ABSTRACT

VASANTH, ARJUN. Evaluation of Evapotranspiration-based and Soil-Moisture-based Irrigation Control in Turf. (Under the direction of Dr. Garry Grabow.)

Turfgrass is a major part of the landscape in North Carolina with its acreage equal to 44% of the state's harvested crop acreage. Proper irrigation of residential, industrial and commercial turf areas is required to ensure healthy and acceptable turf quality. With increasing competition for water resources and better turf quality, an efficient irrigation control technology is essential in meeting the dual goals of water conservation and turf quality. The objective of the research was to compare two general types of commercially available irrigation control technologies; one based on estimates of evapotranspiration (ET) and the other based on feedback from soil moisture sensors. Water application and turf quality resulting from using these technologies were compared to results from using a standard time-based irrigation schedule. The study also incorporated the effect of irrigation frequency. The experimental area, located at North Carolina State University Lake Wheeler Turf Field Laboratories, Raleigh, North Carolina, consisted of forty 4-m x 4-m plots established to 'Confederate' tall fescue (*Festuca arundinacea* Schreb*)* using sod. There were ten treatments combining control type and watering frequency (3 technologies x 3 frequencies + 1 on-demand technology) with four replicates in a randomized complete block design. Technologies included three systems: a time-based system, a soil-moisture-based "add-on" system, an ET-based system each with three frequencies: once per week, twice per week and seven days per week irrigation, and a soil-moisture-based "water on-demand" system which was allowed to schedule irrigation everyday. Rain sensors were connected to the timer-based and ET-based systems to prevent irrigation in case of rainfall. The add-on soil-moisture-based system applied the

least amount of water while the ET-based technology applied the most water averaged across frequencies. Once a week irrigation frequency applied the least amount of water, and daily irrigation frequency applied the most when averaged across all technologies. Minimally acceptable turf quality was met by all the treatments when averaged over the duration of the study period, although during the last month of the study some technologies, especially the timer-based and add-on systems had noticeably drought stressed plots. In general, the ET-based system and the water on-demand system had the best turf quality. The water on-demand system resulted in the best combination of water use efficiency and turf quality. Canopy temperatures were measured once a week and there were significant differences in canopy temperature among treatments averaged over the season. The ET system plots had the lowest canopy temperature while the add-on system plots had the highest canopy temperature. Also there was no significant difference between mean weekly reference ET estimates from an atmometer and Penman-Montieth reference ET estimates using a weather station at the site.

Evaluation of Evapotranspiration-based and Soil-Moisture-based Irrigation Control in Turf

by
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BIOGRAPHY

Arjun Vasanth was born on April 30^{th} 1984 to Nalini Vasanth and Vasanth Narayanan in the city of Chennai, Tamil Nadu, India. He also has a younger sibling, Achyuthan Vasanth. He did his entire schooling in St Johns Senior Secondary school, Chennai. After High School, Arjun attended Sri Venkateswara College of Engineering affiliated to Anna University, Chennai, India to pursue his Bachelors in Chemical Engineering. Working on his senior design project in wastewater treatment which seemed to interest him, Arjun decided to enhance his knowledge by doing a Masters program in Environmental Engineering. He joined the Civil Engineering Department of North Carolina State University to work on his Masters in July 2005. After two semesters of classes in the Civil Engineering department, he was offered a research assistantship position in the Biological and Agricultural Engineering Department to work on a turf irrigation project. He joined the BAE Department in July 2006 and has been working on his Masters since then. Arjun is finishing his Masters in Biological and Agricultural Engineering with a minor in Water Resources.

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CHAPTER 1

1. Introduction

Maintained turf acreage in North Carolina increased by 21.4% between 1995 and 1999 and homeowners accounted for 69% of the increase (NCDA, 2001). Turf irrigation is also on the rise with 96% of the golf courses in NC using some sort of turf irrigation (NCDA, 2001). The largest category of turf installation in the United States includes single-family and multiple-family residences (Cockerham and Gibeault, 1985). Turfgrass is a major part of the landscape in North Carolina with acreage equal to 44% of the state's harvested crop acreage (NCDA, 2001). More than 2.1 million acres of turfgrass add to the functional, recreational and aesthetic value of the state.

Proper irrigation of residential, industrial and commercial turf areas is required to ensure healthy and acceptable turf quality. With recurring drought problems, several municipalities in North Carolina have imposed water-use restrictions limiting or banning landscape irrigation. As of November 6^{th} 2007, most of the counties in North Carolina are classified under one of the following drought conditions; (D0) impending drought, (D1) Moderate drought, (D2) Severe drought and (D3) Extreme drought. The city of Raleigh restricted lawn watering to three days a week until 23^{rd} October after which landscape irrigation was banned. Charlotte, NC banned all landscape irrigation as of 24^{th} September 2007. Efficient irrigation of landscape using new irrigation control technologies may help conserve water and mitigate drought impacts.

1.1 Turfgrass Water Use and Management

Turfgrasses can be classified as cool-season turf or warm-season turf depending on physiological processes. The most common cool-season turf includes tall fescue, Kentucky bluegrass, perennial ryegrass and creeping bentgrass while the most common warm-season turf are bermudagrass, zoysiagrass, St Augustinegrass, kikuyugrass, centipedegrass and bahiagrass (Beard, 1985). Cool-season grasses grow well in the northern United States. They grow actively in cool spring weather and slow down or go dormant in the heat of summer when the temperature reaches 30º C. In areas with a hot climate, tall fescue grows best when irrigated (NCDA, 2004). The improved turf-type tall fescues are finding widespread acceptance as lawn grass in the transition zone of the US. In the southern region under moderately shaded conditions, tall fescue is gaining in popularity (Duble, 1996). Also, the improved tall fescues retain color during the winter months providing a year-round green lawn.

Depending on the area's climate, residential outdoor water use varies from 22% to 67% of the total water use of a household (Mayer et al., 1999). Recent studies in the US reveal that 58% of potable water is used for landscape irrigation (Mayer et al., 1999). In the same study, it was observed that homeowners used an average of 77 mm of water per month for landscape irrigation in the US. However, Baum (2005) found that typical homeowners in Florida used an average of 116 mm per month of water.

In a recent survey of five communities in North Carolina (within the Neuse River Basin), the percentage of homeowners that irrigated turf ranged from 54% in Kinston to

89% in New Bern (Osmond and Hardy, 2004). The same study found that Cary, NC, residents with fixed irrigation systems applied almost twice the amount of water as those irrigating with movable sprinklers.

North Carolina receives an average of 1150 mm of rainfall a year (National Oceanic and Atmospheric Administration [NOAA], 2003). Applying the same amount of water at regular intervals, as with timer-based irrigation scheduling, will often result in over-irrigation and the needless waste of water and energy. North Carolina with its humid environment requires irrigation planned in conjunction with the prevailing rainfall conditions to limit water waste and achieve the high quality landscapes desired by homeowners.

Historically, NC guidelines for irrigation have been to irrigate 25 mm per week in the absence of rain (Bruneau et al., 2000) although turfgrass water use can exceed 25 mm during peak demand periods and be less during cool, cloudy days. Peacock and Bruneau provided newer guidelines that indicated turfgrass water demand to be 48 mm per week during the month of July and 18 mm per week in October.

In order to conserve water, and at the same time have a healthy turf, proper irrigation scheduling (applying the right amount of water at the right time) is required. Irrigation scheduling can be done in a number of ways to allow proper irrigation of turfgrass. The practical methods of scheduling include: daily replacement, fixed day irrigation, fixed amount irrigation, cycle start, soil-water balance checkbook and historical ET override with rain sensor (Mecham, 1997). Irrigation scheduling needs to account for the available water holding capacity of the soil, root depth, effective rainfall and weather conditions including temperature, solar radiation and wind speed.

Available water holding capacity (AWHC) is the fraction of soil-water that is considered available for plant use and is measured in mm m^{-1} of the crop root zone. Traditionally, AWHC is half of the total water content in the soil at field capacity (Allen et al., 1998). This fraction varies for different types of soil. Field capacity is defined as the amount of water held in the soil against the force of gravity after saturating the soil by irrigation or rainfall. Gravity drainage starts with the largest pores draining rapidly. After drainage decreases to a very slow rate, the water content of the soil measured at this point is called the field capacity. It is not a definite water content but an approximation after rapid drainage (Carrow, 1985) and generally speaking it is taken to be the water content at soil-water tension of 0.1 bar (for sandy soil) or 0.33 bar (for clay-loam soil).

To prevent plant stress, irrigation should be scheduled before the soil-water level drops below a certain percentage of field capacity known as the Management Allowable Depletion (Smajstrla et al., 1989).

1.1.1 Effective Rainfall

Effective rainfall (ER) is that portion of total rainfall that plants use to help meet their consumptive water requirements. It is an important component of irrigation requirement estimation. An empirical formula for calculating ER given in SCS TR-21 (USDA, 1970) is

$$\mathrm{ER} = \mathrm{SF} \times (0.70917 \times \mathrm{P_m^{0.82416}} - 0.11556) \times 10^{0.02426\mathrm{ET_c}} \tag{1}$$

where

P_m = precipitation [mm],

ET_c = crop evapotranspiration [mm day^{-1}], and

SF = soil water storage factor calculated using the formula

$$SF = 0.531747 + 0.295164 \times D - 0.057697 \times D^2 + 0.003804 \times D^3 \qquad (2)$$

where

D = usable soil water storage which is fraction of the available water holding capacity of the soil. In this study, D was taken as 0.66 of the AWHC of the crop root zone.

1.1.2 Reference Evapotranspiration

Evapotranspiration (ET) is the process by which water is transferred to the atmosphere through evaporation and transpiration. Evaporation is the physical process whereby water is changed from a liquid to a gas from free water surfaces, such as ponds, streams, and from wet soil or wet vegetation. Transpiration is a process where plants exchange water for carbon dioxide. All leaves have microscopic openings, called stomata. When open, water evaporates due to a concentration gradient. Carbon dioxide can also diffuse into the plant through the open cavity. When the stomata close, little carbon dioxide or water enters or leaves the plant. The plant balances the opening and closing of the stomata to acquire enough carbon dioxide and not lose too much water, so it can stay alive. Environmental conditions such as air temperature, humidity, radiation, wind etc affect the evapotranspiration from plants.

Reference evapotranspiration is used to estimate the amount of water lost by crops. In general, there are two types of reference evapotranspiration; Grass reference evapotranspiration (ET_o) and alfalfa (*Medicago sativa*) reference evapotranspiration (ET_R). According to Allen et al. (1998), reference evapotranspiration is defined as

“the rate of evapotranspiration from a large area, covered by green grass, 8 to 15 cm tall, which grows actively, completely shades the ground and which is not short of water”.

Measurement of reference evapotranspiration is difficult so empirical equations have been developed to estimate it. These include the Thornthwaite, Blaney-Criddle, and the Penman-Montieth equations (Allen et al., 1998). Of these, the Penman-Montieth is currently the most widely used.

In 1948, Penman combined energy balance with a mass transfer method to derive an equation to compute the evaporation from an open water surface using temperature, humidity, wind speed and solar radiation. This equation was further developed by many researchers. Resistance to vapor flow was differentiated between bulk surface resistance and aerodynamic resistance. The bulk surface resistance describes the resistance of vapor flow through stomatal openings and the aerodynamic resistance describes the resistance above the vegetation and includes friction from the air flowing above the vegetative surface (Allen et al., 1998).

The FAO Penman-Montieth equation is

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma(900/(T+273))u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{3}$$

where

ET_o = reference evapotranspiration [mm day^{-1}],

R_n = net radiation at the crop surface [MJ m^{-2} day^{-1}],

G = soil heat flux density [MJ m^{-2} day^{-1}],

T = mean daily air temperature at 2 m height [°C],

u_2 = wind speed at 2 m height [m s^{-1}],

e_s = saturation vapor pressure [kPa],

e_a = actual vapor pressure [kPa],

e_s - e_a = saturation vapor pressure deficit [kPa],

Δ = slope of the saturation vapor pressure curve [kPa $°C^{-1}$], and

γ = psychrometric constant [kPa $°C^{-1}$].

The amount of water required to replace evapotranspiration is termed the crop water requirement, CWR. The CWR can be met by rain and irrigation. To obtain the crop evapotranspiration (ET_c), the reference evapotranspiration, ET_o, is multiplied by a crop coefficient, K_c (Allen et al., 1998):

$$\mathrm{ET_c} = \mathrm{ET_o} \times \mathrm{K_c} \tag{4}$$

The effects of characteristics that distinguish field crops from grass are integrated into the crop coefficient (K_c). The crop coefficient depends mainly on the type of crop, the growth stage of crops and the climate (Allen et al., 1998). Crops like maize with a high leaf area index can transpire more and hence require more water than a reference crop while cucumber requires less water than the reference crop. Crops use more water when fully developed than in the first weeks subsequent to planting. The climate influences the duration of the growing period and various growth stages (Brouwer and

Heibloem, 1986). For this research a crop coefficient of 0.8 specific to cool-season turfgrass was used (Allen et al., 1998).

1.1.3 Net and Gross Irrigation Requirement

The net irrigation requirement (NIR) is defined as the net amount of irrigation water required to replace crop ET after accounting for effective rainfall:

$$\mathrm{NIR} = \mathrm{ET_c} - \mathrm{ER} \tag{5}$$

The gross irrigation requirement (GIR) is the quantity of water to be applied by the irrigation system after accounting for irrigation uniformity (Allen, 1997):

$$\mathrm{GIR} = \frac{\mathrm{NIR}}{\text{System Uniformity}} \tag{6}$$

The gross irrigation requirement can be computed daily, weekly, monthly and seasonally. With the known sprinkler application rates and GIR, the irrigation runtimes for the system can be calculated.

1.2 Turfgrass Irrigation Control

There is a steady increase in the number of people using residential irrigation systems in North Carolina. Residences using irrigation systems increased by 29.4% between 1994 and 1999 (NCDA, 2001). An efficient irrigation schedule is essential in meeting the dual goals of water conservation and acceptable turf quality. Under-irrigation and over-irrigation can negatively affect turfgrass quality (Cardenas-Lailhacar et al., 2005). Over-irrigation results in waste of water and leaching of nutrients while under-irrigation results in poor turf quality. In time-based irrigation, irrigation duration and frequency are normally controlled with irrigation controller clocks. Cardenas-Lailhacar et al. (2005) observed that by just adding a rain sensor to a time-based irrigation schedule reduced water usage by 45%. Improved irrigation efficiency by using the correct amount of water can be achieved by different methods.

1.2.1 Controller Clocks

Controller clock systems are an essential part of automated irrigation systems. While electro-mechanical and mechanical controllers were commonly used in the early 1970's, controllers became exclusively electronic in the 1990's (Zazueta et al., 1993). Even though these controllers offer means to schedule irrigation and control the amount of water applied, they are only as good as the information used to program them. As required knowledge and information are frequently lacking, most of the control clocks are incorrectly programmed. There are two types of controller systems; open loop system and closed loop system. In open loop systems, the operator decides on the amount of water that will be applied and when the irrigation will occur. This information is programmed into the controller and water is applied accordingly. Open loop systems normally have a clock to start irrigation. In a closed loop system, the operator develops a general control strategy using feedback from measurement instruments. Once the general strategy is established, the control system takes over and makes detailed decisions of when to apply water and how much to apply (Zazueta et al., 1993; Boman et al., 2002).

The simplest form of a closed loop irrigation system is an irrigation system that is controlled by a soil-water sensor. The sensor is wired in series with an electrical solenoid valve. The sensor acts as a switch opening the circuit between the controller and the valve when the water content is above a set threshold prohibiting any pre-programmed irrigation and closing the circuit when watering is needed.

1.2.2 Soil-Water Measurement

The most accurate method of measuring soil water content is the thermogravimetric method, which requires heating a known mass of soil at 105º C for a specific time and determining the weight loss. This method is time consuming and destructive to the sampled soil.

Indirect methods of estimation of soil-water include tensiometry, electrical conductivity, measurement of the bulk soil dielectric constant, gamma ray attenuation and neutron thermalization. Various types of sensors such as tensiometers, granular matrix sensors and time domain reflectometry probes have been used to provide feedback in closed loop systems (Dukes and Scholberg, 2004; Blonquist et al., 2005; Boman et al., 2002). A tensiometer is a device used to determine matric water potential Ψ_m (soil-water tension) which is then related to the volumetric soil water content. A study conducted by Neil and Carrow (1982) revealed that Kentucky bluegrass with tensiometer controlled irrigation used 28 to 48 percent less water than time-based irrigation water use.

Granular matrix sensors are similar to tensiometers in that they are made of a porous material that reaches equilibrium with the soil-water. The soil-water tension is correlated to an electrical signal based on a calibration equation (Munoz-Carpena et al., 2003). Granular matrix sensors have been used to automatically irrigate urban landscapes (Qualls et al., 2001). They have also been used for irrigation control using soil-water feedback on corn and cotton in North Carolina (Grabow et al., 2004) and potatoes (Shock et al., 2002).

There has been a significant advancement in the use of electromagnetic methods in the measurement of soil-water content. Use of these electromagnetic methods coupled with the use of computer technology has resulted in the establishment of inexpensive soil-water sensors for automated irrigation of landscapes. There are two main techniques involved, Time Domain Reflectometry (TDR) and Frequency Domain Reflectometry (FDR; Charlesworth, 2000).

1.2.2.1 Time Domain Reflectometry

Time domain reflectometry instruments operate by sending an electromagnetic signal through a pair of parallel rods buried in the soil. This pulse travels the length of the rods and is reflected back to the control unit which detects and analyses it. The time taken by the pulse to travel the length of the rod depends on the length of the rod and also the dielectric constant of the moist soil. This is then related to the volumetric soil water content. Time domain reflectometry has been used to initiate and terminate irrigation of the plots based on soil-water measured by TDR probes installed at a depth of 13 cm (Topp et al., 1984; Dukes and Scholberg, 2004). Time domain transmissivity (TDT) probes are similar to TDR probes in operation but have less signal attenuation (assuming sensor rods are the same length) and are more affordable (Blonquist et al., 2005).

1.2.2.2 Frequency Domain Reflectometry

Frequency domain reflectometry measures the bulk soil dielectric constant by placing the soil between two electrical plates. When a voltage is applied between the two plates, a frequency is measured which varies with the dielectric constant of the soil medium. And the dielectric constant of the moist soil is related to the volumetric soil water content (Charlesworth, 2000).

1.2.3 Evapotranspiration Measurement

Standard irrigation controllers require users to input irrigation schedules and adjust run-times in response to climatic conditions. Another type of system being used in turfgrass irrigation control is based on controllers that use weather information to estimate ET and adjust irrigation using a soil–water budget. These controllers commonly called evapotranspiration controllers receive information from local or on-site weather stations and adjust watering durations based on the climatic conditions.

An atmometer can be used to estimate ET as a substitute for ET estimated using weather data. An atmometer is a device that includes a porous ceramic plate (Bellani plate) that has been modified to make an inverted cup and is filled with distilled water. A water filled supply tube is inserted through an opening of a rubber stopper that attaches to the ceramic cup opening. The cup assembly is then mounted on top of a cylindrical reservoir made of white polyvinyl chloride (PVC) filled with distilled water. The supply tube extends into the cylindrical reservoir and establishes a continuous connection between the water in the cup and the cylindrical reservoir below. Any water lost from the cup by evaporation is replenished with water from the reservoir via the tube due to suction created in the siphon. The drop in the water level from evaporation is read from a glass tube connected by two ports to the reservoir and mounted outside the reservoir. A scale is affixed on the outside wall of the cylindrical reservoir near the glass tube for reading the amount of evaporation. Atmometer-measured evaporation adjusted with an appropriate regression equation to obtain ET_0 can be used in water balance calculations for irrigation scheduling (Alam and Elliott, 2003). An atmometer with a dense fabric (#30 canvas) has been used to simulate grass-based ET_o while a standard model with #54 green canvas is recommended for measuring alfalfa-based ET_R (Alam and Trooein, 2001). Magliulo et al. (2003) found high values of correlation coefficient when comparing ET_o determined by an atmometer and a Penman Montieth equation based ET_o. Research done in Silsoe, United Kingdom, show that evaporation measured with an ETgage (an atmometer made in Colorado, USA) was in close agreement with Penman-Montieth ET_o for grass reference (Hess, 1996).

1.3 Smart Controllers

Smart controllers can be broadly separated into two categories – those that use feedback from a sensor to monitor the amount of water in the root zone and those that use weather data to estimate amount of water required by the turf for irrigation. Automated irrigation using these smart controllers has become the new trend in turf irrigation. Automated irrigation is very useful, particularly in humid areas where unpredictable and unevenly distributed summer rainfall disrupts fixed irrigation schedules (Castanon, 1992).

1.3.1 Soil-water sensor based control

Soil-water-based systems have an add-on module that interfaces with an existing controller. The controller unit powers the soil-water sensor and reads the soil-water content. Allen (1997) found that the use of a simple automated device for overriding a standard electronic irrigation clock by monitoring soil-water can result in an average of 10% savings in water use and can still maintain healthy green lawns compared to a system without a rain sensor. Dukes and Scholberg (2004) noted 23% and 50% water savings while using TDR probes and a commercially available dielectric sensor, respectively, on sweet corn and bell pepper. Granular matrix sensors (GMS) have also been used to automatically irrigate agricultural crops (Shock et al., 2002). Granular matrix sensors were used for irrigation control using soil-water feedback on corn and cotton in North Carolina (Grabow et al., 2004). Although these types of sensors have been used for irrigation of agricultural crops, they have limited use in residential landscape irrigation (Qualls et al., 2001).

A recent study in Florida found that irrigation control using feedback from soil-water sensors applied 59% to 88% less water compared to a time-based irrigation schedule set to replace the historical evapotranspiration for bermudagrass (Cardenas-Lailhacar et al., 2005). In this study the time-based system, typical of homeowners with relatively well-managed automatic irrigation systems, applied an average of 98 mm water per month while the SMS-based treatments averaged 42 mm. Augustin and Snyder (1984) found water savings of 42% to 95% using a tensiometer as compared to conventional irrigation on bermudagrass. Switching tensiometers used in a research study in Florida (Munoz-Carpena et al., 2003) observed 50% reduction in water application with respect to 100% recommended crop water needs treatment. Blonquist, Jr. et al. (2006) had 16% water saving using TDR probes as compared to a sprinkler system set to replace ET-based irrigation requirements.

1.3.2 Evapotranspiration (ET) based control

Standard irrigation controllers require users to input irrigation schedules and adjust run-times with changing weather conditions. An ET-based controller uses weather information to estimate ET and adjust run-times using a soil-water budget. There are a couple of approaches to ET-based control at the residential level. In one approach, meteorological data from local weather stations are used to calculate reference ET. The calculated ET is then sent to individual controllers installed at a residence via wireless communication. The ET controller then adjusts the irrigation run times or number of cycles according to the climate throughout the year. The second type of approach for ET controllers is to use a pre-programmed crop water use curve for different regions. The curve is modified by a sensor, such as a temperature or solar radiation sensor, mounted with the controller to measure on-site weather conditions and modify the generalized crop water use curve based on this measured weather parameter (Dukes, 2005). Commercially available ET controllers from several vendors are being widely used for residential landscape irrigation.

An evaluation of ET-based controllers performed in Florida found that the

Weathermatic controller applied the least water when compared to the other controllers evaluated while the Toro controller had the most accurate cumulative ET_o value and saved water relative to the theoretical requirement (Davis et al., 2007). Both controllers maintained acceptable turf quality for St Augustinegrass. Another study involving ET controllers showed 59% water savings with the Toro Intellisense controller as compared to a standard timer-based scheduling (Shedd et al., 2007) while Aquacraft, Inc (2003) observed water savings of 21% using a WeatherTRAK ET controller. A residential weather-based irrigation scheduling study in Irvine, California (2001) observed a 16% reduction in outdoor water use with respect to a standard schedule. Hunter reported an approximate water saving of 30% for their controller compared to a standard time based schedule while Weathermatic recorded savings of 26% and 32% for 2002 and 2003 respectively (US Bureau of Reclamation, 2007).

1.4 Turf Quality

Proper irrigation scheduling is essential for good quality turf. Over-irrigation and under-irrigation can have negative impacts on turf quality. The National Turfgrass Evaluation Program (NTEP) has developed a rating system for turf with a scale of 1 through 9, with 9 representing excellent quality and 1 poor quality. A rating of 5 or greater is considered to be acceptable (Morris and Shearman, 1997). Turfgrass evaluation is generally a subjective process based on visual estimates of factors like color, stand density, leaf texture, and uniformity and quality. Although visual assessment is very subjective, this method provides quick assessment without much labor (Horst et al., 1984).

Plant or canopy temperature is also a valuable qualitative index for water availability and quality (Tanner, 1963; Gates, 1964). The status of the water in the plant represents an integration of atmospheric demand, soil water potential, rooting density as well as other plant characteristics (Kramer, 1969). Clark and Hiler (1973) found that the canopies were cooler than the air above it when the crop was well-watered. Once a water deficit occurred, the leaf-air temperature differential became positive and the leaf was 2-3ºC hotter than the non-stressed canopies.

There are different types of irrigation controllers that help maintain healthy turf and at the same time are water efficient. The objective of this research was to compare two types of commercially available irrigation control technologies; one based on estimates of evapotranspiration and the other based on feedback from soil-water sensors. These were contrasted with a standard time-based irrigation schedule with respect to applied water and turf quality. The study also incorporated the effect of irrigation frequency. A sub-objective was to compare reference ET estimates from an atmometer and Penman-Montieth reference ET estimates from a weather station. This research focused on application to residential lawns.

CHAPTER 2

2. Materials and Methods

2.1 Site and System Description

The research site for this project was located at the North Carolina State University Lake Wheeler Turf Field Laboratory, Raleigh, North Carolina. The original soil was classified as a Cecil sandy loam (fine kaolinitic, thermic, Typic Kanhapludults) by a NRCS Soil Survey. To estimate field capacity, the plots were watered till saturation and then allowed to drain naturally. Soil-water was monitored from the time of saturation using monitoring sensors buried in the plots at a depth of 13 cm. It was observed that after rapid drainage, the rate of drop in soil-water content decreased and soil-water reached a steady level after 24 hrs. The field capacity was then determined as approximately 32% by volume based on the soil-water plot shown in Figure 2.1.

Forty 4 m x 4 m plots were established to 'Confederate' tall fescue (*Festuca arundinacea* Schreb) using sod. Each plot was irrigated independently by four quarter circle pop-up spray head sprinklers (Toro 570 12 ft series with 23º trajectory), with a discharge rate of 0.315 L s^{-1} at 207 kPa. Prior to sodding, there were substantial cuts and fills that occurred when the two terraces for the plots were built and graded. The irrigation system was installed after the field was graded and plots were irrigated with water from a nearby irrigation pond that serves the Lake Wheeler Turf Field Laboratory facility. The water was pressurized by an electric pump at the pond and supplied through a 2-inch mainline that splits into two 1.5-inch class 200 PVC submain lines serving 20 plots on each terrace. The water was filtered with a 60 mesh filter (Figure 2.2) and the pressure at both submains was regulated by a 1.5 inch (38 mm) 172-517 kPa pressure regulator, set for 207 kPa. Both submains had five water meters (Figure 2.3), (AMCO Water Metering Systems Inc., Ocala, Florida) each serving four plots on a common manifold with separate solenoid valves. The solenoid valve was connected by 1-inch class 200 PVC pipes to the spray heads at each plot. Transitional poly pipes connected the sprinklers to the 1-inch PVC. A Campbell Scientific CR10X datalogger (Figure 2.4) was used to log water meter data. Rotors were used to irrigate the area surrounding the plots.

Plots were mowed twice per week at a height of 5.5 cm. Fertilizer applications were made using NPK (25-6-12) at a N rate of 50 kg ha^{-1} once on 21st February and again on 13th April 2007. The area was also limed with dolomitic lime at a rate of 150 kg ha^{-1}. This was the NCDA recommended rate to increase to increase soil pH (to between 6 and 7) from the soil test pH of 5.7.

2.2. Experimental Design

There were two main factors tested in this study for their effect on water applied and turf quality:

- controller technology
- irrigation frequency

Irrigation controller technologies included a standard time-based controller, ET-based controller system and two soil-water feedback systems.

Two soil-water feedback systems, the Acclima Digital TDT RS-500 “add-on” system (Figure 2.5) and Acclima CS-3500 “water on-demand” system (Acclima Inc., Meridian, Idaho, Figure 2.6) were used to evaluate soil-water sensor-based systems. An Intellisense TIS-240 series (Toro, Inc. Figure 2.7) controller was chosen as the ET-based system. Rain sensors (Irritrol Systems Inc., Riverside, California Figure 2.8) were added to the time-based and ET-based system to override irrigation in case of rainfall events. All technologies, except the water on-demand system, were set to water daily, twice per week and once per week.

The field site had two terraces separated into two replications of ten plots each. Each replication had ten treatments combining control type and watering frequency (3 technologies x 3 frequencies + 1 on-demand technology) in a randomized complete block design (Figure 2.9).

A transformer (Model 9070TF100, 100VA 24volts, Square D) was installed to simultaneously power 4 zones since the irrigation controller clocks did not have sufficient power to activate 4 solenoid valves simultaneously. The controller wires powered the control terminals of the relay switches (Model MY2IN, Omron Electronic components LLC, Figure 2.10) which were connected to the corresponding four replications of any one treatment combination. An anemometer (Figure 2.11) was connected to the datalogger to log wind data and also to interrupt the power supply if wind exceeded 4.5 m s^{-1} during irrigation. If wind speed was greater than 4.5 m s^{-1} a control port was set high, opening the normally closed circuit and interrupting the power supply to the irrigation controller system. This was done to ensure that water did not drift to adjacent plots.

A shelter (Figure 2.12) was built between the two terraces to house all the controllers, datalogger, transformer and relays. The weather station and the atmometer were mounted on arms extending from the shelter. All controllers, except the Intellisense ET controller, were programmed to start between 12:30 am and 6:00 am to reduce potential wind drift and minimize evaporation. The ET controller was allowed to irrigate only after the other technologies had irrigated (after 6:00 am) so that flow through the water meters could be traced to the ET controller as irrigation durations of the controller constantly changed.

2.3 Uniformity Testing

The rate of application by the sprinkler system was calculated using the following formula (Meyer and Camenga, 1985):

$$R_a = \frac{q \text{ x } 65.4}{\text{Sprinkler Spacing (m)} \times \text{Lateral spacing (m)}} \tag{7}$$

where

R_a = rate of application of the sprinkler system [L s^{-1}], and

q = discharge rate of water through the spray head [L s^{-1}].

The sprinkler and lateral spacing were 4 m. The rated discharge for the spray head is 0.315 L s^{-1} (at 207 kPa). The theoretical rate of application was calculated to be 28.9 mm hr^{-1} at 207 kPa.

An irrigation uniformity test measures the distribution of applied water over a given area. Two measures are commonly used to quantify uniformity; Distribution

Uniformity (DU) and Christiansen's Coefficient of Uniformity (CU). Distribution Uniformity is computed by

$$\mathrm{DU} = \frac{100(\mathrm{m_{low}})}{\mathrm{m}} \tag{8}$$

where

m = mean depth of the observations [mm], and

m_{low} = average low-quarter depth of observations [mm]

The average low-quarter depth of water received is the average of the lowest one-quarter of the measured values, where each value represents an equal area (Merriam and Keller, 1978).

Another measure widely used to evaluate sprinkler irrigation uniformity is the Coefficient of Uniformity developed by Christiansen (1942)

$$\mathrm{CU} = 100\left(1 - \left(\frac{\Sigma \mathrm{X}}{\mathrm{nm}}\right)\right) \tag{9}$$

Or

$$\mathrm{CU} = 100\frac{\left(1 - \Sigma(\mathrm{z} - \mathrm{m})\right)}{\Sigma \mathrm{z}} \tag{10}$$

where

z = individual depth of catch from uniformity test [mm],

m = Σz/n = mean depth of the catches [mm], and

n = number of observations.

X = |z – m| = absolute deviation of the individual catch from the mean [mm],

For this evaluation a 5 x 5 grid of 75 mm diameter catch cans at 0.76 m spacing

(Figure 2.13) was deployed in each plot. The sprinklers were run for 20 minutes and the water caught in each of the catch cans was measured in a graduated cylinder. Uniformity testing was done once before the start of the study period and again after the end of the study period. Average wind velocity was less than 4.5 m s^{-1} during both test periods.

The field determined Christiansen Uniformity coefficient was used to calculate the GIR (see Equation 6). The runtimes for these technologies were calculated based on the GIR and the application rate of the sprinklers determined during uniformity testing.

2.4 Technologies

For all technologies, the once per week watering was done on Tuesday and twice per week on Monday and Thursday. The amount of water to be applied for Acclima add-on and time-based irrigation systems was calculated using 30 years of weather and effective rainfall data. Table 2.1 shows the values of the net irrigation requirement (NIR), effective rainfall and gross irrigation requirement (GIR). Gross application depth and runtime settings are given in Table 2.2.

2.4.1 Standard time-based irrigation system

The standard time-based irrigation system represents the control method used by an average homeowner with a controller clock system. The system was set to apply water at fixed frequencies (1, 2, and 7 per week) and duration to replace the long-term irrigation requirement of cool-season turf. A Toro irrigation controller (Custom Command Series-P9, Toro Inc., Riverside, California) was used for this technology. This technology also included a rain switch to override irrigation in case of an appreciable rainfall event.

Different rain thresholds were set for each frequency; once per week – 19 mm, twice per week – 13 mm and daily – 7 mm. The rain sensors contain absorbent disks that swell when they are wet. The swelling interrupts current flow and prevents irrigation. When the disks dry out, current is allowed to flow immediately when the controller sends a signal.

2.4.2 Soil-water sensor based "add-on" irrigation system

The RS500 soil-water feedback system is designed as an add-on system to any standard irrigation clock. For this technology, soil-water feedback sensors were placed in replication 2 plots (see Figure 2.9) for each irrigation frequency and connected to Acclima RS500 modules. These modules were connected to a Toro controller with three independent programs (one for each frequency) similar to the time-based controller. The RS500 system has a time domain transmissivity (TDT) moisture sensor that measures the percent soil-water content by soil volume and prohibits irrigation above a user-supplied water content. The threshold in this study was set at 24% water by volume equivalent to 75% of the volumetric soil-water content at field capacity. The GIR and runtimes settings were the same as the standard time-based technology (Table 2.2).

2.4.3 Soil-water sensor based "water on-demand" irrigation system

The Acclima CS3500 soil-water feedback controller system uses the same sensor as the RS500 system. However, it is designed as a "water on demand" system which means that it initiates irrigation at a pre-determined soil-water level. There are two set points; a lower moisture threshold value to turn the system on and upper moisture threshold to turn the system off. The controller thus maintains the soil water level between these thresholds. In this study the irrigation system was allowed to irrigate between 12:30 am and 1:30 am for up to three 20-minute water and soak cycles (10 minutes on and 10 minutes soak) to avoid runoff and to ensure that the applied water reached the sensor prior to continuing irrigation. The upper and lower thresholds were set at 30% and 21% moisture by volume, respectively, with the lower set point corresponding to a depletion of 67% of plant-available soil water and the upper setpoint being 2% below field capacity to allow for rainfall.

2.4.4. Evapotranspiration-based irrigation system

The ET system was evaluated at the same irrigation frequencies as the timer-based and the RS500 systems. The plots irrigated by the ET controller system received irrigation amounts based upon reference ET estimates downloaded daily from the WeatherTrak "ET everywhere" service (Hydropoint Data Systems, Petaluma, CA) and a soil-water budget. User inputs that affect the soil-water budget include root depth, soil type, crop type, and sun exposure. In this study the rooting depth was set at 15 cm, the soil type set for sandy loam and the crop type was set to cool-season turf crop. The system tested did not use local rainfall data but rather puts the system into a rain pause in the event of regional rainfall. A rain sensor was added to the controller with a rain threshold set at 13 mm to skip irrigation in case of local rainfall. This system has three independent programs that were programmed for the three different frequencies used in the study.

The three programs include two fully automated and one user-defined program.

The two fully automated programs were programmed for the once per week and twice per week irrigation frequencies. Data required included sprinkler precipitation rate, sprinkler efficiency, root depth, soil type, watering window, plant type (cool-season turf), micro-climate (sunny), and slope factor (0%). The daily irrigation frequency was programmed in the "user defined with ET" program. The baseline for the user defined program was obtained from the automated programs. The run times and number of irrigation cycles of the automated programs were viewed in the review mode and the run time, cycles (adjusted for frequency) was adjusted so that the same weekly runtime was achieved in 7 daily cycles.

2.5 Monitoring

Acclima soil-water sensors were installed in all plots of the second replication to continuously monitor soil-water (readings were taken every 10 minutes). These sensors were wired to the Acclima CS3500 system that logged the soil-water measurements. Monitoring sensors were placed 30 cm from control sensors for those plots using sensor feedback.

A weather station (Watchdog 700, Spectrum Technologies, Plainfield, Illinois Figure 2.14) was installed at the site to record weather data and estimate ET_o. Air temperature, relative humidity, wind speed, wind gust, wind direction, solar radiation, and rainfall measurements were taken every 15 minutes. Rainfall was also recorded hourly by a separate tipping bucket rain gauge connected to the data logger. A recording atmometer (Figure 2.15) with a #30 cover was installed to simulate grass reference ET and was logged every 1 hour.

Turf quality ratings were done once per week for all the plots using a standard turf quality index scale (Morris and Shearman, 1997). All the plots were rated on a scale of 1 through 9. Measurements were taken in the morning (at about 10:00 am) to maintain uniformity in rating and because turf is least stressed in the morning. Weekly canopy temperatures were also taken for each plot using an infrared thermometer. This was done late in the afternoon (at around 4:00 pm) under clear skies when the sensible heat at the turf surface would be highest and the ability to see differences in turf stress would be enhanced.

2.6 Data Analysis

Statistical Analysis was performed using the PROC MIXED procedure of the Statistical Analysis System (SAS, Cary, North Carolina). Analysis of Variance was used to determine the differences in technologies and frequencies of weekly applied water data. The least square means (lsmeans) procedure (SAS, 2004) was used for mean separation tests. Similar analysis was done on the turf quality and canopy temperature data to identify differences in means.

A mixed effects statistical model was used to analyze the weekly applied water data. The technology, frequency and their interaction were modeled as fixed effects, and block, week and the interaction term (week x technology x frequency) as random effects. Week was used as a random effect in the model to block out the variability in weekly data. The model is given below:

$$Y_{ijkt} = \mu_{ijkt} + \alpha_i + Q_j + (\alpha Q)_{ij} + B_k + \tau_t + (\tau\alpha Q)_{ijt} + \varepsilon_{ijkt} \qquad (11)$$

where

Y_{ijkt} = water use estimate,

μ_{ijkt} = overall mean response,

α_i = fixed effect due to technology i,

Q_j = fixed effect due to frequency j,

$(\alpha Q)_{ij}$=fixed effect due to the interaction of i level of technology with j level of frequency,

B_k = random effect due to replication k,

τ_t = random effect due to week t,

$(\tau\alpha Q)_{ijt}$ = random effect due to the interaction of technology x frequency x week, and

ε_{ijkt} = random error.

Table 2.1 Monthly long-term reference ET (ET_o), turf ET (ET_c), precipitation, effective precipitation, net irrigation requirement (NIR) and gross irrigation requirement (GIR) (mm).

Month	ET_o	ET_c[1]	Precipitation	Eff. Ppt.[2]	NIR[3]	GIR[4]
April	150.0	120.0	65.8	39.5	80.5	100.6
May	176.4	141.1	99.6	59.0	82.1	102.6
June	169.5	135.6	93.5	52.7	82.9	103.6
July	188.8	151.0	101.8	62.4	88.6	110.7
August	174.5	139.6	102.1	60.0	79.6	99.6
September	140.7	112.6	81.0	44.3	68.3	85.3

[1] $ET_c = ET_o \times K_c$. A K_c of 0.8 was used for cool season turf
[2] Effective Precipitation calculated using the method in SCS TR-21 (USDA, 1970)
[3] Net Irrigation Requirement (NIR) = ET_c – Eff. Ppt.
[4] Gross Irrigation Requirement = NIR/0.8 (CU = 80%)

Table 2.2 Gross irrigation depth (mm) and runtime settings (minutes) for the Acclima add-on and time-based irrigation systems.

Frq/Technology	Gross Irrigation Depth(mm)	Runtimes (min)
April		
Once per week	25.15	17 – 3x
Twice per week	12.70	13 – 2x
Daily	3.56	7 – 1x
May		
Once per week	25.65	18 – 3x
Twice per week	12.70	13 – 2x
Daily	3.56	7 – 1x
June		
Once per week	25.91	17 – 3x
Twice per week	12.95	13 – 2x
Daily	3.81	8 – 1x
July		
Once per week	27.69	19 – 3x
Twice per week	13.97	14 – 2x
Daily	4.06	8 – 1x
August		
Once per week	24.89	17 – 3x
Twice per week	12.45	13 – 2x
Daily	3.56	7 – 1x
September		
Once per week	21.34	15 – 3x
Twice per week	10.67	11 – 2x
Daily	3.05	6 – 1x

1x = one cycle, 2x = two cycles, 3x = three cycles

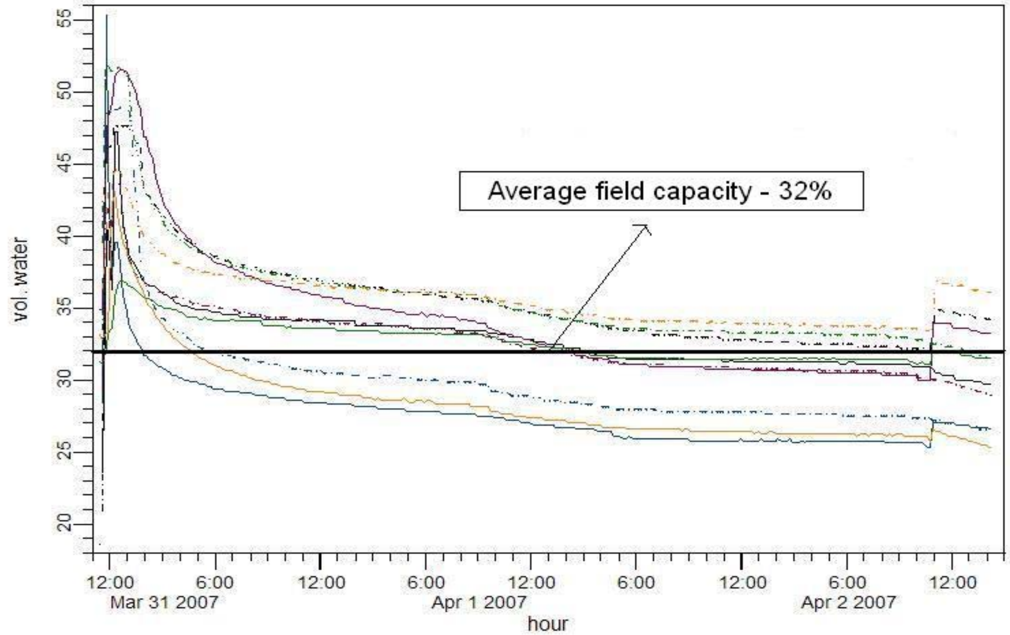

Figure 2.1 Soil-water plot to determine field capacity. Continuous lines represent water-content from monitoring sensors buried in all ten plots of one replication

Figure 2.2 Inline 60 mesh filter at field site

Figure 2.3 Water meter (AMCO Water Metering Systems, Inc.)

Figure 2.4 Campbell Scientific CR10X datalogger with switch closure module

Figure 2.5 Acclima RS 500 module with sensor

Figure 2.6 Acclima CS3500 water on-demand system

Figure 2.7 Intellisense TIS240 ET controller

Figure 2.8 RS500 rain sensors

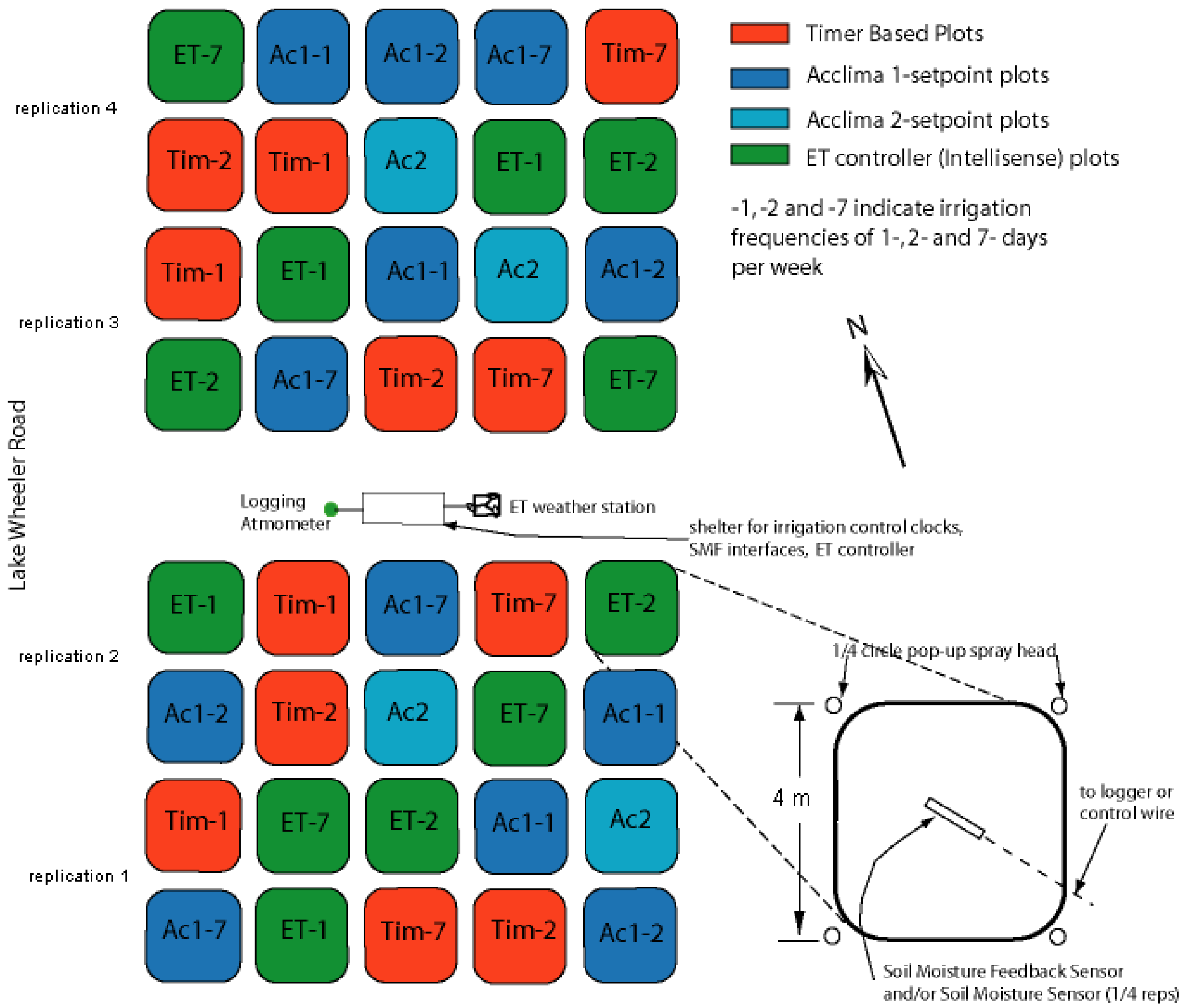

Figure 2.9 Schematic diagram of the plan view of the site showing plot layout and irrigation technologies

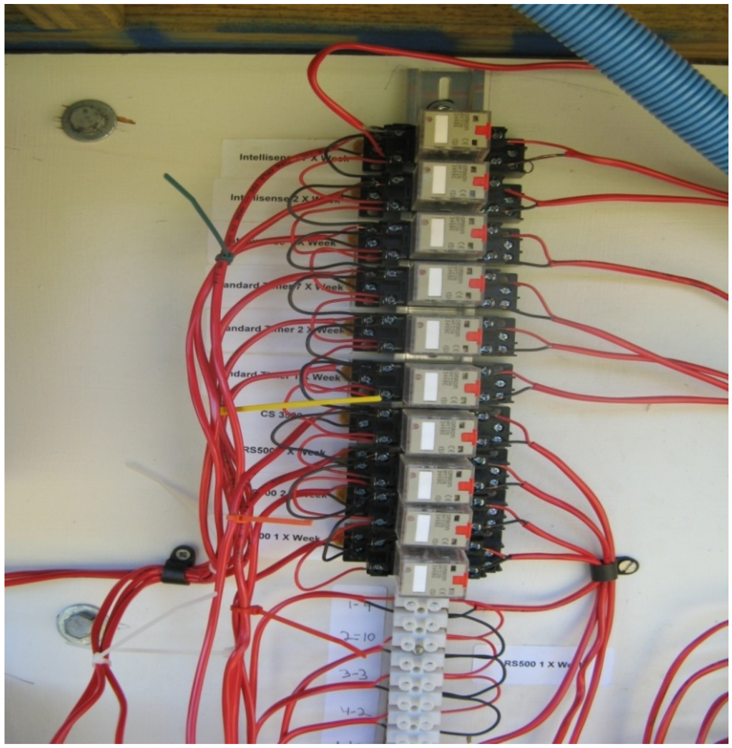

Figure 2.10 Relay Switches

Figure 2.11 Anemometer

Figure 2.12 Shelter housing the controllers, transformer, relays and datalogger

Figure 2.13 Uniformity testing using catch cans

Figure 2.14 Watchdog model 700 weather station

Figure 2.15 Atmometer with #30 canvas cover

CHAPTER 3

3. Results and Discussion

3.1 Sprinkler Uniformity Testing

Sprinkler uniformity testing was done to measure the distribution of applied water over the plot area. The uniformity testing conducted prior to the experimental period on 18 April resulted in a wide range of both DU and CU values. The DU ranged from 25.1% to 83.5% with an average of 69% while CU ranged between 56.5% and 90.7% with an average of 81% (Table 3.1). The low value of 25.1% was due to a malfunctioning sprinkler head that was subsequently replaced. Only one of the forty plots (replicate1 - plot1) was not tested for irrigation uniformity because of a faulty sprinkler head that required a replacement. Cardenas-Lailhacar et al. (2005) found a CU average of 71% with a range of 50% to 89% and an average DU of 52% with a range of 15% to 78% for the same type of sprinkler irrigation system in a similar study conducted in Florida. They reported that the low value of DU (15%) in their study was because of a broken sprinkler head which was replaced after testing.

Table 3.2 gives the values of DU and CU of uniformity testing performed on October 16th (2007). Sprinkler uniformity decreased by 17% for DU and 8% for CU with the DU values between 27.1% and 73.2% with an average of 55.4% and CU values between 59.2% and 84.8% with an average of 73.4%. The possible reasons for the decrease in the uniformity coefficients were clogged sprinkler head filters and wind drift factor.

3.2 Evaluation of the Control Technologies

The study period in 2007 was warmer and drier than average. The 30-year (1971 – 2000) normal maximum temperature was 29.6ºC while the average maximum temperature for the 20-week period was 30.8ºC (see Figure 3.1). Also the cumulative rainfall for the same 30-year period was 540 mm while the cumulative rainfall for the study period was 290 mm with 79 mm falling on the 19^{th} July (see Figure 3.2). A plot of the rainfall and cumulative rainfall that occurred during the experimental period is shown in Figure 3.3. Pump failures occurred during the course of the study preventing possible scheduled irrigations on a total of six days. This impacted the once per week irrigation frequencies more severely, as the next available irrigation was delayed by seven days. While the pressure regulators were set for 207 kPa, cycles of de-pressurization and re-pressurization during pump failures or filter cleaning altered the pressure settings. In general replications three and four were pressurized slightly higher after these instances and received more water than replications one and two until the regulators were manually reset. Total applied water for all the technologies and frequencies is given in Table 3.4.

3.2.1 Standard time-based system

Total gross irrigation amounts applied for the time-based system were; once per week – 429 mm, twice per week – 430 mm, and daily – 395 mm. The values for the cumulative irrigation were similar for the three frequencies as they were programmed to apply the same irrigation amounts weekly and only differed in the setting of rain sensor thresholds. The daily irrigation treatment applied less water than the once per week and twice per week treatments because of a higher proportion of skipped irrigations. No irrigation was applied on 28 out of a possible 140 occasions (22 due to the rain sensor override and 6 due to pump failures) while the once per week treatment did not irrigate on 3 out of a possible 20 occasions and the twice per week treatment did not irrigate on 6 out of a possible 40 occasions due to rain sensor override.

Comparison of the cumulative net irrigation water applied for each frequency to the cumulative estimated crop evapotranspiration (ET_c, using Penman-Montieth generated reference ET from the weather station and a crop coefficient of 0.8) over the experimental period is shown in Figure 3.4. The cumulative ET_c for the entire period was 508 mm while the cumulative net irrigation (gross irrigation x CU) for the three frequencies were; once per week – 343 mm, twice per week – 344 mm, and daily – 316 mm. The volumetric soil water content, irrigation and rainfall depths for the three frequencies are shown in Figures 3.5 - 3.7.

3.2.2 Acclima add-on system

The Acclima add-on system was programmed with an irrigation schedule identical to the timer-based system but applied 18% to 48% less water than the timer-based system. This was due to the volumetric soil water content being above the setpoint on several occasions when irrigation was scheduled. The cumulative gross irrigation amounts were: once per week – 219 mm, twice per week – 325 mm, and daily – 347 mm. The once per week treatment skipped irrigation on 8 occasions and twice per week treatment skipped irrigation on 12 occasions. The lesser amount of applied water for the daily treatment compared to the time-based technology was mainly because of a higher number of skipped irrigation opportunities. The daily irrigation treatment skipped 40 potential irrigations (34 due to sensor override and 6 due to pump failures).

Comparison of the cumulative net irrigation water applied for each of the frequencies to the cumulative estimated ET_c is shown in Figure 3.8. The total net irrigation amounts were: once per week – 175 mm, twice per week – 260 mm and daily – 278 mm. The volumetric water content, rainfall and irrigation depths for the three frequencies are given in Figures 3.9 – 3.11. Figure 3.11 shows that the soil water content was high even though no rainfall occurred between 25th July and 6th of August. This might have occurred because of possible internal drainage and preferential flow of water from rainfall and irrigation from adjacent plots. It was also observed that the neighboring plot (timer-based daily treatment) had a similar spike during the same period.

There have been other studies that evaluated similar add-on type systems. Cardenas-Lailhacar et al (2005) found water savings of 59% to 88% compared to a timer-based system using the same technology in a study conducted in Florida. This is because of the frequency and amount of rainfall during the study that experienced two hurricanes and high rainfall (nearly 950 mm). As a result there were more skipped irrigation events. Even though this research had water savings, there was significant stress in turf towards the end of the experimental period again as a result of dry weather. Dukes and Scholberg (2004) observed 23% and 50% water savings using TDR probes and a dielectric sensor respectively while Augustin and Snyder (1984) observed 42% to 95% water savings compared to a conventional irrigation system. Although water savings of this system was comparable with other research, the system as a whole fell behind in terms of turf quality especially at the end of the study because of the drought conditions that prevailed the entire summer.

3.2.3 Acclima water on-demand system

The total gross irrigation for the 20-week study period was 448 mm or 7% more water than the timer-based system. The Acclima CS3500 system failed twice during the experimental study, once on the 14th of May and again on the 12th of June, perhaps due to lightning at the field site. No soil-water data were collected by the monitoring (continuous) sensors for any of the treatments from 14-18 May and 12-18 June and no irrigation occurred for the on-demand technology during these periods. These failures did not affect the total applied water by the system as replacement units were installed prior to the soil-water level falling below the turn-on setpoint. The volumetric soil-water content, irrigation and rainfall events are plotted in Figure 3.12 and it can be observed that the system tried to maintain the soil-water level between the two setpoints throughout the experimental period. The cumulative net irrigation for this technology was 358 mm, and comparison with cumulative estimated ET_c is shown in Figure 3.8.

3.2.4 ET controller system

The volumetric water content, irrigation and rainfall events plots for the three frequencies are given in Figures 3.13 - 3.15. The total gross irrigation amounts were; once per week – 412 mm, twice per week – 623 mm and daily – 652 mm. The ET-based system applied 2% to 56% more water than the timer-based system. The reference ET estimates of the system were about 30% higher than the atmometer and weather station reference ET values which might also explain the higher application amounts. Also similar research in Florida observed higher reference ET estimates as compared to the on-site ET values (Dukes, Personal Communication. 6^{th} Dec, 2007). The high values for the twice per week and daily treatments may have been because the system did not account for the local rainfall events that occurred. The once per week gross irrigation amount was not as high as the twice per week or daily amounts and this may be because the controller limited the application to the amount that could be stored in the 150 mm root zone during one irrigation event. The cumulative net water applied for each frequency and cumulative estimated ET_c is shown in Figure 3.16.

Similar research that used the same TIS system (Shedd et al., 2007) 59% water savings compared to a standard timer system while this study showed an application of up to 56% more compared to a standard timer system. This study period was hot and dry while their study period included two hurricanes and had a lot of rainfall (950 mm). Other researches observed water savings from ET-based systems ranging from 16% to 59% (Shedd et al., 2007; Aquacraft, 2003; US Bureau of Reclamation, 2007). This is mainly because of the lack of appreciable rainfall over the summer. The ET system evaluated in this study did not account for rainfall in its soil-water budget and also had high reference ET estimates compared to the on-site weather station and atmometer, thereby resulting in a high water application.

3.2.5 Weekly applied water

3.2.5.1 Technology comparison

Analysis of variance shown in Table 3.3 for weekly applied water data reveals that the technology effect, frequency effect, and their interaction were significant. Least Square means (lsmeans) estimates for weekly applied water are given in Table 3.4. When averaged across the different frequencies, the means of all the technologies are significantly different except the on-demand system and the time-based system when compared two at a time. The Acclima one set point system applied the least amount of water followed by the timer-based system and the water on-demand system which were not statistically different. The ET system applied the most irrigation water when averaged across frequencies.

3.2.5.2 Frequency comparison

Average weekly applied water for the once per week frequency was different from the twice per week and daily irrigation frequencies, however, there was no difference between the twice per week and daily frequencies (Table 3.4). On average, the once per week frequency applied the least amount of water followed by the twice per week frequency and the daily frequency. The general trend was an increase in the amount of water applied with an increase in irrigation frequency.

3.2.5.3 Technology x *Frequency comparison*

The Acclima add-on system at a once per week frequency applied the least amount of water followed by the twice per week and daily add-on systems. There was no difference in average weekly applied water between the once per week ET treatment, the daily Acclima add-on treatment and all of the timer-based treatments. The ET controller at twice per week and daily frequencies applied the most water. Comparison among frequencies within a specific technology shows that the trend was an increase in water use with increase in irrigation frequency for all the technologies except the timer-based system which had no difference in the average weekly applied water between the frequencies.

3.2.6 Turf Quality

3.2.6.1 Technology comparison

There was significant difference in mean turf quality between all technologies when averaged across irrigation frequencies. The Acclima water on-demand system had the best turf quality followed by the ET system, the timer-based system and the Acclima add-on system. ANOVA and lsmeans estimates are given in Table 3.5 and 3.6, respectively.

3.2.6.2 Frequency comparison

There was no difference in mean turf quality between the twice per week and daily frequency systems when averaged across the technologies, however, the once per week frequency was different from the twice per week and daily frequencies. In general the twice per week and daily systems had better turf quality than the once per week treatment.

3.2.6.3 Technology x *Frequency comparison*

The means of the turf quality ratings were not different for most of the technologies and frequencies. Though the plots had healthy turf for most of the experimental period, quality declined in some treatments especially the add-on and the time-based systems, in the last month of the study when the daily ET values were high and no appreciable rainfall occurred. In addition there were six days when irrigation did not occur due to pump failures. Some plots suffered from the effects of substantial soil cuts that had occurred when the two terraces were built and leveled. This would likely affect both fertility and soil physical properties (infiltration rate and water holding capacity). The plots that looked the worst also had the highest canopy temperatures. The statistical model included block (replication) as a random effect to block out the effect of cuts and fills on turf quality as the cuts and fills tended to be associated with certain replications. Figures 3.17 and 3.18 show the turf quality of plots in the lower and upper terrace on 11 September 2007. The turf quality of the plots (averaged over the four reps) in Figures 3.17-3.18 are given in Table 3.9. This differs from Table 3.6 because the numbers in Table 3.6 are average turf quality over the entire period (not including 11 Sept 2007 ratings) while the numbers in Table 3.9 depict the quality at the end of the study. Inspection of turf quality plotted against time (Figure 3.19 – 3.21) reveal that turf quality declined for some plots during the last 4 weeks of the experiment. Even though the analysis suggests that there was no statistical difference in turf quality of the different technologies over time, Figures 3.17-3.18 do not depict the same situation. Therefore, canopy temperature data were analyzed as a surrogate measure to address the decline in turf quality for some of the technologies. The last 4 weeks of canopy temperature data were contrasted against the first 11 weeks as turf quality started to decline in some of the treatments after week 11 (Figure 3.19-3.20).

Canopy temperatures were analyzed as a measure of stress in plots for the timer-based and add-on systems at once per week frequency (Figure 3.22 and Figure 3.23). There was poor relationship ($r = 0.04$ to 0.28) in quality with respect to canopy temperature because of averaging turf quality and canopy temperature over the 4 replications. Time series plots for the timer-based and add-on systems at once per week frequency (Figure 3.24 and Figure 3.25) show a trend of decreasing turf quality with decreasing water applied and vice versa ($r = 0.06$ to 0.37) during the last 4 weeks when there was no significant rainfall. The correlation coefficients of applied water and turf quality of the subsequent week were low ($r = 0.09$ to 0.30) for the last 15 weeks.

The canopy temperature of the ET-based system at daily frequency was plotted against the timer-based system at once per week frequency and the Acclima add-on system at daily frequency (Figure 3.26-3.27). It can be seen in both the plots that the two lines trend the same till week 11 after which there is a significant difference in the canopy temperatures between the two treatments.

The canopy temperatures of different technologies were analyzed to check for differences over time to explain the declining turf quality for certain plots during the last month of the study. It was observed that there was no difference in canopy temperature over time when comparing the Acclima water on-demand, ET-based and timer-based technologies, but there was significant difference in the relationship of canopy temperature between the first 11 weeks and last 4 weeks when comparing the water on-demand technology and ET-based technology with all the add-on treatments. Bivariate plots for the water on-demand system and the add-on system (Figure 3.28 – 3.29) reveal that there was significant difference in relationship between the first 11 weeks and last 4 weeks of canopy temperature, while no similar trend was observed when analyzing the timer-based technology with respect to the on-demand system (Figure 3.30-3.31). From the bivariate plots it can be observed that the canopy temperatures of the add-on system plots were higher than the on-demand system plots by 1.3ºC – 2.5ºC while the temperatures were higher by 0.6ºC - 07ºC for the timer-based treatment plots in the last 4 weeks. Other researchers found that canopies were cooler than the air above it when the crop was well-watered. Once deficit occurred, the leaf-air temperature differential became positive and the leaf was 2-3ºC hotter than the non-stressed canopies (Clark and Hiler, 1973). These analyses support the fact that turf quality went down for the add-on system and the timer-based system plots in the last month of the study. Further analysis of canopy temperatures with respect to technology and frequency is given in the next section.

The increase in turf quality in June and then subsequent decrease in the month of August may be because of the trend in rainfall for this summer and the inability of some technologies to adapt to drought conditions. Average rainfall received for the months of

June (100 mm) and July (99 mm) 2007 were nearly the same for the last 30 years. The difference was mainly in late April and May (57 mm) when there was lesser than average rainfall and in August and September when the long-term average for both the months were around 102 mm and this summer had 19 mm in August and none in September.

Turf quality rating is a subjective process when doing visual assessment and varies from person to person. Photographic evidence suggests that the turf quality numbers in this study were high and this is because of the relative inexperience of the researcher in rating turf quality visually.

3.2.7 Canopy Temperature

3.2.7.1 Technology comparison

There was no significant difference in canopy temperatures among the Acclima add-on system, the water on-demand system and the timer-based system when averaged across frequencies. The average temperature for the plots irrigated by the ET system was different from the timer-based and Acclima add-on systems. In general the ET system plots had the lowest canopy temperature while the Acclima add-on system plots had the highest canopy temperature. ANOVA and the lsmeans estimates are given in Table 3.7 and Table 3.8, respectively.

3.2.7.2 Frequency comparison

There was no difference in canopy temperature among any of the frequencies when averaged across all technologies.

3.2.7.3 Technology x *Frequency comparison*

The Acclima add-on system at twice per week and daily frequencies had the highest canopy temperatures. There was no difference among the twice per week ET treatment, daily ET treatment and any of the timer-based treatments. The once per week Acclima add-on treatment was not different from the once per week timer-based treatment. The numbers in the table suggest that the temperatures are inversely correlated to applied water. There were no differences in average canopy temperatures between frequencies across technologies.

3.3 Reference evapotranspiration from atmometer and Watchdog weather station

During the experimental period (20 weeks) evapotranspiration data were collected from both the atmometer and the Watchdog weather station. The radiation sensor in the weather station reported high radiation values during the last 10 days of the study as compared to the State Climate Office values resulting in over-estimation of ET. Excluding the last two weeks of ET data, water demand was estimated to be 440 mm using the Penman-Montieth ET_0 estimates generated from the Watchdog weather station using a crop coefficient of 0.8 to convert to turf water demand. Water demand estimated from atmometer data was 436 mm using the same crop coefficient. There was no difference found in the two weekly ET data sets determined from a paired t-test. The reference ET data are given in Table 3.10 and it can be observed that there is a significant difference in the ET data recorded by both the devices for the last two weeks. A plot of the reference ET from atmometer against the Penman-Montieth generated reference ET from the weather station is given in Figure 3.32.

Table 3.1 Uniformity testing results obtained on 23rd March 2007 before the start of the study.

Replicate 4	CU – 82.0 DU - 66.7	CU – 83.9 DU – 72.3	CU - 83.6 DU – 71.7	CU - 88.7 DU - 78.0	CU - 85.2 DU - 73.1
	CU - 86.3 DU - 74.4	CU – 84.9 DU - 75.1	CU - 76.4 DU – 61.0	CU - 83.2 DU - 69.2	CU - 82.6 DU - 74.3
Replicate 3	CU – 78.0 DU – 70.6	CU - 87.2 DU - 75.9	CU - 76.3 DU - 62.6	CU - 80.6 DU - 63.7	CU - 79.3 DU - 65.4
	CU - 56.5 DU - 25.1	CU - 85.9 DU - 74.1	CU - 88.5 DU - 81.1	CU - 86.3 DU - 76.4	CU - 75.2 DU - 58.7
Replicate 2	CU - 82.9 DU - 74.2	CU - 82.3 DU - 69.8	CU - 83.4 DU - 69.2	CU - 90.7 DU - 83.5	CU - 84.5 DU - 70.1
	CU - 82.1 DU - 68.1	CU - 80.6 DU - 71.7	CU - 78.2 DU - 65.4	CU - 78.4 DU - 63.3	CU - 85.5 DU - 75.1
Replicate 1	- -	CU - 81.7 DU - 69.8	CU – 74.0 DU - 61.1	CU - 82.2 DU - 67.6	CU - 86.8 DU - 79.2
	CU - 84.7 DU - 73.1	CU - 77.8 DU - 63.1	CU - 85.7 DU - 73.5	CU - 66.1 DU - 59.1	CU – 70.0 DU - 48.4

CU – Christiansen Uniformity
DU – Distribution Uniformity
Replicate 1 – column 1 – no value as plot was not tested for uniformity due to broken head.

Table 3.2 Uniformity testing results obtained on 16th October 2007 after the study.

Replicate 4	CU - 74.5 DU - 49.8	CU - 68.7 DU - 49.3	CU - 84.8 DU - 72.9	CU - 75.3 DU - 52.2	CU - 73.5 DU - 57.4
	CU - 76.6 DU - 61.7	CU - 74.7 DU - 55.7	CU - 74.0 DU - 61.3	CU - 77.2 DU – 54.0	CU - 69.8 DU - 50.0
Replicate 3	CU - 77.6 DU - 59.3	CU - 73.7 DU - 56.6	CU - 81.1 DU - 70.8	CU – 77.0 DU - 61.8	CU - 74.1 DU – 56.0
	CU - 75.7 DU - 60.3	CU - 80.1 DU – 70.1	CU - 78.8 DU - 64.8	CU - 81.3 DU - 73.2	CU - 80.9 DU - 68.2
Replicate 2	CU - 72.3 DU - 53.5	CU - 73.4 DU - 54.7	CU - 63.2 DU - 31.5	CU - 69.6 DU - 54.9	CU - 71.6 DU – 55.0
	CU - 67.4 DU - 42.3	CU - 68.5 DU - 51.1	CU - 65.8 DU – 33.0	CU - 68.4 DU - 46.1	CU - 75.1 DU - 52.5
Replicate 1	CU – 76.4 DU – 59.7	CU - 74.8 DU - 56.3	CU - 68.5 DU - 57.3	CU - 75.8 DU - 61.9	CU - 70.0 DU - 53.1
	CU - 72.5 DU - 62.7	CU - 83.1 DU - 68.0	CU - 70.8 DU - 54.3	CU - 59.2 DU - 39.2	CU - 62.5 DU - 27.1

CU – Christiansen Uniformity
DU – Distribution Uniformity

Table 3.3 ANOVA for irrigation depth. Analysis done for data collected during 20 weeks.

Source	DF	Sum of Squares	Mean Squares	F Value	Pr > F
Fixed effects					
Ac2	1	32.15	32.15	0.21	0.6504
Tech[1]	2	18628.00	9314.24	59.73	<0.0001
Frq[2]	2	5137.21	2568.61	16.47	<0.0001
Tech x Frq	4	5559.04	1389.76	8.91	<0.0001
Random effects					
Block	3	763.85	254.62	25.70	<0.0001
Week	19	21825.00	1148.67	7.37	<0.0001
Tech x Frq x Week	150	23389.00	155.93	15.74	<0.0001
Residual	534	5290.38	9.91	-	-

[1]Tech = technologies
[2]Frq = frequencies

Table 3.4 Cumulative irrigation depth between 22nd April and 8th September 2007 (mm), average weekly depth estimates and statistical comparison between treatments and frequencies at $\alpha = 0.05$.

Treatment	Irrigation Depth(mm)	lsmeans estimates	Comparisons[1]		
			A	B	C
AC1-1	219	11.27			e
AC1-2	325	17.36			d
AC1-7	347	18.29			cd
Average AC1[2]		15.64		**c**	
ET1	412	20.15			bc
ET2	623	31.38			a
ET7	652	34.83			a
Average ET[3]		28.79		**a**	
Tim1	429	23.66			b
Tim2	430	22.87			b
Tim7	395	21.09			bc
Average Tim[4]		22.54		**b**	
AC2[5]	448	21.58		**b**	bc
Average of frequency across treatments					
once per week		18.36	**b**		
Twice per week		23.87	**a**		
Daily		24.74	**a**		

[1]A = Comparison among frequencies across treatments
B = Comparison among treatments across frequencies
C = Comparison among different treatments and frequencies
[2] Acclima RS500 add-on system (one setpoint)
[3] Toro TIS-240 Intellisense Controller
[4] Standard timer-based Controller
[5] Acclima CS3500 on-demand system (two setpoint)

Table 3.5 ANOVA for turf quality data. Data collected over a 15-week period.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Fixed effects					
Ac2	1	18.61	18.61	34.59	<0.0001
Tech[1]	2	11.18	5.59	10.39	<0.0001
Frq[2]	2	9.34	4.67	8.68	0.0003
Tech x Frq	4	31.71	7.93	14.73	<0.0001
Random effects					
Block	3	64.62	21.54	32.90	<0.0001
Week	14	43.84	3.13	5.82	<0.0001
Tech x Frq x Week	126	67.79	0.54	0.82	0.9069
Residual	447	292.63	0.65	-	-

[1]Tech = technologies
[2]Frq = frequencies

Table 3.6 Least square means estimates for turf quality ratings taken using a 1 – 9 scale and statistical comparison between treatments and frequencies at α = 0.05.

Treatment	lsmeans estimates	Comparisons[1]		
		A	B	C
AC1-1	8.4			b
AC1-2	8.4			b
AC1-7	7.8			c
Average AC1	8.2		**d**	
ET1	8.3			b
ET2	8.5			b
ET7	8.9			a
Average ET	8.6		**b**	
Tim1	7.9			c
Tim2	8.6			b
Tim7	8.6			b
Average Tim	8.4		**c**	
AC2	9.0		**a**	a
Average of frequency across treatments				
once per week	8.2	**b**		
Twice per week	8.5	**a**		
Daily	8.4	**a**		

[1]A = Comparison among frequencies across treatments
B = Comparison among treatments across frequencies
C = Comparison among different treatments and frequencies

Table 3.7 ANOVA for canopy temperature. Data collected over a 15 week period.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Fixed effects					
Ac2	1	36.08	36.08	2.40	0.1238
Tech[1]	2	397.29	198.64	13.22	<0.0001
Frq[2]	2	29.29	14.65	0.97	0.3802
Tech x Frq	4	165.52	41.38	2.75	0.0309
Random effects					
Block	3	569.55	189.85	16.76	<0.0001
Week	14	38463.00	2747.35	182.80	<0.0001
Tech x Frq x Week	126	1893.69	15.03	1.33	0.0198
Residual	447	5063.92	11.33	-	-

[1]Tech = technologies
[2]Frq = frequencies

Table 3.8 Least square means estimates for canopy temperature (ºC) and statistical comparison between treatments and frequencies at α = 0.05.

Treatment	lsmeans estimates	Comparisons[1] A	B	C
AC1-1	32.42			b
AC1-2	32.98			c
AC1-7	33.18			c
Average AC1	32.86		**c**	
ET1	32.14			ab
ET2	31.46			a
ET7	31.48			a
Average ET	31.70		**a**	
Tim1	32.86			bc
Tim2	32.05			a
Tim7	32.17			ab
Average Tim	32.36		**bc**	
AC2	31.85		**ab**	ab
Average of frequency across treatments				
once per week	32.48	**a**		
Twice per week	32.17	**a**		
Daily	32.28	**a**		

[1]A = Comparison among frequencies across treatments
B = Comparison among treatments across frequencies
C = Comparison among different treatments and frequencies

Table 3.9 Turf quality of the plots (average of four reps) on Sept 11, 2007 (Figure 3.18). Minimum acceptable quality is an index value greater than 7.

Treatments	Turf Quality
Timer-based system – once per week	5.3
Timer-based system – twice per week	5.5
Timer-based system – daily	5.6
Acclima add-on system – once per week	5.5
Acclima add-on system – twice per week	5.8
Acclima add-on system – daily	5.5
ET-based system – once per week	5.5
ET-based system – twice per week	6.0
ET-based system – daily	8.3
Acclima water on-demand system	8.5

These values were not used in the statistical analysis of turf quality

Table 3.10 Weekly evapotranspiration data (mm) from atmometer and Watchdog weather station for the 20 weeks between 22nd April and 8th September 2007

Week	Atmometer	Weather Station
1	28.45	34.04
2	23.11	27.69
3	18.03	28.19
4	21.08	30.23
5	36.58	35.31
6	35.81	36.32
7	33.53	34.54
8	19.30	22.35
9	33.78	31.24
10	26.42	32.77
11	35.05	30.48
12	29.97	28.19
13	33.27	29.46
14	30.73	28.19
15	31.50	28.19
16	37.34	28.96
17	37.59	33.27
18	33.53	31.50
19	27.43	36.07[1]
20	34.29	45.47[1]

[1] – Rs values high compared to State Climate Office values.

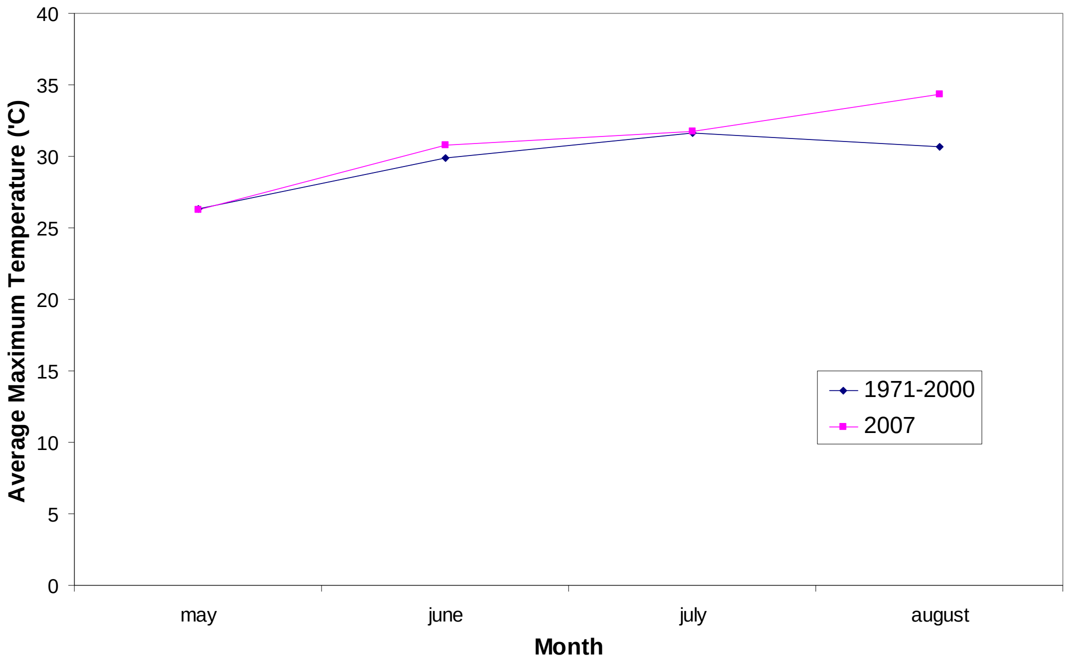

Figure 3.1 Monthly average maximum temperatures (ºC) for May, June, July and August of 1971-2000 and 2007 against month

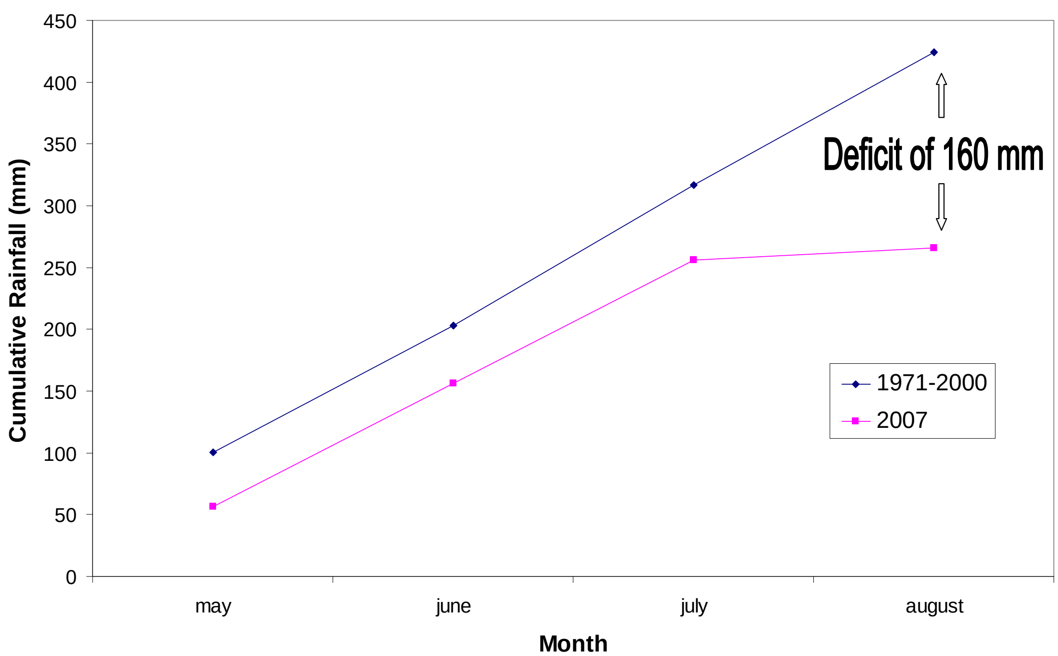

Figure 3.2 Average cumulative rainfall (mm) for the months of May, June, July and August of 1971-2000 and 2007 against month

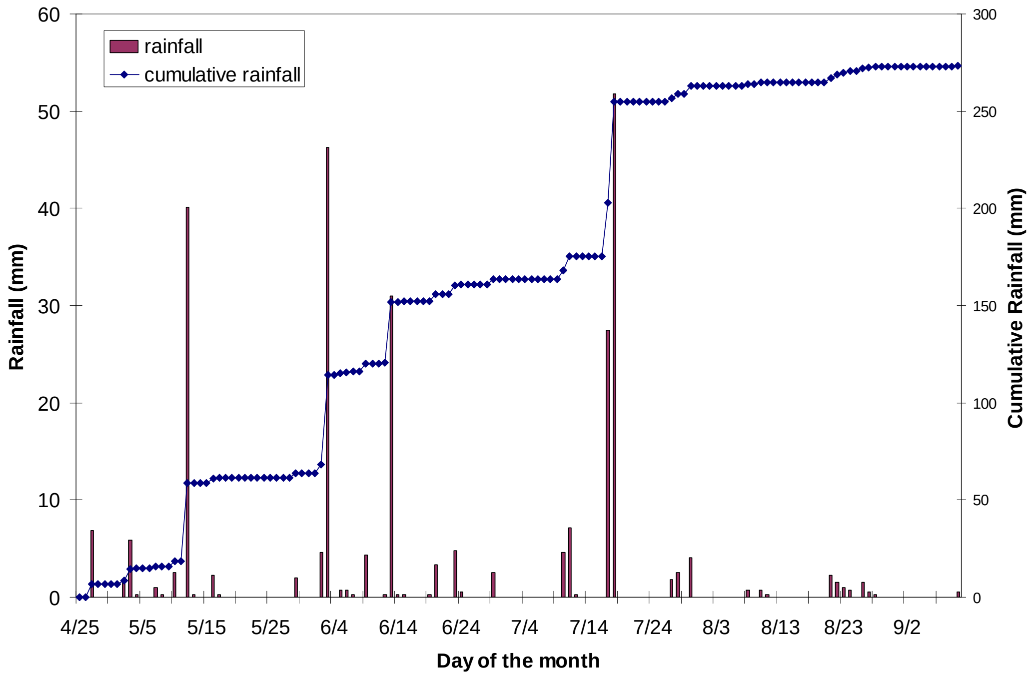

Figure 3.3 Rainfall between 22nd April and 8th September, in mm

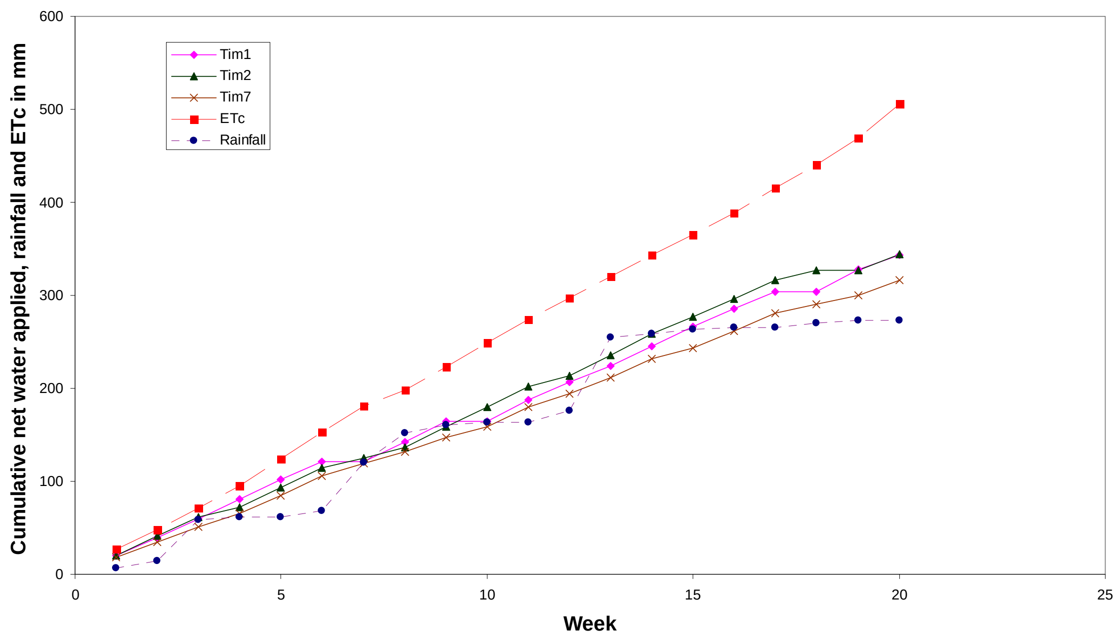

Figure 3.4 Crop evapotranspiration (ET_c) and net applied water from the time-based technology

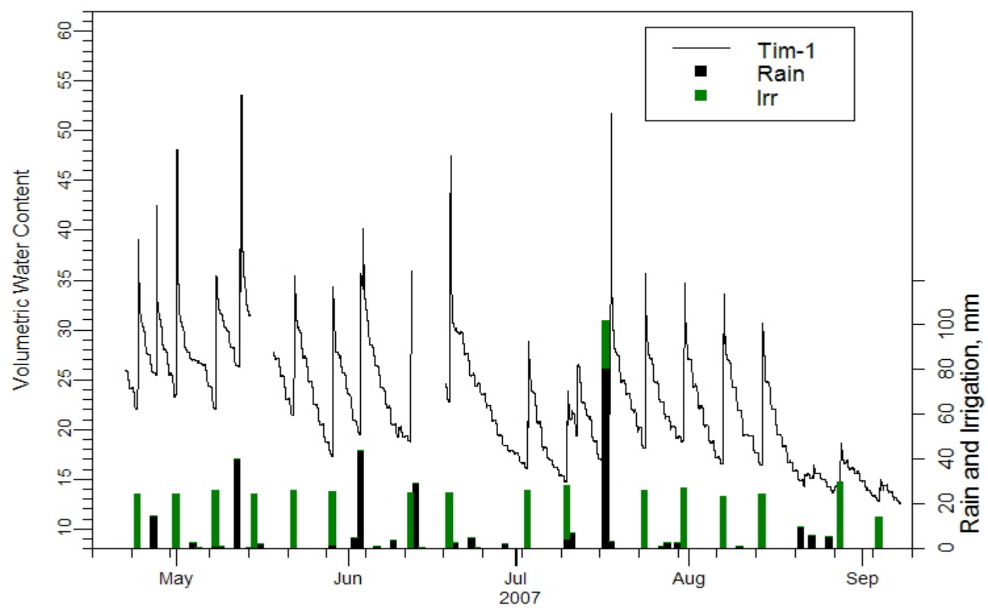

Figure 3.5 Soil-water content, rain and irrigation for the time-based controller set to irrigate once per week.

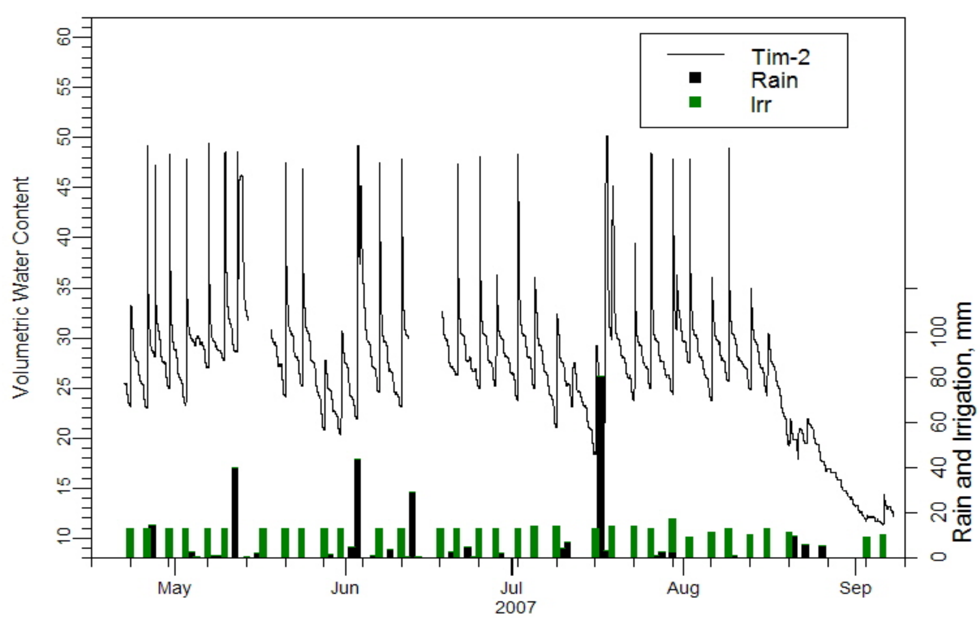

Figure 3.6 Soil-water content, rain and irrigation for the time-based controller set to irrigate twice per week.

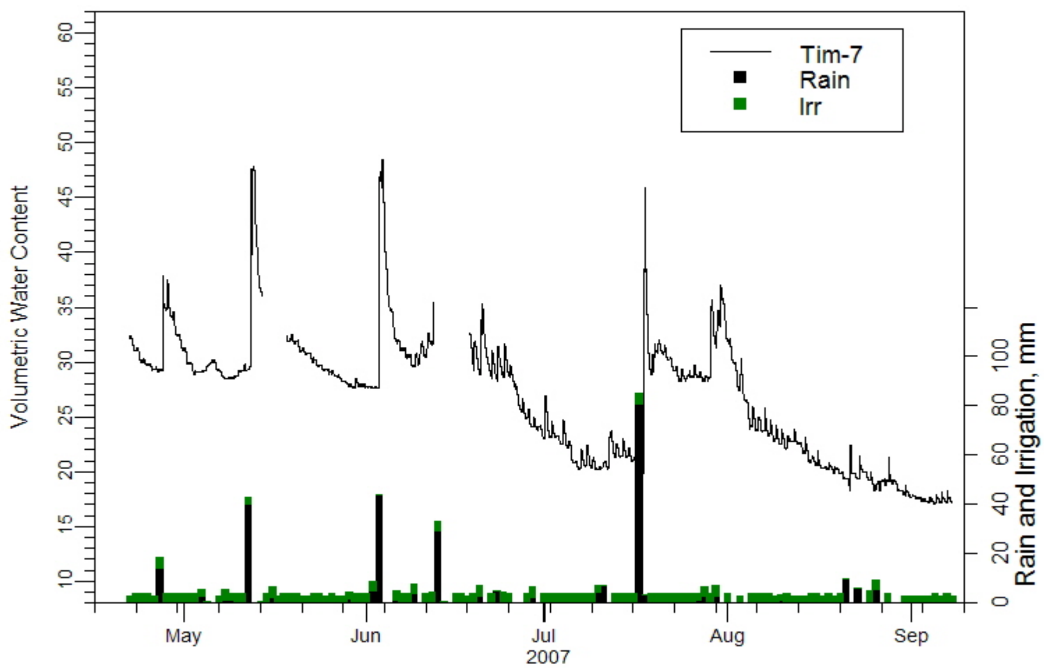

Figure 3.7 Soil-water content, rain and irrigation for the time-based controller set to irrigate daily.

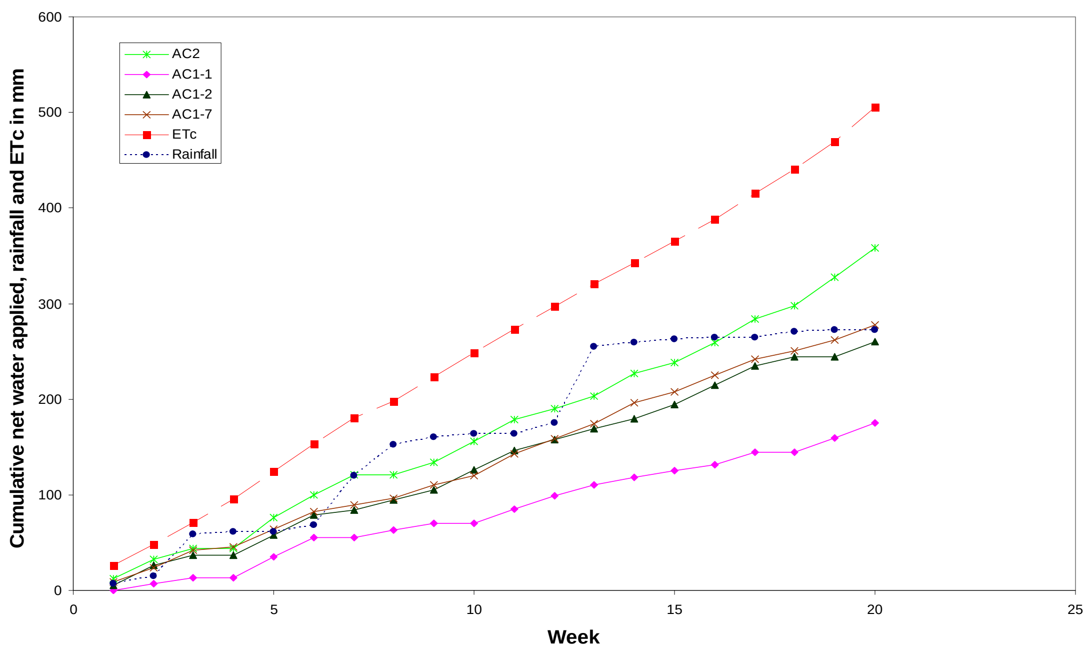

Figure 3.8 Crop evapotranspiration (ET_c) and net applied water from the soil-water-based technologies

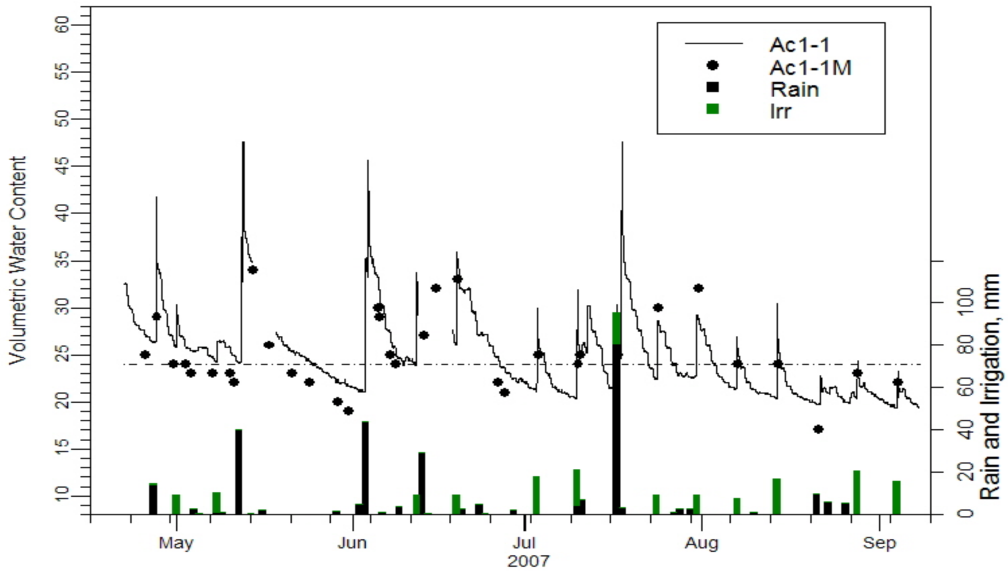

Figure 3.9 Soil-water content, rain and irrigation for the Acclima add-on system set to irrigate once per week. The horizontal dashed line represents the setpoint above which irrigation was disabled. Dots represent soil-water measured by the control sensor placed 30 cm from the monitoring sensor.

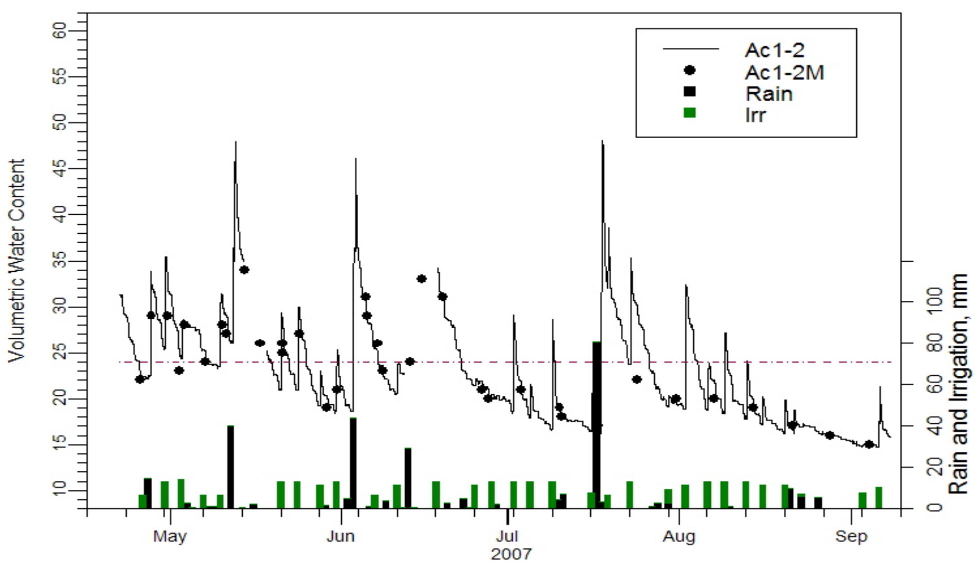

Figure 3.10 Soil-water content, rain and irrigation for the Acclima add-on system set to irrigate twice per week. The horizontal dashed line represents the setpoint above which irrigation was disabled. Dots represent soil-water measured by the control sensor placed 30 cm from the monitoring sensor.

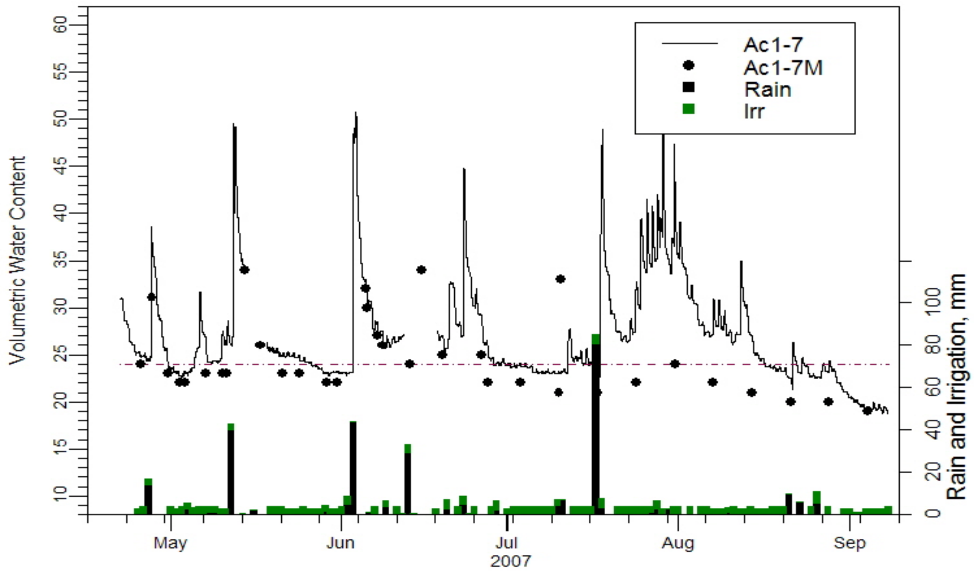

Figure 3.11 Soil-water content, rain and irrigation for the Acclima add-on system set to irrigate daily. The horizontal dashed line represents the setpoint above which irrigation was disabled. Dots represent soil-water measured by the control sensor placed 30 cm from the monitoring sensor.

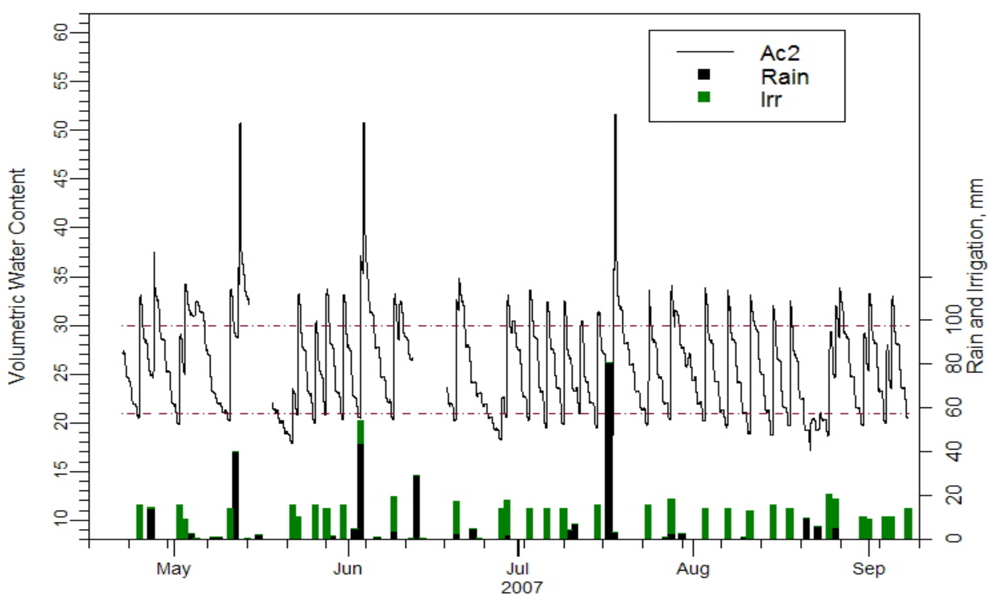

Figure 3.12 Soil-water content, rain and irrigation for the Acclima on-demand system. The horizontal dashed lines represent the upper turn-off and lower turn-on setpoints

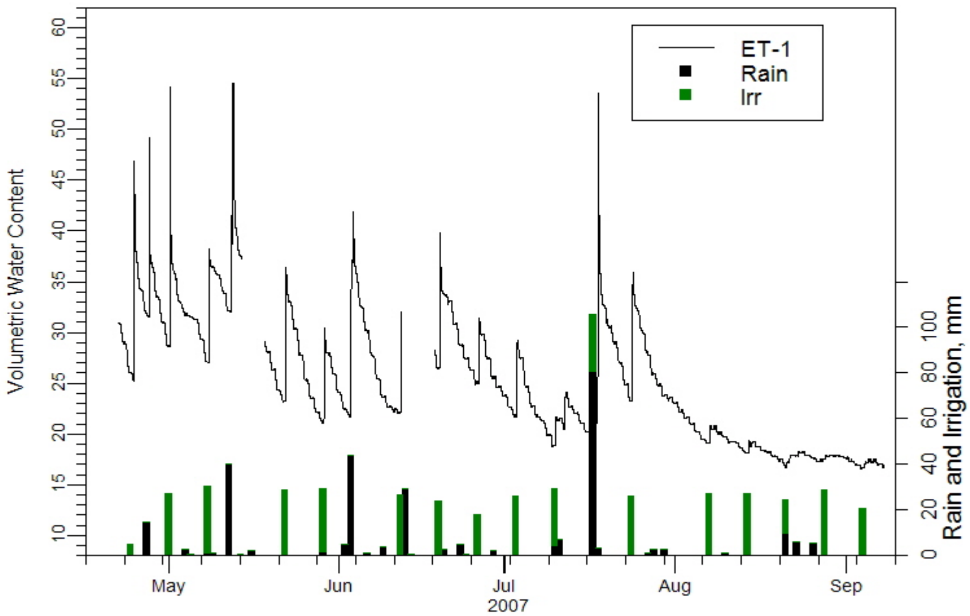

Figure 3.13 Soil-water content, rain and irrigation for the Intellisense TIS 240 controller set to irrigate once per week.

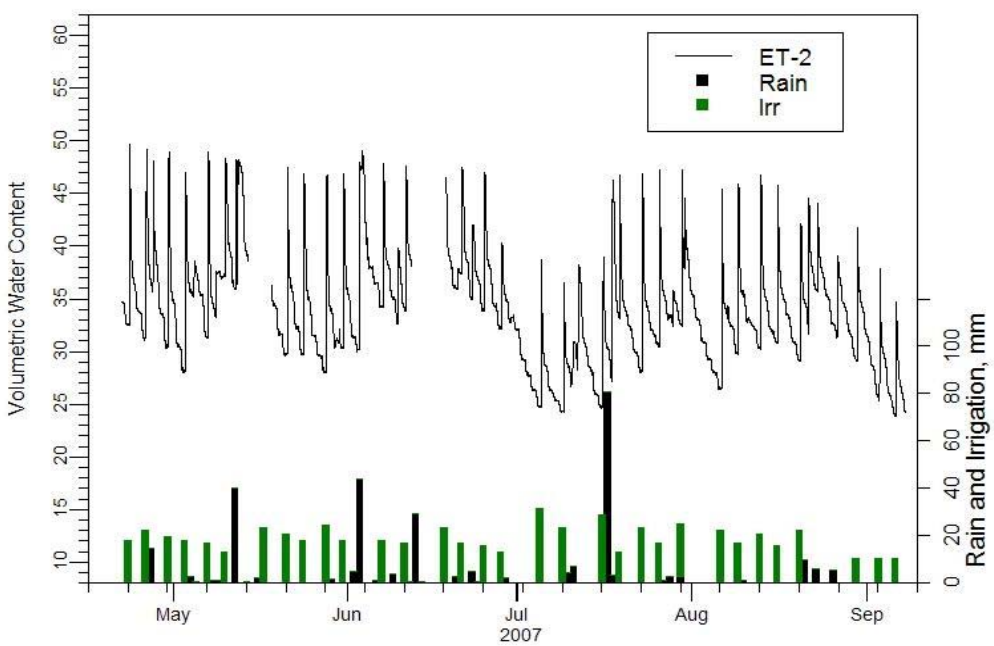

Figure 3.14 Soil-water content, rain and irrigation for the Intellisense TIS 240 controller set to irrigate twice per week.

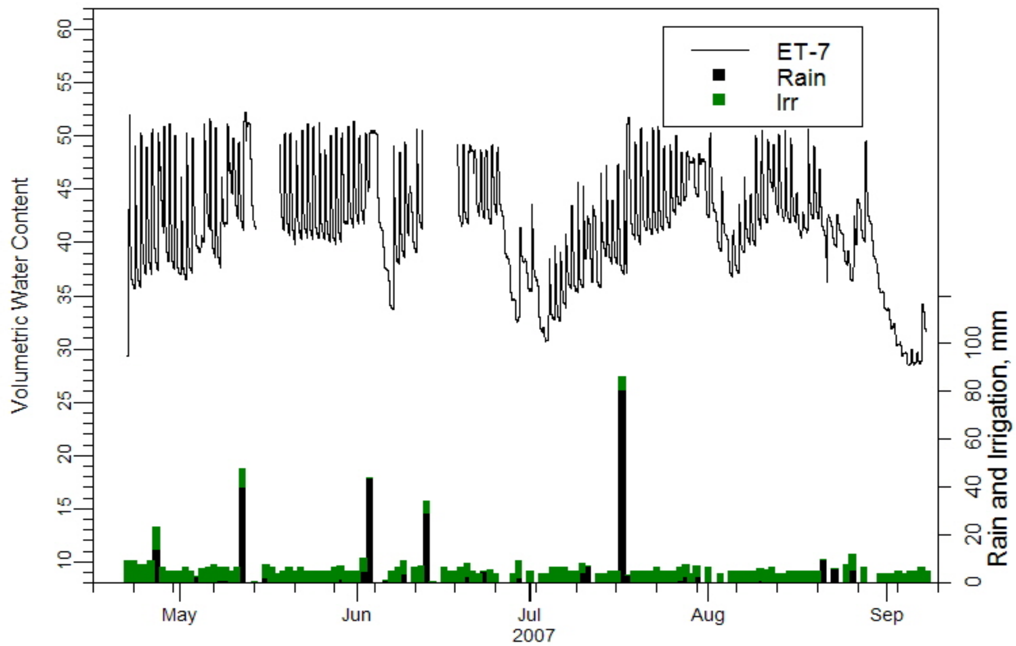

Figure 3.15 Soil-water content, rain and irrigation for the Intellisense TIS 240 controller set to irrigate daily.

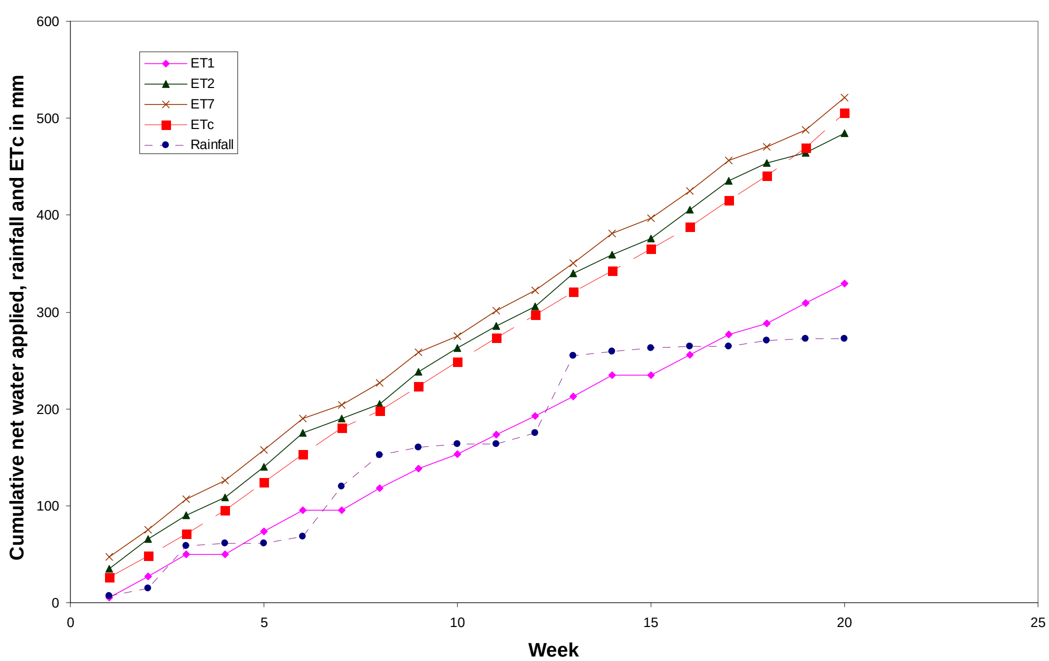

Figure 3.16 ET$_c$ (from weather station) and net applied water from the ET-based technology

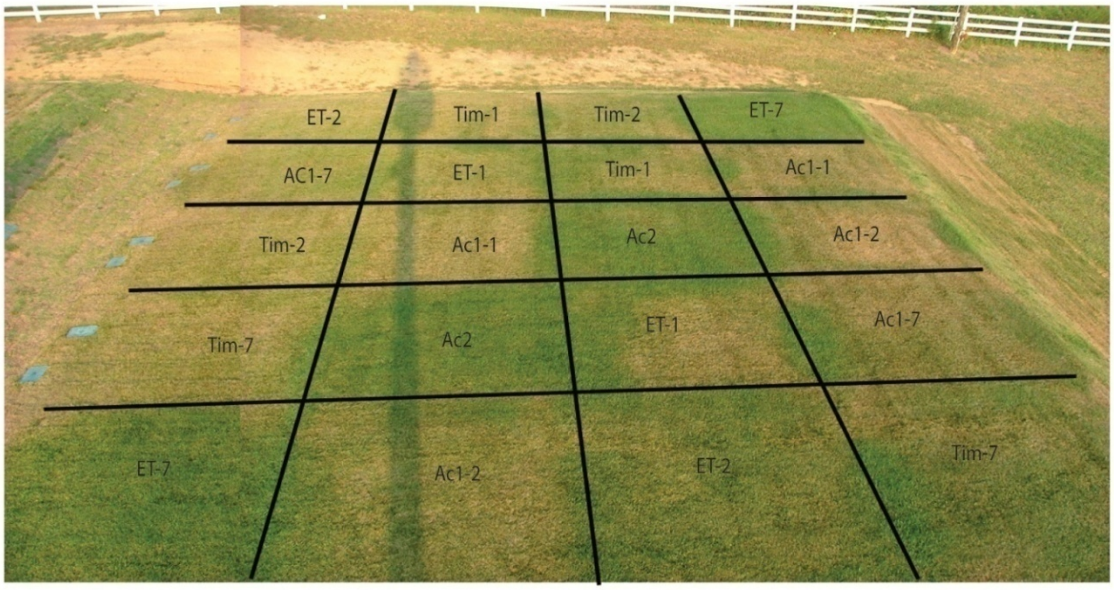

Figure 3.17 Turf quality of plots in the lower terrace on Sept 11, 2007.

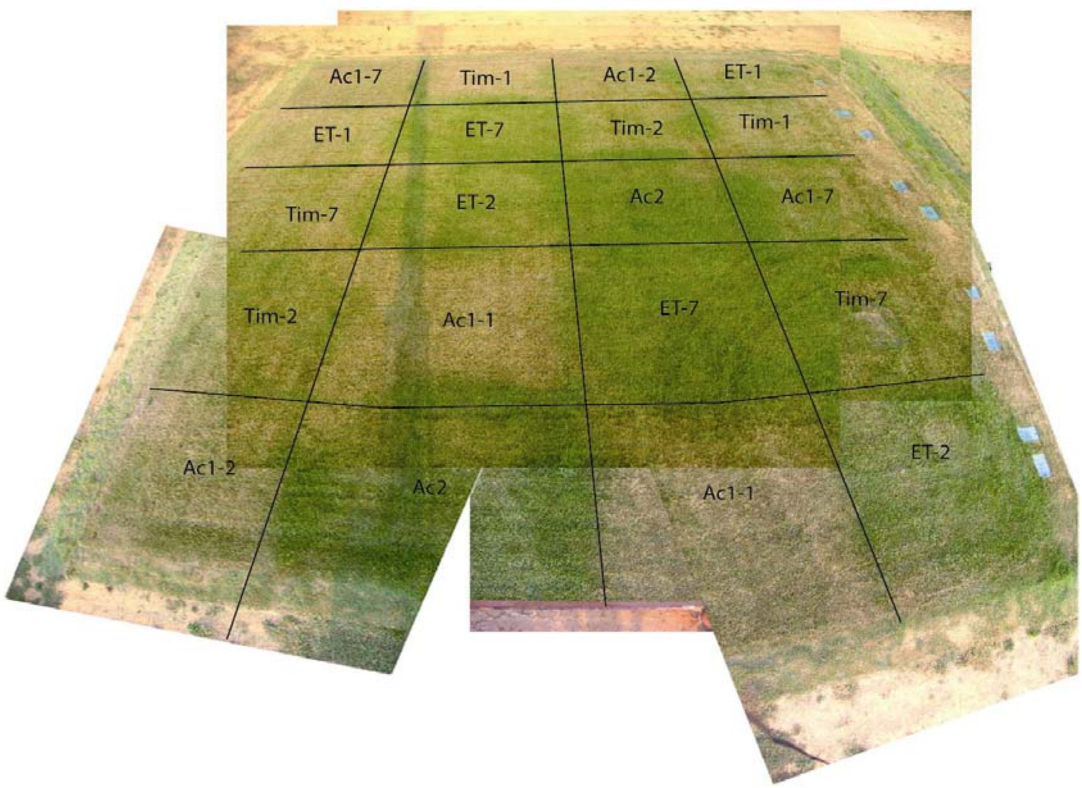

Figure 3.18 Turf quality of plots in the upper terrace on Sept 11, 2007.

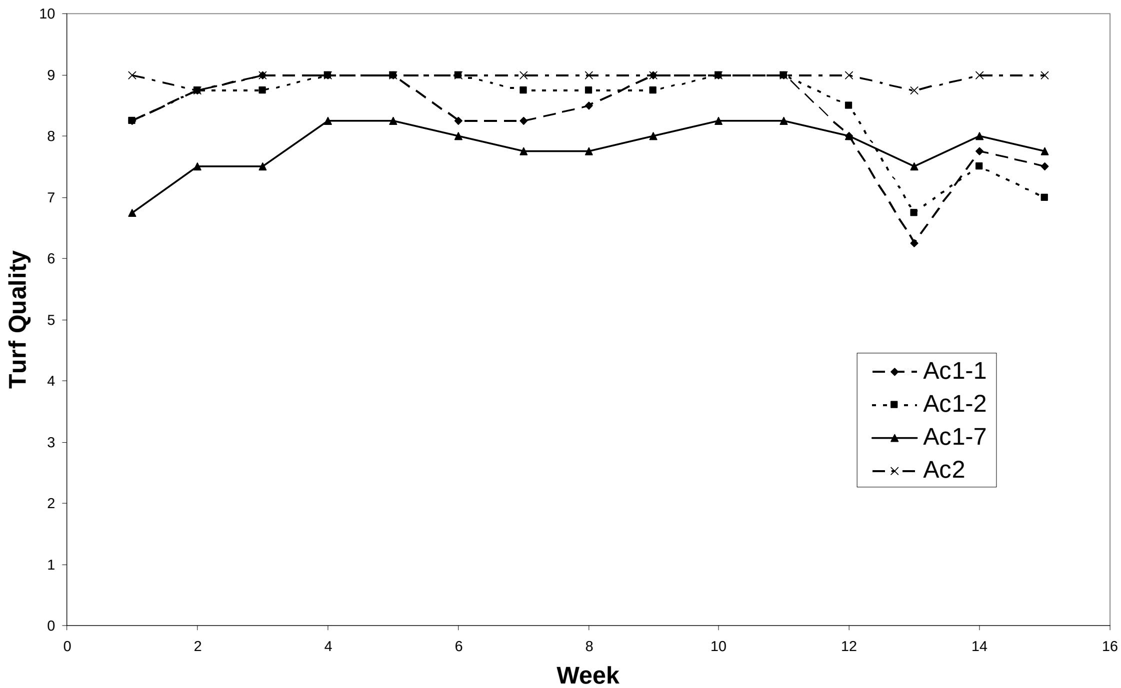

Figure 3.19 Turf quality (average of 4 replications) for add-on and on-demand technologies

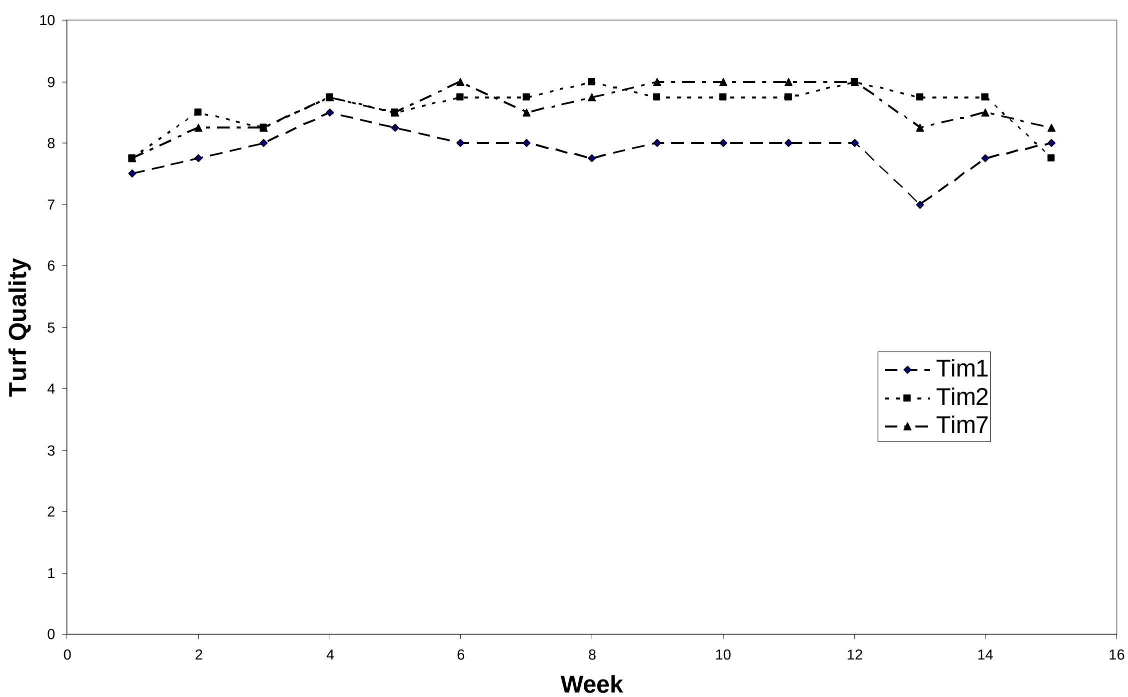

Figure 3.20 Turf quality (average of 4 replications) for Time-based technology

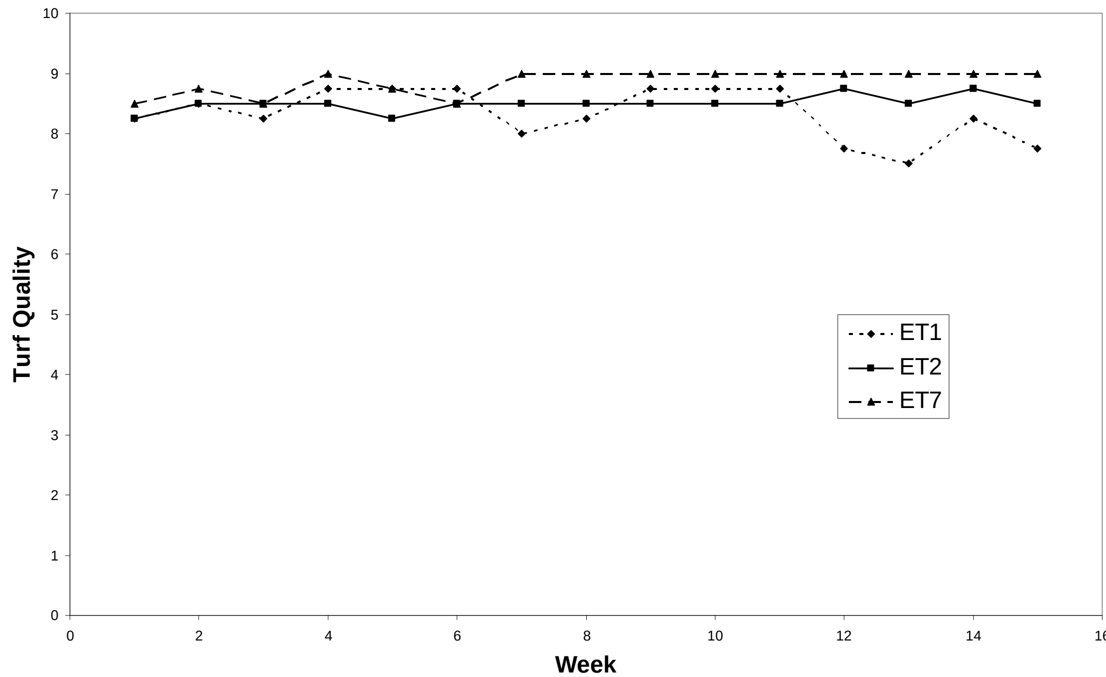

Figure 3.21 Turf quality (average of 4 replications) for ET-based technology

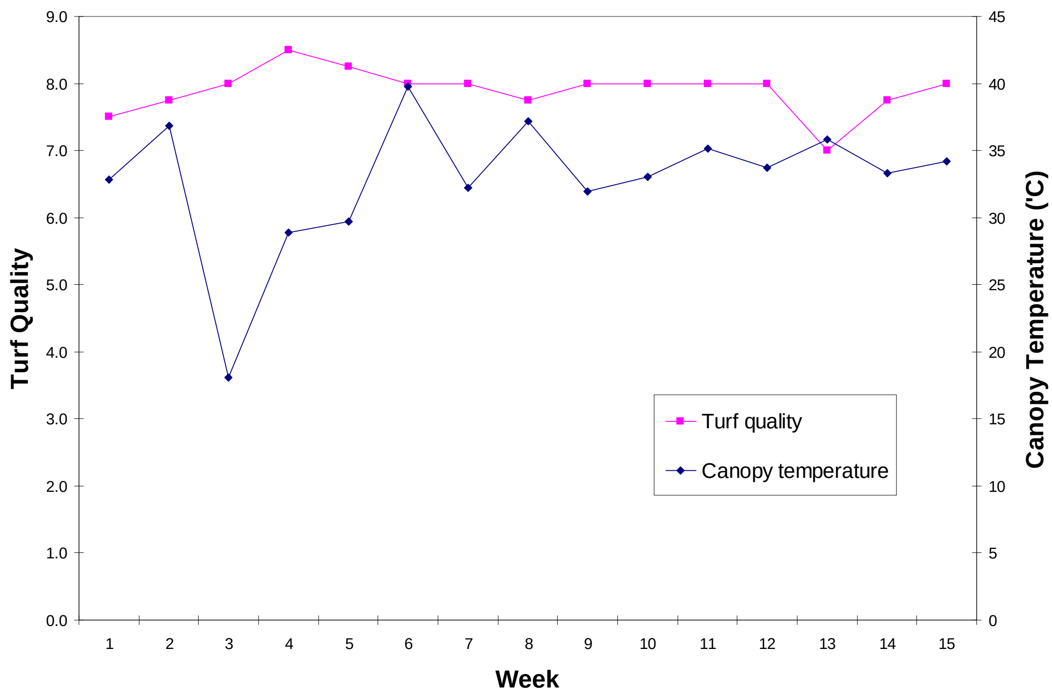

Figure 3.22 Turf quality and canopy temperature against week for timer-based once per week treatment

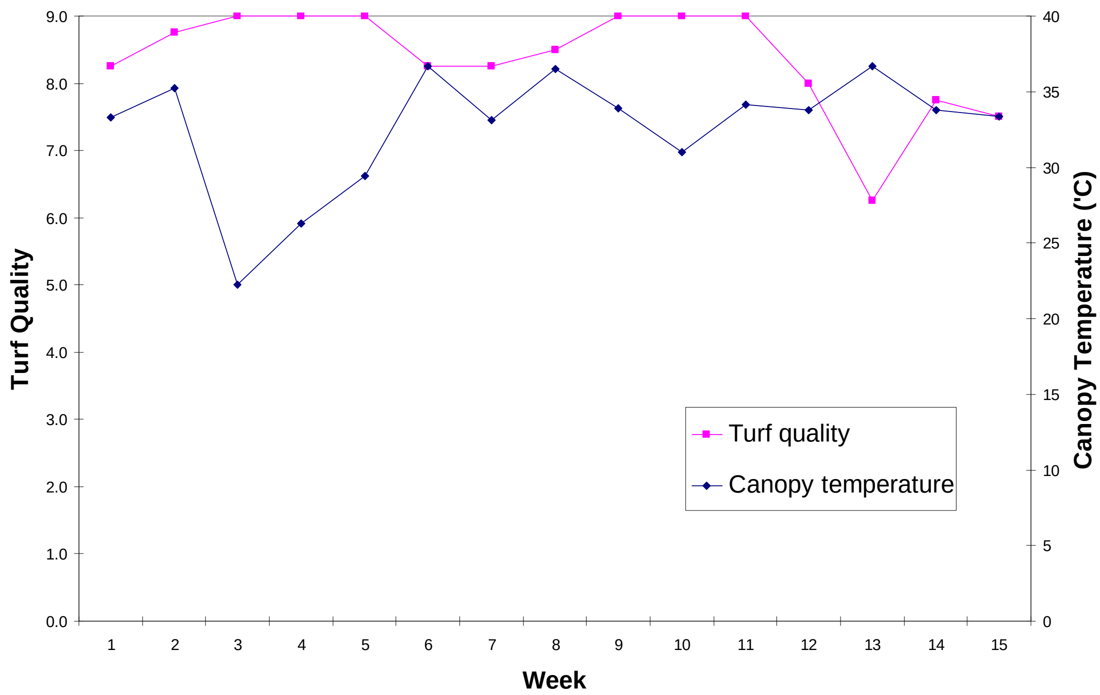

Figure 3.23 Turf quality and canopy temperature against week for Acclima add-on system at once per week frequency

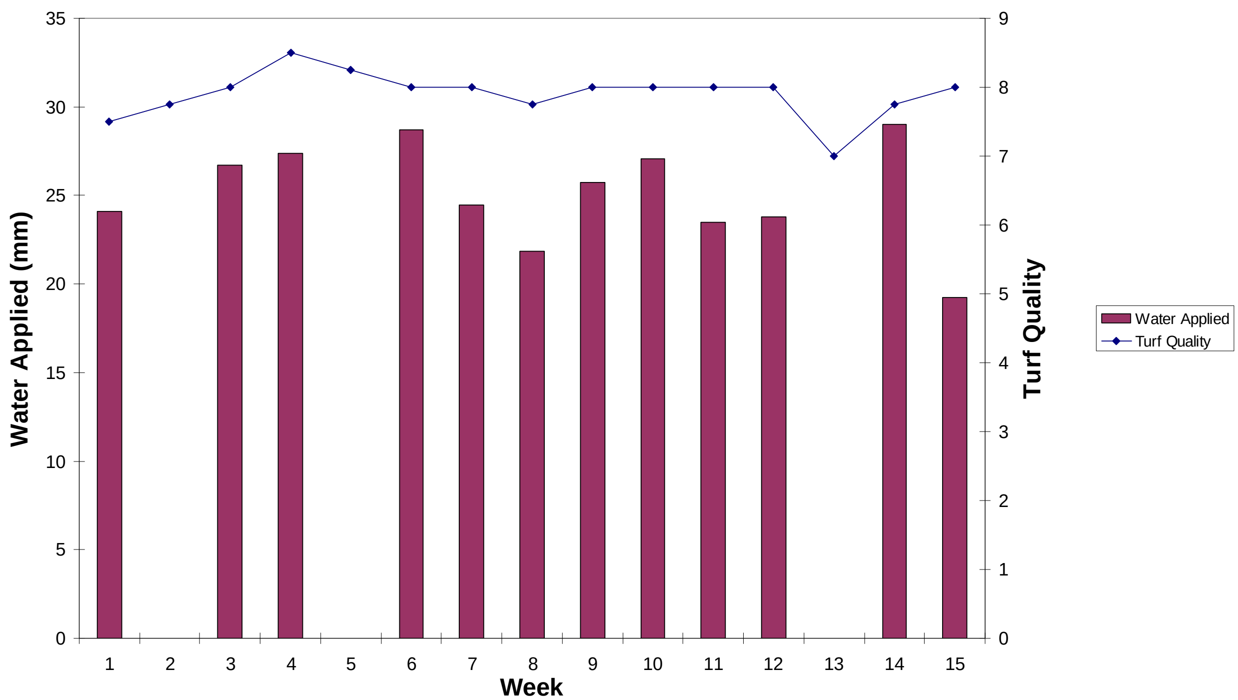

Figure 3.24 Turf quality and water applied against week for timer-based system at once per week frequency

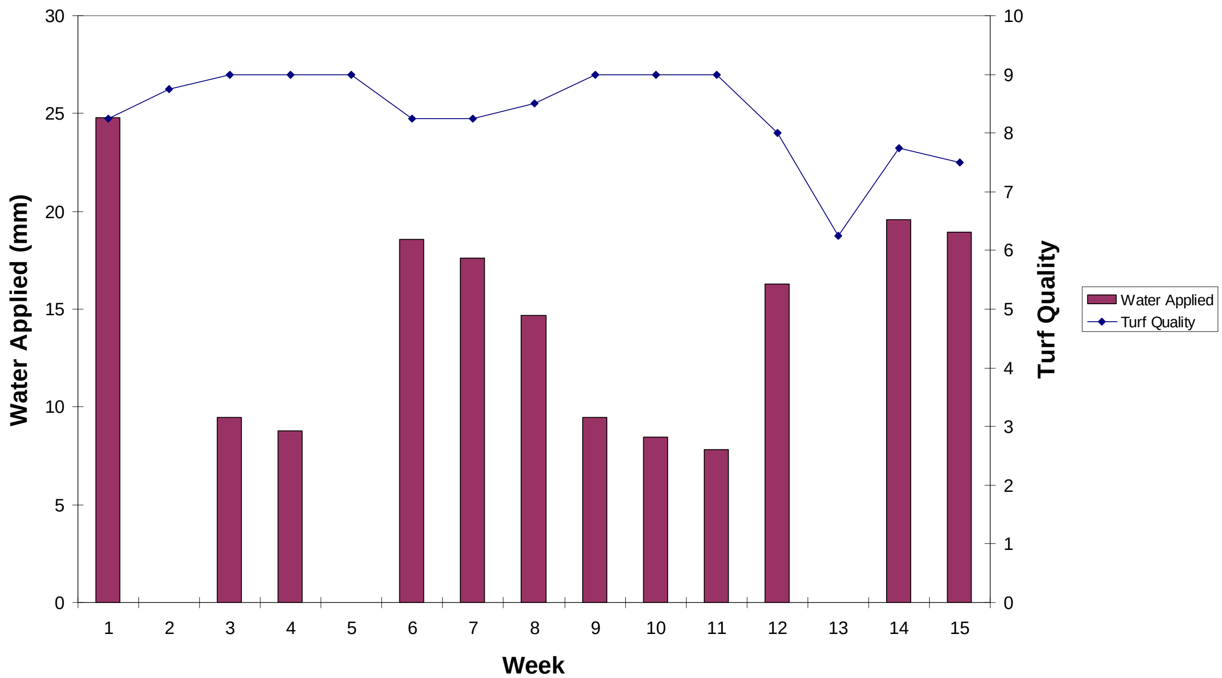

Figure 3.25 Turf quality and water applied against week for Acclima add-on system at once per week frequency

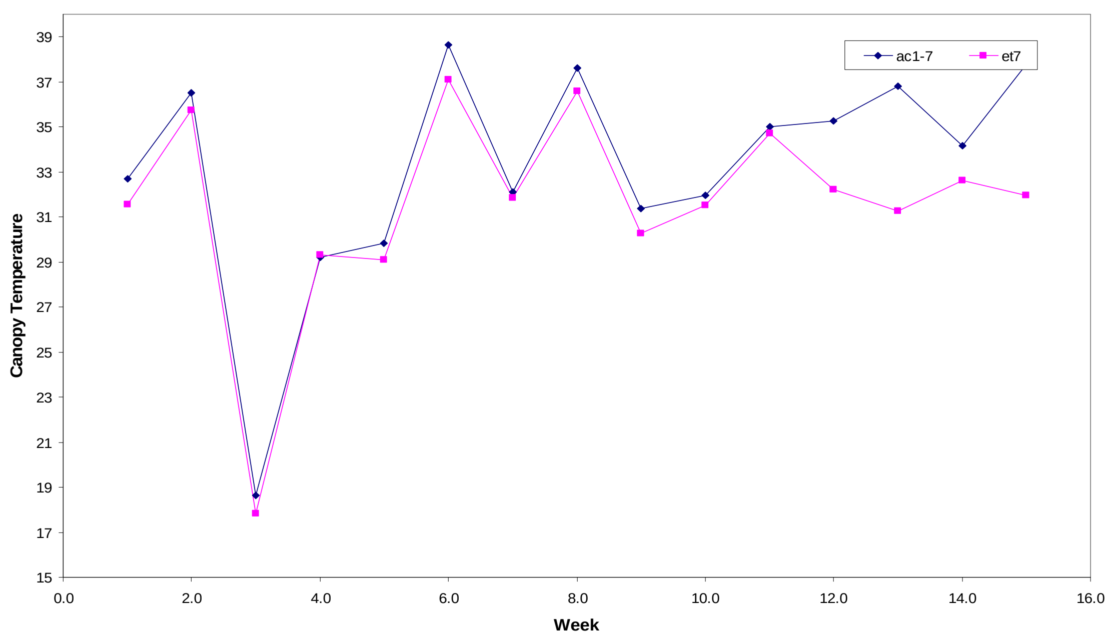

Figure 3.26 Plot of canopy temperature (°C) of ET-7 and AC1-7 over time

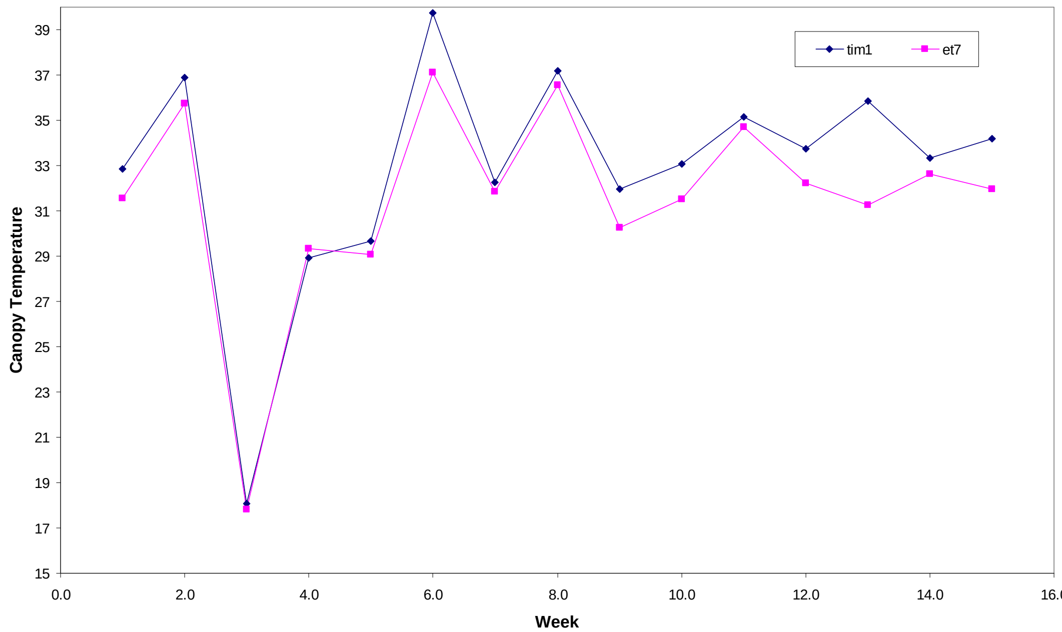

Figure 3.27 Plot of canopy temperature (ºC) of ET-7 and Tim-1 over time

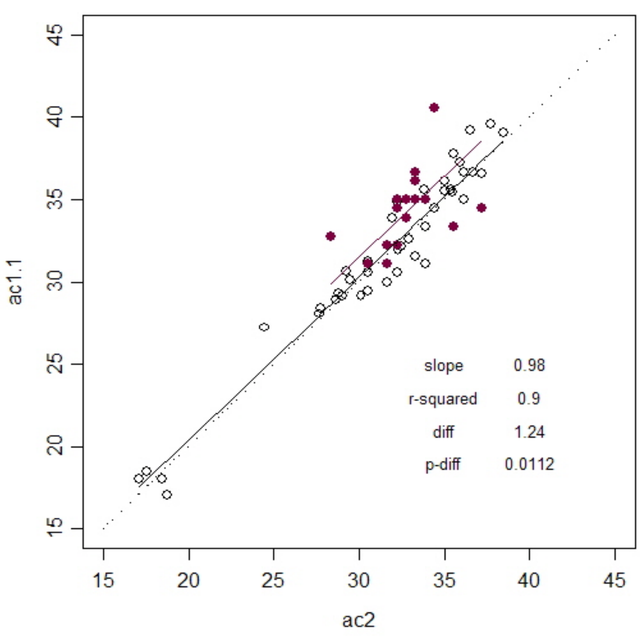

Figure 3.28 Bivariate plot of the relationship in canopy temperatures (ºC) between AC2 and AC1-1 treatments. Open circles for first 11 weeks and closed circles for last 4 weeks. Diff is temperature elevation with respect to AC2 for the last four weeks.

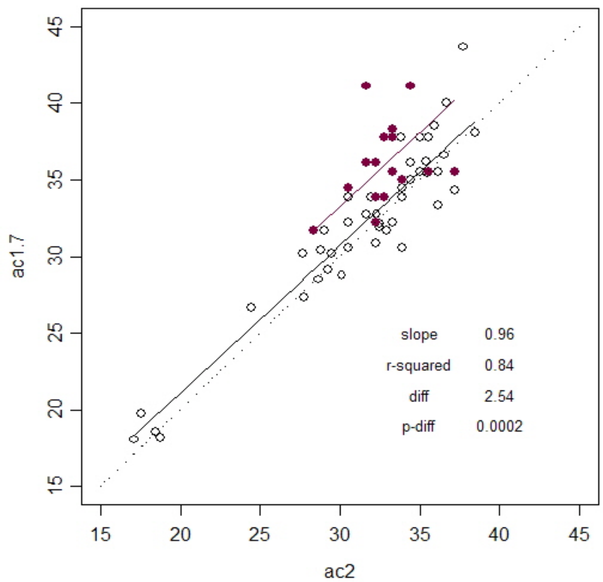

Figure 3.29 Bivariate plot of the relationship in canopy temperatures (ºC) between AC2 and AC1-7 treatments. Open circles for first 11 weeks and closed circles for last 4 weeks. Diff is temperature elevation with respect to AC2 for the last four weeks.

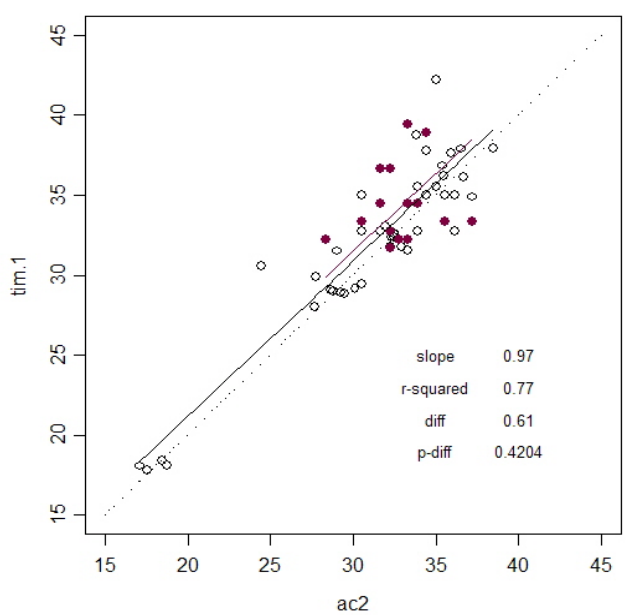

Figure 3.30 Bivariate plot of the relationship in canopy temperatures (ºC) between AC2 and tim-1 treatments. Open circles for first 11 weeks and closed circles for last 4 weeks. Diff is temperature elevation with respect to AC2 for the last four weeks.

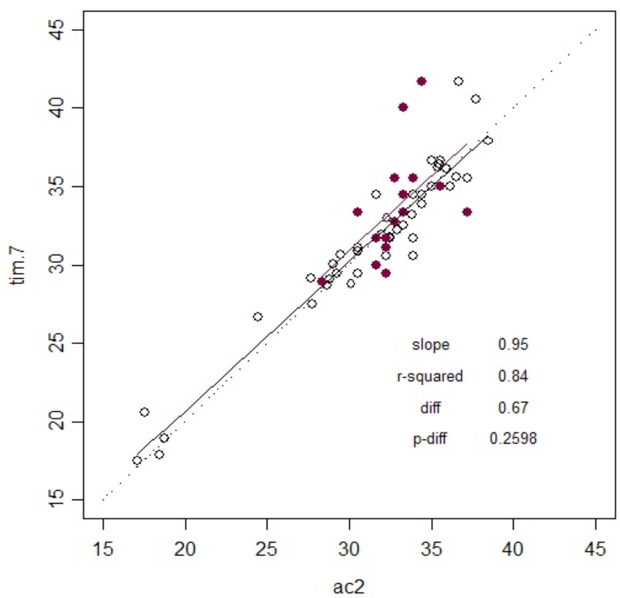

Figure 3.31 Bivariate plot of the relationship in canopy temperatures (ºC) between AC2 and tim-7 treatments. Open circles for first 11 weeks and closed circles for last 4 weeks. Diff is temperature elevation with respect to AC2 for the last four weeks.

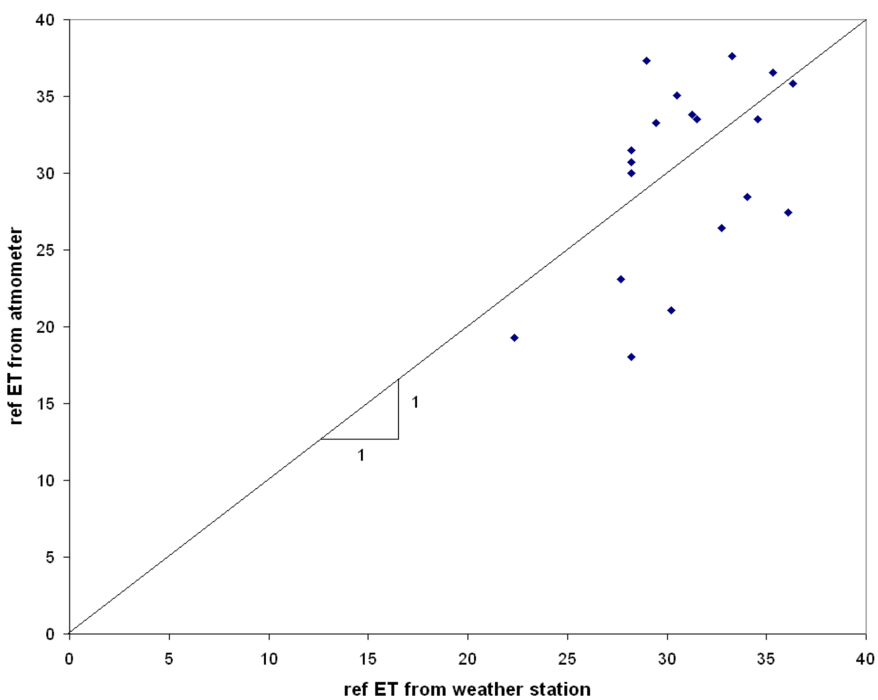

Figure 3.32 Atmometer versus Watchdog weekly reference ET

CHAPTER 4

4. SUMMARY AND RECOMMENDATIONS

The study period in 2007 was warmer and drier than average. Total rainfall during the 20-week study period (22 April to 8 September) was 290 mm with 79 mm falling in one event.

The total applied water for the three frequencies involved in the time-based technology were nearly the same as they were programmed to apply the same amount of water weekly and the applied water amounts differed only due to different rain sensor settings and proximity of rainfall events to scheduled irrigations. On average, the time-based technology applied 418 mm of irrigation water for the experimental period.

The Acclima add-on (one setpoint) system applied less water than the time-based technology because the volumetric soil water content was greater than the moisture threshold on several occasions when irrigation was scheduled. There was a difference in the amount of water applied by the three frequencies associated with this technology. The once per week frequency applied the least amount of water (219 mm) while the daily frequency applied the most water (347 mm). Acceptable turf quality (index value > 7) was met by all the technologies and frequencies during the first fifteen weeks of the experiment. But quality declined for some of the technologies especially the add-on system and the time-based system in the last month (five weeks) of study.

The evapotranspiration based technology had the highest water applied because the reference ET estimates of the system were high. But this technology maintained excellent turf quality throughout the study. The once per week frequency had the least amount of applied water (412 mm) followed by the twice per week (623 mm) and the daily frequencies (652 mm).

The Acclima water on-demand (two setpoint) system had less water applied (448 mm) than the ET system and at the same time maintained acceptable turf quality (index > 7 at all times).

Overall the Acclima add-on system at once per week frequency applied the least amount of water, followed by the twice per week and daily add-on systems. The once per week ET system was not statistically different in weekly applied water than the Acclima add-on daily system or any of the timer-based systems. The ET controller at twice per week and daily frequencies applied the most water. A general trend of increased applied water with increased irrigation frequency was observed for all systems except for the time-based technology which had no difference in water applied for all the frequencies.

Canopy temperatures taken during the experimental period were different among technologies across frequencies while no difference was found for estimates among frequencies across different technologies. The canopy temperatures were inversely correlated to the water applied. There was no significant difference between the weekly reference ET estimates from an Atmometer and the Penman-Montieth reference ET estimates using weather station both located at the site.

CONCLUSIONS

- Smart Irrigation technologies hold promise for efficient irrigation by conserving water while maintaining acceptable turf quality.
- Soil-water feedback systems are an important technology as they not only conserve water but also help maintain acceptable turf quality.
- The Acclima water on demand system was the most effective system applying less water than the ET controller while maintaining excellent turf quality. This system is expensive but may be ideal for commercial landscaping applications.
- The Acclima add-on systems can reduce water use, but if the timer is not programmed to apply enough water, turf quality can suffer as it operates on prohibiting irrigation rather than initiating irrigation. These systems may be more effectively used by setting the controller to apply a daily amount equal to a management allowable depletion (e.g., 25% of field capacity with a set point of 75% of field capacity), and letting the system override irrigation events until that condition is met. In this study, the daily frequency was set to apply only 4 mm or 8% of field capacity to satisfy a long-term irrigation requirement.
- The Toro Intellisense ET controller followed trends in weather but applied more water than required as its reference ET estimates were high and it did not include effective rainfall in its soil-water budget. Quality of turf irrigated by this system was acceptable.

RECCOMMENDATIONS

- Data collection should be done more than once per week. The monitoring sensor and control sensor needs to be checked frequently to make sure they give accurate soil-water readings.

- Soil samples must be collected couple of months before the experiment (sometime in February) and analyzed for particle size distribution, soil-water retention, pH, and nutrients.

- Turf quality rating is subjective and varies from person to person. Instead of assessing qualitatively using a scale index it might be better if it is assessed quantitatively by using some quality indicating device such as TCM 500 Turf color meter (Spectrum Technologies) or using digital image analysis to relate the percent green color to quality (Richardson et al., 2001). Visual ratings are very subjective and are influenced by the rater.

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APPENDICES

Appendix 1 Weather data from Watchdog weather station

		temp		RH	Solar	Wind	Rain-	ET	ET
Date	Mean	High	Low	Mean	Radiation	Speed	Fall	Ref	Crop
	(ºC)	(ºC)	(ºC)		(W/m^2)	(m/s)	(mm)	(mm)	(mm)
4/25/2007	23.17	29.56	15.61	54.00	281.00	1.56	0.00	5.08	4.06
4/26/2007	23.11	29.17	17.50	59.00	220.00	2.24	0.00	4.83	3.81
4/27/2007	21.78	27.56	18.28	73.00	195.00	2.37	6.86	4.32	3.56
4/28/2007	19.22	24.44	14.44	48.00	312.00	1.21	0.00	4.83	3.81
4/29/2007	19.39	26.00	12.89	43.00	319.00	1.03	0.00	4.83	3.81
4/30/2007	22.39	30.78	10.94	32.00	328.00	1.07	0.00	5.33	4.32
5/1/2007	25.33	33.61	16.78	33.00	317.00	1.07	0.00	6.10	4.83
5/2/2007	24.17	32.39	17.50	48.00	302.00	1.48	1.78	6.10	4.83
5/3/2007	17.17	20.56	12.11	75.00	117.00	1.83	5.84	2.54	2.03
5/4/2007	11.89	12.89	10.56	92.00	42.00	1.21	0.25	1.02	0.76
5/5/2007	15.28	20.22	12.11	76.00	92.00	0.31	0.00	1.78	1.27
5/6/2007	14.50	18.28	8.56	51.00	331.00	3.04	0.00	5.08	4.06
5/7/2007	13.17	19.83	6.11	42.00	345.00	2.91	1.02	5.59	4.32
5/8/2007	14.56	19.06	9.33	73.00	117.00	2.41	0.25	2.79	2.29
5/9/2007	19.11	26.00	16.00	90.00	151.00	1.48	0.00	3.05	2.29
5/10/2007	21.50	27.94	16.39	75.00	255.00	0.49	2.54	4.06	3.30
5/11/2007	23.22	30.78	15.22	67.00	308.00	0.63	0.00	5.08	4.06
5/12/2007	20.17	27.94	17.89	90.00	124.00	0.58	40.13	2.54	2.03
5/13/2007	17.89	21.33	11.33	79.00	166.00	1.48	0.25	3.05	2.54
5/14/2007	16.11	23.67	8.56	56.00	348.00	0.58	0.00	4.57	3.81
5/15/2007	19.61	27.17	10.94	58.00	326.00	1.83	0.00	5.59	4.57
5/16/2007	21.56	27.94	15.22	62.00	278.00	2.28	2.29	5.33	4.32
5/17/2007	17.17	20.56	13.67	76.00	202.00	1.03	0.25	3.30	2.54
5/18/2007	15.44	21.33	8.94	70.00	262.00	1.43	0.00	4.06	3.30
5/19/2007	15.22	23.28	6.11	54.00	323.00	0.72	0.00	4.32	3.56
5/20/2007	20.00	28.33	9.78	33.00	321.00	0.80	0.00	5.08	4.06
5/21/2007	23.11	31.17	13.67	43.00	278.00	0.58	0.00	4.57	3.81
5/22/2007	20.50	26.39	15.61	61.00	258.00	1.30	0.00	4.57	3.56
5/23/2007	20.00	26.39	12.89	55.00	328.00	0.98	0.00	5.08	4.06
5/24/2007	19.89	26.78	12.11	56.00	339.00	0.85	0.00	5.08	4.06
5/25/2007	21.78	29.94	13.28	58.00	328.00	0.72	0.00	5.33	4.32
5/26/2007	23.39	31.17	15.22	57.00	306.00	1.25	0.00	5.59	4.57
5/27/2007	23.56	31.17	15.61	54.00	315.00	1.30	0.00	5.84	4.57
5/28/2007	23.67	31.56	16.39	56.00	312.00	1.16	0.00	5.84	4.57
5/29/2007	24.50	34.06	17.50	60.00	268.00	0.67	2.03	5.08	4.06
5/30/2007	24.28	31.17	17.89	57.00	295.00	1.03	0.00	5.33	4.32
5/31/2007	23.50	31.17	15.61	57.00	285.00	1.25	0.00	5.33	4.32
6/1/2007	23.33	31.56	16.00	57.00	318.00	1.16	0.00	5.59	4.57

		Temp		RH	Solar	Wind	Rain-	ET	ET
Date	Mean	High	Low	Mean	W/m2	Speed	Fall	Ref	Crop
6/4/2007	24.39	31.56	16.00	60.00	324.00	1.92	0.00	6.10	4.83
6/5/2007	25.00	32.00	18.28	56.00	268.00	1.03	0.76	5.08	4.06
6/6/2007	22.28	29.56	15.22	58.00	321.00	0.76	0.76	5.08	4.06
6/7/2007	25.17	32.78	16.39	60.00	289.00	1.30	0.25	5.59	4.32
6/8/2007	27.94	35.78	21.72	66.00	282.00	1.07	0.00	5.59	4.32
6/9/2007	26.44	33.22	20.22	64.00	250.00	0.89	4.32	4.57	3.81
6/10/2007	24.17	29.94	19.83	66.00	278.00	0.89	0.00	4.83	3.81
6/11/2007	21.28	27.94	16.39	72.00	195.00	0.40	0.00	3.30	2.54
6/12/2007	21.67	29.94	16.00	76.00	224.00	0.45	0.25	3.56	2.79
6/13/2007	19.56	25.61	17.50	89.00	115.00	0.54	30.99	2.03	1.78
6/14/2007	17.11	19.83	15.22	85.00	121.00	0.80	0.25	2.03	1.52
6/15/2007	17.89	24.06	14.44	72.00	166.00	0.40	0.25	2.54	2.03
6/16/2007	21.39	27.56	13.67	74.00	265.00	0.67	0.00	4.06	3.30
6/17/2007	24.67	32.39	17.50	61.00	310.00	0.49	0.00	4.83	3.81
6/18/2007	27.72	36.61	17.11	47.00	290.00	0.45	0.00	4.83	3.81
6/19/2007	27.33	34.50	20.56	59.00	273.00	0.98	0.25	5.08	4.06
6/20/2007	22.50	27.17	18.28	80.00	163.00	0.63	3.30	2.79	2.29
6/21/2007	23.94	30.78	16.78	54.00	324.00	0.63	0.00	5.08	4.06
6/22/2007	25.17	33.61	17.50	52.00	277.00	0.58	0.00	4.57	3.56
6/23/2007	23.00	29.56	19.44	64.00	255.00	0.58	4.83	4.06	3.30
6/24/2007	24.94	32.78	18.67	66.00	245.00	1.03	0.51	4.57	3.56
6/25/2007	25.89	33.61	20.22	70.00	286.00	0.85	0.00	5.08	4.06
6/26/2007	26.78	34.89	20.56	65.00	286.00	0.89	0.00	5.08	4.06
6/27/2007	26.06	32.78	20.94	72.00	286.00	1.34	0.00	5.08	4.06
6/28/2007	26.39	33.22	21.33	72.00	246.00	1.39	0.00	4.83	3.81
6/29/2007	24.94	34.06	20.94	79.00	185.00	1.16	2.54	4.06	3.30
6/30/2007	25.50	32.39	20.94	74.00	221.00	0.76	0.00	4.06	3.05
7/1/2007	24.33	29.56	19.83	52.00	315.00	1.21	0.00	5.33	4.32
7/2/2007	22.83	29.17	16.78	56.00	243.00	0.63	0.00	3.30	2.79
7/3/2007	22.83	28.33	17.11	61.00	225.00	1.25	0.00	3.56	2.79
7/4/2007	23.72	30.33	16.39	55.00	294.00	1.61	0.00	5.08	4.06
7/5/2007	25.33	32.00	17.89	55.00	312.00	1.79	0.00	5.84	4.83
7/6/2007	26.83	34.06	20.56	59.00	236.00	0.80	0.00	4.06	3.05
7/7/2007	26.22	34.50	20.22	62.00	200.00	0.72	0.00	3.30	2.54
7/8/2007	26.89	34.06	20.22	67.00	271.00	1.12	0.00	4.83	3.81
7/9/2007	27.28	35.33	20.56	70.00	278.00	1.21	0.00	5.08	4.06
7/10/2007	25.72	35.33	21.33	83.00	187.00	0.85	4.57	3.30	2.79
7/11/2007	25.67	34.50	20.56	77.00	256.00	1.65	7.11	5.08	4.06
7/12/2007	25.56	32.00	20.56	63.00	292.00	0.63	0.25	4.57	3.81
7/13/2007	23.17	27.17	17.50	55.00	107.00	0.40	0.00	1.78	1.52
7/14/2007	23.83	30.78	16.78	63.00	243.00	0.76	0.00	3.56	3.05
7/15/2007	24.94	32.00	17.89	66.00	234.00	0.85	0.00	3.81	3.05

		Temp		RH	Solar	Wind	Rain-	ET	ET
Date	Mean	High	Low	Mean	W/m2	Speed	Fall	Ref	Crop
7/16/2007	26.33	32.78	20.56	65.00	274.00	1.16	0.00	4.83	3.81
7/17/2007	26.72	34.89	20.94	69.00	256.00	1.39	27.43	4.83	3.81
7/18/2007	25.89	32.78	20.56	76.00	196.00	0.98	51.82	3.30	2.54
7/19/2007	28.56	34.89	21.33	63.00	332.00	0.80	0.00	5.84	4.83
7/20/2007	26.44	30.78	22.50	59.00	186.00	0.85	0.00	2.79	2.29
7/21/2007	23.17	27.94	17.50	49.00	250.00	1.21	0.00	4.06	3.30
7/22/2007	22.22	28.72	15.22	51.00	270.00	1.12	0.00	4.32	3.56
7/23/2007	22.83	29.56	16.78	53.00	295.00	0.58	0.00	4.32	3.56
7/24/2007	23.39	30.78	16.39	60.00	237.00	0.45	0.00	3.30	2.54
7/25/2007	23.39	29.94	17.89	62.00	263.00	0.76	0.00	4.06	3.30
7/26/2007	25.17	32.78	18.67	62.00	285.00	0.36	0.00	4.32	3.30
7/27/2007	25.11	33.61	19.44	74.00	250.00	0.76	1.78	4.06	3.30
7/28/2007	24.17	32.39	19.44	80.00	238.00	0.72	2.54	3.81	3.05
7/29/2007	25.17	31.17	18.67	73.00	270.00	0.72	0.00	4.32	3.30
7/30/2007	24.06	30.78	21.33	84.00	164.00	0.54	4.06	2.29	1.78
7/31/2007	25.33	31.17	20.22	71.00	268.00	0.89	0.00	4.32	3.56
8/1/2007	26.39	33.22	20.56	60.00	253.00	0.54	0.00	3.81	3.05
8/2/2007	26.28	33.22	20.22	61.00	279.00	0.58	0.00	4.57	3.56
8/3/2007	26.44	32.78	20.56	66.00	287.00	0.85	0.00	4.83	3.81
8/4/2007	27.56	34.50	20.22	62.00	255.00	0.58	0.00	4.06	3.30
8/5/2007	28.89	36.61	21.33	57.00	282.00	0.58	0.00	4.57	3.81
8/6/2007	29.06	35.78	23.67	64.00	241.00	0.49	0.00	4.06	3.05
8/7/2007	30.44	37.94	23.67	58.00	252.00	0.45	0.00	4.32	3.30
8/8/2007	31.11	39.28	24.44	60.00	276.00	0.80	0.76	5.33	4.32
8/9/2007	31.50	39.28	24.83	56.00	246.00	0.94	0.00	4.83	3.81
8/10/2007	30.00	39.72	23.67	64.00	254.00	0.72	0.76	4.57	3.81
8/11/2007	24.67	27.56	21.33	82.00	110.00	0.67	0.25	1.27	1.02
8/12/2007	25.39	32.78	19.06	62.00	292.00	0.67	0.00	4.83	3.81
8/13/2007	27.72	35.33	20.56	49.00	269.00	0.63	0.00	4.32	3.56
8/14/2007	26.94	33.22	21.33	39.00	308.00	0.72	0.00	5.08	4.06
8/15/2007	27.39	34.89	20.22	61.00	261.00	1.34	0.00	5.08	4.06
8/16/2007	29.22	35.78	23.67	65.00	253.00	2.50	0.00	5.84	4.83
8/17/2007	27.89	34.50	23.28	70.00	177.00	1.52	0.00	3.56	2.79
8/18/2007	25.83	32.00	19.06	49.00	283.00	0.72	0.00	4.57	3.56
8/19/2007	26.72	34.50	19.06	63.00	238.00	1.79	0.00	4.83	3.81
8/20/2007	29.83	37.50	22.89	51.00	269.00	1.61	0.00	5.84	4.83
8/21/2007	29.22	38.39	22.50	61.00	254.00	1.34	2.29	5.33	4.32
8/22/2007	26.56	32.78	21.33	73.00	197.00	0.58	1.52	3.05	2.29
8/23/2007	25.94	31.56	23.28	81.00	135.00	0.67	1.02	1.78	1.52
8/24/2007	27.78	34.50	21.72	71.00	256.00	1.03	0.76	4.57	3.56
8/25/2007	28.61	35.78	22.89	65.00	304.00	1.43	0.00	6.10	4.83
8/26/2007	25.83	33.61	21.72	77.00	213.00	1.03	1.52	3.81	3.05

		temp		RH	Solar	Wind	Rain-	ET	ET
Date	Mean	High	Low	Mean	W/m2	Speed	Fall	Ref	Crop
8/27/2007	25.33	31.17	20.22	74.00	327.00	0.54	0.51	5.33	4.32
8/28/2007	26.61	32.78	21.33	65.00	365.00	0.76	0.25	6.35	5.08
8/29/2007	25.94	31.17	21.33	63.00	328.00	1.25	0.00	5.84	4.57
8/30/2007	25.11	31.17	21.33	69.00	251.00	0.89	0.00	4.06	3.30
8/31/2007	25.17	31.56	19.83	62.00	332.00	0.49	0.00	5.33	4.32
9/1/2007	23.89	29.56	19.83	60.00	327.00	1.03	0.00	5.33	4.32
9/2/2007	23.22	29.56	16.78	51.00	434.00	0.94	0.00	7.11	5.84
9/3/2007	23.67	32.00	15.61	55.00	387.00	0.36	0.00	6.10	4.83
9/4/2007	25.72	34.06	17.89	54.00	407.00	0.49	0.00	6.60	5.33
9/5/2007	26.06	34.06	18.28	52.00	413.00	0.63	0.00	7.11	5.59
9/6/2007	25.72	33.22	18.67	59.00	393.00	1.07	0.00	6.86	5.59
9/7/2007	24.89	31.56	18.67	63.00	324.00	0.94	0.00	5.33	4.32
9/8/2007	24.00	31.56	16.39	53.00	392.00	0.63	0.00	6.35	5.08
9/9/2007	24.89	34.06	17.11	52.00	417.00	0.49	0.00	6.86	5.33
9/10/2007	23.06	30.78	18.67	60.00	302.00	0.54	0.51	4.57	3.81

Appendix 2 SAS code used for Statistical Analysis

For Wateruse data

```
options  ls=75;

/*column names
treatments  Ac2  Ac1-1  Ac1-2  Ac1-7  ET-1  ET-2  ET-7  Tim-1  Tim-2
Tim-7
*/
data rep1;
   block=1;
   drop j f1-f3;
   array farray{3} f1-f3 (7,1,2);
   input month $ day $ weekname $ @ ;
   week=substr(weekname,5);
   do trt=1 to 10;
      plot=trt;
        plot2=trt;*assign a unique number to each plot - not equal to
plot numbering system;
      if trt<5 then method="AC";
      else if trt<8 then method="ET";
      else method="Tim";
      if (trt=1) then frq=7;
      else do;
      j=mod(trt-1,3)+1;
      frq=farray{j};
      end;
      input wateruse @;
      output;
   end;
   cards;
april 22-28  week1  14.351  0  5.207  10.4394  7.8232  36.4998  59.944
23.4696  23.4696  23.495
april 29-may5  week2  23.4696  7.8232  24.765  18.2626  0  36.5252
35.2044  24.765  23.4696  19.5834
may 6-12  week3  14.351  7.8232  13.0556  23.495  0  29.972  39.0906
26.0858  23.4696  22.1742
may 13-19  week4  0  0  0  3.9116  0  22.1742  24.7904  24.765  13.0302
15.6718
may 20-26  week5  39.1414  27.3812  24.765  24.7904  28.6766  36.4998
37.7952  23.4696  23.4696  23.495
may 27-june2  week6  29.9974  24.765  26.0604  26.0858  27.3812
40.4114  37.7698  22.1742  24.765  26.0858
june 3-9  week7  24.7904  0  5.207  7.8232  0  16.9418  16.9418  0
11.7348  14.351
june 10-16  week8  0  9.1186  13.0302  7.8232  28.6766  16.9418
26.0858  23.4696  11.7348  14.351
june 17-23  week9  15.6464  7.8232  11.7348  15.6464  23.4696  36.5252
37.7952  23.4696  24.765  18.2626
june 24-30  week10  29.9974  0  23.4696  11.7348  18.2626  24.7904
```

```
13.1572  0  22.1742  11.7602
july 1-7  week11  28.702  18.2626  26.0604  31.2674  24.765  28.6766
37.7952  24.765  26.0604  26.0858
july 8-14  week12  14.351  18.2626  14.351  19.558  24.765  22.1742
26.035  20.8534  13.0302  16.9672
july 15-21  week13  14.351  14.351  14.351  19.558  24.765  37.7952
31.2674  19.558  26.0604  19.5834
july 22-28  week14  29.9974  9.1186  13.0302  28.6766  26.0858  22.1742
36.4744  23.4696  24.765  26.0858
july 29-aug4  week15  14.351  9.1186  19.558  15.6464  0  20.8534
20.8534  23.4696  20.8534  13.0556
aug 5-11  week16  27.4066  7.8232  26.0604  23.495  27.3812  36.4998
32.5628  19.558  20.8788  23.495
aug 12-18  week17  29.9212  16.9418  24.8412  24.7904  27.3812  35.2044
34.925  20.8534  23.4696  24.7904
aug 19-25  week18  19.558  0  13.0302  13.0302  14.351  20.8534
16.9418  0  10.4394  10.4394
aug 26-sept1  week19  35.2044  22.1742  0  13.0556  28.6766  11.7348
18.2626  26.0858  0  13.0556
sept 2-8  week20  36.5252  14.351  16.9672  16.9672  19.558  19.558
32.5628  14.351  15.6464  18.288
;
run;
data rep2;
   block=2;
   drop j f1-f3;
   array farray{3} f1-f3 (7,1,2);
   input month $ day $ weekname $ @ ;
   week=substr(weekname,5);
   do trt=1 to 10;
      plot=trt;
        plot2=trt+10;
      if trt<5 then method="AC";
      else if trt<8 then method="ET";
      else method="Tim";
      if (trt=1) then frq=7;
      else do;
      j=mod(trt-1,3)+1;
      frq=farray{j};
      end;
      input wateruse @;
      output;
   end;
   cards;
april 22-28  week1  15.6464  0  6.5278  9.144  5.207  40.4368  50.8254
24.765  26.0604  24.7904
april 29-may5  week2  24.765  9.1186  27.4574  15.6718  27.3812
37.8206  32.5628  24.765  26.0604  22.1742
may 6-12  week3  14.351  9.1186  13.0556  20.9042  28.6766  29.972
44.323  24.765  26.0604  19.5834
may 13-19  week4  0  0  0  3.9116  0  23.4696  20.8534  24.765  13.0302
18.2626
may 20-26  week5  41.7322  0  26.0604  22.1996  28.6766  39.116
```

```
39.0906  26.0858  26.0604  23.495
may 27-june2  week6  29.9974  0  24.765  20.9042  27.3812  43.0276
37.7698  23.4696  26.0604  23.495
june 3-9  week7  26.0858  0  6.5278  6.5278  0  18.2626  16.9418  0
13.0302  15.6464
june 10-16  week8  0  9.1186  11.7348  7.8232  26.0858  16.9418
24.7904  24.765  13.0302  15.6464
june 17-23  week9  14.351  9.1186  13.0302  14.351  23.4696  40.4114
31.496  24.765  26.0604  18.2626
june 24-30  week10  29.9974  0  24.765  11.7348  18.2626  28.6766
18.034  0  26.0604  15.6464
july 1-7  week11  28.702  18.2626  26.0604  26.0858  26.0858  31.2928
32.6136  26.0858  27.3812  27.3812
july 8-14  week12  14.351  16.9418  13.0302  18.2626  24.765  23.4696
22.1488  23.4696  14.351  18.2626
july 15-21  week13  15.6464  14.351  14.351  19.558  24.765  41.7068
31.242  20.8534  27.3812  23.4696
july 22-28  week14  31.2928  9.1186  13.0302  26.0858  26.0858  23.4696
37.7698  26.0858  27.3812  26.0858
july 29-aug4  week15  14.351  9.1186  18.2626  14.351  0  22.1742
18.2118  27.3812  23.4696  14.351
aug 5-11  week16  27.4066  7.8232  26.0604  22.1996  27.3812  39.116
36.449  23.4696  24.765  24.7904
aug 12-18  week17  29.9212  16.9418  24.8412  13.2842  27.3812  36.4998
35.179  24.765  23.4696  22.1996
aug 19-25  week18  20.8534  0  13.0302  11.7348  14.351  22.1742
18.2372  0  11.7348  11.7348
aug 26-sept1  week19  29.9974  20.8534  0  14.351  28.6766  10.4394
20.6248  29.9974  0  13.0556
sept 2-8  week20  35.2298  15.6464  18.2626  16.9672  20.8534  20.8788
35.179  14.351  19.558  20.9042
;
run;


data rep3;
   block=3;
   drop j f1-f3;
   array farray{3} f1-f3 (7,1,2);
   input month $ day $ weekname $ @ ;
   week=substr(weekname,5);
   do trt=1 to 10;
      plot=trt;
        plot2=trt+20;
      if trt<5 then method="AC";
      else if trt<8 then method="ET";
      else method="Tim";
      if (trt=1) then frq=7;
      else do;
      j=mod(trt-1,3)+1;
      frq=farray{j};
      end;
      input wateruse @;
```

```
   output;
   end;
   cards;
april 22-28  week1  15.6464  0  6.5278  11.7348  6.5278  49.5554
59.944  24.765  26.0604  22.1996
april 29-may5  week2  28.6766  7.8232  27.3812  20.8534  27.3812
37.8206  35.2298  24.765  28.6766  19.5834
may 6-12  week3  13.0302  7.8232  13.0556  24.7904  29.9974  33.909
44.3484  24.765  27.3812  20.8788
may 13-19  week4  0  0  0  3.9116  0  23.4696  22.1488  27.3812
13.0302  16.9672
may 20-26  week5  41.7322  27.3812  24.765  22.1996  31.2928  40.4368
40.4114  26.0858  26.0604  26.0858
may 27-june2  week6  29.9974  24.765  27.3812  20.9042  28.6766
46.9392  41.7322  24.765  27.3812  27.3812
june 3-9  week7  28.702  0  6.5278  9.1186  0  22.1742  18.2626  0
14.351  16.9418
june 10-16  week8  0  9.1186  14.351  10.414  31.2928  20.8534  29.9974
27.3812  15.6464  16.9418
june 17-23  week9  18.2626  7.8232  13.0302  19.5326  27.3812  46.9392
40.4622  31.2928  28.6766  19.558
june 24-30  week10  26.0604  0  26.0858  13.0302  18.2626  35.2044
20.8534  0  26.0858  14.351
july 1-7  week11  28.702  18.2626  26.0604  28.6766  26.0858  31.2928
29.972  36.4998  26.0604  24.7904
july 8-14  week12  15.6464  18.2626  13.0302  22.1488  23.4696  29.9974
24.7396  29.9974  13.0302  16.9672
july 15-21  week13  16.9418  14.351  14.351  19.558  26.0858  48.2346
32.5628  24.765  26.0604  20.8788
july 22-28  week14  29.9974  9.1186  14.351  28.6766  28.6766  28.6766
35.179  27.3812  28.702  26.0858
july 29-aug4  week15  14.351  7.8232  18.2626  14.351  0  19.558
16.9418  31.2928  22.1488  13.0556
aug 5-11  week16  27.4066  7.8232  23.4696  22.1996  26.0858  41.7068
29.972  27.3812  22.1742  24.7904
aug 12-18  week17  31.2928  14.351  23.4696  26.0858  26.0858  40.4114
35.179  26.0858  24.8412  26.0858
aug 19-5  week18  15.6464  0  11.7348  11.7348  14.351  28.6766
16.9418  0  13.0302  11.7348
aug 26-sept1  week19  43.0276  16.9418  0  14.351  24.765  16.9418
22.1488  35.2044  0  11.7602
sept 2-8  week20  41.7322  22.1742  22.1742  23.495  31.2928  33.909
40.4114  27.3812  20.8788  22.1996
;
run;

data rep4;
   block=4;
   drop j f1-f3;
   array farray{3} f1-f3 (7,1,2);
   input month $ day $ weekname $ @ ;
   week=substr(weekname,5);
   do trt=1 to 10;
```

```
        plot=trt;
        plot2=trt+30;
      if trt<5 then method="AC";
      else if trt<8 then method="ET";
      else method="Tim";
      if (trt=1) then frq=7;
      else do;
      j=mod(trt-1,3)+1;
      frq=farray{j};
      end;
      input wateruse @;
      output;
   end;
   cards;
april 22-28  week1  14.351  0  6.5278  11.7348  5.207  50.8508  65.2018
26.0858  26.0604  22.1996
april 29-may5  week2  26.0858  9.1186  26.0604  18.2626  27.3812
37.8206  36.4998  23.4696  27.3812  20.8788
may 6-12  week3  13.0302  9.1186  13.0556  26.0858  28.6766  31.2928
32.5882  27.3812  23.5204  19.5834
may 13-19  week4  0  0  0  3.9116  0  23.4696  26.0858  28.6766
15.6464  19.558
may 20-26  week5  39.116  27.3812  28.702  24.7904  28.6766  40.4368
40.386  27.3812  28.702  24.7904
may 27-june2  week6  28.6766  24.765  27.3812  24.7904  26.0858  44.323
44.3484  26.0858  27.3812  24.7904
june 3-9  week7  26.0604  0  7.8232  9.1186  0  18.2626  19.558  0
14.351  20.828
june 10-16  week8  0  10.4394  14.351  9.1186  28.6766  18.2626
32.6136  31.2928  14.351  16.9418
june 17-23  week9  18.2626  10.4394  15.6464  20.828  26.0858  44.3484
46.9138  29.9974  33.909  19.5326
june 24-30  week10  23.2156  0  28.6766  13.0302  18.2626  29.9974
31.2674  0  32.5882  16.9418
july 1-7  week11  27.3812  19.558  26.0604  26.0858  24.765  26.0858
33.909  27.3812  29.972  27.3812
july 8-14  week12  14.351  16.9418  13.0302  19.558  23.4696  22.1742
31.2928  23.4696  15.6464  18.2626
july 15-21  week13  15.6464  15.6464  16.9418  19.558  26.0858  43.0276
43.0276  22.1742  32.5882  23.4696
july 22-28  week14  27.3812  10.4394  13.0302  26.0858  26.0858
23.4696  45.593  26.0858  32.5882  24.7904
july 29-aug4  week15  13.0302  7.8232  16.9672  13.0556  0  19.558
23.4696  26.0858  24.8412  14.351
aug 5-11  week16  26.0604  7.8232  24.8412  19.6088  24.765  33.909
39.116  23.4696  28.702  22.1996
aug 12-18  week17  28.702  16.9418  26.0604  19.6088  24.765  33.909
52.1462  23.4696  31.2928  22.1996
aug 19-25  week18  14.351  0  11.7348  7.8486  14.351  20.8534  20.8788
0  18.2626  11.7348
aug 26-sept1  week19  41.7322  18.2626  0  15.6464  23.4696  15.6464
26.0858  24.765  0  13.0556
sept 2-8  week20  39.116  23.4696  22.1742  19.6088  29.9974  24.765
```

```
56.0832  20.8534  27.3812  19.6088
;
run;

data all4;
   set rep1 rep2 rep3 rep4;
   *d=(trt="d");
   week=1*week;
   if trt=1 then do; ac2=1; trt=999;end;
/* (code to make ac2 last alphabetically) */
   else ac2=0;
   *if week >6;
   *wateruse=log(wateruse+1);
run;

ods listing close;
ods csv file='C:\Documents and Settings\garry
grabow\Desktop\thesis\results4.csv';
proc mixed data=all4 method=type3;
   title "3 X 3 factorial plus AC2 treatment";
   class trt method frq week block plot ac2;
   *model wateruse=method|frq /outp=predz;  /* 3X3 analysis */
   model wateruse=ac2 method(ac2) frq(ac2) method*frq(ac2)/ddfm=kr
Residual VCIRY outp=residz outpm=scaled;  /* 3X3+1 analysis */
   *model wateruse=method|frq;
   *model wateruse=trt|week;  /* 3X3 analysis */
   *random block block*method*frq(ac2) week week*method*frq(ac2);
   random block week week*method*frq(ac2);
   *random block week;
   *random block block*trt;
   *repeated / subject=plot type=cs;
   lsmeans method(ac2) frq(ac2)/diffs;
   lsmeans method(ac2) frq(ac2)/adjust=tukey pdiff;*adjust and pdiff
added by glg;
   lsmeans method*frq(ac2)/slice=method pdiff;*pdiff added by glg;
   lsmeans method*frq(ac2)/slice=frq pdiff; *pdiff added by glg;
   ods output lsmeans=lsm;
run;
ods csv close;
ods listing;
symbol value=dot r=3;
proc gplot data=lsm;
   plot estimate*method=frq;
   plot estimate*frq=method;
run;

*symbol value=dot r=3;
proc gplot data=residz;
   plot resid*pred=method;
   plot resid*pred=frq;
   plot resid*pred=week;
 run;
data timeres;
```

```
merge residz;
run;
proc sort data=timeres;
by plot2;
run;
symbol i=join value=dot;
proc gplot;
 plot resid*week;
 by plot2;
 run;
proc arima data=timeres;
identify var=resid nlag=6;
by plot2;
run;
proc gchart;
   vbar resid;
run;
```

Appendix 3 Reference ET data from atmometer and Watchdog weather station

Day	atmometer (mm)	Weather Station(mm)	Day	atmometer (mm)	Weather Station (mm)
4/25/2007	4.57	5.08	6/6/2007	5.33	5.08
4/26/2007	2.03	4.83	6/7/2007	5.33	5.59
4/27/2007	4.32	4.32	6/9/2007	5.59	4.57
4/28/2007	1.27	4.83	6/10/2007	5.33	4.83
4/29/2007	4.83	4.83	6/11/2007	4.57	3.30
4/30/2007	5.08	5.33	6/12/2007	3.05	3.56
5/1/2007	6.60	6.10	6/13/2007	3.30	2.03
5/2/2007	7.37	6.10	6/14/2007	0.76	2.03
5/3/2007	2.54	2.54	6/15/2007	1.27	2.54
5/4/2007	0.51	1.02	6/16/2007	2.79	4.06
5/5/2007	0.25	1.78	6/17/2007	3.56	4.83
5/6/2007	0.76	5.08	6/18/2007	5.59	4.83
5/7/2007	3.81	5.59	6/19/2007	5.08	5.08
5/8/2007	4.06	2.79	6/20/2007	5.59	2.79
5/9/2007	1.52	3.05	6/21/2007	2.03	5.08
5/10/2007	1.52	4.06	6/22/2007	5.59	4.57
5/11/2007	1.02	5.08	6/23/2007	5.84	4.06
5/12/2007	4.57	2.54	6/24/2007	4.06	4.57
5/13/2007	1.52	3.05	6/25/2007	4.57	5.08
5/14/2007	2.29	4.57	6/26/2007	4.57	5.08
5/15/2007	0.51	5.59	6/27/2007	1.52	5.08
5/16/2007	4.57	5.33	6/28/2007	4.32	4.83
5/17/2007	4.32	3.30	6/29/2007	4.32	4.06
5/18/2007	2.03	4.06	6/30/2007	3.30	4.06
5/20/2007	4.32	5.08	7/1/2007	3.81	5.33
5/21/2007	5.84	4.57	7/2/2007	5.84	3.30
5/22/2007	5.84	4.57	7/3/2007	4.32	3.56
5/23/2007	4.32	5.08	7/4/2007	4.32	5.08
5/24/2007	5.08	5.08	7/5/2007	5.08	5.84
5/25/2007	4.83	5.33	7/6/2007	5.59	4.06
5/26/2007	5.08	5.59	7/7/2007	5.08	3.30
5/27/2007	5.59	5.84	7/8/2007	4.83	4.83
5/28/2007	5.59	5.84	7/9/2007	5.08	5.08
5/29/2007	5.59	5.08	7/10/2007	4.83	3.30
5/30/2007	5.08	5.33	7/11/2007	3.05	5.08
5/31/2007	5.59	5.33	7/12/2007	3.81	4.57
6/1/2007	5.59	5.59	7/13/2007	5.33	1.78
6/2/2007	5.59	3.30	7/14/2007	3.30	3.56
6/3/2007	2.79	2.54	7/15/2007	4.57	3.81
6/4/2007	0.76	6.10	7/16/2007	4.06	4.83
6/5/2007	5.84	5.08	7/17/2007	4.83	4.83

Day	atmometer	Weather Station
7/18/2007	4.83	3.30
7/19/2007	3.81	5.84
7/20/2007	5.84	2.79
7/21/2007	4.83	4.06
7/22/2007	5.08	4.32
7/24/2007	5.08	3.30
7/25/2007	4.32	4.06
7/26/2007	4.32	4.32
7/27/2007	5.08	4.06
7/28/2007	4.06	3.81
7/29/2007	3.05	4.32
7/30/2007	4.06	2.29
7/31/2007	2.54	4.32
8/1/2007	4.06	3.81
8/2/2007	5.59	4.57
8/3/2007	5.33	4.83
8/4/2007	4.83	4.06
8/5/2007	5.08	4.57
8/6/2007	5.84	4.06
8/7/2007	4.83	4.32
8/8/2007	6.10	5.33
8/9/2007	6.35	4.83
8/10/2007	6.60	4.57
8/11/2007	5.84	1.27
8/12/2007	1.78	4.83
8/13/2007	5.08	4.32
8/14/2007	6.10	5.08
8/15/2007	6.60	5.08
8/16/2007	5.33	5.84
8/17/2007	5.08	3.56
8/18/2007	3.81	4.57
8/19/2007	5.59	4.83
8/20/2007	4.57	5.84
8/21/2007	6.60	5.33
8/22/2007	6.10	3.05
8/23/2007	3.56	1.78
8/24/2007	2.79	4.57
8/25/2007	4.32	6.10
8/26/2007	5.59	3.81
8/27/2007	3.30	5.33
8/28/2007	3.56	6.35
8/29/2007	4.83	5.84
8/30/2007	4.32	4.06
8/31/2007	3.05	5.33
9/1/2007	4.57	5.33
9/2/2007	3.81	7.11
9/3/2007	5.08	6.10
9/4/2007	4.57	6.60
9/5/2007	5.33	7.11
9/6/2007	5.33	6.86
9/7/2007	4.83	5.33
9/9/2007	4.83	6.86
9/10/2007	5.08	4.57

Appendix 4 Weekly reference ET from atmometer, weather station and Hydropoint Data Systems (mm)

Week	atmometer (mm)	weather station (mm)	Hydropont Data Systems (mm)
1	28.448	34.036	48.768
2	23.114	27.686	45.974
3	18.034	28.194	35.814
4	21.082	30.226	39.116
5	36.576	35.306	43.18
6	35.814	36.322	39.116
7	33.528	34.544	44.45
8	19.304	22.352	37.846
9	33.782	31.242	44.45
10	26.416	32.766	46.228
11	35.052	30.48	42.672
12	29.972	28.194	37.338
13	33.274	29.464	42.672
14	30.734	28.194	41.148
15	31.496	28.194	39.878
16	37.338	28.956	44.958
17	37.592	33.274	44.45
18	33.528	31.496	41.402
19	27.432	36.068	34.798
20	34.29	45.466	38.354