

## **ABSTRACT**

NAUTIYAL, MAYANK. Residential Irrigation Water Use and Evaluation of Two Smart Irrigation Technologies in Cary, North Carolina. (Under the direction of Dr. Garry Grabow.)

Since 1950, the U.S. population has doubled and public demand for water has increased more than three fold. The occurrences of frequent drought conditions had made the reality of limited water resources more apparent. New home construction is the major contributor to the expansion of the turfgrass area. Increasing turfgrass area demands an increase in irrigation which places additional demand on already depleted water resources. Municipalities seek to conserve water to lessen costly system expansion due to growth, while homeowners, many of whom have invested significantly in landscaping, find themselves strained between rising water bills and keeping expensive landscape plants alive. Decreasing the amount of water applied by residential irrigation systems without causing negative effects on turfgrass quality is a challenge. A variety of technologies are available in the market that seeks to reduce irrigation water use. These technologies include rain sensors, and soil moisture sensor (SMS) based and evapotranspiration (ET) based controllers.

The first objective of the study was to quantify residential irrigation water use in Cary, North Carolina, and to develop distributions of monthly reference evapotranspiration ( $ET_o$ ) and gross irrigation requirements (GIR). The second objective was to determine the effectiveness of two “smart irrigation” technologies, i.e., SMS and ET systems based on the amount of irrigation applied and turf quality in residential settings.

This study was conducted in Cary, Wake County, North Carolina. In order to quantify the residential irrigation water use, outdoor irrigation system data from 2005, 2006 and 2007

was evaluated for 120 residential sites. Collected data included water consumption in gallons per month, landscape area, and type of irrigation zones i.e. spray, rotor or drip. For the 120 houses sampled, the average lawn area was 691 m<sup>2</sup>. The depth of water applied from May through October, ranged from 84% to 89% of the total water applied to the landscape. During the this period, the mean monthly irrigation depth applied ranged from 55.8 mm to 77.2 mm, 41 mm to 73.4 mm, and 46.1 mm to 83.6 mm for 2005, 2006 and 2007, respectively.

In the development of ET<sub>o</sub> and GIR, it was found that the method of solar radiation estimation proposed by Doorenbos and Pruitt was superior to the temperature differential method given by Hargreaves and Samani. Seasonal ET<sub>o</sub> ranged from on average from 141 mm in June to 67 mm in October.

Twenty-four sites were selected for evaluating the effectiveness of the two smart irrigation technologies, and divided into six geographical regions; each group within a region received four different treatments. The treatments were: SMS) an irrigation controller with a soil moisture sensor, ET) an evapotranspiration based controller, ED) a standard irrigation controller using seasonal runtimes based on historical climate data, and Control) irrigation controller with no intervention. Data was collected from May 2009 through September 2009. Maximum water savings were achieved by the SMS treatment followed by ET, ED, and Control treatments. According to visual turfgrass ratings, only the Control group was found to have turf quality below an acceptable level. The ED group had the best turf quality according to Normalized Difference Vegetation Index readings and visual ratings.

Residential Irrigation Water Use and Evaluation of Two Smart Irrigation Technologies in  
Cary, North Carolina

by  
Mayank Nautiyal

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APPROVED BY:

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Dr. Rodney L Huffman

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Dr. Grady L Miller

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Dr. Garry L Grabow  
Chairman of Advisory Committee

## **DEDICATION**

This work is entirely dedicated to my parents and brothers for all their sacrifices, never-ending support and encouragement during my educational endeavors and pursuit of life.

## **BIOGRAPHY**

Mayank Nautiyal was born in the city of Uttarkashi, Uttarakhand, India but grew up in Dehradun, Uttarakhand. He also has two elder brothers, Ambuj and Anuj. Mayank did most of his schooling in St. Thomas' College, Dehradun and after that attended G.B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand for his bachelor's in Agricultural Engineering. During his time as an undergraduate, he was an active squash player and served the University Squash team as a Captain in 2007-08. He continued his education at North Carolina State University by working towards his master's degree in Biological and Agricultural Engineering under the direction of Dr. Garry Grabow. This thesis completes the requirements for his master's degree.

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## TABLE OF CONTENTS

LIST OF TABLES .....	vii
LIST OF FIGURES .....	viii
INTRODUCTION .....	1
1.1 Background .....	1
1.2 Residential Irrigation Water Use.....	2
1.3 Reference Evapotranspiration and Gross Irrigation Requirement .....	4
1.4 Smart Irrigation Controllers .....	5
<i>1.4.1 Evapotranspiration-based Controllers.....</i>	<i>6</i>
<i>1.4.2 Soil-Moisture-Sensor-based Controllers.....</i>	<i>7</i>
1.5 Turfgrass Overview and Turfgrass Quality Assessment.....	8
1.6 Study Objectives .....	10
REFERENCES .....	12
RESIDENTIAL IRRIGATION WATER USE IN CARY, NORTH CAROLINA.....	19
2.1 Abstract .....	19
2.2 Introduction .....	20
2.3 Effective Rainfall .....	24
2.4 Reference Evapotranspiration .....	25
2.5 Crop Evapotranspiration .....	26
2.6 Gross Irrigation Requirement.....	27
2.7 Materials and Methods .....	28

2.7.1 Residential Irrigation Water Use .....	28
2.7.2 Reference Evapotranspiration and Gross Irrigation Requirement .....	30
2.7.2.1 Long-Term Weather Data .....	30
2.7.2.2 Solar Radiation Estimation .....	30
2.7.2.3 Reference Evapotranspiration and Gross Irrigation Requirement Estimation.	32
2.7.3 Statistical Analysis.....	33
2.8 Results and Discussion.....	33
2.8.1 Residential Irrigation Water Use .....	33
2.8.2 Reference Evapotranspiration and Gross Irrigation Requirement .....	35
2.8.2.1 Solar Radiation Estimation .....	35
2.8.2.2 Reference Evapotranspiration and Gross Irrigation Requirement Estimation.	35
REFERENCES .....	55
EVALUATION OF TWO SMART IRRIGATION TECHNOLOGIES IN CARY, NORTH	
CAROLINA.....	
3.1 Abstract .....	60
3.2 Introduction .....	61
3.3 Effective rainfall.....	62
3.4 Reference evapotranspiration .....	63
3.5 Gross irrigation requirement .....	65
3.6 Smart irrigation controllers .....	66
3.6.1 Evapotranspiration (ET)-based controllers.....	68

3.6.2 <i>Soil-moisture-sensor-based controllers</i> .....	69
3.7 Turfgrass overview .....	71
3.8 Materials and Methods .....	73
3.8.1 <i>Data collection</i> .....	76
3.8.2 <i>Statistical Analysis</i> .....	77
3.9 Results and Discussion.....	77
3.9.1 <i>Water use</i> .....	78
3.9.2 <i>Turfgrass quality</i> .....	79
3.10 Summary and Conclusions.....	79
REFERENCES .....	89

## LIST OF TABLES

Table	Page
Table 2.1 Pearson's correlation coefficient (r) between $S_1$ , $S_2$ and $S_3$ by month.....	47
Table 2.2 Mean of $ET_o$ and GIR for datasets A, B and C .....	51
Table 2.3 Median of $ET_o$ and GIR for datasets A, B and C .....	52
Table 2.4 80 <sup>th</sup> percentile of $ET_o$ and GIR for datasets A, B and C.....	53
Table 3.1 Average weekly water applied by treatment.....	87
Table 3.2 Average turf quality by treatment.....	88

## LIST OF FIGURES

Figure	Page
Figure 2.1 Geographical locations of Cary and weather stations used in the study (A, L and R represent Apex, Lake Wheeler Field Laboratory and Raleigh-Durham Weather station respectively).....	38
Figure 2.2 Distribution of lawn area (m <sup>2</sup> ) for homes included in this study (n = 120).....	39
Figure 2.3 Distribution of monthly applied water depth in 2005.....	40
Figure 2.4 Distribution of monthly applied water depth in 2006 .....	41
Figure 2.5 Distribution of monthly applied water depth in 2007.....	42
Figure 2.6 Mean applied water depth (mm) in 2005, 2006 and 2007.....	43
Figure 2.7 Mean applied water depth and gross irrigation requirement (mm) in 2005.....	43
Figure 2.8 Mean applied water depth and gross irrigation requirement (mm) in 2006.....	44
Figure 2.9 Mean applied water depth and gross irrigation requirement (mm) in 2007.....	44
Figure 2.10 Fit of computed solar radiation using Hargreaves method (S2) versus actual measured solar radiation (S1).....	45
Figure 2.11 Fit of computed solar radiation using percent sunshine (S3) versus actual measured solar radiation (S1).....	46
Figure 2.13 Distribution of average monthly ET <sub>o</sub> computed using dataset A.....	48
Figure 2.14 Distribution of average monthly GIR computed using dataset A.....	48
Figure 2.15 Distribution of average monthly ET <sub>o</sub> computed using dataset B.....	49
Figure 2.16 Distribution of average monthly GIR computed using dataset B.....	49

Figure 2.17 Distribution of average monthly $ET_o$ computed using dataset C.....	50
Figure 2.18 Distribution of average monthly GIR computed using dataset C.....	50
Figure 3.1 Map of site and weather station locations where A, L and R represent the Apex, Lake Wheeler and Raleigh-Durham Airport weather stations respectively.....	80
Figure 3.2 Precipitation and Crop evapotranspiration during the 20-week study period.....	81
Figure 3.3 Weekly mean water depth applied by the different treatments.....	82
Figure 3.4 Distribution of weekly applied water depth by ET treatment (n = 6).....	83
Figure 3.5 Distribution of weekly applied water depth by SMS treatment (n = 5).....	84
Figure 3.6 Distribution of weekly applied water depth by ED treatment (n = 5).....	85
Figure 3.7 Distribution of weekly applied water depth by Control treatment (n = 6).....	86
Figure 3.8 Mean monthly water applied by each treatment and the gross irrigation requirement for the period of study in 2009.....	87

## CHAPTER 1

### INTRODUCTION

#### 1.1 Background

Turfgrass is an integral part of a residential landscape in the United States. It not only increases the aesthetic beauty and property value of a home but also reduces runoff and soil erosion, and acts as biological filter by removing atmospheric pollution. There are approximately 163,800 km<sup>2</sup> of turfgrass in the continental United States which is nearly three times the area of any irrigated crop (Milesi et al., 2005). New home construction is a major contributor to the expansion of turfgrass area. Increasing turfgrass area demands an increase in irrigation thus causing a negative impact on already depleted water resources. According to an estimate by the Environmental Protection Agency (EPA, 2007), the U.S. population has doubled and public demand for water has increased more than three fold since 1950. Increasing population and recurring droughts has made water conservation an issue of concern. Outdoor water use comprises approximately 30% of the total residential water use in the U.S., the majority from watering lawns and gardens (EPA, 2007). There is a perception that water is free, but the reality is that treating and transporting water is very expensive. Municipalities seek to conserve water to lessen costly system expansion due to growth, and many have enacted ordinances aimed at reducing irrigation water use. Some water suppliers have adopted a tiered rate structure as a strategy to reduce water use, while homeowners, many of whom have invested significantly in landscaping, find themselves strained between rising water bills and keeping expensive landscape plants alive.

## **1.2 Residential Irrigation Water Use**

On average, household water use in the United States is 260 gallons per day while during peak water use periods demand may range from 1,000 gallons to 3,000 gallons per day (EPA, 2009). Peak water use usually occurs during July to August depending upon the region. Summer water use is typically two to four times that of winter. Nationwide, nearly 1.5 billion gallons of water is wasted from inefficient landscape irrigation (EPA, 2009). Depending upon the climate of a region, annual outdoor water use may vary from 22% to 67% of total water use. Households with a garden uses 30% more water outdoor than those without a garden (Mayer et al., 1999). Controllable factors like price, water restrictions, and rebate programs, and uncontrollable factors like climate and weather, and demographic characteristics, play an important role in residential water demand (Kenney, 2008).

In a typical residential setting, a landscape receives 30% to 40% more applied water than is required by the plants (Adhikari et al., 2006). Much of the over-irrigation occurs during the fall of the year when plant-water demand drops off but corresponding irrigation run times are not reduced accordingly.

Several studies have quantified residential water use and outdoor irrigation efficiency. A residential irrigation water use study conducted by Haley et al. (2007) in the Central Florida ridge region found that on average a typical residential landscape applies 149 mm/month of water. Barnes (1977) monitored lawn water application rates of individual homes in Laramie and Wheatland, Wyoming and found that residential irrigation rates ranged from 122% to 156% of seasonal evapotranspiration (ET) rates. Aurasteh et al. (1984)

measured irrigation water use, distribution uniformity, and application efficiency on 20 private lawns in Logan, Utah. It was found that in general, homeowners were unaware of the evapotranspiration requirements of their lawn grass and landscape vegetation, and did not measure the amount of water applied. Reported distribution uniformity (DU) for solid-set sprinkler systems was reported higher than for hand-move systems; however, the DUs were generally low compared to normal agricultural DU values, which indicated poor application efficiencies. Baum et al. (2005) conducted uniformity tests on residential irrigation systems, and found average low quarter distribution uniformity ( $DU_{lq}$ ) of 45. Rotary sprinklers had a statistically significantly higher  $DU_{lq}$  (49) than fixed pattern spray heads that had an average  $DU_{lq}$  of 41. Rotor heads also had more uniform distribution than spray head (55 compared to 49) when uniformity tests were performed under ideal conditions.

A steady increase in the number of residents using irrigation systems has been observed in North Carolina. Residences using irrigation systems increased by 29% between 1994 and 1999 (NCDA, 2001). In a study of five communities in North Carolina's Neuse River basin, Osmond and Hardy (2004) found that on an average 67% of the residents water during dry period while the frequency of watering varied from 0.5 to 7 times per week.

Typically, a residential in-ground automated irrigation system consists of stationary spray heads and gear driven rotor sprinklers for the turf and landscape. Microirrigation systems, commonly referred to as drip or low volume irrigation are often used for watering shrubs and herbaceous plants. In-ground sprinkler systems may be operated automatically or manually with a timer controller.

Programmable controllers make programming irrigation easy, but can lead to water waste since the controller turns on the system, irrespective of whether the plants need water. Timer-based irrigation scheduling typically applies the same amount of water at regular intervals which may result in over-irrigation. Survey results of 2,500 residential water users across the United States indicated more than half either made no changes to their watering schedule during the year or changed their scheduled watering run-times twice only in a twelve-month period (Addink and Rodda, 2002). Results of two different studies, conducted by Mayer et al., (1999) and Osmond and Hardy (2004) found that residents using automated irrigation systems apply nearly twice the amount of water than non-automated irrigation systems.

### **1.3 Reference Evapotranspiration and Gross Irrigation Requirement**

Evapotranspiration from a reference crop or surface is called reference evapotranspiration ( $ET_o$ ).  $ET_o$  has been defined as ET from a hypothetical crop with an assumed crop height of 0.12 m, a fixed surface resistance of  $70 \text{ s m}^{-1}$  and an albedo of 0.23 (Allen et al., 1998). This hypothetical reference surface closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground.  $ET_o$  values are used with crop coefficients ( $K_c$ ) for estimating crop evapotranspiration ( $ET_c$ ).

The net amount of irrigation water required to replace crop ET after accounting for effective rainfall (ER) is called the net irrigation requirement (NIR). The quantity of water to

be applied by the irrigation system is called gross irrigation requirement, GIR (Allen, 1997) and can be calculated as

$$\text{GIR} = \frac{\text{NIR}}{\text{Irrigation system uniformity}} \quad (1.1)$$

where, system irrigation uniformity is the measure of how evenly water is distributed by the irrigation system. Generally, DU (Water Requirements of North Carolina Turfgrasses, 2006) is used as a measure of system irrigation uniformity for the purpose of calculating GIR. The procedure to calculate can be found DU in Landscape Irrigation Scheduling and Water Management-DRAFT (IA, 2004).

A precise estimation of  $ET_o$  and GIR plays a very important role in scheduling of irrigation. Solar radiation and temperature account for at least 80% of the variation in  $ET_o$  (Samani, 2000). Solar radiation data is not widely available, so empirical methods have been derived for estimating it. Doorenbos and Pruitt (1977) suggested estimating solar radiation using percent sunshine data while a temperature difference method is given in Hargreaves and Samani (1982).

#### **1.4 Smart Irrigation Controllers**

Smart irrigation controllers are controllers that automatically update the watering schedule whenever there is change in plant water needs. Application of smart irrigation controllers in an automated irrigation system has become a trend in the turf industry (Castanon, 1992).

Depending on the type of information used, smart controllers can be classified into two categories - those that use weather information to estimate the amount of water required

by the turf and those that use information from a sensor monitoring the water content in the root zone.

#### *1.4.1 Evapotranspiration-based Controllers*

The concept of using weather-based information to schedule irrigations of turfgrass and other landscape plants is not new (Devitt et al., 2008), but transferring this technology to the homeowner is new. An Evapotranspiration (ET)-based controller uses weather information to estimate ET and accordingly adjust runtimes with changing weather conditions. Some controllers use historical data to compute the plant water requirements while some controllers use historical data to determine base watering time but then adjust runtime using an on-site temperature sensor. Another class of controllers either use off-site data communicated to them via internet, radio, or phone connection from a central provider, or use an on-site weather station.

According to a smart irrigation controller evaluation of single family dwellings in Irvine, California, an ET controller resulted in average single-family water savings of 37 gallons per day, representing a 7% reduction in total household use, or a 16% reduction in estimated outdoor use (Hunt et al., 2001). Aqua Conserve (2002) reported that in comparison to historic water usage, the weather-based Aqua Conserve controller provided individual residence water savings ranging from 7% to 25% for three study areas located in California. A study conducted in Colorado, that evaluated Hydropoint WeatherTRAK controllers, reported average water savings of 19% for 2001 and 21% for 2002 in comparison to historic outdoor water use (Aquacraft, 2003). Pittenger et al. (2004) evaluated four weather based

controllers using five hypothetical landscapes and one actual grass landscape at the Center for Landscape and Urban Horticulture in Riverside, California. The study found varying accuracy of irrigation schedules for different controllers and different landscapes. The Aqua Conserve controller was found to over-irrigate in most cases, the WeatherSet controller under-irrigated while the Hydropoint WeatherTRAK controller over-irrigated in some cases and under-irrigated in others. In a recently conducted study in Florida, the Weathermatic controller saved 43% while the Toro and ETwater controllers saved 59% and 50% compared to a historical net-irrigation based treatment (Davis et al., 2009).

#### *1.4.2 Soil-Moisture-Sensor-based Controllers*

Soil moisture sensors (SMS) have been extensively used primarily in agricultural applications and within the past several years they have shown promising results in residential settings (US Bureau of Reclamation, 2007). A SMS based controller uses soil moisture information for scheduling irrigation. In these systems, a soil-moisture-sensor is buried in an irrigation zone and connected to solenoid valve wiring. These systems can be a stand-alone system, comprising both an irrigation controller and sensor(s) or can be a sensor and add-on module that connects the soil moisture sensor to an existing irrigation controller through a user interface module mounted near the controller. The soil moisture sensor measures the amount of water in the soil and overrides the scheduled watering event by interrupting the irrigation controller circuit when the moisture level is above a user-set threshold.

Several studies have been conducted to evaluate SMS based systems. Allen (1997)

found that residential sites with soil moisture sensors applied 10% less water relative to the control sites in a study in Utah. In three different studies at University of Florida Agricultural and Biological Engineering facility in Gainesville, Florida, Cardenas-Lailhacar et al., (2005), Shedd et al. (2007), and Haley et al. (2007) reported water savings from 59% to 82%, 11% to 28%, and 51 % respectively. All the three studies compared water savings with time based irrigation clock.

A study conducted in Florida by McCready et al. (2009) found that in comparison to a no sensor treatment, the reductions in irrigation were 7-30% for rain sensor based treatments, 0–74% for soil moisture sensor treatments, and 25–62% for ET-based treatments.

A study conducted at the North Carolina State University Lake Wheeler Turf Field Laboratory, in Raleigh, North Carolina (Grabow et al., 2008) compared water applied and turf quality from an Intellisense TIS-240 series ET-based system, an “add-on” RS500 SMS system and a CS500 “on-demand” SMS based system to a standard time based irrigation schedule. Frequency of irrigation was also an experimental factor in the study. It was found that on average, the least amount of water was applied by the add-on soil-moisture-based system while the ET-based treatment applied the most water. Acceptable turf quality was maintained by all the treatments and frequencies when averaged over the three year study.

### **1.5 Turfgrass Overview and Turfgrass Quality Assessment**

Selection of an appropriate type of turfgrass and landscape plants can play an important role in water conservation. Based on climatic adaptation, turfgrasses may be classified into two groups: warm-season grasses, adapted to tropical and subtropical areas,

and cool-season grasses that are adapted to temperate and sub-arctic climates (Huang, 2006). Tall fescue, Kentucky bluegrass, fine fescue, and perennial ryegrass are popular cool-season lawn grasses that stay reasonably green in the winter while the most common warm-season turfgrasses used for lawns are bermudagrass, zoysiagrass, St. Augustinegrass, centipedegrass and bahiagrass (Bruneau et al., 2008). Crop evapotranspiration ( $ET_c$ ) rates for warm season grasses are comparatively lower than cool-season grasses (Romero, 2009).

North Carolina ranks eighth in turfgrass acreage nationally. Approximately, 2,007,100 acres of land is devoted to turfgrasses in North Carolina, and single family dwellings account for 61% of the total area in turf (Brandenburg, 2004). Both cool-season and warm-season grasses are grown in North Carolina. Cool-season perennial grasses are mostly grown in the mountain and piedmont regions of North Carolina (Bruneau et al., 2008). Depending upon location, cool-season grasses are best seeded from mid-August to mid-October. All warm season grasses except bahiagrass are recommended for lawns in the piedmont and coastal plain of North Carolina. Summer is the best period for the growth of these grasses while they go dormant during winters and then green up slowly in the spring (Carolina Lawns, 2009). Tall fescue is the most common turf specie grown in home lawns, accounting for 37% (742,600 acres) of the total turf acreage, followed by bermudagrass representing 12.3% (247,873 acres) of the turf acreage in North Carolina (NCDA, 2004).

The functional and aesthetic aspects of turfgrass are important in turfgrass quality evaluation. Turfgrass quality rating varies with turfgrass species, intensity of management and time of year (Morris, 2009). There are various methods of evaluating turfgrass quality.

Among all, visual rating is the most common; however, it is a subjective method of evaluation varying from person to person. Typically, visual observations of color, texture, uniformity and density aid in evaluating the turfgrass quality. The visual turf quality rating is based on a scale of 1 to 9 where 9 is considered outstanding or ideal turf and 1 is poorest or dead. A rating of 6 or above is generally considered acceptable (Morris and Shearman, 1998).

Turfgrass quality can also be measured using a Normalized Difference Vegetation Index (NDVI), which is a normalized ratio of near-infrared reflectance to red reflectance. The NDVI value is obtained with the use of a measured consistent internal light source, which ranges from 0 to 1 (Spectrum Technologies, Inc., 2009). NDVI provides a quantitative method for evaluating turfgrass quality and limits variability in turfgrass quality evaluation due to human perception.

## **1.6 Study Objectives**

This study had two main objectives. The first objective of the study was to quantify residential irrigation water use in Cary, North Carolina. The second objective was to determine the effectiveness of two smart irrigation technologies, i.e., a SMS system and an ET system based on the amount of irrigation applied and turf quality in residential settings. A sub-objective was to develop distributions of monthly  $ET_0$  and GIR using long-term weather data. As part of sub-objective, an investigation was performed to compare daily measured solar radiation with empirically estimated solar radiation. The goal was to evaluate the

accuracy of the two empirical methods of estimating solar radiation and to compute  $ET_0$  and GIR in the Raleigh-Durham region using measured and estimated solar radiation.

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## CHAPTER 2

### RESIDENTIAL IRRIGATION WATER USE IN CARY, NORTH CAROLINA

#### 2.1 Abstract

Irrigation is the most common and standard practice for maintaining turfgrass and landscape plants in residential settings. Several studies have quantified residential water use and outdoor irrigation efficiency. Depending upon the climate of a region, residential outdoor water use varies from 22% to 67% of the total water use of a household. In a typical residential setting, a landscape receives 30% to 40% more applied water than is required by the plants. The main objective of this study was to quantify the residential irrigation water use in Cary, North Carolina. A sub-objective was to develop distributions of monthly reference evapotranspiration ( $ET_o$ ) and gross irrigation requirements (GIR) using long-term weather data. As part of the sub-objective, an investigation was performed to compare daily measured solar radiation with empirically estimated solar radiation. The goal of this investigation was to evaluate the accuracy of the two empirical methods of estimating solar radiation and to compute  $ET_o$  and GIR in the Raleigh-Durham region using measured and estimated solar radiation.

One hundred and twenty lawns were randomly sampled and irrigation water use evaluated. Solar radiation was computed using two different methods; one based on temperature difference given by Hargreaves and Samani (1982), and another based on percent sunshine given by Doorenbos and Pruitt (1977).

The average lawn area of the sampled residences was 691m<sup>2</sup>. None of the households sampled used drip irrigation. A negative correlation existed between the irrigated area and applied water depth. The period May through October accounted for 84 – 89 percent of the total annual outdoor water use. A trend of applying more water than the gross irrigation requirement was observed during the lawn over-seeding period (mid-September through late October).

Solar radiation estimated using percent sunshine data method (Doorenbos and Pruitt, 1977) showed a strong relationship ( $R^2 = 0.88$ ) with measured solar radiation, and proved to be a much more reliable way of estimating solar radiation than Hargreaves and Samani method (1982) in the Raleigh-Durham region. Estimates of mean, median and P<sub>80</sub> (80<sup>th</sup> percentile) of monthly ET<sub>o</sub> obtained using a dataset based on Hargreaves and Samani method were higher than those obtained by using datasets based on measured solar radiation, or the Doorenbos and Pruitt method.

## **2.2 Introduction**

Water wastage is a growing concern for many countries including the United States. There are numerous municipalities that have initiated various regulations to conserve their water supply. In some areas, violation of these regulations can result in very heavy fines. According to the Town of Cary (TOC) Department of Public Works and Utilities (DPWU) (1998) violation of Town's "Waste Water" ordinance (Chapter 36 / Article 3, Sec.36-83) may result in a fine ranging from \$100 - \$500. There is a perception that water is free, but the reality is that treating and transporting water is very expensive. Municipalities seek to

conserve water to lessen costly system expansion due to growth, and many have enacted ordinances aimed at reducing irrigation water use. Some water suppliers have adopted a tiered rate structure as a strategy to reduce water use, while homeowners, many of whom have invested significantly in landscaping, find themselves strained between rising water bills and keeping expensive landscape plants alive.

Irrigation is the most common and standard practice for maintaining turfgrass and landscape plants in residential settings. Depending upon the climate of a region, residential outdoor water use varies from 22% to 67% of the total household water use (Mayer et al., 1999). In a typical residential setting, a landscape receives 30% to 40% more applied water than is required by the plants (Adhikari et al., 2006). Much of the over-irrigation occurs during the fall of the year when plant water demand drops off but corresponding irrigation run times are not reduced accordingly.

In an irrigation water use study, Mayer et al. (1999) found that 10% of the 1,188 homes in the study were responsible for 58% of the leaks found. Irrigation water consumption was lowest in the winter months (December through March), as would be expected due to reduced plant water needs.

In a study of five communities in North Carolina's Neuse River basin, Osmond and Hardy (2004) found that on an average 67% of the residents water during dry periods. The frequency of watering was 0.5 to 7 times per week and the range in watering duration varied from 5 to 300 minutes. It was also reported that in Cary, NC, homeowners with a fixed

irrigation system applied nearly twice the amount of water than those who irrigated with movable sprinklers.

In Florida, Baum et al. (2005) found that homeowners typically used an average of 146 mm of water per month for irrigation. According to NC guidelines for turfgrass irrigation (Bruneau et al., 2000), in the absence of rain, 25 mm of irrigation per week should be adequate to maintain turf although turfgrass water use can exceed that amount during peak demand periods and be less during cool, cloudy periods. Henceforth, new guidelines were provided by Bruneau et al. (2006) that showed turfgrass water demand ranging from 18 mm to 48 mm per week for the Central Piedmont of North Carolina.

Typically, a residential in-ground automated irrigation system consists of stationary spray heads and gear driven rotor sprinklers for turf and landscape. Microirrigation commonly referred to as drip or low volume irrigation, is normally used for watering shrubs and herbaceous plants. In a study funded by the American Water Works association (AWWRA), Mayer et al. (1999) found that average automated, in-ground irrigation systems use 47% more water than non-automated, above ground systems. It was also reported that households with only drip irrigation systems use 16% more water than those without a drip irrigation system and households with garden, use 30% more water for outdoor use than those without any garden.

Cary is the second most populous municipality in Wake County to Raleigh. The town's population was 94,536 at the 2000 census but according to the town's statistics, the population had grown to 137,483 by October 2009, a 45.4% increase since 2000. This

population growth made Cary the seventh largest municipality statewide. Cary was also marked as the 5th fastest growing municipality in the country between July 1, 2006, and July 1, 2007 (U.S. Census Bureau, 2008).

According to North Carolina's drought bill legislation (Session Law 2008-143) all local government and large community water systems require installation of separate meters for new in-ground irrigation systems that are connected to their systems. Under an Integrated Water Resources Management Plan (IWRMP), the Town of Cary conducted a survey and analysis of the water system profiles of their customers in Cary and Morrisville. Billing data from 2001 to 2005, geographic information system (GIS) parcel mapping, and other available customer data revealed that for single-family residential customers with separately-metered irrigation, approximately 42 percent of water use in Cary and 28 percent of water use in Morrisville was for irrigation. Residential accounts with separate irrigation meters demonstrated significantly higher daily water use ( $1.32 \text{ m}^3$  per day/account) than accounts without separately metered irrigation ( $0.80 \text{ m}^3$  per day/account). It was also reported that homes constructed after 1995 use more water on an average basis than older homes, due to more outdoor use ( $0.19 \text{ m}^3$  per capita per day versus  $0.06 \text{ m}^3$  per capita per day outdoor usage). In the Cary service area, houses with a tax value between \$200,000 and \$500,00 and lot sizes between 0.5 and 1 acre, accounted for the greatest growth in separately-metered irrigation accounts.

Whenever climatic variables like temperature and rainfall depart from normal values, both seasonal water demand and production is affected. According to the Town of Cary's

DPWU (2005) report, a one-degree increase above the average monthly temperature will cause a 492 m<sup>3</sup> per day and 3.8 m<sup>3</sup> per day increase in daily water production for Cary and Morrisville respectively. For Cary, a one-inch increase above the normal monthly rainfall will cause a 416 m<sup>3</sup> per day decrease in daily water production. In order to prevent irrigation during a rainfall event, Town Ordinance 19-48 (DPWU, 1997) requires a rain sensor to be installed on all new and existing residential and commercial irrigation systems. It also requires that the rain sensor must be set to shut off the system when 6 mm of rainfall has occurred.

### 2.3 Effective Rainfall

Effective rainfall (ER) is the portion of total rainfall that is available to plants to help meet their consumptive water requirements, and is an important component of water resource budgeting for irrigation (Obreza and Pitts, 2002). According to the NRCS (formerly SCS) TR21 (USDA, 1970) method, effective rainfall is estimated as:

$$ER = SF \times \left[ 0.70917 \times \left( \frac{P_m}{25.4} \right)^{0.82416} - 0.11556 \right] \times 10^{0.000955 ET_c} \quad (2.1)$$

where,

- ER = Effective Rainfall, mm
- SF = Soil water storage factor
- P<sub>m</sub> = Average monthly precipitation, mm
- ET<sub>c</sub> = Crop evapotranspiration, mm

The Soil water storage factor (SF) is given in TR-21 as:

$$SF = 0.531747 + 0.295164 \left( \frac{D}{25.4} \right) - 0.057697 \left( \frac{D}{25.4} \right)^2 - 0.003804 \left( \frac{D}{25.4} \right)^3 \quad (2.2)$$

where,

D = usable soil water storage which is fraction of the available water holding capacity of the soil within the root zone, mm

## **2.4 Reference Evapotranspiration**

Evapotranspiration (ET) is the combination of two separate processes, whereby, water is lost from the soil surface by evaporation and from the crop by transpiration. During the process of evaporation, liquid water is converted to water vapour and removed from the evaporating surface. Water evaporates from a variety of surfaces, such as lakes, rivers, pavement, soil and vegetation like turfgrass. The process of transpiration is similar to evaporation but in this case the water is lost through the stomata of the leaf. The principal weather parameters that affect evapotranspiration are solar radiation, air temperature, humidity and wind speed.

Reference evapotranspiration ( $ET_0$ ) is defined as "the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of  $70 \text{ sec m}^{-1}$  and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground" (Allen et al., 1998). Several climatologically based empirical equations have been developed for computing reference evapotranspiration. The applicability of these equations varies depending on the availability of data of various weather parameters. The Penmen-Monteith equation is the standard method (Allen, 2001) for computing  $ET_0$  and is given by:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1+0.34u_2)} \quad (2.3)$$

where,

- $ET_o$  = reference evapotranspiration, mm day<sup>-1</sup>  
 $R_n$  = net radiation at the crop surface, MJ m<sup>-2</sup> day<sup>-1</sup>  
 $G$  = soil heat flux density, MJ m<sup>-2</sup> day<sup>-1</sup>  
 $T$  = mean daily air temperature at 2 m height, °C  
 $u_2$  = wind speed at 2 m height, m s<sup>-1</sup>  
 $e_s$  = saturation vapor pressure at mean daily air temperature, kPa  
 $e_a$  = actual vapor pressure, kPa  
 $e_s - e_a$  = saturation vapor pressure deficit, kPa  
 $\Delta$  = slope of the saturation vapor pressure curve at mean air temperature, kPa °C<sup>-1</sup>  
 $\gamma$  = psychrometric constant, kPa °C<sup>-1</sup>

## 2.5 Crop Evapotranspiration

Crop evapotranspiration ( $ET_c$ ) refers to the amount of water that is lost through evapotranspiration and is computed by multiplying  $ET_o$  by a crop coefficient,  $K_c$  (Allen et al., 1998).

$$ET_c = K_c \times ET_o \quad (2.4)$$

Factors like crop type, climate, soil evaporation, and crop growth stages play a major role in determining  $K_c$  value. The California Department of Water Resources (CDWR) has suggested a crop coefficient of 0.8 for cool season grasses (CDWR, 2000).

## 2.6 Gross Irrigation Requirement

The net amount of irrigation water required to replace crop ET after accounting for effective rainfall (ER) is called net irrigation requirement (NIR) and is calculated by the formula:

$$\text{NIR} = \text{ET}_c - \text{ER} \quad (2.5)$$

After accounting for system irrigation uniformity, the quantity of water to be applied by the irrigation system is called the gross irrigation requirement, GIR (Allen, 1997) and is calculated as:

$$\text{GIR} = \frac{\text{NIR}}{\text{System Irrigation Uniformity}} \quad (2.6)$$

where, system irrigation uniformity is the measure of how evenly water is distributed by the irrigation system. It determines the effectiveness with which the irrigation system extracts water from a water supply source and applies it to produce the target crop. Generally, DU (Water Requirements of North Carolina Turfgrasses, 2006) is used as a measure of system irrigation uniformity for the purpose of calculating GIR. The procedure to calculate can be found DU in Landscape Irrigation Scheduling and Water Management—DRAFT (IA, 2004).

An accurate estimation of  $\text{ET}_o$  and GIR plays a very important role in scheduling of irrigation. Direct measurement of  $\text{ET}_o$  is costly and time consuming (Irmak et al., 2003) and thus the most common procedure for  $\text{ET}_o$  estimation is using climatic variables like solar radiation, air temperature, wind speed, and relative humidity with an equation. The Penman-

Monteith equation (FAO-56 PM) is the most widely recommended and standard method for computing  $ET_o$  (Allen et al., 1998). Often, the number of climatological variables monitored at a weather station can be limited. Solar radiation and temperature account for at least 80% of the variation in  $ET_o$  (Samani, 2000). Doorenbos and Pruitt (1977) suggested a method of computing solar radiation using percent sunshine data while a temperature difference method is given in Hargreaves and Samani (1982).

The main objective of this study was to quantify the residential irrigation water use in Cary, North Carolina. A sub-objective was to develop distribution of monthly  $ET_o$  and Gross Irrigation Requirement (GIR) using long-term weather data. In order to meet the sub-objective, an investigation was performed to compare daily measured solar radiation with empirically estimated solar radiation. This allowed us to evaluate the accuracy of the two empirical methods of estimating solar radiation and to compute  $ET_o$  and GIR in the Raleigh-Durham region using measured and estimated solar radiation.

## **2.7 Materials and Methods**

### *2.7.1 Residential Irrigation Water Use*

This study was conducted in Cary, Wake County, North Carolina (Figure 2.1). In order to quantify the residential water use, a random sample of 120 residential sites was selected and irrigation data were collected for the years 2005, 2006, and 2007. Data included water consumption, landscape area, and type of irrigation zones, i.e., spray, rotor, or drip. The residential sites included in this analysis are supplied with water from the Town of Cary and have automatic in-ground irrigation system with separate irrigation meters.

Irrigation water demand for the years 2005 through 2007 was estimated using weather data from two local weather stations and the FAO-56 Penman-Monteith equation (Allen et al., 1998). Daily temperature, relative humidity, solar radiation and wind speed data were collected from the Lake Wheeler Road Field Lab weather station (35°43'41" N,-78°40'47" W) while daily precipitation data was obtained from the Apex weather station (Station ID: 310212) (35°74'25"N, -78°83'69"W) due to closer proximity to the residential sites and 100% availability of rainfall data. REF-ET (Allen, 1998), a compiled, stand-alone computer program, was used to compute reference  $ET_o$ . REF-ET provides calculations that are compatible with United Nations Food and Agriculture Organization (FAO) Irrigation Paper No. 56 (Allen et al., 1998) and with standardized forms of the ASCE Penman-Monteith equation recommended in 2000 by the ASCE Task Committee on Standardized Evapotranspiration Calculations (Allen, 2001).

Monthly effective rainfall (ER) was estimated by the NRCS TR-21 (USDA, 1970) method. The Soil storage factor was computed by setting D equal to 0.66 times (Obreza, 2002) the available water holding capacity (AWHC) of the turf root zone while the AWHC was assumed to be 17 mm/m. AWCH is the amount of water (mm) held per m of soil.

Monthly gross irrigation requirements were generated from reference ET estimates, cool-season turf crop coefficients, effective rainfall data and standard irrigation uniformity estimates. A turf crop coefficient of 0.8 (Allen et al., 1998) and system irrigation uniformity (DU) of 80% (Water Requirements of North Carolina Turfgrasses, 2006) was used in this study.

## 2.7.2 Reference Evapotranspiration and Gross Irrigation Requirement

### 2.7.2.1 Long-Term Weather Data

Long-term daily measured weather data was obtained from two different weather stations, i.e., Lake Wheeler Road Field Lab and KRDU-Raleigh-Durham Airport (35°52'40" N, -78°47'15" W) which are located 19.17 km apart. The two stations are referred as L (Lake Wheeler Road Field Lab) and R (Raleigh-Durham Airport) in this study. The State Climate Office (SCO) of North Carolina maintains station L and R is maintained by the National Weather Service (NWS). The climate of the location under study is semi-humid with an average annual rainfall of 1,178 mm (SCO, 2010). Daily mean temperature ranges from 5.0°C to 25.6°C during summers and 5.9°C to 10.2°C during winters (NCDC, 1997)

### 2.7.2.2 Solar Radiation Estimation

Daily minimum and maximum temperature (January 1984 – May 2009) and daily percent sunshine (January 1984 – January 1996) data were obtained for R weather station while daily measured solar radiation data ( $S_1$ ) (January 1984 – May 2009) was obtained for L. Station L had missing data for January, February and September in 1990 and January 1993 through September 2001.

Solar radiation was computed using two different methods; ( $S_2$ ) based on daily temperature difference given by Hargreaves and Samani (1982) and ( $S_3$ ) based on percent sunshine given by Doorenbos and Pruitt (1977). Hargreaves and Samani's temperature difference method for estimating solar radiation ( $S_2$ ) is given by:

$$R_s = K_r (T_{max} - T_{min})^{0.5} R_a \quad (2.7)$$

where,

- $R_s$  = solar radiation,  $\text{MJ m}^{-2} \text{d}^{-1}$   
 $K_r$  = empirical coefficient,  
 $T_{\max}$  = daily maximum temperature,  $^{\circ}\text{C}$   
 $T_{\min}$  = daily minimum temperature,  $^{\circ}\text{C}$   
 $R_a$  = extraterrestrial radiation,  $\text{MJ m}^{-2} \text{d}^{-1}$

The empirical coefficient ( $K_r$ ) was set to 0.16 for interior region (Hargreaves, 1994).

According to Doorenbos and Pruitt (1977), solar radiation can be estimated using the formula given below ( $S_3$ ):

$$R_s = \left(0.25 + 0.5 \frac{n}{N}\right) R_a \quad (2.8)$$

where,

- $R_s$  = solar radiation,  $\text{MJ m}^{-2} \text{d}^{-1}$ ,  
 $n/N$  = ratio of actual possible bright sunshine hours and maximum possible sunshine hours  
 $R_a$  = extraterrestrial radiation,  $\text{MJ m}^{-2} \text{d}^{-1}$

In both equations 2.7 and 2.8,  $R_a$  is computed using equations given below:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin(\varphi) \sin(\delta) + \sin(\omega_s) \cos(\varphi) \cos(\delta)] \quad (2.9)$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{265} J - 1.39\right) \quad (2.10)$$

$$\omega_s = \pi/2 - (\arctan(-\tan\varphi \tan\delta)) \quad (2.11)$$

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{265} J\right) \quad (2.12)$$

$$J = Day - 32 + Int\left(\frac{275Month}{9}\right) + 2Int\left(\frac{3}{Month+1}\right) + Int\left(\frac{Month}{100}\right) - \frac{Mod(Year,4)}{4} + 0.975 \quad (2.13)$$

where,

$G_{sc}$  = solar constant,  $4.92 \text{ MJ m}^{-2} \text{ h}^{-1}$

$d_r$  = inverse relative distance Earth-Sun

$\omega_s$  = sunset hour angle, rad

$\delta$  = solar declination, rad

$\phi$  = latitude, rad

$J$  = Julian day

### 2.7.2.3 Reference Evapotranspiration and Gross Irrigation Requirement Estimation

Using three different values of solar radiation, three replicate weather datasets (A, B, C) were prepared for R weather station. All three datasets had common variables i.e., maximum and minimum temperature, wind speed, solar radiation, and relative humidity. Measured solar radiation at L was used in dataset A (January 1984 – May 2009) while solar radiation computed using the Hargreaves and Samani method, and Doorenbos and Pruitt method in dataset B (January 1984 – May 2009) and C (January 1984 – January 1996) respectively. Dataset A had missing solar radiation data for January, February and September in 1990 and January 1993 through September 2001 Dataset A, B and C were individually used to compute monthly  $ET_o$ , NIR and GIR for all available months. RefET was used for computing  $ET_o$ . Monthly effective rainfall (ER) was estimated by the NRCS TR-21 method. Monthly gross irrigation requirements were generated from reference ET estimates, turf crop

coefficients, effective rainfall data and run-time adjustment estimates. Here run-time corresponds to inverse of irrigation system uniformity. A turf crop coefficient of 0.8 (Allen et al., 1998) and run time adjustment of 1.25 (Water Requirements of North Carolina Turfgrasses, 2006) was used to calculate distributional plots of monthly  $ET_o$  and GIR. Run time adjustment is equal to the inverse of system irrigation uniformity.

### *2.7.3 Statistical Analysis*

Data analysis was performed using Statistical Analysis System (SAS Institute Inc., Cary). The landscape irrigated area was used to convert volume of water applied to depth applied. Pearson's correlation coefficient was used to determine the correlation between depth of water applied and lawn size area. Boxplots were developed using the average monthly irrigation water consumption to obtain the general trend and variation of water application by homeowners. The PROC REG (SAS, 1987) procedure was used to perform regression on solar radiation in the three datasets i.e. A, B and C, while PROC CORR (SAS, 1988a) was used to determine the Pearson's correlation coefficient between  $S_1$ ,  $S_2$  and  $S_3$ .

## **2.8 Results and Discussion**

### *2.8.1 Residential Irrigation Water Use*

The average lawn area was 691 m<sup>2</sup> for the 120 houses sampled. Figure 2.2 shows the distribution of lawn area. None of the residential sites sampled had drip irrigation.

The depth of water applied during the period May through October, ranged from 84% to 89% of the total water applied. During this period, the mean monthly irrigation depth applied ranged from 56 mm to 77 mm, 41 mm to 73 mm, and 46 mm to 84 mm for 2005,

2006 and 2007 respectively (Figure 2.3-2.5). In 2005, two homeowners applied 350 mm or more water in a month.

Correlation analysis showed a negative correlation between the irrigated area and the irrigation application depth ( $r = -0.18$ ) which can be explained by the increasing block rate structure used by TOC in its water utility bills (NCDENR, 2004). According to increasing block rate structure more water the consumers use above a specified threshold, the greater is the cost of each unit.

Average monthly irrigation water depths applied and average monthly gross irrigation requirements for 2005, 2006 and 2007 are shown in Figure 2.7-2.9. June 2006 was a wet month and the gross irrigation requirement was zero, while on average approximately 50 mm of irrigation depth was applied by sampled homeowners (Figure 2.8). May through September period of 2007 was warmer and drier than the same period in 2005 and 2006 (NCDENR, 2007). Thus, a relatively high gross irrigation requirement is observed in 2007 (Figure 2.9). A spike in gross irrigation requirement (Figure 2.9) is seen in August and September of 2007. Wake County was declared to be under severe to extreme drought conditions in August and September by NCDENR's Division of Water Resources (2007).

Figure 2.7 and 2.8 show that in 2005 and 2006, the applied water depth surpassed the gross irrigation depth in September and October. Cool-season turfgrasses are normally overseeded and aerated from September to early October (Bruneau et al., 2000). For the seeds to germinate they must be kept moist which encourages homeowners to increase water usage. In 2007, the applied water depth remains below the gross irrigation requirement even during the

over-seeding period (Figure 2.9). The TOC (2007) introduced a ban on outdoor watering using irrigation systems, sprinklers, or other automated watering devices after October. Even the issuance of three-week exemption to the year-round watering rules for establishing new grass or reseeding was discontinued, however, hand watering was allowed any day of the week (TOC, 2007). The restriction on outdoor irrigation was removed 1<sup>st</sup> April, 2008.

## *2.8.2 Reference Evapotranspiration and Gross Irrigation Requirement*

### *2.8.2.1 Solar Radiation Estimation*

The regression relationships of  $S_2$  vs  $S_1$ ,  $S_3$  vs  $S_1$  and  $S_3$  vs  $S_2$  were all significant ( $p < 0.0001$ ). The coefficient of determination,  $R^2$ , was strongest between  $S_1$  and  $S_3$  ( $R^2 = 0.88$ ) while a  $R^2$  of 0.70 existed between  $S_2$  vs  $S_1$ . Regression fits among  $S_1$ ,  $S_2$  and  $S_3$  are shown in Figures 2.10 and 2.11. Table 2.1 gives Pearson's correlation coefficient ( $r$ ) between daily values of  $S_1$ ,  $S_2$  and  $S_3$  by month. Correlation of  $S_1$  with  $S_2$  tends to decrease as the winter months approach. A similar trend was observed in the correlation between  $S_2$  and  $S_3$ . A reverse trend in correlation is observed between  $S_1$  and  $S_3$ , the correlation table showing lower correlation during summer months and greater correlation during winters.

### *2.8.2.2 Reference Evapotranspiration and Gross Irrigation Requirement Estimation*

Distributional plots of monthly  $ET_o$  and GIR, computed using Dataset A, B and C are presented in Figures 2.12-2.17. The mean, median and 80<sup>th</sup> percentile ( $P_{80}$ ) of monthly  $ET_o$  and GIR for datasets A, B and C are shown in Table 2.2, 2.3 and 2.4 respectively. Comparison of Figure 2.12 with Figure 2.14 and 2.16 suggests that monthly  $ET_o$  computed using dataset B does not capture the variability in  $ET_o$ . Mean, median and  $P_{80}$  monthly  $ET_o$

estimated using dataset B (solar radiation estimated by the Hargreaves and Samani method) are higher than those obtained by datasets A (measured solar radiation) and C (solar radiation estimated by the Doorenbos and Pruitt method). The difference between these estimates tends to increase during summer months and decrease in winter.

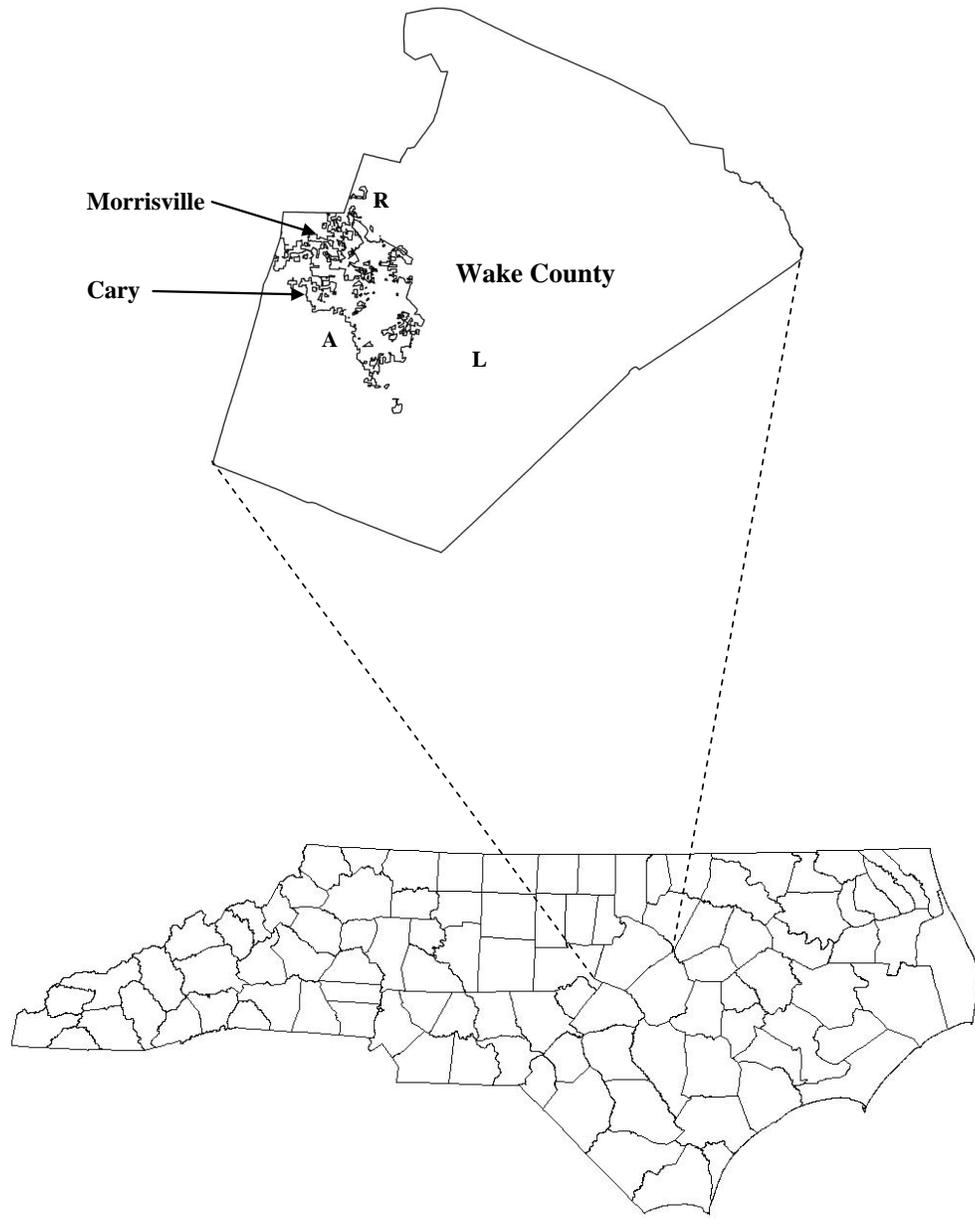
## **2.9 Summary and Conclusions**

The average lawn area of the 120 sampled residences was 691m<sup>2</sup>. None of the households sampled used drip irrigation. A negative correlation existed between irrigated area and applied water depth. A general trend throughout the irrigation season of a gradual rise, plateau and gradual decline in irrigation water usage was observed. The irrigation period (May through October) accounted for 84 to 89 percent of the total annual irrigation water use. Little outdoor irrigation was observed in winter since plant water requirements are low during this period.

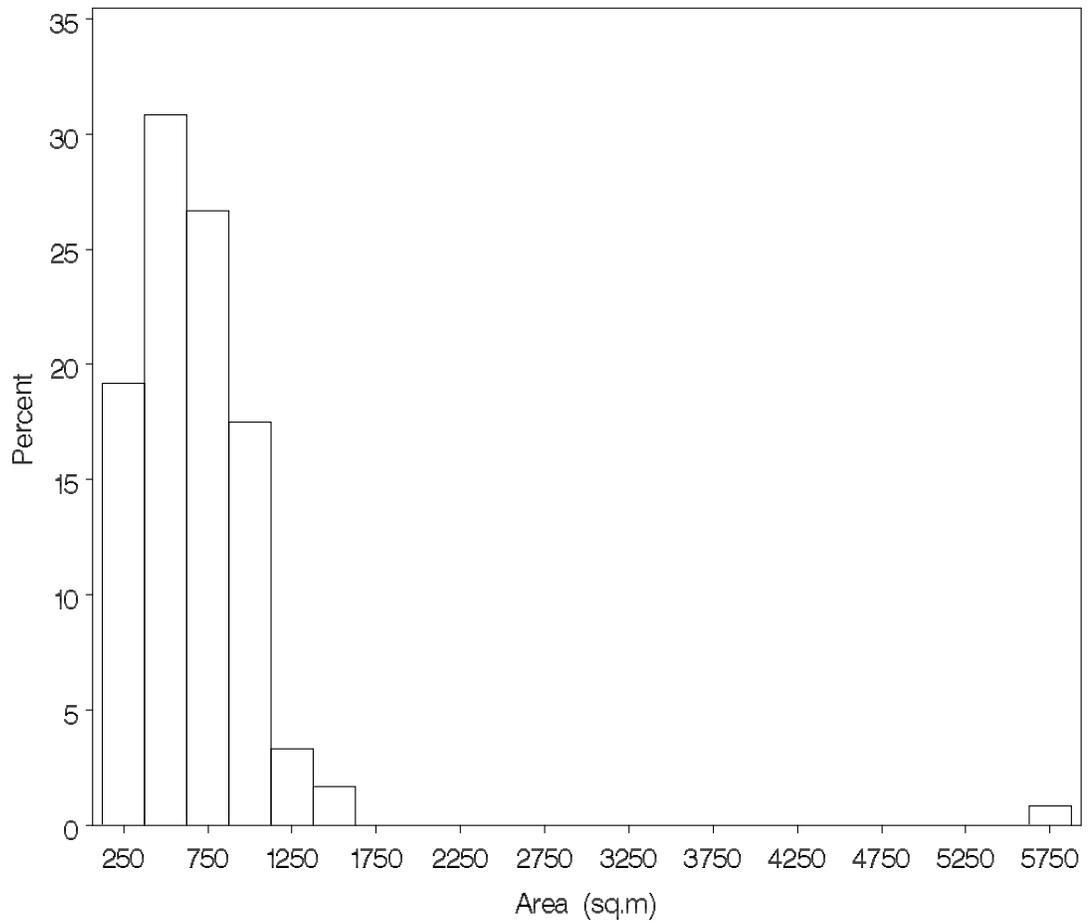
A usual trend of applying more water than the gross irrigation requirement was observed during the lawn over-seeding period (mid September through October) except in 2007 due to a complete ban (except hand watering) on outdoor irrigation that was introduced by the Town of Cary in October.

Solar radiation computed using percent sunshine data showed a closer relationship ( $R^2 = 0.88$ ) with measured solar radiation than solar radiation computed using the Hargreaves and Samani method. A coefficient of determination of 0.70 existed between measured solar radiation and solar radiation computed using Hargreaves and Samani method. Therefore, the Doorenbos and Pruitt method seems to be a much more reliable way of estimating solar

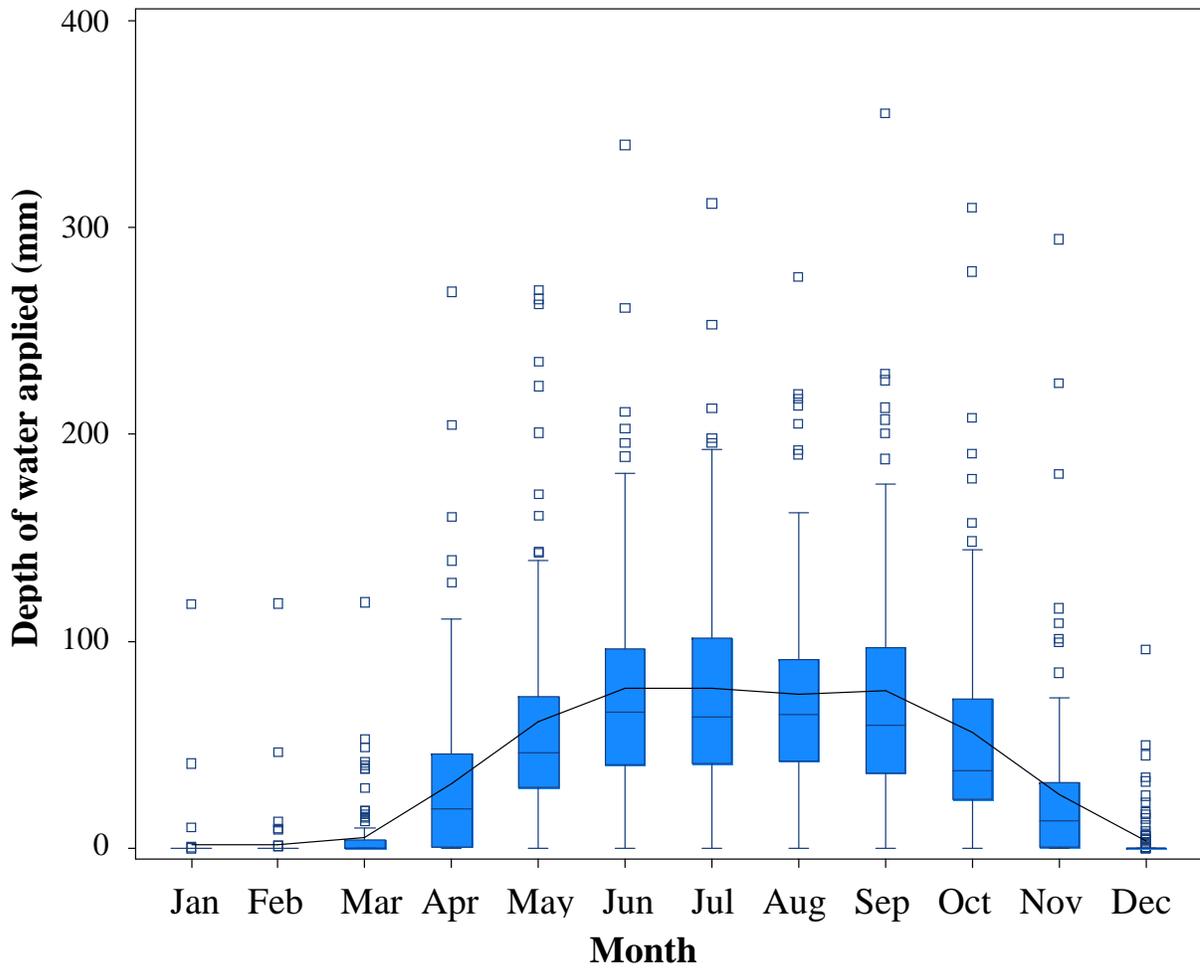
radiation in the Raleigh-Durham region. Comparison of distributions of monthly  $ET_o$  computed using dataset B with those computed using dataset A and C suggests that monthly  $ET_o$  computed using dataset B did not capture the variability in  $ET_o$ . Mean, median and  $P_{80}$  of monthly  $ET_o$  were higher using dataset B (solar radiation estimated by the Hargreaves and Samani method) than those obtained using datasets A (measured solar radiation) and C (solar radiation estimated by the Doorenbos and Pruitt method).



**Figure 2.1** Geographical locations of Cary and weather stations used in the study (A, L and R represent Apex, Lake Wheeler Field Laboratory, and Raleigh-Durham Weather station respectively)

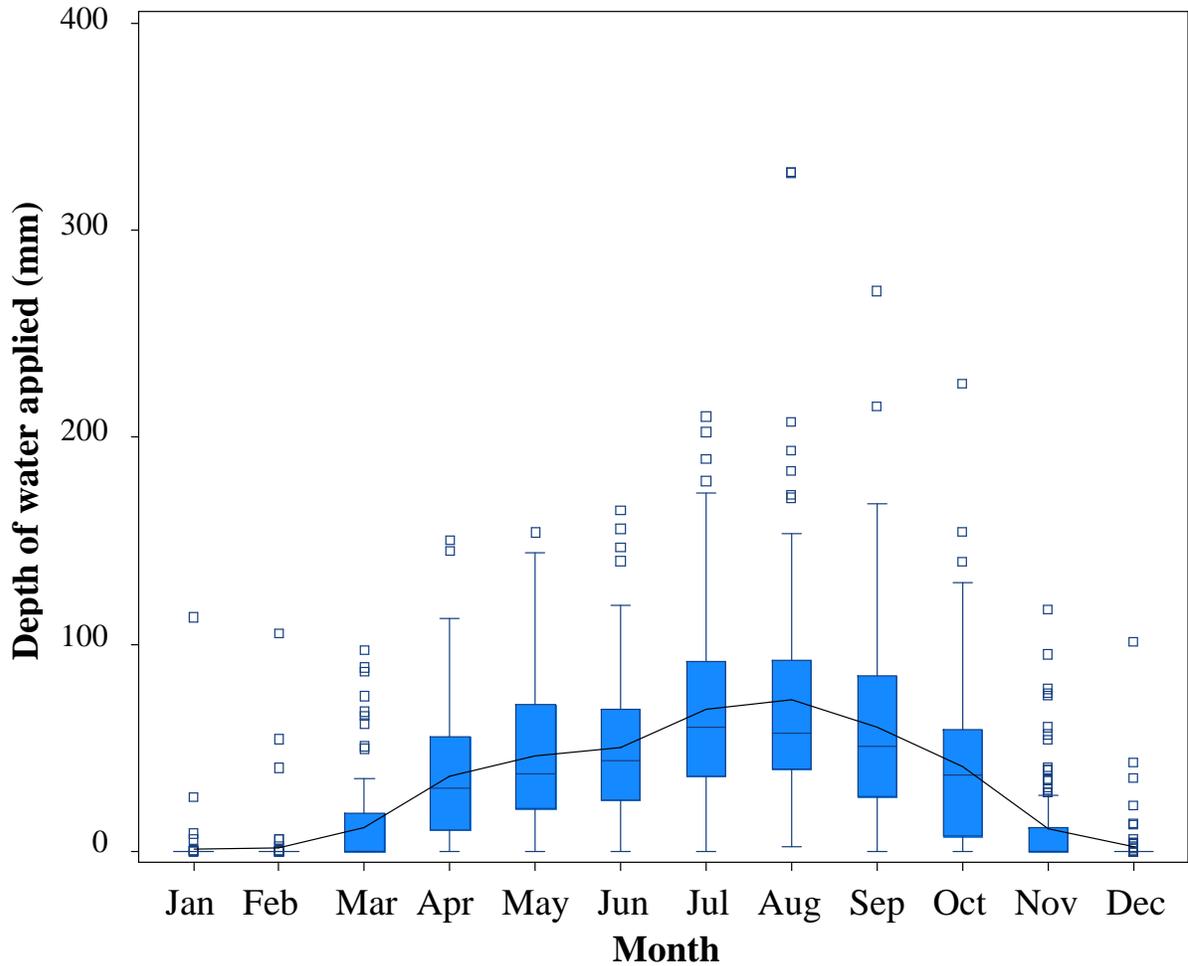


**Figure 2.2** Distribution of lawn area ( $m^2$ ) for homes included in this study ( $n = 120$ )



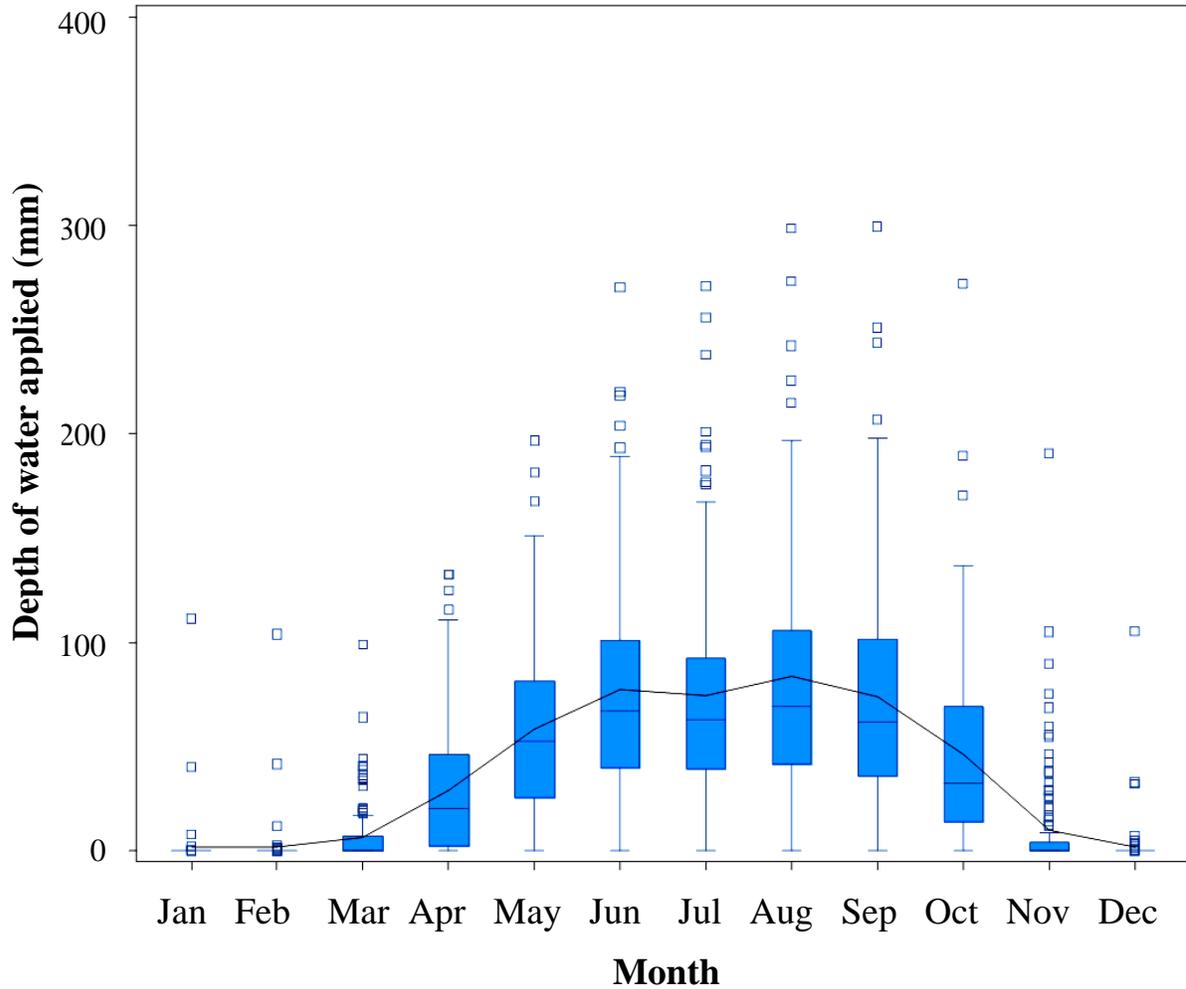
**Figure 2.3** Distribution of depth of water applied in 2005 (n = 120)

**Note:** The center horizontal line in each box corresponds to the sample median and the line connecting all the boxes passes through mean. The bottom and top of the box corresponds to the 25<sup>th</sup> and 75<sup>th</sup> percentile (i.e.  $Q_{25}$  and  $Q_{75}$ ) respectively while the whiskers extend 1.5 times the interquartile range from the box. Points beyond the whiskers are extreme values.



**Figure 2.4** Distribution of depth of water applied in 2006 (n = 120)

**Note:** The center horizontal line in each box corresponds to the sample median and the line connecting all the boxes passes through mean. The bottom and top of the box corresponds to the 25<sup>th</sup> and 75<sup>th</sup> percentile (i.e.  $Q_{25}$  and  $Q_{75}$ ) respectively while the whiskers extend 1.5 times the interquartile range from the box. Points beyond the whiskers are extreme values.



**Figure 2.5** Distribution of depth of water applied in 2007 (n = 120)

**Note:** The center horizontal line in each box corresponds to the sample median and the line connecting all the boxes passes through mean. The bottom and top of the box corresponds to the 25<sup>th</sup> and 75<sup>th</sup> percentile (i.e.  $Q_{25}$  and  $Q_{75}$ ) respectively while the whiskers extend 1.5 times the interquartile range from the box. Points beyond the whiskers are extreme values.

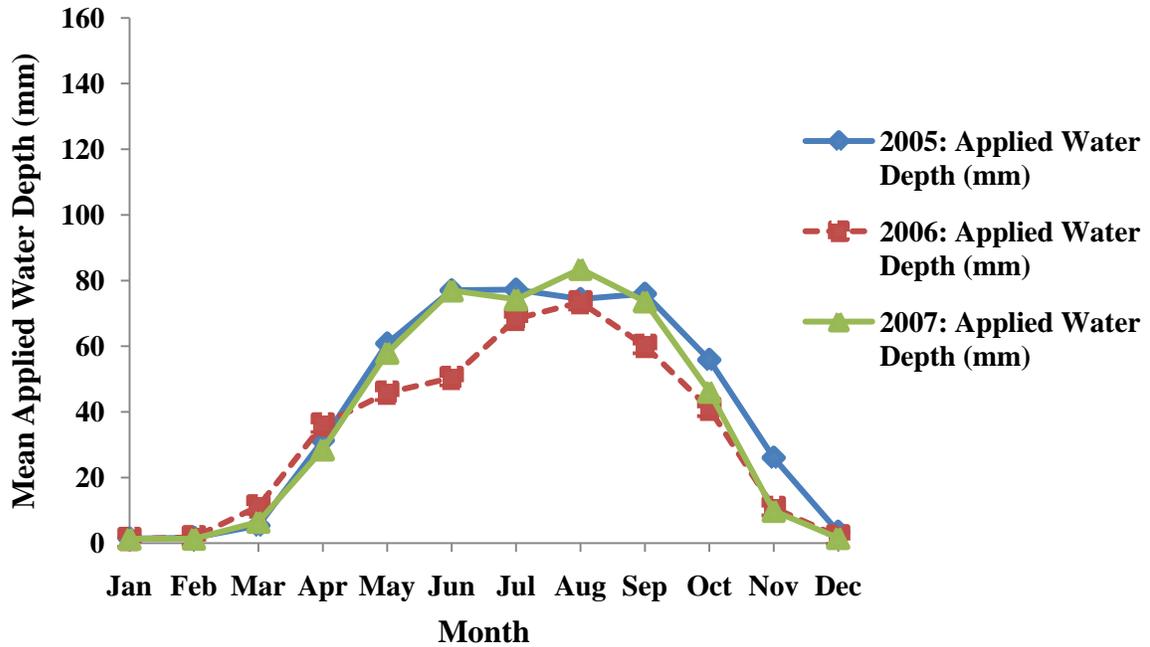


Figure 2.6 Mean applied water depth (mm) in 2005, 2006 and 2007

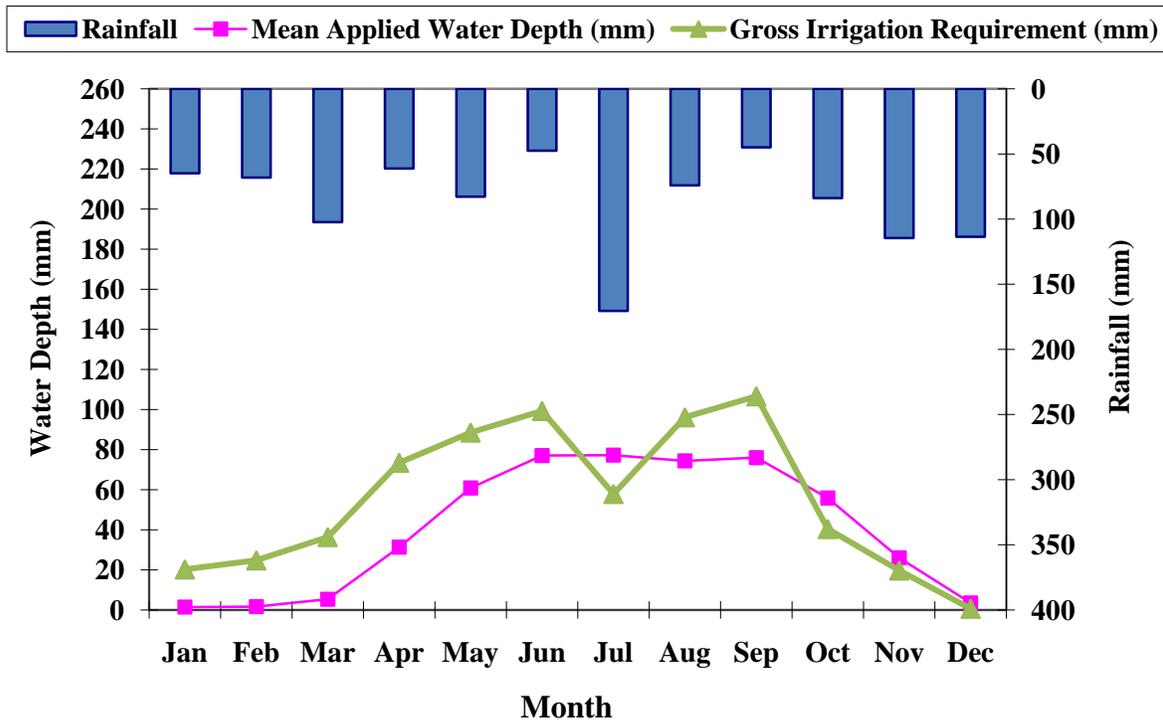


Figure 2.7 Mean applied water depth and gross irrigation requirement (mm) in 2005

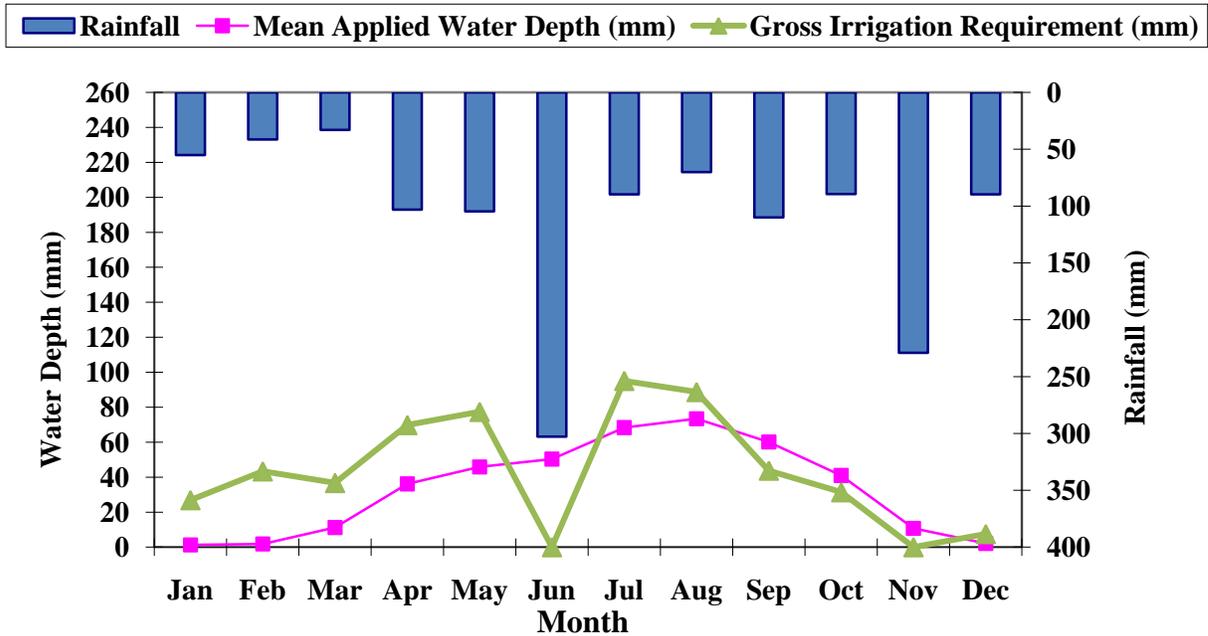


Figure 2.8 Mean applied water depth and gross irrigation requirement (mm) in 2006

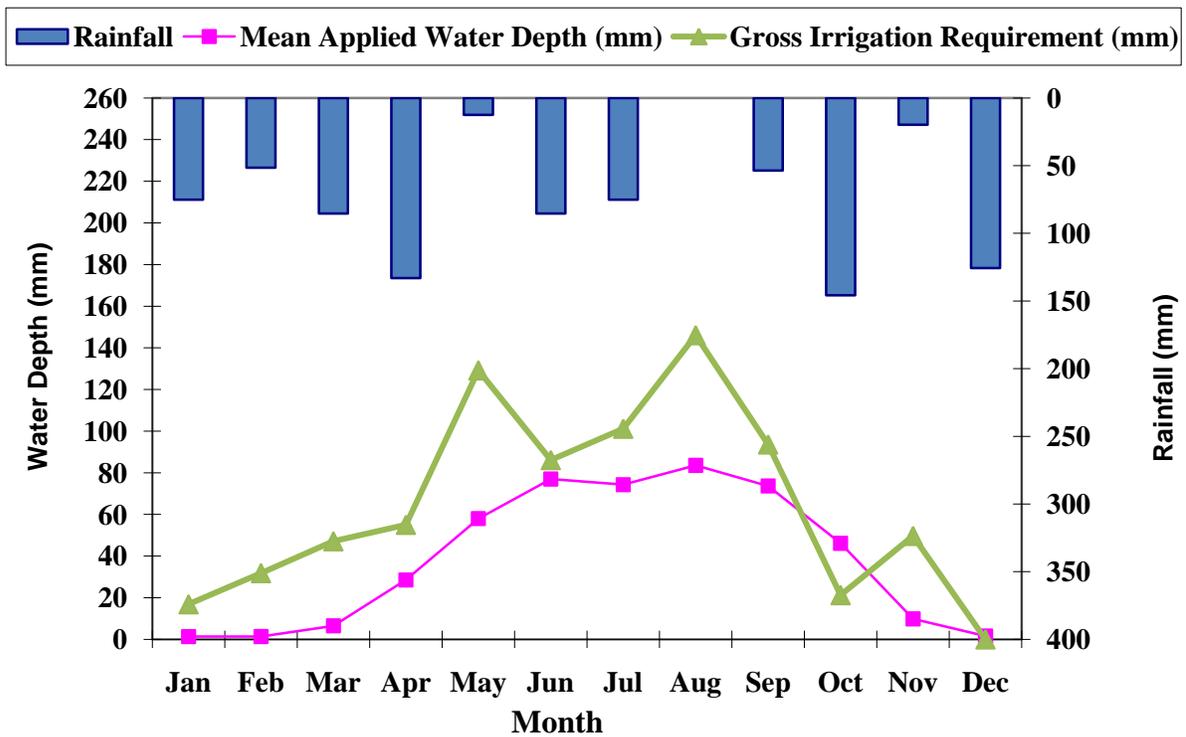
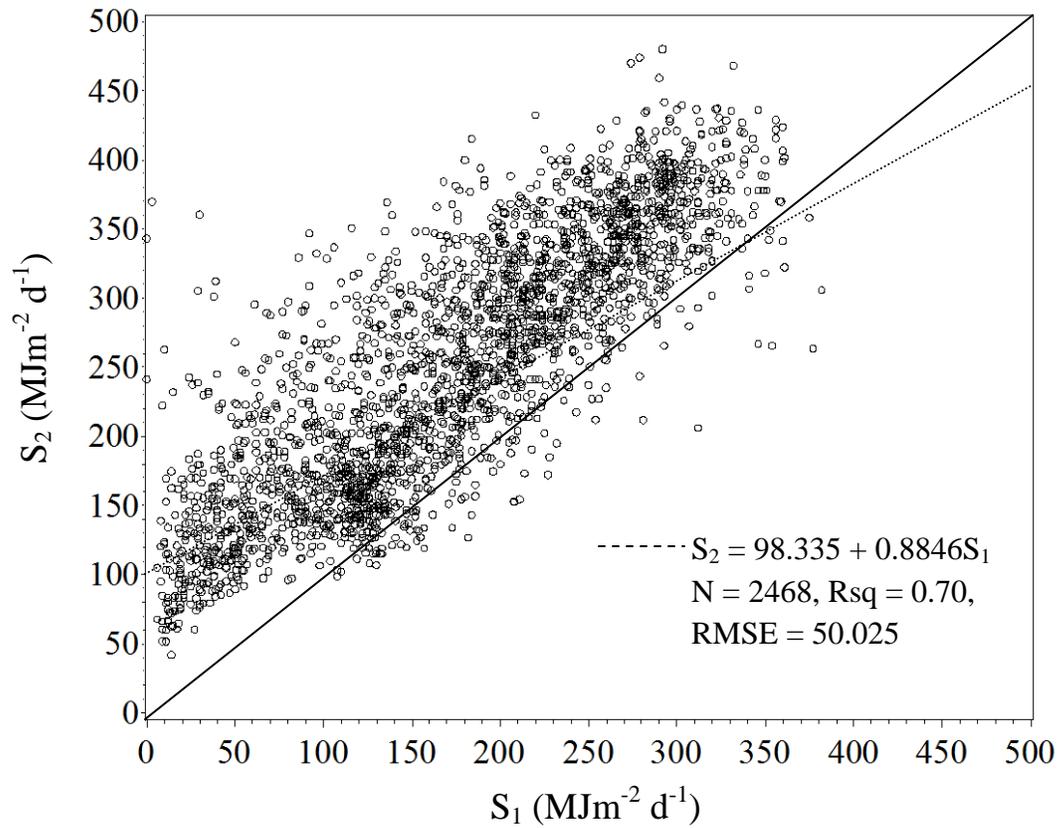
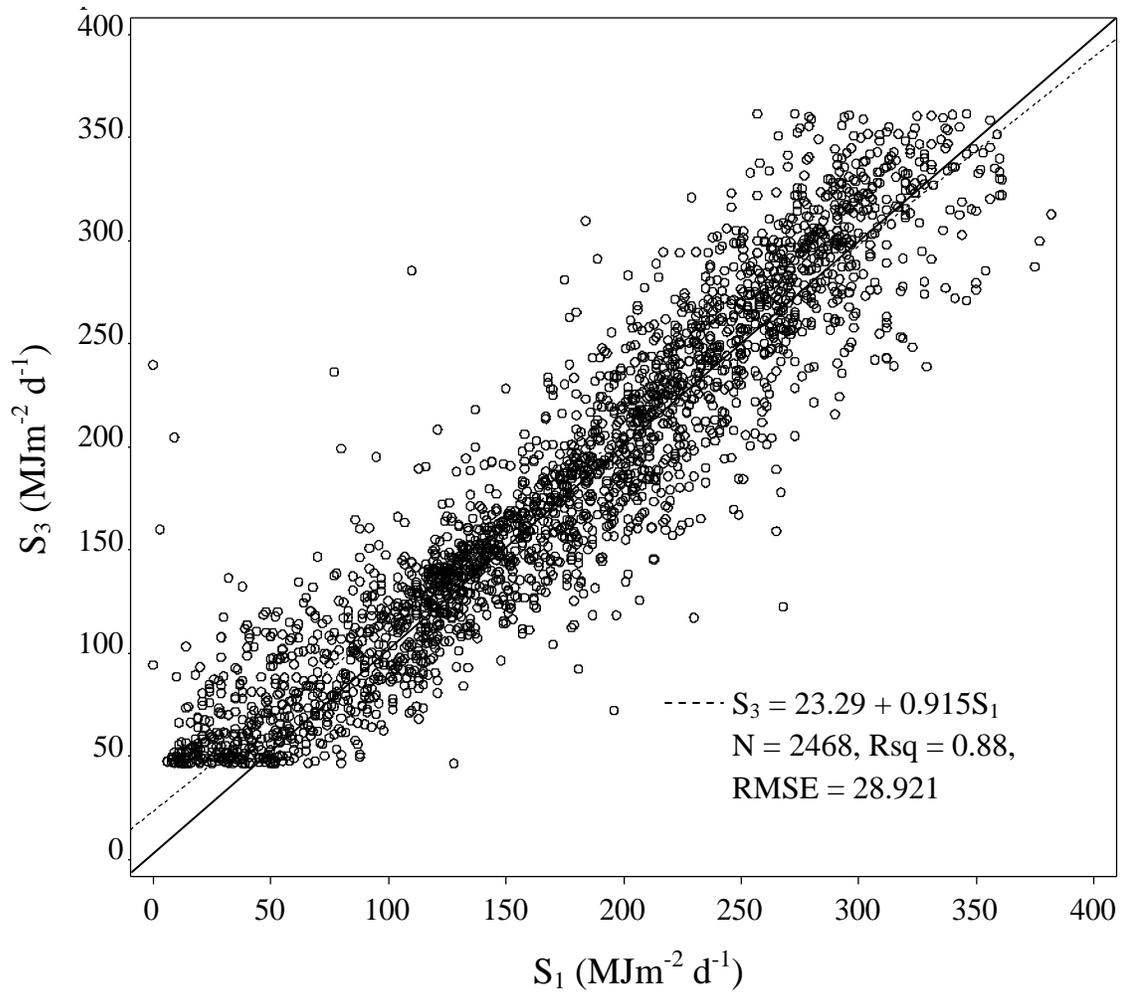


Figure 2.9 Mean applied water depth and gross irrigation requirement (mm) in 2007



**Figure 2.10** Fit of computed daily solar radiation using Hargreaves method ( $S_2$ ) versus actual measured daily solar radiation ( $S_1$ )

**Note:** Period of record: January 1984 – December 1989, March 1990 – August 1990, October 1990 – Dec 1992, October 2001 – May 2009.

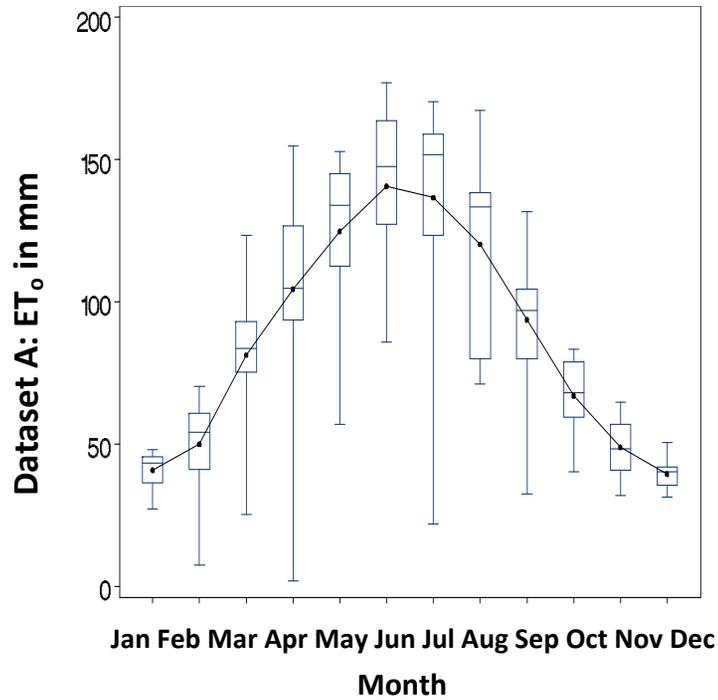


**Figure 2.11** Fit of computed solar radiation using percent sunshine (S3) versus actual measured solar radiation (S1)

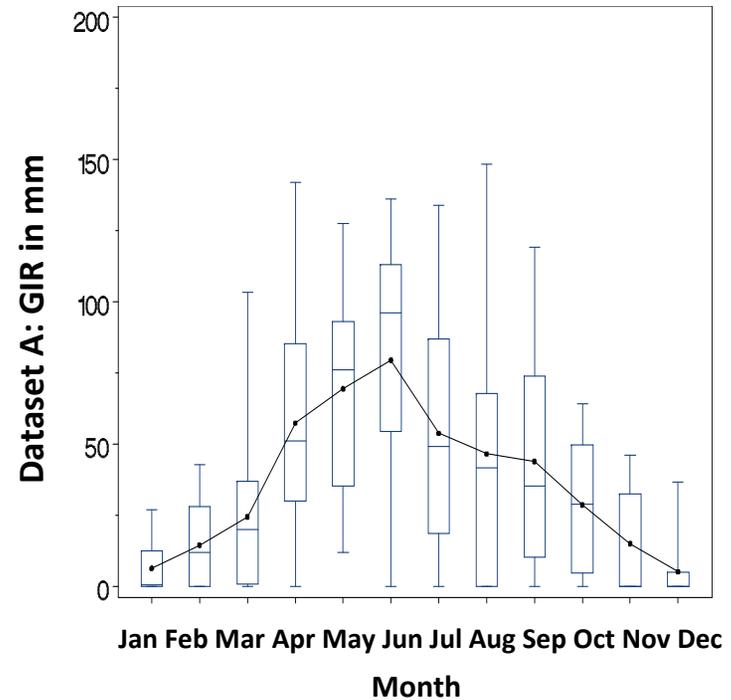
**Note:** Period of record: January 1984 – January 1996

**Table 2.1** Pearson's correlation coefficient ( $r$ ) between  $S_1$ ,  $S_2$  and  $S_3$  by month

<b>Month</b>		<b>S2</b>	<b>S3</b>
<b>Jan</b>	<b>S1</b>	0.639	0.941
	<b>S2</b>		0.601
<b>Feb</b>	<b>S1</b>	0.601	0.938
	<b>S2</b>		0.61
<b>Mar</b>	<b>S1</b>	0.626	0.91
	<b>S2</b>		0.658
<b>Apr</b>	<b>S1</b>	0.702	0.914
	<b>S2</b>		0.73
<b>May</b>	<b>S1</b>	0.709	0.876
	<b>S2</b>		0.733
<b>Jun</b>	<b>S1</b>	0.662	0.843
	<b>S2</b>		0.649
<b>Jul</b>	<b>S1</b>	0.724	0.828
	<b>S2</b>		0.727
<b>Aug</b>	<b>S1</b>	0.767	0.858
	<b>S2</b>		0.641
<b>Sep</b>	<b>S1</b>	0.82	0.923
	<b>S2</b>		0.767
<b>Oct</b>	<b>S1</b>	0.755	0.882
	<b>S2</b>		0.788
<b>Nov</b>	<b>S1</b>	0.738	0.927
	<b>S2</b>		0.694
<b>Dec</b>	<b>S1</b>	0.67	0.873
	<b>S2</b>		0.553

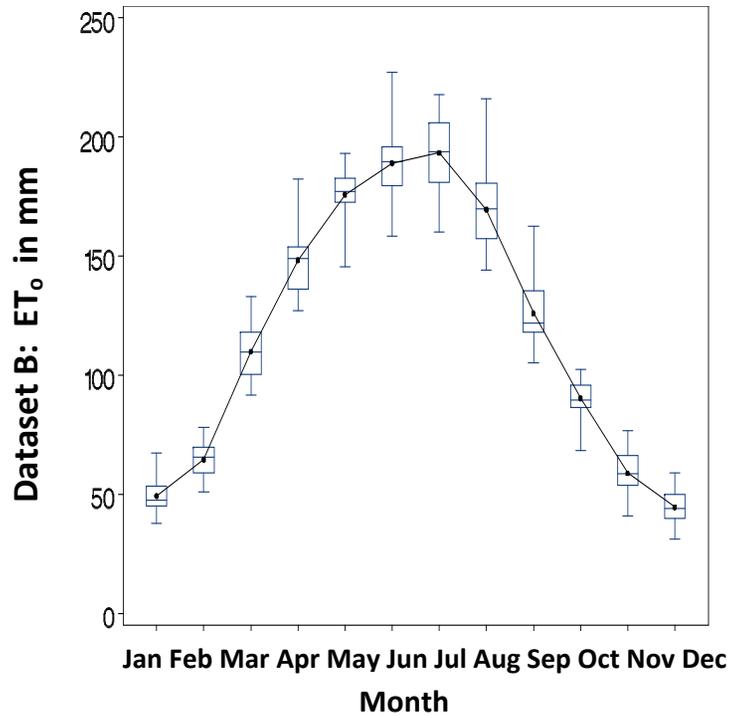


**Figure 2.12** Distribution of monthly  $ET_0$  computed using dataset A (measured solar radiation based)

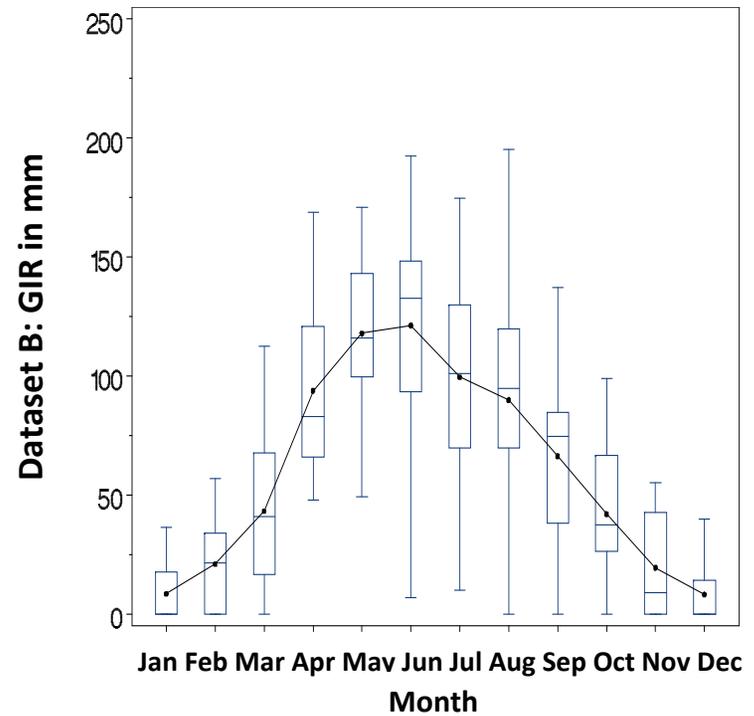


**Figure 2.13** Distribution of monthly GIR computed using dataset A (measured solar radiation based)

**Note:** Period of record: Jan. 1984 – Dec. 1989, Mar. 1990 – Aug. 1990, Oct. 1990 – Dec 1992, Oct. 2001 – May 2009. The center horizontal line in each box corresponds to the sample median and the line connecting all the boxes passes through mean of the sample. The edges of the box corresponds to the 25<sup>th</sup> and 75<sup>th</sup> percentile while the end of the tails represent maximum and minimum values.

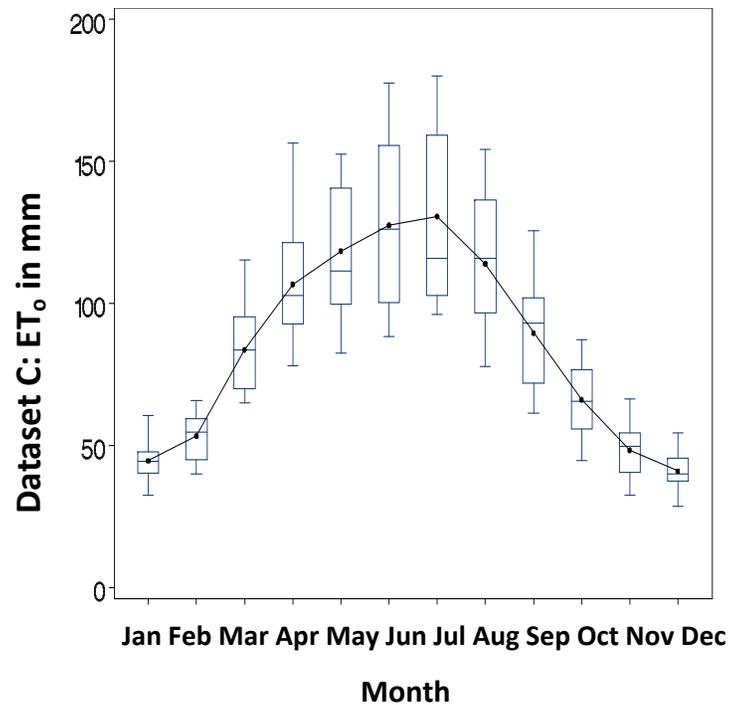


**Figure 2.14** Distribution of monthly  $ET_0$  computed using dataset B (Hargreaves and Samani method based)

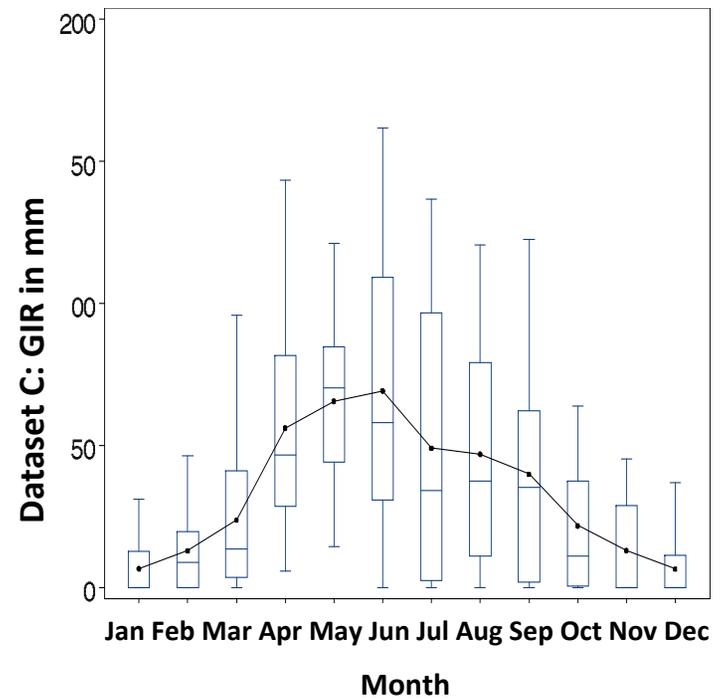


**Figure 2.15** Distribution of monthly GIR computed using dataset B (Hargreaves and Samani method based)

**Note:** Period of record: January 1984 – May 2009. The center horizontal line in each box corresponds to the sample median and the line connecting all the boxes passes through mean of the sample. The edges of the box correspond to the 25<sup>th</sup> and 75<sup>th</sup> percentile while the end of the tails represents maximum and minimum values.



**Figure 2.16** Distribution of monthly  $ET_0$  computed using dataset C (Doorenbos and Pruitt method based)



**Figure 2.17** Distribution of monthly GIR computed using dataset B (Doorenbos and Pruitt method based)

**Note:** Period of record: Jan 1984 – Jan 1996. The center horizontal line in each box corresponds to the sample median and the line connecting all the boxes passes through mean of the sample. The edges of the box corresponds to the 25<sup>th</sup> and 75<sup>th</sup> percentile while the end of the tails represent maximum and minimum values.

**Table 2.2** Mean of ET<sub>o</sub> and GIR for datasets A, B and C

<b>Month</b>	<b>Dataset A: ETo in mm (Mean)</b>	<b>Dataset B: ETo in mm (Mean)</b>	<b>Dataset C: ETo in mm (Mean)</b>	<b>Dataset A: GIR in mm (Mean)</b>	<b>Dataset B: GIR in mm (Mean)</b>	<b>Dataset C: GIR in mm (Mean)</b>
<b>Jan</b>	40.8	49.2	44.6	6.3	8.4	6.6
<b>Feb</b>	49.9	64.6	53.3	14.4	20.9	12.9
<b>Mar</b>	81.3	109.9	83.7	24.4	43.2	23.7
<b>Apr</b>	104.4	148.3	106.7	57.3	93.8	56.1
<b>May</b>	124.8	175.9	118.4	69.4	117.9	65.6
<b>Jun</b>	140.6	189.1	127.5	79.5	121.3	69.2
<b>Jul</b>	136.6	193.4	130.6	53.8	99.5	49.0
<b>Aug</b>	120.2	169.5	113.9	46.5	89.9	46.9
<b>Sep</b>	93.7	126.0	89.6	43.9	66.3	39.8
<b>Oct</b>	66.9	90.4	66.0	28.6	41.9	21.7
<b>Nov</b>	48.8	58.8	48.3	15.0	19.4	12.9
<b>Dec</b>	39.4	44.5	40.9	5.1	8.1	6.4

**Table 2.3** Median of  $ET_0$  and GIR for datasets A, B and C

<b>Month</b>	<b>Dataset A: <math>ET_0</math> in mm (Median)</b>	<b>Dataset B: <math>ET_0</math> in mm (Median)</b>	<b>Dataset C: <math>ET_0</math> in mm (Median)</b>	<b>Dataset A: GIR in mm (Median)</b>	<b>Dataset B: GIR in mm (Median)</b>	<b>Dataset C: GIR in mm (Median)</b>
<b>Jan</b>	43.1	47.5	44.4	0.5	0.0	0.0
<b>Feb</b>	54.0	65.5	54.6	11.9	21.3	8.7
<b>Mar</b>	83.4	109.6	83.5	20.0	40.9	13.5
<b>Apr</b>	104.8	149.1	102.7	51.0	82.9	46.5
<b>May</b>	134.0	177.1	111.4	76.1	116.0	70.2
<b>Jun</b>	147.5	189.5	126.2	96.1	132.7	57.9
<b>Jul</b>	151.8	193.7	115.9	49.2	101.0	34.1
<b>Aug</b>	133.3	170.0	115.7	41.6	94.6	37.4
<b>Sep</b>	97.0	121.7	93.1	35.3	74.5	35.3
<b>Oct</b>	67.9	89.5	65.5	28.7	37.3	11.0
<b>Nov</b>	48.3	58.7	49.7	0.0	8.8	0.0
<b>Dec</b>	40.1	44.0	39.9	0.0	0.0	0.0

**Table 2.4** 80<sup>th</sup> percentile ( $P_{80}$ ) of  $ET_o$  and GIR for datasets A, B and C

<b>Month</b>	<b>Dataset A: <math>ET_o</math> in mm (<math>P_{80}</math>)</b>	<b>Dataset B: <math>ET_o</math> in mm (<math>P_{80}</math>)</b>	<b>Dataset C: <math>ET_o</math> in mm (<math>P_{80}</math>)</b>	<b>Dataset A: GIR in mm (<math>P_{80}</math>)</b>	<b>Dataset B: GIR in mm (<math>P_{80}</math>)</b>	<b>Dataset C: GIR in mm (<math>P_{80}</math>)</b>
<b>Jan</b>	45.5	54.4	47.8	12.6	15.7	20.3
<b>Feb</b>	61.5	69.6	59.6	28.3	23.7	34.1
<b>Mar</b>	93.8	118.5	96.3	38.2	46.0	68.7
<b>Apr</b>	128.1	153.9	122.0	100.9	87.5	123.2
<b>May</b>	147.2	183.1	141.2	103.3	87.0	146.9
<b>Jun</b>	165.3	197.8	164.8	113.2	110.6	157.6
<b>Jul</b>	162.3	207.0	163.1	90.8	98.5	139.3
<b>Aug</b>	138.9	182.3	138.7	69.7	89.3	126.2
<b>Sep</b>	106.5	138.5	106.4	82.1	68.6	104.4
<b>Oct</b>	79.1	99.7	80.2	51.4	53.9	69.1
<b>Nov</b>	57.6	67.0	57.0	35.0	32.6	45.2
<b>Dec</b>	42.7	51.1	46.8	8.6	12.1	15.2

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**CHAPTER 3**  
**EVALUATION OF TWO SMART IRRIGATION TECHNOLOGIES IN CARY,**  
**NORTH CAROLINA**

**3.1 Abstract**

With the construction of new homes there is expansion of the urban landscape and an increase in turfgrass covered area. Increasing turfgrass area results in an increase in irrigation, thus causing a negative impact on already depleting water resources. Decreasing the amount of water applied by residential irrigation systems without causing negative effects on turfgrass quality is a challenge. A variety of technologies are available in the market that seeks to reduce irrigation water use. These technologies include rain sensors, and soil moisture sensor (SMS) based and evapotranspiration (ET) based controllers. A study was conducted in Cary, North Carolina with the purpose of evaluating the effectiveness of two smart systems, based on the amount of irrigation applied and resulting turf quality in residential settings. The study included 24 residential sites that were divided into six geographical regions, each treatment within a region receiving four different treatments. The treatments were: SMS) an irrigation controller with a soil moisture sensor, ET) an evapotranspiration based controller, ED) a standard irrigation controller using seasonal runtimes based on historical climate data and Control) irrigation controller with no intervention. Maximum water savings were achieved by the SMS treatment followed by ET, ED and Control treatments. The turf quality results for the NDVI meter ratings were different from the visual ratings. According to visual ratings, a difference existed between the average

turf quality of SMS and Control treatments but no difference in NDVI readings was found between these treatments. The ED treatment had the best turf quality according to NDVI readings. The SMS and ED treatments had the best turf quality according to visual ratings.

### **3.2 Introduction**

As population continues to grow and drought conditions occur more frequently, the reality of limited water resources becomes more apparent. The drought periods of 1976-77 and 1977-78 in the western United States led to the realization of the importance of wise-water use for turfgrass irrigation (University of California Division of Agriculture and Natural Resources, 1985). Since 1950, the U.S. population has doubled and public demand for water has increased more than threefold (EPA, 2007). In 1999, Mayer et al. reported that residential outdoor water use varied from 22% to 67% of total household water use. In a typical residential setting, a landscape receives 30% to 40% more applied water than is required by the plants (Adhikari et al., 2006). Much of the over-irrigation occurs during the fall of the year when plant water demand drops off but corresponding irrigation run times are not reduced accordingly. Baum et al. (2005) found that typically homeowners used an average of 146 mm per month of water for irrigation in central Florida.

According to North Carolina guidelines for turfgrass irrigation (Bruneau et al., 2000), in the absence of rain, 25 mm of irrigation per week should be adequate although turfgrass water use can exceed 25 mm per week during peak demand periods and be less during cool, cloudy periods. Henceforth, new guidelines were provided by Bruneau et al. (2006) that

suggest turfgrass water demand ranges from 18 mm to 48 mm per week for the Central Piedmont of North Carolina.

Cary is the second most populous municipality in Wake County to Raleigh. The town's population was 94,536 at the 2000 census but according to the town's statistics the population had grown to 137,483 by October 2009, a 45.4% increase since 2000. This population growth made Cary the seventh largest municipality statewide. Cary was also the 5th fastest growing municipality in the country between July 1, 2006, and July 1, 2007 (U.S. Census Bureau, 2008).

Unpredictable and unevenly distributed rainfall in humid areas makes fixed irrigation schedules less efficient than in arid areas. Since North Carolina has a humid environment, irrigation scheduling that considers prevailing rainfall conditions will limit water waste and achieve the high quality landscapes desired by homeowners.

Proper irrigation scheduling plays a very important role in maintaining healthy turf and conserving water. Irrigation scheduling basically takes the following factors into account: available water holding capacity of the soil, root depth, effective rainfall, and weather conditions including temperature, solar radiation, wind speed and humidity. For a healthy landscape, the soil moisture in the root zone should be maintained well above the wilting point. Daily water replacement, fixed day irrigation, fixed amount irrigation, cycle start, percent-key change, soil-water balance checkbook, and historical ET override with rain sensor are some of the practical methods used in scheduling irrigation (Mecham, 1997).

### 3.3 Effective Rainfall

Effective rainfall (ER) is the portion of total rainfall that plants use to help meet their consumptive water requirements, and is an important component of water budgeting for irrigation (Obreza and Pitts, 2002). According to NRCS (formerly SCS) TR21 (USDA, 1970) method, effective rainfall is estimated as:

$$ER = SF \times \left[ 0.70917 \times \left( \frac{P_m}{25.4} \right)^{0.82416} - 0.11556 \right] \times 10^{0.000955 ET_c} \quad (3.1)$$

where,

- ER = Effective Rainfall, mm
- SF = Soil water storage factor
- $P_m$  = Average monthly precipitation, mm
- $ET_c$  = Crop evapotranspiration, mm

The Soil water storage factor (SF) is given in TR-21 as:

$$SF = 0.531747 + 0.295164 \left( \frac{D}{25.4} \right) - 0.057697 \left( \frac{D}{25.4} \right)^2 - 0.003804 \left( \frac{D}{25.4} \right)^3 \quad (3.2)$$

where

- D = usable soil water storage which is expressed as the fraction of the available water holding capacity of the soil.

### 3.4 Reference Evapotranspiration

Evapotranspiration (ET) is the combination of two separate processes whereby water is lost from the soil surface by evaporation and from the crop by transpiration. During the process of evaporation, liquid water is converted to water vapour and removed from the evaporating surface. Water evaporates from a variety of surfaces, such as lakes, rivers, pavement, soil and vegetation like turfgrass and plant canopies. The process of transpiration is similar to evaporation but in this case the water evaporates through the stomata of the leaf. The principal weather parameters that affect evapotranspiration are solar radiation, air temperature, humidity and wind speed.

Reference evapotranspiration ( $ET_o$ ) is defined as "the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of  $70 \text{ sec m}^{-1}$  and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground" (Allen et al., 1998). Several climatologically based empirical equations have been developed for computing reference evapotranspiration. The applicability of these equations varies depending on the availability of data of various weather parameters. The Penmen-Monteith equation is the standard method for computing  $ET_o$  and is given by:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (3.3)$$

where

$ET_o$  = reference evapotranspiration,  $\text{mm day}^{-1}$

$R_n$  = net radiation at the crop surface,  $\text{MJ m}^{-2} \text{day}^{-1}$

$G$  = soil heat flux density,  $\text{MJ m}^{-2} \text{day}^{-1}$

$T$  = mean daily air temperature at 2 m height,  $^{\circ}\text{C}$

$u_2$  = wind speed at 2 m height,  $\text{m s}^{-1}$

$e_s$  = saturation vapor pressure at mean daily air temperature, kPa

$e_a$  = actual vapor pressure, kPa

$e_s - e_a$  = saturation vapor pressure deficit, kPa

$\Delta$  = slope of the saturation vapor pressure curve at mean air temperature,  $\text{kPa}^{\circ}\text{C}^{-1}$

$\gamma$  = psychrometric constant,  $\text{kPa } ^{\circ}\text{C}^{-1}$

The amount of water required to balance the evapotranspiration loss from the cropped field is defined as the crop water requirement. The crop water requirement and crop evapotranspiration ( $ET_c$ ) have identical values; the difference is that the crop water requirement refers to the amount of water that needs to be supplied, while crop evapotranspiration refers to the amount of water that is lost through evapotranspiration.  $ET_c$  can be computed by multiplying  $ET_o$  by a crop coefficient,  $K_c$  (Allen et al., 1998).

$$ET_c = K_c \times ET_o \quad (3.4)$$

Factors like crop type, climate, soil evaporation and crop growth stages play a major role in determining  $K_c$  value. The California Department of Water Resources (CDWR) has suggested a crop coefficient of 0.8 for cool season grasses (CDWR, 2000).

### **3.5 Gross Irrigation Requirement**

The net amount of irrigation water required to replace crop ET after accounting for effective rainfall (ER) is called the net irrigation requirement and is calculated by the formula:

$$\text{NIR} = \text{ET}_c - \text{ER} \quad (3.5)$$

After accounting for system irrigation uniformity, the quantity of water to be applied by the irrigation system is called the gross irrigation requirement, (GIR) (Allen, 1997) and is calculated as:

$$\text{GIR} = \frac{\text{NIR}}{\text{System Irrigation Uniformity}} \quad (3.6)$$

where, system irrigation uniformity is the measure of how evenly water is distributed by the irrigation system on the ground. It determines the effectiveness with which the irrigation system extracts water from a water supply source and applies it to produce the target crop.

### **3.6 Smart Irrigation Controllers**

The Smart Water Application Technology (SWAT) committee of the Irrigation Association (IA, 2007) defines ‘smart controllers’ as those technologies that

*“Estimate or measure depletion of available plant soil moisture in order to operate an irrigation system along with replenishment of water as needed while minimizing excess water use. A properly programmed smart controller requires initial site specific set-up and will make irrigation schedule adjustments, including run times and required cycles, throughout the irrigation season without human intervention.”*

Application of smart irrigation controllers in an automated irrigation system has become a trend in turf industry (Castanon, 1992). There are numerous smart irrigation controller manufacturers that already exist or are emerging in the marketplace.

Depending on the type of information used by smart controllers, they can be classified into two categories - those that use information from sensor monitoring the water content in the root zone, and those that use weather information to estimate the amount of water required by the turf. With the variation in environment (either atmospheric or soil environment) there is a change in the plant water requirements that is updated by the smart irrigation controller. So an ET-based smart controller will automatically reduce the watering times as the weather gets cooler and less water is needed or will add more watering time when temperatures rise. The integration of an irrigation controller and soil moisture based technology makes it function similar to a thermostat. Generally, an irrigation controller irrigates on a preset schedule but the incorporation of the technology permit irrigation when required. In essence the concept is to apply appropriate irrigation amounts at the appropriate time (US Bureau of Reclamation, 2007).

### *3.6.1 Evapotranspiration (ET)-based Controllers*

Various weather based methods are used by different ET controllers to determine watering time. Some controllers use historical data to compute the plant water requirements while some controllers use historical data to determine base watering time but then adjust time based on an on-site weather sensor. Another class of controllers uses either real time off-site data communicated via internet, radio, or phone connection from a central provider, or use an on-site weather station.

According to a smart irrigation controller evaluation of single family dwellings in Irvine, California, an Evapotranspiration (ET) controller resulted in average single-family water savings of 37 gallons per day, representing a 7% reduction in total household use, or a 16% reduction in estimated outdoor use (Hunt et al., 2001). In the second post-retrofit year of the same study, Bamezai (2001) conducted a customer satisfaction survey which showed that almost 97% of the ET controller participants reported either improvement or no change in the appearance of their landscapes and all found the ET controller convenient to use. Aqua Conserve (2002) reported that in comparison to historic water usage, the weather-based Aqua Conserve controller provided individual residence water savings ranging from 7% to 25% for three study areas located in California. A study conducted in Colorado that evaluated Hydropoint WeatherTRAK controllers, reported average water savings of 19% for 2001 and 21% for 2002 in comparison to historic outdoor water use (Aquacraft, 2003). Pittenger et al. (2004) evaluated four weather based controllers using five hypothetical landscapes and one actual grass landscape at the Center for Landscape and Urban Horticulture in Riverside,

California. The study found varying accuracy of irrigation schedule for different controllers and different landscapes. In general, the Aqua Conserve controller was found to over-irrigate in most cases, the Accurate WeatherSet controller under-irrigated while the Hydropoint WeatherTRAK controller over-irrigated in some cases and under-irrigated in others.

In an eighteen month study in Las Vegas, Devitt et al. (2008) used signal-based WeatherTrak ET irrigation controllers in seventeen residential sites and compared their water use with ten standard irrigation controllers. He found an average of 20% water savings by the ET-based treatment in comparison to standard controller group. In one of the recently conducted studies in Florida, the Weathermatic controller saved 43% while the Toro and ETwater controllers saved 59% and 50% compared to an historical net-irrigation requirement based treatment (Davis et al., 2009).

### *3.6.2 Soil-Moisture-Sensor-based Controllers*

In recent years, much advancement has occurred in soil moisture sensor based technologies that has made its application successful in landscape irrigation (US Bureau of Reclamation, 2007). These systems can be a stand-alone system, comprising both an irrigation controller and sensor(s) or can be a sensor and add-on module that connects the soil moisture sensor to an existing irrigation controller through a user interface module mounted near the existing controller. In soil moisture sensor based systems, a soil moisture sensor is buried in an irrigation zone and connected to solenoid valve wiring. The soil moisture sensor measures the amount of water in the soil and overrides the scheduled watering event by

interrupting the irrigation controller circuit when the moisture level is above a user-set threshold.

Several studies have been conducted to evaluate soil-moisture based systems. Allen (1997) found that residential sites with soil moisture sensors applied 10% less water relative to the control sites in a study in Utah. Qualls et al. (2001) conducted a study using granular soil matrix sensors in urban settings in Colorado and found that the sensor based systems limited water application to 73% of the theoretical water requirement. In three different studies at the University of Florida Agricultural and Biological Engineering facility in Gainesville, Florida, (Cardenas-Lailhacar et al., 2005; Shedd et al., 2007, and Haley et al., 2007) reported water savings from 59% to 82%, 11% to 28%, and 51 % respectively. In an another study, Cardenas-Lailhacar et al. (2010) evaluated four different brands of sensors; Acclima, Rain Bird, Irrrometer, and Water Watcher on research plots and found that on average, 71% of scheduled irrigation cycles were bypassed by the sensors without causing any harm to the turf quality. The Acclima and Rain Bird sensors were more precise and consistent in measuring and bypassing the scheduled irrigation than the Irrrometer and Water Watcher systems.

A study conducted in Florida by McCready et al. (2009) found that in comparison to a no sensor treatment, the reductions in irrigation were 7-30% for rain sensor based treatments, 0–74% for soil moisture sensor treatments, and 25–62% for ET-based treatments. A study conducted at the North Carolina State University Lake Wheeler Turf Field Laboratory, in Raleigh, North Carolina (Grabow et al., 2008) compared water applied

and turf quality from one ET-based system and two soil moisture sensor-based systems to a standard time based irrigation schedule. Frequency of irrigation was also an experimental factor in the study. It was found that on an average, the add-on soil-moisture-based system applied the least amount of water while the ET-based treatment applied the most water. Acceptable turfquality was maintained by all the treatments and frequencies when average over the three year study.

### **3.7 Turfgrass Overview**

Due to a strong demand for turfgrass in residential and commercial properties, the turfgrass industry has seen a rapid growth in the United States. North Carolina ranks eighth in turfgrass acreage nationally. Approximately, 2,007,100 acres of land is devoted to turfgrasses in North Carolina, and single family dwellings account for 61% of the total area in turf (Brandenburg, 2004). Based on climatic adaptation, turfgrasses are classified into two groups; warm-season grasses, adapted to tropical and subtropical areas, and cool-season grasses which are adapted to temperate and sub-arctic climates (Huang, 2006). Both cool-season and warm-season grasses are grown in North Carolina. (Carolina Lawns, 2009) Generally spring and fall is the best season for cool-season grasses while warm season grasses grow best in the summer. Tall fescue, Kentucky bluegrass, fine fescue, and perennial ryegrass are popular cool-season lawn grasses which stay reasonably green in the winter while the most common warm-season lawn grasses are bermudagrass, zoysiagrass, St. Augustinegrass, centipedegrass and bahiagrass (Carolina Lawns, 2009).

In home lawns, tall fescue is the most common turf specie grown, accounting for 37% (742,600 acres) of the total turf acreage followed by bermudagrass, which represents 12.3% (247,873 acres) of the turf acreage in North Carolina (NCDA, 2004).

The functional and aesthetic aspects of turfgrass are important in turfgrass quality evaluation. Turfgrass quality rating varies with turfgrass species, intensity of management and time of year (Morris, 2009). There are various methods of evaluating turfgrass quality. Visual rating is the most common; however, it is a subjective method of evaluation, varying from person to person. Typically, visual observations of color, texture, uniformity and density are used in evaluating the turfgrass quality. The visual turf quality rating is based on a scale of 1 to 9 where 9 is considered outstanding or ideal turf and 1 is poorest or dead. A rating of 6 or above is generally considered acceptable (Morris and Shearman, 1998).

Turfgrass quality can also be measured using a Normalized Difference Vegetation Index (NDVI), which is a normalized ratio of near-infrared reflectance to red reflectance. The NDVI value is obtained with the use of a measured consistent internal light source, which ranges from 0 to 1 (Spectrum Technologies, Inc., 2009). NDVI provides a quantitative method for evaluating turfgrass quality and limits variability in turfgrass quality evaluation due to human perception.

The objective of this study was to determine the effectiveness of two smart irrigation technologies, i.e., a Soil Moisture Sensor (SMS) system and an Evapotranspiration (ET) system based on the amount of irrigation applied and turf quality in residential settings.

### 3.8 Materials and Methods

The residential homes included in this study were located in Cary and Morrisville (Figure 3.1), two neighboring towns in Wake County, North Carolina. The study began with 24 residential sites with automatic in-ground irrigation systems and separate irrigation meters. The sites were divided into six geographically-based groups with each group consisting of four different treatments. The treatments were; an irrigation controller with a soil moisture sensor (SMS), an evapotranspiration based controller (ET), an “educational” group with a standard irrigation controller using provided seasonal runtimes based on historical climate data (ED), and a standard irrigation controller with no intervention (Control). Within a geographical group, all treatments (homeowner residences) were located within 0.8 km radius except for one of the groups where the maximum distance between two treatments was 1.3 km. Of the six geographical groups, five were located in Cary while one was in the town of Morrisville. Two sites were dropped during the course of the study due to equipment failure at one location and a resident turning off the irrigation system at another location.

At the beginning of the study, 3,000 informational fliers were distributed by the Town of Cary to residents with in-ground irrigation systems to which nearly 450 responses were received. Out of these 450 interested homeowners, thirty were selected for the purpose of an irrigation audit. Selection was limited to those residences with tall fescue (*Festuca arundinacea* Schreb.) to limit variability in water use and turf quality across treatment groups. Thereafter, twenty five irrigation audits were performed in which catch-can data

were used to estimate the distribution uniformity and application rate of the irrigation system. All residential sites selected had either spray or rotor heads for irrigating turf while micro-sprays and some drip systems were used for non-turf areas that were irrigated. Controller settings, broken heads and other system discrepancies were documented during the audit process and were also used for identifying candidates for specific technology type. After the audits were completed, six of each (i.e. SMS and ET) technology were installed at twelve residential sites. Both types of technologies are referred to as “add-on” systems because existing controllers can be used with these systems. The SMS technology used in the study was an Acclima SCX system (Acclima, Inc., Meridian, Idaho) that comes with a sensor and a control module. The sensor was buried approximately 10 cm beneath the turf and wired to an existing solenoid valve at the valve box, and the control module was wired into the existing controller. The sensors were installed in drier areas (full sun and away from slope toes). After installation the soil was soaked to saturation near the sensor area. After a 24-hr period soil moisture content was read on the module. This reading corresponds to the field capacity of soil. There soil moisture threshold was set to 75% of the field capacity. The SMS system was programmed for an irrigation frequency of three times per week.

The ET technology used was a Hunter Solar Sync system (Hunter Industries, San Marcos, CA) that is compatible with Hunter controllers. It uses a small sensor pack to measure solar radiation and temperature. This data is used to adjust controller run times. The sensor pack also includes a rain shutoff switch. A small module connects the sensor pack to the controller and automatically increases or decreases watering run times based on changes

in the weather. The station runtimes programmed in the ET system were for the peak watering month (July). Runtimes were set with the seasonal adjustment level set to 100%. The seasonal adjustment feature on the controller adjusts the run times daily based upon on-site weather conditions. The ET technology was installed such that the sensor pack received maximum sunlight during the day and had no obstructions to rainfall. One SMS system failed a few weeks into the study, which reduced that group to five participants.

Gross irrigation requirements and associated irrigation runtimes were computed for six residential sites which received educational material as a treatment (ED group). The ED group received laminated cards with zone run times for three irrigation periods and an extension publication that guided them on how to maintain quality turf in their landscape. Net irrigation requirements were computed using long-term reference ET and effective precipitation estimates. REF-ET (Allen, 1998), a compiled, stand-alone computer program that calculates reference evapotranspiration ( $ET_o$ ), was used to compute monthly reference ET using Raleigh-Durham (RDU) airport (35°52'40" N, -78°47'15" W) long term climate normals (NCDC, 1997) of temperature, dew point, percent sunshine, and wind speed. A crop coefficient of 0.8 was used to calculate turf ET ( $ET_c$ ) and effective precipitation was computed using the SCS TR-21 (USDA, 1970) method and subtracted from  $ET_c$  to obtain a net irrigation requirement. A run time adjustment of 1.25 (Water Requirements of North Carolina Turfgrass, 2006) was used to compute run times. Here run time adjustment corresponds to the inverse of system irrigation uniformity. For irrigation zones that had considerable shade, a landscape microclimate factor of 0.8 was assumed (CDWR, 2000).

Irrigation frequency adhered to the Town of Cary's water restriction requirements, i.e., three times a week.

To determine the irrigation requirement during the study period, weather data was obtained from two local weather stations. Solar radiation, relative humidity, temperature and wind speed data was obtained from the Lake Wheeler Road Field Laboratory weather station (35°43'41" N,-78°40'47" W) while precipitation data was obtained from the Apex weather station (Station ID: 310212) (35°74'25"N, -78°83'69"W) due to closer proximity to the residential sites and 100% availability of rainfall data.

The Control group received an audit of their irrigation system and was encouraged to irrigate their lawn as they normally would. As the Town of Cary has an ordinance requiring rain sensors, rain sensors were common to all the groups (the Solar Sync unit used by the ET group had a rain sensor integrated in the sensor pack).

### *3.8.1 Data Collection*

Data collection included weekly outdoor irrigation meter reading and turf quality rating for a period of five months (May through September 2009). ArcGIS (ESRI, 2006) was used to measure the turfgrass area of all the residences so that applied water could be converted to depth applied.

Turf quality was assessed using a Normalized Difference Vegetative Index (NDVI) using a Field Scout TCM 500 (Spectrum Technologies, Inc., Plainfield, IL) turf color meter, and visual turf quality rating. The NDVI meter measures color and converts it to a value on the same scale as the visual grass index. Turf was rated visually for each irrigation zone and

then averaged for each address. For NDVI readings, each zone was sampled at a minimum of four locations. The distance between the sampled locations varied according to the size of the irrigation zone. An average was computed for each address.

### *3.8.2 Statistical Analysis*

The PROC MIXED procedure of Statistical Analysis System (SAS, 1990) was utilized to test fixed and random effects in the model and least square means (lsmeans) (SAS, 2004) used to determine the differences in treatment means of both weekly water use and turf quality. Treatment was entered as a fixed effect in the statistical model while week and replication (geographical location) were treated as random effects. It was observed that, though all the treatments were assigned randomly, an unintentional biasness was found in the case of educational treatments. Most of the educational treatments were allocated to the residents with comparatively better turfgrass quality than other treatments. To acknowledge this biasness, the initial turfgrass quality reading was assigned an indicator variable and entered as a random effect in the model. Residuals were modeled as an autoregressive lag one process using the AR(1) option in a repeated statement to address autocorrelated errors. Address (location) was treated as the subject in the repeated statement.

## **3.9 Results and Discussion**

During the 20-week study period (May- September) the average daily maximum temperature was 30.5°C and cumulative rainfall was 464 mm while for the same period, the long-term normal maximum daily temperature and cumulative rainfall is 27.7°C and 347 mm

respectively (NCDC, 1997). Figure 3.2 shows the crop evapotranspiration and rainfall during the study period.

### *3.9.1 Water Use*

Treatment and week were significant factors in explaining mean weekly applied water ( $p < 0.0001$ ) while the interaction between treatment and week was not significant ( $p = 0.9996$ ). The SMS treatment applied the least amount of water, 15 mm/week, whereas the Control treatment had the highest average weekly irrigation water application of 27 mm/week. The SMS group was followed by the ET and ED groups in water conservation with average weekly water applications of 21 mm/week and 23 mm/week respectively. Average weekly water use by each treatment is shown in Figure 3.3. A distribution of weekly water use is shown in Figures 3.4-3.7. Table 3.1 shows the average weekly water applied by each treatment while Figure 3.8 shows the average monthly water applied by each treatment. All treatments, including the SMS treatment, applied more water than the gross irrigation requirement in the month of August and September (Figure 3.8).

The SMS and ET treatments applied 44% and 20% less water than the Control treatment respectively, while water savings by the ED treatment was 14% compare to the Control treatment. Comparing the two smart irrigation technologies, the SMS treatment applied 30% less water than the ET treatment ( $p = 0.0034$ ). No difference in average weekly applied water was observed between the ET and ED treatments ( $p = 0.4297$ ) and no significance difference was found between the Control and ED treatments ( $p = 0.0894$ ).

### *3.9.2 Turfgrass Quality*

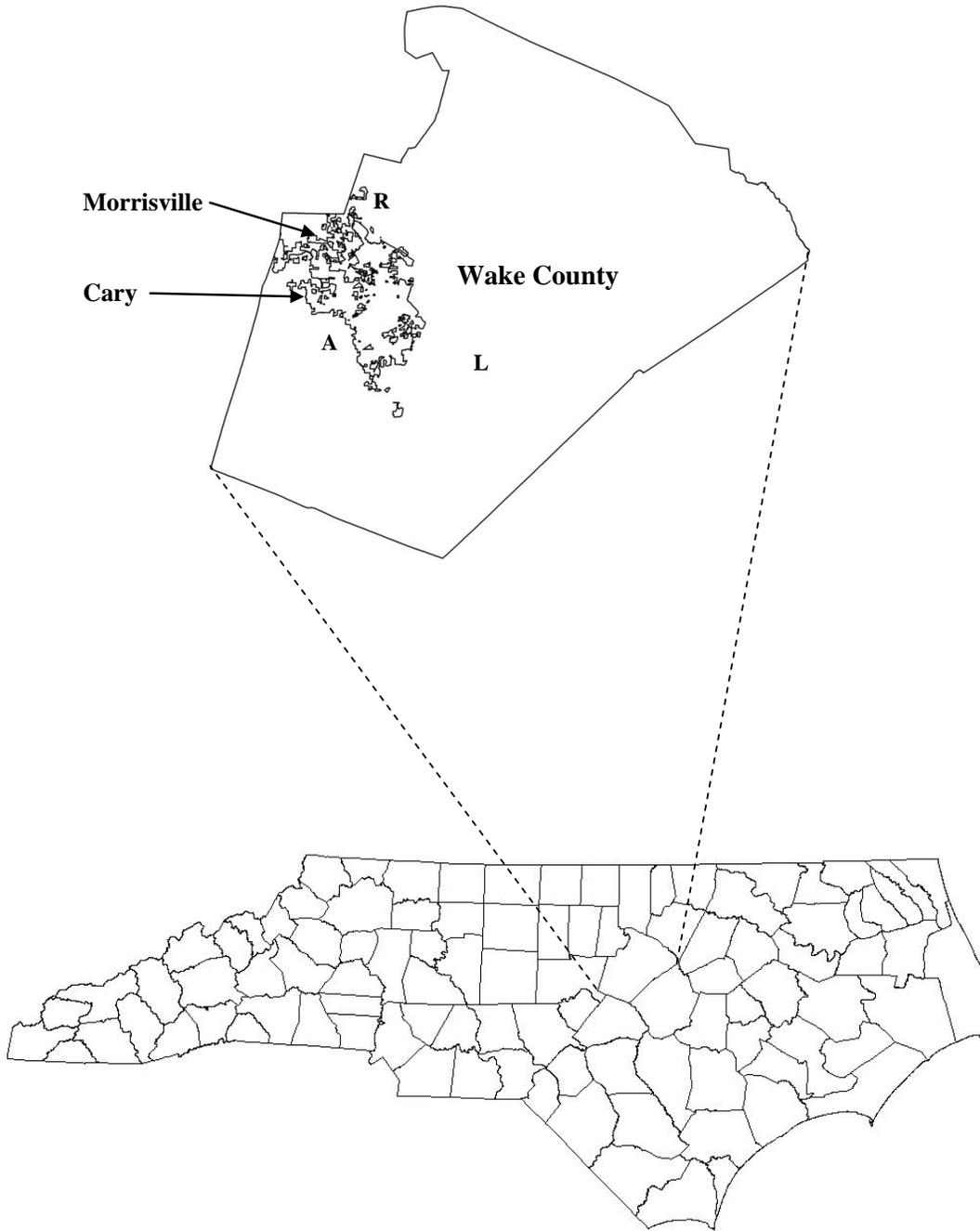
The ED and SMS treatments had the best average visual quality, followed by the ET treatment. The average visual turf quality of the Control treatment was below the acceptable level. The control treatment was lower than the SMS and ED treatments but not different from the ET treatment (see Table 3.2). According to visual ratings, a difference existed between the average turf quality of SMS and Control treatments but no difference was found between them in the case of NDVI ratings. The average NDVI value of the ED treatment was the best but none of the treatment was different from the other. Table 3.2 summarizes the results of the turf quality for each treatment over the study period.

### **3.10 Summary and Conclusions**

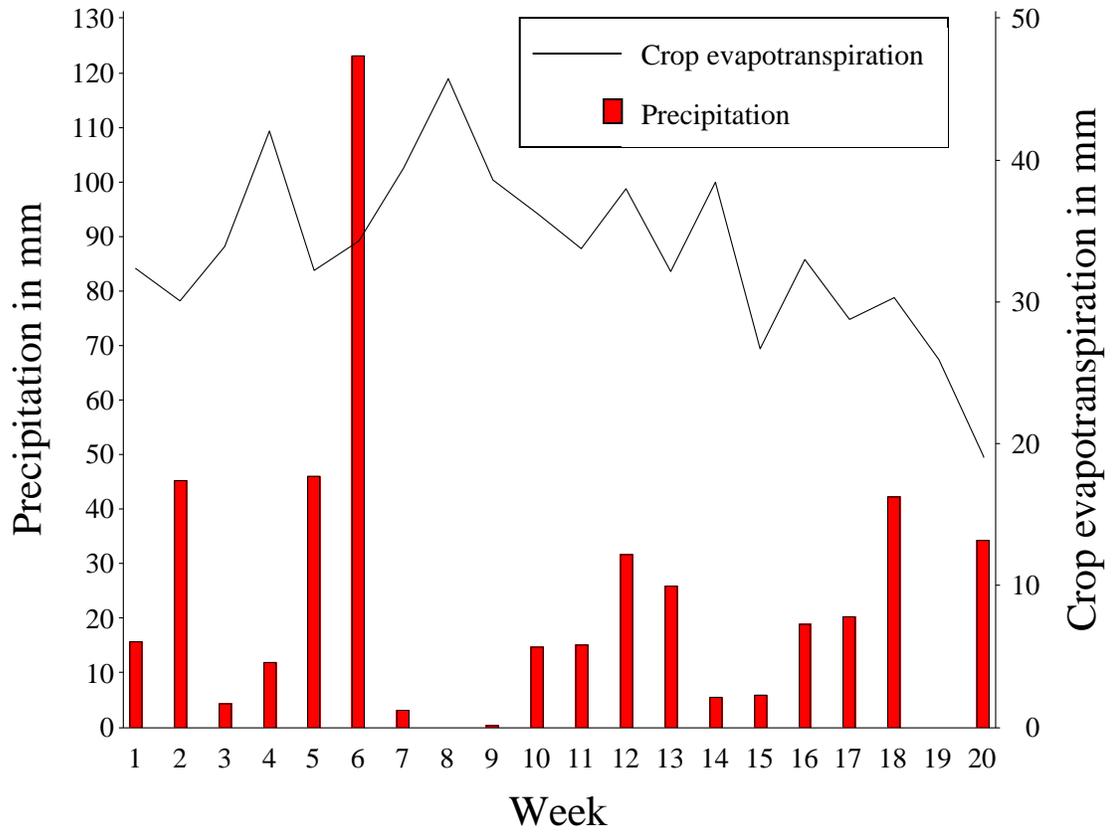
The control treatment applied the most water (an average of 27 mm per week) while the SMS and ET systems applied a weekly average of 15 mm and 21 mm, respectively. In comparison to the Control treatment, both smart irrigation technologies managed to significantly reduce water consumption. Water savings of the SMS treatment was 44% while that of ET treatment was 20%. Thus maximum water savings along with maintenance of acceptable turfgrass quality was achieved by the SMS technology followed by the ET technology.

The average visual turfgrass quality rating was found to be below the acceptance level only in the case of the Control treatment. On average, the ED treatment maintained better turfgrass quality than the other treatments.

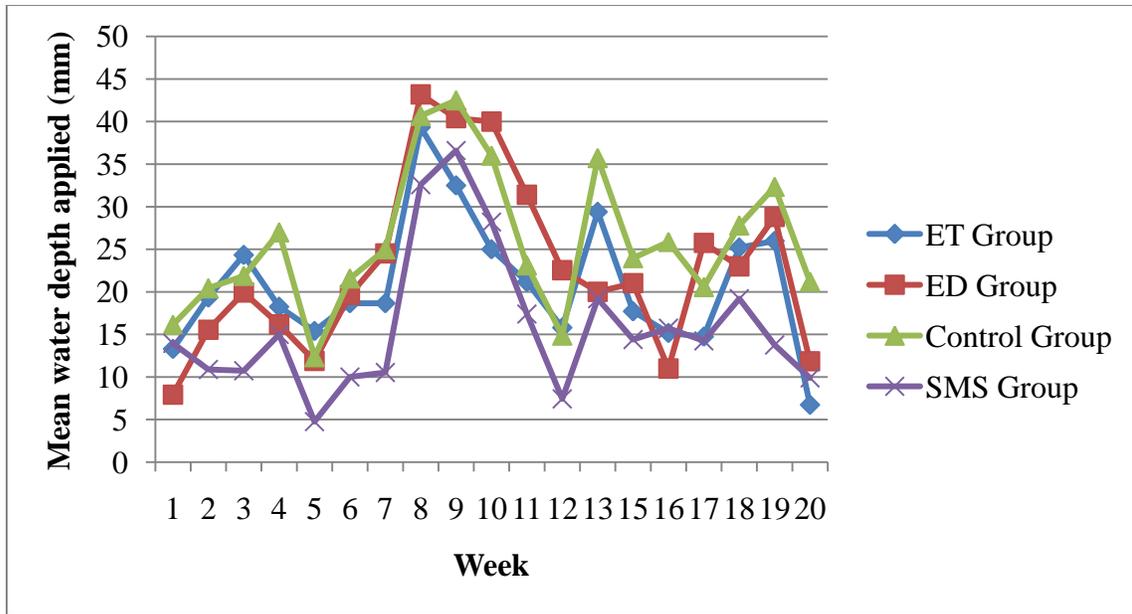
It should be noted that performance of these smart irrigation technologies depends not only on the water savings achieved but also on their capability to maintain the aesthetic quality of the turfgrass. Hence a good overall turf management program should be established and an efficient irrigation system maintained in order to obtain the full benefit of smart irrigation technologies.



**Figure 3.1** Map of site and weather station locations where A, L and R represent the Apex, Lake Wheeler and Raleigh-Durham Airport weather stations respectively.

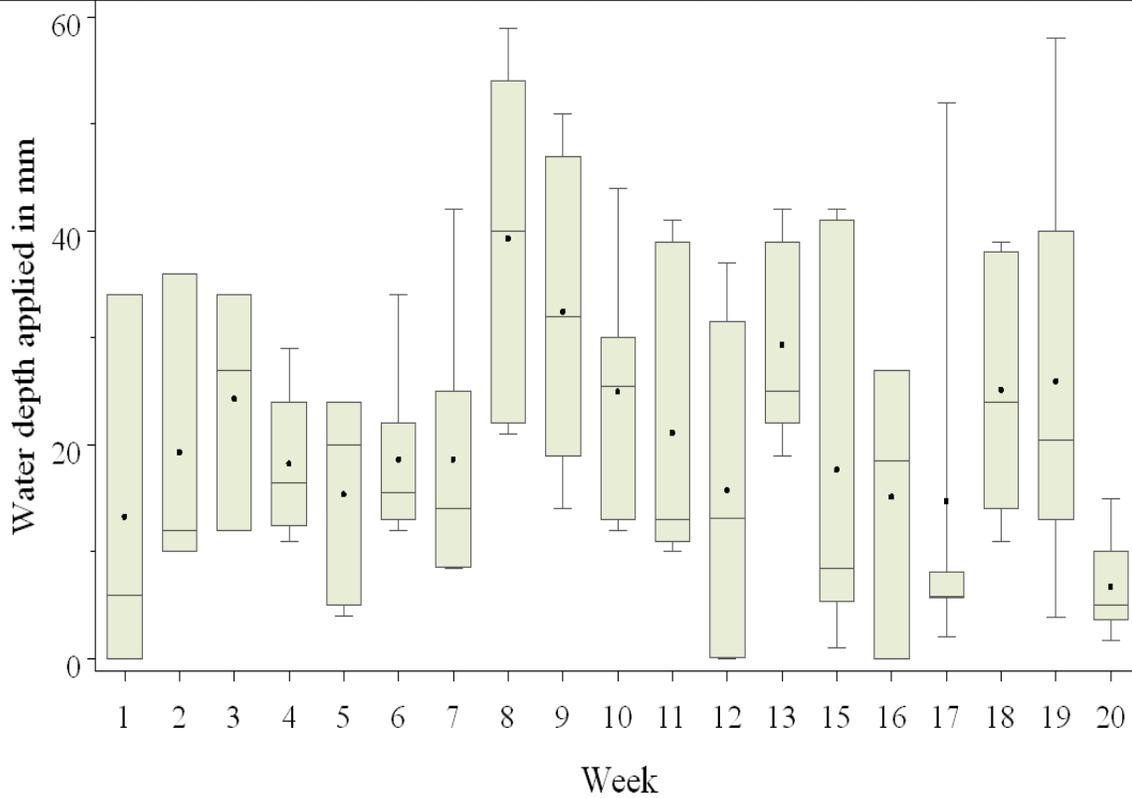


**Figure 3.2** Precipitation and crop evapotranspiration during the 20-week study period



**Figure 3.3** Weekly mean water depth applied by the different treatments during May-September (2009)

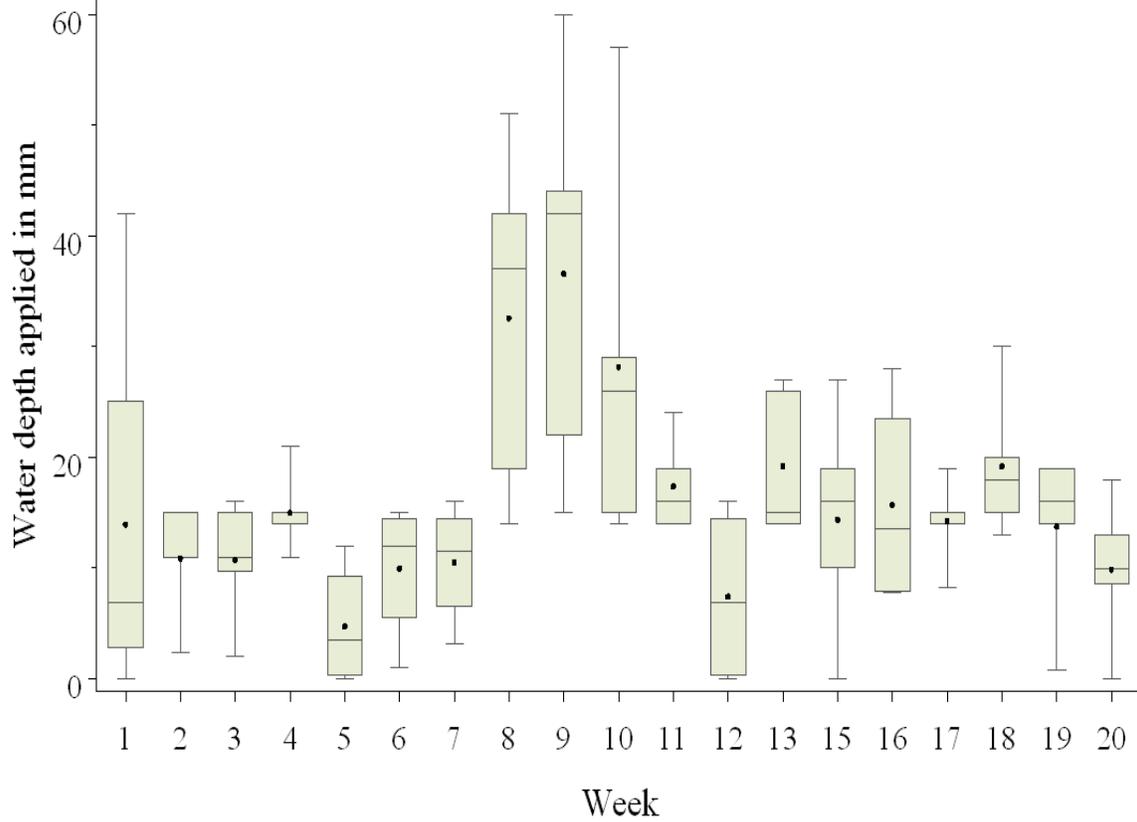
Mean	13.3	19.3	24.3	18.3	15.4	18.7	18.7	39.3	32.5	25.0	21.2	15.8	29.4	17.7	15.2	14.7	25.2	26.0	6.7
Min	0	10	12	11	4	12	8.4	21	14	12	10	0	19	1	0	2.1	11	3.9	1.7
Max	34	36	34	29	24	34	42	59	51	44	41	37	42	42	27	52	39	58	15



**Figure 3.4** Distribution of weekly applied water depth for ET treatment (n = 6)

**Note:** The center horizontal line in each box corresponds to the sample median and the black dot within box represents the mean. The bottom and top of the box corresponds to the 25<sup>th</sup> and 75<sup>th</sup> percentile respectively while the end of the whiskers represent maximum and minimum values.

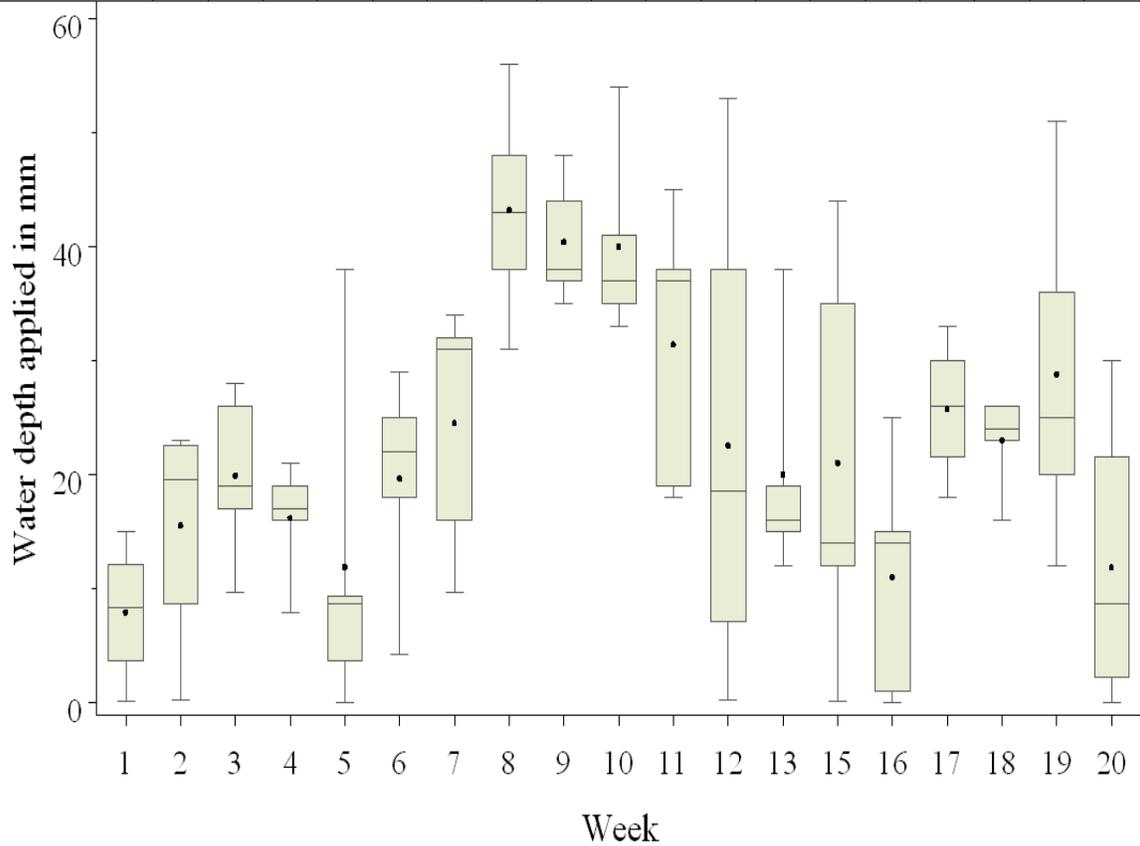
Mean	14.0	10.9	10.7	15.0	4.8	10.0	10.5	32.6	36.6	28.2	17.4	7.4	19.2	14.4	15.7	14.2	19.2	13.8	9.9
Min	0	2.4	2	11	0	1	3.1	14	15	14	14	0	14	0	7.8	8.2	13	0.8	0
Max	42	15	16	21	12	15	16	51	60	57	24	16	27	27	28	19	30	19	18



**Figure 3.5** Distribution of weekly applied water depth by SMS treatment (n = 5)

**Note:** The center horizontal line in each box corresponds to the sample median and the black dot within box represents the mean. The bottom and top of the box corresponds to the 25<sup>th</sup> and 75<sup>th</sup> percentile respectively while the end of the whiskers represent maximum and minimum values.

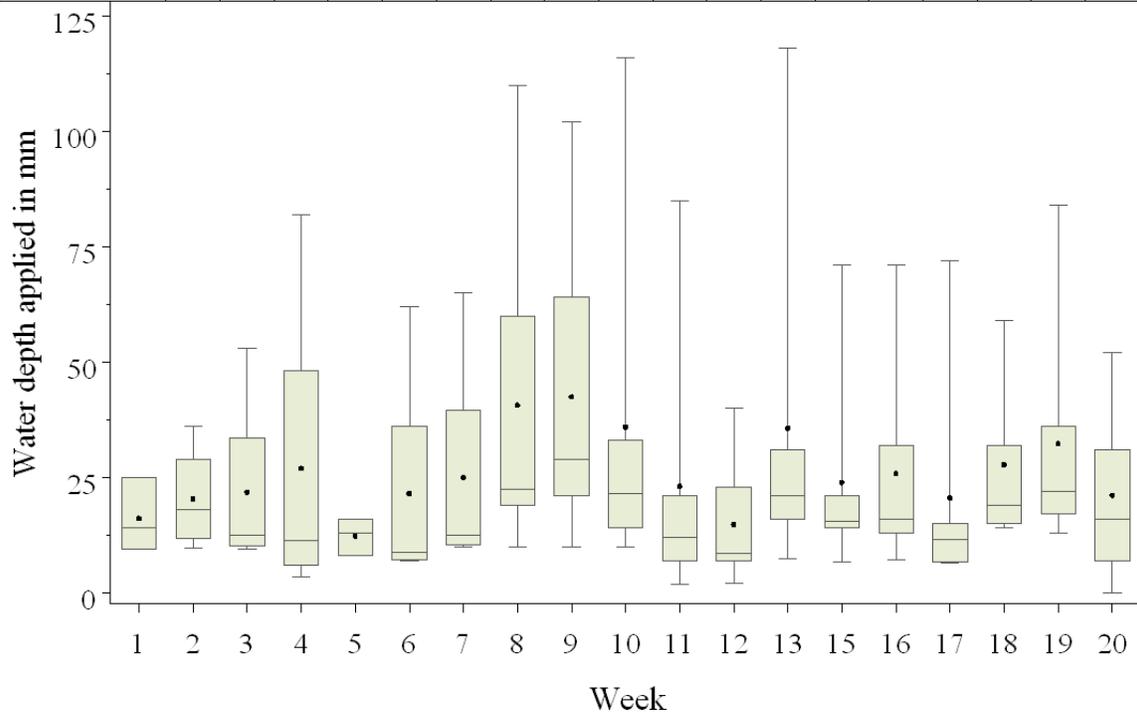
Mean	7.9	15.6	19.9	16.2	11.9	19.6	24.5	43.2	40.4	40.0	31.4	22.6	20.0	21.0	11.0	25.8	23.0	28.8	11.9
Min	0.1	0.2	9.6	7.9	0	4.2	9.6	31	35	33	18	0.2	12	0.1	0	18	16	12	0
Max	15	23	28	21	38	29	34	56	48	54	45	53	38	44	25	33	26	51	30



**Figure 3.6** Distribution of weekly applied water depth by ED treatment (n = 5)

**Note:** The center horizontal line in each box corresponds to the sample median and the black dot within box represents the mean. The bottom and top of the box corresponds to the 25<sup>th</sup> and 75<sup>th</sup> percentile respectively while the end of the whiskers represent maximum and minimum values.

Mean	16.1	20.4	21.9	27.0	12.3	21.6	25.0	40.7	42.5	36.0	23.1	14.9	35.7	24.0	25.9	20.6	27.8	32.3	21.2
Min	9.4	9.7	9.5	3.5	8	6.9	10	10	10	10	1.8	2	7.3	6.8	7.2	6.5	14	13	0
Max	25	36	53	82	16	62	65	110	102	116	85	40	118	71	71	72	59	84	52



**Figure 3.7** Distribution of weekly applied water depth by Control treatment (n = 6)

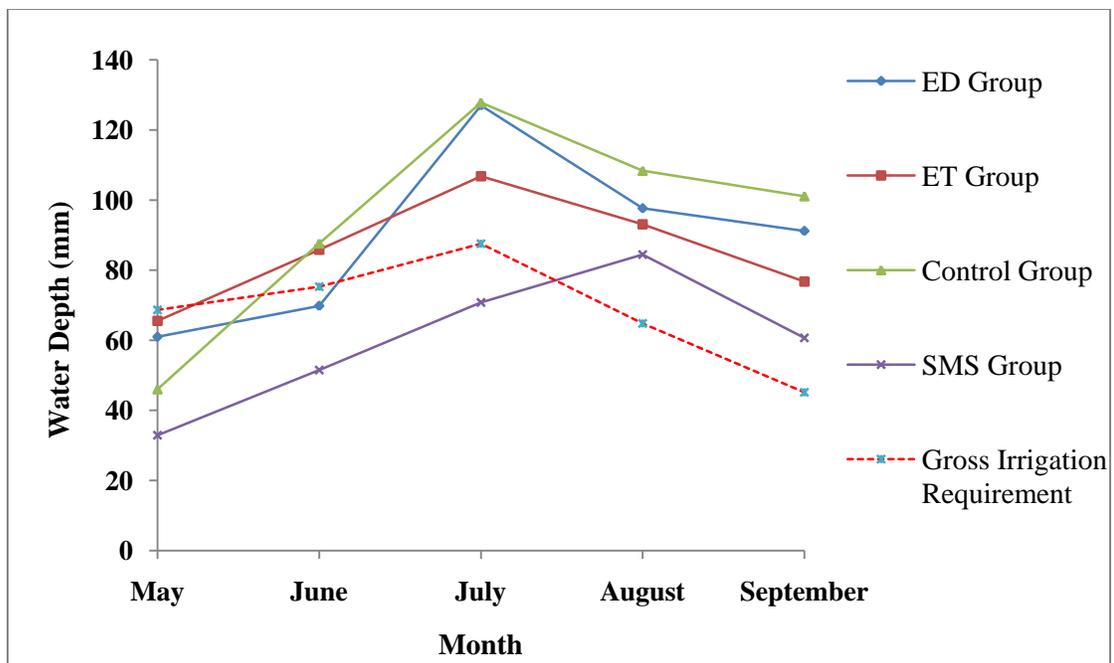
**Note:** The center horizontal line in each box corresponds to the sample median and the black dot within box represents the mean. The bottom and top of the box corresponds to the 25<sup>th</sup> and 75<sup>th</sup> percentile respectively while the end of the whiskers represent maximum and minimum values.

**Table 3.1** Average weekly water applied by treatment

Treatment	Average depth of water applied per week (mm) <sup>†</sup>
ET	21.3 b
ED	22.9 bc
Control	26.7 c
SMS	15.0 a

**Note:** One 2-week period included in the calculation of average weekly water applied.

<sup>†</sup> F-values with the same letter within a column are not different at 95% probability level using LSD mean separation test.



**Figure 3.8** Mean monthly applied water depth by each treatment and the gross irrigation requirement for the period of study in 2009

**Table 3.2** Mean turf quality and NDVI readings for three irrigation technology treatments and a control. Data taken using a 1 to 9 scale with 1 equal to dead turf and 9 as ideal turf quality turf quality or NDVI reading

Treatment	Visual Rating †	NDVI meter rating †
ET	6.4 ab	6.7 a
ED	6.8 a	6.9 a
Control	5.6 b	6.7 a
SMS	6.9 a	6.8 a

† F-values with the same letter within a column are not different at 95% probability level using LSD mean separation test.

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