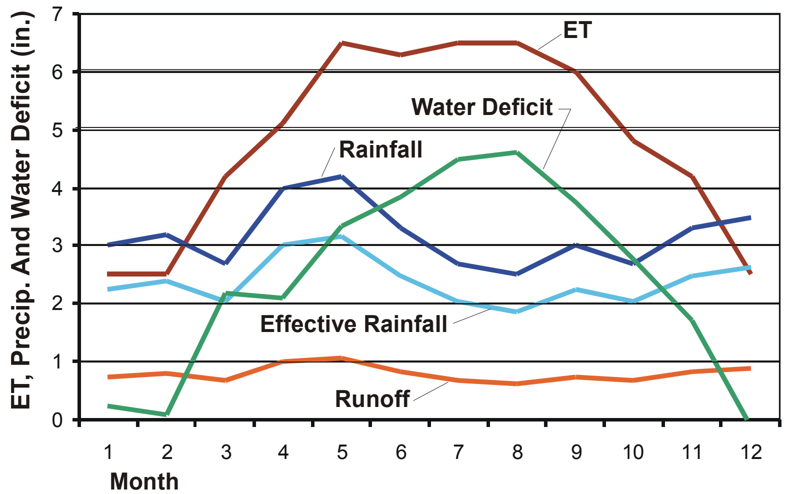

Figure 2. Water deficit for College Station, TX (30-year average)

Ideally moist soil conditions and maximum turf growth are implied in the ET curve of Figure 2. Generally, however, turf growers do not desire maximum growth of turf grass. Most users desire to minimize irrigation and mowing frequency while maintaining an acceptable appearance of their lawn. In addition to the turf or crop factor, a second multiplier is used to further reduce the applied water. This parameter is called allowable stress (AS) and represents the appearance of the turf that is acceptable to the user. Allowable stress factors range from about 1.0 for turf with no stress (e.g., golf greens) to 0.4 for highly stressed (discolored) turf. A common AS selection from this range might be a value of 0.6 that represents the appearance of sod in well-managed public parks. Multiplying the raw ETo values by both the crop factor and the allowable stress factor provides the modified ET value that represents the actual need of the turf as determined by the user, and which is then offset by effective rainfall to calculate the required irrigation supplement. The irrigation supplement together with effective precipitation matches the loss of turf moisture due to evaporation and transpiration. In the included performance models, I modify the ETo values for a cool-season grass crop factor of 0.8 and a stress factor of ~0.6. These combined factors reduce the actual ET values for cool-weather turf grass to ~50% of the reference ETo values. Using different values for the individual ETo adjustment multipliers will not invalidate the techniques and conclusions — the numerical results may vary, but the overall irrigation-control logic based on RH measurements remains valid.

Most irrigation systems, especially those employing sprinklers, apply water unevenly. A really balanced sprinkler system will have a system efficiency of perhaps 80% while poorer systems drop to 50% or even lower. To protect minimally irrigated areas, the supplemental water values calculated above must be divided by the irrigation system efficiency to schedule the total water to be applied. Since this correction is site specific, it is not considered in the following calculations of turf watering need. I also ignore runoff as being largely site specific. Its effects, while not included in the numerical calculations, are considered after the data matrices that illustrate control performance have been created.

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[8] This high (for the author) value may be caused by intense Texas rainfall, often exceeding several inches for a single storm. Summer thunderstorms produce most of the offsetting precipitation.

Control of Irrigation for Daily Weather Variations

Annual data provides the basis for initially programming the irrigation water for monthly or daily application. However, the programmed "normal" irrigation should be updated daily by some means to account for sporadic periods of rain and high humidity. At present, to avoid "watering in the rain" timer-programmed watering sequences for residences or other small-plots typically are interrupted by hit-or-miss manual intervention. While ET calculations are sometimes provided on a daily basis to urban small-plot irrigators, to effectively use this data manual intervention is again required. Professional irrigation schemes use costly irrigation controllers interactively connected with computerized data centers that integrate daily weather and ET data for a broad area of coverage. These controllers automatically make watering adjustments based on the conditions of the site at which the weather data is taken. Unfortunately, for climatological regions that receive their summer rainfall mainly from thunderstorms, irrigation-site conditions may differ radically on a day-to-day basis from those even at a nearby measurement station.

The crux of this paper is that for several different climatological regions, a strong correlation of some portion of the continuous RH trace with daily excursions of the ET trace indicates that near-real-time, responsive, efficient, hands-off irrigation control is feasible even for small plots. RH comparisons made by an inexpensive sensor (humidistat) included in the irrigation system's control circuit adjust the applied water (scheduled on historical averages) to the plant's actual daily varying needs. This new control option eliminates the inconsistency of manual intervention, bypasses the cost and suspect areal applicability of the high-tech approach, and yet provides an effective, economical, automatic or hands-off solution to over-watering. Furthermore, the proposed system has the unique advantage of being irrigation-site specific; it is little concerned with weather conditions perhaps fifteen miles away at the weather station. This latter advantage is particularly important for geographical regions for which the rainfall during the irrigation season is mainly from thunderstorms. The areal inconsistency of such rainfall is well recognized.

In its simplest real-time RH-control configuration, a humidistat is internally coupled to an integral electrical switch such that whenever the ambient RH is above a user-selected RH set-point the electrical switch remains open. The humidistat includes a means for varying the RH set-point. The user manually selects the value of the RH set-point, and whenever the sensed ambient RH is greater than the set-point no irrigation can occur because the open-switch condition prevents the valves from operating. The irrigation-system architecture shown in Figure 3 is that presented by the Caprio patent. The humidistat is installed in series with the common return wire from each of several sprinkler valves. In the usual system configuration, the irrigation valves use a single or common return wire in their circuit. Although my newly proposed RH-controlled irrigation-system configuration includes time-delay functions for optimizing the system's water-conservation efficiency, the basic action of interrupting the timer-controlled watering cycles is analogous.

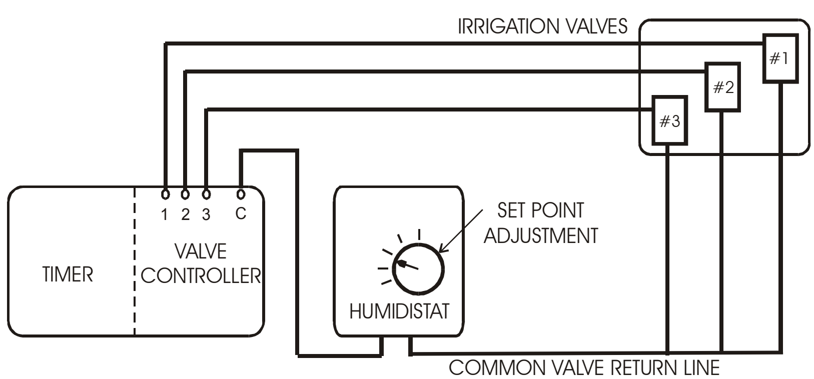


Figure 3. Humidistat interrupter installed in "real-time" control circuit

The proposed new hardware systems and database usage should raise users' and water suppliers' expectations for better performing irrigation systems. The forgoing and following discussions, however, do not imply a diminished need for irrigation professionals. On the contrary, for properly installed and programmed irrigation systems, the new methods permit professionals to offer improved water savings to small-plot users at affordable prices. I fully realize that most such users will not ponder the detailed technical intricacies that yield the general conclusions presented herein. However they will use the results when the advantages are verified and publicized by trusted sources. Especially for the small-plot irrigator, the control schemes and logic that determine the RH set-point should be straightforward and easily applied. Accordingly, my goal is to minimize RH-control adjustments. Ideally a single unchanging site-specific RH set-point value can be calculated that is effective for the entire irrigation season. I show that this goal has been realized for sites from several different meteorological regions.

Regional Climatological Difference

Regional climatological differences require different approaches to controlling irrigation with sensed RH. In order for any sensed parameter to provide effective control, the variation of the parameter must be broad enough to permit the selected sensor (humidistat) to provide a meaningful measurement. Even more important, the selected control parameter must show good correlation with variations in the target parameter — ET in our discussion. I use tabulated daily entries of selected parameters for an entire month to calculate the effectiveness of competing RH-control schemes. I convert such to a graphical format to allow rapid visual appraisal of the results. The general format for information presentation is that shown in Figure 4.

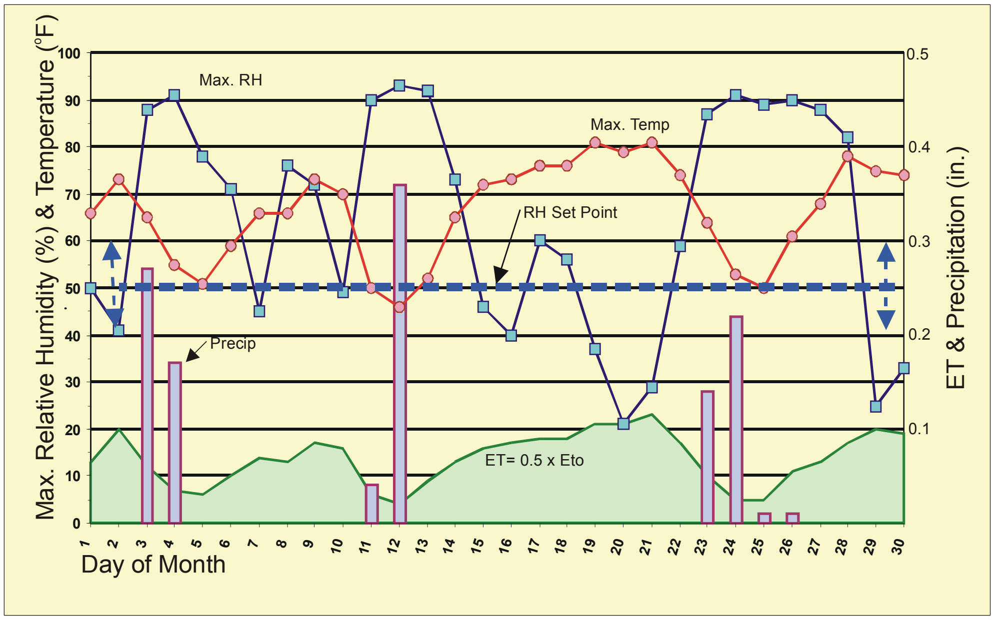


Figure 4. Albuquerque Daily Weather/ET History (April 1997)

The solid green area representing the evapotranspiration (ET) trace in this figure is bounded by 0.5 times the daily ETo as described earlier. To keep the chart simple, only the maximum RH trace is included in this data grouping since it is an acceptable control parameter for this arid site and is better adapted for using real-time control. The daily maximum RH charted is the highest instantaneous value of RH measured for the 24-hour period regardless of the time of day at which it occurred. Note that the ET trace and the daily precipitation columns are plotted to the same scale (indicated on the right-hand vertical axis). The daily variations of ET are considerable (~ 4:1), as is usual when appreciable sporadic rainfall occurs. This observation underscores the need for coordinated daily irrigation control.

Ignoring runoff as negligible, the accumulated daily ET and precipitation values for the month are 2.06 inches and 1.22 inches respectively resulting in a monthly water deficit of 0.84 inches. I set the daily water-application level to be near the peaks of the ET entries (averaged over many years) to always satisfy lengthy dry periods. This water-application amount is higher than recommended by many irrigation professionals because their water-application settings usually attempt to compensate for historical (average) rainfall. Because year-to-year precipitation is markedly inconsistent, I adjust for the rainfall on a real-time daily basis rather than historical basis. The dry-period ET values (peaks) are much more constant year after year, and thus the water-application value based on these periods will be reasonably consistent for the same month of any year for this site. I select a water application level of 0.08 inches per day accumulating to a total (if not interrupted) of 2.40 inches for the month. However, dividing the monthly water deficit by the application per day (0.84/0.08) yields only 10.5 days for which watering should occur. April having 30 days, the difference is 19.5 no-water days (nwd) to be selected by the control system.

Now consider the RH set-point to be a horizontal line spanning the entire chart. It represents a fixed value of RH for the entire month. Move this "set-point" line up or down until 10 or 11 of the daily maximum RH data points are on or below the line. A position near 50% (dashed blue line in Figure 4) meets this stipulation. Only for those days where the RH trace is below the set-point line will irrigation be allowed. An astute observer will note that an RH set-point similarly can be made to match the water deficit for any particular month if, like in our example, the set-point selection is made after the fact. What is promising, however, is that for many prior or subsequent years for April in Albuquerque, the same results prove valid, i.e., the ideal RH set-point remains nearly constant. In fact, multi-year studies are the optimal method for establishing both the monthly watering rate and the RH set-point. Many similar examples constitute the bases for my conclusions.

Refer again to Figure 4 for some important observations. First, note that the ET trace is mirrored by the maximum temperature trace. Also, the temperature and RH traces are generally reversed mirror images. These observations satisfy our intuition that higher temperatures and lower RH are consistent with increased watering needs. RH and temperatures values are not independant from each other. (Having demonstrated these relationships, temperature will not be included in subsequent illustrations.) The more important observation in Figure 4 is the relationship of the maximum RH trace with the ET trace. The curves show an inverse relationship: the higher the RH trace, the lower the ET trace. This behavior is especially pronounced for the three rainy periods — the major peaks of the maximum RH trace match the timing of the troughs of the ET trace. Also, it does not require actual precipitation to lower the ET trace; often high humidity suffices. Observe the ET values for the 13th and 25th through 28th. The first day has no rain and the second period received only a trace. It is not uncommon for an RH-controlled system to stop irrigation a day or two before the actual onset of rain because of increased RH (and accompanying lowered ET) preceeding the rainfall.

Another significant observation of Figure 4 is that the "water-day" periods allowed by the RH-controlled system (i.e., those days whose maximum RH value is below the set-point level) generally correspond to the periods of higher ET, that is to say, the sequential days with the greater needs for supplemental water. However, it is not necessary to precisely match the ET needs on a day-by-day basis. This topic is pursued in detail on several of the irrigation web sites, but such details are not relevent to the main thrust of this paper. The essential result is that soil has the capability to bank a few to several days of moisture. The banking capacity is generally site specific, and depends on several variables including location, meteorological conditions, pre-existing soil moisture, time of year, the turf crop, and the soil type and topography. A typical summer carry-over period for fully moist loamy soil might span three to six days. Our goal for use of RH-controlled irrigation is to match turf-moisture needs over a moderately lengthy time period.

In the preceding example we assumed that daily maximum RH provided our control parameter. We now consider the daily variation in RH. The continuous daily RH trace typically varies in roughly sinuisoidal fashion as shown in Figure 5. This graph shows slightly smoothed traces of the continuous RH values for two consecutive days from Ft. Lupton, CO. This trace is not a record of water content in the atmosphere. In fact, the actual amount of moisture in the atmosphere typically remains fairly constant over a "normal" 24-hour period while the instantaneous RH values fluctuate considerably, especially for high-altitude regions. The causitive factor of RH fluctuation is diurnal temperature variation usually peaking at about 4:00 or 5:00 pm and reaching its low at about 5:00 or 6:00 am. Considering the inverse RH/temperature relationship noted earlier, we would expect that the maximum RH level normally occurs in early morning, while the minimum RH level occurs in early evening. This is precisely what most often happens. While similar data for other sites may show greater or less peak-to-peak variation than the curve shown in Figure 5, the argument made in the preceeding paragraph universally holds true. Early morning typically yields the highest RH values while afternoon yields the lowest RH values. Only the occurrence of summer storms, passage of frontal systems or squall lines, and other moisture-generating phenomena upset this regular behavior. Their effect on RH behavior will be examined later.

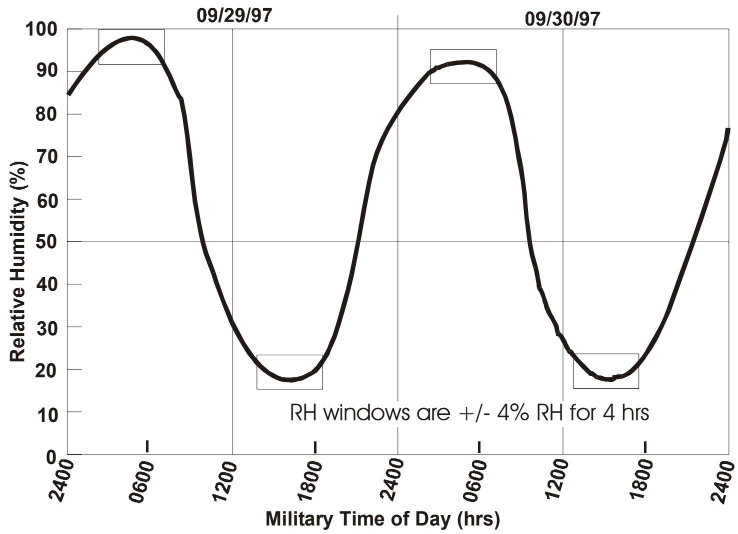


Figure 5. Continuous RH trace for two successive days

The RH trace in Figure 5 also illustrates that at the peaks and lulls of the RH trace the instantaneous RH values are fairly constant for several hours, i.e., they are not particularly sensitive to RH measurement timing at these positions. Conversely, the extremely steep slopes of the traces between the peaks and valleys indicate that RH values from these regions are extremely sensitive to measurement time. This observation of typical RH behavior is important because irrigation programmers already include a clock, the simplest and most economical means for timing the comparison of the ambient RH with the humidistat's set-point. Simply select a fixed time of day that corresponds to a flatter portion on the RH curves. Stations producing daily ET information usually include maximum and/or minimum RH. Based on availability of this data, as well as the fact that the maximum and/or minimum RH values usually change little for several hours, I restrict selection of irrigation-control parameters to periods of either the maximum or minimum RH.

Figure 6 shows the continually changing RH trace for an entire month (August) at Ft. Lupton, CO. At first glance, this raw trace looks very irregular, but the time-axis has been compressed ~15 times relative to Figure 5. I include Figure 6 to illustrate the predictable regularity of diurnal variation of RH for longer periods of time. This lengthier trace also encompasses several rainy periods that upset the diurnal RH regularity. For example, the rain accumulated from the 4th through the 6th exceeded 1.7 inches and the minimum RH levels during and following this period increased significantly implying generally high average

RH throughout this entire rainy period. A second rainy period was the 09th through the 13th with similar RH increase noted. The third rainy period was from the 17th to the 18th. All three rainy periods have have strong correlations with selected portions (minimum RH) of the continuous RH trace spanning this month. Since a thorough understanding of atmospheric RH variation is vital to assessing the nuances of the proposed RH control of irrigation, Appendix II includes an expanded discussion of this topic.

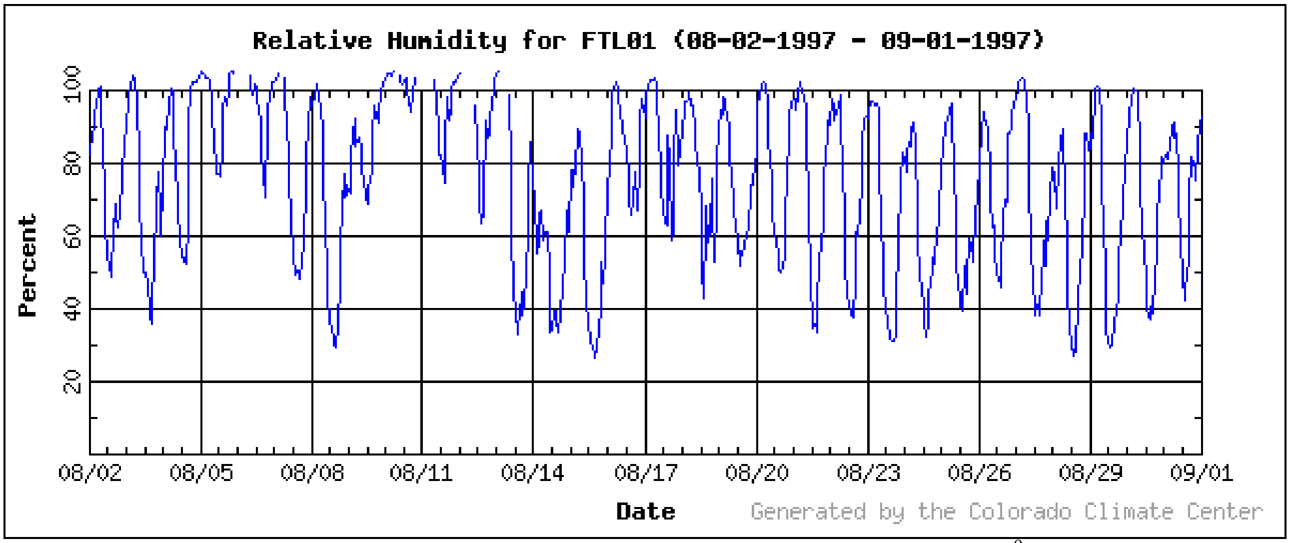


Figure 6. Continuous RH trace for Ft. Lupton, September 1997[9]

This continuous graphical RH trace allows determinination of precisely when an RH set-point is actually exceeded (on a minute-to-minute basis) for uncertain situations when the tabulated RH value is very close to the set-point. This uncertainty arises because some stations list the RH values averaged for each one-hour period thus masking both the maximum and minimum extremes. These stations typically calculate an ET value for each hour and then sum them over the 24-hour period to arrive at the daily ET value. As a result neither a "true" maximum or minimum RH is provided. Data-user judgement must consider these factors. If the graphed data of Figure 6 is greatly expanded along the time axis, the actual sensed RH value at any selected instantaneous time can be extracted. Because of the previous discussions about how tabulated hourly RH entries are often calculated (averaged), similar graphical presentations of RH vs. time, if available, may be the only means of fixing an absolute ambient RH value to a precise time of day. Likewise, this graphical data can establish the actual time of day at which the maximum or minimum RH occurs. Some stations include this information in their raw digital format for presenting daily data. In any event, I caution the reader to determine how the data provider generates tabulated RH values.

We examined an arid site (Albuquerque) postulating maximum RH as our control parameter in Figure 4. We now examine another arid site (Tucson — September, 1999) in Figure 7. Because of regularly higher temperature, Tucson's ET values are generally greater than those of Albuquerque. Dry months indicate fairly consistant ET requirements with minimal need of irrigation interruption. For the included weather-history examples, I have deliberately selected months that have relatively more rainfall. With the data included in Figure 7 we compare effectiveness of irrigation control using either maximum or minimum RH entries for establishing the set-point. To accommodate the drier periods in Figure 7 the irrigation application rate is 0.13 in./day. The daily ET values sum to 3.32 inches. The accumulated precipitation is 1.44 in. resulting in a water deficit of 1.88 inches. However, the last day of the preceding month (August) had a

[9] The data shown are extracted directly from the CoAgMet (Colorado Agricultural Meteorological Network) website material. This site provides unusually complete year-round ET and weather data summaries primarily for agricultural purposes. Although slightly north of Denver, the completeness of the data sets makes this site a better source for fixing RH-controlled irrigation behavior for Denver than the less complete local data sets available from Denver Water.

rainfall of 0.71 inches with a carryover into September of about three or four additional no-water days. All things considered, the deficit equates to about 12 days that need irrigation. For using maximum RH as the control parameter, the RH set-point (dashed blue horizontal line) is adjusted to about 83%. There are 12 days for which the maximum RH is below this set-point. Likewise, for minimum RH the set-point is ~18-19%. This latter set-point value introduces the use of "minimum RH" as the control parameter.

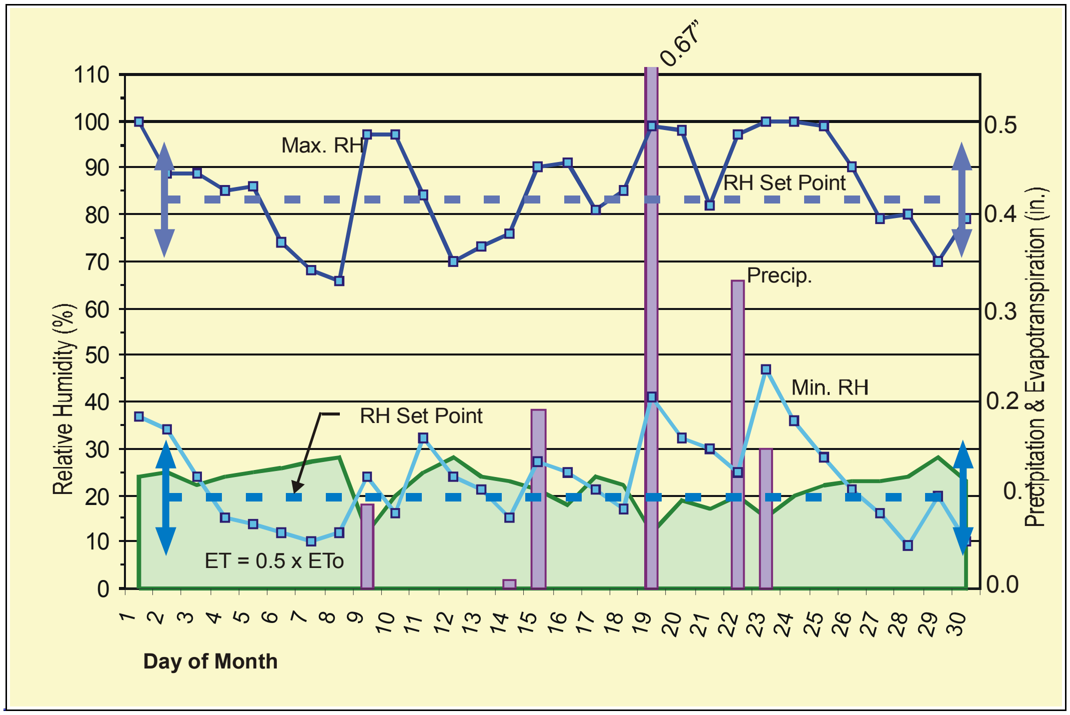


Figure 7. Tucson daily weather/ET history (September 1999).

Figure 8 duplicates and expands the data set of Figure 7 and allows comparison of all competing RH entries that are candidate control parameters for the modeled irrigation control system. Figure 8 presents graphical interpretation of the each of six selected RH values available from some agricultural data providers. For Tucson, the Arizona Meteorological Service (AZMET) data provides all of the discussed RH parameters. The dark blue traces of Figure 8 duplicate the instantaneous maximum and minimum RH curves of Figure 7. They are the true instantaneous maximum and minimum RH values listed for each day. The light blue traces are the maximum and minimum of the RH values from averaged hourly data entries for each day. These daily RH entries are the maximum and minimum of the 24 values averaged over each hourly period, e.g., the 0200-hr value averages the RH occurring between 0100 and 0200 hrs. While one of the 24 RH entries for hourly listings of each day is close to the instantaneous maximum or minimum RH value, by definition the instantaneous RH values listed for a particular day always bound the hourly-averaged values. The orange traces are the hourly-averaged value for the listed fixed time for each day of the month. The times selected are the "normal" time near which the maximum and minimum diurnal RH values commonly occur. It is this third option that is more compatible with existing irrigation-programmer systems.

For an irrigation study that adopts hourly-averaged maximum RH (upper light blue trace in Figure 8) to model as the control parameter, for this particular month the RH control point can be lowered 4% (from 83% to 79%) to produce the same number of no-water days. However, there are now five days that have RH matching or within a few percent of this new RH set-point value. These near matches with hourly-averaged RH entries, as mentioned earlier, introduce uncertainty as to what the actual ambient RH is at the instant of measurement. Typically daily RH entry values within about 3-4% of the RH set-point are assigned this uncertainty. More importantly, for a fixed-time-of-day RH comparison, the ambient RH at the precise time selected for making the measurement, rather than either of the tabulated “maximum RH” entries of the daily record controls the irrigation logic. We next compare control by these various parameters.

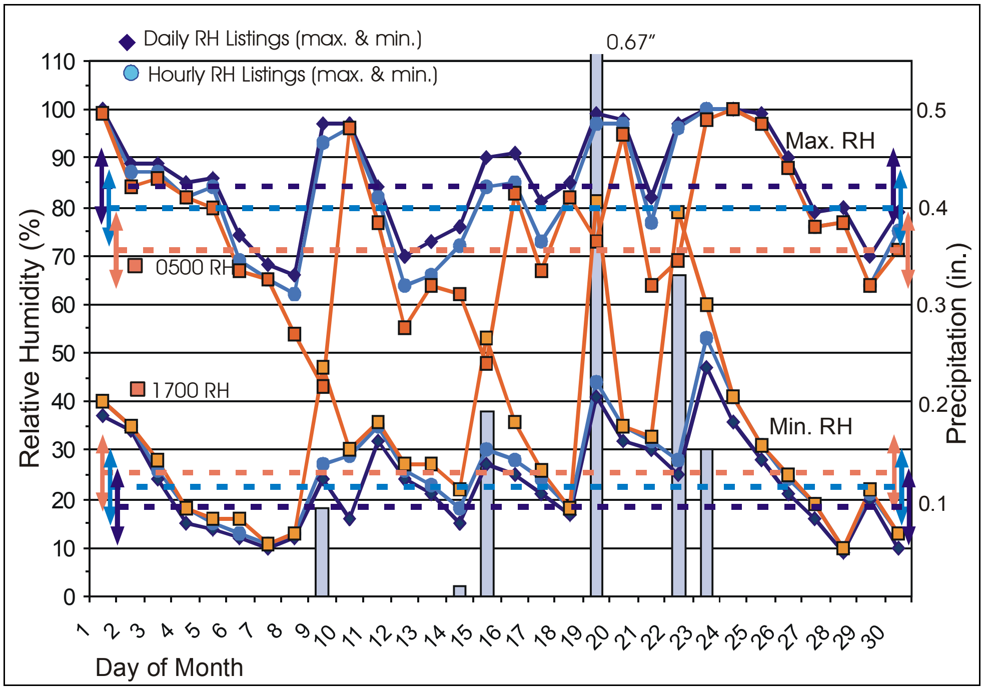


Figure 8. Tucson Daily RH Value Comparisons (September 1999)

Recall that I earlier proposed that the “maximum RH” measurement be made at a fixed time of day expected to correlate with minimum daily temperature (for most sites ~6:00 am), and hopefully approximating the instant at which RH is maximum. The orange traces in Figure 8 are the hourly averaged 0500-hr (assumed to approximate maximum RH) and 1700-hr (assumed to approximate minimum RH) values for the precise times used by the humidistat to make the decision on whether or not to irrigate. For also accommodating a “real-time” control-system modeling response, I select a time slightly earlier than the expected maximum RH peak of 6:00 am; opting for 5:00 am to center a two-hour watering period around the actual 6:00 am peak. The 1700-hr readings also precede the historical time of maximum daily temperature by about one hour. This time-offset approach is geared toward evaluating “real-time” RH control for which we need the RH to remain fairly constant for the duration of watering cycle (perhaps several hours).

None of the hourly-averaged entries (light blue or orange traces) are instantaneous values. At any instant of time within the listed hour these entries have uncertainties from the tabulated value typically of a few percent. This uncertainty is observed in Figure 8 by comparing the light blue and dark blue traces for typically dry periods. Within the two sets of three matched traces, the individual RH traces show clear differences recalling my caveat to determine the precise definition of the RH data being availed. With this illustration the daily instantaneous maximum RH value can be compared to the hourly-averaged “maximum RH” entry and the RH value tabulated for 0500 hours for the same data set.

For all dry days the daily instantaneous maximum or minimum RH (dark blue traces) and the hourly-averaged maximum or minimum RH (light blue traces) are very close, varying by a few percent or less. The fixed-time values (orange traces — 0500 hours or 1700 hours) also closely mimic the other maximum or minimum RH traces for the dryer periods. However rainfall dramatically upsets this regularity, especially for the 1700-hour RH values. The reason for these excursions is the usual daily timing of the rainfall together with rapid RH increase. If the rain could be programmed to fall at 0500 hours, the three curves would merge. In reality, rainfall and accompanying high RH on many summer and fall days occurs in the afternoon or evening. The 1700-hour RH trace clearly illustrates this behavior. For every rainy day or period in Figure 8, the 1700-hour RH value represents an appreciable increase above either of the two "minimum RH" listings for that day. There are four days where the 1700-hour RH is actually higher than the 0500 RH. From this observation alone (and confirmed by the tabulated hourly precipitation data), we assess mostly afternoon rainfall. A consequence of this observation is that for this site the 1700-hour RH value is an even more effectual parameter than "minimum RH" for correlating with precipitation and the accompanying ET-trace behavior.

With the expanded data bases like that shown Figure 8, I establish an RH set-point (at either morning or afternoon) for a fixed-time control system that controls the number of allowed irrigation days as well as by using any of the maximum or minimum RH values tabulated for each day. I adopt fixed-time ambient RH measurements that usually approximate the other RH entries for both of the times that are candidates for RH control. The selected-time hourly RH values are tabulated for the entire month (the orange-colored traces). However, these values listed in the raw hourly format also are averaged over the previous one-hour period. As observed in Figure 8, the tabulated hourly "maximum" and "minimum" RH values for most dry days closely approach either the maximum and minimum instantaneous values that likely were made during the same hour. The fixed-time error introduced by averaging any one-hour period of continuous RH data should usually be within the same few percent.

In the current example, to allow 12 watering days the RH set-point for the 0500-hr measurement will be ~71%; for the 1700-hour measurement it will be ~27%. Regardless of timing, the irrigation system functions the same — for all days at which the ambient RH is above the set-point at the time of the measurement, irrigation is prevented. The set-point values calculated for the fixed-time RH measurements of 71% (~ maximum RH, 0500 hours) and 27% (~ minimum RH, 1700 hours) compare with similar set-point values estimated for instantaneous RH (absolute maximum and minimum) from Figure 7 of ~83% and ~18% respectively, i.e., roughly a 10% inward adjustment in both cases. For maximum RH, the adjustment is downward; for minimum RH it is upward. The potential value of this adjustment is that it probably can be applied to weather data sets that do not include RH data as complete as that used in these examples.

Using the fixed-time tabulated hourly RH values from the raw database offers superior control while using an ultra-simple timer-controlled irrigation system. However the compact data listing that includes absolute maximum and minimum RH for each day is more available and also much easier to manipulate in the models for deriving the RH set-point. The latter consideration is important when acknowledging the multitude of sites to be studied, together with the fact that the raw hourly data required for the fixed-time analyses is available for only limited agricultural sites. This dilemma suggests only two solutions. If the actual (instantaneous) maximum or minimum daily RH values are to be used, a control-circuit logic must be developed that can accumulate continuously monitored RH data for a 24-hour period and extract the maximum and/or minimum RH values for control purposes. Modern integrated circuits can be designed to accomplish this task inexpensively if they are made in quantity; however the output from the humidistat must now be digital. Alternatively, perhaps an RH correlation for both morning and evening fixed times can be estimated from maximum and minimum instantaneous RH values recorded for each site in like manner to that of the previous example. Regardless of the RV value being compared, the ambient RH comparison (to the set-point) results in a simple go/no-go logic instruction to be used or retained by the irrigation programmer. For this arid site the 1700-hr RH measurements show excellent correlation with precipitation and ET. In this single-month example we also determined that both fixed-time RH set-point levels could derive from the daily instantaneous maximum or minimum RH data by adjusting (inward) the resulting set-point levels by about 10% for fixed-time control. Although fixing the set-point values should consider many years of RH data from the same month for this site, perhaps the ~10 % correction is valid for many months of every year. Possibly a simple approach that correlates these results for each site on a statistical basis can be realized.

To evaluate this idea, individual plots similar to Figure 8 were created for June through September for the consecutive years 1997 through 2000 for Tucson. In Table 2 the target values (bold numerals in the first row) for no-water days (**nwd**) were established by the techniques presented earlier. Set-points based on both the maximum instantaneous RH or its 0500-hour surrogate (yellow highlight) require RH set-point-value changes in mid season for the most economical irrigation control. A single-value set-point for 0500 measurements (blue highlight) averages the two earlier settings but shows some performance degradation. Although not necessarily expected for this arid region, the minimum RH (not listed in Table 2) and its 1700-hour surrogate correlate even better with the target **nwd**s. Additionally, use of the 1700-hr RH set-point comparisons does not require a set-point change during the irrigation season. For this site the simplest scheme for the humidistat-controlled irrigation system makes the RH measurement at 1700 hours and shows exceptional correlation with the target **nwd**s. The 1700-hr RH values (lowest row in Table 2) allow selection of a <u>constant set-point of ~30% for the entire 4-year study period</u>. Compare the number of controlled no-water days in this last row with the target **nwd** values in the first row.

Table 2. Correlation of various irrigation-control schemes with target **nwd** values for Tucson

	June (0.19"/day				July (0.18"/day				Aug. (0.14"/day				Sept. (0.13"/day			
	1997	1998	1999	2000	1997	1998	1999	2000	1997	1998	1999	2000	1997	1998	1999	2000
Target **nwd**	**0**	**0**	**0**	**21.5**	**4.6**	**25.6**	**31**	**7.1**	**17.5**	**19.5**	**19**	**21.6**	**20.2**	**9.8**	**16.5**	**5.8**
Max RH SP=72%	1	1	0	13	9	25	29	12								
Max RH SP=82%									17	23	22	22	21	10	19	9
0500 RH SP=62%	1-2	0	0	11	6	23-26	22-24	8-10								
0500 RH SP=72%									14-21	20-23	15-21	15-17	19-22	11-12	17-19	9-10
0500 RH SP=67%	0-1	0	0	10-11	2-6	19-23	24-26	9-10	23-28	23-27	20-24	17-19	23-27	12-17	19-23-	12-13
1700 RH SP=30%	0-1	0	0	9-10	3-6	16-18	23-26	3-4	19-28	17-24	12-17	12-19	16-21	5-8	12-16	1-2

NOTES:
1. Daily water application is based on ~maximum daily ETs for the month.
2. ET = 0.5 x ETo. Assumes turf factor = 0.8; allowable stress ~ 0.6.
3. Target no-water-days (**nwd**) = no. days per month less (ΣET – Precipitation) / daily water application. Runoff reductions not included.
4. Target no-water-days (**nwd**) in red should be reduced for heavy rainfall runoff. Local soil conditions are involved.
5. AZMET hourly RH entry is average for the previous 60 minutes.
6. Uncertainty of RH-controlled **nwd** entries in the body of the table occurs when the (averaged) hourly RH entries are within a few percent of the RH set-point.

The variation in required water application over this period is appreciable as evinced by the dissimilar entries for target no-water-days for each month. In spite of this, the modeled RH-controlled irrigation system shows remarkable correlation with watering needs on both daily and monthly bases. Because of its control-circuit simplicity and hands-off consistency, I would opt for the 1700-hr RH control scheme for this site. While hourly-averaged minimum RH values do not exhibit extensive variation from instantaneous RH levels, the 1700-hr values show considerable departures from both (see Figure 8) as well as exceptionally strong correlation with precipitation, both of which promote the 1700-hr RH measurement as a good control-parameter option. In fact the 1700-hr RH values show much better correlation with ET needs and precipitation irregularity than the minimum RH entries. However, for the simple proposed timer/humidistat irrigation-control scheme to be proved broadly effective for conserving irrigation water at other sites, comparable studies that are based on other similarly complete RH data sets are needed. Unfortunately, databases that include ready access to similarly complete information are limited, and this shortcoming suggests the need of an alternative approach for evaluating fixed-time RH measurements in our control system. Shortly I will reinvestigate a simple method that shows promise for estimating the effectiveness of fixed-time control systems using only the more commonly available RH data.

Thus far I have examined monthly climatological detail for only arid sites (Albuquerque and Tucson). Either maximum or minimum RH (or their timed "surrogates) have been shown to effectively balance controlled irrigation for these sites. Let's look at another type of climatological zone in semiarid Denver. Denver, like Tucson, has progressive municipal water-conservation programs and likewise benefits from summer monsoons. However it usually has higher RH levels and typically more rain. Figure 9 presents data for a representative summer month. (The data is actually from Ft. Lupton, a nearby CoAgMet agricultural station.) The month was selected to demonstrate both dry- and wet-period behavior. The first observation is that the maximum RH is consistently high and doesn't show much variation. Like for the continuous RH trace shown earlier for September at this site as Figure 6, only a few days have maximum RH excursions below 85% likely precluding use of this parameter for irrigation control for June in Denver — there simply isn't enough variability. Consistently high morning-RH levels synchronize with many days for which dew is observed, a regular occurrence in Denver for the entire May-September irrigation season, and further suggests that maximum RH would be a poor irrigation-control parameter. However, the minimum-RH trace exhibits considerable variation and, as shown in Figure 9, seems well correlated with precipitation. We therefore opt for irrigation control using only minimum RH or 1700-hr RH for our set-point comparisons.

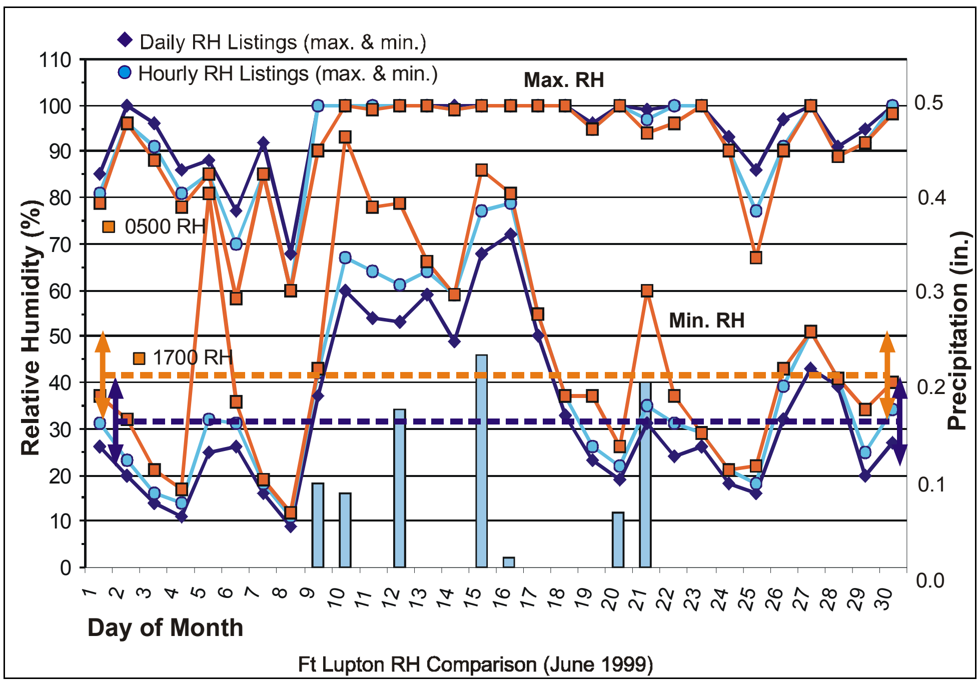


Figure 9. June, 1999 Daily RH Comparisons for Denver (Ft. Lupton)

Calculating the daily water application similar to the previous examples (0.16 in./day for June although I have omitted the ET trace in Figure 9), we estimate the number of no-water days for the month: 12. As stated previously, we opt for the 1700-hr RH comparison as the candidate control parameter. For this single month of Figure 9, the corresponding 1700-hr (fixed-time) set-point should be about 42%. Eleven to fourteen "no-water" days result. The uncertainty of the number of days again arises because the (averaged) 1700-hr RH values on several days (9,th, 26,th 28,th and 30th) are within a few percent of the selected set-point value. Similar to the Tucson example, multi-year and multi-month extension of the data set suggests an approximately 40% RH set-point level for the entire irrigation season. However, this set-point value is applicable only for this site, and only when the RH measurement is made near 1700 hours[10]. Referring again to Figure 9, note the excellent correlation of the no-water days with the rainy periods.

Similar to the Tucson example that compares 1700-hr set-point values (lower orange trace) with those based on instantaneous minimum daily RH entries (lower dark blue trace), the correction applied is again ~10% to convert minimum RH set-points to 1700 RH set-points. For example, to get the 12 no-water days calculated for this month, the instantaneous minimum-RH trace indicates a set-point of 33% while the 1700 RH trace indicates a set-point of ~42%. The magnitude of this correction seems fairly consistent for these two sites (one arid, one semiarid). However, other sites need comparable studies to establish the universality of this correction.

Also, like for Tucson, when using the 1700-hour RH comparisons, a unchanging set-point for the entire irrigation season provides excellent correlation to fluctuating water needs indicated by the ET trace. Table 3 shows four years of data for Denver spanning May through August. The target "no-water-day" (**nwd**) values again are shown by the bold numerals in the upper row. Only the minimum RH and 1700-hour RH correlations with the monthly target **nwd**s are shown. The italicized numerals below the set-point **nwd** entries are the monthly deviation from the target **nwd** days. Red entries indicate over watering; blue entries indicate shortages. Both italicized entries assume that the average value of the listed monthly **nwd** uncertainty span is the appropriate value to compare with the target value.

Table 3. Correlation of RH control effectiveness for Denver (Ft. Lupton)

	May (0125"/day)				June (0160"/day)				July (0.160"/day)				August (0.120"/day			
	1997	1998	1999	2000	1997	1998	1999	2000	1997	1998	1999	2000	1997	1998	1999	2000
Tgt nwd	**13.4**	**15.8**	**15.5**	**21.1**	**21.8**	**8.2**	**11.6**	**11.9**	**19.1**	**18.1**	**15.9**	**10.2**	**23.9**	**12.1**	**26.4**	**17.6**
Min RH SP=30%	15	12	16	12	17	12	14	11	12	20	19	7	22	17	21	15
	1.6	***3.8***	***1.5***	***9.1***	***4.8***	***3.8***	***2.4***	***0.9***	***7.1***	***1.9***	***3.1***	***3.2***	***1.9***	***4.9***	***5.4***	***2.6***
1700 RH SP=40%	18-21	11-16	16-21	9-12	19-22	12-16	13-19	10-13	11-16	19-22	18-23	7-11	22-28	18-21	18-24	18-21
	6.1	***2.3***	***3.0***	***10.6***	***1.3***	***5.8***	***4.4***	***0.4***	***5.5***	***2.4***	***4.6***	***1.2***	***1.1***	***7.4***	***3.4***	***1.9***

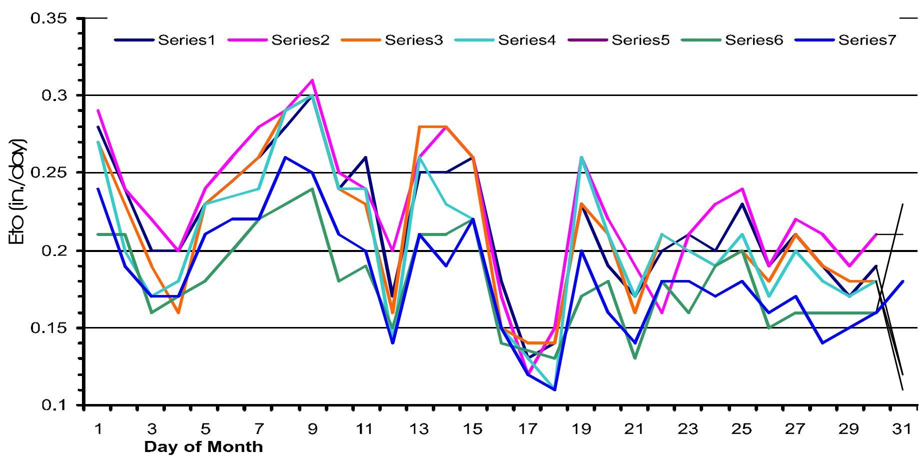
NOTES:
1. Daily water application (title headers) is based on ~maximum daily ETs for the month.
2. ET = 0.5 x ETo. Assumes turf factor = 0.8; allowable stress ~ 0.6.
3. Target no-water-days (**nwd**) = number of days in month less (ΣET – ΣPrecipitation) / daily water application for that month. Runoff reductions not included.
4. Target no-water-days (**nwd**) in red should be reduced for heavy rainfall runoff. Local soil conditions and topography are involved.
5. CoAgMet hourly RH entry is average for the previous 60 minutes.
6. Uncertainty of RH-controlled **nwd** entries in the 1700-hr table entries occurs when the (averaged) hourly RH entries are within a few percent of the RH set-point.
7. Italicized entries are monthly over-watering (red) or under-watering (blue) accumulations.

The accumulation of the **nwd** deviations over the four-month irrigation-season study period for any year can roughly evaluate the long-term effectiveness of the proposed control system. The ideal accumulation is zero. For example, with the 1700-hr set-point fixed at 40%, the 1997 irrigation season shows monthly deviations of +6.1 days (May), -1.3 days (June), -5.5 days (July), and +1.1 days (August), resulting in a seasonal deviation of only +0.4 days relative to the accumulated target "no-water days." The other three years have seasonal **nwd** deviations accumulation of +12.7 days for 1998, +8.6 days for 1999, and –10.3 days for 2000.

[10] The better time might be 1630 hrs for the 1700-hour RH listing since the 1700-hour listing is the average RH from 1600 hours to 1700 hours. Although the RH measured at the mid-hr likely is closer to the reported value than either of the end values, this subtlety is beyond the scope of the present study.

Assuredly the sod would be healthy even for the year 1998 that shows a moderate irrigation deficit. The fact that no corrections have been made to account for the high run-off days (target **nwd**s in red) probably skews the performance predictions conservatively downward. Nevertheless, the correlation to the desired target values is again remarkable, especially when considering that the RH set-point is the same for the entire irrigation season and for all four years of the study period.

Earlier I touted the advantage of the RH control system being site specific. I then used a site somewhat remote from Denver (~15 miles) to establish a control system for metropolitan Denver. This apparent contradiction is countered by assessing that the overall RH control behavior for these two sites will be predictable. While the input values of RH, precipitation, and ET might be considerably different, the overall control response within this geographical region should be similar. Figure 10 compares ETo traces for August, 2000 from seven different sites in the metropolitan Denver region. This information is extracted from the user-accessible Denver Water ET web site. Also listed is the accumulated precipitation for this month. Note the considerable variation (spanning a factor of greater than 3 times) in this latter parameter, at least for these August entries.



1. 56th Ave. Pump 4.79"
2. Lonetree Pump 3.83"
3. Marston Water 2.62"
4. Moffat Water 1.34"
5. Aurora North Satellite 1.62"
6. Aurora Tierra Park 2.45"
7. I-25 mousetrap 3.79"

Figure 10. ETo and precipitation comparisons for multiple Denver stations for August, 2000

The substantial differences noted for parameters from these sites, all within the greater Denver region, support the earlier assertion that a single weather station cannot effectively serve a large geographical area with daily data entries for RH, ET, and precipitation. Comparisons of similar data from four widely dispersed stations in metropolitan Albuquerque show similar results. Intuitively we know that while the applied water may be comparable over longer periods for all of these sites, the precipitation differences for these Denver stations during the selected month must result in considerable differences of the directed "no-water days" for individual stations. The limited Denver Water database does not allow a detailed study similar to those presented earlier. The essential conclusion however, is that each Denver site has a distinctive behavior, and local irrigation control would be better served by using the local data set. This site-specific behavior is a distinct advantage for the on-site RH-controlled irrigation system.

I have examined many other locales, some with considerably lesser data bases, and am encouraged that for most sites RH-controlled irrigation can lead to substantial matching of irrigation-needs for both extended wet and dry periods. The more difficult sites for establishing RH control set-points involve areas that have persistently high average RH. However these sites have comparatively low ET requirements and, unless also accompanied by persistent high temperature that elevates the ET values, turf in such sites is minimally irrigated if at all, i.e., the potential for significant water savings is low. Accordingly, most of my study sites are those that are classified as arid or semiarid. Acceptance of RH as an effective control parameter for balancing irrigation for these selected sites should lead to other marginal areas being studied, perhaps by universities or extension programs that now, to a large degree, already provide most of the ET and weather data on which my studies are based.

Conclusions

The technical results of the study are summarized in the Findings Section at the beginning of this report. In order to emphasize the potential effectiveness of RH control of irrigation systems, I have consciously ignored the hardware needed for modifying existing irrigation systems. My rationale is that the potential irrigation economies can be confidently verified by utilizing existing meteorological/ET databases such as are demonstrated in the included system-performance models. My patent (U.S. Patent No. 6,145,755) discloses several schemes for synthesizing commercial humidistat-control hardware into some existing irrigation-programmer systems to provide the necessary RH-comparison signal lock-in and time delays. These component arrangements introduce into timer-controlled irrigation systems such electronic devices as latching relays and time-delay relays as are detailed in the text and drawings of the referenced patent. A block diagram showing the essence of the new RH-controlled irrigation system is extracted from that document as Figure 13. I include this schematic in the report primarily for those who may not accept my professed results that are based solely on the database studies. Such users can avail the referenced schemes to inexpensively demonstrate proof-of-concept results.

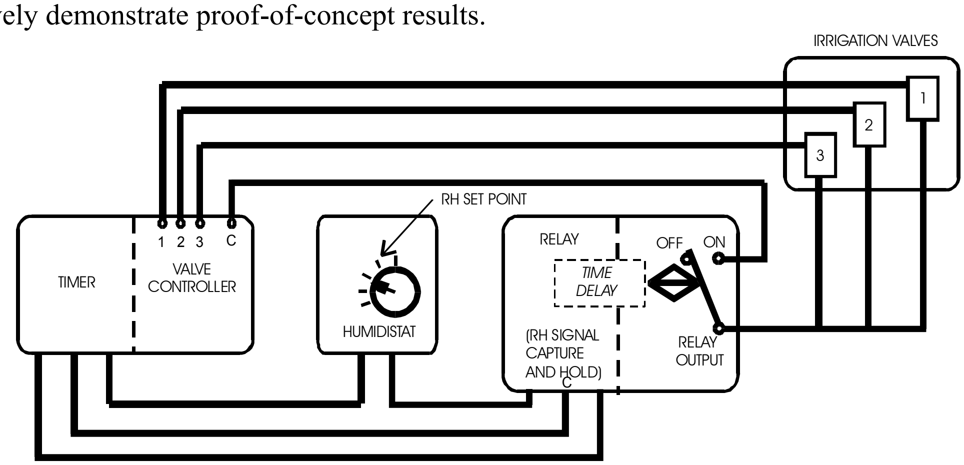


Figure 13. Schematic of irrigation-control system with RH sensor and time delay

Regarding commercial hardware integration in general, I concluded in the early phases of my study that in order for the proposed RH-control schemes to be widely used, the timer-programmer itself should be modified. It should include the option of setting a selectable time for making the RH comparison, and also include the means of holding the irrigation-control command until the entire following irrigation cycle has been initiated and completed. Only the humidistat would be a distinct, remote component of the irrigation-system programmer. I became convinced that only this approach would simplify the system hardware sufficiently to encourage widespread application of the proposed RH-controlled irrigation schemes.

APPENDIX I. Definition of Terms

allowable stress (AS) parameter defining the minimum acceptable grass appearance controlled by the soil water content.
cool-season grass grass appropriate for moderate to harsh winters; typically bluegrass, rye, bentgrass, and fescue.

crop evapotranspiration (ET) parameter indicating plant-water needs that combines transpiration and evaporation. For cool-season grasses the quantities of moisture converted by transpiration and evapotranspiration are roughly equivalent.
dew point temperature at which moisture begins to condense from an air mass.
effective rainfall precipitation that contributes to turf crop needs; i.e., that which can be stored in the root zone.
evaporation change of state from a liquid phase to a gas phase (e.g., from soil to atmosphere).
irrigation cycle time period encompassing the complete irrigation process — for our purposes this period includes all of the irrigation stations (sprinklers) being controlled by the programmer.
irrigation schedule timing sequence that specifies the days to irrigate, the time of day to initiate the irrigation cycle, and the valve operation-periods for each sequential station.
irrigation station single or multiple irrigation-valve grouping operated by a dedicated control signal from the timer
latching relay basically an electrically controlled on/off switch. A latching relay receives an electrical signal, operates the switch, and retains the switch position until the relay receives a second electrical signal that reverses the switch position.
manual intervention manual timer/programmer manipulation that overrides the preset timing sequence of an irrigation programmer. Many commercial irrigation programmers have a "water-saver" setting that allows the user to temporarily cancel the programmed watering sequence. The operator must be on site and must remember to reset the timer for normally scheduled irrigation.
no-water-days (nwd) days for which high ambient RH (low ET) indicates that scheduled water application is not required.
percolation liquid water filtering down into the deep soil. For our purposes deep percolation is water that penetrates to the soil beneath the root zone and is therefore not available to offset plant evapotranspiration.
potential evapotranspiration (ETo) a crop-need parameter calculated for a reference crop. The ETo generally represents the amount of water that the reference crop can use to produce maximum growth.
real-time control irrigation control for which the RH control parameter is continually monitored for allowing/interrupting the ongoing irrigation. If the ambient RH changes across the RH set-point during the irrigation cycle, some stations will irrigate; others will not.
reference evapotranspiration (ETo) another term for potential evapotranspiration.
relative humidity (RH) ratio (in percentage) of water that a volume of air contains compared to the amount of water that it could contain if it were fully saturated (RH = 100%).
RH set-point user-selected, fixed-RH setting on the humidistat controller. For all occurrences of higher ambient RH at the time of measurement irrigation is prevented.
runoff rainfall lost from the soil because it cannot be absorbed for various reasons, e.g., the rain is too intense or the soil is already saturated.
saturated soil soil that holds all the near-surface water that it is capable of holding.
soil moisture-holding capacity the amount of water that the root zone of the turf is capable of holding when fully "charged" or saturated. For typical grassed soils this value is from 0.4 to 0.7 inches.
solar radiation essentially the sun's energy received by the crop. This parameter can be measured by radiometers, but many stations estimate the reported parameter based on integrating clear/cloudy sky conditions. Especially for arid regions, this latter method provides satisfactory results for calculating ETo.
stress factor user-determined parameter that reduces water usage based on an acceptable turf appearance (see also turf quality). Applied when maximum crop growth is not essential
turf quality parameter selected by the user to control the appearance of the turf. Values typically range from 0.4 (low water use, high turf stress, probable browning) to 1.0 (maximum water use).
supplemental water calculated quantity that factors in ET, precipitation, crop factor, stress factor, and irrigation-system efficiency to determine the scheduled water needs.
timed-delay relay relay that locks a switch position (on or off) for a set period of time initiating from the time that it receives the activation signal.
transpiration water that is cycled from the soil through the plant to the atmosphere.

turf coefficient crop parameter for converting ETo to ET. There are two generally accepted coefficients for turf grasses — warm-season grass: 0.6 and cool-season grass: 0.8.
warm-season grass grass varieties suitable for regions with relatively mild winters. They include Bermuda, Zoysia, and St. Augustine, and typically require 25% less water than cool-season grasses.
water budget method scheme for regulating the moisture content in the soil by factoring applied water (precipitation and irrigation) against the accumulated ET losses for a moderately lengthy time period.
water deficit generally the difference between the effective precipitation and the crop needs as defined by ET.
yield threshold depletion level of soil moisture at which further loss will threaten the turf health. This condition is often used to trigger full moisture recovery when using the budget method.

APPENDIX II. Relative Humidity as it Relates to Evapotranspiration

Relative Humidity (RH) in atmosphere is a measure of continually changing moisture content only when it is used together with other weather-related parameters such as temperature. Water vapor content in the atmosphere is not uniform; it varies with land mass categories (e.g., arid versus tropical) and latitude, and for a given location, shows considerable variation over time especially with the passage of weather fronts. Warmer climates are capable of holding more moisture. Equatorial regions hold ~ten times the moisture of polar regions. Similarly, in atmosphere, water vapor-content decreases rapidly with altitude because of cooling temperatures. More than half the total water in the atmosphere is contained within about one mile above sea level. This fact explains why higher-altitude regions generally receive relatively less precipitation.

Definition of RH: the ratio of the actual vapor pressure to the saturation vapor pressure at a given temperature expressed as a percentage. Temperature is related to RH by the Ideal Gas Law: $\mathbf{P\nu=RT}$; where $\mathbf{P}$ = vapor pressure, $\boldsymbol{\nu}$ = specific volume, $\mathbf{R}$ = a gas constant, and $\mathbf{T}$ = temperature. Distilling this relationship to the content essential for our consideration, we note that vapor pressure is directly proportional to temperature. This fact implies that at higher temperature water vapor has more energy, i.e., more of it can remain in the vapor phase. When the temperature of an air volume is lowered, the accompanying reduction of the vapor pressure means that the air can hold less water vapor. If this air mass had been initially saturated (RH = 100%), the cooling causes the excess water vapor to be condensed, for example, as rain, dew, or clouds and fog. Understanding the concepts of vapor pressure and energy exchanges helps one to grasp the fact that atmospheric RH, rather than total water vapor content, is the parameter that controls rates of evaporation and transpiration. In this respect RH can be considered as the inverse potential that controls the rates at which these two natural phenomena can occur.

The forgoing has considered the maximum amount of moisture that a volume of air can contain. RH is always measured against this standard. Simply put, assuming quasi-static meteorological conditions of the atmosphere, the actual content of moisture in an air volume is little changed over a typical 24-hour period. RH however is constantly changing because of the diurnal temperature variation. With the moisture content relatively stable, the quantity of moisture that the air is capable of holding is what changes. Thus in the cool early morning hours that have the lowest possible saturation vapor content, ambient RH typically is at its highest level of the day, and conversely for hot afternoon periods. In the same vein, higher-elevation locations have relatively more diurnal RH variation because of greater variation in temperature. The latter effect arises because the thinner layer of atmosphere is less capable of holding the preceding day's solar energy close to the earth's surface.

The above considerations form the basis of why RH is a useful parameter for controlling irrigation scheduling. Considerable variation of this parameter is necessary if it is to be used as a control signal. What remains is to associate this RH variability with changing supplemental-water needs of turf, i.e., with evapotranspiration (ET). We next examine how RH is involved in ET calculations.

The ETo calculation usually involves some modification of what is known as a Penman Equation. Most agricultural data-provider networks have similar approaches that differ only in minor details. Four parameters are combined: RH, temperature, wind, and solar radiation. Earlier we showed how some of these parameters are strongly inter-related. Typically for data presentation, hourly averages are summed to calculate daily ET values. The Arizona (AZMET) hourly equation is: **ETo = W** x **Rn + (1-W) x VPD x FU2**; where **W** is a dimensionless partitioning factor, **Rn** is solar radiation (strongly related to temperature), **VPD** is the vapor pressure deficit (directly related to RH), and **FU2** is an empirical wind function. Temperature and RH are included in the makeup of both **W** and **VPD**. Because both collected terms at the right side of the equation factor RH into their makeup, it is rational to expect a strong correlation of RH behavior with the ET behavior. Indeed, the major conclusion of this study is the existence of a strong correlation of these two traces (RH and ET) that results in effective RH-controlled irrigation for the studied sites. For sites from several different meteorological-zone types, the ET needs of the turf are well matched by RH-controlled irrigation

APPENDIX III. Web-based ET/Weather Resources (western United States)

Arizona: University of Arizona, Arizona Meteorological Network (AZMET), 28 stations mostly in the southern part of the state, full data, **http://ag.arizona.edu/azmet/**

California: California Information Management Information Systems (CIMIS), ~100 stations, adequate data, **http://www.wateright.org/**

Colorado: Colorado Agricultural Meteorological Network (CoAgMet), about 30 stations, full data, **http://ccc.atmos.colostate.edu/~coag/**

Montana (east of Continental Divide), U.S. Bureau of Reclamation, Great Plains Region, AgriMet Data System, 21 stations**,** full data, **http://www.usbr.gov.pn/agrimet**

North Dakota: North Dakota Agricultural Weather Network (NDAWN), ~50 stations, **http:/www.ext.nodak.edu/weather/ndawn/**

New Mexico: New Mexico State University, 280 stations, full data, **http://weather.nmsu.edu/convert.html**

Nevada: Limited web-based information: two northern sites included in the Agrimet system (See Pacific Northwest region below.)

Oklahoma: Oklahoma now has the (fee required) MesoNet Service (also available for several other states), rainfall and accompanying high RH**,** **http://www.mesonet.org**

Pacific Northwest (Washington, Oregon, Idaho, Montana (west of the Continental Divide): Pacific Northwest Cooperative Agricultural Weather Network, Bureau of Reclamation, Agrimet Systems, ~50 stations, full data, **http:usbr.gov.pn/agrimet**

Utah: access to detailed worldwide ET and precipitation data (but not RH), **This latter set-point value introduces the use of "minimum RH" as the control parameter.** **http://climate.usu.edu**

Wyoming, eastern Colorado, Nebraska, Kansas, parts of North and South Dakota and Colorado: High Plains Regional Climate Center, good regional coverage, (fee required for detailed information), **http://www.hprcc/unl.edu/**

Texas (south central): Texas Evapotranspiration Web Site, Texas A & M University, 18 stations, full data, **http://agen.tamu.edu/wqit/petnet**

Texas (Panhandle): TX North Plains PET Network, Texas A & M University Agricultural Research and Extension Center, Amarillo TX, 9 stations, full data, **http:/amarillo2.tamu.edu.nppet/petnet1.html**

Entire country: A valuable source for the most comprehensive historical weather data (although not including ET information): National Climatic Data Center. Provides digitized and graphical data summaries called CLIMVIS reports. **http://www.ncdc.noaa.gov**

Reducing Residential Irrigation Water Use in Florida

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Abstract

With one of the largest rapidly growing state populations in the U.S., competition between urban, agricultural, and other water users in Florida is increasing. This project was conducted to determine if residential irrigation use in Central Florida could be influenced through changes in irrigation system design, irrigation scheduling, or landscape configuration. Three treatments were established in 2002 as follows: typical irrigation practices (T1), irrigation based on historical evapotranspiration (T2), and water wise landscape plus irrigation designed to minimize water use (T3). T1 and T2 irrigation systems consisted of sprinkler irrigation that included landscape plants and turfgrass on the same irrigation zones. T1 irrigation was scheduled by individual homeowners. T2 irrigation was scheduled based on 60% replacement of historical evapotranspiration. T3 irrigation systems were scheduled the same as T2 and included microirrigation in landscape bedding. T1 averaged 142 mm of irrigation per month while T2 and T3 averaged 119 and 87 mm, respectively. T2 and T3 irrigation water use corresponds to a 16% and 39% reduction in water use compared to T1, respectively. Turfgrass quality was not impacted by the reduced irrigation amounts. These results indicate that irrigation water use can be reduced by evapotranspiration-based scheduling and with landscape and irrigation systems designed to minimize irrigation.

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Introduction

Turfgrass is normally the most commonly used single type of plant in the Florida residential landscape. Although this region has a humid climate where the average precipitation rate is greater than the evapotranspiration (ET) rate, the spring and winter seasons are normally dry. The average annual precipitation for the Central Florida ridge is approximately 1320 mm, with the majority of this in the summer months. The spring months are typically the hottest and driest (USDA, 1981). This region is also characterized by highly permeable sandy soils with a low water holding capacity; therefore, storage of water is minimal. The dry spring weather and sporadic large rain events in the summer coupled with low water holding capacity of the soil make irrigation necessary to maintain the high quality turfgrass and ornamental landscapes desired by homeowners.

Residential water use comprises 61% of the public supply category. Public supply is responsible for the largest portion, 43%, of groundwater withdrawn in Florida. Groundwater withdrawals increased by 135% between 1970 and 1995 (Fernald and Purdum, 1998). The current Florida population of 16 million is projected to exceed 20 million people by 2020 (USDC, 2001) and with the average residential irrigation cycle consuming several thousand gallons of water, water conservation has become a state concern. Competition between residential, agricultural, and industrial users will continue to grow. Conservation of current supplies may be one approach to satisfy the needs of all users.

Several research projects regarding residential irrigation distribution uniformity and or irrigation water use were found in the literature. Barnes (1977) found residential irrigation rates that were 122 to 156% of seasonal ET rates. A study using soil moisture sensors to control residential or small commercial irrigation systems resulted in 533 mm used for irrigation compared to the theoretical requirement of 726 mm (Qualls et al., 2001). Residential irrigation uniformities (DU_{lq}) have been found to average 0.37 (Aurasteh et al., 1984) to 0.49 (Pitts et al., 1996). Reasons for non-uniform systems have been documented as lack of maintenance, mixed sprinklers within zones, poor nozzle selection, and improper sprinkler spacing (Pitts et al., 1996; Thomas et al., 2002).

The objectives of this project were as follows: 1) determine residential irrigation water use across typical landscapes in the region and 2) determine if combinations of irrigation scheduling and landscape/irrigation design could reduce water use.

Materials and Methods

Homeowners were recruited in Marion, Lake, and Orange Counties to participate in the project (Fig. 1). A total of 27 residents (9 in each county) were selected and randomly distributed into three treatments of three replicates within each county. Treatment one (T1) consisted of existing irrigation systems and typical landscape plantings, where the homeowner controlled the irrigation scheduling (Fig. 2). Existing irrigation was rotary sprinklers and spray heads installed to irrigate both landscape and turfgrass during the same irrigation cycle. Treatment two (T2) consisted of existing irrigation systems and typical landscape plantings similar to T1 (Fig. 3) and the irrigation schedule was set on a seasonal basis to replace 60% of historical ET according to guidelines established by Dukes and Haman (2001). Treatment three (T3) consisted of a landscape design that minimized turfgrass and maximized the use of native drought tolerant plants (Fig. 4). Ornamental landscape plants were irrigated by micro-irrigation as opposed to standard spray and rotor heads to achieve further water savings. Irrigation was scheduled based on the same methodology used on T2.

The average T1 or T2 irrigated landscape was comprised of approximately 75% turfgrass (60-88% range) where turfgrass and landscape plants were irrigated on the same irrigation zones. The turfgrass portion of the T3 landscape averaged 31% (5-66% range). The remaining landscaped area was irrigated with microirrigation or in some cases not irrigated after establishment.

A positive displacement meter was installed in the irrigation main line on each home. The irrigation meter and the utility meter were monitored monthly. Weather stations were installed in each county to monitor weather parameters such as temperature, relative humidity, wind speed and direction, incoming solar radiation, and precipitation. This allowed the calculation of reference ET (ET_o) according to procedures outlined by Allen et al. (1998).

The catch-can method of uniformity testing was used to test the distribution uniformity of the system as reported by Dukes et al. (2004). This testing was performed to determine differences, if any, in irrigation system distribution uniformity across treatments. As an index of distribution uniformity, the low quarter distribution uniformity (Merriam and Keller, 1978) was calculated as,

$$DU_{lq} = \frac{\overline{D}_{lq}}{\overline{D}_{tot}} \qquad [1]$$

where DU_{lq} is the low quarter distribution uniformity, $\overline{D}_{lq}$ is the average of the lowest 25% of catch can depths, and $\overline{D}_{tot}$ is the average of all catch can depths.

Turfgrass quality was assessed seasonally on each home across the entire turfgrass area to determine if the irrigation system uniformity impacted turf quality. Winter, spring, summer, and fall were defined as follows: December-February, March-May, June-August, and September-November, respectively. The assessment of turfgrass is a subjective process following the National Turfgrass Evaluation Program procedures (Shearman and Morris, 1998). This evaluation is based on visual estimates such as color, stand density, leaf texture, uniformity, disease, pests, weeds, thatch accumulation, drought stress, traffic, and quality. Turfgrass quality is a measure of aesthetics (i.e. density, uniformity, texture, smoothness, growth habit, and color) and functional use.

Statistical analyses were performed in SAS (SAS Institute, Inc., Cary, NC, 2003, version 8.02) using the GLM procedure. Means separation was performed with Duncan's Multiple Range Test at the 5% significance level.

Results and Discussion

<u>Irrigation Distribution Uniformity</u>

Measured DU_{lq} values of irrigation systems in this project averaged 0.45 with rotor zones averaging 0.49 and spray zones averaging 0.41 (Dukes et al., 2004). These values are in the range of research findings on similar systems in other states (Aurasteh et al., 1984; Pitts et al., 1996). Rotary sprinkler DU_{lq} was statistically higher than spray zone DU_{lq} ($p = 0.044$). The low-quarter distribution uniformities can be classified by the overall system quality ratings in Table 1 (IA, 2003) as "fair" to "fail", with the exception of one "good". When looking at the DU_{lq} of the spray and rotor zones individually, it can be noted that the ratings of the spray zones were much lower, with half of the spray zone uniformities receiving a "fail" rating. The ratings of the rotor zones were in the "good" to "fail" range (Dukes et al., 2004). Although the irrigation systems tested had relatively poor DU values, the overall turfgrass quality for the landscapes was consistently acceptable.

Pressure differences across residential irrigation zones did not vary more than 10%, which is considered acceptable (Pair, 1983). As a result, it was concluded that pressure variations did not negatively impact uniformity. Head spacing likely resulted in non-uniformity; however, well designed systems did not have higher uniformity when compared to typical systems in this study. This is due to the difficult design areas such as small side yards and strips of turfgrass that are difficult to irrigate evenly with minimal overspray (Baum et al., 2003).

Several types and brands of sprinkler heads were tested under controlled conditions and it was found that at recommended pressure levels, rotary sprinklers had a higher DU_{lq} (0.58) than spray heads (0.53). This was a similar trend as was found in the testing of the landscape irrigation systems at the residential sites (Dukes et al., 2004). In addition, the DU_{lq} values under controlled conditions (i.e. proper spacing; pressure and low wind) were higher than in the home tests. This indicates that irrigation system design was a small component of system nonuniformity. If sprinkler spacing and irrigation system design accounted for all of the variation in DU_{lq}, then testing equipment under controlled conditions would have resulted in DU_{lq} values in the ranges specified by the IA (Table 1). Based on these results, by improving irrigation system design in the tested landscapes, DU_{lq} could theoretically be improved only by 0.09 and 0.12 points for rotary sprinklers and spray heads, respectively. The distribution uniformities measured on the residential irrigation systems tested are in many cases as high as practically possible. The rating scales published by the IA (Table 1; 2003) may be unrealistically high for the equipment tested in this study.

Residential Irrigation Water Use

Overall, the average household used 62% of total water consumption for irrigation. This is in the range observed by previous research (Mayer et al., 1999; Aurasteh et al., 1984). T1 homes averaged 75% of total water use for irrigation, T2 averaged 66%, and T3 averaged 46% (Table 2), which were statistically different ($p<0.0001$). Part of the difference can be attributed to the size of the irrigated area which averaged 1347, 966, and 850 m^2 for T1, T2, and T3, respectively. Figure 5 shows the monthly fraction of total water use for irrigation. In all treatments, fraction of water used for irrigation tended to increase in the hot and dry spring months of March through May.

Many homeowners were out of town for extended periods of time in the summer months. During these periods, the percentage of water use consumed for irrigation purposes was higher in proportion to amount of water consumed inside the house. Three of the T3 homes were vacant for part of the data collection period because the irrigation system and landscape was installed prior to the sale of the house. This lack of occupancy did not affect the irrigation water use for the homes because the controller settings were adjusted as part of the study. The lack of occupancy did however affect the percentage of water used for irrigation by the household; therefore, months in which the irrigation water use percentage was 100% were omitted.

T1 homes had the highest average (averages calculated as weighted averages based on number of homes monitored a particular month) monthly irrigation water use, 141 mm (Table 2; Fig. 6). On average, T2 consumed 119 mm for irrigation purposes, while T3 used the least water for irrigation at 87 mm (not including establishment). T2 consumed 16% less water than T1, and T3 consumed 39% less than T1. The average monthly irrigation depth was significantly different ($p<0.0001$) across all treatments.

Figure 6 shows the variability of irrigation over the study period. Note that T3 homes had water use higher than T1 and T2 in much of 2002 (Fig. 6). This was a time period when four of the landscapes in T3 homes were being established (i.e. new landscape and irrigation system). During the establishment period, irrigation is often applied several times a day every day for 30 days or more. Although the first two months of irrigation data were removed from T3 due to establishment watering, some excess occurred in 2002 due to homeowner and contractor adjustment of the controllers. T1 and T2 homes did not have this establishment period during the study since the landscapes already existed. Table 6 shows monthly water use over the study period with the two-month establishment irrigation volume removed. Removing the establishment water from the 29-month monitoring period resulted in a total of 2945 mm of irrigation water on T3 while leaving the establishment water increased the total by 261 mm (total of 3206 mm).

Table 2 shows the seasonal average irrigation use for each treatment and turfgrass quality for each season. In the winter months, when the turfgrass growth rate is typically lowest, T3 used the least water, 55 mm, primarily because irrigation was limited and the microirrigation zones resulted in a smaller wetted irrigation area compared to sprinkler irrigation. In spring months, T1 used the most irrigation water (176 mm) with T2 (135 mm) and T3 (95 mm) using less in that respective order. The impact of microirrigation on irrigation water use of T3 compared to T2 homes is again apparent. However in the summer months, there was not a statistically significant difference in irrigation water use between the treatments. In these months, calculated ET_o was the highest and the adjusted controller run time settings were similar to that of typical user set run times. In addition, with frequent rainfall and rain sensors on the systems, the small differences between T1 compared to T2 and T3 scheduling were minimized since irrigation was not required during this season. In the fall months, T1 and T2 consumed similar amounts of irrigation water, 155 mm and 148 mm, while T3 consumed significantly less, 102 mm. Turf quality was statistically lower on T3 landscapes in the winter season. In part, this may have been due to reducing the irrigation amounts such that the turf went partially dormant. Homeowners many times tried to avoid this process by irrigating and fertilizing excessively in the cooler months. However, in all seasons over all treatments, turf quality did not fall below the acceptable limit of “5” (Table 5). In addition, the turfgrass experienced green up in the spring and there was not a significant difference in turf quality across treatments for other seasons of the year.

Calculated ET_o for the monitoring period totaled 3055 mm. Over the 29-month monitoring period, all treatments used more irrigation water than ET_o not including rainfall as an input. While the actual crop water use is unknown because turfgrass crop coefficients (Kc) for this region and Kc values for landscape plants in mixed communities such as residential yards are not available, we estimate that annual turfgrass water use is approximately 75% of ET_o for this region. If these values are used to roughly calculate actual water requirements for the irrigated yards in the study assuming the entire irrigated area were turfgrass (landscape plants not included) for the monitoring period, T1, T2, and T3 resulted in 82%, 52%, and 29% (not including establishment) more water use than necessary, respectively. It is unknown how much of the rainfall is effective (i.e. available for plant consumption); however, if it is estimated that 50% of the total rainfall is effective, then over-irrigation was considerable on all treatments (155%, 124%, and 101%, respectively). Microclimates in each yard, mixed plant communities, and irrigation inefficiencies could account for some of the over-irrigation. The increased irrigation water savings on T3 was due to irrigation of landscape beds with microirrigation where a fraction of planted area (i.e. in between plants) is not irrigated, as opposed to sprinkler irrigation which is intended to irrigate a given area evenly.

Although it appears that precipitation alone would have met crop needs, the sporadic and intense rain events in the study region often resulted in short dry periods even in the summer rainy season. Irrigation was generally necessary in the spring months (Mar-May), in the fall (Sep-Nov), and during short dry periods in the summer (Jun-Aug).

Conclusions

In this project the following conclusions were developed:

1. Changing head spacing in the irrigation system of cooperator homes would have increased measured distribution uniformity 0.09 to 0.12. Much of the non-uniformity was due to equipment performance.
2. Setting irrigation controllers seasonally based on historical ET resulted in 16% average monthly water savings compared to the "typical" user.
3. Setting irrigation controllers based on historical ET and establishing 39% of the irrigated area with microirrigation or no irrigation resulted in 39% average monthly water savings compared to the "typical" user.
4. Turf quality was above acceptable limits on all treatments throughout this project.
5. Irrigation water use on all treatments could be reduced further since all treatments still irrigated in excess of plant water requirements.

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Table 1. Irrigation Association (IA, 2003) overall system quality ratings, related to distribution uniformity.

Quality of Irrigation System	Irrigation System Rating (ISR)	Distribution Uniformity (DUlq)
Exceptional	10	> 0.85
Excellent	9	0.75 – 0.85
Very Good	8	0.70 - 0.74
Good	7	0.60 - 0.69
Fair	5	0.50 - 0.59
Poor	3	0.40 – 0.49
Fail	< 3	< 0.40

Table 2. Seasonal water use and turfgrass quality rating across irrigation/landscape treatments.

		Winter	Spring	Summer	Fall	Average
Treatment 1	Water Use (mm)	103a*	176a	134a	155a	142
	Turf Quality Rating#	5.7a	5.9a	5.8a	6.6ab	6.0
Treatment 2	Water Use (mm)	78b	135b	110ab	148a	119
	Turf Quality Rating	6.4a	6.6a	5.6a	6.9a	6.3
Treatment 3$	Water Use (mm)	55b	95c	96b	102b	87
	Turf Quality Rating	5.4b	6.4a	5.1a	5.8b	5.7

*Letters indicate differences across season as indicated by Duncan's Multiple Range Test at the 95% confidence level.
#"1" is lowest, "5" is rated as acceptable, and "9" is highest.
$The first two months excluded due to increased water use for landscape establishment period.

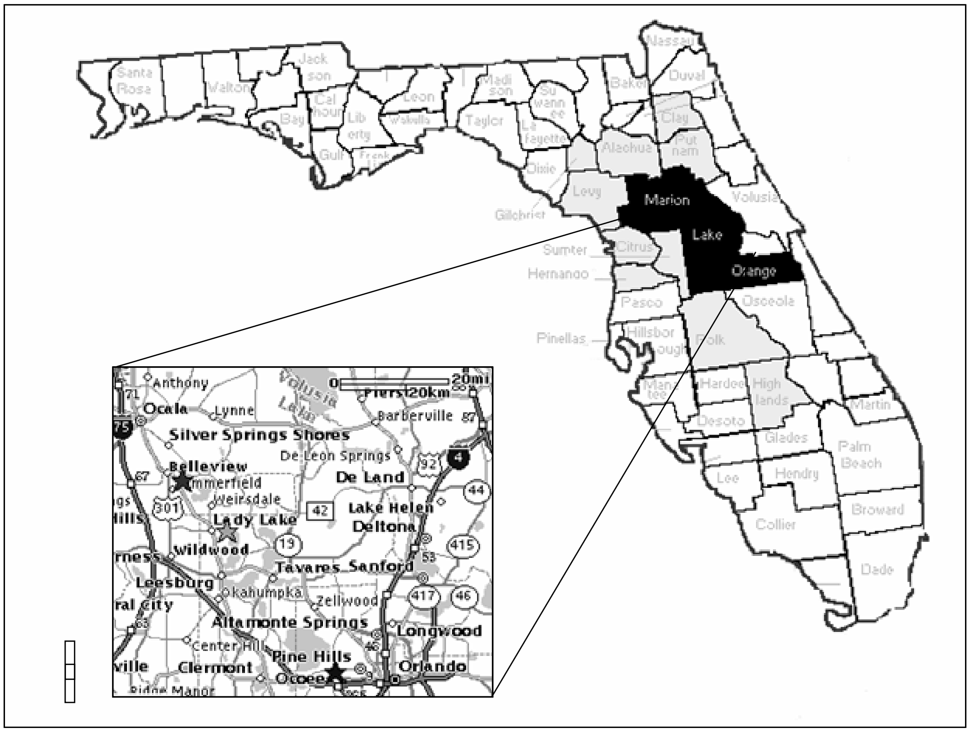

Figure 1. Project site locations in Marion, Lake, and Orange Counties.

Figure 2. Example T1 cooperator home.

Figure 3. Example T2 cooperator home.

Figure 4. Example T3 cooperator home.

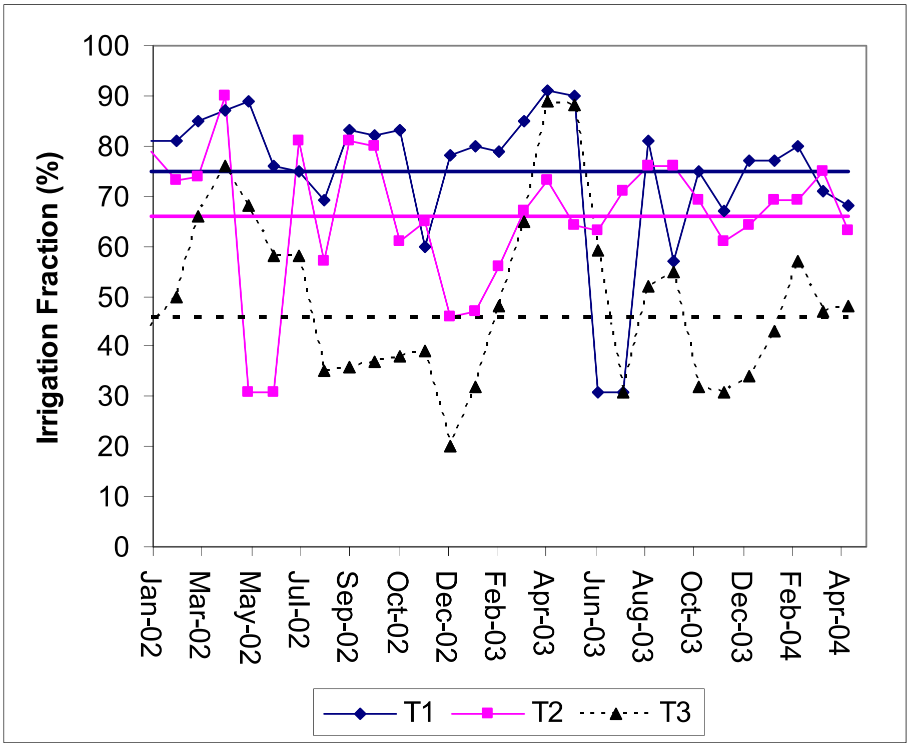

Figure 5. Monthly fraction of water used for irrigation Jan 2002 – May 2004. Averages are shown as horizontal lines.

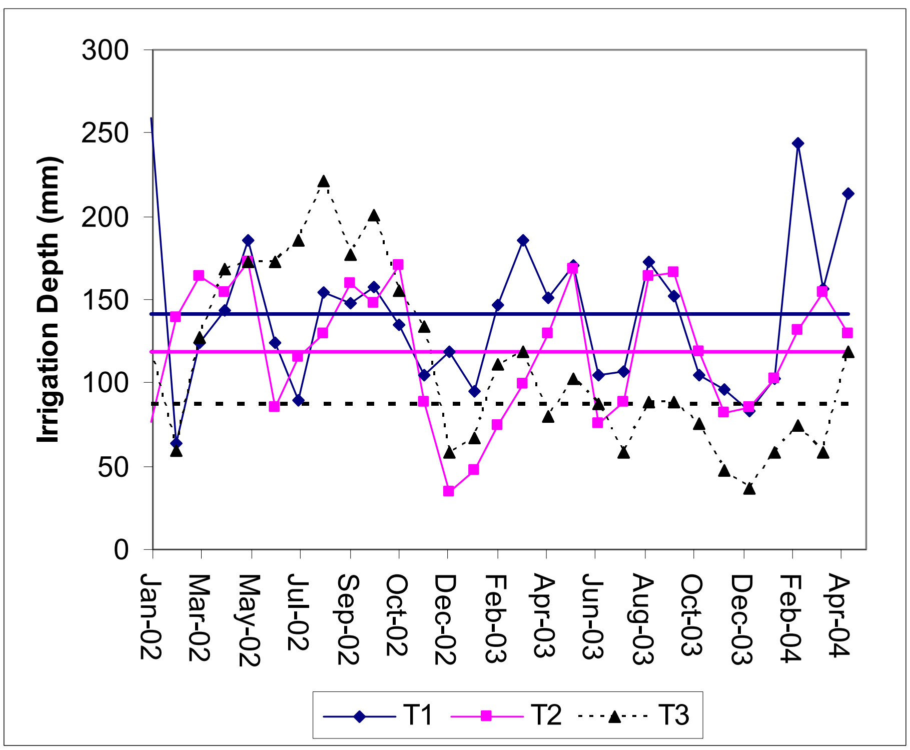

Figure 6. Monthly irrigation water use Jan 2002 – May 2004. Averages are shown as horizontal lines. T3 average not including landscape establishment.

What's all the Fuss About ET Controllers?

- Why the Need
- Public Agency Studies
- What's Next

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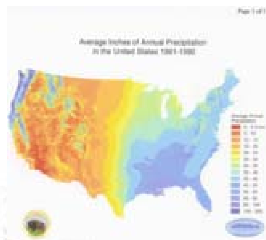
HydroPoint data systems, inc.

The Current State of Landscapes

36 States will have water shortages even with average rainfall within 5 years.

US GAO



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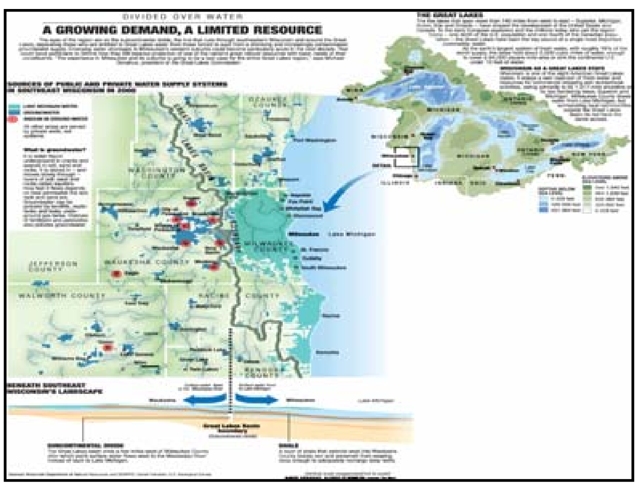
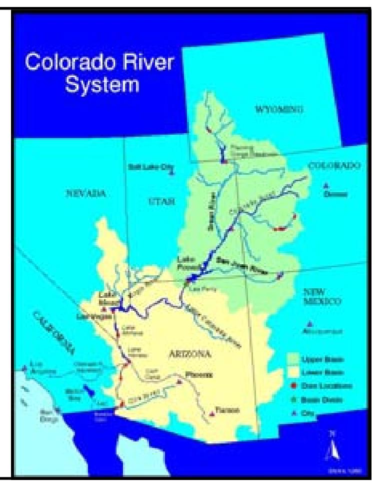


Colorado River

- Sustains over 20 million people and the US's most productive agriculture
- 5 years of below normal runoff
- 2002 lowest flow in over 1,400 years; just 26% of average.
- Current storage about 60 percent of capacity
- 2003 runoff about 65 percent of normal

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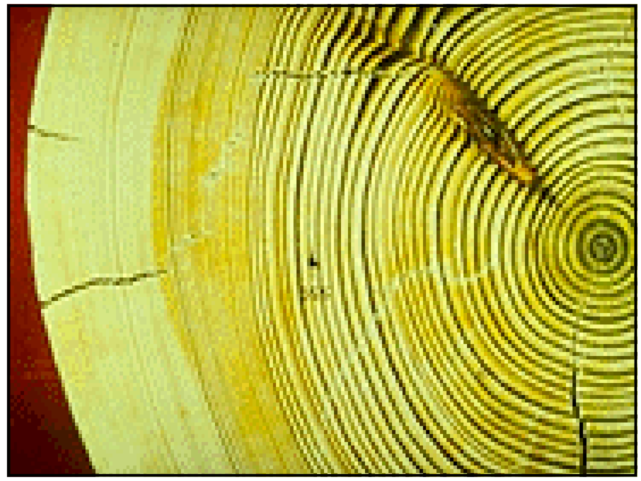
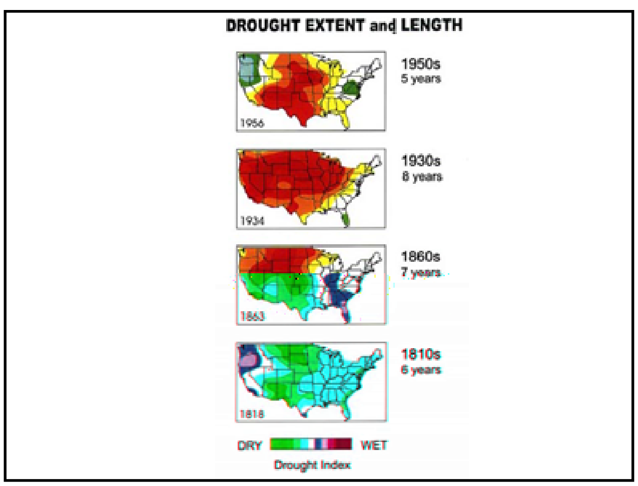



DROUGHT EXTENT and LENGTH
1950s
5 years
1956
1930s
8 years
1934
1860s
7 years
1863
1810s
6 years
1818
DRY
WET
Drought Index


04.25.2004


03 14 2004

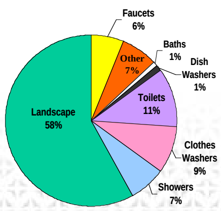

OCV

Public Perception of Landscapes…

URBAN WATER USE
LANDSCAPE IRRIGATION

58% of all urban water use goes to landscape irrigation

(American Water Works Association)



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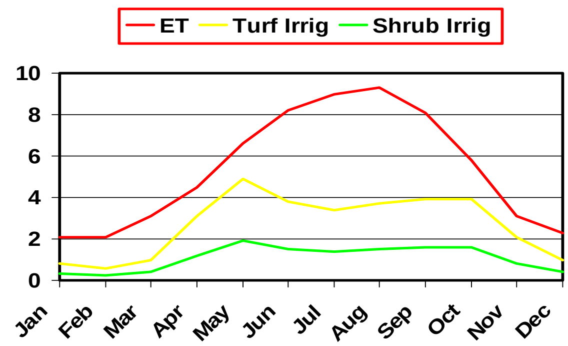
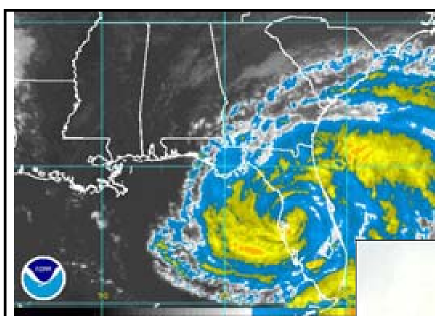
Tampa ET & Estimated Rain Adjusted Irrigation





Florida

Residential Irrigation Efficiency Assessment

Dr. David Dukes, Univ. of Florida

- 61% of home water goes to landscapes
- GW withdrawls increasing at a 135% rate
- Turf homes use 82% more water than needed
- Xeriscape homes use 29% more water than needed
- Average irrigation system efficiency was 45%

Result? Limits on Landscaping...

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How Much Water Is Wasted in Landscapes?

- Irvine Landscape water reduced 58%
- Denver homes use about 48% more water
- Utah Extension measures 53% over-water
- Florida study shows 29%-82% over watering

50%

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How Much Water Should a Landscape Use?

Contractor: 1" ET, Turf, Clay Loam, Spray, Full Sun, Flat?

7-20 Minutes	4.2 Minutes
4 Days / Week	2/3 Days / Week
1 Cycle	2/3 Cycles

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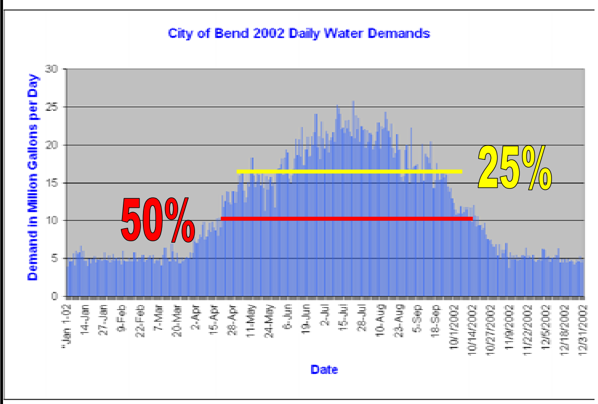
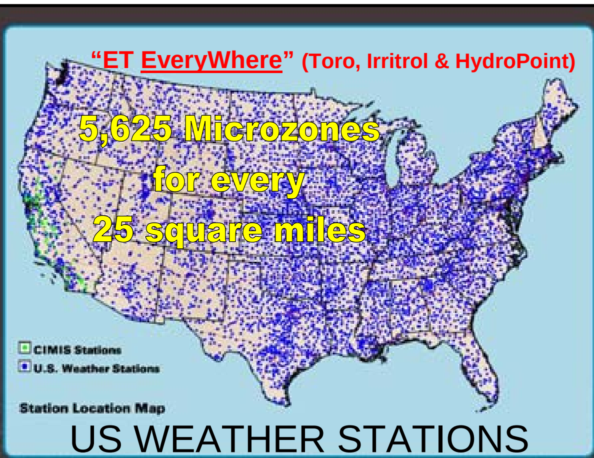


ET Data?

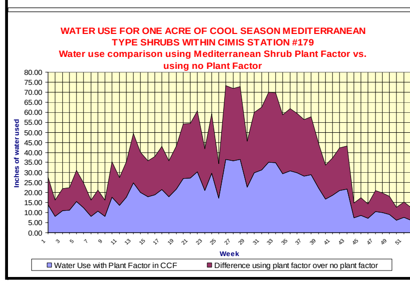
- State systems (CIMIS, AgriMet)
  - Penman Montieth modified equation
  - Solar Radiation
  - Wind
  - Humidity
  - Temp

How Many Do You Need?



ET? So What!

Need: Crop Coefficients (Kc) that relate actual plant water to the local weather (ETo)



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Irrigation Association:

Steps for a Proper Schedule

- **Soil type** (infiltration rate, h2o holding capacity)
- **Sprinkler type** (precipitation rate, uniformity)
- **Plant type** (Kc, root depth)
- **Slope** (for runoff control)
- **Sun / shade**
- **Allowable moisture depletion value**

"Smart" Irrigation

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ET Controller Studies

1st Study in 1998:

- 16% - 25% Savings
- 97% customer satisfaction
- 97% reported plant appearance good or better

2nd Study in 2001

- Residential Runoff Reduction / EPA
- 71% reduction in the test neighborhood
- Same findings on landscape appearance

Led to $5 million in state grants

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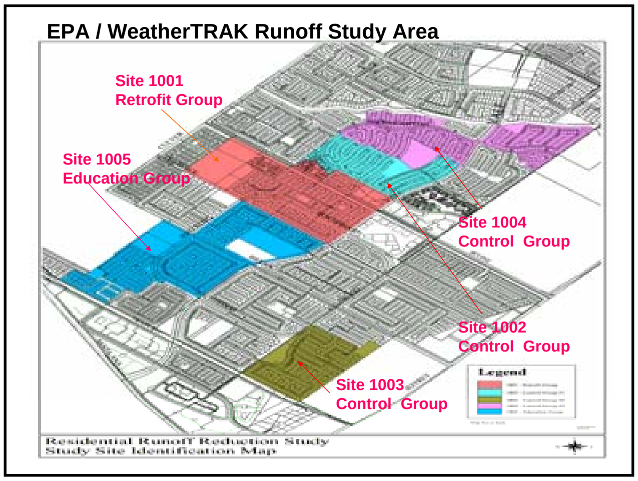

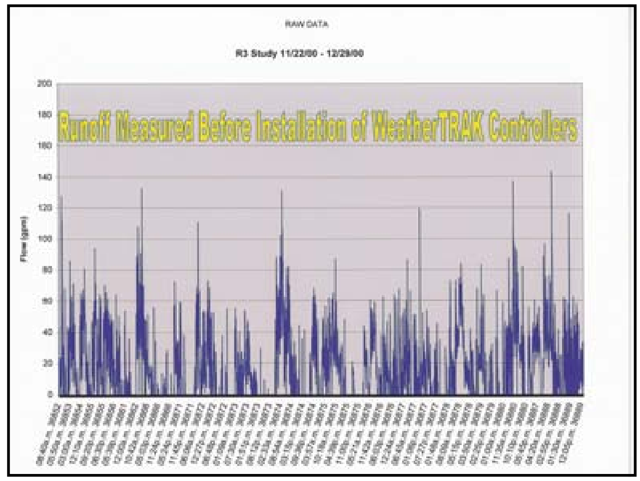

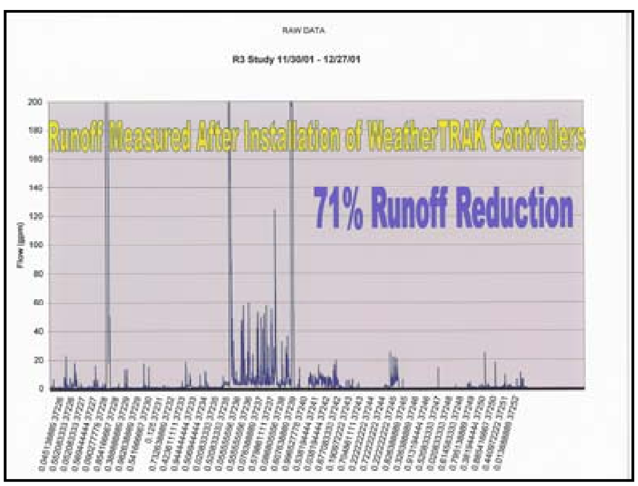

Agency Studies: "ET" Controllers

- **Irvine (2)** (field test)
- **Los Angeles DWP** (field test comparing 2 products)
- **Metropolitan Water District of So. Calif.** (bench test w/ 3 products)
- **UC Riverside** (bench test comparing 4 products)
- **Santa Barbara Water District** (field test)
- **Colorado** (field tests with 3 products)
- **Lake Arrowhead, Ca. / USBR** (field test)
- **Seattle** (field test)
- **Univ. Nevada Reno / UNLV** (field tests)
- **Utah** (field test with 2 products)
- **Univ. of Arizona** (field test with 3 products)
- **Santa Rosa/Sonoma Co.** (field test)
- **Marin, Ca.** (field test with 2 products)

EPA "Water Star" Labeling

Center for Irrigation Technology (bench testing to "certify" products)

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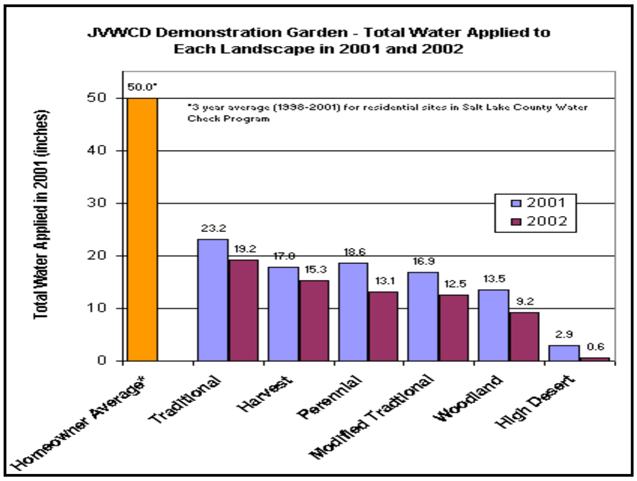
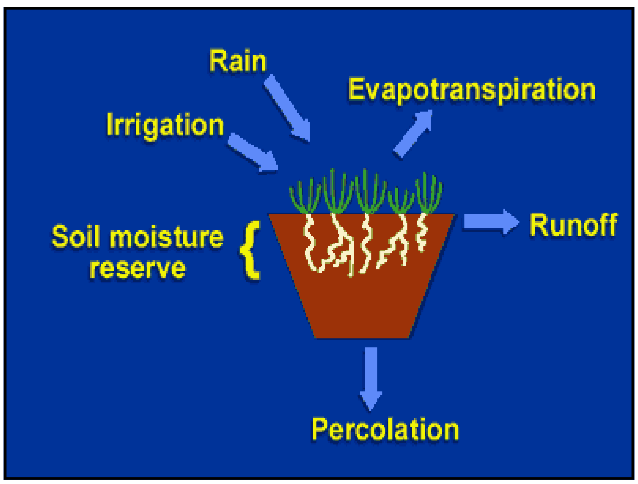
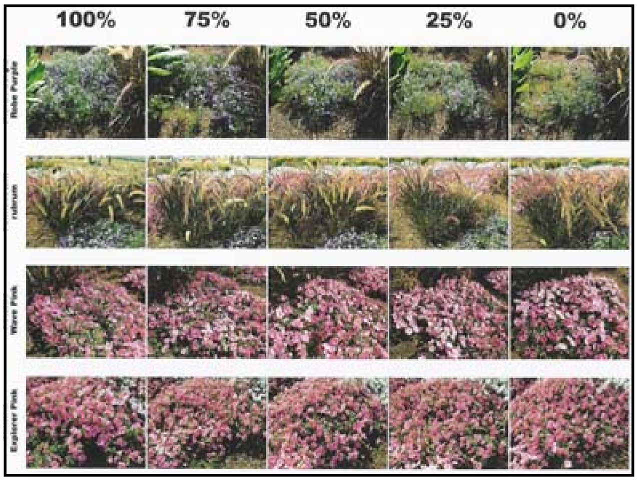
ET Controllers: Next Steps

- **Center for Irrigation Technology (CIT) Bench Testing Certification**
- **EPA "Water Star" Labeling Program**







ET Controllers Are Not Created Equal!

Group 1: Real Time ET, ET Everywhere, Automatic Scheduling Engine (IA Steps), Subscription Fee

Group 2: Real Time ET (existing stations), Managed Schedules, Initial User Schedule, Mgt. Service Fee
Sub-group: On/off signals to existing controllers

Group 3: Historical ET, Pre-Set Changes, Initial User Schedule, No Service Fee

Group 4: Single Sensor(s) linked to Schedule Changes, Initial User Schedule, No Service Fee

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Expectations of ET Controllers…

- They **will** save water…
  - Water can only be saved if there is wasted water
- They will save ____% of your landscape water…
  - They will only save some portion of the wasted water
- "Set it" and "forget it"…
  - Most units need an initial schedule; what if the schedule is inaccurate; what if someone changes something...

*Anything that goes wrong in the Landscape will be blamed on the "New" Controller…

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Issues Raised by Agencies, Experts & the Public?

- **User schedules** (quality of schedules)
- **Maintenance of sensors** (who, who much, etc.)
- **Placement of sensors** (creates poor data)
- **Size of companies with the technologies**
- **Ability to change controller settings**
- **Customer Service ability** (does the business model support long-term support?)
- **Acceptance of subscription/service fees**
- **Need for weather stations/communications infrastructure**
- **Buy or lease the equipment**
- **Rain recognition**

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What Have Studies Shown?

- **Water that is wasted can be saved**
- **Water use can also go up** (one study found 40% of participants water bills went up)
- **Studies can be poorly designed or have inaccurate set-up** (one study put controllers into homes that had prior deficit irrigation; another study set up controllers w/ inaccurate data; one study placed sensors in the wrong locations…)
- **Studies show that applying the right amount of water (ET x Kc) exposes poor irrigation systems**

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Landscape Industry Opportunity

1. Use **proven** smart controllers to save water…and help avoid landscape restrictions
2. Use **certified** controllers to apply the right amount of water…and expose poor irrigation systems
3. Provide **services** to fix/upgrade poor irrigation systems

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Benefits of "Transformation"

- Protects landscapes and the landscape industry by using the right amount of water & reducing water runoff
- Offers increased business opportunity

$$$$$$

Risk?

- Poorly performing products hurt the "transformation" to significantly improved landscape water management
- Industry needs to fully understand the products, the issues and the business opportunities

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What to Do Right Now!

- Visit product booths out on the trade show floor
- Assist local agencies and universities w/ studies on plant water needs (Kc)
- Try products on your sites to become an expert

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Current State of Landscapes

- Landscapes waste water
- Precise water management will be required (or landscapes will be regulated)
- Water supply and water waste will force changes in the way landscapes are designed, maintained, irrigated, etc.

"Water shortages will create crisis management and conflict."
US Dept. of Interior

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Landscape Species Performance under Irrigation Levels based on Reference Evapotranspiration

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Riverside, CA, USA

Keywords: Xeriscape, ET, ornamental, water, drought tolerance

Abstract

Landscape irrigation scheduling using reference evapotranspiration (ET_0) information is being adopted by the industry with little research-based information relevant to landscape performance. The objective of this study was to determine the aesthetic response of 30 species to irrigation treatments based on ET_0. Experimental plots were established in Encinitas, California, consisting of nine, 1920 ft^2 blocks allowing three drip irrigation treatments replicated three times. Treatments initially were 0.36, 0.24, and 0.12 ET_0, but were adjusted to 0.36, 0.18, and 0.0 ET_0 during the second and third years of the study. The aesthetic quality of 16 species was reduced with reduced irrigation. Many of these species performed well at the 0.36 and 0.18 ET_0 treatments but suffered at 0.0 ET_0. Quality was not affected by irrigation treatment in 11 species. The results show that ET_0 treatments affect landscape quality for some species and acceptable appearance can be maintained with reduced irrigation.

INTRODUCTION

The use of reference evapotranspiration (ET_0) information for scheduling irrigations and for determining water allotments for landscapes is being adopted by water purveyors, agencies, landscape architects, and maintenance personnel. Although ET_0 information is available in California from a statewide network utilizing local weather station data, the information must be adjusted using a crop coefficient (K_c) or correction factor for use in scheduling irrigations for different plant materials. Many scientific studies have established K_c values for agricultural crops based on ET_0 and yield response. K_c values have also been determined for cool and warm season turfgrasses (Gibeault, et al.1990). However, there is little research-based information relevant to landscape ornamental plant materials. One confounding factor is that landscape plant materials are valued for their appearance and the yield concept is not relevant. Landscapes are also difficult to characterize because they often consist of small plantings of numerous species. In addition, some species utilized for landscapes have the ability to maintain acceptable aesthetic quality under reduced irrigation (Pittenger, et al. 2001). The objectives of this project were to determine the response of 30 ornamental species to irrigation treatments based on ET_0 and to further refine estimates of ornamental plant water needs for acceptable aesthetic appearance.

MATERIALS AND METHODS

The study was conducted at Quail Botanical Gardens in Encinitas, California, which has a coastal Mediterranean climate. The soil is a Chesterton fine sandy loam [fine, kaolinitic, thermic Abruptic Durixeralf] with pH 6.8 and ECe 1.7 dS m^{-1}. The soil available water is approximately 1.2 in.ft^{-1} soil.

The experiment was a randomized complete block design with three irrigation treatments and three replicates for a total of nine blocks. Each 1920 ft^2 block was separated by an 8 ft walkway and divided into 30 square, 64 ft^2 experimental units (plots). Thirty woody shrub species were selected for the experiment (Table 1). Each 64 ft^2 plot contained four individual plants of each species with the exception of *Chamaerops humilis* and *Correa alba*, which contained five and six test plants, respectively. The planting locations for each species within blocks were randomized to minimize bias resulting from factors such as shading, root competition, and block edge effects. The plants were transplanted from one gallon containers between December 1994 and February 1995.

Each block was irrigated using Roberts Irrigation Ro-Drip tubing with three equally spaced drip lines running across each plot. The tubing contained 3.0 gal/hr emitters spaced at 1.0 ft, which resulted in a precipitation rate of 0.17 in/hr. The drip lines were connected to buried PVC pipe with a valve, pressure regulator, and meter for each irrigated block. Distribution uniformity of the irrigation system was approximately 0.90. For establishment, plants received irrigation based on tensiometer readings and assessment with a soil probe to achieve maximum vigor and growth rate.

Irrigation treatments of 0.36, 0.24, and 0.12 ET_0 were initiated in June 1996. During 1997 and 1998, irrigation treatments were adjusted to 0.36, 0.18, and 0.0 ET_0 because initial treatments were not significantly affecting plant quality in many of the species. ET_0 data from the California Irrigation Management Information System (CIMIS) weather station in Oceanside were used for irrigation scheduling. A 0.5 inch irrigation was applied when the accumulated ET_0 of a given treatment (projected soil moisture deficit) reached 0.5 inch. Irrigation scheduling by this method resulted in different intervals between applications and different amounts of water applied over a season among the treatments, but similar penetration of water (12-18 in.) into the root zone at each irrigation event. No additional water was applied to compensate for non-uniformity of the irrigation system. Irrigation treatments were applied during the summer and fall months, while rainfall and irrigation supplied equal amounts of water among treatments during the winter and spring (Table 2).

Cultural practices included fertilization, weed control, and minimal pruning. The study plots received approximately 2.0 lb. per 1000 ft^2 N per year. Hand weeding and preemergent (oxadiazon) and systemic (glyphosate) herbicides were used to control weed problems on the site. Coarse wood chip mulch was spread three inches deep along pathways between blocks and in open areas within blocks to control weeds, protect irrigation lines, and reduce evaporation.

Data collection consisted of measurements of plant height, ratings of aesthetic quality, water applied, and observational notes. The visual rating of aesthetic quality was recorded 12 times during the study using a 1 to 9 scale where 1 = dead or dying plants, 5 = aesthetically unacceptable in a landscape, and 9 = optimum appearance (Pittenger, et al. 2001). Ratings were based on the density, vigor, color, and uniformity for each species. Analyses of variance of the height and quality data for each observation date were performed and mean separation was calculated using Fisher's (protected) LSD tests at the P = 0.05 significance level.

RESULTS AND DISCUSSION

Applied water, rainfall, and ET_0 data for the three-year study are summarized in Table 2. All plant materials (hereafter referred to by genus name) performed well in the study with the exceptions of *Chamaerops*, *Ceanothus*, and *Salvia*. These species failed to establish adequately for treatment replication. Two species, *Echium* and *Myoporum* performed so well that they overgrew the plot area and were removed or severely pruned during the second year of the study. Analysis of variance (AOV) of data from the entire experiment indicated that there were significant differences between irrigation treatments and interaction between species response and irrigation treatment. Height data indicated that there were significant differences in growth of several species due to irrigation treatment. This could have significant implications for maintaining these species adequately with minimal green waste production. However, we feel that the type of measurements taken were not precise enough to characterize the treatment effects.

Figure 1 contains charts illustrating aesthetic performance of representative species. Data is not shown for species that responded similarly. AOV of aesthetic quality data indicated that there were significant differences due to irrigation treatments in 16 of the species studied. Performance of these species was typically reduced at the lower irrigation treatment (0.18 or 0.0 ET_0) in the late summer and fall months and not significantly different for the remainder of the year. These species can be divided into several groups based on their response to the 0.0 ET_0 treatment. In *Arbutus* (Figure 1-A), *Arctostaphylos*, and *Calliandra*, more water resulted in higher aesthetic rating. Performance at the 0.0 treatment was usually less than at the 0.36 treatment and at the lower limit of what we would consider acceptable in the landscape. Plants of these species in the 0.0 ET_0 treatment recovered during the winter months. In *Otatea*, *Pittosporum*, and *Xylosma* (Figure 1-B), the response was similar but aesthetic quality of plants in the 0.0 ET_0 treatment dropped below the acceptable level during the summer and fall. Nevertheless, these species recovered each year. In *Correa*, *Escallonia*, *Lantana*, *Leptospermum*, *Phormium* (Figure 1-C), *Rhaphiolepis*, *Teucrium*, and *Westringia*, plants in the 0.0 ET_0 treatment either died or were severely injured and failed to recover.

In eight species (*Artemisia, Cistus*, *Echium*, *Grevillea*, *Heteromeles*, *Myoporum*, *Prunus,* and *Pyracantha*), there were no significant differences in appearance among treatments and their quality was consistently rated at 6.0 or greater (acceptable for landscapes). Response of *Cistus* (Figure 1-D) was representative of these eight species. *Prunus* performance remained greater than 6.0 for most of the study but varied year to year probably due to general climatic or species adaptation factors rather than irrigation amount. Similarly, *Artemisia* needed some renovation after three growing seasons to maintain acceptable appearance.

Aesthetic appearance of *Cassia* (Figure 1-E), *Galvezia*, and *Leucophyllum*, was not significantly different between treatments but their ratings were less than 6.0 from late summer through winter, which meant they were unacceptable as landscape ornamentals for part of each year regardless of irrigation treatment. Although not significant, there was a trend for *Galvezia* to perform better with less water.

Hibiscus (Figure 1-F) and *Ligustrum* expressed reduction in quality over the three-year period in all treatments and severe injury at the 0.0 ET_0 treatment indicating that these plant materials were probably under-irrigated even at the highest treatment level.

In conclusion, several species of shrubs, many of them common landscape plants, appear capable of providing acceptable landscape performance with very low amounts of summer irrigation in coastal Mediterranean areas such as coastal urban southern California. Eight shrub species performed well with no irrigation during the treatment periods (*Artemisia*, *Cistus*, *Echium*, *Grevillea*, *Heteromeles*, *Myoporum*, *Prunus* and *Pyracantha*), while 13 species were able to do so with 0.18 ET_0 (*Arbutus*, *Arctostaphylos*, *Calliandra*, *Correa*, *Escallonia*, *Lantana*, *Leptospermum*, *Otatea*, *Phormium*, *Pittosporum*, *Rhaphiolepis*, *Westringia*, and *Xylosma*). Data for these 21 species suggest that in the landscape, acceptable appearance is possible for a wide range of applied water levels. While *Teucrium* performed well only at the 0.36 ET_0 treatment, *Hibiscus* and *Ligustrum* were probably under-irrigated at this level. Future studies need to be performed to verify these findings in climates with higher ET_0 values and to further document growth reduction without loss of aesthetic quality at reduced irrigation levels. These findings provide useful information for incorporation into irrigation scheduling procedures and for landscape water conservation programs.

ACKNOWLEDGEMENTS

We wish to thank Quail Botanical Gardens, Roberts Irrigation Products and the San Diego County Water Authority for support of this research.

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Table 1. Genus, species, citation, and common names of plant materials studied.

Genus, Species, and Citation	Common Name
Arbutus unedo 'Compacta', L.	Compact strawberry tree
x*Arctostaphylos* 'Pacific Mist', (L.) Spreng.	Bearberry
Artemisia x 'Powis Castle', L.	Wormwood
Calliandra haematocephala, Hassk.	Pink powder puff
Cassia artemisioides, Gaud.	Feathery cassia
Ceanothus griseus horizontalis 'Yankee Point', McMinn.	Carmel creeper
Chamaerops humilis, L.	Mediterranean fan palm
Cistus purpureus, Lam.	Orchid spot rock rose
Correa alba 'Ivory Bells', Andr.	White Australian correa
Echium fastuosum, Jacq.	Pride of Madeira
Escallonia x *exoniensis* 'Fradesii', Veitch.	Frades escallonia
Galvezia speciosa, Gray.	Bush snapdragon
x*Grevillea* 'Noell', Knight.	Noell grevillea
Heteromeles arbutifolia, M.J.Roemer.	Toyon
Hibiscus rosa-sinensis, L.	Rose of China
Lantana montevidensis, Briq.	Trailing lantana
Leptospermum scoparium, J.R.Forst.& G.Forst.	New Zealand tea tree
Leucophyllum frutescens 'Green Cloud', I.M.Johnst.	Texas ranger
Ligustrum japonicum 'Texanum', Thunb.	Texas privet
Myoporum x 'Pacificum', Banks & Sol. ex Forst.f.	Myoporum groundcover
Otatea acuminata, (Munro)C.E.Calderon & Soderstr.	Mexican bamboo
Phormium tenax, J.R.Forst.& G.Forst.	New Zealand flax
Pittosporum tobira, Ait.	Mock orange
Prunus caroliniana, Ait.	Carolina cherry laurel
Pyracantha koidzumii 'Santa Cruz', Rehd.	Santa Cruz pyracantha
Rhaphiolepis indica, Lindl.	Indian hawthorn
Salvia leucantha, Cav.	Mexican bush sage
Teucrium chamaedrys, L.	Germander
Westringia rosmariniformis, Sm.	Rosemary bush westringia
Xylosma congesta, Merrill.	Shiny xylosma

Table 2. ET_0, precipitation and applied irrigation water (inches) for treatment periods from June 1996 through October 1998.

Dates (inclusive)	ET_0 (in.)	Precipitation (in.)	Water Applied (in.)		
			0.36 ET_0	0.18 ET_0	0.0 ET_0
Jun 1996 to Oct 1996	27.5	-	10.4	6.9	3.0
Nov 1996 to May 1997	25.2	12.3	4.9	4.7	4.8
June 1997 to Oct 1997	27.2	-	8.9	4.8	0
Nov 1997 to Mar 1998	12.1	21.5	0	0	0
Apr 1998 to Oct 1998	36.6	-	13.4	7.3	0

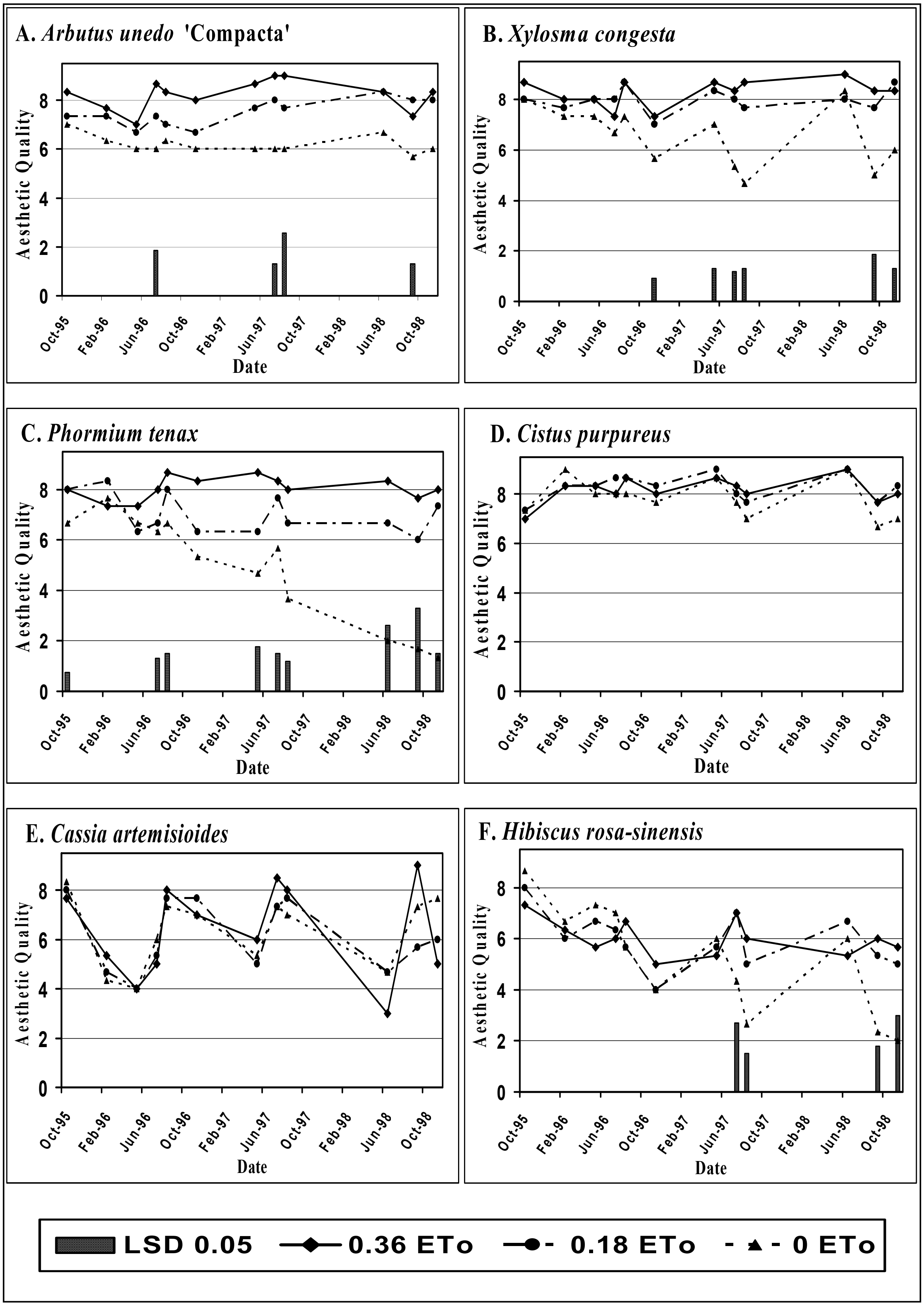


Figure 1.A-F. Aesthetic quality and LSD values (on dates when significant) for landscape species given 0.36, 0.18, and 0.0 ET_0 treatments from October 1995 to October 1998.

Free, Untapped Water For Irrigation in Humid Regions

Introduction

Humid regions have an untapped water source that is virtually free and unrestricted during drought. Air conditioning produces large amounts of condensate ideal for landscape irrigation. This water is reliable, clean and is produced when irrigation demand is high. Large buildings send millions of gallons of condensate to sewers and storm drains. Changing this practice is simple during design, but can also be achieved through retrofits.

The amount of condensate water produced in San Antonio is surprising. A shopping mall measured their June collection from seven air handlers at 2.5 gallons each minute. The downtown library easily fills their 26,000 gallon system at a one gallon/minute collection rate. These high yields provide a quick payback for the small investment needed to harvest condensate water.

Condensate Recovery Manual Draft

By Eddie Wilcut & Brian Lilibridge

This session will review design and cost/benefit analysis steps outlined in the Draft San Antonio Water System Condensate Recovery Manual produced by Eddie Wilcut and Brian Lilibridge of San Antonio Water System. To provide feedback contact Eddie or Brian at ewilcut@saws.org.

Condensate 101

Simply put, **condensation** is the process by which water vapor turns from a gas state into a liquid state. Consider what happens when you set a glass of ice water outside on a warm, sunny day. The temperature of the outside air is higher than the temperature of the surface of the glass. As the water vapor in the air surrounding the glass cools down it changes from a gaseous state to a liquid and the glass appears to sweat. This "sweat" is actually condensate forming on the surface of the glass. The same effect can be seen in the winter when condensate forms on the inside of windows.

A few other related terms that might be helpful in understanding the process of condensation are "absolute humidity", "relative humidity", and "dew point". **Absolute humidity** is the total amount of moisture that air can hold at a given temperature. **Relative humidity** is given as a percent value and indicates the amount of moisture air contains in relation to the absolute humidity. When your local meteorologist refers to humidity during the forecast, they are actually talking about relative humidity. Another staple in most weather forecasts is the dew point. The **dew point** is the temperature at which water vapor condenses out of the air and forms moisture on the ground and other surfaces outside. As air cools, it's ability to hold water in the form of vapor decreases. The dew point is reached when the air temperature cools sufficiently in relation to the absolute humidity to allow dew to form. These same principles that cause condensate to form on the glass of ice water or windowpane and dew to form on the grass are responsible for the generation of condensate by air conditioning equipment.

Air Conditioning System Basics

Air conditioning systems vary in size and configuration. But whether it is a small window unit, a 5-ton system used for a single-family residence, or a 1,000-ton system used at a manufacturing facility, the process of conditioning air is basically the same. Single-family residences and many businesses can be effectively cooled by a **split-system** where the condensing unit is placed outside and the air handler is located inside the structure. Very large or multi-story facilities may require a different type of system that uses chilled water instead of a refrigerant gas.

In a split-system, the **condensing unit** contains a compressor, exhaust fan, and condenser coils. A refrigerant gas is compressed and ran through the coils where it is condensed into a liquid. Once in liquid form, the refrigerant is passed through an expansion valve where it evaporates back into a gas and in the process, cools rapidly. The chilled gas is then run through another series of coils (the **evaporator**) inside the building where it absorbs heat from the surrounding air. The evaporator along with a ventilation fan make up the part of the A/C system often referred to as the **air handler**, and this is where condensation occurs. As the fan pushes the warm, moisture-laden air over the evaporator, the water vapor condenses out and accumulates on the coils. The condensate is collected in a drip tray where it is usually drained to the outside of the structure or into the sanitary sewer. But as you will see in the following sections, the reuse potential for condensate makes it much too valuable to simply be drained away.

Condensate Production in Commercial/Industrial Facilities

Influencing Factors

Facility managers may question whether their facility can produce enough condensate to make collecting it a cost-effective venture. Homeowners that have had the misfortune of having their home partially flooded by a blocked condensate line have seen first-hand the potential of condensate production in our area. The average residential air conditioning system can produce anywhere from 5 to 10 gallons of condensate a day. It is not hard to realize the potential of industrial air conditioning systems to produce large amounts of condensate. Several factors will determine how much condensate can be produced by a facility, but some of the predominant ones are weather, industrial processes/human factors, and cooling capacity.

Weather

San Antonio experiences an abundance of warm, sunny weather. In the winter, 50 percent of the days are sunny and in the summer that figure increases to 70 percent. In fact, this area averages over 300 sunny days annually. Maximum daily temperatures during the summer are above 90 degrees over 80 percent of the time.

San Antonio Weather Statistics

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Median Temperature (deg. F)	Max.	60.8	66.2	73.4	80.6	86.0	91.4	95.0	95.0	89.6	82.4	71.6	64.4
	Min.	37.4	41.0	50.0	59.0	66.2	73.4	75.2	75.2	69.8	59.0	48.2	41.0
	Mean	50.0	53.6	62.6	69.8	75.2	82.4	84.2	84.2	78.8	69.8	60.8	51.8
Amount of Sunshine	hrs/mon.	159	170	216	210	222	276	309	294	235	218	172	150
Relative Humidity (%)	Morning	80	80	79	82	87	88	86	85	85	84	81	80
	Afternoon	60	58	56	58	61	59	54	53	56	56	58	59

In addition to that, San Antonio enters a sub-tropical weather pattern in the summer. The relative humidity is highest in the early morning and decreases as temperatures warm up during the day. The average relative humidity in San Antonio humidity ranges around 50% in the late afternoon. That's not as much as our neighbors to the east- Houston's average relative humidity ranges around 63% in the afternoon. But it's still a substantial amount of moisture in the air, and it makes a hot day feel even hotter. The result of all of these climatic factors combined is that air conditioning equipment must operate constantly throughout the day in order to meet the requirements of most industrial/commercial facilities.

Industrial Processes/Human Factors

Condensate production will also be greatly influenced by the manufacturing processes and human activities that occur within a facility. Computers, copy machines, and other office necessities as well as lighting, and manufacturing equipment all introduce heat into the working environment. Manufacturing processes such as sterilization or food preparation that generate large amounts of steam and heat will increase the potential for condensate production by introducing added moisture in the air. Also, certain working environments like clean rooms require a closely controlled humidity. These situations require A/C equipment to worker harder and run longer to maintain specific working environments and therefore lead to increased condensate production.

Large-scale facilities that are not used for manufacturing can still produce a useable amount of condensate. Human activity alone can dramatically influence the potential for condensate recovery. Facilities that experience a high amount of foot traffic have large amounts of outside air continually brought inside, causing increases in the indoor temperature and humidity. Human respiration and body heat also increase indoor temperature and humidity. While seemingly insignificant on an individual basis, the heat and moisture generated by a large number of people can significantly affect indoor air characteristics.

Cooling Capacity

A facility's cooling capacity plays perhaps the most direct role in condensate production. Systems with a higher rated tonnage and load factor will produce condensate in greater amounts. **Tonnage** is a measurement that relates a system's cooling capacity to the equivalent cooling effect of melting ice. For example, a system rated at 2 tons can produce the same amount of cold air as melting two tons of ice per hour. Also, air conditioning systems are seldom operated at full capacity. The **load factor** is a ratio of the average system load over a certain period of time to the maximum rated capacity of the system. Multiplying the tonnage by the load factor gives an indication of the actual amount of cooling a system is doing. In effect, a 1,000-ton system operated at a load factor of 70% is equivalent to a 700-ton system operating at 100%.

Estimating Condensate Production

Although numerous factors influence condensate production, most large facilities in this area can expect to produce around 0.1 to 0.3 gallons of condensate for every hour the cooling system is operated. This range is based on measurements taken at several large facilities around San Antonio. It is best to use 0.2 gallons per hour to provide a conservative estimate of condensate production for planning purposes. To calculate condensate production for a specific system multiply tonnage, load factor, and .02 gallons. For example:

1,000 tons X 70% load factor X 0.2 gallons = 140 gallons per hour

The following chart provides condensate estimates for a variety of system sizes and load factors:

ESTIMATED GALLONS OF CONDENSATE PRODUCED PER TON HOUR OF OPERATION

LOAD FACTOR (%)	CONVERSION FACTOR**	COOLING EQUIPMENT TONNAGE										
		50	**100**	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
50	0.1	2.5	5.0	10.0	15.0	20.0	25.0	30.0	35.0	40.0	45.0	50.0
	0.2	5.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0
	0.3	7.5	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	135.0	150.0
55	0.1	2.8	5.5	11.0	16.5	22.0	27.5	33.0	38.5	44.0	49.5	55.0
	0.2	5.5	11.0	22.0	33.0	44.0	55.0	66.0	77.0	88.0	99.0	110.0
	0.3	8.3	16.5	33.0	49.5	66.0	82.5	99.0	115.5	132.0	148.5	165.0
60	0.1	3.0	6.0	12.0	18.0	24.0	30.0	36.0	42.0	48.0	54.0	60.0
	0.2	6.0	12.0	24.0	36.0	48.0	60.0	72.0	84.0	96.0	108.0	120.0
	0.3	9.0	18.0	36.0	54.0	72.0	90.0	108.0	126.0	144.0	162.0	180.0
65	0.1	3.3	6.5	13.0	19.5	26.0	32.5	39.0	45.5	52.0	58.5	65.0
	0.2	6.5	13.0	26.0	39.0	52.0	65.0	78.0	91.0	104.0	117.0	130.0
	0.3	9.8	19.5	39.0	58.5	78.0	97.5	117.0	136.5	156.0	175.5	195.0
70	0.1	3.5	7.0	14.0	21.0	28.0	35.0	42.0	49.0	56.0	63.0	70.0
	0.2	7.0	14.0	28.0	42.0	56.0	70.0	84.0	98.0	112.0	126.0	140.0
	0.3	10.5	21.0	42.0	63.0	84.0	105.0	126.0	147.0	168.0	189.0	210.0
75	0.1	3.8	7.5	15.0	22.5	30.0	37.5	45.0	52.5	60.0	67.5	75.0
	0.2	7.5	15.0	30.0	45.0	60.0	75.0	90.0	105.0	120.0	135.0	150.0
	0.3	11.3	22.5	45.0	67.5	90.0	112.5	135.0	157.5	180.0	202.5	225.0
80	0.1	4.0	8.0	16.0	24.0	32.0	40.0	48.0	56.0	64.0	72.0	80.0
	0.2	8.0	16.0	32.0	48.0	64.0	80.0	96.0	112.0	128.0	144.0	160.0
	0.3	12.0	24.0	48.0	72.0	96.0	120.0	144.0	168.0	192.0	216.0	240.0
85	0.1	4.3	8.5	17.0	25.5	34.0	42.5	51.0	59.5	68.0	76.5	85.0
	0.2	8.5	17.0	34.0	51.0	68.0	85.0	102.0	119.0	136.0	153.0	170.0
	0.3	12.8	25.5	51.0	76.5	102.0	127.5	153.0	178.5	204.0	229.5	255.0
90	0.1	4.5	9.0	18.0	27.0	36.0	45.0	54.0	63.0	72.0	81.0	90.0
	0.2	9.0	18.0	36.0	54.0	72.0	90.0	108.0	126.0	144.0	162.0	180.0
	0.3	13.5	27.0	54.0	81.0	108.0	135.0	162.0	189.0	216.0	243.0	270.0
95	0.1	4.8	9.5	19.0	28.5	38.0	47.5	57.0	66.5	76.0	85.5	95.0
	0.2	9.5	19.0	38.0	57.0	76.0	95.0	114.0	133.0	152.0	171.0	190.0
	0.3	14.3	28.5	57.0	85.5	114.0	142.5	171.0	199.5	228.0	256.5	285.0
100	0.1	5.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0
	0.2	10.0	20.0	40.0	60.0	80.0	100.0	120.0	140.0	160.0	180.0	200.0
	0.3	15.0	30.0	60.0	90.0	120.0	150.0	180.0	210.0	240.0	270.0	300.0

**The conversion factor will vary based on location and site conditions.

Reusing Condensate

Water Quality
Condensate is a high quality source of water, making it ideal for numerous applications. Because of the removal of minerals during the evaporation process, condensate is similar in water quality to distilled water. In condensate, suspended solids, turbidity, and salinity are low and the pH is neutral to slightly acidic. It is important to keep air-conditioning equipment as clean as possible in order to ensure that condensate stays uncontaminated In particular, the evaporator coils and drip trays should be kept free of dust, dirt and other debris since the condensate comes in direct contact with their surfaces.

One concern that deserves special attention when dealing with condensate is the possible presence of microbial pathogens. If condensate is allowed to stagnate and become warm in a cooling system, it can lead to favorable growth conditions for the *legionella pnuemophila* bacteria that is the cause of Legionnaires' disease. Although legionella pnuemophilia is commonly found in a variety of natural and man-made aquatic environments, it can become a public health threat if water containing the bacteria is atomized and inhaled. Outbreaks of Legionnaires' Disease have been traced to poorly maintained cooling towers, but the bacteria can be easily controlled by several commercially available biocides.

Methods of Collection
With careful planning, collecting and reusing condensate is an easy process. The materials used to construct a condensate collection system are readily obtainable and easy to assemble. The three main components of a condensate collection system are collection piping, a storage tank, and a method of delivery to the point of reuse- this can be achieved by gravity or a pump. Incorporating a condensate collection system into the design of a new facility will significantly lower the cost and decrease the time it takes the system to pay for its self. Air handlers can be positioned in such a way that gravity can be used to move the condensate to storage tanks or nearby cooling towers. It is also important to maintain easy access to the condensate drip trays so that they can be cleaned regularly.

Considerations for Irrigation
The water produced by condensate from cooling processes is clean. However, it easily picks up contamination from drip pans and other surfaces. The same would be true for rainwater collected from a roof. ANY water stored for more than a few days should be considered a potential hazard and treated accordingly before public contact.

Irrigation systems in public areas are one potential way for people to come in contact with water from a collection tank. If water is applied through drip irrigation, there is very little potential for human contact with the water and not much reason for concern. However, if water will be sprayed through traditional spray heads it is necessary to consider a biocide process. Options can be as simple as regularly dropping pool chlorine tablets into a tank. Pool equipment that automates chlorination is even more convenient.

There are pool equipment devices that allow chlorine tablets to be added and then circulated periodically into the tank. This adds slightly to the cost of the condensate project because the chlorination device and a pump are added. However, the payback and peace of mind that the water is safe are worth the investment.

Case Studies

Sony Semiconductor, San Antonio, Texas
In 1999, Sony Semiconductor began construction on a system to collect condensate from three outside air handlers. The project involved the routing of condensate from three outside air handlers through a system of pipes connected to cooling tower make-up lines. The construction involved installation of new piping and three return pumps. This system also incorporated an in-line meter, to allow for the tracking of water savings.

The average monthly cooling tower usage is 2,700,000 gallons. The potential average monthly condensate collected by this system equals 155,940 gallons or 1,871,000 gallons per year.

Based on a $5,777.00 investment and financial savings of $4,371.08 per year, the simple payback period was calculated at 16 months.

San Antonio Public Library Alternative Irrigation Project
In 2002, the San Antonio Library began work on a new 26,000 square foot educational garden. In order to further the educational impact, it was suggested that a rainwater harvesting system be considered. San Antonio Water System's (SAWS) Conservation Department was contacted for assistance in evaluating the effectiveness of installing a rainwater harvesting system. As a result, Conservation Planners evaluated the potential based on such factors as the type of landscape, evapotranspiration, annual rainfall, storage requirements and cost.

Because rainfall events in Texas can often be sporadic, it is important to size an effective rainwater harvesting system with sufficient storage capacity to collect enough water during rain events and store it until those months when little or no rainfall is received. For example, if one were to assume median rainfall during the month of July in San Antonio, TX, a rainwater harvesting system for a 26,000 square foot landscape would need to employ approximately 26,000 gallons of storage capacity. For this reason, rainwater-harvesting systems, within urban settings such as San Antonio, TX, are not usually cost effective measures.

As an alternative, Conservation Planners also evaluated the potential for condensate collection. The potential was determined simply by locating the building's condensate drain and recording collection readings over span of several days. Based on collection data, it was determined that the building's air conditioning system was producing condensate at the rate of one gallon per minute (gpm) or 1,440 gallons per day or 43,200 gallons per month.

Based on a complete evaluation, a condensate collection system was designed and constructed. The system incorporates a collection system comprised of three interconnected concrete cisterns with a total storage capacity of 8,400 gallons.

Condensate is pumped into the tanks from a collection sump and is gravity fed into a specially designed irrigation system. The condensate collection system provides all supplemental landscape water even during periods with little or no rainfall. Total cost of the system, including drip irrigation is $21,500.00, an amount that is less than 1/3 of cost of a rainwater harvesting system.

Rivercenter Mall, San Antonio, Texas

In 2002, the Rivercenter Mall completed construction of a condensate collection system capable of capturing condensate water from four large air-handlers. This system incorporates a three-inch drain line system, a 500-gallon collection tank, and a pump for transferring the captured condensate to the cooling towers as make-up water.

An analysis of five years of pre-retrofit consumption data and two years of post-retrofit consumption data reveals average savings of 1.1 million gallons per month or 13.2 million gallons per year.

The significant water savings are a result of a reduction in potable water necessary for cooling tower make-up and increased cooling tower efficiency attributed to the introduction of a water source that has virtually no hardness and is very low in total dissolved solids.

The total installed cost of the Rivercenter Mall system was $32,057.92. Based on water and sewer savings of $49,500.00 per year, the simple payback for this system has been calculated at approximately eight months.

H.E.B. Grocery Company Distribution Center, San Antonio, TX

In 2003, the H.E.B. Grocery Company constructed a condensate recovery system capable of providing boiler feed makeup water in replacement of potable water. The system captures condensate from air-handlers and refrigeration systems, saving more that 6.2 million gallons of potable water each year.

Based on an installed cost of $19,000.00 and financial savings of $20,600.00 per year, the simple payback was calculated at 11 months.

Additional References

- Emory article
- North Carolina article
- UT article

Rain Harvesting for Supplemental Irrigation

Historically, rainwater was harvested out of necessity. Where potable water systems were unavailable, rainwater or well water were the only choices. Wells ran dry or provided poor quality water, so rainwater was sometimes the best alternative.

Now, most people rely on water from a municipal provider or a water district. This costly, high quality water is also used for landscape irrigation, when rainwater harvesting could provide an alternative source.

Why collect rainwater? Rainwater pH is almost neutral in most geographic areas of the U.S. It does not have dissolved minerals from the soil or chemicals from water treatment facilities. By harvesting rainwater, you may be able to reduce erosion. Substituting rainwater for potable water in the landscape may reduce your client's overall water bill. Most plants thrive with rainwater.

Rainwater harvesting is not new. It has been practiced in the desert of southern Israel for over 4,000 years. Ancient Romans had cisterns and aqueducts. Even in this country, early 1900's farms and ranches had cisterns. So, consider adding a simple rainwater harvesting system into your next irrigation bid package.

Components for a low-cost rainwater system that stores 3,000 gallons could cost less than $1,000. There is no need for a pump because this (illustrated) gravity feed system is just hooked up to soaker hoses in landscape beds. Some, high quality drip systems may also work, but their gallons per hour rate is usually based on a minimum of about 15 p.s.i. Remember your irrigation calculations? You only gain .43 p.s.i. per foot of elevation, so a 10-foot tall tank full of water would produce less than 5 p.s.i.

How much will it cost? Well, it depends. There are quite a few variables. Are gutters already provided? If not, what type of gutters will be installed? What type of tank will be specified and how much capacity will it have? Will there be a pressure tank and pump? How is the soil? Does a pad need to be designed to hold the weight of a water filled tank. A system diagram and parts list has been provided. An irrigator could add an easy $1,000 profit to the next job with a simple system.

The least expensive tanks are polyethylene. They run about $900 for 3,000 gallons in Central Texas. ($.35 to $1.00 per gallon, depending on size.) In our market, they are available from farm and ranch stores or rural fencing suppliers. We even have several "big box" stores that stock cisterns. Poly tanks are the most common for urban landscape watering. If you do not use the black or green ones, you have to paint the outside to reduce the growth of algae. The next type, at a little higher price, is galvanized metal. Most suppliers have gone to epoxy liners to reduce early failure, but our experience shows that galvanized tanks do not last long in areas with frequent high humidity. Condensation forms every morning and does not disappear until late morning. Consequently, rust forms at the seams. Pinhole leaks are common. Newer methods of reducing condensation include the use of a web-like material inside the tank for drainage, with a vinyl liner to actually hold the water. This may provide a longer life to metal cisterns. Their cost is about $.40 to $.60 per gallon.

Fiberglass is probably next in line as we go higher in initial cost. They are usually available direct from regional manufacturers and sometimes from distributors. The lifespan is good, but you may need to occasionally repaint the outside to make them last longer.

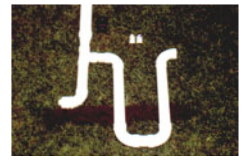
Novices do usually not install the next few cistern types, but you may want to familiarize yourself about their availability in your market. Wooden tanks are being manufactured in the U.S. as well as being imported from New Zealand. Their cost is $2.00 per gallon or more. They are ideal for remote locations, as they are assembled on site from a "kit". They can be disassembled and reused. Some large timber tanks are 2 million gallons in size.

Cement tanks made from cast rings that are stacked together may be available in your area. These are sometimes used in agricultural irrigation systems.

Steel fabricated tanks can be ordered through manufacturers. These need to be painted to enhance longevity.

Concrete or ferro-cement tanks can be constructed on site. Some swimming pool companies have experience making a formed bottom for a cistern, then forms are installed to support a poured concrete top. Hand lay-up or hydraulic pumping may be used for the bottom and sides. These tanks are durable and can be buried or on the surface.

Stone tanks are very expensive to build correctly, but were the method of choice years ago. They can be difficult to repair and maintain.



Components for a rainwater system include some sort of "first flush" filtration. That is a simple way to keep the leaves, bird droppings and dust on the roof out of the cistern. These range from simple to more complex. A "poor man's roof washer" consists of PVC pipe that collects the first few gallons of water, before the cleaner water is diverted into the cistern.

A roof washer may also be constructed or purchased that uses serviceable filters to eliminate debris. These require maintenance and cost between $300 and $600. They are not necessary for non-potable landscape watering systems.

Any type of roofing material works for landscape watering, but metal roofs are preferred for potable water systems. The ideal roof for rainwater harvesting is smooth and non-absorbent.

Gutters run about $30 per foot for plastic, up to $15 per foot for copper. You do not need to pay for downspouts if you are immediately building the rainwater system, because the downspouts need to be solid PVC piping starting at least 6" higher on the wall than the inlet into the tank. Gutter screens or leaf omitting caps may be necessary in areas with trees.

Pumps cost from $200 to $600, but are not required in a simple system. A 3/4 hp pump will pump water 400 feet, depending upon terrain. Provision must be made for an in-tank float switch and a process to protect the pump in freezing weather. Install the pump as close to the tank as possible.

Maintenance would include frequent cleaning of the first flush filter. If you have screens, clean them also. Most systems that have been installed for 5 years, have not required tank cleaning, but if silt builds up, use a wet/dry vacuum or borrow a small kid.

Where mosquitoes are a problem (let me know where you live where they are not a problem), Bt tablets and granules are available in pond supply stores. You just need a little each month.How can you begin? Hire a consultant or experienced rainwater installer for your first few jobs. Let them know up front that at some point you expect to be installing complete systems on your own. Rather than actually installing systems, you might just contract with qualified installers for your rainwater equipped job and add in profit to the bid submittal.

Why not connect a small rainwater system into the irrigation system? 3,000 gallons would be gone in just one irrigation cycle in a typical landscape.

My experience with these systems is limited to non-potable uses in areas with moderate winters. In areas with frequent freezing temperatures, consult with a qualified local rainwater installer.

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Rainwater Harvesting Resources

Organizations:

American Rainwater Catchment Systems Association:
http://www.arcsa-usa.org
International Rainwater Catchment Systems Association:
http://www.ircsa.org

Books, Magazine Articles & Videos:

City of Tucson Water Harvesting Guidance Manual:
http://www.ci.tucson.az.us/planning/whm.pdf
Harvesting Rainwater for Landscape Use, Patricia Waterfall, Arizona Department of Water Resources:
http://www.water.az.gov/adwr
Rainwater and You, Group Raindrops. Order through Makoto Murase, Ph.D.,:
murase-m@jcom.home.ne.jp
Rainwater Harvesting for Drylands, Brad Lancaster:
http://www.harvestingrainwater.com
Rainwater Harvesting for the Mechanically Challenged, Richard Heinichen:
http://www.rainwatercollection.com
Rainwater Collection Systems:
http://www.oikos.com/catalog/videos/rainwater.html
"Rainwater Harvesting", Daniel Winterbottom, from Landscape Architecture, April, 2000:
http://dnr.metrokc.gov/wlr/PI/pdf/Rainwater-Harvesting.pdf
Texas Guide to Rainwater Harvesting:
http://www.twdb.state.tx.us/assistance/conservation/Alternative_Technologies/Rainwater_Harvesting/Rain.htm
"Water Saving in the Garden", King County Department of Natural Resources and Parks, King County, Washington:
http://dnr.metrokc.gov/wlr/PI/pdf/cistern-water-saving.pdf

Tanks:

American Tank, polyethylene tanks:
http://www.watertanks.com
Norwesco, Inc., polyethylene tanks, 14 plants throughout U.S. and Canada via local distributors:
http://www.norwesco.com
Red Ewald, Inc., fiberglass tanks:
http://www.redewald.com

Tanks (cont.):

Timber Tanks America, Inc., wooden tanks:
http://www.timbertanks.com
Xerxes Corporation, fiberglass tanks:
http://www.xerxescorp.com

Roof Washers, Diverters, First Flush Filters, Gutters, Gutter Leaf Excluders:

FloTrue International Corporation:
http://www.flotrue.com
Gutter Helmet:
http://www.gutterhelmet.com
Gutter Shield:
http://www.aok.org/shield.htm
GutterTopper:
http://www.guttertopper.com
K-Guard Leaf Free Gutter System:
http://www.kguard.com
LeafGuard:
http://www.leafguard.com
Permaflow Gutter Guard System:
http://www.permaflow.com
WaterFall Gutter Guard System:
http://www.waterfall.crane-plastics.com
Waterloov by Gutter Covers Company:
http://www.waterloov.com
Wedge Downspout Screen:
http://www.avlis.com
Wisy Products:
http://www.wisy.de

Other Information:

Mosquito Dunks:
http://www.summitchemical.com
http://www.bugpage.com/mosquito.html
or at a local home store or pond supplier.

Cistern Modeling:
http://www.treepeople.org/trees/cistern2.htm

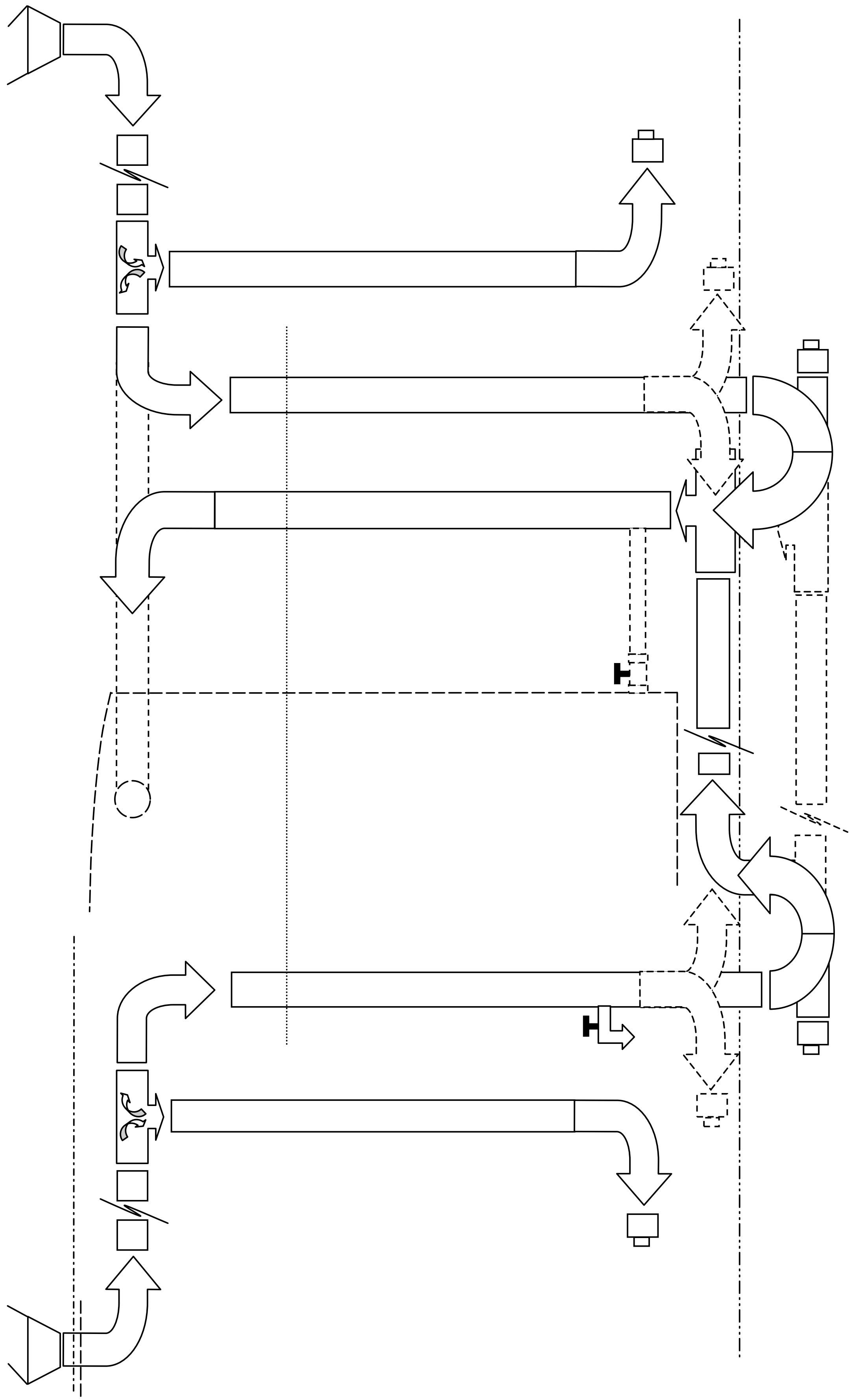
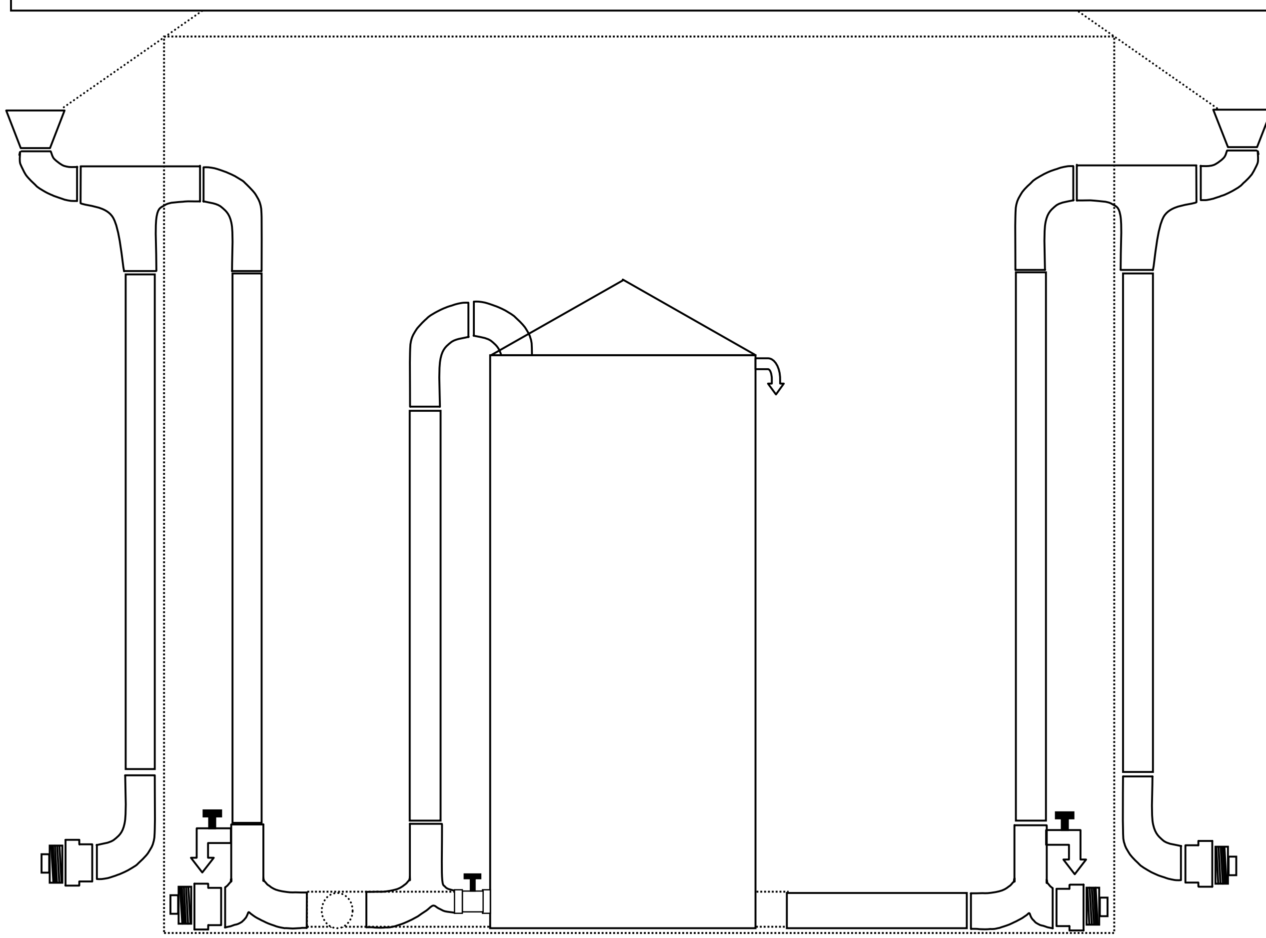


Diagram of a Simple Rainwater Collection System for Landscape Use

There are many ways to harvest rainwater for landscape use. This simple system provides for an additional valve controlled inlet into the tank. Most tanks come with a 2" bulkhead fitting at the bottom. In this illustration, when the valve is open, water will fill the tank from the bottom. If there is a large volume of water, the top inlet will also flow. With the valve open, water will flow out the two hose bibs. When selecting fittings, think of which way the water is flowing. Several shapes may be available and one may be better than the other. Schedule 40 PVC may be used, but the thin wall drain pipe and fittings are lighter weight and may cost less.



Estimated Costs for a Small System

3,000 Gallon Poly* Tank	<$1,000
2 downspout pipe system	<$200
Labor to install	<$200
Total for Rainwater System	<$1,400
Gutters not included	

Your price for this system as an option, can be $3,000 or more.

*Poly tanks are used in areas where freezing weather is limited. Fiberglass tanks are about $1 per gallon in this size. If you have long periods below freezing, check with other rainwater harvesters in your area about freeze protection.

AUSTIN ENERGY

AUSTIN ENERGY'S GREEN BUILDING PROGRAM

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IRRIGATION SCHEDULING FOR LARGE WATER USERS

Earl K. Jackson, Professor, Utah State University Extension
J. Robert Leigh, Slow the Flow Database Manager

ABSTRACT

Utah is in its sixth year of drought and water audits of large properties is an effective water conservation educational program. Over the past five years, 164 audits have been conducted (17 apartments, 23 businesses, 13 churches, 7 golf courses, 37 homeowner associations, 22 parks, 20 public facilities and 25 schools). Information from audits is used in developing a watering schedule for each property. By following the schedule over the growing season, the water used will be close to the turf water requirement (evapotranspiration). Water use records are evaluated over a five year period. The year of the audit, the average property saved 12.5% on their irrigation water. During the following year the average property was able to save another 13.8% on landscape water. The total savings over two years was 24.6%. The average water wasted before the water audit was 632,827 gallons per acre during the growing season.

INTRODUCTION

Utah is one of the fastest growing states and is also the second driest state in the nation. Enough people are added to the Utah population to make a new city the size of Salt Lake City (160,000) about every three years *(Utah Division of Water Resources, 2003*). It is also the third most urban state in the nation with about 80% of the population living along the Wasatch Mountain Front in six counties (Wahlquist, 1981). With wise planning by the pioneers and several reservoirs completed by the U.S. Bureau of Reclamation (usually with a two year irrigation supply), Utah has enjoyed inexpensive water for many years. Consequently, inefficient irrigation systems are tolerated and poor lawn watering schedules are promoted.

[1] Utah State is an affirmative action/equal opportunity institution

With six years of drought, water conservation issues became very important in Salt Lake County as well as in the entire state of Utah. Our future water supply will not be adequate for the growing population (Utah Division of Water Resources, 2001). Our first step is to stop water waste. Using water more efficiently will accomplish two important things 1) Utah's precious water supply is conserved, and 2) costly water development projects may be delayed. Over the past five years, Utah State University Extension in Salt Lake, Utah and other Counties have developed a partnership with many water districts; the lead agencies being Jordan Valley Water Conservancy District (JVWCD), the Central Utah Water Conservancy District (CUWCD) [administers the Central Utah Water Completion Act] and the Salt Lake City Public Utilities (SLCPU). USU Extension hires, trains, and oversees the college interns (mostly horticulture and plant science students) serving the requests of the water districts while JVWCD, CUWCD and SLCPU and their partner water districts fund the Slow the Flow Save H_2O program making water audits free to the public. Appointments are scheduled by calling to a toll free 'Slow the Flow Save H_2O' telephone line or directly to a USU County Extension office. Television and radio advertising is professionally created and changed each year. Advertisements have popularized the Slow the Flow slogan so that it is generally recognized by the public. The Water Check Educational Program is promoting a new ethic of efficient outdoor, culinary water use (*Jackson, 2002; Jackson and Hinton, 2002; Jackson and Mohadjer, 200*3).

WATER CONSERVATION EDUCATION

The Slow the Flow Save H_2O Water Conservation Program, including both the large property irrigation audits and the residential Water Check program, was designed to help Utah citizens use water more wisely in the landscape. Outdoor water use clearly represents the greatest opportunity for water savings. In 1998, the Utah State Legislature passed the "Water Conservation Plan Act" which required all water conservancy districts and water retailers with over 500 service connections to submit water conservation plans to the Utah Division of Water Resources. Most of the conservation plans focused on outdoor water use since most of the culinary water along the Wasatch Front is used in the landscape. In 1999, the Jordan Valley Water Conservancy District (JVWCD) initiated the Slow the Flow Save H_2O water conservation program in Salt Lake County. They were joined by the Central Utah Water Conservancy District (CUWCD), Salt Lake City Public Utilities (SLCPU) and Utah State University Extension (USU EXTENSION) in magnifying this program. As part of the overall conservation effort, the Water Check program is a personalized water conservation education program. We found that conservation efforts can be most effective when consumers are well informed from a one-on-one session at their own site evaluating their own system (Jackson, 2000).

FUNDING FOR WATER AUDITS

The Slow the Flow Save H_2O Water Check Program is provided free of charge as a public service in Salt Lake, Utah, Wasatch, Juab, Duchesne and Uintah counties by the CUWCD, JVWCD, SLCPU and their partner water districts. The water audit program is a personalized water conservation education program serviced by Utah State University Extension.

IRRIGATION WATER AUDITS OF LARGE PROPERTIES

Both the Jordan Valley Water Conservancy District and the Central Utah Water Conservancy District expanded the partnership with USU Extension to accomplish full water audits of large water users such as parks, schools, churches and public facilities. For 2003 they asked to make the priority with large water users over the residential program. A full water audit of all the zones of a large property is much more time consuming than a residential water check. It is still a series of tests which are conducted on the watering system to determine how much water the system puts out (precipitation rate), the soil type, infiltration rate, the evenness of the water application (distribution uniformity or efficiency) and includes the walk through of numerous zones on several time clocks. Water use records are requested, analyzed and used to recommend a watering schedule. A confidential report is issued to those requesting the water audit. All computerized reports are made available to the water districts.

WATER AUDIT METHODS

Water audit methods determining the distribution uniformity, precipitation rate, water pressure, etc. follow the guidelines established by the Irrigation Association (*IA Handbook, 1996*). The guidelines are summarized in the "Landscape Irrigation Auditor Training Manual" (1). The procedures were originally developed by the Irrigation Training and Research Center (ITRC) at California Polytechnic State University as part of their landscape water management program. About half of the 22 Utah State University Interns participating in the water check program are certified Landscape Irrigation Auditors. The term "Water Check" was developed for the public and is a shortened version of a full water audit.

Catch cups used during 1999 and 2000 were from ITRC supplied in the water audit kits. Catch cups supplied by the U.S. Bureau of Reclamation were used in the later water checks.

The Utah Division of Water Resources has calculated the Net ET for the past 50 years at a Salt Lake County weather station maintained by Utah State University Extension along with weather records from the Salt Lake City Airport. The average net ET for the area is 22.9 inches of water during the growing season. Our net ET value (averaging three weather stations along the Wasatch Front local term for Utah Mountainous Area with the urban population) is 24.7 inches. A typical Utah lawn has an irrigation water requirement beginning in mid-April, rises to a peak in July, and then falls rapidly until mid-October. The summer rainfall pattern for the past ten years averages 8.4 inches during the growing season. The rest of the lawn water requirement is through irrigation, usually using culinary water. The turf water requirement used to compare water use in the Water Check Program has been estimated using a 30 year average of three weather stations in Salt Lake County. Data is summarized by county in Research Report 145 by the Utah Agricultural Experiment Station. The average evapotranspiration for turf is calculated in the publication at 24.7 inches of water required for the growing season of April 1st through October 15th to maintain a green lawn (*Hill, 1998; Ervin, 1998; U.S. Geological Survey, 1995*).

BACKGROUND OF OUTDOOR WATER AUDITS

As the Irrigation Association started certifying outdoor irrigation audits, several Utah State University County Agents and Specialists became certified. We first initiated outdoor water audits in Salt Lake County during 1995. To establish the value of water audits as an educational water conservation program, a partnership was established between Salt Lake City Public Utilities, the Audubon Society and Utah State University Extension in Salt Lake County. The first outside funding came by a grant from the Central Utah Water Conservancy District under the Water Conservation Credit Program. Additional funding came to USU Extension from the Utah Division of Water Resources, Salt Lake City Public Utilities and the U.S. Bureau of Reclamation.

The Water Check Program was built upon the early water audit education program established by Utah State University Extension in Salt Lake County. Funding for advertising by the water districts made a terrific difference in educating the public about water conservation and the availability of personalized site assessments. A demonstration water audit was performed at the State Capitol in 2000 and a residential water check at the Governor's home during 2001. The Governor and his wife made use of the water check information to improve their sprinkler system and conserve outdoor water. The Governor has now established a state-wide water conservation initiative and the slogan and principles established in the Slow the Flow Save H_2O program. Because of the generous funding and statewide advertising, the water audit program remains a personalized water conservation education program funded by the water districts and serviced by Utah State University Extension (Jackson, 2000).

INTERN TRAINING FOR WATER AUDITS

Interns are given five days of orientation, training and field experience with water auditing procedures and irrigation systems the first week of May. We move to a new site each day covering the various topics. Friday is a day for water checks where a new water checker accompanied an experienced person. At the end of the five days, even our least experienced intern in horticulture is ready to meet the public and accomplish water checks. Every intern has their own audit kit and tool box.

SCHEDULING IRRIGATION WATER AUDITS

The Slow the Flow Save H_2O telephone number was continued this year as 1- 877-728-3420. The telephone system was up-graded and interesting water conservation messages added for customers to listen to while waiting. The link to Utah County performed smoothly with their new telephone number. The toll free number serves all six counties involved in the Slow the Flow Water Conservation Program. Citizens leave their name and address if they live outside Salt Lake County. These messages are automatically transferred to the Utah County Extension Office.

TABLE 1

2003 FULL IRRIGATION AUDITS IN SALT LAKE COUNTY

CITY	# of AUDITS
Draper	2
Holladay	4
Midvale	2
Murray	5
Riverton	3
Salt Lake City	9
Sandy	4
South Jordan	3
Taylorsville	4
West Jordan	7
West Valley City	5
2003 TOTAL	48

TABLE 2

2003 FULL IRRIGATION AUDITS OUTSIDE SALT LAKE COUNTY

CITY	# of AUDITS
Bountiful	3
Eagle Mountain	1
Highland	1
Layton	3
Mona	1
Nephi	2
Ogden	3
Orem	12
Provo	9
Saratoga Springs	2
Springville	1
2003 TOTAL	38

WATER AUDIT DISTRIBUTION BY CITY

During the summer of 2003, a total of 86 irrigation water audits were accomplished on large properties. **Table 1** shows the distribution of water audits between the eleven cities represented in Salt Lake County. Salt Lake City had the most audits (9) followed b y West Jordan City (7).

The Utah County team accomplished 38 audits of large properties during 2003. **Table 2** shows the distribution of audits by city. Orem had the most audits (12) followed by Provo (9). From 2001 through 2003, a total of 185 irrigation audits of large water users have been accomplished.

GROWTH IN THE NUMBER OF LARGE SYSTEM AUDITS

Irrigation audits of large properties were initiated under the Slow the Flow Save H_2O program during 2001. A total of 25 properties within Salt Lake County were accomplished this first year. The program has grown each year (**Table 3**) with a total of 186 full reports completed and organized in the computer. **Table 3** summarizes the number of audits by year both within Salt Lake County and in other counties (124 properties in Salt Lake County and 61 in other counties). Confidential summaries of these water audits are available from individual water districts.

TABLE 3

NUMBER OF LARGE PROPERTY AUDITS BY YEAR

YEAR	SALT LAKE COUNTY	OTHER COUNTIES	TOTAL
2001	25	0	25
2002	51	23	74
2003	48	38	86
TOTAL	**124**	**61**	**185**

TABLE 4

Water Audits of Large Properties

Reports	Type of Property
16	Apartments
44	Businesses
13	Churches
6	Golf Courses
37	Homeowner Associations
22	Parks
21	Public Facilities
25	Schools
2	Other
186	Total Audits Completed

LARGE SYSTEMS DIVIDED INTO CATEGORIES

There are eight categories for data summarization and report organization: 1) Apartments 2) Businesses 3) Churches 4) Golf Courses 5) Homeowner Associations 6) Parks 7) Public Facilities and 8) Schools. If an audit doesn't fall into one of these categories, it is reported under the "other" category. **Table 4** lists all of the audits completed in each category. Businesses (44) and Homeowner Associations (37) were the most popular categories requesting fact sheets and water conservation assistance. Additional information about each participant is listed in confidential reports on file with the water purveyor.

RECOMMENDED WATERING SCHEDULE

In order to simplify a watering schedule, a schedule was developed based on an interval between deep irrigations (with the accompanying recommendation that at least ½ inch of water be applied at each irrigation) and ET values over the past thirty years. This makes it so that ET calculations need not be made on a daily or weekly basis by property managers. Adjusting the timer monthly to better follow this demand curve will save water and money. It took two years of discussions with various agencies and water districts before everyone could agree to the schedule based on intervals between irrigations. Now, during the fifth year of drought, all agencies recommend this schedule shown on **Table 5**. If followed, this schedule will bring the water use down near the turf water requirement (net ET of 22.9 inches of water per growing season). As with any irrigation schedule, there is a need to know the precipitation rate of a zone. This schedule is included in every audit report and has been well received by those having irrigation audits.

TABLE 5

Customized Water Schedule

- **Sprinkler run time is based on precipitation rate measurements, soil type, and slope**
- **Run time remains the same but watering intervals change monthly**

MONTH	INTERVAL
Startup until April 30	Once Every 6 Days
May	Once Every 4 Days
June	Once Every 3 Days
July	Once Every 3 Days
August	Once Every 3 Days
September	Once Every 6 Days
October 1 to Shutdown	Once Every 10 Days

IRRIGATION TIMING EXAMPLE FOR POP-UP HEADS

The water check program recommends application of at least ½ inch of water at each irrigation and to let the soil surface dry between waterings. Water should wet the soil at least eight inches deep. In order to use the schedule properly, one needs to determine how long it takes each zone of a sprinkler system to put out ½ inch of water. Since the average fixed pop-up head system output is 1.4 inches/hour, the sprinklers should run for 21 minutes on sandy or loam soils to put out ½ inch of water. If the property has a clay soil, split the 21 minutes into three cycles of 7 minutes applied about one hour apart. Remember that the larger rotor type heads on the average have a precipitation rate about half (0.7 inches per hour) the rate of fixed pop-up heads. Therefore, to apply ½ inch of irrigation water, run the system for 45 minutes on sandy and loam soils and three cycles of 15 minutes each (about one hour in between each cycle). The schedule recommends applying 0.5 inches of water at each irrigation (21 minutes), but if the soil and root depth allow, one should increase the application to 0.75 inches (32 minutes) or 1.0 inch of water (43 minutes) assuming an average precipitation rate of 1.4 inches per hour.

Although the average precipitation rate is about 1.4 inches per hour for pop-up heads and 0.7

TABLE 6

Time Required to Apply
1/2 inch of Water to a Loam Soil

Precipitation Rate	Minutes
4 inch/hour	4 min in 2 cycles
3 inch/hour	5 min in 2 cycles
2 inch/hour	7 min in 2 cycles
1.4 inch/hour	21 minutes
1 inch/hour	30 minutes
0.7 inch/hour	43 minutes
0.3 inch/hour	100 minutes

Irrigation times for a Loam Soil
Average precipitation rates based on catch cup tests.

TABLE 7

Time Required to Apply
1/2 inch of Water to a Clay Soil

Precipitation Rate	Minutes
4 inch/hour	3 min in 3 cycles
3 inch/hour	3 min in 3 cycles
2 inch/hour	5 min in 3 cycles
1.4 inch/hour	7 min in 3 cycles
1 inch/hour	10 min in 3 cycles
0.7 inch/hour	15 min in 3 cycles
0.3 inch/hour	50 min in 2 cycles

Irrigation times for a Clay Soil
Average precipitation rates based on catch cup tests.

TABLE 8

Time Required to Apply 1/2 inch of Water to a Sandy Soil	
Precipitation Rate	**Minutes**
4 inch/hour	8 minutes
3 inch/hour	10 minutes
2 inch/hour	15 minutes
1.4 inch/hour	21 minutes
1 inch/hour	30 minutes
0.7 inch/hour	43 minutes
0.3 inch/hour	100 minutes

Irrigation times for a Sandy Soil
Average precipitation rates based on catch cup tests.

inches per hour for rotor heads, the sprinkler head range varies from 0.3 to 4 inches per hour. A water check also supplies information on the required time to apply ½ inch of water to a loam (**Table 6**), clay (**Table 7**) or a sandy (**Table 8**) soil.

FOLLOWING THE RECOMMENDED SCHEDULE

A water audit was performed at a business facility in Salt Lake County (NPCEJ04). This organization came close to watering at the turf water requirement (ET) in spite of an average irrigation system. Their 'watering deep about twice a week' brought them close to ET with a very lush, green lawn. They used 9,918,411 gallons of culinary water during the season for 12.9 acres of irrigated landscape. This is only 123% of ET. Yet, for their fixed heads, they had a water pressure of 80 psi (way too high), a distribution uniformity of 34% (should be close to 70%), and a precipitation rate of 2.5 inches per hour (should be close to 1.4 inches). For their rotor heads (which was the majority of the heads on this large property) they had a pressure of 95 psi, a distribution uniformity of 62% and a precipitation rate of 0.9 inches per hour. Even with low uniformity in the fixed head areas, they timed their irrigations for deep water penetration into the soil and then waited several days for the next irrigation.

POOR WATERING HABITS

A shallow watering every day is about the worst thing you can do for a lawn because it keeps the roots short. Short roots make it necessary to water every day during the hot days of July and August to keep the lawn from going dormant. With a uniform soil and proper irrigation, a bluegrass lawn should have a root system up to 12 inches deep. The deeper the root system, the more days you can wait between irrigations. Unfortunately, many residents and managers of large properties along the Wasatch Front water every day. The average residential lawn has a root system only 5.7 inches deep. It was a surprise to find that the average grass roots on the large properties were only 4.3 inches deep as shown in **Table 9**. This illustrates the effect of overwatering. The average large property uses two or three times as much water as the turf water requirement.

TABLE 9

Large Water Users

185 Large Water Audits Done in 2001-2003

	Average	High	Low
Landscape Information			
Property Size	654,426 ft ^{2}	7,492,320 ft ^{2}	9,011 ft ^{2}
Acreage	15 acres	172 acres	0.21 acres
Landscape Size	265,177 ft ^{2}	5,488,866 ft ^{2}	4,448 ft ^{2}
Landscape Size in Acres	6 acres	126 acres	0.10 acres
% of Lot Landscaped	55%	100%	12%
Hardscape Size	363,508 ft ^{2}	7,492,320 ft ^{2}	0 ft ^{2}
Root Depth	4.3 inches	16 inches	1 inches

INEFFICIENT SPRINKLER SYSTEMS

Efficient irrigation is an important water conservation goal. Overwatering not only wastes water, but it weakens and kills more plants than underwatering. Another wasteful practice seen all too often is misapplication of water, resulting in rotted fences and house siding, flooded sidewalks and rivers of water wastefully flowing down gutters. The average distribution uniformity (efficiency) of fixed pop-up heads is 55% (**Table 10**). The larger rotor heads operated by the large water use properties audited to date should be more efficient at a higher water pressure but also averaged out at 55% distribution uniformity (**Table 10**). A properly installed irrigation system should be a minimum of 70% efficient. An efficient irrigation system is also based on zoning plants with similar water needs together and using the irrigation method that waters each zone most efficiently. Turf and non-turf areas definitely need separate zones because of the differing water needs. As a rule of thumb, shrub areas require about one-half as much water as turf areas.

TABLE 10

Large Water Users

185 Large Water Audits Done in 2001-200

	Average	High	Low
Irrigation System			
Fixed Head Pressure	49 psi	112 psi	1 psi
Rotor Head Pressure	50 psi	104 psi	1 psi
Fixed Distribution Uniformity	55%	82%	7%
Rotor Distribution Uniformity	55%	84%	8%
Fixed Precipitation Rate	1.49	3.1	0.26
Rotor Precipitation Rate	0.74	2.46	0.13

PICTURE 1

With large water use sites, we found irrigation systems that were poorly designed, improperly installed, out of adjustment, and/or in need of repair. We found some new irrigation systems (3 schools and 1 church) installed during the year by contractors to be between 50% and 60% efficient. We found most controllers (timers) set to apply more water than needed by the landscape especially those with a high precipitation rate where water was applied faster than the soil infiltration rate. With regards to scheduling, most of the controllers were set to irrigate more frequently than required by the landscape.

Precipitation rate is a measure of how much water is emitted from a sprinkler head over time. It is measured either in inches of water per hour (like a rain storm) or in gallons per minute. **Picture 1** illustrates a typical catch cup test performed at all sites. Initial catch cups (cone with metal stand) used in this program were from the Irrigation Association. During the last two years the cones with plastic legs (U.S. Bureau of Reclamation) were used. There was very little variation in water measurement when the two styles of cups were compared side by side.

The average fixed pop-up head puts out 1.5 inches of water per hour (**Table 10**). We found a range in precipitation rates from 3.7 inches per hour down to 0.3 inch per hour. Most soils can not absorb water at this fast of an application rate. Sprinklers generally apply water faster than a very heavy rainstorm which weathermen classify as rainfall greater than 0.4 inches/hour. The precipitation rate for the larger rotor heads was about half the rate of the fixed pop-up heads at 0.74 inches per hour (**Table 10**).

HIGH WATER PRESSURE

We found high water pressure to be a major problem in every city and county. Homes with in-ground sprinkler systems should have pressure regulators installed. The average water pressure measured during the day at a sprinkler head is about 50 pounds per square inch (psi) (**Table 10**). This is too high for the typical fixed pop-up sprinkler head and increases misting and evaporation. Nearly all fixed pop-up sprinkler heads are manufactured for use between 15 and 30 psi of water pressure. On the other hand, the large rotor sprinkler heads usually work best at pressures greater than 50 psi (**Picture 2**). Irrigation system pressure is a major problem along the Wasatch Front. It needs to be corrected by separating the water pressure to fixed pop-up heads and to rotor heads or to have the system designed with the correct head spacing for the pressure delivered.

PICTURE 2

SOIL TEXTURE DETERMINATION

Soil cores were taken with standard soil probes to determine grass root depth and soil type. For soil type determination, a portion of the soil is slowly moistened and kneaded in the hand to determine a sandy soil, a clay soil or a loam soil (outlined by Utah State University and the U.S. Bureau of Reclamation). A soil that is predominately sand can have water retention problems, while a clay-dominated soil will have problems with water infiltration. The infiltration rate of the soils evaluated in this study ranged from 0.1 to about 1.5 inches per hour (**Table 11**). As part of the watering schedule, water cycling is promoted for those sites with slopes and/or clay-type soils. The amount of water applied

TABLE 11

Soil Infiltration Rates

Sandy Soils	1.5 inch/hour
Sandy Loam Soils	0.7 inch/hour
Loam Soils	0.5 inch/hour
Clay Loam Soils	0.3 inch/hour
Clay Soils	0.1 inch/hour

during an irrigation event is dependent upon the application (precipitation) rate and the run time. Where infiltration rates are low, multiple run cycles may be required to avoid excessive runoff. Multiple run cycles should be separated by soak times lasting about an hour each. There appears to be no uniform soil texture for a residential yard in Salt Lake Valley. Homes are built on the benches and hills with sandy soils and in the valley where clay-type soils dominate. For soil textures, this study found that 53.2% of the residential sites had clay-type soils, with 34.3% sandy-type soils and only 12.5 % had silty-type soils. The variability of the soil type at parks, schools, churches and public facilities was not quite as variable as at residential sites, but a layer of sand or subsoil was a common occurrence. Compaction of the soil was a common situation at schools as one would suspect.

CULINARY WATER WASTE

The great majority of landscapes in the five counties covered by this study use culinary water outdoors as well as indoors. The average resident uses twice as much water as a healthy lawn requires. Parks, churches, apartments and schools studied were more wasteful than homeowners, using nearly three times as much water as required (**Table 12**). Irrigation water audits include a measurement of the landscape size (expressed in either acres or square feet) and evaluation of the total gallons of water used on the landscape during the growing season. The tables included in this report express the outdoor water used in gallons per acre of turf or in inches of water used over any given area. The initial group of properties studied during 1995 and 1996 used an average of 79.1 inches of water (345% of the turf standard water use of 22.9 inches). Adding all of the apartments, churches, parks, schools and public facilities now in the data base, the average water use is down to 226% (51.8 inches) of the standard for turf which is still a horrendous amount of water to waste. This is far greater than the 201% of standard used by the average homeowner with the turf water requirement being 100%. **Table 12** breaks out the water waste calculation compared to ET by category. In this study to date, apartment complexes, public facilities and churches appear to be the most wasteful.

TABLE 12

Water Waste by Large Properties

% of ET_{TURF}	Type of Property
307%	Apartments
304%	Public Facilities
300%	Churches
288%	Schools
262%	Homeowner Associations
218%	Small Businesses
200%	Home Owners
165%	Parks
120%	Water-wise Citizens
100%	Turf Water Requirement (ET)
88%	Golf Courses
70%	Xeriscape Landscapes

A water audit was completed on a public facility (6PFEJ08) in Salt Lake County. The report demonstrated an inefficient system (50% distribution uniformity averaged over all zones) with 13% of their 412 sprinkler heads needing adjustment or replacement. The six controllers varied in irrigation system run times by 35%. The average precipitation rate for fixed, pop-up heads was 1.8 inches per hour and for rotor heads, 0.6 inches per hour. Irrigation of many flower and shrub areas was included in lawn watering zones.

An examination of the water use records indicated that 13,421,527 gallons of culinary water was used during the growing season on the landscape. To maintain a healthy lawn, only 4,558,659 gallons of water would be required. With an irrigated landscape area of 7.33 acres, the water use during 1996 was 42 gallons of drinking water per square foot of landscape. The turf water requirement [evapotranspiration (ET for turf)] is only 14.28 gallons per square foot per season. Therefore, irrigation water used on this facility was 294% of ET. A total of 8,498,001 gallons of water were wasted during the year on this property at a cost of $15,224 (in 2001 dollars calculated from the Salt Lake City Public Utilities summer water charge of $1.34 per 100 cubic feet of water outside of the Salt Lake City boundary).

At the request of a public official in June 2001, a second water audit was conducted on the same landscape. The precipitation rates, mixed head zones and mixed landscape zones were about the same. As was recommended in the first audit, the Imperial Controllers had been replaced and many of the misaligned heads had been repaired and replaced. The 2000 water year was significantly warmer than 1999, and 14% more outdoor water was used during the 2000 growing season over the 1999 year. For the calculation of landscape water used, we averaged 1998, 1999 and 2000 water use records. The current landscape area is 319,489 square feet and the average irrigation water used during the last three growing seasons was 9,911,499 gallons (31 gallons/square foot/season). Compared to the turf water demand (14.28 gallons/square foot/season) the average annual turf requirement for the landscape was 4,923,526 gallons/square foot/season. It is evident from these numbers that city park personnel had reduced their landscape water use at this facility by 35% from the 1996 values. Unfortunately, they were still wasting a great amount of culinary water (201% of ET). This example points to the fact that it sometimes takes years to budget for the installation of a new irrigation system; yet a tune up of an irrigation system pays for itself in water conservation.

Using this site to calculate water waste, a total of 4,987,973 gallons of culinary water are being wasted annually at this site. This amount of water is equal to 15.3 acre feet. The average residential lot size along the Wasatch Front is 13,589 square feet (0.31 acres). The average residential irrigated landscape is 7,894 square feet (0.19 acres). On the average, lots are 61% landscape and 39% hardscape. This means that the 4,987,973 gallons of water wasted at this site would irrigate the average size landscape along the Wasatch Front for 41 years. Another way of saying this is that the wasted water for one growing season at this public facility would be adequate for 41 homes. The cost of the wasted water in 2001 dollars was $8,935.67 a year at that site.

SECOND EXAMPLE OF A LARGE WATER WASTER

As bad as the public facility was in the previous example (6PFEJ08), there are several examples in the 186 audit reports that illustrate greater water waste. Public facility 8PFEJ05 used 14,369,241 gallons of culinary water during the growing season on 4.6 landscaped acres. This equates to 71.7 gallons/square foot/season. Compared to the turf water requirement of 14.28 gallons/square foot/season, these maintenance professionals were watering at 502% ET. Calculations indicate an annual waste of 28.8 acre feet (9,381,268) or enough water to irrigate the lawns of 77.1 average residential landscapes for a whole year! Unfortunately, our water audit database includes one property using 8.52 times the turf water requirement.

WATERING FAILURE AT A PUBLIC FACILITY

At the request of the director of a Salt Lake County Public Facility, we determined that trees in the newly planted landscape were dying from overwatering and worked out a watering schedule for them. They also determined to replace the lawn in the front landscape with native plants including a separate drip irrigation system. The building is located on a 2.61 acre site with 1.08 acres under irrigation. A full 25% of the landscape is classified as a xeriscape type landscape with 75% under turf. The water use records for the site were evaluated for 1999 and 2000. We expected the outdoor water use to be very close or less than the turf water demand value because of the change in landscape. Of the 1,998428 gallons of water used annually, only 6% is used indoors while 94% was used outdoor during the landscape growing seasons. The year after reducing their lawn area, the landscape was still overwatered by 64%. A xeriscape landscape is not the answer to saving water unless people change their watering schedule to fit the landscape zones.

WATER SAVINGS AFTER WATER AUDITS

The question is always asked, "Do water audits save water and money?" The answer of course is "It depends...." There are many factors that influence large water use properties and their ability to immediately start saving water. Experience demonstrates that by shifting to the recommended irrigation schedule and adjusting head alignment can result in a 10 to 20% reduction in water use the month after a water audit. On the other hand, some facilities require a year or more to alter the budget for major adjustments or a totally new irrigation system.

Summarizing the large water audits conducted during 2001, we had 13 audits with outdoor water values for multiple years. With a turf water requirement (ET) value of 22.9, one property used only 26.7 inches of water (117.8% of ET). The range of values for the properties was 26.7 inches to a high of 95.8 (418% of ET) with a mean of 67.1 inches. The average water waste was 42.4 inches above ET which indicates an average value of 285%.

TABLE 13

2002 Water Audits
Water Conservation by Large Properties

AUDIT	1999	2000	2001	2002	2003
	TOTAL LANDSCAPE GALLONS USED PER YEAR				
02GC05	132,213,937	158,144,853	191,189,249	**148,166,533**	136,412,461
02GC01	102,124,739	105,591,719	113,893,771	**122,820,403**	102,426,183
02GC07	118,570,566	148,768,822	135,527,726	**118,790,478**	93,537,250
02PK17	103,849,446	123,108,950	104,037,942	**69,581,322**	65,536,886
02GC06	66,386,197	74,887,965	69,838,217	**73,953,713**	58,869,545
02GC04	16,925,594	37,951,126	97,009,466	**103,214,126**	56,372,122
02GC02	41,639,365	50,359,549	50,763,469	**33,456,245**	50,530,093
02PK15	42,305,982	44,410,106	46,095,350	**43,056,226**	41,420,350
02APT02	16,204,971	19,544,791	17,046,471	**17,714,435**	12,230,099
02APT11	11,150,436	7,922,816	7,033,444	**8,410,512**	9,737,464
02PK20	13,223,892	11,938,080	12,041,304	**11,533,412**	9,535,504
02HOA02	5,812,708	8,082,888	8,111,312	**5,665,352**	9,092,688
02PK14	7,274,450	8,819,818	9,853,554	**7,893,046**	8,759,230
02PF06	11,424,307	12,665,987	12,175,299	**10,730,911**	8,449,511
02PK09	9,688,844	9,560,188	6,578,660	**4,661,536**	5,808,220
02PK07	6,989,312	6,580,904	6,624,288	**4,279,308**	4,752,044
02PK11	8,217,977	10,247,301	7,226,129	**5,647,101**	4,673,205
02PK06	4,794,381	6,151,253	5,335,933	**3,614,785**	3,800,289
02HOA02	3,976,678	3,106,006	2,488,906	**1,801,494**	3,689,446
02PK10	5,628,700	10,601,404	8,685,028	**4,606,184**	3,587,408
02APT03	5,419,363	5,841,983	4,479,875	**4,613,767**	3,384,055
02APT08	1,659,722	2,060,650	2,386,030	**1,222,890**	2,644,090
02OT01	3,881,746	3,248,938	3,673,802	**2,834,546**	1,913,758
02APT01	1,529,959	1,495,850	957,290	**1,138,830**	1,040,094
02PF07	1,835,031	1,860,463	1,126,675	**540,991**	800,547
02APT06	3,826,618	3,154,914	1,629,742	**1,397,114**	520,458
02CH01	892,813	841,949	838,957	**753,685**	507,593
02HOA04			1,921,612	**1,092,080**	445,808
02CH07			1,507,500	**690,500**	1,266,500
02SCH05			3,735,000	**3,496,000**	2,905,000
02HOA01			1,707,684	**1,084,600**	982,872
Average	**27,683,249**	**32,479,603**	**30,178,054**	**26,402,004**	**22,762,283**
	Average % water use from previous year			**87.5%**	**86.2%**
	% Water Reduction (24.6%) over two years by 2002 Audits				**75.4%**

LWA db Outdoor Savings 0204

Table 13 summarizes the total gallons of water used in the landscape by 28 large water use properties audited by our interns during 2002. (Unfortunately, we are still struggling to obtain the water use records on the other half of the properties as well as those audited during 2003). Data in the table 13 shows that even in the third year of drought (2001) properties used about the same level of water as the prior two years. The year of the audit (2002) the average property saved 12.5% (listed as 87.5%) on their irrigation water. During the following year the average property was able to save another 13.8% on landscape water. The total savings over two years was 24.6%. The State Division of Water Resources announced recently that the

Governor's Slow the Flow Save H_2O media campaign at a cost of over $400,000 saved an average of nearly 9% over the same period of time. Most of these water savings were accomplished by a sprinkler system tune-up, purchasing more modern controllers, and paying attention to irrigation scheduling.

REDUCED WATER USE AT A SCHOOL IN WEST JORDAN CITY

A new RainBird Maxicom central control irrigation system was installed at a school in West Jordan City. The system had its own weather station with sensors for air temperature, solar radiation, relative humidity, wind speed, wind direction and rainfall. The information is calculated for Evapotranspiration for turf on a daily basis and supplied to the computer running the irrigation system. Each irrigation zone is then programmed for the correct minutes to water each week. A total of 54% of the 10.8 acre site is irrigated landscape. During 1998, 1999 and 2000, the school used an average of 3,314,112 gallons of irrigation water during the growing season. This equated to a value of 28.8 gallons of culinary water per square foot per season. Before automation they were watering at 189% of the actual turf water requirement. After the Maxicom automated system was installed, the water use records indicated that this facility irrigated at 98% of the current years water requirement. When an entire sprinkler system is replaced with an automated system based on a weather station, the total water used can be brought down to the same level as the standard (ETturf).

TABLE 14

2002 Water Audits of Large Properties
Water Conservation Compaired to ET Values

		TOTAL LANDSCAPE GALLONS USED per YEAR per ACRE				
AUDIT	Acres	1999	2000	2001	2002	2003
02GC05	387.9	340,845	407,695	492,883	381,971	351,669
02GC01	170.5	598,972	619,306	667,999	720,354	600,740
02GC07	161.1	736,006	923,456	841,265	737,371	580,616
02GC06	144.8	458,468	517,182	482,308	510,730	406,558
02GC04	172.0	98,405	220,646	564,009	600,082	327,745
02GC02	58.1	716,684	866,774	873,726	575,839	869,709
02APT02	6.7	2,418,652	2,917,133	2,544,249	2,643,946	1,825,388
02APT11	2.5	4,460,174	3,169,126	2,813,378	3,364,205	3,894,986
02PK20	15.6	847,685	765,262	771,878	739,321	611,250
02PK14	8.9	817,354	990,991	1,107,141	886,859	984,183
02PF06	4.0	2,856,077	3,166,497	3,043,825	2,682,728	2,112,378
02PK09	17.5	553,648	546,296	375,923	266,373	331,898
02PK07	8.7	803,369	756,426	761,412	491,874	546,212
02PK11	5.6	1,467,496	1,829,875	1,290,380	1,008,411	834,501
02PK06	5.3	904,600	1,160,614	1,006,780	682,035	717,036
02HOA02	3.2	1,242,712	970,627	777,783	562,967	1,152,952
02PK10	4.5	1,250,822	2,355,868	1,930,006	1,023,596	797,202
02APT03	3.3	1,642,231	1,770,298	1,357,538	1,398,111	1,025,471
02APT08	3.7	448,574	556,932	644,873	330,511	714,619
02OT01	3.1	1,252,176	1,048,045	1,185,097	914,370	617,341
02APT01	0.7	2,185,656	2,136,929	1,367,558	1,626,900	1,485,849
02PF07	0.9	2,038,923	2,067,181	1,251,861	601,101	889,497
02APT06	0.8	4,783,273	3,943,643	2,037,178	1,746,393	650,573
02CH01	1.4	637,723	601,392	599,255	538,346	362,566
02HOA04	1.3			1,478,163	840,062	342,929
02CH07	1.1			1,370,455	627,727	1,151,364
02SCH05	5.8			643,966	602,759	500,862
02HOA01	1.0			1,707,684	1,084,600	982,872
02PF05	3.7				1,213,892	1,226,054
02APT04	0.6				4,096,774	3,601,613
02SCH02	0.3				4,729,273	2,954,515
02PF03	9.1				581,758	406,484
32	**37.9**	Number of Audits and Average Landscape Size				
AVG Gallons per Acre		**1,407,639**	**1,438,333**	**1,219,925**	**1,218,423**	**1,062,422**
Turf Water Requirement		**632,781**	**681,666**	**687,097**	**678,950**	**678,950**
Gallons Wasted per Acre		**774,857**	**756,667**	**532,827**	**539,474**	**383,472**
Turf ET in Inches		**23**	**25**	**25**	**25**	**25**
Times 27,158 gal/ac in.		**632,781**	**681,666**	**687,097**	**678,950**	**678,950**
% OVER ET		**222%**	**211%**	**178%**	**179%**	**156%**

WATER SAVINGS COMPARED TO TURF WATER REQUIREMENT

The water savings information presented in **Table 13** was recalculated to compare with the turf water requirement (ETturf). **Table 14** presents the data in total landscape gallons used per year on a per acre basis. With ET at a value of 100% on the bottom line, the properties were using about twice as much water as the turf required during 1999 and 2000. After working with the properties and recommending a watering schedule based on an irrigation system audit, the average property was only 36% over evapotranspiration.

SATISFACTION SURVEY OF CONTACT PEOPLE FOR LARGE PROPERTIES

A Utah State University Extension telephone survey was conduced in November of 2003 to determine the impacts of the Large Water Audit Program. The survey was summarized as follows: “The participants surveyed were very positive about the Water Check Program and felt that it was a useful tool in helping them to save water. Several participants even wanted to thank us again for our efforts. Several other positive comments included: "The water auditors did a great job, were knowledgeable and well prepared"; "The report was extremely helpful. I was able to take it to my boss and the property owners to show what could be done to lower costs, great information"; "Water information in reports had great impacts on money handlers"; "Nice to have an objective opinion from the Extension Service because they were not selling anything"; "Great analysis, schedule seems to work well"; "The report was very well done, the water auditors were very knowledgeable".

“This phone survey was conducted for the participants who received a Large Water Audit either in 2002 or 2003. Contacts for 61 properties were surveyed representing 38% of the 2002-2003 Water Audit participants. A few of the survey participants were responsible for more than one property. Survey participants were asked five standard questions and also given a chance to elaborate on their answers. The standard questions were: 1.Was the Water Check Helpful? 2. Was the irrigation system improved as a result of the Water Check? 3. Was the landscape altered or lawn size reduced as a result of the Water Check? 4. Was the report helpful? 5. Was there anything that could have been done better? / Suggestions for improvements?”

Results by Question Number:

1. Was the Water Check Helpful?

   59 yes 1 no 1 don't know

2. Was the irrigation system improved as a result of the Water Check?

   53 yes 2 no 4 plan to 2 no need

3. Was the landscape altered or lawn size reduced as a result of the Water Check?

   3 yes 55 no 2 plan to

   1 stated that perennials will be used next year instead of annuals

4. Was the report helpful?

   60 yes 1 mentioned that the report was sent to the wrong person

5. Was there anything that could have been done better? / Suggestions for improvements?

This was an open-ended question in which many people responded no, and then expressed positive feelings about things that went well. A few suggestions for improvements were: Cover information about fertilization, shrubs, trees, low water use plants, and water conservation tips for outdoor water features. It was also mentioned that getting the report sooner would have been helpful. This may be resolved by sending a preliminary report without water information and then following up after water records have been received.

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LANDSCAPE SIZE BASED ON TAX ASSESSOR RECORDED LOT SIZE

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Executive Summary

Residential outdoor water waste is a major problem in the state of Utah. State and city governments are continually seeking ways to cut waste and conserve water. The primary goal is to get homeowners to water their turf according to its basic needs. In Utah, this basic water need for turf is 22.9 inches of water per watering season (about 15 gallons per square foot). One of the problems that face water conservation programs is that water is distributed and measured in gallons per household and not gallons per square foot of landscape. In order to convert total gallons to gallons used per landscaped foot, there needs to be a way to calculate average landscape size based on a total lot size measurement.

The *Slow the Flow* Program

In order to help residents and large property owners conserve water, two of Utah's water conservation districts gave funding to Utah State University to organize the *Slow the Flow, Save H2O* program[2]. The *Slow the Flow, Save H2O* program began conducting modified water audits, called water checks, in 1996. These water checks have reached over 6,000 homeowners and 200 large water users (parks, businesses, golf courses, etc.). Water checks are free to those who request them through a toll free telephone number. A water check consists of a visual inspection of ones irrigation system, a test to measure precipitation rate and distribution uniformity, a soil test, and a measurement of the property. With this information the water checkers can construct a watering schedule that is specific to the homeowner's needs.

The program tracks the water use of the resident over the next several years to see if the water check is helping to change watering habits. Because of the measurements taken at each lot, water use can be calculated at the turf water requirement.

[1] Utah State is an affirmative action/equal opportunity institution
[2] Earl K. Jackson, Paula Mohajer; 2003 National Irrigation Show proceedings

Measurement Methods

Measurements are made using a measuring tape and a measuring wheel. Because of the irregular shape of most landscapes, the total lot size if first measured and then the hardscape is measured. Hardscape is anything that is not watered, such as the house, driveway, patio, and sidewalk. Total lot size includes all easements. The hardscape size is then subtracted from total lot size to get total irrigated landscape size.

On properties larger than one acre, for example, parks and golf courses, water checkers use GPS units to get measurements. All measurements for large lots, as well as residential lots, are recorded in square feet measurements.

Correlation between Total Landscape Size and Tax Assessor's Recorded Lot Size

With the information on landscape sizes collected from the water checks, we hope to derive an equation that will allow anyone to approximate total landscape size on any given lot.

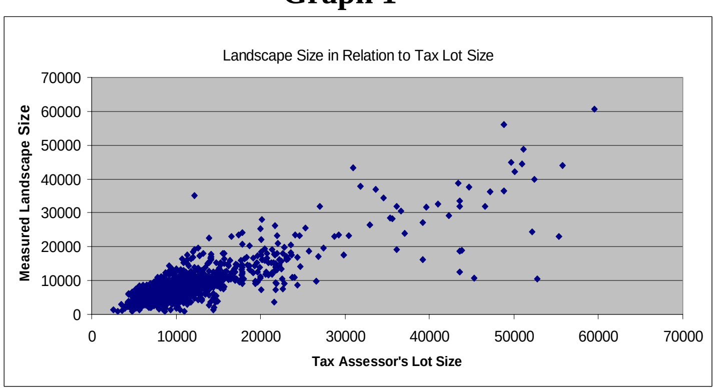
County recorder offices have records on each residential lot in their county. This record contains some information on lot sizes. This lot size information is used by the county tax authority to assess property taxes on residential lots. The lot size information is recorded in acres and does not include easements and common areas. This record is public knowledge and can be accessed from the recorder's office. Some counties are even starting to offer this record online. The goal of our research will be to estimate landscape size based on this public tax assessor's lot size information.

The *Slow the Flow* program has completed 6,242 water audits across Utah. They have been done in seven counties, with the majority being in Salt Lake and Utah counties. Of these 6,242 participants, assessor's tax lot size information was collected on 1,746. These were the records that had the most complete address information and lot measurements.

After we collected the tax assessor's lot size information we started to compare it to our measured lot sizes. The theory was that the assessor's lot size would be on average 8-15% smaller than our total measured landscape size. The reasoning being that the easements would make our total measurements larger. We observed that the average tax lot size was 13% smaller than our measured lot size.

Once we collected our data, we took a look at the relationship between tax lot size and landscape size. **Graph 1** shows the relationship between tax lot size (the X axis) and measured landscape size (the Y axis).

Graph 1



In order to explain the data we ran a regression equation using the data collected. A regression equation[3] is a mathematical formula that will let us insert any given tax lot size and get the corresponding landscape size. Each regression equation has an R-squared value that tells what percent of the variation is defined by the regression equation[4]. The closer the R-squared value is to 100%, the better the "fit" the data is to the regression equation. The data was analyzed using both linear and non-linear regression. Both yielded nearly the same results; however, the linear equation yielded a slightly higher R-squared value and is easier to implement.

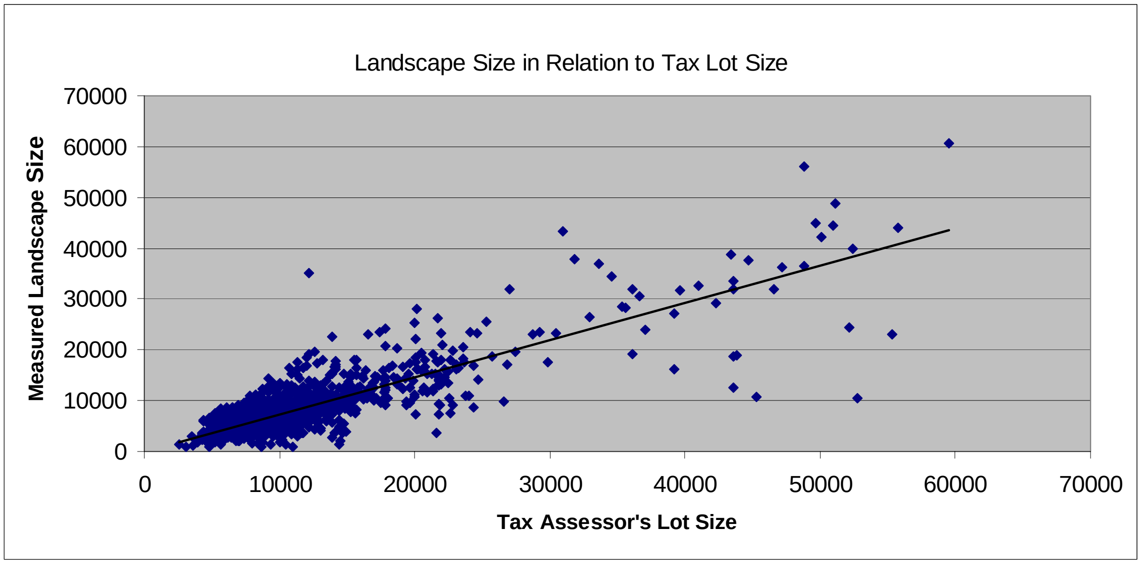
The regression equation is as follows:

L = 8 + .73(A)

L = Irrigated Landscape Size in square feet
A = Tax Assessor's Recorded Lot Size in square feet (multiply acres by 43,560 to get sq. ft.)

The regression equation is surprisingly simple. It is telling us that the average lot in Salt Lake County is about 73% of the recorded tax lot size. If we apply this to the data shown in graph 1 we can now see **graph 2**.

Graph 2



The regression equation has an R-squared value of 71%. This tells us that 71% of the variation in the data is defined by the regression equation.

[3] Statistics for Business and Economics; Heinz Kohler, 2002. Chapter 17.
[4] Regression equation was computed using "MiniTab" statistical software

Variance in observations can be explained several ways. The first being personal preferences in landscaping. Looking at the graph we see that the smaller lots are grouped closer to the regression line while the larger lots become more sporadic. One explanation for this is that smaller lots are more confined and have less leeway in landscaping choices. Larger lots have a lot more variety in landscaping. Some larger lots choose to have larger houses and driveways which make landscape smaller. Others have smaller houses and most of the lot covered with grass.

Some of the variation in the data can be described by recording error. County tax assessor's information is not always 100% accurate. We noticed many lots that were obviously larger than .5 acres recorded as .1 acre or less. These records that were obviously wrong were thrown out of the study. We assume that there are many minor differences that can not be detected.

Variation can also be explained by landscape measuring techniques. Lot sizes were measured by a dozen different USU interns. Before the program starts each year, interns are all given the same training on how to measure lots. However, this does not mean that each intern ends up measuring the same way.

Possible Applications

The *Slow the Flow* program will use this information to estimate how much water people who did not have a water check are using. Water savings are based on a comparison of how much water everyone else is using. With the help of water retailers we pick random lots in the city and compare water use. Because we do not measure these lots, this study will help us determine landscape size, and thereby calculate water use according to the turf water requirement, for any given resident.

Many cities in Utah are trying to manage water use by creating tiered water pricing structures. One such example is Salt Lake City. In Salt Lake City a resident pays $.72 for each ccf (thousand cubic feet of water, approximately 748 gallons) of water used, as long as they use less than 9 ccf. If the resident uses more than 9 ccf they pay $1.10 per ccf in excess of 9. If they use more than 29 ccf they are charged $1.53 per ccf in excess of 29. The problem with a tiered pricing structure is that it penalizes those people with large lots that may be trying to save water, while not punishing smaller lots that may be wasting large amounts of water. Instead of pricing water in tiers according to total gallons, cities could base pricing on a lot's given landscape size. This landscape size would be based on the lot size designated by the tax assessment. Because the data describes the average, it will not be completely accurate but will be fairer than current pricing structures.

As cities instigate customized pricing structures, residents will become more concerned about accurate tax assessor lot sizes. Help in correcting inaccuracies in recorded lot sizes would help county tax assessors make a better accounting of property taxes.

Conclusion

Our research can be used as a model for other counties and cities in the United States to determine landscape sizes based on tax assessor's lot sizes. We would expect the percent of landscape verses recorded lot size to change in different cities across the US. Due to the linear nature of the relationship, a few accurate lot size measurements can be made to create a case specific regression equation.

With a case specific water pricing structure, cities could more effectively reward people for water conservation efforts. Such a pricing structure would also allow water retailers to capture profits from water wasters.

As the *Slow the Flow* program progresses, so will the number of observations added to this research. As we add more observations, we hope to make an even more accurate regression equation. It is also our hope that more counties across the nation will contribute to our research.

Surviving the Worst Drought in 300 Years

Donna Pacetti, Water Conservation Specialist, Denver Water

Abstract

1954 had been the driest year in recent Denver Water history. The runoff in Spring 2002 was 1/3 less than 1954. This was a major wake-up call for Denver Water and the Green Industry. 2003's runoff was a little better than 2002. But, it looks like the 2004 runoff season will be about the same 2002. This paper will explain the ins and outs of what the Denver metro area has been through in the past three + years. The Green Industry played a major role in developing Denver Water's drought rules. The paper will explain how this worked. What were some of the problems created? What was the driving force that changed customer's habits? What are we looking at in the future if this drought continues? What are things that Denver Water would do differently? This paper will detail all the ramifications that drove different decisions.

History of Water Restrictions in Denver

Water restrictions in Denver date back to 1922. From 1922 to 1936 the Denver Water Board imposed mandatory lawn watering restrictions basically due to lack supply/infrastructure. The construction of Eleven Mile Dam and the start of the Fraser Basin collection system allowed Denver Water to lift the restrictions.

Water restrictions were again put into place in 1954 due to drought conditions. The drought lasted through 1956. In 1957 the mandatory restrictions were lifted.

Denver customers again faced restricted water use in1977 from lack of supply in the Northern collection system. The restrictions lasted through 1981 which also resulted in limiting the number of taps sold over four year.

The drought that started in 2002 was ramping up prior to 2002. In 2001 the Denver area experienced warm/dry fall which turned into a dry winter. March of 2002 the snow pack readings in our collection basin were 40% below normal. The state of Colorado experienced above normal temperatures in March which prematurely melted the snow pack. The month of April continued with warm/dry weather. April 29, 2002, Denver Water hit a record of 370 million gallons treated water used by our customers in one day.

2002 – One Tough Year

The hot/dry weather continues through May. On May 22, 2002 the Schoonover fire starts. The fire was started from lighting and burned to 4000 acres in size.

The Denver Water Board adopts voluntary watering restrictions the beginning of June. The Hayman fire starts on June 8, 2002 from arson. In one day this fire grew to 60,000 acres in size. The combination of fuels, weather, and topography positioned the fire for a major run lasting the entire day and burning 60,000 acres along the South Platte River corridor for 16 to 19 miles. (Figure 1)

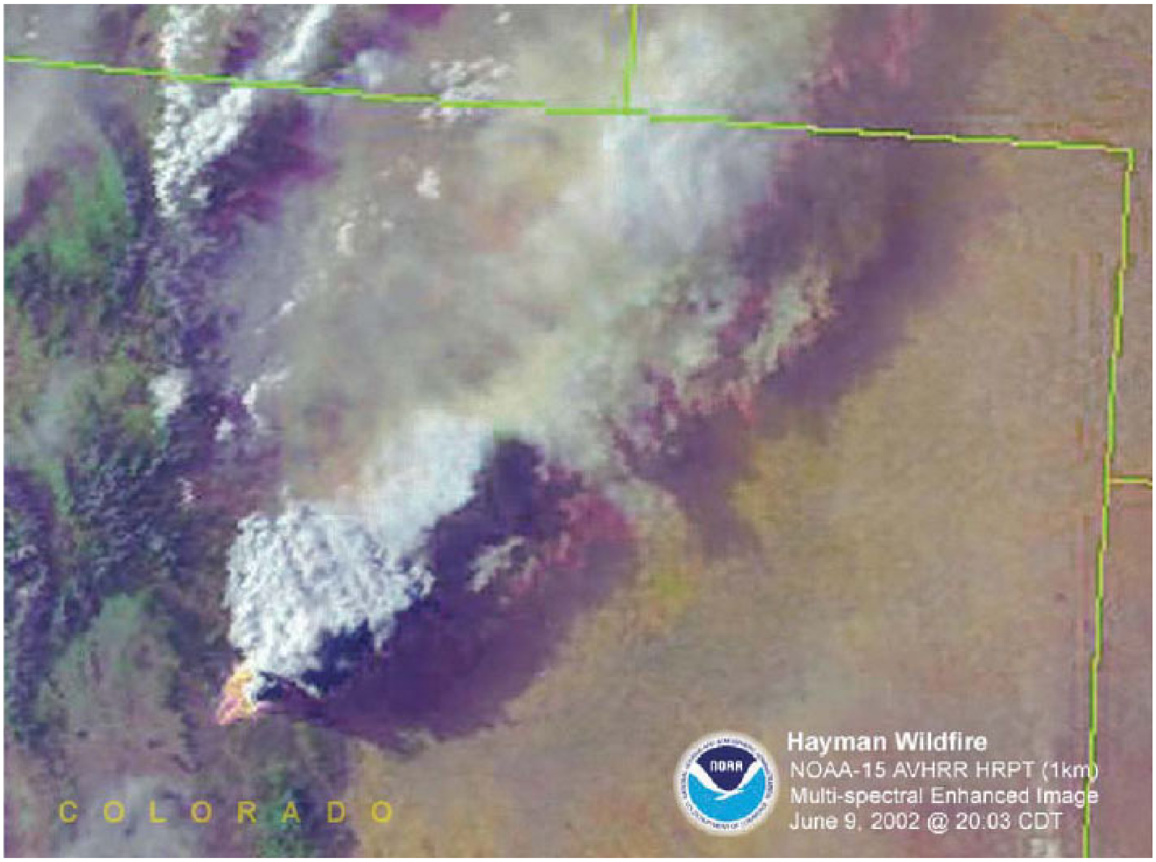


Figure 1

Twenty days later the fire had grown to 138,000 acres and was under control.

The fire was located in one of Denver Water's largest water sheds almost causing the shut down of their largest, most modern water treatment plant (Figure 2). This fire ended up being the largest fire in Colorado's History causing numerous social and economic impacts.

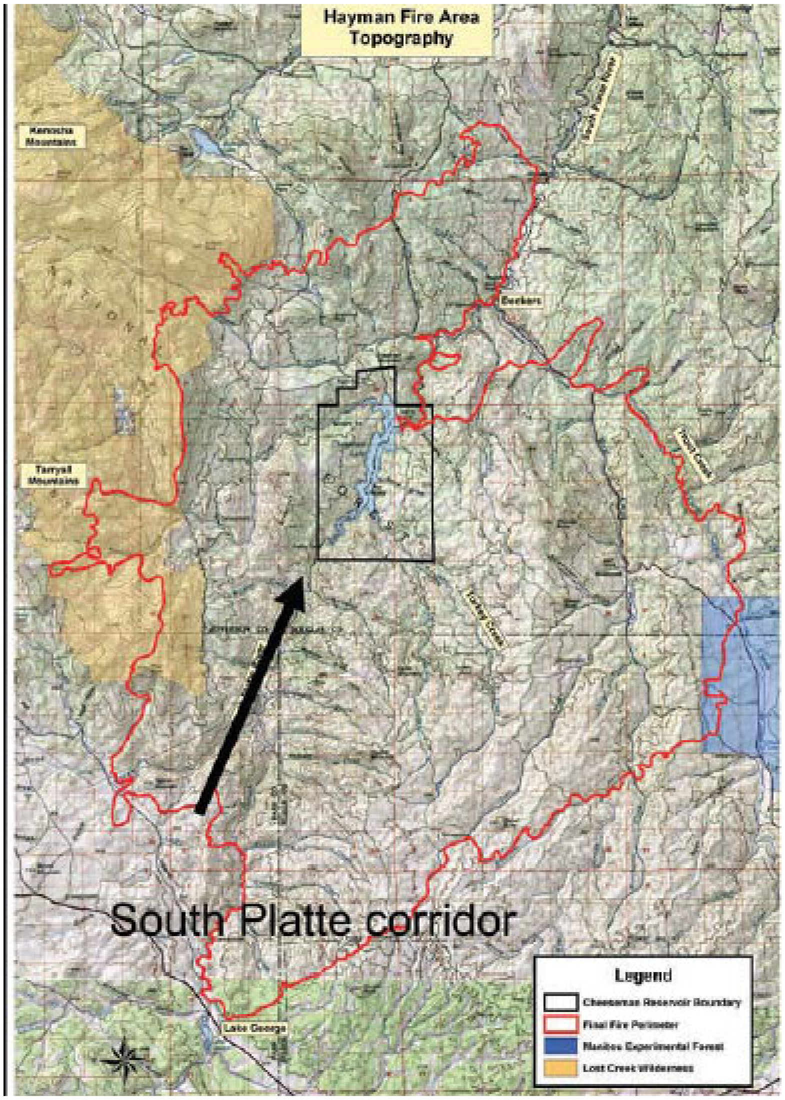


Figure 2

Due to continuing dry/hot weather and the devastation to one of their major water sheds, the Board decides to go to mandatory water restriction the beginning of July.

2002 Drought Program Details

Watering Restrictions

The mandatory water restrictions consisted of every 3rd day watering and a three-hour water window per watering day. Other basic rules were no watering between 10 a.m. and 6 p.m and no water waste can occur. Denver Water created a rule for almost everything and it was too lengthy to list.

September 1, 2002 – water restrictions tightened. Each customer gets 2-days per week to water and a 2 hour time limit per watering day. No watering on Sundays. No exemption for permits.
October 1, 2002 – ban on outdoor watering

Exemption Permits

July 1, 2002 launches the permit process for getting exemptions from drought restrictions.

- Sod and seed permits = 1432
- Large landscape permits =3821
- Total permits = 5253

Large landscape permits allowed customers with larger landscaped areas to receive more water. Most of these permits were issued to commercial properties and large residential. Some customers thought permits were unfair. Permits were perceived by some customers as the rich buying their way out of a drought. 66% of the permitted customers used less water than their historical use. 44% of the permitted customers used more water than their historical use.

Drought Monitors

23 people were hired to canvas the city looking for water waste
Penalties for water waste were as follows:

- 1st time a warning. (9,600 warning notices issued in 2002)
- 2nd $250 fine
- 3rd $500 fine
- 4th $1000

  (A total of $136,550 collected in violations in 2002)
- 5th install flow restrictor. (Sixteen flow restrictors installed in 2002)

Getting the Word Out

Denver Water used the typical marketing tools to get the word out, such as:

- Paid ads in newspapers and radio
- Billboards through out service area
- Sandwich boards on people walking down busy streets
- Bus placards
- Direct mailings to customers
- Media coverage
- Public presentations

Winter Rebate Program

Denver Water launched November 1, 2002 a residential/commercial rebate program to accelerate the replacement of high water using toilets and clothes washers.

Residential

- ULV toilets $100, limit 2 per household within our service area
- Clothes washers, horizontal axes $125, limit 1 per household

Commercial/Industrial

- ULVs $150

2003 Drought Program Details

Drought Conditions Continue to Decline
January 2003– Reservoirs are 44% full. In January 2002 reservoirs were 79% full. A normal year reservoirs are normally 82% full.

Mother Nature Intervenes
March 19, 2003 a snow storm in Metro area dumped more than 3 feet of snow (Figure 3).

Figure 3

Customers thought the drought was over. Denver Water had to regroup with their advertising to get the word out that the drought is not over.

Changes from 2002
- Denver water started a summer rebate program for customers for landscape/irrigation materials.
- Board approved surcharges to get customers attention.
- Developed water budgets for Commercial/Industrial irrigation only accounts.
- No permits were issued.
- Water utilities working together in the metro area agreed on a watering calendar

2003 Watering Restrictions
May 1: Start of irrigation season and mandatory restrictions.
- Can only water 15 min/zone
- Maximum of 8 zones
- Common Front Range watering calendar
  - Two days per week
  - No watering between 10 AM and 6 PM

June 11: Board allows unlimited zones at an average of 15 min/zone.
July 14: Board adds one watering day per week to watering calendar.

2004 Drought Program Details

Basically the same as 2003

- Exceptions
  - **average** of 15 minutes per zone
  - decreased number of drought monitors
  - increased surcharges from 2003
  - different rebate program

Green Industries of Colorado (GreenCO) Involvement

The relationship between Denver Water and GreenCo was a good "partnership" before the drought.

The major conflicting issues are outlined below:

GreenCO feels . . . …

Denver Water is singling out the Green Industry with the rules – not being equal to all businesses.
15 minutes per zone is not enough time for rotor type heads and can't understand why Denver Water would impose such a rule
Denver Water is driving the Green Industry out of business
Denver Water doesn't understand all the situations that GreenCO deals with and they don't listen to GreenCO's concerns
Denver Water needs to develop individual water budgets for each customer
Denver Water doesn't have a long-term conservation strategy
The general public is outraged at Denver Water for not having an established plan
Denver Water's financial arguments are hollow
Denver Water in general has no long-term plan

The battles between the two agencies have been ugly. Unfortunately, GreenCO developed a letter of accusations and sent the letter to numerous individuals in the metro area, including the Mayor and media.

Financial Ramifications

Drought can be a financial nightmare for a community. The green industry companies depend on water to keep in business. Water utilities get a double whammy with having to spend more money on advertising, hiring additional employees and offering incentive programs, but the utility also receives less revenue from the restricted water use. Homeowners have to live with ugly, dry yards, and surcharges on their water bills. Then the homeowner has to face the expenditure of landscaping when the drought is over. Drought is a natural disaster for a community, and in Colorado, its not going away.

Each group that is deeply affected by drought needs to develop a plan on how to minimize the financial effects. Denver Water has been working on developing individual water budgets. This is not an easy process for a utility the size of Denver Water. In the interim, Denver Water is encouraging customers to take action and make changes to be more water efficient. For example: Homeowners can install Xeriscapes and very efficient irrigation systems to eliminate losing their entire landscape. The green industry companies must start promoting and installing more water efficient landscapes and irrigation. A small percentage of the green industries in Colorado promote this concept and they need to expand their efforts.

Denver Water is constantly readjusting their business plan to compensate for new challenges. In drought conditions, water surcharges will always be one of a water utilities tools to keep consumption down. The vary nature of surcharges is to encourage customers to do something they would not do otherwise or to penalize those that do not do what is needed. From the customer's viewpoint surcharges are not fair. The issue of fair surcharges during a drought is not the point. They helped develop awareness of the importance of the drought in our community. Another benefit of surcharges is centered on enforcement. Water copes can not be everywhere at all time, but surcharges can.

A drought to a water utility is very expensive. As a drought worsens, a utility will make a request to their customers to drop their consumption. The majority of customers will honor this request. This decrease in consumption directly decreases the revenue the utility receives. Most water utilities operate off the revenue they receive and are not tax supported. In an attempt to balance the budget, utilities start cutting their operating cost and the hardest hit is usually improvements and maintenance to the operating system.

When maintenance and replacement projects are delayed during a drought they must eventually be brought back into schedule. There is not way to catch up on needed work and not spend money that is above "normal" levels. While Denver Water can do things to help shelter their customers from the full financial blow, the customer will ultimately have to pay. Rate increases after a drought is normal procedure to bring the budget back into balance.

A water utility also has many additional expenses during a drought. The table below summarizes some of the additional expenses.

Type of Expense	Year-End Cost/2003
Drought Monitors	$360,000
Landscape/Indoor Rebate Program	$1,800,000
Advertising/Marketing	$700,000
Temporary Staffing costs	$160,000
Total Additional Costs for One Year	**$3,020,000**

Denver Water is proposing a rate increase for 2005. Denver Water compared their rates to other water utilities in the metro area and found that their rates fell into the lower 1/4 of the range. The rates group is proposing an increase to the Board that would bring

Denver Water into the lower 1/3 of the price range. The increase would range from 4.6% inside, to 9.6% outside the city of Denver.

Because Denver Water customers are now using less water than they did in 2001 before the drought, 56% of average customers pay less now for water bills. Some customers may continue to pay less, even with the rate increase.

Cloud Seeding

Denver Water started cloud seeding the winter of 2002 in their Summit County watersheds. Winter cloud seeding is performed to produce more snow which would melt in the spring and fill Denver Water reservoirs. Cloud seeding has been widely used by ski resort in Utah and Colorado for last past few years. Cloud seeding involves the introduction of silver iodide which causes more water drops to condense within the cloud and then fall to earth. In cold cloud seeding, silver iodide is used which causes the super cooled liquid water droplet to freeze. This produces precipitation which falls to the ground as snowflakes if the air temperatures are below freezing.

Vail ski resort in Colorado is in their 16^{th} year of cloud seeding. Vail is attributing a 15 percent increase in the amount of snowfall over historical averages.

However, scientists are not in agreement on the effectiveness of cloud seeding. The main problem with proving the effectiveness is that it is difficult to determine if the seeding was the contributing factor or nature alone.

Denver Water knows that three months after starting cloud seeding, the Denver area experienced a three foot dump of well needed wet snow (Figure 3).

Challenges

This drought has allowed Denver Water to analyze and readjust their approach to the current drought or droughts in the future. Some of the decisions that were made and created challenges for Denver Water's staff are detailed below.

Permits for extra watering – This was not a repeater. The initial problem was Denver Water developed its drought rules without considering all of their customers that use water for landscapes. The "Drought Committee" did not address commercial and large residential site with the rules. This is a small percentage of the customers, but still shouldn't have been over looked. To compensate for this, Denver Water issued permits. Too much time was spent in this process and it opened the door for people to take advantage of the situation. In future droughts, Denver Water will craft the drought rules to encompass all the customers.

"Voluntary" reductions – When Denver Water customers were asked to reduce their water use, and a large percentage of customers did not comply. Denver Water observed less than a 10 percent reduction.

Small surcharges – Denver Water did not have steep enough steps to get the customers attention. Surcharges need to be enough of a sting to make people want to conserve.
Cute, fun advertising – Following the advice of an advertising agency, Denver Water launched an advertising campaign to get our customers attention. A sizeable percentage of people hated the campaign which just added more fuel to existing problem.

Trying to enforce all those rules – Keep it simple. More rules just breed more rules. Don't try to address all the possible problems that will surface.

One-size-fits-all watering times – Staff was divided on this issue. Some of Denver Water's staff tried to convince the Drought Committee that the15 minutes per zone rule was wrong. While other staff members (on the committee) felt that the public wouldn't understand anything different. The committee members were successful in their lobbying efforts to the Manager's staff and the Board. This issue ended up being one of the black eyes that Denver Water received during the whole drought process.

Can't please all the people all the time – When drought rules are developed and decisions are made, it is so true that not all customers will be pleased. There is no way to avoid this.

Summing Things Up

Drought cycles are hard to predict and even harder to manage all the ramifications. A water utilities response to a drought needs to be consistent and consumption driven. The public hated surcharges, but it did get the results Denver Water needed. Denver Water should have kept the public informed from the beginning on the financial implications facing the utility.

Denver Water's rate structure needs to be overhauled to support their long-term conservation objectives. Rates need to be a component of conservation to capture additional savings in non-drought years. Drought measures and Conservation measures need to be separate, and this difference needs to be better defined.

The success of conservation is a function of education, marketing, water rates and people taking actions to change their habits. Conservation is a community wide effort, we all need to work together to insure enough supply for the future. Growth is going to happen in Denver, that's a given. It's critical to get customers on board with Conservation so supply can continue to meet demand.

Denver Water needs to continue to educate it's customers on all the benefits of conservation. Conservation helps postpone the costs of developing more storage, which decreases the costs of environmental the impacts. Conservation also allows a community the option of future growth, which is good for the economy. Without conservation, most water utilities in the West would be forced to put a moratorium on growth.

Denver Water is aware of numerous mistakes that were made in the last few years of drought. It is easy for others to find fault when they don't have to walk down the path. It's important to learn from previous problems and design future responses to mitigate negative outcomes.

Using Distribution Uniformity to Evaluate the Quality of a Sprinkler System

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Introduction:

As demand upon urban water resources continues to increase, more attention has been focused upon landscape irrigation. The expectation is that automatic sprinkler systems will save water, but the reality seems that they use even more water. The possibility to save water exists if the sprinkler system is well managed, but overall irrigation efficiency cannot be better than the sprinkler system. The Irrigation Association offers the Certified Landscape Irrigation Auditor program that includes taking the auditor training class and passing an exam. As part of this class, students learn a standardized method to evaluate how well a system performs including how much water is applied in a given time frame as well as how evenly the water is applied. By using catch cans to perform an irrigation audit, the data collected can provide an indication on the quality of the sprinkler system that reflects the quality of the components, design, installation and long-term maintenance of the system. The lower quarter distribution uniformity is often used as the basis to judge the quality of the system. Current IA Turf and Landscape Irrigation Best Management Practices (February 2004) state that fixed spray heads should have a minimum lower quarter distribution uniformity of 55% and rotors should have a minimum DU of 70%.

This paper presents the findings from landscape irrigation audits done in various parts of the United States when evaluating the quality of the sprinkler systems using catch can data and calculating lower quarter Distribution Uniformity (DU).

Background Information:

In the Turf & Landscape BMPs as well as several training manuals from the Irrigation Association such as Landscape Irrigation Auditor, Sprinkler System Scheduling and Predicting and Estimating Landscape Water Use to name a few, the following table is provided describing the quality of the sprinkler system based upon the type of sprinkler heads based on lower quarter distribution uniformity.

Rating of Lower Quarter Distribution Uniformity (DULQ) for Sprinkler Zones

Type of Zone	Excellent (%)	Very Good (%)	Good (%)	Fair (%)	Poor (%)
Fixed Spray	75	65	55	50	40
Rotor	80	70	65	60	50
Impact	80	70	65	60	50

One item that jumps out to users of the BMPs is that minimal acceptable performance for spray heads of 55% falls in the “Good” category while rotor and impacts heads are in the “Very Good” category with 70% as the acceptable minimal performance. This has caused some confusion among end users and perhaps needs better explanation as to why the minimal expectation is not the same for different types of heads. This standard is not unique to the Irrigation Association only but has been implemented by various water purveyors or governmental agencies. Some agencies have used 60% as the minimal DULQ for fixed spray heads that is between good and very good according to the above table. In Australia the recommended minimum distribution uniformity based on lowest quartile is 75% and in the Georgia program for Landscape and Turf Irrigation Auditing a low quarter DU of 80% was deemed “adequate”.

In the August 2004 draft document “Landscape Irrigation Scheduling and Water Management from the Irrigation Association Water Management Committee, section Four provides a table discussing the quality rating of the overall irrigation system based on a weighted average of area as follows:

Quality Rating of the Overall Irrigation System

Quality of the Irrigation System	Irrigation System Rating (ISR)	Distribution Uniformity (DU_{LQ} overall)
Exceptional	10	> 85%
Excellent	9	75-84%
Very Good	8	70-74%
Good	7	60-69%
Fair	5	50-59%
Poor	3	40-49%
Fail	< 3	< 40%

Although this table is an idea presented by the Water Management Committee and needs further discussion it points out the need for most zones on a project to perform very well in order to compensate for those zones that fall at or below the minimal acceptable range. This table is for the overall irrigation system as a whole and not sprinkler individual zones. The quality of sprinkler system has an impact on the amount of water used to maintain a landscape. For example, in California Assembly Bill 325, the Water Conservation in Landscaping Act of 1990 requires that the Department of Water Resources develop a Model Water Efficient Landscape Ordinance. This Model Ordinance was adopted and went into effect January 1, 1993. In this ordinance irrigation efficiency for landscape irrigation systems must be a minimum of 62.5%. That would require that a site have a “Good” irrigation system and perfect water management in order to comply with the requirements. To compensate for the lack of perfect management, then a better quality sprinkler system such as “Very Good” or “Excellent” would be needed.

Turf Irrigation System Audits:

A few papers have been published discussing the results from audits, but most audit information is not formally published but is used to help educate the water manager or homeowner. But a sufficient number of audits have been conducted with similar results from the various locations in the United States that is makes for an interesting study to see how well turf irrigation systems are performing. Auditing techniques have been somewhat varied and adapted to local circumstances as well as needs of the auditing agency.

It is not the intent to discuss which auditing method or technique is the best or most correct but I will propose that there should be a minimum number of catch cans used to determine distribution uniformity. The size of area or the number of heads used to irrigate the area quite often dictates the number of catch cans used to perform the audit. The more catch cans used, the better or more reliable the measurement will be.

The method taught by the Irrigation Association and it is similarly taught by the Irrigation Training and Research Center at Cal Poly San Luis Obispo or the Landscape Irrigation Auditing and Management program offered by Texas A & M is to put a catch can near the head and then half-way between the head. Other areas used a grid pattern within the area being irrigated with a fixed spacing for the catch cans. Some auditing programs used two catch cans near the head and two in-between the sprinkler heads. Still other areas have used an abbreviated method to measure sprinkler system performance by using three or four catch cans strategically placed within the zone. While there are various ways the audits are being done, many programs have a minimum number of catch cans required for their method of conducting an irrigation system audit.

In Utah the guideline is 12-20 catch cans as a minimum. Colorado communities along the Front Range that are conducting audits for their customers have standardized informally on a minimum of 20 catch cans. Mobile Irrigation Laboratories (MIL) in Florida has a 16-24 catch can minimum requirement that is based upon how other mobile irrigation laboratories have operated in California and Texas. In Australia the minimum number of catch cans to be used is 20.

As can be seen there is not an absolute number of catch cans required, but those that have a minimum requirement see the need for a sufficient number of data points to calculate lower quarter distribution uniformity. Too few data points can lead to erroneous results. An item of observation is that most auditors choose to do the minimum when in reality more data points will provide a better measurement of sprinkler head performance. This becomes especially true when auditing large radius rotors. “Near a head and halfway between the heads” on large rotor systems leaves a lot of space between catch cans and the results could be eschewed. Moving the catch cans a few feet one way or another can dramatically change the results. In the Golf Irrigation Auditor Training by the IA the minimum recommended catch can spacing is to divide the space between the heads into thirds (use two catch cans between the heads) for auditing the fairways and on the tee boxes and greens a grid pattern is established placing the catch cans 10-15 feet apart depending on the size of area.

Although there are not any standards specifically for performing a landscape irrigation audit, some have adopted existing standards and modified them to fit the landscape situation. Some of these existing standards include:

ASAE S398.1 Dec 99 Procedure for Sprinkler Testing and Performance Reporting
ASAE S436.1 Dec 2001 Test Procedure for Determining the Uniformity of Water Distribution of Center Pivot and Lateral Move Irrigation Machines Equipped with Spray or Sprinkler Nozzles
ISO 7749/2 Irrigation Equipment Part 2, Uniformity Distribution & Test Methods

As already stated, these standards do not specifically address turf and landscape irrigation systems but they do provide guidelines that could be used for performing sprinkler system evaluations.

Sources of Audit Information:

The data used for this paper come from a variety of sources. For Utah three sources were used. Earl K. Jackson is the primary author for two reports documenting the results for the Slow the Flow, Save H2O campaign in Utah. The report "Saving Utah Water in the Fifth Year of Drought" focuses on residential properties after more than 4500 audits have been performed covering communities in six counties, while the other report "Irrigation Water Audits of Large Properties 1999 through 2003" summarizes the audit results on 166 commercial type properties. Another source of information was personal communication provided by Roger Kjelgren with Utah State University showing the audit results of 164 residences in the Logan, Utah area during the summer of 2004.

The data for Colorado was personal communication to the author from Laurie D'Audney, City of Fort Collins, Anne Haueter formally a summer intern with City of Loveland and now with Centennial Water & Sanitation District in Highlands Ranch, Colorado and Tiffany Graham working with communities in Boulder County. These audits were performed in 2003 and 2004.

Jill Hoyenga, Water Management Specialist with the Eugene Water & Electric Board provided data from the "quick & easy" audit versus a "full-blown IA" audit that she uses to teach homeowners about uniformity and irrigation scheduling. She uses only three catch cans and the calculated distribution uniformity would be best described as lower-third distribution uniformity. From past audits conducted by the author, the lower third distribution uniformity was usually 3-9 points higher than the lower quarter distribution uniformity. For purposes of comparing sprinkler uniformity in the various parts of the country, the lower-third distribution uniformity numbers she provided have been reduced by an average of 6 points to reflect a lower quarter distribution uniformity number.

In a paper presented at the 2003 ASAE Florida Section Meeting entitled “Residential Irrigation Uniformity and Efficiency in Florida”, the authors Melissa Baum, Michael Dukes and Grady Miller all with the University of Florida have done comparison studies of auditing techniques based upon the standards mentioned previously. In this case study, the audits involved hundreds of catch cans that covered the entire yard and placed in a grid pattern. Catch cans were placed five foot on center for spray heads and 10 foot on center for sprinkler zones with rotor heads. Catch cans were place about 30 inches from any structures, property boundaries or hardscapes to minimize the impact of “edge effects”. The basis for this method was derived from the standards previously mentioned. The results from doing an extensive audit on 19 homes in three different counties were likewise compared to the technique used by the mobile irrigation laboratories. In the comparison example, the largest zone of each of the nineteen homes using the grid procedure had a DU_{LQ} of 43.4% (range of 32-60%) while the Florida Mobile Irrigation Lab method of using 16-24 catch cans the DU_{LQ} was 55.1% (range of 36-70%). They also included the results of over 500 audits conducted by the Mobile Irrigation Laboratory of homes in seven different counties over the years.

Joe Kissinger, an independent auditor in southern California and consultant to several water agencies, provided the data for the California case study. These are audits he has done while doing studies to improve irrigation performance on existing sprinkler systems. The results were part of a report entitled “Landscape Water Conservation with Improved Irrigation Efficiency”.

A report entitled “Evaluating the Irrigation Efficiencies and Turf/Landscape Maintenance Practices on the Campus of Northern Arizona University” was the source of information and results for audits done on seven major turf areas at the Northern Arizona University in Flagstaff, Arizona.

A final report “Quantifying the Effectiveness of the Landscape Irrigation Auditing and Management Program” by Guy Fipps, Douglas F. Welsh and David W. Smith provided project results for six sites including a golf course, soccer field, football field, baseball field, a small commercial property and a residence. It was assumed that most of these properties are large and used rotor type heads and so the overall result is reported as rotors.

Results from Audits Performed:

The lower quarter distribution uniformity results from audits performed on residential sprinkler systems as well as large commercial type projects are given in the following table. Over 6800 audits are represented in this table with the average results shown.

Sprinkler System Performance

Residences		**Fixed Spray**				**Rotors**			
Location	# of Audits	Avg. DU_{LQ} %	Range %	Avg. PR (in/hr)	Range (in/hr)	Avg. DU_{LQ} %	Range %	Avg. PR (in/hr)	Range (in/hr)
Utah	4500	**52**		1.4	.70-3.70	**58**		.70	.10-2.30
Utah USU	164	**52**	18-80	1.57	.50-3.20	**49**	15-86	.76	.20-1.70
Colorado	973	**53**	20-89	1.34	.22-4.06	**54**	19-92	.62	.12-1.60
Oregon	398	**55***				**54***			
Florida MIL	576	**54**	11-89						
U of FL Case Study	19	**40**				**48**			
California Case study	19	**41**	16-54	1.61	.66-2.97				
Commercial		**Fixed Spray**				**Rotors**			
Location	# of Audits	Avg. DU_{LQ} %	Range %	Avg. PR (in/hr)	Range (in/hr)	Avg. DU_{LQ} %	Range %	Avg. PR (in/hr)	Range (in/hr)
Utah	166	**55**	7-82	1.49	.26-3.10	**55**	8-84	.74	.13-2.46
Colorado	20	**52**	6-77	1.36	.60-2.12	**50**	3-88	.60	.10-1.12
Arizona	7					**41**	20-56	.76	.57-.92
Texas	6					**58**	27-79		

* reflects the lower-third distribution uniformity information of 61 and 60 reduced by 6 points

Conclusion:

With over 6800 audits used to measure how well the typical sprinkler system performs it appears that the average DU_{LQ} is about 50% no matter what type of sprinkler head is being used. The results from the audits have in common that typically only one or two zones that appeared to be operating best (such as good coverage, no leaks or missing heads etc.) or were at least representative (by visual observation) of the sprinkler zones in the yard were actually audited for the residential programs. With that in mind, the overall sprinkler system distribution uniformity (DU_{LQ}) is probably less than what is reported in the above table. These findings are consistent with the findings from field assessments of irrigation system performance in California. Pitts et al. (1996) found less than desirable distribution uniformity values. The average DU for non-agricultural turfgrass sprinklers (residential lawns) was 49% with more than 40% of the tested systems having a DU of less than 40%.

By referring to the Quality Rating of Sprinkler Systems table most sprinkler systems fall into the “Fair” or “Poor” category. If water is a precious resource and there is such high demand upon water resources, this is not an acceptable situation.

Improving sprinkler system performance is an integral part of improving irrigation management so that overall irrigation efficiency can improve.

Another surprise is the fact that there seems to be very little difference in distribution uniformity between fixed spray heads and rotor heads. Frequently fixed spray heads are considered to have poor distribution uniformity and that is why they have a lower acceptable minimum distribution uniformity in the practice guidelines of the Irrigation Association's Turf and Landscape Best Management Practices. It can be seen from the audit results that most fixed spray zones come close to meeting the current BMP while rotor zones come up very short. As can be seen in the range of DU_{LQ}, either type of head can perform in the "Very Good" or "Excellent" category. Type or brand of equipment has the least impact on performance quality compared to proper design (including spacing, pressure and hydraulics), installation and maintenance.

Lastly what should be the realistic expectation of distribution uniformity of a sprinkler system? Should the IA BMPs state the minimum expectation or should the bar be raised? The current usage of the BMPs suggests that the minimum distribution uniformity as stated is the standard to be achieved. Some agencies such as Tucson Unified School District expect a 65% DU measured in the field on new projects. The City of Boulder, Colorado expects 70% distribution uniformity without regard to type of sprinkler head on commercial properties. As mentioned in the beginning the minimum DU_{LQ} considered acceptable in Australia is 75% and Georgia thinks that 80% DU_{LQ} is achievable for the average system. These higher expectations suggest that the irrigation industry including manufacturers, irrigation designers and contractors, needs to find ways to meet expectations and based upon the findings of these audits there is plenty of room for improvement. As water management is improved with the new technology of ET based controllers or soil moisture based controllers better performing sprinkler systems will be mandatory to properly manage water resources and achieve acceptable landscape quality and appearance

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A Model to Determine Residential Landscape Size Using Total Lot Size

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ABSTRACT

Assigning water allocation to residential water users is an effective tool in promoting conservation and efficient water use. Allocation can be based on four factors that are easily determined: crop coefficient, evapotranspiration, system efficiency, and indoor use. Landscape area is an additional factor that is more difficult to determine. This study details a model to determine landscape sizes for residential lots when only total lot size is available.

For this study, samples of residential lots were grouped in 1,000 square foot increments. Each sample lot was measured along with their respective landscape. The measurements were taken using aerial photography and mapping software to provide efficient and accurate measurements. An additional sample of lots was measured on site to confirm the accuracy of the software-based method of measurement. A regression curve was developed based on the landscape sizes versus the total lot sizes.

INTRODUCTION

California presents a clear example of a state that is growing in population, while its water supplies are shrinking. The Department of Interior's report, Water 2025: Preventing Crises and Conflict in the West, states that at the present time in some areas of the west, existing water supplies are or will soon be inadequate to meet the water demands of people, cities, farms and the environment even under normal water supply conditions. Solutions involving water conservation and formulas limiting scarcity that work in California may also work in other parts of the country .

California's water is supplied by a number of resources. These include existing groundwater aquifers, native mountain snow packs and rivers, rainwater stored in water tanks, and most notably, the Colorado River. In addition to the lower than average rainfall in recent years, water delivered from the Colorado River is rapidly facing reduction.

Californians must live within their 4.4 million acre-feet basic annual apportionment of Colorado River water in the absence of surplus river water and unused river water apportionments of Arizona and Nevada. Over the last three years however, the Colorado River Basin has experienced unprecedented drought and the surplus that has been provided to California is no longer available. .

Residential Water Use and Irrigation

The average Southern California family uses approximately 500 gallons of water every day (Water Facts 1). Outdoor use is approximately 50 percent of total residential demand and this water is primarily used for landscape irrigation. For this reason landscape irrigation must be looked at when considering water use and water conservation.

Efficient Irrigation and Resistance to Conservation

An incentive that is being used in many water districts is one based on customer allocation rates.

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Depending on certain factors, customers are allocated a certain amount of water per month or billing cycle. Most of the time, residential water allocation is based on meter size and elevation in relation to the water supply (City of Glendora, 2003). With the Irvine Ranch Water District (IRWD), residential water allocation is based on an allocation formula. This formula(Formula 1) combines the computed outdoor needs of each average IRWD customer with the average indoor needs of all customers, to arrive at an allocation amount for each customer district-wide. If a customer exceeds the allocation prescribed, the cost of water, for that portion over the allocation amount, is raised significantly. Water used over allocation is no longer *cheap*. This is called an increasing block-rate structure. For a number of water agencies, in areas where water supplies are becoming increasingly limited, and population has grown rapidly, this method of allocation and management has become successful at reducing wasteful consumption (Gilbert, Bishop & Weber 34-39, Featherstone 42-51). An important element in the success of an increasing block-rate structure is a clear and concise water bill for customers. It is important that customers learn the system and understand what they need to do to comply with their specific water allocation amount (Nieswiadomy & Molina 352-359).

<u>Background</u>
In 1991Irvine Ranch Water District adopted a tiered-rate billing system, or block-rate structure, based on a water budget allocation to encourage conservation and discourage substandard irrigation systems. The rate structure is based upon providing customers with the water they need at the lowest rates in Orange County (75 cents per CCF). Inefficient use is penalized with higher rates, ranging from \$1.50 to \$6.00 per CCF. Since the introduction of this rate structure, water consumption has dropped significantly, and the health of the landscape has improved (Barry, Pagano).

By 1997, inclining rates and outreach education programs had accounted for a reduction of 29.8 inches per acre of water per year (Barry, Pagano). From 1994 to 1997 a visual assessment study of the turf at 16 different sites was conducted comparing turf appearance prior to 1991. The study showed that despite the reduction in allocation due to the introduction of the new rate structure, turf quality either improved or remained unchanged. Sites that were initially *poor* prior to the introduction of the new rate structure improved the most (Chestnut, Pekelney). Since 1991, water use has dropped from an average of 4.4 acre-feet per acre to 2.2 acre-feet per acre. In the year 2000, the number of acres that were developed in IRWD's service area doubled, and water use only increased by 3 percent over water use in 1992.

Table 1. IRWD's single-family residential rate structure(Effective July 1, 2003)

Tier	Rate Per CCF	Use (As a Percent of Allocation)
Low Volume Discount	\$0.59	0-40%
Conservation Base Rate	\$0.75	41-100%
Inefficient	\$1.50	101-150%
Excessive	\$3.00	151-200%
Wasteful	\$6.00	201% +

Residential Use

IRWD's residential use has dropped from 0.32 AF/yr/customer (acre feet per year per customer), in 1989-90 to 0.28 AF/yr/customer in 2002-03. This is a 12.5 percent decrease in residential use per customer. The residential water use per customer for Los Alisos (an area annexed to IRWD, but not yet on IRWD's water-budget rate structure) was 0.35 AF/yr/customer in 2002-3. This is 25 percent higher than the IRWD amount per customer.

Water Budget Allocation

In the following equation, all of the figures are readily available, including landscape size. The majority of IRWD's service area is made up of planned communities. This unique situation makes it relatively simple to calculate landscape area. IRWD uses a standard default of 1,350 sq. ft of irrigated landscape for calculating single-family residential allocations.

$$\textbf{Single Family Allocation (CCF)} = \frac{Kc \times ET \times LA(acres)}{Eff} + \text{Indoor Use of 8,976 gal./month (4 people per home/3 CCF/person per month (billing period))}$$

(Source: Irvine Ranch Water District Allocation Formula)

Kc - crop coefficient for Irvine Ranch Water District, it is assumed that all of the irrigatable area is covered with cool-season turf**.**

ET (reference ET) - ET is computed daily from all three of Irvine Ranch Water District's weather stations. 100 percent of ET calculated is used for allocation and is adjusted daily. (Multiply by 36.3 to convert to CCF). (Ash 33).

Indoor Use - Each customer (single family residence) is automatically allocated 3 CCF, per person, per month for 4 people or, a total of 12 CCF (12 x 748 gallons = 8,976 gallons) per month.

LA - Landscape area is calculated in acres. IRWD has established 1,350 square feet as the universal landscape area default for single family residences in IRWD's service area. The allocation is set up with 100 percent of the landscape being cool-season turf grass.

Eff Efficiency - This is the efficiency of the irrigation system.. Irvine Ranch Water District assumes 80 percent.

Applicability to Other Areas

In 1997, Irvine Ranch Water District acquired the community of Santa Ana Heights. Santa Ana Heights is very different than the rest of IRWD's service area and is mostly made up of single-family residences built in the 1950's. It is not a *cookie cutter* community like Irvine. Parcel sizes range from 4,000 square feet to 140,000 square feet, with most falling in a range between 7,000 to 10,000 square feet. IRWD needed to develop an alternative methodology for calculating irrigated area that would give Santa Ana Heights customers an equitable allocation based upon each residential site.

GOALS AND OBJECTIVES

The goal of this study is to provide standard landscape sizes based on total residential lot sizes to use in the IRWD residential water allocation formula. The objective of these findings is to use a standard landscape size based on an individual customer's total lot size to determine water allocation without the need to conduct any actual measurements.

Literature Review

Prior to developing a methodology for estimating landscape, different measurement techniques for measuring land parcels must be studied; the following are a number of ways to determine landscape area.

- Actual physical measurement using a measuring wheel.
- Electronic distance measurements (EDM).
- Aerial photographs (remote sensing) and infrared imagery to measure parcels.
- Aerial photographs and Geographic Imaging Software (GIS) to measure parcels.

All of these techniques are discussed in Evaluation of Techniques to Determine Landscape Areas, prepared by California Polytechnic State University, San Luis Obispo for the United States Bureau of Reclamation. Additional information specific to measuring landscape area using aerial photography and GIS software was found in the BMP 5 Handbook: A Guide to Implementing Large Landscape Conservation Programs as Specified in Best Management Practice 5, by Gary F. Kah, John B. Whitcomb and Warren C. Willig.

Environmental Systems Research Institute, Inc., ESRI, developed the software, ArcView, to allow the measurements of the parcels. The California Department of Transportation uses aerial photography for mapping. Land and object measurements are included in the mapping process and a background of their procedure is detailed in the June 2004 Surveys Manual.

Based on the accuracy, cost and practicality, measurements using orthogonal aerial photographs projected in ArcView GIS software, was chosen as the best method for parcel and landscape measuring.

Measuring Method

Global Imaging Software (GIS) coupled with aerial photographs of the Santa Ana Heights community were used as the method for landscape area measuring. Stewart GEO Systems of Irvine, California provided the orthogonal aerial photographs and ArcView by the software company ESRI was the GIS used to measure the areas. Lot size data was obtained from the county assessor's office and added to the GIS database.

To begin the study Stewart GEO Systems requested specifications for the aerial photographs. Orthogonal photographs were required due to the accuracy required for measurement. A resolution of 3" per pixel was chosen, however later it was discovered that 6" per pixel would probably be sufficient. Another specification required was digital track modeling which allows for accurate measurements along elevation changes. The aerial photographs were also scaled using aerial triangulation and an onboard global positioning system (GPS) aboard the aircraft. When the aerial photographs were completed, the data from the county assessor was added. The cost for the photography and setup in ArcView was approximately $24,000. The total area photographed was approximately 4 square miles.

In the case of this study, the primary interest was landscape and hardscape measurement. The data added to the photographs allows the parcels to be outlined and grouped according to the customer type. All of the residential customers were individually outlined in red, then, using the query tool provided, the residential customers were grouped according to total parcel or lot size. Once these parameters are established, a parcel can be clicked using the cursor and information specific to that parcel appears in a window next to that parcel. This allows the landscape sizes to be grouped according to their respective total lot size, and results in the median landscape sizes for each lot size category.

Figure1. Photograph with parcels outlined.

Another tool included in ArcView is a measuring device. The hardscape measurements can then be subtracted from the total individual lot area. Hardscape was traced because it provided a more solid line to trace along. In addition, total lot size was traced and compared with the database to confirm accuracy of this method. It takes roughly one minute to measure the total lot size and the hardscape. Using this method of measurement, the only question in accuracy is in identifying landscape or hardscape that is hidden underneath any sort of canopy.

RESULTS AND ANALYSIS

The following is a summary of measurements categorized by each lot size. Samples are in 1,000 square foot increments, starting with the smallest lots of 4,000 sq.ft. up to 12,000 sq.ft., at which point the square footage of the categories is increased. Out of a total population of 1,380 for all categories, the sample size was 437. Included in the spreadsheet(Table 2, Figure 2) are the lot size groups and their respective landscape sizes and landscape sizes plus one standard deviation.

Table 2. Measurement summary grouped according to lot size

Lot Sizes (Sq.Ft.)	Total Pop.	Sample Size	Median Lot Size (Sq.Ft.)	Median Lndscp. Size (Sq.Ft.)	Median Lndscp.%	Max. Landscape Size with 1 Std.Dev. (Sq.Ft.)	1 Std.Dev. (Sq.Ft.)
4,000 - 5,000	59	40	4332	1358	31%	1,823	465
5,000 - 6,000	59	50	5750	2225	39%	2,765	540
6,000 - 7,000	160	50	6267	3015	48%	3,582	567
7,000 - 8,000	414	50	7368	3735	51%	4,330	595
8,000 - 9,000	346	50	8686	4433	51%	5,298	865
9,000 - 10,000	103	50	9506	5080	53%	5,922	842
10,000 - 11,000	56	50	10473	5532	53%	6,585	1,053
11,000 - 12,000	37	30	11597	6384	55%	7,964	1,580
12,000 - 16,000	44	30	13819	7607	55%	9,218	1,611
16,000 - 80,000	95	30	19800	12531	60%	23,506	10,975
80,000 - 140,000	7	7	114715	85229	74%	100,014	14,785

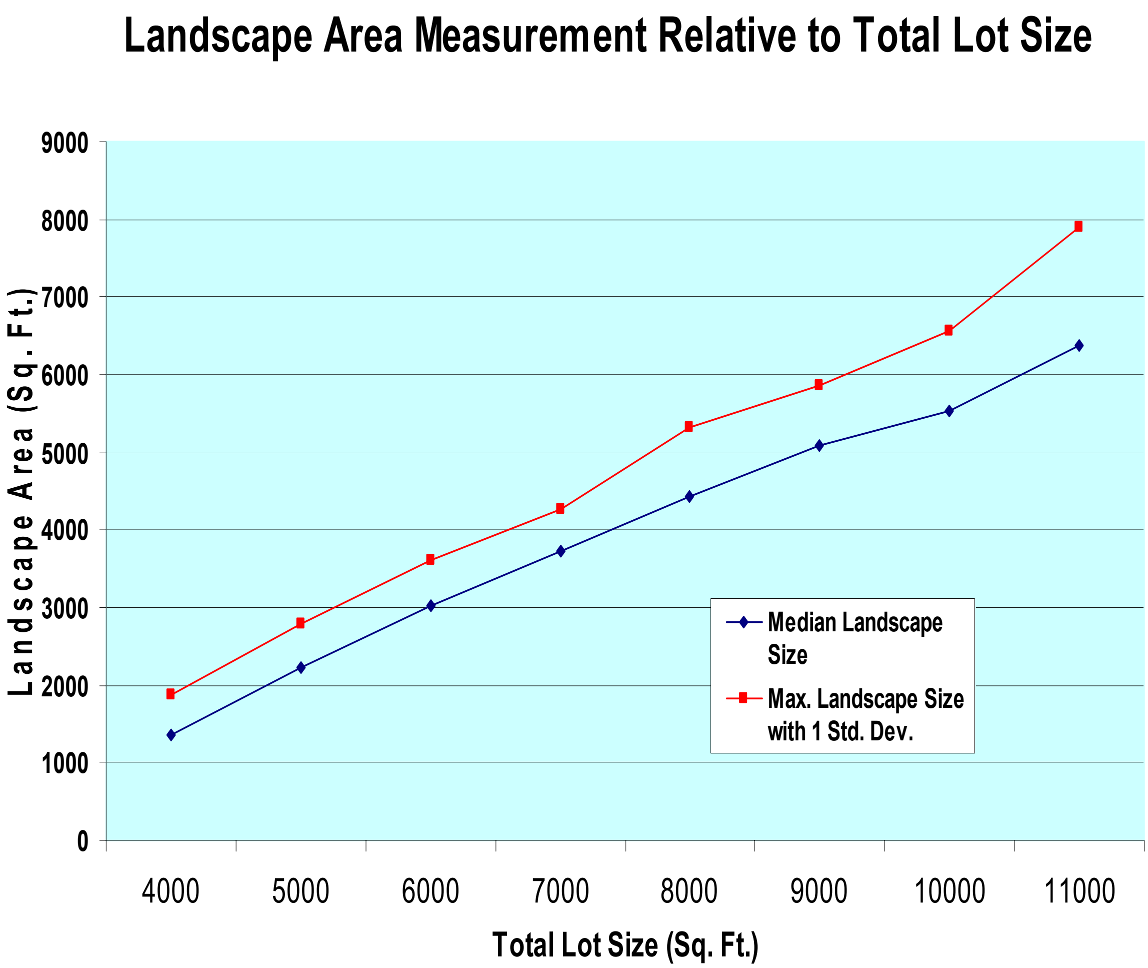

Figure 2. Landscape area measurement relative to total lot size

<u>Regression Analysis</u>
Figure 3 show the statistical relationship between total lot size and landscape size, using median landscape sizes plus one standard deviation for each lot size group with lot sizes over 12,000 square feet omitted. Most residential lots in Santa Ana Heights are actually less than 16,000 square feet. Although a regression line and formula was derived for lot sizes between 80,000 and 140,000 square feet, it is highly recommended that traditional surveying techniques are used to measure landscapes of lots over 43,560 square feet (1 acre).

For most months, the percentage of excessive and wasteful customers is almost the same between IRWD and SAH(Table 3). The percentages for inefficient customers are considerably different, however. This is believed to be due to IRWD's use of a 1,350 square foot default per residence which is not as accurate as the methodology prescribed in this thesis. The inefficient tier includes any water use over 100 percent and under 150 percent of the allocation. It is possible that if this methodology were used in determining Irvine's allocation, the comparison at the inefficient level would be closer. This would be a suggestion for further study. In addition, customers in Irvine that fell into the inefficient range did not receive conservation bulletins until September 2002. It is apparent that by October 2002, inefficiency comparisons were much closer. Although an observation, this comparison shows how closely Santa Ana Heights matches the trend of overuse in Irvine, where the allocation formula is in practice, albeit using a standard default for landscape area for all residential properties.

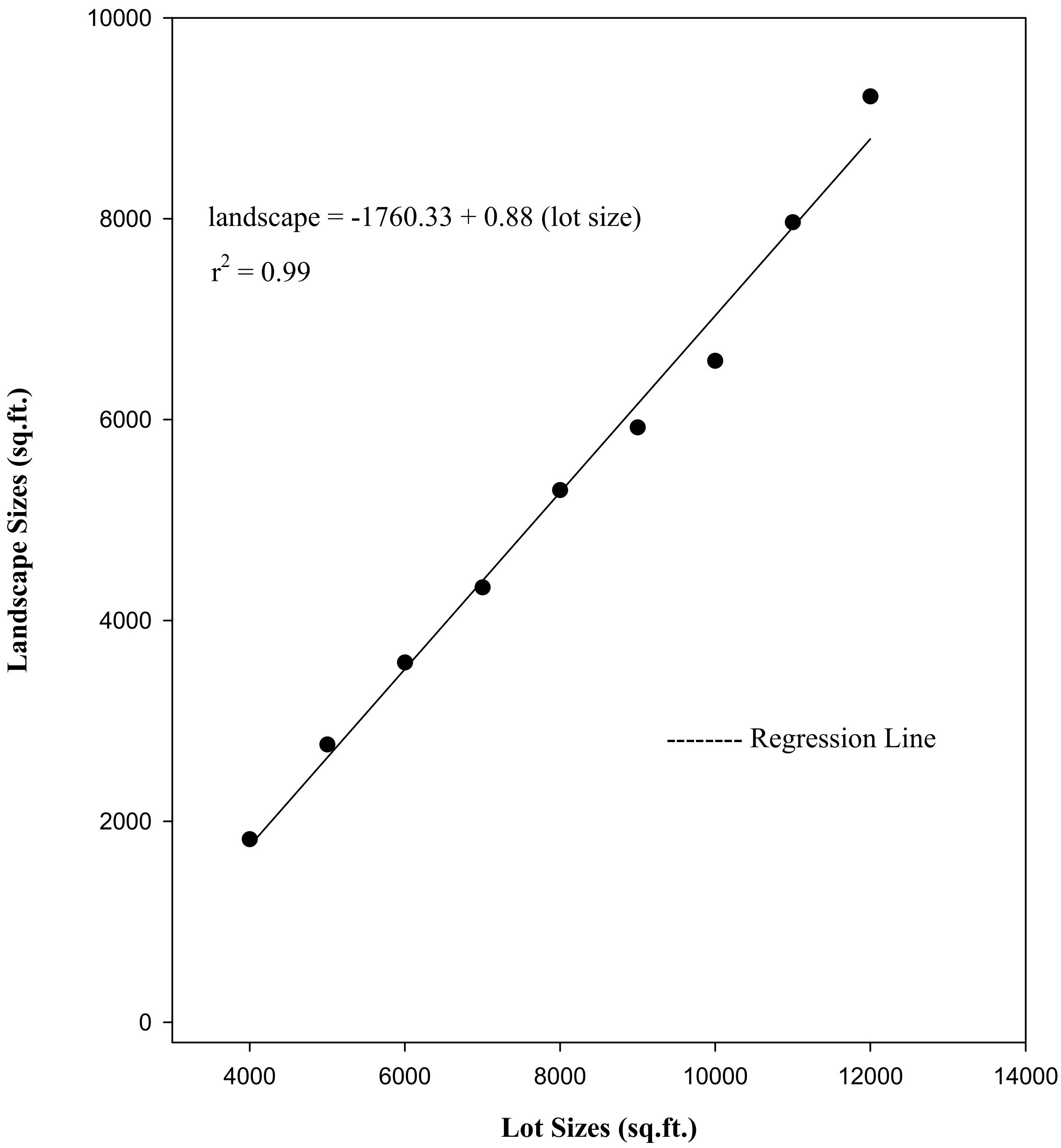

Figure 3. Regression line for lot sizes between 3,000 and 80,000 square feet

Table 3. 2002 Water over use for Irvine verses Santa Ana Heights.

Tier	Jan		Feb		Mar		Apr		May		June	
	Irvine	SAH	Irvine	SAH	Irvine	SAH	Irvine	SAH	Irvine	SAH	Irvine	SAH
% Inefficient	34	9	34	11	36	8	35	6	36	8	39	13
% Excessive	3	1	3	2	3	2	3	1	3	1	4	2
% Wasteful	1	2	1	1	1	1	1	1	1	1	1	1
	July		Aug		Sept		Oct		Nov		Dec	
	Irvine	SAH	Irvine	SAH	Irvine	SAH	Irvine	SAH	Irvine	SAH	Irvine	SAH
% Inefficient	22	12	20	14	24	17	24	24	21	18	18	18
% Excessive	5	3	6	2	6	4	6	7	6	5	4	4
% Wasteful	2	1	2	1	2	2	2	3	2	2	1	3

The Importance of Accuracy and Measuring

A total of 30 residential customers were selected at random for on-site wheel measurement verification of the ArcView measurements. The total lot and landscape areas for each of the randomly selected sites were measured and compared with ArcView measurements, drawing polygons and using infrared data. The average error rate for the 30 samples was 4.7 percent for the manual polygon tracing method. Previous studies recorded error rates under 3 percent which would fall within this study's parameters (California Polytechnic State University, San Luis Obispo 23-24). The infrared method produced an error rate of 11.6 percent.

SUMMARY

The accuracy of approximately 95 percent compared to the measuring wheel method supports the validity of using the ArcView GIS method of tracing polygons around hardscapes to determine individual landscape sizes. The practice of using a measuring wheel is too costly in time and is logistically inefficient. The use of infrared spectrometry as an added option to aerial photographs in ArcView is more time efficient, however it is not as accurate as the ArcView GIS method of tracing polygons and it is more expensive.

Since a reliable method of measurement has been established, median landscape sizes can be established. The theory of taking the median landscape size of each lot size group and adding landscape area to include one standard deviation allows for any variances in residential developments. Grouping the lot sizes in 1,000 square foot increments and assigning median landscape sizes based on sample measurements provided the data needed to derive the regression formula. The regression formula:

Landscape Size = -1760.33 + (0.88 x Lot Size)

provides a landscape size for any residential lot over 3,000 square feet. (It is recommended to measure lots over 43,560 square feet by traditional survey methods, due to more extreme variability of landscapes over 1 acre.)

CONCLUSION

The reason for setting water allocation limits is to encourage conservation and efficient irrigation practices. It is important to have an accurate and fair method for developing allocation levels in order to implement a billing rate system in which the public will be confident. Irvine Ranch Water District plans to estimate landscape area by this method for water allocation purposes.

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