ABSTRACT

VICK, JR., ROBERT LINWOOD. Residential Irrigation and Water Conservation Potential of Smart Irrigation Technologies in the Catawba-Wateree River Basin. (Under the direction of Dr. Garry L. Grabow).

Residential irrigation accounts for a large portion of municipal water withdrawals. High value landscapes require irrigation during periods when evapotranspiration (ET) exceeds rainfall to prevent irreversible plant stress, hence automated irrigation systems have become common components of the modern day residence, even in the humid southeastern United States. Coupled with population growth and recent droughts, these conditions have strained water supplies and challenged water managers to find new ways to conserve. In an increasingly fast paced society, water conservation must not only be sold as necessary, but also must be made convenient. As manager of thirteen hydropower electric stations and eleven reservoirs along the Catawba-Wateree River Basin, Duke Energy, has taken interest in "smart irrigation" technologies as a means to meet the modern needs of water conservation and convenience.

In 2009, Duke Energy joined with North Carolina State University (NCSU) to fund a three year residential water use study considering irrigation practices and water conservation potential of smart irrigation controllers in the Catawba-Wateree River Basin. The objectives of the study were to 1) quantify residential irrigation water withdrawals from Duke Energy lakes via a survey instrument and sampling at thirty-six homes along three Duke Energy lakes and 2) evaluate potential water savings of two ET based controllers and one soil-moisture sensor based controller.

This study was different from other smart irrigation studies in that the direct irrigation water source was a Duke Energy lake, not a municipal system. Additionally, none of the

study sites had irrigation water meters prior to the study and there was no charge for use of lake water.

Notifications of an online survey pertaining to irrigation systems and practices were sent to about 19,000 lakeside lot owners, from which 1405 responses were received. Survey responses were used to help select thirty-six sites (twelve each on Lake Hickory, Lake Norman, and Lake Wylie) that had a Duke Energy lake as their irrigation water source to be included in the study. Water meters with data loggers were installed on each irrigation system at the beginning of the 2009 irrigation season. Irrigation system audits were also conducted at each site. Average low quarter distribution uniformities (DU_{LQ}) were 0.28 and 0.37 across all sites for spray and rotor zones, respectively. The average weekly irrigation applied across all thirty-six sites in 2009 was 22.2 mm wk^{-1}, with sites on Lake Wylie withdrawing the most water.

In 2010, two types of ET controllers, one that relied on an offsite weather service (Toro) and one that included an onsite weather module (WM), and a soil-moisture sensor add-on controller (SMS) were installed at twenty-seven of the thirty-six study sites, with the remaining nine making up a control group (Ctrl). The SMS treatment applied the most water per week (31.9 mm wk^{-1}) and there were no differences among average weekly irrigation depths for the Ctrl (26.6 mm wk^{-1}), Toro (23.8 mm wk^{-1}), and WM (23.5 mm wk^{-1}). Although it applied more water, the SMS treatment also reduced the average difference (Diff) between weekly irrigation applied (I_{app}) and weekly gross irrigation requirement (GIR) from 2009 to 2010 by 15.7 mm wk^{-1}, compared to reductions of 8.7 mm wk^{-1} and 5.9 mm wk^{-1} for Toro and WM, respectively. Only the Ctrl treatment had an average turf quality visual rating (5.0) that was less than minimally acceptable (6.0). There were no significant differences in turf quality between the smart technology treatments, but there was evidence that homeowners manually changed their irrigation schedules during the season. In many cases, changes were made without notifying study representatives, and were presumably based on the perception of the homeowner that the smart technologies were not adequately meeting turf water demands.

Survey results and measured water use from 2009 were used to develop prediction methods for estimating weekly irrigation withdrawals for homes with automated in-ground irrigation systems that use a Duke Energy lake as their source. Audit data revealed that many of the survey responses for the thirty-six cooperators were incorrect, giving reason to question the potential of using the survey data to build withdrawal predictions. It was estimated that during irrigation weeks, total weekly direct water withdrawals from Duke Energy lakes for residential irrigation would equal 488.1 ML wk^{-1}, or 69.7 ML d^{-1} (18.4 MGD).

Residential Irrigation and Water Conservation Potential of Smart Irrigation Technologies in the Catawba-Wateree River Basin

by
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DEDICATION

First and foremost, this project is dedicated to the honor and glory of my Lord and Savior, Jesus Christ. My commitment to Him is the least that I can offer for His unfailing love for me.

Secondly, my work on this project is dedicated to my grandmothers, Betty Williams Vick and Elizabeth Parker Harrison, both of whom had vital roles in bringing me to this point in my life and both of whom have graduated to their eternal glory with Him. Thank you Grandma Betty and Grandma Lib.

> *"A man who was merely a man and said the sort of things Jesus said would not be a great moral teacher. He would either be a lunatic - on the level with a man who says he is a poached egg - or he would be the devil of hell. You must take your choice. Either this was, and is, the Son of God, or else a madman or something worse. You can shut Him up for a fool or you can fall at His feet and call Him Lord and God. But let us not come with any patronizing nonsense about His being a great human teacher. He has not left that open to us."*
>
> -C.S. Lewis, *Mere Christianity*

BIOGRAPHY

Robert "Bobby" Linwood Vick, Jr. was born in Rocky Mount, North Carolina on May 31, 1987. Raised in Wilson, North Carolina, he is the only child of Robert and Martha Vick. Bobby developed a love for the game of baseball at an early age, much like his paternal grandfather Linwood Beal "Ben" Vick, Jr., whom he never knew. Bobby played baseball from the age of four until he graduated from Ralph L. Fike High School in 2005. Robert, like many others throughout generations of Bobby's family, was a tobacco farmer during Bobby's early childhood until changes in the industry directed him into the furniture business in 1999. Martha was the executive director of the Tobacco Farm Life Museum in Kenly, North Carolina until going to work for the Wilson Education Partnership while Bobby was in elementary school. Even after his parents left careers that were directly associated with North Carolina agriculture, agriculture remained an important part of the family life. Until this day, Robert and Martha maintain a large vegetable garden behind the house that Bobby's Grandma Betty lived in, which happens to be next door to theirs.

Growing up, Bobby spent many afternoons and summers at Grandma Betty's house with his cousin Susan, who was more like a sister, waiting for his parents to get home. He has fond memories of them coming home and changing clothes to go work in the garden, even though the work part was never particularly appealing to him.

Around the age of nine, Bobby was given permission to start what many would call the chore of cutting grass. Since completing this chore meant the chance to drive the riding lawn mower, it was a task that Bobby quickly came to enjoy. He spent many summers cutting grass at neighboring houses and with his Uncle Dennis, who had a lawn care business, to earn a little extra cash even through starting college.

It was during those spring days on the baseball field, those hot summer evenings in the garden, and those muggy afternoons on a lawn mower that Bobby developed the appreciation and love for agriculture that he has today. Specifically, Bobby became fascinated with how and why plants grow, and specifically the role of water in the growth process. He always enjoyed the pristine appearance of a freshly cut infield with irrigation running in the background, often trying to mimic the striped turf patterns in his parents front yard. It was always a treat for him to ride down country roads in June and see large travelling gun irrigation reels running through tobacco fields or the occasional center pivot system in the fields on the way to Grandma Lib's in Williamston.

Upon graduation from high school, Bobby attended North Carolina State University, receiving a Bachelor of Science in Biological and Agricultural Engineering, with concentrations in Agricultural Engineering and Environmental Engineering in 2009. As an undergrad, Bobby had the opportunity to work as a part-time assistant on a "smart irrigation" project for Dr. Garry L. Grabow. It was on this project that Bobby discovered the opportunity to blend his academic interests with his childhood fascinations. Following graduation, Bobby began work on his Master of Science degree under Dr. Grabow on smart irrigation technologies.

Bobby married the love of his life, Meredith Sullivan Vick, whom he has known all of his life, on July 17, 2010. They currently live in Cary, North Carolina. Bobby is pursuing a PhD also in Biological and Agricultural Engineering at NC State under Dr. Mike D.

Boyette and hopes to follow with a career that will allow him to contribute back to the agricultural community that has had such a large role in his development.

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I would like to acknowledge all those who have contributed to this project in anyway. First and foremost, thank you Dr. Grabow for providing me the opportunity to work on this project and for your essential guidance, hard work, and especially patience along the way. You are an incredibly gifted and detailed academic, but an even greater person. I also appreciate the assistance and involvement of my other committee members, Dr. Huffman and Dr. Miller, on this project. I know it rare that a student has committee members that all have an active role throughout the duration of his or her research project, but I was fortunate to experience exactly that scenario.

I would like to thank Duke Energy and the Catawba-Wateree Water Management Group for funding this research. A specific thank you is due to Phil Fragapane of Duke Energy for his leadership on this project and for making sure that all of the logistics worked out successfully. Thank you also to all of the thirty-six study cooperators for literally opening your homes so that we could conduct the research of this project.

Thank you Phil Harris, Carl Tutor, L. T. Woodlief, Joe Moore, and John McNeill for your work on this project. Thank you Ihab Ghali and Mayank Nautiyal for sharing your experiences from working on similar projects. Thank you Brandon Batten, Xu Zhou "Joshua," and Tiffany Messer for being great office mates. And thank you to all of my fellow graduate students who have shared many great times and especially meals together.

To my parents, thank you for your incredible love and support that you have always shown me and for the guidance you have always provided me. You have given me a

wonderful example of what it is and what it takes to be a loving family and for that I cannot thank you enough.

Lastly, but most importantly, to my beautiful wife Meredith, thank you for listening, for talking, for waiting, for pressing, for praying, for encouraging, for not being afraid to say what needed to be said, for laughing, for crying, for smiling, and most of all, for loving me. I admire you more than anyone in the world and I love you more each day. Thank you for your love and for making me an incredibly blessed man.

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CHAPTER 1. REVIEW OF LITERATURE

Introduction

Continued population growth in the United States, coupled with severe regional droughts in recent years, has increased the demand for fresh water. Subsequently, water managers, in both private and public sectors, have been forced to reprioritize their water allotments while seeking improved methods of water conservation. Despite this need to conserve water, homeowners still desire a visually appealing landscape, which usually requires some sort of regular irrigation to supplement plant water needs not met by rainfall. As a result, irrigation systems have become considered as a "standard appliance" (Dukes, 2009) for many homeowners and have created a demand that consumes as much as 71% (Baum et al., 2005) of some municipal supplies. Thus, many water managers have either imposed irrigation restrictions or have at least begun looking for ways to reduce the amount of water that is used for irrigation.

Duke Energy can be classified as one of such water managers because it owns and manages several lakes along the Catawba and Wateree Rivers in North and South Carolina. Bordering these Duke Energy Lakes are thousands of residential lots of various sizes. Many of these lots have automated irrigation systems that draw water from the lakes. However, current water withdrawals are unknown because these systems are not metered. Duke Energy does not charge homeowners for the use of the lake water and restrictions on irrigation times are rarely implemented. These conditions along with the recent droughts and increased development alongside the lakes have resulted in large volumes of water being withdrawn from the lakes for irrigation of turf and landscape. As are other water managers, Duke Energy is interested in quantifying the amount of water that is being withdrawn for irrigation, as well as looking for ways to conserve the strained supply of the Catawba-Wateree River Basin.

Irrigation Management

Most residential irrigation systems apply water through rotor or spray sprinklers that are operated by timer-based controllers. Irrigation events are programmed into the controllers and run for a prescribed amount of time when the scheduled events occur. Ideally, the application events deliver a sufficient amount of water to the soil profile to replace any water deficiency, but no more. Proper irrigation management requires an understanding of plant, soil, and atmospheric interactions.

Soil Water Storage

Soil is composed of three primary components: solids, air, and water. The soil solid fraction usually comprises 35% to 75% of the total soil volume with the remaining volume consisting of pore space, which can be filled with either air or water. The percentage of the total soil volume that is made up of pore space is known as the soil porosity. Soil porosity affects the soil water holding capacity. Additional soil properties, including texture and structure, also affect the ability of the soil to store and release water.

Sustaining optimal plant growth requires that the soil water content (SWC) be maintained between an upper threshold, above which additional water would go to waste, and a lower boundary, below which an unacceptable amount of plant stress would occur. The upper limit is normally field capacity (FC), which is “the water content after a soil is well wetted and allowed to drain 1 to 2 days” (Fangmeier et al., 2006). Permanent wilting point (PWP) is the “lower limit of water available to plants” (Fangmeier et al., 2006) or the moisture content at which plants will permanently wilt (USDA, 1993). The difference between FC and PWP is the plant available water (AW) and is calculated as:

$$AW = \frac{(\theta_{FC} - \theta_{PWP}) \times RZ}{100} \quad [1.1]$$

where,

AW = available water, mm

θ_{FC} = volumetric soil water content at field capacity, %

θ_{PWP} = volumetric soil water content at permanent wilting point, %

RZ = root zone depth, mm.

Only a portion of the plant available water can be removed by the plants before stress will begin to occur, therefore irrigation should be applied before the PWP is reached. The depth of soil water that can be depleted before irrigation is necessary is readily available water (RAW) and is a function of the management allowed depletion (MAD). MAD is determined by the irrigation manager depending on how much plant stress is acceptable. Readily available water is defined as:

$$RAW = MAD \times AW \quad [1.2]$$

where,

RAW = readily available water, mm

MAD = management allowed depletion, fraction

AW = available water, mm.

Irrigation should be applied when the RAW has been depleted, but the application depth should not raise the SWC above FC. If the crop is in a region that receives rainfall during the growing season, irrigation should return the SWC to less than FC to allow storage for rainfall events.

Effective Precipitation

Effective precipitation (P_e) is the portion of total precipitation (P) that contributes to the consumptive water requirements of plants (Obreza and Pitts, 2002). Rainfall that exceeds the soil water storage capacity is lost via runoff (RO) or deep percolation (DP) and typically does not benefit plants. P_e is defined as (Obreza and Pitts, 2002):

$$\mathrm{P_e = P - RO - DP} \qquad [1.3]$$

Effective precipitation can be estimated posteriori using a daily soil water balance, but is commonly predicted on a monthly basis for irrigation scheduling using the NRCS (formerly SCS) TR-21 methodology (USDA, 1970). The equation for estimating effective rainfall is (Fangmeier et al., 2006):

$$\mathrm{P_e = f(D)\left[1.25{P_m}^{0.824} - 2.93\right]\left[10^{0.000955ET_c}\right]} \qquad [1.4]$$

where,

P_e = monthly effective precipitation, mm

P_m = monthly mean precipitation, mm

ET_c = monthly mean crop evapotranspiration, mm

f(D) = soil water storage factor.

The soil water storage factor is defined by:

$$f(D) = 0.53 + 0.0116D - 8.94 \times 10^{-5}D^2 + 2.32 \times 10^{-7}D^3 \qquad [1.5]$$

where,

D = the usable soil water storage, mm.

The term D is usually calculated as 40% to 60% of the available soil water holding capacity within the plant root zone, depending on the irrigation management practices used (USDA, 1993).

Evapotranspiration

Evapotranspiration (ET) is the process by which water is lost to the atmosphere by evaporation from wet surfaces and by transpiration from plant material (Allen et al., 1998). Evaporation is defined as "the transfer of liquid surface water into vapor in the atmosphere" (Fangmeier et al., 2006) and can occur from a range of surfaces, including open water bodies, soil particles, and wet vegetation. Transpiration is also the vaporization of liquid water into the atmosphere, but it takes place within the plant tissue and is controlled by the stomata of the plant. A high percentage of water that is taken up by plants is released into the atmosphere via transpiration, while only a small portion is retained for use within the plant itself (Allen et al., 1998).

ET is affected by several factors, namely weather, crop characteristics, management decisions, and soil properties. The predominant weather factors affecting ET are solar radiation, temperature, relative humidity, and wind speed. Solar radiation and heat from the ambient air provide the energy needed to drive the phase change of water in ET. Relative humidity affects the vapor pressure gradient between the evaporative surfaces (leaf and soil surfaces) and the atmosphere, which also drives the process of ET. Wind speed affects the rate at which dry air replaces saturated air during the ET process. Crop characteristics, including plant type and stage of growth, affect the rate of ET. Additionally, different plants have varying degrees of stomatal resistance, which regulates transpiration rates depending on plant water availability. Crop management decisions, such as nutrient application and irrigation frequency, can also affect ET rates by increasing or decreasing the plant water demand and by changing the level of soil water depletion.

Reference Evapotranspiration

Because of the various factors that affect ET and the challenges of measuring it directly, numerous methods have been developed for estimating its value. Crop specific evapotranspiration (ET_c) is rarely measured directly and is instead more commonly estimated using reference evapotranspiration (ET_o), which can be related to ET_c by a crop coefficient K_c (Allen et al., 1998). Methods for estimating ET_o include soil water balance with lysimeters (Allen et al., 1998) or soil water sensors, eddy covariance methods (Jia et al., 2009), and pan evaporation (Fangmeier et al., 2006) in which ET_o is related to measured pan evaporation (E_{pan}) via a conversion factor (K_{pan}). Additionally, numerous mathematical models that require various weather inputs have been developed for estimating ET_o. The most commonly used equation is the Penman-Monteith, which was originally proposed in 1965 by John Monteith and was developed on the basis of previous work by Howard Penman (Penman, 1948). This "combination equation," as it is commonly termed, has been modified and adjusted multiple times since its inception to better fit the model to specific conditions. The ASCE Standardized Penman-Monteith equation for daily time steps and a short reference crop (grass) is (Allen et al., 1998):

$$\mathrm{ET_o} = \frac{0.408\Delta(\mathrm{R_n} - \mathrm{G}) + \gamma \frac{900}{\mathrm{T} + 273}(\mathrm{e_s} - \mathrm{e_a})\mathrm{u_2}}{\Delta + \gamma(1 + 0.34\mathrm{u_2})} \qquad [1.6]$$

where,

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

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

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

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

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

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

e_a = actual vapor pressure at mean daily air temperature, kPa

Δ = slope of the saturation vapor pressure curve at mean air temperature, kPa°C^{-1}

γ = psychometric constant, kPa °C^{-1}.

Software packages such as Ref-ET (Allen, 2004) allow users to quickly generate daily ET_o estimates using the desired version of the Penman-Monteith equation, with the input of climatological data, including temperature, solar radiation, humidity, wind speed, and precipitation, and site information.

For water managers that desire a more direct estimation of ET_o, an additional option exists in the in-field installation of an atmometer. An atmometer consists of a covered ceramic evaporator atop a reservoir filled with distilled water. The covered ceramic evaporator mimics the desired ET_o dependent on the type of cover selected. A sight tube on the side of the atmometer reservoir allows the user to view the depth of water depleted due to ET in the same manner that one would read rainfall depths in a rain gauge. Studies have shown that atmometer estimates of ET_o were comparable to those generated using the Penman-Monteith equation for the same site, but without the cumbersome requirement of entering extensive weather data (CSU-CE, 1999; Alam and Elliott, 2003).

Irrigation Requirement

When determining the irrigation requirement for a given period of time, it is useful to consider the soil water balance, which is a form of a mass balance equation, which written in its simplest form is:

$$\text{Input} - \text{Output} = \text{Change in Storage} \qquad [1.7a]$$

In the soil system, inputs are irrigation, precipitation, and capillary rise and outputs are evapotranspiration, deep percolation, and runoff (Blonquist et al., 2006). The soil water balance can therefore be rewritten as:

$$(\mathrm{I} + \mathrm{P} + \mathrm{CR}) - (\mathrm{ET_c} + \mathrm{DP} + \mathrm{RO}) = \Delta\mathrm{S} \qquad [1.7b]$$

where,

I = irrigation, mm

P = precipitation, mm

CR = capillary rise contribution, mm

ET_c = crop evapotranspiration, mm

DP = deep percolation, mm

RO = surface runoff, mm

ΔS = change in soil water storage, mm.

If the crop has a shallow root zone or the water table is deep, CR can be considered negligible. Given that $P_e = P – RO – DP$ (eq. 1.3) and assuming that irrigation does not contribute to runoff or drainage, the water balance can be rewritten as:

$$\mathrm{I} + \mathrm{P_e} - \mathrm{ET_c} = \Delta\mathrm{S} \qquad [1.7c]$$

Irrigation (I) as defined above is independent of P_e, ET_c, and ΔS, though it does affect ΔS. ΔS is often measured as the deviation in the soil water content from some desired level (typically at or just below FC) and irrigation management seeks to maintain ΔS as close to zero as possible. The irrigation required to keep ΔS equal to zero is a function of P_e and ET_c and is called the net irrigation requirement (NIR). NIR is defined as:

$$\mathrm{NIR} = \mathrm{ET_c} - \mathrm{P_e} \qquad [1.8]$$

The amount of water actually applied will normally need to exceed NIR to account for irrigation system inefficiency. This value is called the gross irrigation requirement (GIR) and is determined based on the irrigation system uniformity:

$$\mathrm{GIR} = \frac{\mathrm{NIR}}{\mathrm{Irrigation\ System\ Uniformity}} \qquad [1.9]$$

Uniformity is used instead of efficiency because of the difficulty in measuring irrigation efficiency, the percentage of total irrigation that is beneficially used.

Distribution Uniformity

The efficiency of an irrigation system can be defined as the percentage of total irrigation that is beneficially used. Because irrigation efficiency is difficult to quantify, distribution uniformity (DU) is commonly used as an "indicator of potential efficiency for sprinkler irrigated areas" (Baum et al., 2005). DU is a measure of how uniformly irrigation is applied over an irrigated area and is often presented as low quarter distribution uniformity (DU_{LQ}), which can be calculated as:

$$\mathrm{DU_{LQ}} = \frac{\overline{\mathrm{D}}_{\mathrm{LQ}}}{\overline{\mathrm{D}}_{\mathrm{TOT}}} \qquad [1.10]$$

where,

DU_{LQ} = low quarter distribution uniformity

$\overline{D}_{LQ}$ = average depth of low quarter catch measurements

$\overline{D}_{TOT}$ = average depth of all catch measurements.

A high DU in itself does not guarantee a highly efficient irrigation system because over application, regardless of uniformity, will still result in inefficiency, but application efficiency and therefore overall system efficiency cannot be high without also having a high DU.

Residential Irrigation Practices

Nationwide, landscape irrigation accounts for approximately one-third of all residential water use (EPA, 2008). In a study to evaluate and quantify "end uses" of residential water, Mayer et al. (1999) found that homes with in-ground sprinkler systems used 35% more water outdoors than homes without. The same study revealed that homes that use an automatic timer to control irrigation used 47% more water outdoors than those without. Rates at which homeowners irrigate vary based on several factors including geographic location and season (EPA,2008; Aurasteh et al., 1984), but multiple studies have found that homeowners tend to irrigate beyond plant water requirements (Aurasteh et al., 1984; Barnes, 1977; Haley et al., 2007).

In a study of twenty private lawns in Logan, Utah, Aurasteh et al. (1984) found that solid set irrigation systems applied 38% more water than the plant ET requirements. Similarly, Barnes (1977) found that homeowners in two Wyoming cities applied irrigation at rates ranging from 122% to 156% of seasonal ET rates. A recent study of monthly residential irrigation totals in Central Florida found that timer-based irrigation systems that were controlled by the homeowners applied 2.4 times the calculated irrigation requirements (Haley et al., 2007). Similar systems on similar landscapes in the study that had their time clocks adjusted seasonally based on historical ET data applied 30% less water than the control group, but still substantially over irrigated.

Part of the reason for over-irrigation in many residential systems is that irrigation run times have been increased to compensate for low distribution uniformity. Studies have found that DU_{LQ} for residential systems is typically about 0.50, regardless of what type of sprinkler head is being used (Baum et al., 2005; Mecham, 2004). This, in part, can be attributed to smaller irrigated areas (as compared to traditional agricultural irrigated areas) and irregular shapes in irrigated landscapes (Aurasteh et al., 1984); however, much of the problem is associated with poorly designed, installed, and/or maintained systems.

While placing the blame on the systems themselves can be justified and has appeal because of the perception that "if it is a physical flaw, we can fix it," the reality is that over-irrigation is largely a product of human mismanagement, which seems to be a more challenging problem to address. Most homeowners "have no idea" whether or not they are irrigating their lawn in an efficient way (Aurasteh et al., 1984). Despite the continually changing irrigation demands throughout the growing season, most homeowners infrequently, if ever, change their watering schedules during the growing season (Addink and Rodda, 2002). A multidisciplinary study by Endter-Wada et al. (2008) aimed at understanding landscape water use suggested that convenience is the motivating factor that explains over-watering with automated systems and under-watering with manual systems. Just as it is more convenient for residents that rely on hose watering of their lawn to under-water because of the labor required, it is convenient for homeowners with automated systems to schedule their run times for peak demand and then allow over-irrigation throughout the season because of the inconvenience involved in adjusting the watering schedule. Thus there is a need not only for better designed and functioning irrigation systems, but also for systems that make water conservation more convenient. Tools that are quickly gaining interest for their water conservation potential and ease of use are “smart irrigation” technologies.

“Smart Irrigation” Technologies

The most recent development in the approach to address over-irrigation in residential settings has been the introduction of “Smart Controllers” (IA, 2007). According to the Irrigation Association, “smart controllers estimate or measure depletion of available plant soil-moisture in order to operate an irrigation system, replenishing water as needed while minimizing excess water use” (IA, 2007). The two most common forms of these smart technologies are evapotranspiration (ET)-based controllers and soil-moisture sensor (SMS) controllers. There are forms of both technologies that can be purchased as add-ons to standard timer based systems as well as stand-alone controllers, which completely replace standard controllers. ET controllers and SMS controllers are relatively new technologies in the residential irrigation sector, thus there have only been a limited number of scientific studies on both technologies (McCready et al., 2009).

ET Controllers

Evapotranspiration-based controllers work on the same premise of the water balance described in the Irrigation Requirement section. ET controllers use either current or historic weather data to estimate the ET needs of the plants being irrigated, and subsequently adjust the irrigation schedule (McCready et al., 2009). Some ET controllers have weather modules installed on the irrigated site that send collected weather data to the controller. This data is then used to estimate ET_o. Other ET controllers rely on weather data that is collected from nearby weather stations. The weather data is typically collected by a third party service, which estimates ET_o for the location and then broadcasts it back to the controller. Some ET controllers (e.g., the Toro Intelli-Sense) are capable of using ET_o estimates to calculate irrigation runtimes and days while others (e.g., the Rainbird ET Manager) do not actually alter run times, but simply are capable of bypassing scheduled irrigation events based on the calculated soil-moisture content (McCready et al., 2009).

An 18-month study in the Las Vegas Valley conducted by Devitt et al. (2008) compared seventeen residences that were equipped with ET controllers to ten control sites with standard, timer based controllers. The average reduction in outdoor water use (without a negative impact on turf quality) at sites that had ET controllers was 20%, which translated to approximately $48 per year per residence saved in water expenses; however, some ET controller sites actually had increased water use (Devitt et al., 2008). More importantly, if the ET controllers were to be implemented on only 10% of the single-family residences in the Las Vegas Valley, it would save approximately 900 million gallons of water per year based on average savings (Devitt et al., 2008).

A similar study conducted by the University of Florida at the Plant Science Research and Education Unit in Citra, Florida, that compared ET controllers and SMS controllers with standard timer-based controllers, also found significant potential for water savings (McCready et al., 2009). Tests were conducted on St. Augustinegrass plots with each treatment replicated four times. Applied water from two ET controllers, one capable of calculating an irrigation schedule and the other only able to bypass scheduled events, were compared using an irrigation schedule that allowed a maximum of two irrigation events per week. Both controllers produced applied water reductions between 25% and 62%; however, the self-scheduling controller produced greater water savings while maintaining a higher turf quality than the bypass unit (McCready et al., 2009).

SMS Controllers

Soil-moisture content has been used as an aide in irrigation scheduling and management for years (Blonquist et al., 2006). Unfortunately, older methods such as gravimetric measurement (soil cores are collected, wet massed, dried, and dry massed to determine moisture content) are time consuming and destructive to the soil, while others rely on devices such as tensiometers to measure the soil matric potential, from which the soil-moisture content can be inferred (Blonquist et al., 2006). Recent advancements in computer technologies and the application of electromagnetic (EM) methods in soil parameter estimation have significantly improved soil-moisture sensors (Cardenas-Lailhacar et al., 2008). Modern soil-moisture sensors rely on the high relative permittivity (dielectric constant) of water compared to soil solids and air to precisely estimate soil-moisture content in a real-time and nondestructive manner (Blonquist et al., 2006; McCready et al., 2009; Blonquist Jr. et al., 2005; Cardenas-Lailhacer et al., 2005). Common EM soil-moisture measurement techniques include time domain reflectometry (TDR) and time domain transmission (TDT), which both rely on travel time of an EM pulse through probes that are inserted into the soil layer. A further description of TDR and TDT methods can be found in Blonqueist et al. (2005).

Some SMS based irrigation controllers rely on data from soil-moisture sensors to allow or bypass scheduled irrigation events (McCready et al., 2009). Other SMS controllers can initiate and terminate irrigation based on soil-moisture readings. As with ET controllers, SMS controllers can be purchased as add-ons to existing irrigation controllers or as stand-alone units. SMS controllers typically require site calibration of the threshold soil-moisture content (θ_{Thresh}) to which the soil will be allowed to dry before irrigation will be permitted (Blonquist et al., 2006; McCready et al., 2009). The threshold value is determined relative to field capacity, the permanent wilting point, and the management allowed depletion between irrigation events (Blonquist et al., 2006). Depending on the controller, multiple soil-moisture sensors can be installed in different irrigation zones to control irrigation or one sensor can be installed on an entire site to control all irrigation events by the system (Blonquist et al., 2006; McCready et al., 2009).

Limited studies using SMS controllers have offered promising results for reducing overall irrigation totals without negatively impacting turf quality. A study by McCready et al. (2009) found that bypass SMS controllers set to a θ_{Thresh} approximately equal to field capacity (10% volumetric water content) on a Florida soil composed of 97.3% sand yielded water use reductions between 11% and 53%, without negatively impacting turf quality. Setting θ_{Thresh} at a lower value (7% volumetric water content) significantly reduced water use, but also had a negative effect on the quality of the turf plots (McCready et al., 2009). The study found that if using bypass controllers instead of controllers that adjust run times and frequencies, irrigation efficiency could be improved by shortening the duration of scheduled irrigation events and increasing the frequency of potential events.

A similar study of SMS-based controllers versus standard timer-based controllers on bermudagrass considered SMS controllers set to irrigate one, two, and seven days per week (Cardenas-Lailhacar et al., 2008). During the periods when irrigation depths were recorded, July 20 through December 14, 2004 and March 25 through August 31, 2005, the average cumulative depth of irrigation by the SMS controllers was 420 mm (10 mm week^{-1}) compared to 1044 mm (24 mm week^{-1}) for the timer-based systems. Within the SMS controller treatments, plots set to irrigate seven days per week yielded greater water savings compared to those that irrigated only once or twice per week because of more bypassed rainfall events (Cardenas-Lailhacar et al., 2008). This corresponds with the suggestions of McCready et al. (2009) that more frequent, shorter duration scheduled irrigation events would produce greater irrigation efficiency because of the potential for more bypassed irrigation events following short, intermittent rainfall that otherwise might not affect the once or twice per week scheduled events.

Objectives

The primary objectives of this study were to:

1) Estimate quantities of irrigation water withdrawals from the Duke Energy Lakes (specifically Lake Hickory, Lake Norman, and Lake Wylie) via the use of a survey instrument
2) Investigate the water savings potential of “smart irrigation” technologies (specifically soil-moisture sensor based controls and evapotranspiration based controllers).

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CHAPTER 2. IRRIGATION WATER WITHDRAWALS AND THE EFFECTIVENESS OF SMART IRRIGATION TECHNOLOGIES IN THE CATAWBA-WATEREE RIVER BASIN

Introduction

Irrigation is typically required to maintain the high quality, visually appealing landscapes that are desired by most homeowners. Even in the southeastern United States where substantial rainfall occurs during the summer, landscapes typically need irrigation because of irregular rainfall patterns and low water holding capacity of many of the soils (McCready and Dukes, 2010). Many landscapes consist primarily of turfgrass, which typically has a shallow root zone of between 100 and 150 mm (Bruneau and Peacock, 2006). Shallow roots further limit beneficial water storage and increase the need for irrigation. For most turfgrass, 25 mm of water per week is adequate, preferably applied in more than one application (Bruneau et al., 2008). The portion of the turf water needs that should be met by irrigation depends on weather. Unfortunately, most automated irrigation systems are not adjusted to account for changing irrigation requirements.

Nationwide, landscape irrigation accounts for approximately one-third of all residential water use (EPA, 2008). In a study to evaluate and quantify residential water use, Mayer et al. (1999) found that outdoor water use was 35% higher for homes with in-ground sprinkler systems than for homes without. The same study revealed that homes that used an automatic timer to control irrigation used 47% more water outdoors than those without. In a study of twenty private lawns in Logan, Utah, Aurasteh et al. (1984) found that solid set irrigation systems applied 38% more water than the plant ET requirements. Similarly, Barnes (1977) found that homeowners in two Wyoming cities applied irrigation at seasonal rates ranging from 122% to 156% of ET. A recent study of monthly residential irrigation totals in central Florida found that timer-based irrigation systems that were controlled by homeowners applied on average 2.4 times the calculated irrigation requirement (Haley et al., 2007). As a result, many municipalities across the United States have implemented restrictions on outdoor watering.

The town of Cary (TOC) and Morrisville in central North Carolina have adopted alternate day watering schedules in which residents are only allowed to irrigate on certain days of the week depending on their address (TOC, 2010). In Florida, the entire St. Johns River Water Management District (SJRWMD) is limited to watering two days per week, including users that extract directly from ground or surface water sources (SJRWMD, 2011). Several water managers have also implemented tiered rate structures, in which unit charges for water increase with usage. Despite these efforts, water managers, such as Duke Energy, continue to look for additional means to conserve water while still meeting the needs of their consumers.

Duke Energy is the manager of the Catawba-Wateree Hydroelectric Project, which consists of thirteen hydropower stations and eleven reservoirs along the Catawba and Wateree Rivers in North and South Carolina (Duke Energy, 2011). The Catawba River originates in western North Carolina, flowing through or adjacent to several large municipalities, including Charlotte, before flowing into north-central South Carolina, where it joins the Big Wateree Creek to form the Wateree River. Residential lots along the approximately 1700 miles of lake shoreline in the basin (Duke Energy, 2011) have become prime real-estate for people living in the quickly growing region. There are approximately 19,000 lots that border the Duke Energy reservoirs. Built on many of these lots are homes that have automated irrigation systems that use the lake they border as the water source.

Currently, water withdrawals for irrigation are not metered and there is no charge to homeowners for using the lake water. Duke Energy does impose limited watering restrictions when there are periods of drought and reduced lake levels, but typically homeowners are able to withdraw and use lake water without restriction. In 2007, as a part of the Federal Energy Regulatory Commission (FERC) relicensing of the Catawba-Wateree Hydro Project, the Catawba-Wateree Water Management Group (CWWMG) was formed to "identify, fund, and manage projects that help extend and enhance the capacity of the Catawba-Wateree River to meet human water needs while maintaining the ecological health of the waterway" (CWWMG, 2011). In 2009, Duke Energy and the CWWMG joined to fund this residential water study conducted by North Carolina State University. The first objective of the study was to quantify residential irrigation water withdrawals from Duke Energy lakes via a survey instrument and sampling at thirty-six homes along three Duke Energy lakes. The second objective was to evaluate the water conservation potential of three different smart irrigation controllers within the basin.

Smart irrigation controllers automatically schedule irrigation events based on measured or estimated soil-water depletion (IA, 2007). Two ET-based controllers, the Toro Intellisense TIS-612 (The Toro Company, Bloomington, MN) and the Weathermatic Smartline 1600 (Weathermatic, Garland, TX), and one soil-moisture sensor system, the

Acclima SCX (Acclima Inc., Meridian, ID), were selected to comprise treatment groups for the study.

The objectives of this study were similar to others regarding smart irrigation technologies; however, there were several unique circumstances that distinguished this study from others. This project did not offer the privileges of highly controlled research settings, but provided valuable information regarding the challenges of implementing new technologies in "real world" settings. Most smart irrigation field studies have been conducted in urban environments where water use is metered and homeowners are routinely billed. None of the sites in this study had water meters prior to the study and there was no charge for access to water from the Duke Energy lakes. Water restrictions had rarely been implemented even during times of extreme drought and the capacity for enforcement of restrictions was limited. This resulted in a scenario where there was no incentive for the homeowners to conserve water other than their personal level of environmental conscientiousness. Additionally, there were many poorly designed and maintained irrigation systems at study sites. Inadequate nozzle pressure, mixed sprinkler types within zones, mixed vegetation types in zones, and lack of head-to-head sprinkler coverage were common problems in the systems.

Materials and Methods

The study was divided into two phases. The first phase focused on quantitatively assessing current irrigation practices at residences withdrawing their irrigation water from the Duke Energy lakes along the Catawba River. The second phase focused on determining the water conservation potential of three types of smart irrigation technologies, as well as their impacts on turf quality, at thirty-six homes on three Duke Energy lakes.

Survey and Site Selection

An online survey was developed by NCSU and administered by Duke Energy in the spring of 2009 to assess the current state of landscape irrigation within the Catawba-Wateree River Basin. The survey was also used for selecting participants for the field portion of the study. Lot owners on nine Duke Energy lakes (Fishing Creek Lake, Lake Hickory, Lake James, Lookout Shoals Lake, Mountain Island Lake, Lake Norman, Lake Rhodhiss, Lake Wateree, and Lake Wylie) were mailed post cards that informed them of the survey and pointed them to the website where the survey could be completed. The survey was comprised of twenty-one questions that focused on the landscape (lot size, turf type, etc.), the irrigation system (water source, sprinkler type, percent lot irrigated, etc.), irrigation practices (average months per year irrigated, irrigation frequency, average zone run times, etc.), and interest in participating in an irrigation study to be conducted by NCSU.

Duke Energy compiled the data from the 1405 completed surveys. Lake Hickory, Lake Norman, and Lake Wylie were selected for the field portion of the study because they had the most survey responses. Homeowners that expressed interest in participating in the study were invited to information sessions held near each of the lakes and a series of site visits were made to select final participants. Only homeowners who drew their irrigation water from one of the Duke Energy lakes, who had a timer-based automated irrigation system, and who had tall fescue (*Festuca arundinacea* Schreb.) lawns were considered. Priority was given to perspective sites that irrigated primarily turf areas (not ornamentals or shrubbery) and where the irrigation main line was accessible for installation of a water meter. The pool of candidates was narrowed to fewer than twenty residents on each lake and potential cooperators were contacted. After completion of participation waivers, twelve cooperators on each of the three lakes (thirty-six total) were selected as final participants in the study.

Irrigation System Audits

Irrigation system audits were performed on each of the thirty-six cooperator irrigation systems in order to characterize typical irrigation system performance on lakeside lots and to gather information needed for programming smart controllers. System information, including controller make and model, number of irrigation zones and sprinkler types, plant type in each zone, and system run and start times, was collected and recorded during audits. Rough maps of the irrigated areas, including irrigation zone boundaries, were sketched in field books. Where feasible, zone areas were measured and recorded.

Catch cans consisting of 75 mm diameter plastic cups inserted into 100 mm sections of 75 mm diameter (3 in. nominal ID) schedule 40 PVC were placed in each turf irrigation zone. Each zone was run between five and twenty minutes, depending on sprinkler type, and collection volumes were measured and recorded. The catch can data was processed to determine low quarter distribution uniformity (DU_{LQ}) using the equation:

$$DU_{LQ} = \frac{\overline{D}_{LQ}}{\overline{D}_{TOT}} \qquad [2.1]$$

where,

DU_{LQ} = low quarter distribution uniformity

$\overline{D}_{LQ}$ = average depth of low quarter catch measurements

$\overline{D}_{TOT}$ = average depth of all catch measurements.

A high DU in itself does not guarantee a highly efficient irrigation system because over application, regardless of uniformity, would still result in inefficiency, but application efficiency and therefore overall system efficiency cannot be high without also having a high DU.

Average application rate was calculated for each audited zone using the difference between meter readings (volumetric) taken before and after the zone was run divided by the measured zone area. This rate was called the "meter rate." Average application rates were also estimated using the average depth collected in the zone catch cans (deemed "can rate"). The meter rates averaged 75% greater than can rates because some of the spray inevitably hit the outside of the catch cans during the audits and therefore could not be measured. This problem was enhanced in many cases due to steep slopes within audited zones. For this reason, meter rates were used in the analysis of audit data and for the programming of smart technologies.

Irrigated Areas

Total irrigated area (including non-turf irrigated areas) for each study site was measured using county aerial imagery and ArcGIS software (Esri, Redlands, CA). Software-estimated irrigated areas were ground-truthed using on-site area measurements for a sample of study sites. Irrigated area measurements were used to normalize water withdrawal data by converting from volumetric measurements to depths of irrigation applied. This allowed comparison of applied irrigation between homes of varying lot sizes.

Phase I Data Collection

Water Meters

A 25 mm (1 in.) water meter (model DLJ 100 with pulse output, Daniel Jerman Company, Hackensack, NJ) was installed on each of the thirty-six cooperator irrigation systems to monitor irrigation water withdrawals throughout the course of the study. Meters were installed on the main line of each system on the discharge side of the pump. Main lines ranged from 25 mm (1 in.) to 37 mm (1.5 in.) nominal ID. At most of the study sites, the meter was installed above ground. Meters were installed below ground in meter boxes where above ground clearance was an issue. Hobo event loggers (Onset Computer Corporation, Pocasset, MA) were connected to each meter to record irrigation water withdrawals. During the course of meter installations, it was determined from initial data that some loggers were incorrectly logging pulse counts (meter output was one gallon per pulse) from the meters. To remedy the situation, a custom circuit was designed that accumulated ten gallon counts prior to pulsing to the logger. The subsequently increased interval between pulse events corrected the errors and provided the added benefit of increasing the volume of water that could be logged ten-fold.

Weather Stations & Atmometers

Weather data and reference evapotranspiration (ET_o) were measured within 1 km of each of the study lakes throughout the study. Two Watchdog Model 2900 weather stations (Spectrum Technologies, Plainfield, IL) were installed on Duke Energy property, one at Cowans Ford Dam (Lake Norman) and the other at Oxford Dam (Lake Hickory). The stations recorded rainfall and wind direction in addition to air temperature, relative humidity, solar radiation, and wind speed, the necessary parameters for estimation of reference evapotranspiration by the Penman-Monteith method (Allen et al., 1998). Three atmometers (ET gage company, Loveland, Colorado), with number 30 canvas covers meant to simulate grass reference evapotranspiration, were installed at each of the study lakes. One atmometer was placed next to the weather station at the Cowans Ford Dam (Lake Norman) while the others were installed at the Lake Wylie Hydropower Station (Lake Wylie) and Sherrills Ford Fire Station (north end of Lake Norman). Hobo event loggers were connected to each of the atmometers to record evapotranspiration with 0.2 mm (0.01 in.) resolution.

At the beginning of the 2010 irrigation season, an additional atmometer was installed at the Lakeside Marina on Lake Hickory. The atmometer was identical to the three installed in 2009 and was configured with a Hobo event logger to record ET_o.

Phase II Data Collection

Installation of Smart Irrigation Technologies

During the second year of the study (2010), nine of the twelve study sites on each study lake received one of three types of smart irrigation technologies. Two ET-based controllers, the Toro Intellisense TIS-612 (The Toro Company, Bloomington, MN) and the Weathermatic Smartline 1600 (Weathermatic, Garland, TX), and one soil-moisture sensor system, the Acclima SCX (Acclima Inc., Meridian, ID), were selected to comprise treatment groups for the study. Three cooperators on each lake had their irrigation controllers replaced with the Toro Intellisense TIS-612 (Toro), three had their controllers replaced with the Weathermatic Smartline (WM), three had their existing controllers retrofitted with the Acclima SCX "add-on unit" (SMS), and three systems on each lake were left unchanged, comprising a control group (Ctrl). Information collected during the irrigation system audits was used in assigning treatments to cooperators and in programming the smart controllers. Smart controller installations began on April 22, 2010 and were completed on June 25, 2010.

Both ET controllers were programmed according to manufacturers' instructions using default values for most inputs. Irrigation zones that had been audited were programmed with application rates determined from the meter readings and zone areas measured during the audits (meter rates). Slope and shade adjustments for each zone were input into the controllers and system efficiency was assumed as 80% for all systems. Actual DU_{LQ} values were not used because they were so poor that they would have resulted in excessive over-irrigation.

A SLW15 wireless weather monitor (Weathermatic, Garland, TX) was installed at each site that received a Weathermatic controller. The monitor measured air temperature, which was then used by the controller to determine daily ET_o by the Hargreaves equations (Hargreaves and Samani, 1982), and included a rain switch set to 6 mm. The Weathermatic controllers were programmed to irrigate on Monday, Wednesday, and Friday, with irrigation run times determined automatically by the controller based on the inputs entered during installation and the weather data collected from the onsite weather monitor. The Weathermatic controller maintains a running soil water deficit based on daily ET_o. When a scheduled irrigation event occurs, run times are adjusted automatically to refill the soil water reservoir completely and the deficit is reset to zero. When the rain switch is triggered, irrigation is suspended and the soil water deficit is decreased at a rate of 25.4 mm hr^{-1} until zero. After the rain switch resets, the controller enters an additional user-defined rain pause (set to 24 hours for this study) before regular operation and deficit accumulation resumes (Weathermatic, 2009).

A small external antenna was installed alongside each of the Toro controllers to amplify the signal that provided daily ET_o and rainfall estimates via the WeatherTRAK ET Everywhere™ service (Hydropoint Data Systems, Petaluma, CA). The controller maintains a daily soil water balance using this data. The soil water balance, along with the user inputs entered at the time of installation, is used daily by the controller to automatically schedule irrigation for each zone. When the controller receives a signal indicating rainfall has occurred, it automatically activates a calculated rain pause, during which irrigation is suspended.

The Acclima SCX soil-moisture systems were installed only at sites that had easy access to a solenoid valve that controlled one of the turf irrigation zones. The soil-moisture sensor was installed in a sunny spot and wired to the solenoid valve serving the zone in which it was installed, and the controller interface was wired to the existing system controller. A soil-moisture monitoring sensor (S-SMC-M005, Onset Corporation, Pocasset, MA) was installed in the same trench as the SCX soil-moisture sensor and connected to a Hobo Micro Station H21-002 logger (Onset Corporation, Pocasset, MA) that was placed in the solenoid valve box. This sensor was used to monitor soil-moisture in the controlling irrigation zone throughout the irrigation season. After sensor installation, the turf above the controlling sensor was saturated with water and a moisture reading was recorded. Soil-moisture readings were requested from the cooperators the day following installation. These readings and knowledge of the soil type were used to determine the soil-moisture set point for each controller. Initial set points ranged from 21% to 30% soil-moisture by volume. The pre-existing controllers were programmed to allow irrigation each day, depending on whether the add-on unit suspended or allowed watering, with run times set to return the soil-moisture level to approximately field capacity. This translated to gross application depths between 8 and 13 mm.

Homeowners in the smart technology treatment groups were encouraged to not adjust the settings programmed at installation. Some program adjustments were made by NCSU representatives at sites where drought stress arose. Homeowners comprising the control group were encouraged to irrigate their lawn in the same manner that they had traditionally followed prior to the study and were exempted from any potential irrigation restrictions imposed by Duke Energy; however, no such restrictions were ever implemented during the study period.

North Carolina State Climate Office

Supplemental weather data was downloaded from the State Climate Office of North Carolina (NC-SCO) because of periods of missing data from atmometers and weather stations during both irrigation seasons. Daily precipitation totals were collected from fourteen water stations and daily precipitation and ET_o were collected from seven weather stations (Table 2.1) that are part of the NC Climate Retrieval and Observation Network of the Southeast Database (CRONOS). The average distance from each study site to the nearest precipitation station was 7.9 km and ranged from 0.3 to 15.8 km. The average distance from each study site to the nearest ET_o station was 12.6 km and ranged from 3.3 to 27.2 km. The data provided additional localized estimates of precipitation and ET_o conditions at study sites beyond what was available from the installed instrumentation and was available for the entirety of the study.

The NC-SCO estimates ET_o using the ASCE Standardized Penman-Monteith equation (Allen et al., 1998) using temperature, relative humidity, wind speed, and solar radiation collected at each weather station. Most of the weather stations do not collect solar radiation directly, but estimate it using the Hargreaves solar radiation formula (Allen et al., 1998):

$$R_s = k_{Rs}\sqrt{(T_{max} - T_{min})}R_a \qquad [2.2]$$

where,

R_s = solar radiation, MJ m^{-2} day^{-1}

R_a = extraterrestrial radiation, MJ m^{-2} day^{-1}

k_{Rs} = adjustment coefficient, $°C^{-0.5}$

T_{max} = maximum air temperature, °C

T_{min} = minimum air temperature, °C.

The NC-SCO uses an adjustment coefficient (k_{Rs}) of $0.18°C^{-0.5}$ for all of North Carolina.

The Taylorsville Tower (TAYL) weather station was the only NC-SCO site near the study area that measured all of the necessary parameters for the ASCE Standardized Penman-Monteith equation, including solar radiation (R_s). Daily data collected at TAYL between January 1, 2009 and December 31, 2010 were used to calculate two sets of daily ET_o estimates using the Ref-ET software package version 3.01.02 (Allen, 2004), one using measured R_s and the other using R_s calculated by the Hargreaves solar radiation formula with $k_{Rs}=0.18°C^{-0.5}$. The differences between the sets of daily ET_o estimates were compared to see if using measured R_s versus estimated R_s had an impact on estimated ET_o. The mean difference was 0.264 mm day^{-1} with a standard error of the difference of 0.020 mm day^{-1}. Daily ET_o estimated using estimated R_s was typically slightly higher than daily ET_o estimated using measured R_s. The linear regression of daily ET_o estimated using both methods is shown in Figure 2.1.

Daily TAYL ET_o estimates downloaded directly from the NC-SCO website for the same time period were compared with the daily ET_o estimates calculated with Ref-ET using measured R_s to verify that the NCS-CO ET_o estimation procedures were accurate. The linear regression of daily ET_o calculated with Ref-ET using measured R_s and daily ET_o from the NC-SCO are shown in Figure 2.2. The mean difference was 0.064 mm day^{-1} with a standard error of the difference of 0.005 mm day^{-1}.

Weekly ET_o estimates for January 1, 2009 through December 31, 2010 generated using all three procedures are shown in Figure 2.3. Weekly ET_o estimates during the same time period from both of the study installed weather stations are shown in Figure 2.4. It can be seen that there were several weeks of missing data from both stations during both years of the study. The decision was made to use daily ET_o estimates downloaded from each of the NC-SCO weather stations (regardless of whether R_s was measured or estimated at the stations) for all of the irrigation data analysis for the following reasons:

1. Consistency
2. ET_o estimates from the NC-SCO were available for the entire study period whereas there were several weeks of missing data for the study-installed weather stations and atmometers.
3. The ET_o estimates calculated by the NC-SCO for TAYL matched ET_o estimates calculated in Ref-ET using raw weather data from TAYL.
4. The ET_o estimates calculated using estimated R_s were only slightly higher than those calculated using measured R_s, which meant the estimates of weekly irrigation requirements would be more conservative, if anything, in the water use analysis.

Turf Quality Assessment

Turf quality was assessed during the first week of July (early season), the middle of August (mid season), and the first part of November in 2010 (late season) at each of the study sites. These assessment times were chosen because they represent three distinct phases of the Tall Fescue growing season. The early assessment took place before drought or heat stress is typically expected. The mid season assessment occurred when drought or heat stress is most likely to be expressed, and the late assessment was after temperatures had dropped and reseeding had taken place such that recovery from any turf damage could have occurred. Each lawn was assigned a visual turf rating of one to nine based on the standards developed by the National Turfgrass Evaluation Program (NTEP) (Morris and Shearman, 2009) that base the rating on turf density, uniformity, and color. A rating of one is considered poorest turf quality with nine being the best, and a score of six is considered to be minimally acceptable (Morris and Shearman, 2009). A single composite rating was given to each address for each visit. Some allowances were made for weed infestations since these were mature lawns. Crabgrass (*Digitaria spp.*), white clover (*Trifolium repens*), and bermudagrass (*Cynodon dactylon*) were the primary weeds in the landscapes.

Turf evaluations were also made using a FieldScout TCM 500 NDVI Turf Color Meter (Spectrum Technologies, Plainfield, IL) during each phase. The turf color meter uses an internal light source to measure spectral reflectance from the turf canopy, which is then converted into a Normalized Difference Vegetation Index (NDVI) using the equation:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{R})}{(\mathrm{NIR} + \mathrm{R})} \qquad [2.2]$$

where,

NDVI = Normalized Difference Vegetation Index

NIR = Reflectance in the band of 850 ± 5 nm

R = Reflectance in the band of 660 ± 5 nm.

Thirty NDVI readings were taken at each address and averaged to produce a single NDVI value for each site for each visit. Samples sites were randomly selected during each visit to avoid biased readings from any particular area in each lawn.

Data Processing

Water meter data and irrigated areas were used to determine weekly irrigation depths for each site during 2009 and 2010. The first full week of April was assigned as Week 1 for both years. Weekly irrigation depths were combined into a database by address for comparison. Weeks that had any missing data were treated as missing weeks all together. Data that were collected before the ten-count circuit was installed in 2009 were not used because of the discrepancy between them and visual meter readings taken during the same period. Some of the ten-count circuits inexplicably failed at times during the study and multiple water meters failed after being submerged under water. This led to periods of missing data at a few sites until the instrumentation could be repaired or replaced.

An indicator variable was assigned to each site for each week during the 2010 season to account for weeks when smart controllers were not operational. A value of "1" represented a fully operational controller and system while "0" indicated controller failure or manual overrides by the homeowner. Weeks with a “0” indicator variable were not considered in the water use analysis.

Gross Irrigation Requirement via Soil Water Balance

Weekly gross irrigation requirements (GIR) were calculated for each site for comparison to measured weekly irrigation depths applied. A daily soil water balance (SWB) was simulated to generate daily GIRs, from which weekly GIRs were determined. The daily soil water balance summed soil water inputs and outputs to estimate the soil water level at the end of each day and was calculated using the equation (Allen et al., 1998):

$$D_i = D_{i-1} - (P - RO)_i - I_{net,i} - CR_i + ET_{c,i} + DP_i \qquad [2.3a]$$

where,

D_i = depletion of water from the root zone at the end of day i, mm

P = precipitation, mm

RO = runoff on, mm

I_{net} = net irrigation depth, mm

CR = capillary rise contribution, mm

ET_c = crop evapotranspiration, mm

DP = deep percolation, mm.

D_i was considered as the soil water deficit below field capacity (FC) of the soil in the root zone at the end of the day and was not allowed to drop below the permanent wilting point (PWP). CR was treated as negligible because the water table depth was more than 1 meter (Allen et al., 1998; Allen, 2004). Though heavy rainfall or excessive irrigation could raise the soil water level above FC for a period of time, it was assumed that the soil water level drained to FC by the end of each day (Allen et al., 1998) via deep percolation. Additionally, it was assumed that DP and RO only occurred when FC was exceeded, thus having no bearing on D_i. This reduced the soil water balance to:

$$D_i = D_{i-1} - P_{e,i} - I_{net,i} + ET_{c,i} \qquad [2.3b]$$

where,

P_e = effective rainfall, mm.

P_e was the depth of rainfall that effectively reduced depletion without exceeding FC, thus P_e could not exceed D, at the time just before the rainfall credit. In other words:

$$\begin{aligned} P_{e,i} &= D_{i-1} - I_{net,i} + ET_{c,i} && \left(\text{for } P_i > D_{i-1} - I_{net,i} + ET_{c,i}\right) \\ &= P_i && \left(\text{for } P_i \leq D_{i-1} - I_{net,i} + ET_{c,i}\right). \end{aligned} \qquad [2.4]$$

The soil water balance depends on the plant available water (AW) in the root zone, which was calculated using the equation:

$$AW = \frac{(\theta_{FC} - \theta_{PWP}) \times RZ}{100} \qquad [2.5]$$

where,

AW = available water, mm

θ_{FC} = soil volumetric moisture content at field capacity, %

θ_{PWP} = soil volumetric moisture content at permanent wilting point, %

RZ = root zone depth, mm.

Values of 34% and 20% (by volume) for field capacity and permanent wilting point for a clay loam soil were assumed (Fangmeier et al., 2006). A root zone depth of 150 mm (6 in.) was used for tall fescue, which resulted in an AW depth of 21 mm.

Only a portion of the AW can be removed by the plants before stress will begin to occur, therefore irrigation should be applied before the permanent wilting point is reached. The depth of soil water that can be depleted before irrigation is necessary is readily available water (RAW) and is a function of the management allowed depletion (MAD), which is determined by the irrigation manager depending on how much plant stress is acceptable. Readily available water is defined as:

$$\mathrm{RAW} = \mathrm{MAD} \times \mathrm{AW} \qquad [2.6]$$

where,

RAW = readily available water, mm

MAD = management allowed depletion, fraction

AW = available water, mm.

A MAD of 0.50 (Irrigation Association, 2008) was selected which resulted in a RAW depth of 10.5 mm.

The daily SWB was conducted independently for each study site for 2009 and 2010. Daily precipitation depths and reference evapotranspiration (ET_o) collected from the NC-SCO weather stations were used for the SWB. Each study site was assigned a precipitation station and an ET_o station based on proximity. The closest precipitation station and the closest ET_o station for each site are shown in Table 2.2. A crop coefficient (K_c) of 0.8 for cool season grasses was used to calculate ET_c as follows (Allen, 2004):

$$\mathrm{ET_c} = \mathrm{K_c} \times \mathrm{ET_o} \qquad [2.7]$$

where,

ET_c = crop evapotranspiration, mm

K_c = crop coefficient

ET_o = reference evapotranspiration, mm.

In calculating the SWB, the order of crediting/debiting was irrigation, evapotranspiration, and then precipitation because irrigation should be scheduled to run in the early morning hours and most rainfall events during the irrigation season take place in the late afternoon to early evening. The SWB was conducted from January 1 to December 31 for both years, but only the GIR from the irrigation season (assumed as April 1 – September 30) were considered for the water use analysis. For January 1 of both years, the net irrigation requirement (NIR) and soil water deficit at the beginning of the day were assumed to be zero. For each day after January 1, the net irrigation requirement was calculated as:

$$\begin{aligned} \mathrm{NIR_i} &= \mathrm{D_{i-1}} \quad (\text{for } \mathrm{D_{i-1}} > RAW) \\ &= 0 \qquad (\text{for } \mathrm{D_{i-1}} \leq \mathrm{RAW}). \end{aligned} \qquad [2.8]$$

I_{net} was simulated as equal to the NIR for each day, such that the soil water level was returned to FC after irrigation. To account for system non-uniformity, the daily GIR was determined by dividing NIR by 0.8, which was the uniformity adjustment used in programming the smart controllers.

Water Use Analysis

2010 Weekly Irrigation Depths

Weekly irrigation depths were analyzed using SAS version 9.2 (SAS Institute, Inc., Cary, NC). Only data collected from weeks 10 through 26 (the first full week of June through the last week of September) were used for the analysis. Most of the smart technologies were installed by week 10 and the end of September was considered as the end of the irrigation season. Some homeowners overseeded their lawns in September, which required a manual override of the smart controllers for a period of time to ensure germination. Data collected at such sites during the recorded manual override period was not used in the analysis.

Boxplots were developed to show the variation in weekly applied irrigation by treatment. The PROC MIXED procedure was used to test fixed and random effects on weekly irrigation depths. Treatment was entered as a fixed effect, and week number, lake, and week number nested within lake were entered as random effects. Least square means (LS-means) were used to determine differences between treatments in mean weekly applied irrigation.

Irrigation Accuracy

In order to evaluate how accurately the treatments met weekly GIR and to subsequently explore changes in water use behavior before and after smart irrigation technology installation, a difference value (Diff) was calculated for each site for each week as:

$$\text{Diff} = \text{I}_{\text{app}} - \text{GIR} \qquad [2.8]$$

where,

Diff = difference, mm

I_{app} = irrigation applied, mm

GIR = gross irrigation requirement, mm.

A Diff value of zero indicated that the GIR was perfectly met for the week. A positive value indicated over irrigation, while a negative value meant under (or deficit) irrigation had occurred.

Weekly Diffs were analyzed in the same manner as weekly irrigation applied. Boxplots were created to show the variation in weekly Diffs by treatment. The PROC MIXED procedure was used to test fixed and random effects on the model for Diff. Treatment was modeled as the fixed effect, and week number, lake, and week number nested within lake were modeled as random effects. The LS-Means statement in SAS was used to determine differences between mean Diffs by treatment.

Changes between 2009 and 2010

Change in irrigation behavior based on assigned treatment was analyzed using data from weeks 15 through 26 from 2009 and 2010 (July 12 – October 3, 2009; July 11 – October 2, 2010). These periods were selected to represent comparable time spans before treatment and after treatment in which data were available for both years.

Three models were created using the PROC MIXED procedure to test fixed and random effects on weekly I_{app}, GIR, and Diff and differences in the response variables between 2009 and 2010. The model for I_{app} had year, treatment, and interaction between year and treatment as fixed effects, and week-begin-date and week-begin-date nested within lake entered as random effects. The models for GIR and Diff had year, treatment, and their interaction entered as fixed effects and lake entered as a random effect. For each model, LS-means by year and by year by treatment (interaction) were compared to determine overall differences from 2009 to 2010, differences from 2009 to 2010 based on treatment group, and differences by treatment group within 2009 and 2010. Bar graphs were used to show average weekly I_{app} relative to average weekly GIR for both years by treatment group and by treatment group within lake.

Turf Quality Analysis

Turf quality data were analyzed using SAS version 9.2 (SAS Institute, Inc., Cary, NC). Boxplots were produced to display variation in turf visual ratings and NDVI readings by treatment and by time of season in which the readings were taken. The PROC MIXED procedure was used to test treatment, time of season, and the interaction between treatment and time of season as fixed effects on the models predicting turf visual rating and NDVI. LS-means were compared within treatment, within time of season, within time of season by treatment, and within treatment by time of season for both models.

Results

Survey

The majority of the 1405 survey responses came from Lake Norman (61%), Lake Wylie (19%), and Lake Hickory (9%), the three lakes chosen for the study. The distribution of lot sizes was: 16% less than 0.2 hectares (0.5 acres), 60% between 0.2 and 0.4 hectares (0.5 and 1.0 acres), and 24% greater than 0.4 hectares (1.0 acres). For some respondents, several survey questions were left blank when the response data was provided to NCSU. It was unclear whether the respondents simply did not answer the questions or if the data was lost in transfer from Duke Energy to NCSU.

For questions pertaining to the irrigation system design, 1026 of the 1405 total respondents had non-blank answers. Of those, 88% indicated that their irrigation water source was one of the Duke Energy lakes. About 62% said that they irrigated between 25% and 75% of their lot. Most responded that their irrigation system was composed of either both rotor and spray heads (48%) or exclusively spray heads (36%).

For questions regarding irrigation scheduling, only 662 of the total respondents had non-blank answers. The majority of them indicated that they irrigated between five and eight months of the year (80%) with the most frequent responses being six months (26%) and seven months (24%). About 37% responded that they irrigated on average two days per week during the months that their system was running, while 42% indicated three days per week.

Almost 94% of the respondents that answered the question said that they would be interested in participating in the study with NCSU. A more complete discussion of survey responses and how they were used is provided in Chapter 3.

Audits

Irrigation system audits revealed poor system uniformity at most sites. The average DU_{LQ} across all zones was 0.34 while zones containing only rotor sprinklers had an average DU_{LQ} of 0.37. Only two of eighty-five rotor zones audited (2%) had a DU_{LQ} greater than or equal to 0.65, the lower boundary of the target DU_{LQ} range established by the Irrigation Association (IA) (2010). Three of thirty-eight spray zones (8%) met the IA minimum DU_{LQ} of 0.55. Table 2.3 shows the average DU_{LQ} for mixed zones, rotor zones, and spray zones across all zones audited and the average application rates by sprinkler type. Mixed zones had both rotor and spray head sprinklers (one site had two zones with both rotor and impact sprinklers, which were also considered as "mixed"). The variation of zone DU_{LQ} was consistent across all three lakes as seen in Figure 2.5. Rotor and mixed zones had slightly less variation of DU_{LQ} than sprinkler zones (Figure 2.6).

Average zone application rates varied by sprinkler type and there was also variation within sprinkler types as shown in Figure 2.7. Spray zone application rates ranged from 18 mm hr^{-1} to 94 mm hr^{-1}, with an interquartile range (IQR), the difference between the 75th and 25th percentiles, of 27 mm hr^{-1}. Rotor zone application rates were not as varied, ranging from 4 mm hr^{-1} to 48 mm hr^{-1}, with an IQR of 8 mm hr^{-1}. Measured application rates are presented in relation to default application rates of the Toro and WM controllers in Table 2.4.

Irrigated Areas

The average irrigated areas for study sites on Lake Hickory, Lake Norman, and Lake Wylie were 1567 m^2, 1252 m^2, and 867 m^2 respectively. Forty-two percent of the sites had irrigated areas between 500 and 1000 m^2, and two sites had areas greater than 2500 m^2. The smallest irrigated area was 240 m^2 and the largest was 3313 m^2. The distribution of irrigated areas is shown in Figure 2.8.

Weather

Average cumulative ET_c and rainfall from across all thirty-six sites for 2009 and 2010 are presented in Table 2.5. The weather data corresponds with the thirty-week period from the first full week of April to the last full week of October in which irrigation measurements were recorded. ET_c and rainfall were nearly the same in 2009 (709.1 mm and 699.8 mm, respectively) whereas ET_c was 22% higher than rainfall during the same period in 2010 (734.3 mm and 602.7 mm, respectively). Average weekly ET_c exceeded average weekly rainfall for eighteen of thirty weeks (60%) in 2009 and twenty-two of thirty weeks (73%) in 2010.

In addition to receiving less cumulative rainfall in 2010, rainfall events were also less frequent and of greater depths, resulting in a large portion of the rainfall being ineffective (lost to runoff or deep percolation). There were three periods of five weeks or more in 2010 in which no one week had greater than 25.0 mm of rainfall. The largest span in 2009 between 25.0 mm rainfall weeks was one four week period. Average rainfall and ET_c are shown by week for 2009 and 2010 in Figures 2.9 – 2.10.

Water Use

Water Use by Lake

Average weekly irrigation depths for 2009 by lake are shown in Figure 2.11. An average of 22.2 mm of water was applied per week over all sites in 2009. Average weekly water applied on Lake Wylie (29.3 mm wk^{-1}) was 66% more than on Lake Norman (17.6 mm wk^{-1}) and 47% more than on Lake Hickory (19.9 mm wk^{-1}). The pattern of water use was similar across all lakes except for weeks 17 through 18 when Lake Norman water application increased and application on Lake Hickory and Lake Wylie decreased.

Average weekly irrigation depths for 2010 by lake are shown in Figure 2.12. Lake Wylie sites again had the highest average weekly irrigation applied (27.6 mm wk^{-1}) in 2010. This was 48% more than Lake Norman (18.6 mm wk^{-1}) and 14% more than Lake Hickory (24.2 mm wk^{-1}). The peaks in water applied in weeks 14 and 25 followed two five-week periods where weekly precipitation averaged 4.8 mm and 4.5 mm, respectively. The average depth of water applied dropped from 41.0 mm in week 14 to 24.0 mm in week 15 when there was an average of 70.0 mm of rainfall at each site and from 37.2 mm in week 25 to 9.1 mm in week 26 when there was 77.0 mm average rainfall.

2010 Applied Water by Treatment

Average weekly irrigation depths are shown by treatment in Table 2.6 and in Figure 2.13. Variation in weekly irrigation depths by treatment are shown via boxplots in Figures 2.14 – 2.17. Outlier labels identify lake (first letter), treatment (second letter) and site number within treatment within lake, e.g. “HW2” corresponds with the second Weathermatic site on Lake Hickory.

Treatment was a significant factor in explaining average weekly applied water ($p < 0.0001$). The SMS treatment had the highest average weekly water applied (31.9 mm wk^{-1}), which contradicted the findings of similar studies. Ghali (2011) found that over a three year period, Acclima SCX soil-moisture “add-on” systems produced average water savings of 38% compared to timer-based treatments. In a residential study conducted in Cary, NC, the same type of controller applied the least amount of weekly irrigation (15 mm wk^{-1}) compared to an ET controller (21 mm $week^{-1}$), an educational group (23 mm wk^{-1}) that was given guidance on scheduling timer-based controllers, and a comparison group (27 mm wk^{-1}) that was allowed to irrigate without restriction (Nautiyal, 2010).

The Ctrl, Toro, and WM groups applied average depths of 26.6, 23.8, and 23.5 mm wk^{-1}, respectively, and were not different at the $\alpha = 0.05$ level. There was evidence that the Ctrl group differed from the WM group ($p = 0.07$) and from the Toro group ($p = 0.13$), but the Toro and WM groups showed no difference ($p = 0.88$). WC1 and WC2 were consistently higher water users in the Ctrl group (Figure 2.14), as was WW1 in the WM treatment (Figure 2.17). NS3 was one of the five SMS sites that required installation of a new controller due to current leakage, but there was no indication that the zero measured irrigation in weeks 16 and 17 was bad data (Figure 2.15).

The distribution of how accurately the GIR was met for each week by treatment is shown in Figures 2.18 – 2.21. The SMS treatment on average applied 7.6 mm more water than the GIR per week. The average weekly difference between irrigation applied and the

GIR (Diff) was not different among the other treatments at the $\alpha = 0.05$ level (Table 2.6). There was evidence of a difference in Diff between Ctrl and Toro ($p = 0.06$) and Ctrl and WM ($p = 0.12$), but not between Toro and WM ($p = 0.65$). The Toro treatment applied less irrigation on average than the average GIR in ten out of sixteen weeks, while the SMS treatment on average applied more than the average GIR in all weeks but one.

Changes in Water Use from 2009 to 2010

Data collected between weeks 15 and 26 in both years indicated that all of the treatments except for the Ctrl group more accurately met the GIR in 2010 than in 2009, as shown in Figure 2.22. The change in average weekly water applied and average weekly GIR from 2009 to 2010 by treatment within lake is shown in Figure 2.23. Average weekly irrigation applied by Toro sites on Lake Wylie and on Lake Norman well exceeded average weekly GIR in 2009, but was less than average weekly GIR in 2010. There was also evidence that systems on Lake Wylie tended to apply more irrigation per week than those on Lake Norman and Lake Hickory during both years.

LS-means of weekly irrigation applied, weekly GIR, and weekly Diff in 2009, in 2010, and the change in each from 2009 to 2010 are presented by treatment in Figure 2.24. The average weekly difference (Diff) between irrigation and GIR decreased from 11.2 mm wk^{-1} in 2009 to 3.8 mm wk^{-1} in 2010, across all sites ($p < 0.0001$). Each of the smart irrigation technologies reduced Diff (reduced over irrigation) while Diff for the Ctrl group did not change. The change in average weekly Diff for the SMS treatment from 2009 to 2010 was -15.7 mm wk^{-1}, compared to 0.7, -8.7, and -5.9 mm wk^{-1} for the Ctrl, Toro, and

WM treatments, respectively. This indicates that the SMS controller had the greatest impact of all the smart controllers on irrigation scheduling relative to previous practices.

The smart irrigation treatment groups reduced average weekly irrigation depths from 2009 to 2010, despite the average weekly GIR increasing from 2009 to 2010 for all treatment groups (Figure 2.24). Average weekly treatment GIRs were not statistically different in 2009 or 2010 as expected due to similar weather patterns across the study area during both years. The sites composing the SMS treatment group applied 54% more water per week than any of the other treatment groups in 2009, which indicates the SMS treatment may have had a stronger home owner behavioral pattern to overcome than any of the other controllers.

Turf Quality

Turf quality visual ratings and NDVI ratings are shown in Tables 2.7 – 2.8 and in Figure 2.25. The average visual rating was above the minimally accepted level of 6 (Morris and Shearman, 2009) for each treatment except for the Ctrl group, which had an average rating of 5.0. Treatment did have an effect on turf visual rating ($p = 0.0076$), but not on NDVI ratings ($p = 0.995$). The Ctrl group average visual rating (5.0) was the lowest of all treatments, but the overall average visual ratings of the SMS (6.2), Toro (6.1), and WM (6.2) treatments were not different at the $\alpha = 0.05$ level. For the mid and late season evaluations, visual ratings did vary by treatment. SMS and Toro had the highest visual ratings during the August assessment (mid), while WM had the highest visual rating in November (late). Although no visual ratings or NDVI ratings were taken at the very beginning of the growing season, it was noted during technology installations that many of the homes in the Ctrl group had poor turf quality, which may have contributed to their lower visual ratings more than the treatment itself. There was no evidence that time of season had an impact on turf quality overall or within treatments based on visual ratings and NDVI ratings. No difference was observed between treatments by time of season either. There was less variation in NDVI ratings than in visual ratings because NDVI ratings are solely a measure of color, while visual ratings account for density, uniformity, texture, and stress in addition to color (Morris and Shearman, 2009).

Problems Encountered

Existing controllers at five of the nine SMS sites had to be replaced with new Hunter Pro-C controllers (Hunter Industries Inc., San Marcos, CA) in order for the system to function correctly. The old controllers leaked current through the system, even when no irrigation was taking place, which prevented the SMS controller module from changing states from "watering allowed" to "watering suspended," or vice-versa. Without this fix, irrigation would have either occurred every day or none whatsoever, regardless of the soil-moisture level.

Six of nine soil-moisture sensors failed during the season and had to be replaced. Some of the failed sensors came from a manufacturing lot with known defects discovered after sensor installation. One sensor failed as a result of a lightning strike and others failed inexplicably. Sensor failure typically resulted in a "0.0%" soil-moisture reading on the add-on unit, which resulted in systems watering daily until the problem was discovered and fixed.

The irrigation zone containing the faulty sensor typically would not run at all until the sensor was replaced.

Communication between one of the Toro controllers on Lake Norman and the offsite weather service failed about a month after installation. The controller was replaced with a Weathermatic Smartline with an onsite wireless weather monitor.

A cooperator on Lake Hickory with a Weathermatic Smartline controller opted to replace the smart controller with his timer-based controller in August of 2010, but agreed to allow continued monitoring of irrigation withdrawals. Additionally, one SLW 1500 wireless weather station, used with the Weathermatic Smartline controller, had to be replaced due to a faulty circuit that drained the batteries.

There was evidence that homeowners altered irrigation schedules by changing smart controller settings and or manually running the system throughout the 2010 irrigation season, as shown in Figures 2.26 – 2.33. Homeowners were made aware that scheduling adjustments could be made as needed, but were asked to consult with NCSU representatives before making any changes. Some homeowners notified NCSU that they used manual overrides on their controllers while reseeding (between September and October); however, recorded runtimes revealed that several homeowners adjusted their irrigation schedules throughout the season without notifying NCSU.

Figures 2.26 – 2.29 show the distribution of days when irrigation occurred for each study site in 2010, grouped by treatment. There were no restrictions on irrigation days for the Ctrl treatment and the Toro and SMS controllers were programmed to allow irrigation every day if needed, but the WM controllers were all initially programmed to run on

Monday, Wednesday, and Friday only, with the exception of site HW1 which was set to allow irrigation at intervals of every other day. HW3 also used interval scheduling for a portion of the season, but then returned the settings to Monday, Wednesday, and Friday. Sites HW2 and WW3 present clear evidence that schedules were adjusted by the homeowners. It should be noted that HW2 was the site where the WM controller was replaced with the original controller in August of 2010 and also that site WW2 had a faulty weather module that created a need for manual watering during periods of 2010, explaining the deviation from Monday, Wednesday, and Friday operation.

Figures 2.30 – 2.33 show the distribution of times of irrigation events for each site during 2010, grouped by treatment. Again, there were no schedule restrictions on the Ctrl treatment; however, each of the smart controllers was programmed to start between 12:00 AM and 6:00 AM such that the majority of irrigation, if not all, should have occurred in the morning hours (12:00 AM – 11:59 AM). Most of the sites irrigated mainly in the morning hours, but several had substantial afternoon (12:00 PM – 5:59 PM) watering, which can lead to greater evaporative losses, and evening (6:00 PM – 11:59 PM) watering, which can increase susceptibility to disease in turfgrass. Site NS2 particularly irrigated outside of the preferred irrigation window, with over one-third of the irrigation events taking place during the afternoon or evening hours.

Summary and Conclusions

Weather data confirmed the need for irrigation in predominantly turf landscapes in the Catawba-Wateree River Basin. Weekly ET_c exceeded weekly rainfall for over half of the irrigation season in both years, in some cases for as long as five weeks straight. Without irrigation, the soil water level would have approached the permanent wilting point, likely causing irreversible damage to turf and presumably to other landscape plants as well. Thus, the ability to provide irrigation during periods of insufficient rainfall is critical for preserving the high value landscapes that surround many homes in the Catawba-Wateree River Basin. Unless homeowners are willing to provide the time required to adequately irrigate their landscape manually, installation of an automated irrigation system is required.

Many of the irrigation systems within the study showed signs of poor system design and maintenance. Most had low distribution uniformity, regardless of sprinkler types. Low DU_{LQ} in some cases could be attributed to irregularly shaped turf areas, but was generally a product of design and/or maintenance failures. Such problems included mixed sprinkler types within the same irrigation zone, inadequate pressures within zones, and lack of head-to-head sprinkler coverage. These same issues also caused substantial variability in zone average application rates. For any irrigation scheduling to be effective, it is imperative that the true application rate of the system be known. Many smart controllers have default application rates that users can select depending on the sprinkler type, but this study revealed that actual application rates can be anywhere from one-fourth to two times default rates (Table 2.4), thus reiterating the need for accurate system audits in order for smart controllers to be effective.

Weekly water withdrawals from 2009 showed that irrigation schedules were adjusted throughout the season, either by the user or potentially by a rain switch; however, most systems did not have a functioning rain switch installed at the time of system audits. Despite the adjustments, average weekly irrigation was 1.7 times the average weekly GIR. Installation of smart controllers on 75% of the study sites in 2010 reduced over-application across all sites to 1.1 times the GIR.

There was not a significant water savings in 2010 for any of the smart controllers compared to the Ctrl treatment. In fact, the SMS treatment applied more water than the Ctrl treatment. This could have been due to undetected sensor failures, but it also could have been a product of the water use tendencies of the SMS cooperators. Cooperators in the SMS group used the most water prior to smart controller installations and they may have been more willing to override the smart technologies than other cooperators. The SMS treatment actually improved the average weekly Diff more than the other smart controllers, which suggests that it may have had the greatest impact on water use behavioral patterns, although the SMS controllers were installed at sites with the most potential for improvement. Only the Ctrl treatment had turf quality ratings less than the minimally accepted level and poor turf quality was noted at several of the Ctrl sites before treatments were assigned.

The overall results suggest that smart irrigation technologies may provide long term water savings within the Catawba-Wateree River basin. A cheaper and more immediate impact could be achieved from installing rain switches on irrigation controllers, which prevent irrigation during and following rainfall events of a user set depth. Properly scheduling timer-based controllers, which can only be done if the true zone application rates are known from a system audit, would also help prevent over-watering. As discussed previously, several system flaws including inadequate pressure, incorrect sprinkler placement, and mixed vegetation types within irrigation zones were common at study sites. Correcting these system errors would be more costly than installing rain switches or conducting system audits, but are critical in order for smart irrigation technologies to function as water saving devices.

Part of the challenge in successfully implementing smart irrigation technologies in the basin will lie in overcoming the behavioral tendencies of the homeowners. Whether a result of years of having no charge for irrigation water except the energy cost to pump it or other factors, several homeowners were reluctant to rely on the scheduling of the smart controllers and tended to manually apply irrigation or adjust the schedules as they saw fit. There was also an underlying perception that if any landscape stress occurred, it must have been a result of the smart controller, not any other factors.

This study revealed the challenges of retrofitting systems with smart controllers as opposed to installing them at the time the system is installed. Installation of the soil-moisture sensors required trenching in established turf. Additionally, the SMS add-on module would not function with many of the existing controllers because of current leaking from the controller when the system was not running, preventing the module from changing states. Establishing and maintaining communication with the offsite weather service, for the Toro treatment, and with the onsite weather module, for the WM treatment, was problematic at some sites due to the location of the controller in the house or because of poor signal reception in the area. Presumably, some of these challenges would have been lessened if the systems had been planned and installed with the specific smart controller in mind.

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Tables and Figures

Table 2.1 NC-SCO "weather" and "water" stations from which daily rainfall and ET_o were downloaded. Weather data were used to calculate weekly NIR for each study site.

Station Type	ID	Name	Latitude	Longitude
Weather	KAKH	Gastonia Municipal Airport	35.20266°	-81.14987°
Weather	KCLT	Douglas International Airport	35.21401°	-80.94313°
Weather	KHKY	Hickory Airport	35.74115°	-81.38955°
Weather	KIPJ	Lincoln County Airport	35.48333°	-81.16126°
Weather	KSVH	Statesville Municipal Airport	35.765°	-80.9539°
Weather	KUZA	Rock Hill-York County Airport	34.98783°	-81.05717°
Weather	TAYL	Taylorsville Tower	35.9139°	-81.19087°
Water	CRN-34	Cowans Ford Dam	35.43°	-80.96°
Water	CRN-37	Berryhill Elem	35.21°	-80.99°
Water	CRN-38	Tega Cay Town Hall	35.03°	-81.04°
Water	CRN-40	Westport Golf Course	35.5°	-80.99°
Water	CRN-42	Norman Shores	35.5°	-80.88°
Water	CRN-45	Withers Cove	35.15°	-81.01°
Water	CRN-59	Camp Thunderbird	35.11°	-81.04°
Water	CRN-62	Cookson Dairy Farm	35.42°	-80.9°
Water	311579	Catawba 3 Nnw	35.74444°	-81.08472°
Water	311690	Charlotte Douglas Ap	35.22361°	-80.95528°
Water	311990	Conover Oxford Shoals	35.82139°	-81.19194°
Water	314020	Hickory Faa Ap	35.7425°	-81.38194°
Water	317229	Rhodhiss Hydro Plt	35.77389°	-81.43722°
Water	383216	Ft Mill 4 Nw	35.02167°	-81.00722°

Note: Both rainfall and ET_o were available from the "weather" stations, while only rainfall was available from the "water" stations. ET_o estimates were generated by the NC-SCO with the Standardized Penman-Monteith equation using measured temperature, relative humidity, and wind speed, and solar radiation estimated by the Hargreaves' radiation formula (with k_{Rs} = $0.18°C^{-0.5}$) at each site, except for TAYL, where solar radiation was measured.

Table 2.2 Abbreviated site label, irrigated area, technology installation date, closest precipitation station, closest ET_o station, and distance to stations for each site by lake within treatment.

Treatment	Lake	Label	Irr. Area (m^2)	Installation Date	Precip. Station (km)*	ET_o Station (km)*
Ctrl	Hickory	HC1	2871	.	KHKY (14.7)	TAYL (11.9)
Ctrl	Hickory	HC2	1345	.	KHKY (07.4)	KHKY (07.4)
Ctrl	Hickory	HC3	1712	.	KHKY (12.6)	TAYL (13.9)
Ctrl	Norman	NC1	1630	.	CRN-42 (13.3)	KIPJ** (23.6)
Ctrl	Norman	NC2	812	.	CRN-42 (15.8)	KSVH (14.9)
Ctrl	Norman	NC3	1379	.	CRN-42 (06.9)	KSVH (27.2)
Ctrl	Wylie	WC1	802	.	CRN-38 (02.2)	KUZA (07.6)
Ctrl	Wylie	WC2	523	.	CRN-59 (01.3)	KUZA (12.5)
Ctrl	Wylie	WC3	1212	.	CRN-59 (03.9)	KUZA (15.4)
SMS	Hickory	HS1	899	6/9/2010	KHKY (08.4)	KHKY (08.4)
SMS	Hickory	HS2	413	6/9/2010	KHKY (08.4)	KHKY (08.4)
SMS	Hickory	HS3	959	6/7/2010	KHKY (14.9)	TAYL (12.9)
SMS	Norman	NS1	844	6/25/2010	CRN-34 (04.7)	KIPJ** (20.7)
SMS	Norman	NS2	807	4/28/2010	CRN-34 (05.0)	KIPJ** (22.2)
SMS	Norman	NS3	1557	5/6/2010	CRN-42 (14.9)	KSVH (15.7)
SMS	Wylie	WS1	885	5/21/2010	CRN-38 (01.9)	KUZA (07.2)
SMS	Wylie	WS2	386	5/19/2010	CRN-38 (00.4)	KUZA (05.7)
SMS	Wylie	WS3	706	6/7/2010	CRN-38 (00.4)	KUZA (04.9)
Toro	Hickory	HT1	751	6/10/2010	KHKY (03.3)	KHKY (03.3)
Toro	Hickory	HT2	1280	6/8/2010	KHKY (13.9)	TAYL (13.0)
Toro	Hickory	HT3	1373	6/7/2010	KHKY (08.4)	KHKY (08.4)
Toro	Norman	NT1	939	4/29/2010	CRN-34 (05.6)	KIPJ** (21.7)
Toro***	Norman	NT2	1592	5/6/2010	CRN-42 (15.8)	KSVH (14.9)
Toro	Norman	NT3	1473	4/29/2010	CRN-42 (15.2)	KSVH (15.4)
Toro	Wylie	WT1	776	5/20/2010	CRN-45 (02.9)	KCLT (10.4)
Toro	Wylie	WT2	1749	5/19/2010	CRN-38 (00.3)	KUZA (05.1)
Toro	Wylie	WT3	848	5/20/2010	CRN-45 (02.9)	KCLT (09.3)
WM	Hickory	HW1	2386	5/21/2010	KHKY (14.4)	TAYL (12.2)
WM	Hickory	HW2	3313	6/8/2010	KHKY (07.8)	KHKY (07.8)
WM	Hickory	HW3	1503	6/8/2010	KHKY (14.9)	TAYL (12.9)
WM	Norman	NW1	794	5/7/2010	CRN-34 (05.0)	KIPJ** (22.2)
WM	Norman	NW2	1081	4/28/2010	CRN-42 (15.5)	KSVH (15.0)
WM	Norman	NW3	2116	4/29/2010	CRN-42 (15.2)	KSVH (15.2)
WM	Wylie	WW	240	4/22/2010	CRN-45 (01.3)	KCLT (10.2)
WM	Wylie	WW	938	5/19/2010	CRN-38 (02.7)	KUZA (07.4)
WM	Wylie	WW	1336	5/20/2010	CRN-45 (02.6)	KCLT (09.5)

*Note: *Number in parentheses indicates distance in km to station used for precipitation or ET_o data.*
***ET_o station KIPJ was missing data from Jan 23, 2009 – May 2, 2009. Weekly ET_o for study sites closest to KIPJ was obtained from KSVH, the next closest ET_o station during this period.*
****The controller at study site NT2lost communication with the weather service in 2010 and was replaced with a WM controller with an onsite weather module on Aug 18, 2010. From that point forward, NT2 was treated as part of the WM treatment group.*

Table 2.3 Average DU_{LQ} and application rates measured across 143 audited zones at study sites.

Zone Type	Number Audited	Average DU_{LQ}	Average Application Rate (mm hr^{-1})
Mixed	20	0.30	23
Rotor	85	0.37	16
Spray	38	0.28	46
Overall	143	0.34	25

Table 2.4 Default application rates for the smart controllers used in the study compared to audit measured application rates (meter rates).

		Application Rate (mm hr^{-1})	
		Rotor	Spray
Default	Toro Intelli-Sense	19.1 * (0.75 in hr^{-1})	43.2 (1.7 in hr^{-1})
	Weathermatic SL 1600	12.7 (0.5 in hr^{-1})	38.1 (1.5 in hr^{-1})
Audit Measured	Mean	15.9	46.5
	Max	48.2	94.4
	Min	4.4	17.6

*Note: *The Toro Intelli-Sense has three default rotor types, "full circle," "mixed," and "partial circle," with default application rates of 12.7, 19.1, and 25.4 mm hr^{-1} (0.5, 0.75, and 1.0 in hr^{-1}), respectively.*

Table 2.5 Weekly and seasonal ET_c and rainfall averages across all 36 study sites in 2009 and 2010.

	Average ET_c (mm)		Average Rainfall (mm)		Number of Weeks	
Year	Weekly	Total	Weekly	Total	Rainfall > 25 mm	ET_c > Rainfall
2009	23.6	709.1	23.3	699.8	12	18
2010	24.5	734.3	20.1	602.7	8	22

Note: Weather data collected from NC-SCO stations over a 30 week period for both years (first full week of April through last full week of October)

Table 2.6 Average weekly irrigation applied (I_{app}) and difference (Diff), I_{app} - GIR, by treatment in 2010.

Treatment	Average I_{app} (mm week^{-1})	Average Diff (mm week^{-1})
Ctrl	26.6 b	2.9 b
SMS	31.9 a	7.6 a
Toro	23.8 b	-1.0 b
WM	23.5 b	0.0 b

Note: Different letters in columns indicate differences between treatments using LSD means test with α=0.05. There was evidence of a difference between Ctrl and WM (P=0.07) and Ctrl and Toro (P=0.13) in I_{app}. There was similar evidence of a difference between Ctrl and Toro (P=0.06) and Ctrl and WM (P=0.12) in Diff.

Table 2.7 Comparison of turf quality visual rating LS-Means by treatment and time of season for the 2010 growing season. NTEP turf quality rating system of 1-9 (Morris and Shearman, 2009) was used for each assessment with a rating of 6 considered minimally acceptable.

	Time of Season			
Treatment	Early (July)	Mid (August)	Late (November)	*LS-Mean* [A]
Ctrl	5.1 bc	4.8 c	5.1 bc	*5.0 b*
SMS	6.1 abc	6.3 ab	6.2 ab	*6.2 a*
Toro	6.2 ab	6.2 ab	6.0 abc	*6.1 a*
WM	6.0 ab	5.9 abc	6.6 a	*6.2 a*
LS-Mean [B]	*5.9 a*	*5.8 a*	*6.0 a*	$\bar{x}$ **= 5.9**

Note: Different letters indicate significant differences at the α=0.05 level. Unitalicized letters in body of table are for comparison of treatment x time of season.
A – comparison between treatments across months
B – comparison between time of seasons across treatments

Table 2.8 Comparison of turf NDVI rating LS-Means by treatment, by time of season, and by treatment by time of season for the 2010 growing season.

	Time of Season			
Treatment	Early (July)	Mid (August)	Late (November)	*LS-Mean* [A]
Ctrl	0.6494 a	0.6823 a	0.6548 a	*0.6621 a*
SMS	0.6531 a	0.6622 a	0.6678 a	*0.6610 a*
Toro	0.6515 a	0.6786 a	0.6636 a	*0.6646 a*
WM	0.6456 a	0.6684 a	0.6825 a	*0.6655 a*
LS Mean [B]	*0.6499 a*	*0.6729 a*	*0.6672 a*	$\bar{x}$ **= 0.6631**

Note: Different letters indicate significant differences at the α=0.05 level. Unitalicized letters in body of table are for comparison of treatment x time of season.
A – comparison between treatments across months
B – comparison between time of seasons across treatments

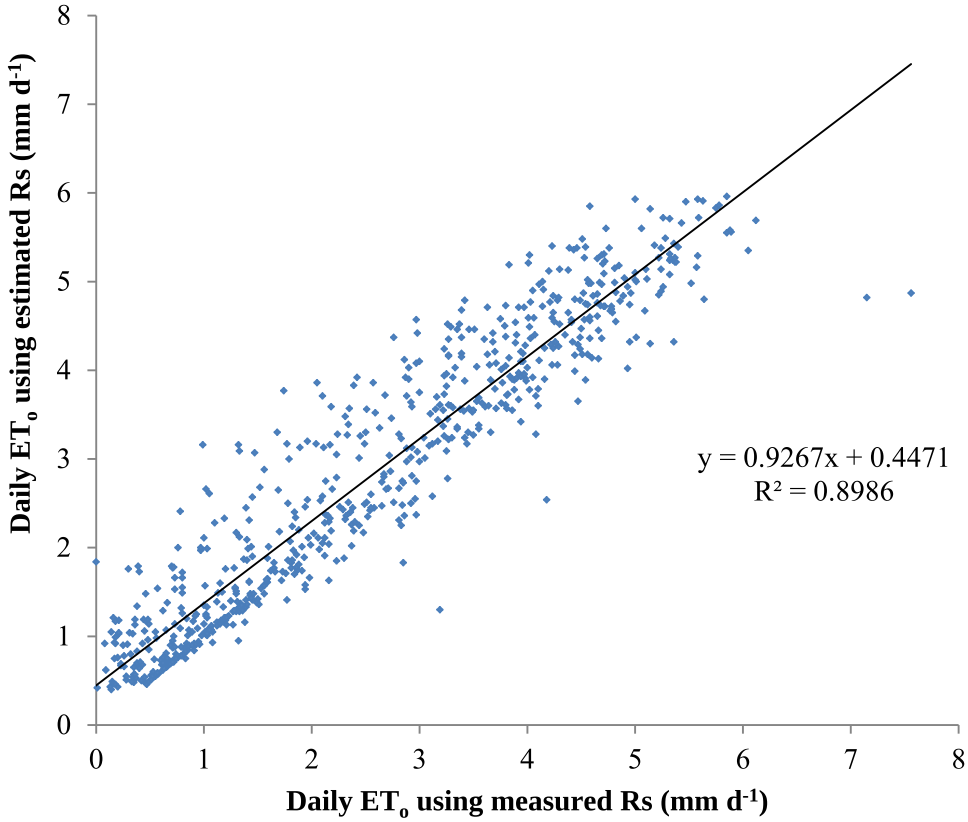

Figure 2.1 Comparison of daily ET$_o$ estimates (mm d^{-1}) calculated in Ref-ET with weather data from TAYL between Jan 1, 2009 and Dec 31, 2010 using measured R_s versus R_s estimated by the Hargreaves radiation formula with k_{Rs} = 0.18°C$^{-0.5}$.

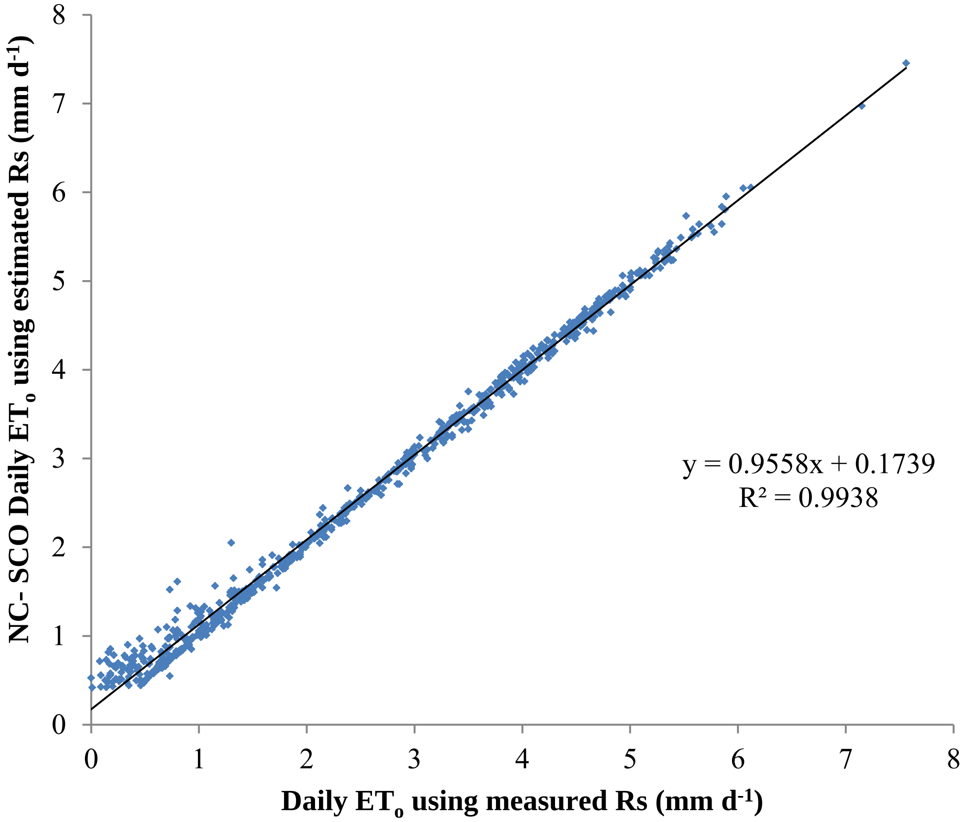

Figure 2.2 Comparison of daily ET$_o$ estimates calculated by the NC-SCO for TAYL and daily ET$_o$ estimates calculated in Ref-ET using downloaded weather data (including measured R$_s$) from TAYL between Jan 1, 2009 and Dec 31, 2010.

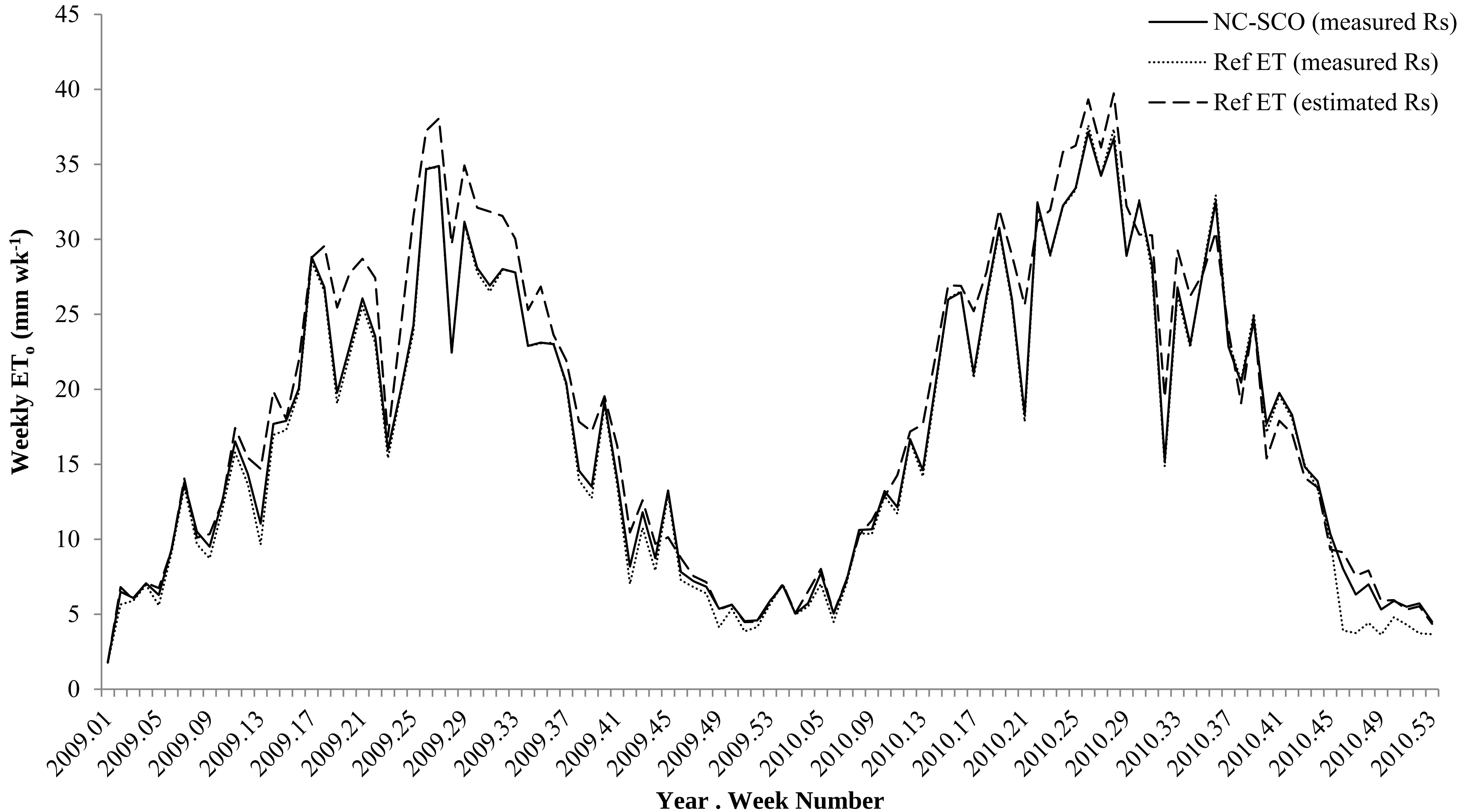

Figure 2.3 Weekly ET_o estimates from TAYL between Jan 1, 2009 and Dec 31, 2010 calculated by the NC-SCO (using measured R_s), in Ref-ET (using measured R_s), and in Ref-ET (using R_s estimated by the Hargreaves radiation formula with $k_{Rs} = 0.18°C^{-0.5}$.

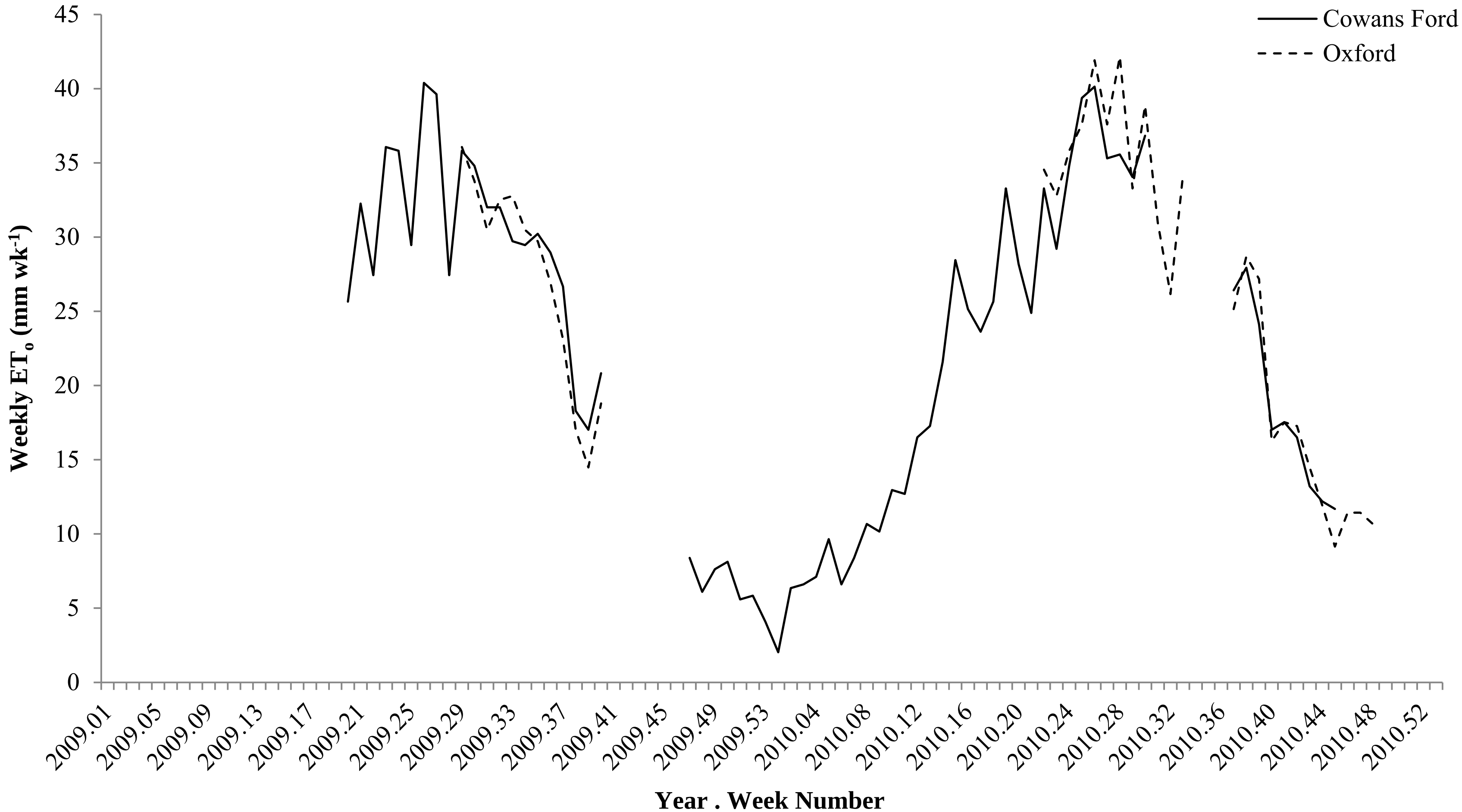

Figure 2.4 Weekly ET_o estimated by the project installed weather stations at Cowans Ford Dam and Oxford Dam. Blank periods represent missing data.

Mean	0.32	0.33	0.37
Min	0.00	0.00	0.02
Max	0.63	0.75	0.78
N	54.00	54.00	35.00

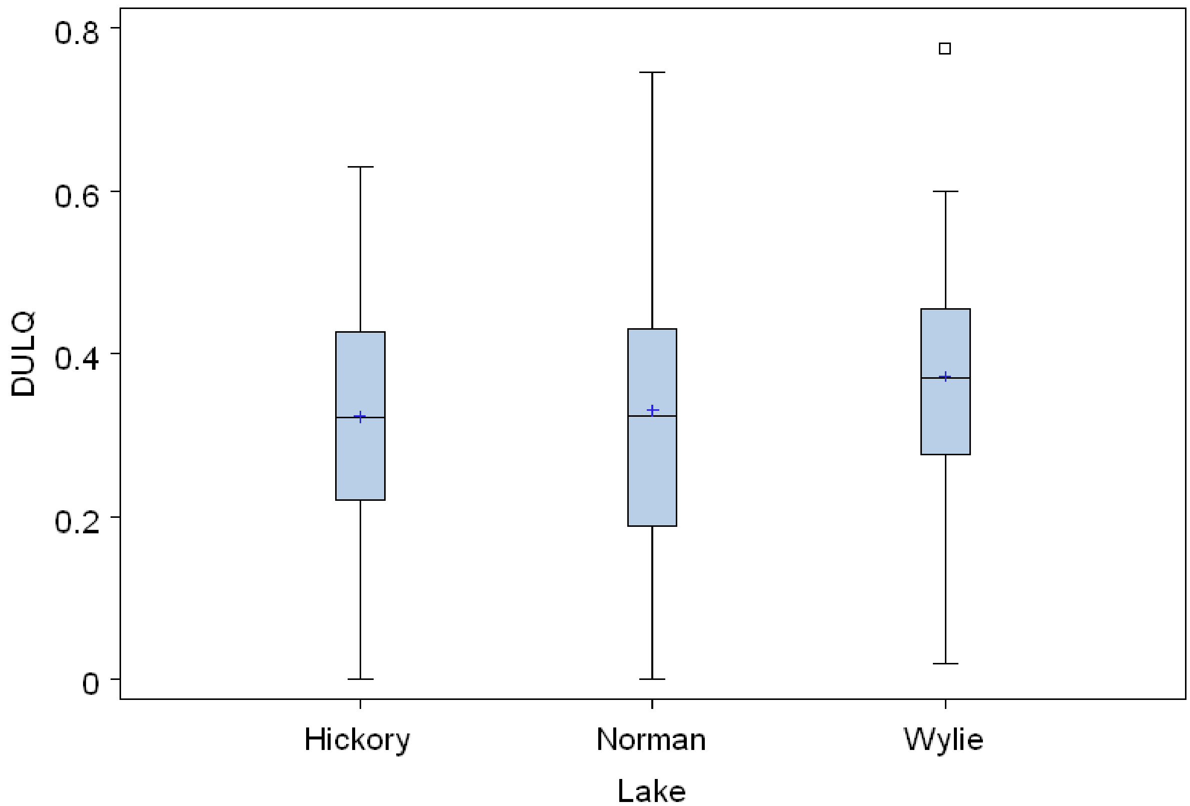

Figure 2.5 Distribution of zone DU_{LQ} by lake for all audited zones.

Mean	0.30	0.37	0.28
Min	0.07	0.01	0.00
Max	0.78	0.73	0.75
N	20.00	85.00	38.00

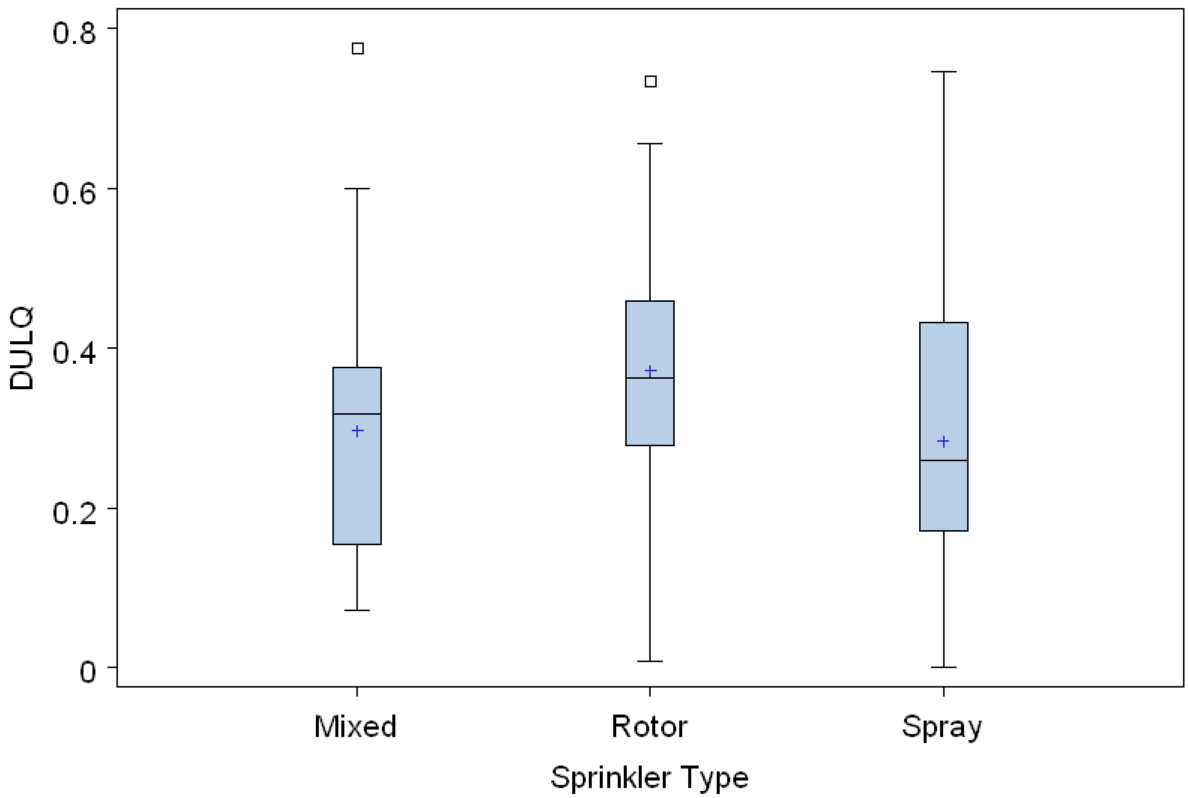

Figure 2.6 Distribution of zone DU_{LQ} by sprinkler type for all audited zones.

Mean	22.94	15.92	46.47
Max	138.49	48.24	94.41
Q3	20.87	19.17	56.57
Q1	10.39	11.05	30.06
Min	6.88	4.44	17.60
N	19.00	84.00	38.00

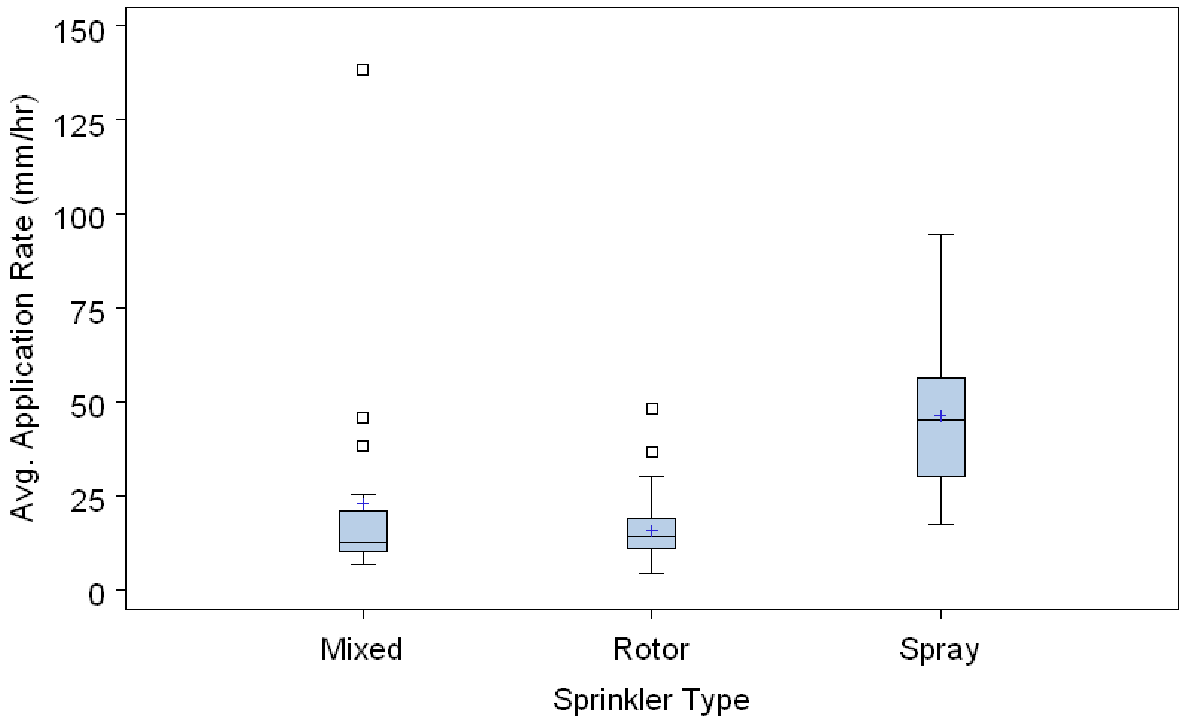

Figure 2.7 Distribution of zone average application rates by sprinkler type for all audited zones.

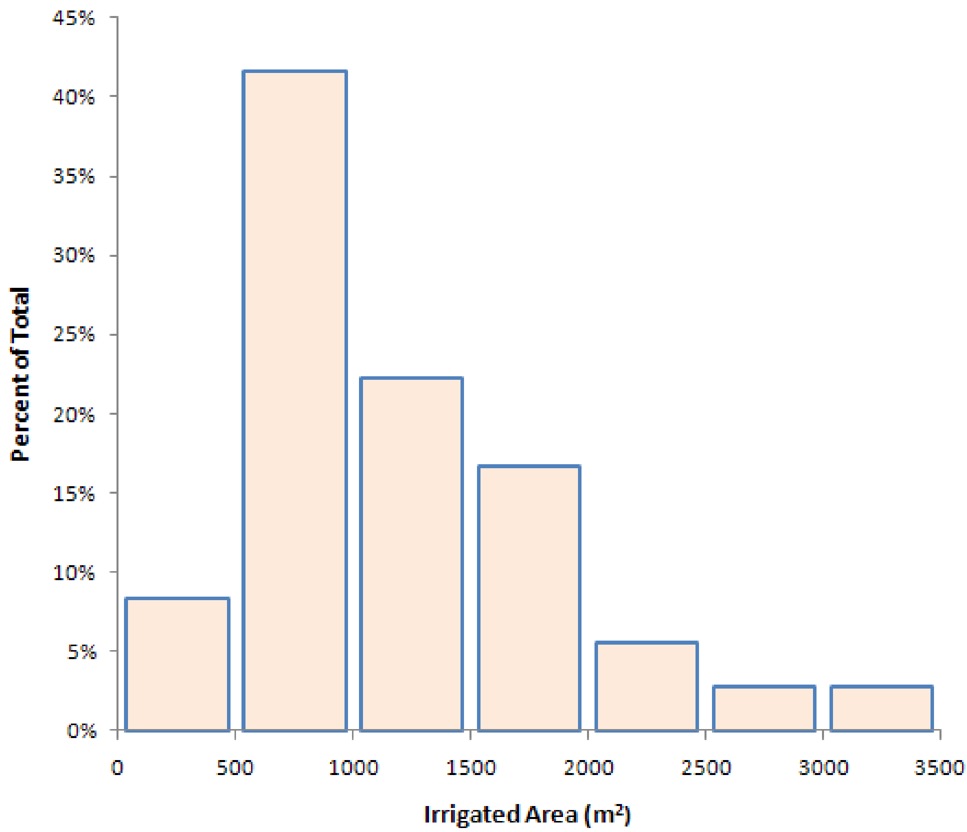

Figure 2.8 Distribution of study site irrigated areas measured using aerial imagery in ArcGIS.

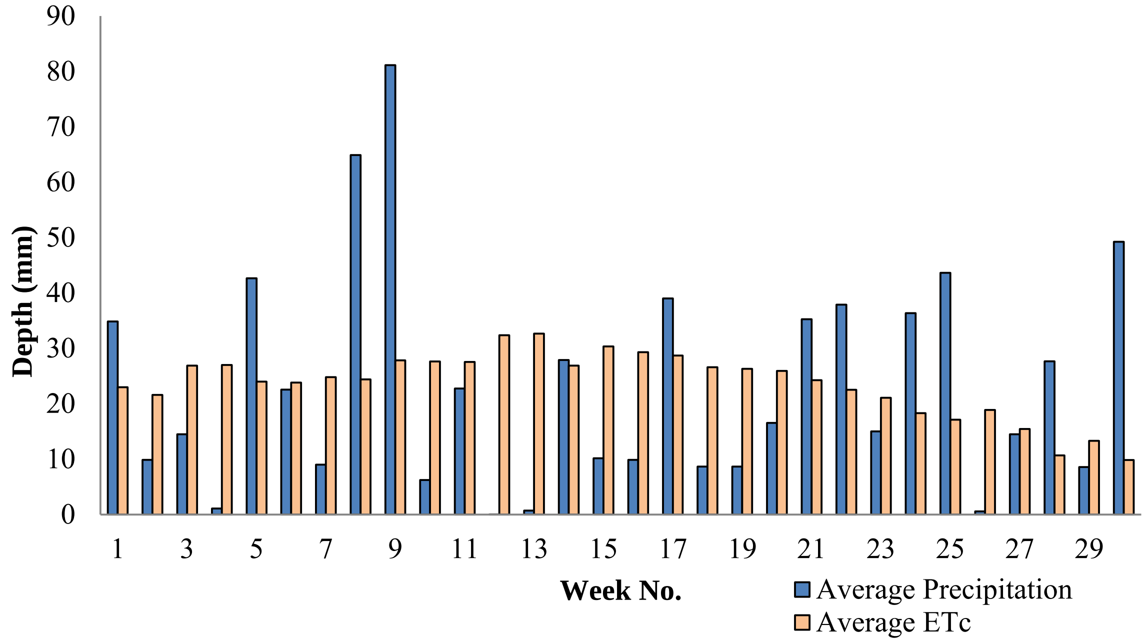

Figure 2.9 Average site precipitation and ET_c by week, 2009.

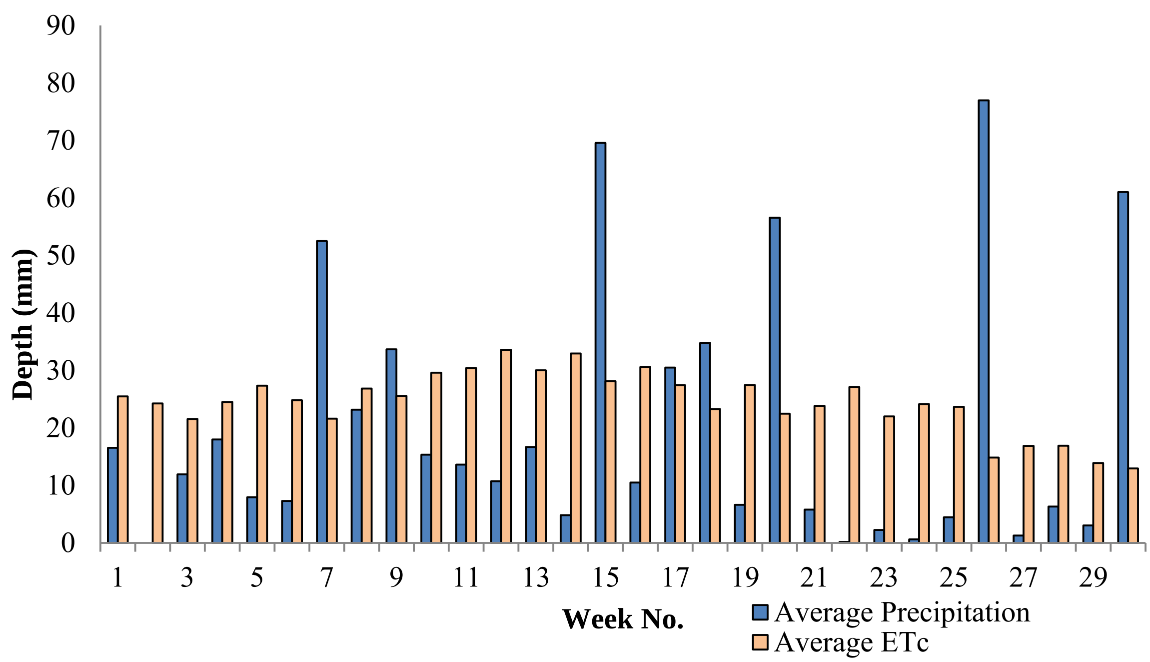

Figure 2.10 Average site precipitation and ET_c by week, 2010.

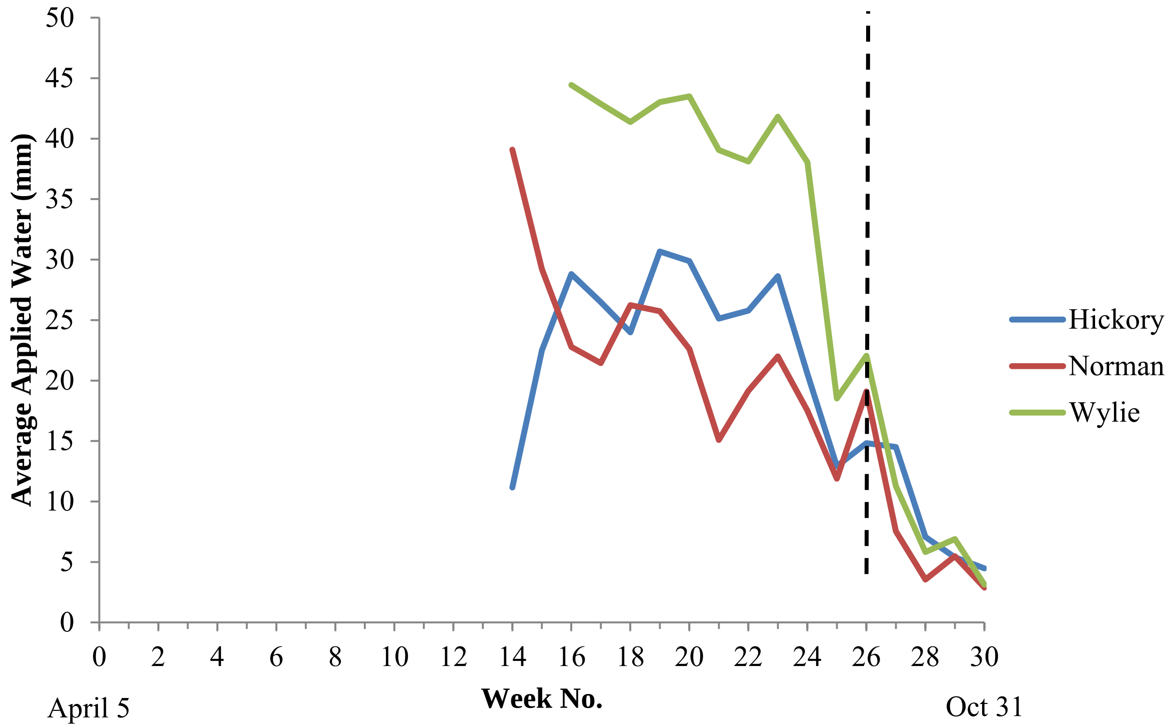

Figure 2.11 Average weekly applied irrigation by lake, 2009.

Note: Dashed line at the end of week 26 represents the end of the irrigation season.

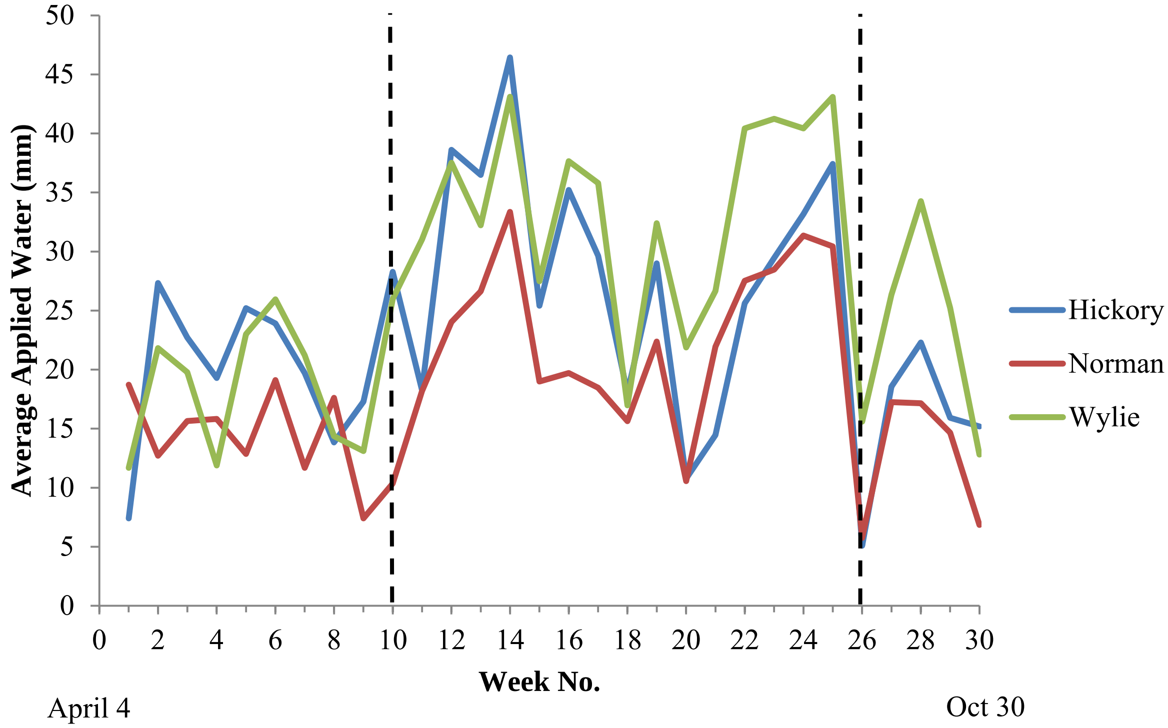

Figure 2.12 Average weekly applied irrigation by lake, 2010.

Note: Dashed lines as the beginning of week 10 and the end of week 26 mark the boundaries of the data used for statistical analysis.

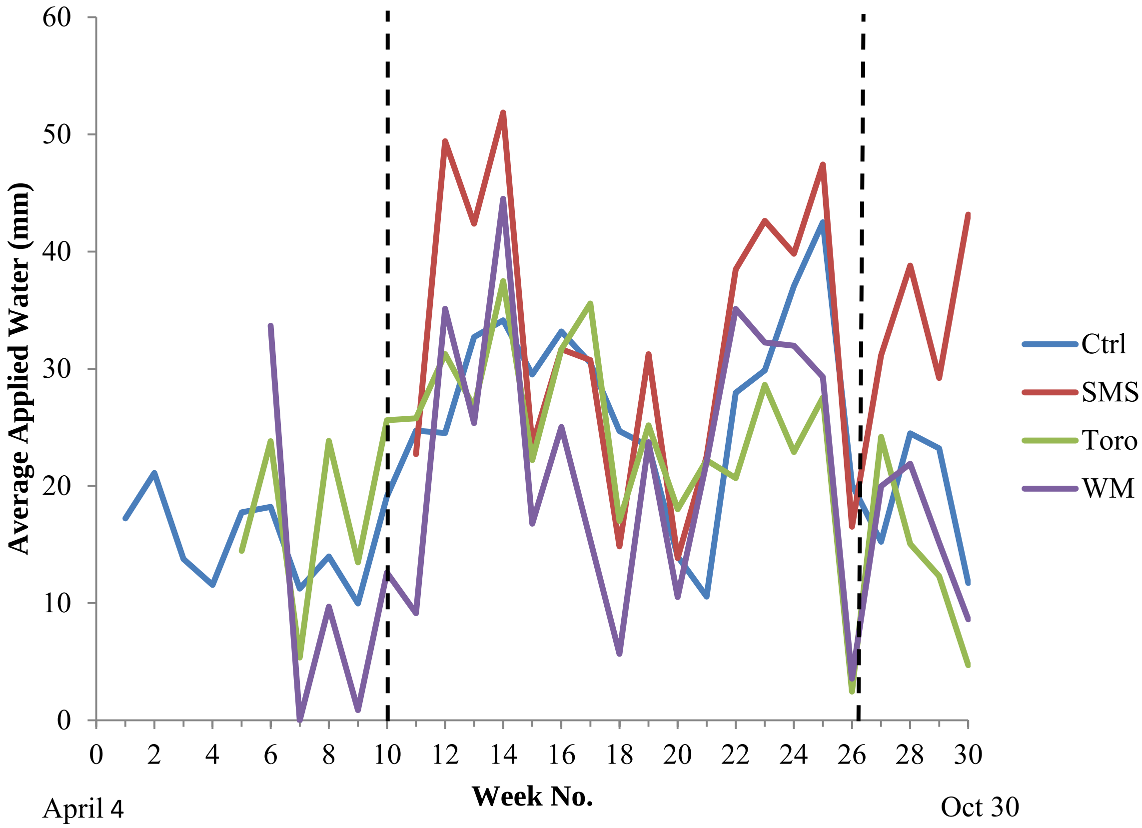

Figure 2.13 Average weekly applied irrigation by treatment, 2010.

Note: Dashed lines as the beginning of week 10 and the end of week 26 mark the boundaries of the data used for statistical analysis.

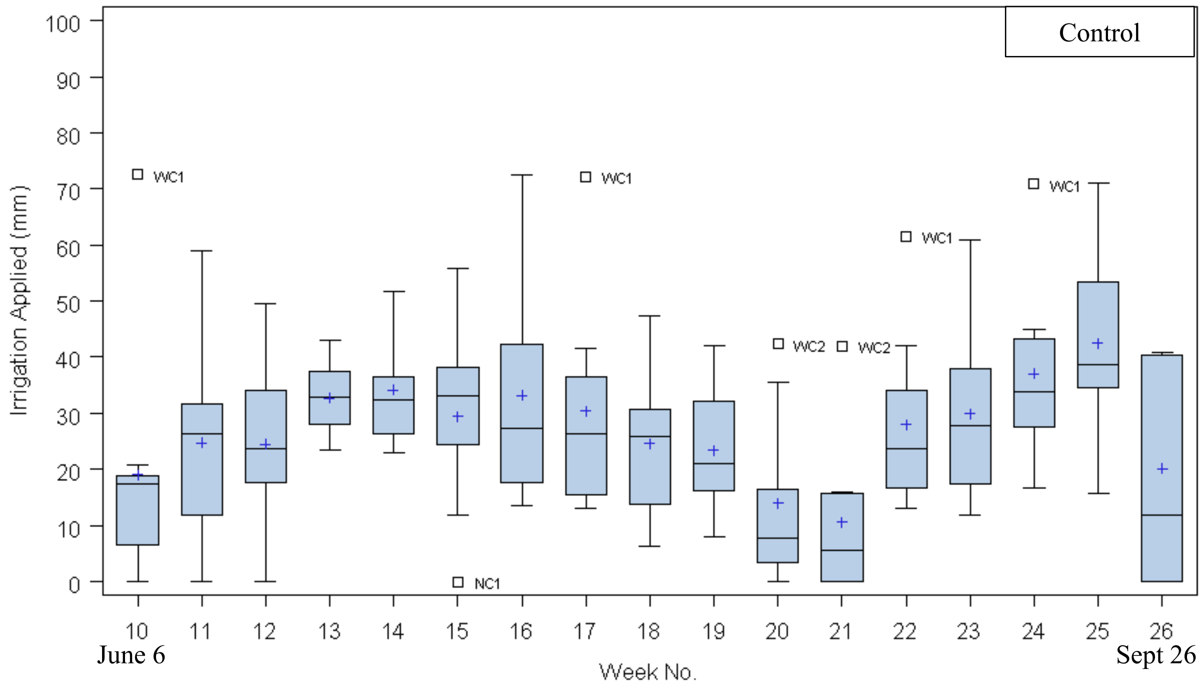

Figure 2.14 Distribution of weekly irrigation applied by the Ctrl treatment, 2010.

Note: Outliers are labeled with corresponding site labels which are presented in Table 2.2. The first letter indicates lake (H-Hickory, N-Norman, or W-Wylie), the second letter treatment (C-Ctrl, S-SMS, T-Toro, or W-WM), and the number indicates site number within treatment within lake (1, 2, or 3).

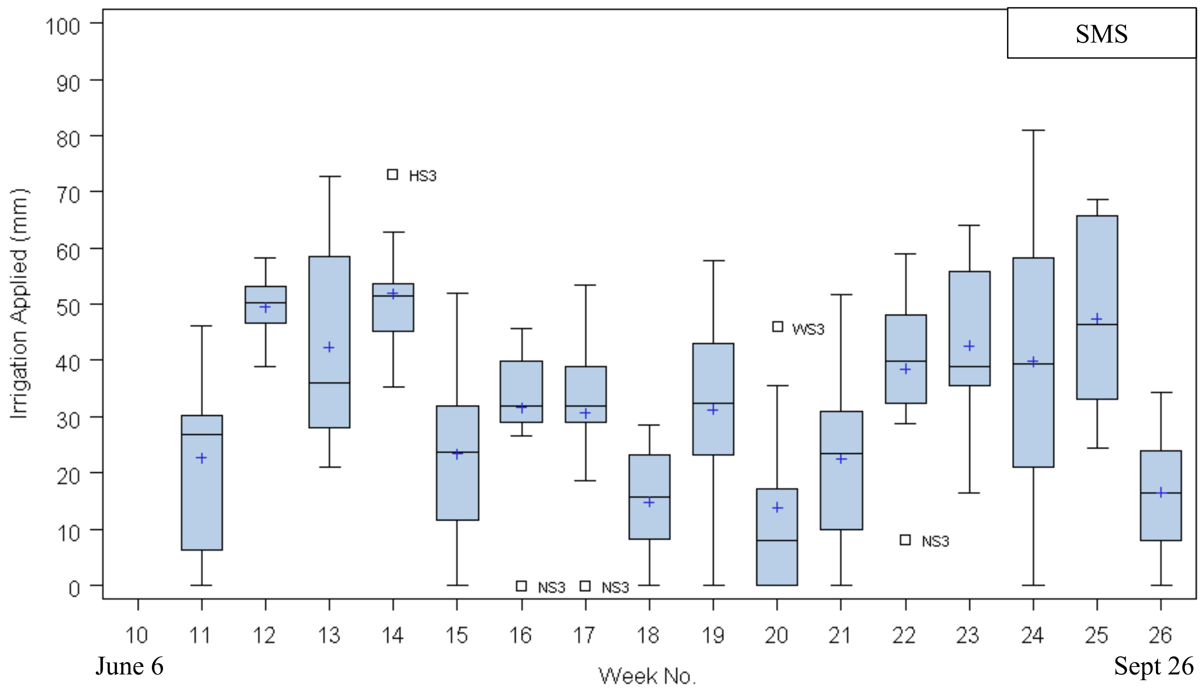

Figure 2.15 Distribution of weekly irrigation applied by the SMS treatment, 2010.

Note: Outliers are labeled with corresponding site labels which are presented in Table 2.2. The first letter indicates lake (H-Hickory, N-Norman, or W-Wylie), the second letter treatment (C-Ctrl, S-SMS, T-Toro, or W-WM), and the number indicates site number within treatment within lake (1, 2, or 3).

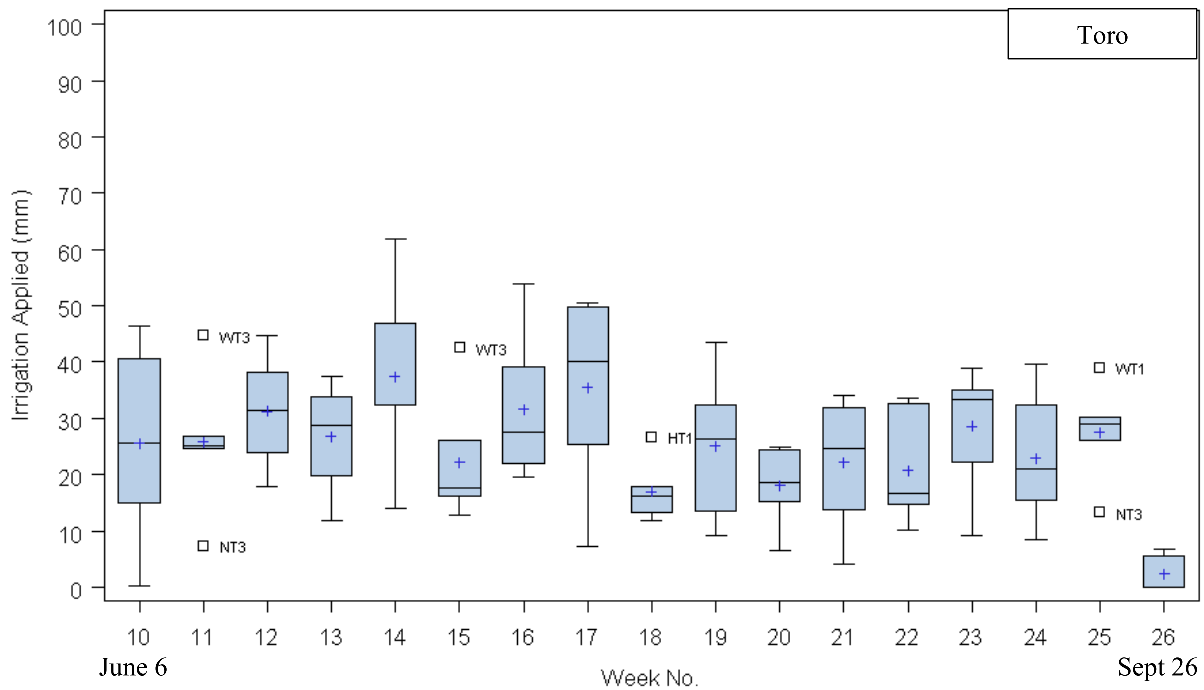

Figure 2.16 Distribution of weekly irrigation applied by the Toro treatment, 2010.

Note: Outliers are labeled with corresponding site labels which are presented in Table 2.2. The first letter indicates lake (H-Hickory, N-Norman, or W-Wylie), the second letter treatment (C-Ctrl, S-SMS, T-Toro, or W-WM), and the number indicates site number within treatment within lake (1, 2, or 3).

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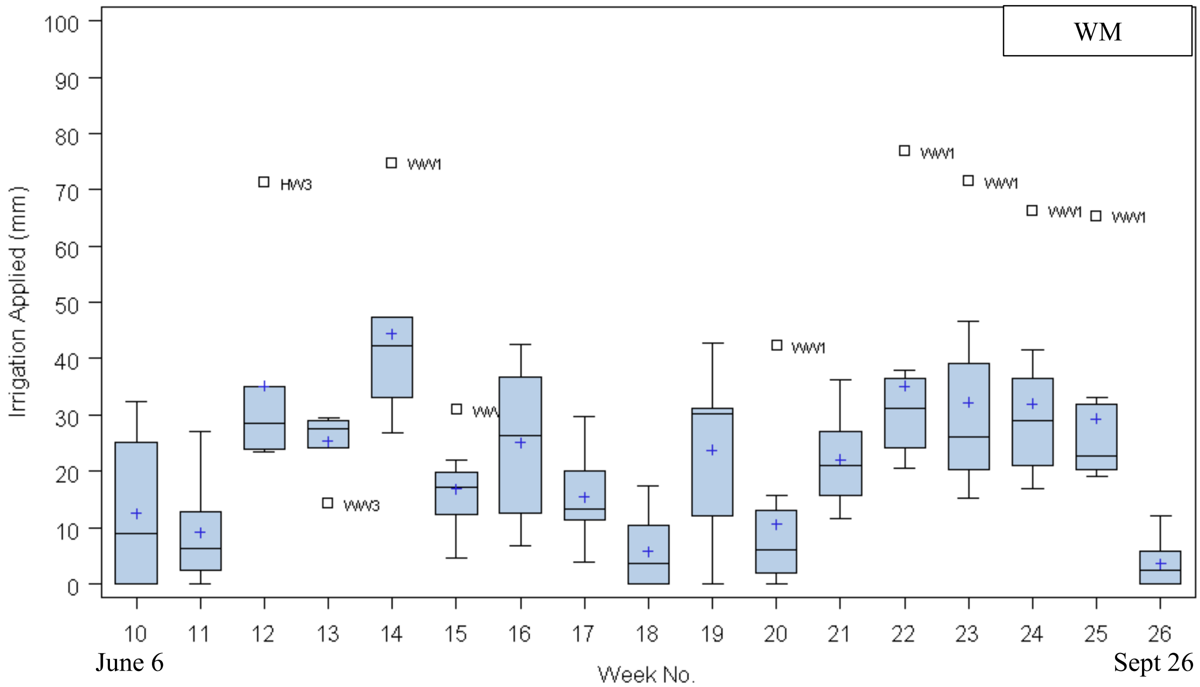

Figure 2.17 Distribution of weekly irrigation applied by the WM treatment, 2010.

Note: *Outliers are labeled with corresponding site labels which are presented in Table 2.2. The first letter indicates lake (H-Hickory, N-Norman, or W-Wylie), the second letter treatment (C-Ctrl, S-SMS, T-Toro, or W-WM), and the number indicates site number within treatment within lake (1, 2, or 3).*

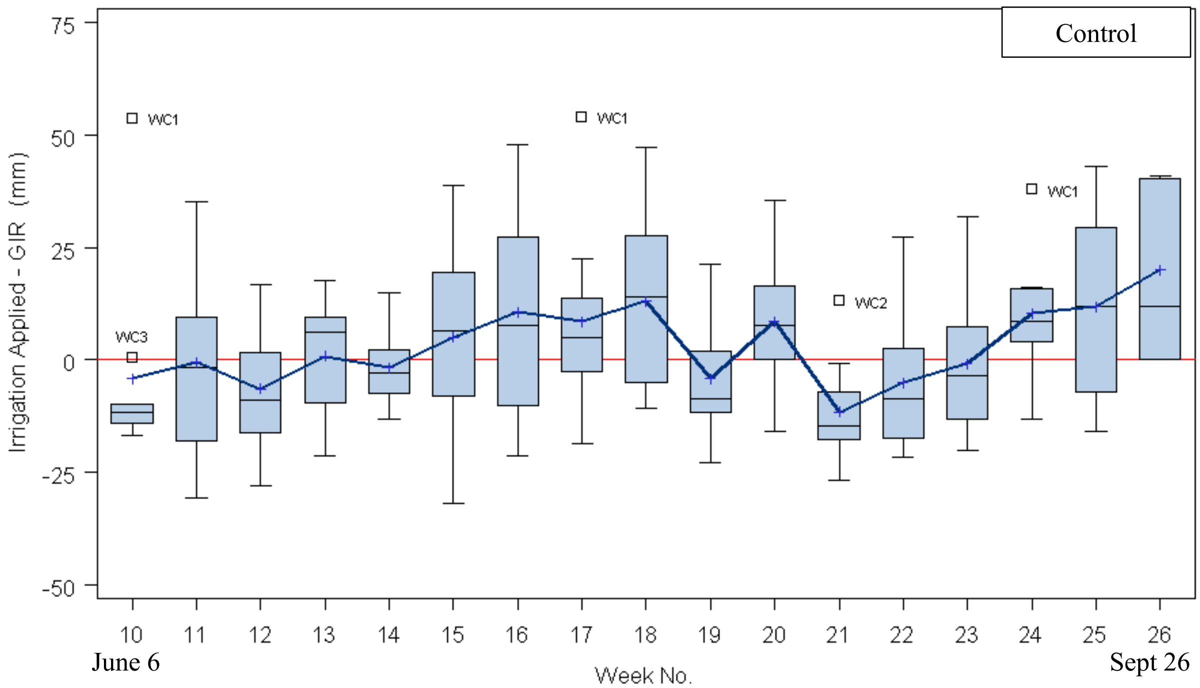

Figure 2.18 Distribution of weekly irrigation accuracy (Diff) for the Ctrl treatment, 2010.

Note: Red line indicates perfect accuracy, i.e., Applied Water = GIR. Blue line connects weekly means. Outliers are labeled with corresponding site labels which are presented in Table 2.2. The first letter indicates lake (H-Hickory, N-Norman, or W-Wylie), the second letter treatment (C-Ctrl, S-SMS, T-Toro, or W-WM), and the number indicates site number within treatment within lake (1, 2, or 3).

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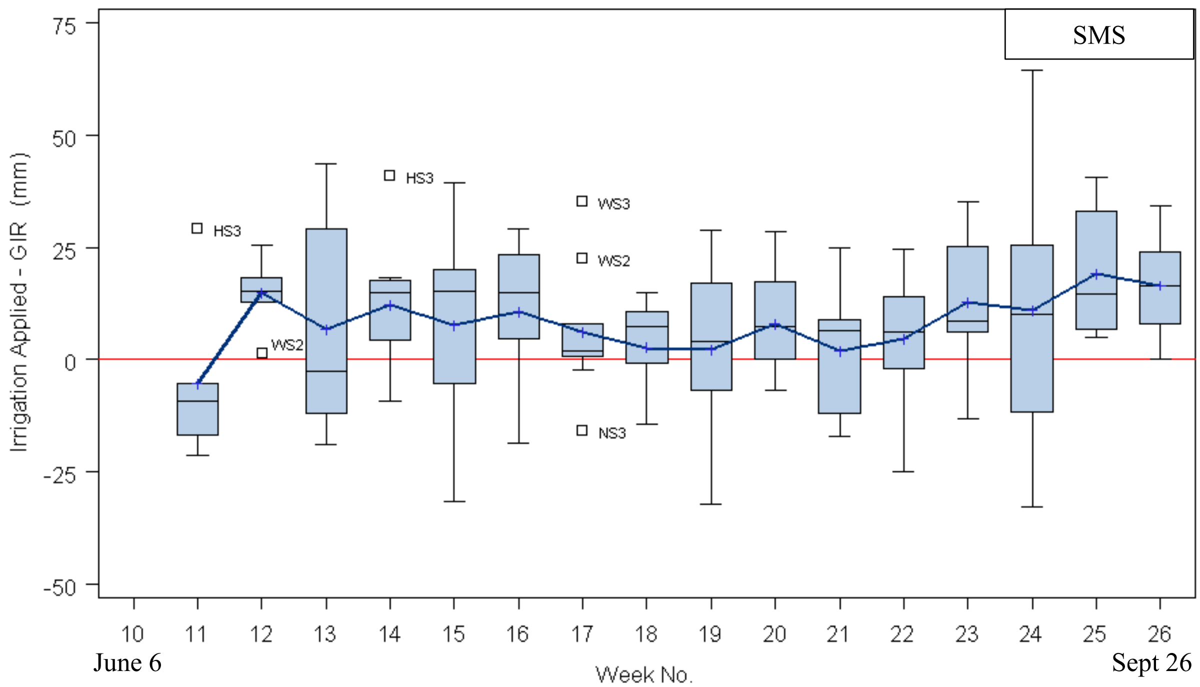

Figure 2.19 Distribution of weekly irrigation accuracy (Diff) for the SMS treatment, 2010.

Note: Red line indicates perfect accuracy, i.e., Applied Water = GIR. Blue line connects weekly means. Outliers are labeled with corresponding site labels which are presented in Table 2.2. The first letter indicates lake (H-Hickory, N-Norman, or W-Wylie), the second letter treatment (C-Ctrl, S-SMS, T-Toro, or W-WM), and the number indicates site number within treatment within lake (1, 2, or 3).

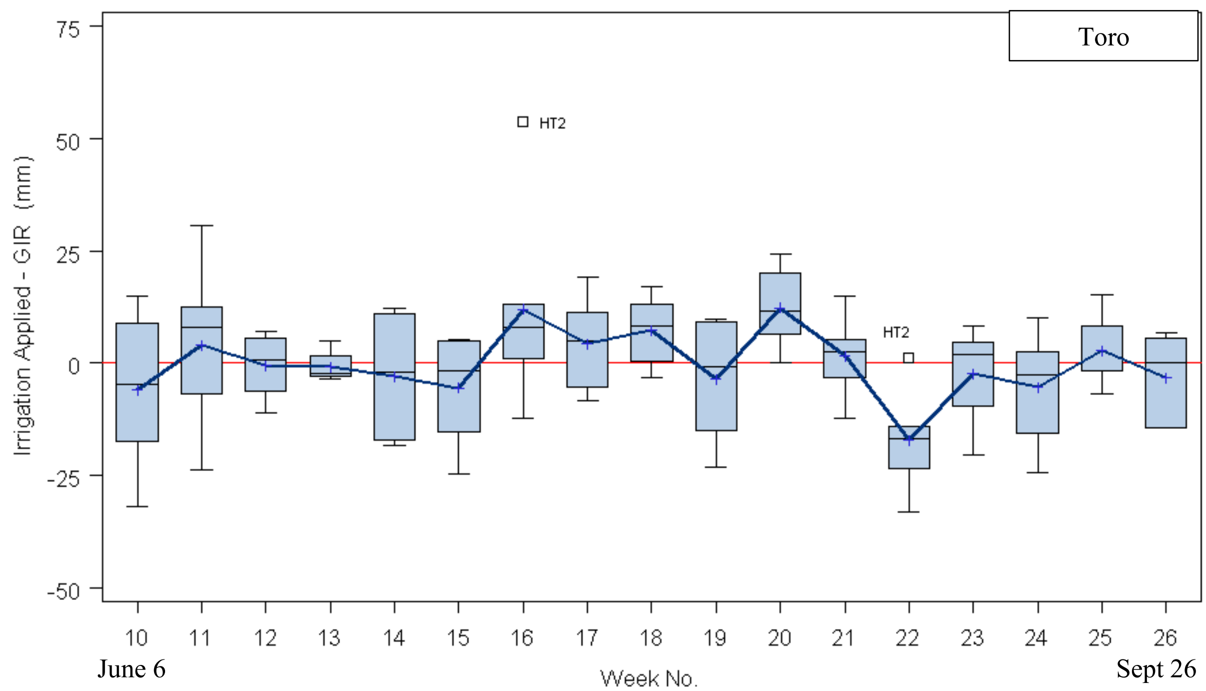

Figure 2.20 Distribution of weekly irrigation accuracy (Diff) for the Toro treatment, 2010.

Note: Red line indicates perfect accuracy, i.e., Applied Water = GIR. Blue line connects weekly means. Outliers are labeled with corresponding site labels which are presented in Table 2.2. The first letter indicates lake (H-Hickory, N-Norman, or W-Wylie), the second letter treatment (C-Ctrl, S-SMS, T-Toro, or W-WM), and the number indicates site number within treatment within lake (1, 2, or 3).

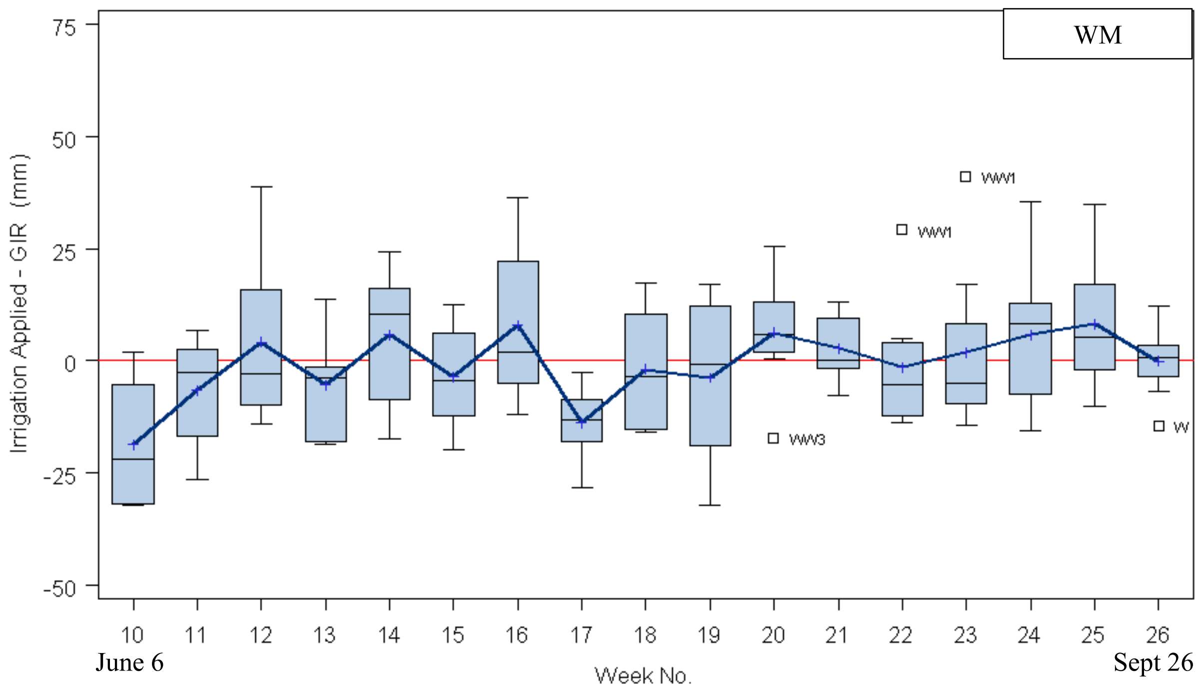

Figure 2.21 Distribution of weekly irrigation accuracy (Diff) for the WM treatment, 2010.

Note: Red line indicates perfect accuracy, i.e., Applied Water = GIR. Blue line connects weekly means. Outliers are labeled with corresponding site labels which are presented in Table 2.2. The first letter indicates lake (H-Hickory, N-Norman, or W-Wylie), the second letter treatment (C-Ctrl, S-SMS, T-Toro, or W-WM), and the number indicates site number within treatment within lake (1, 2, or 3).

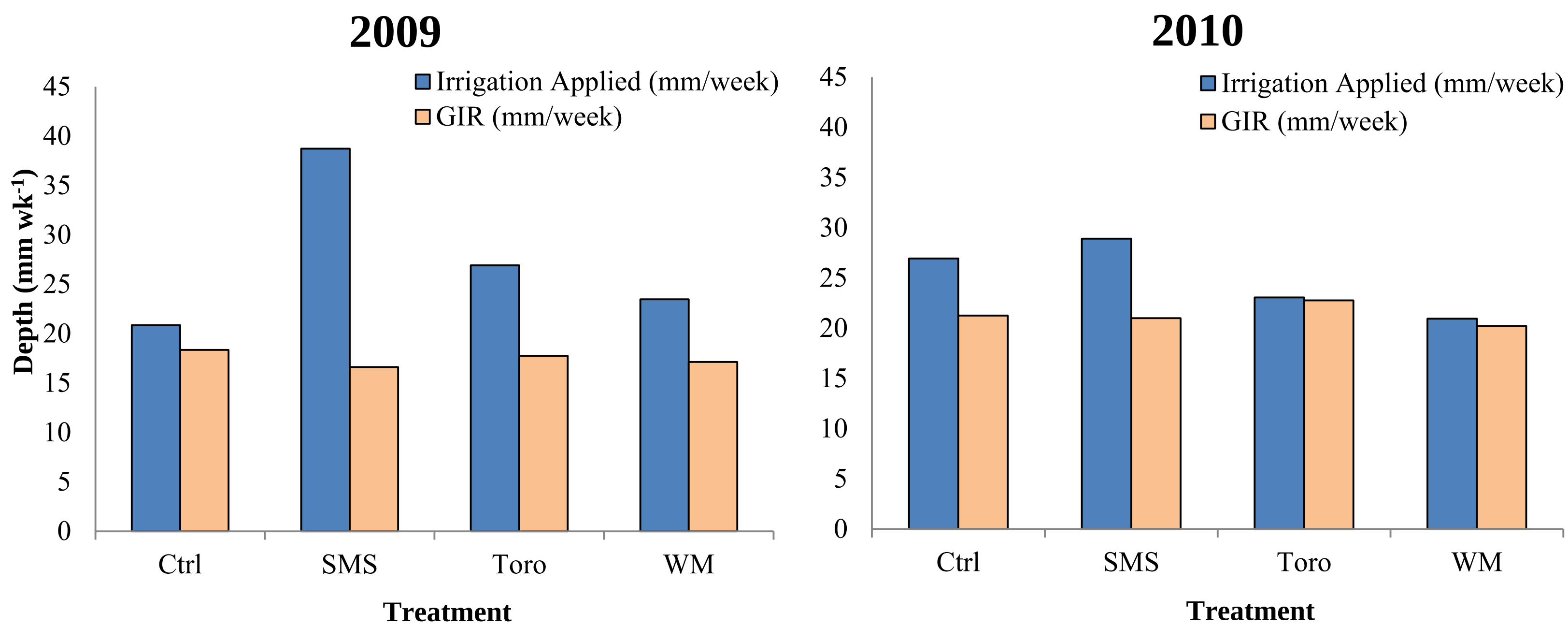

Figure 2.22 Mean weekly irrigation applied (I_{app}) and average weekly gross irrigation requirement (GIR) by treatment for 2009 and 2010. The 2009 plot represents water use behavior before treatment and the 2010 plot represents behavior after treatment.

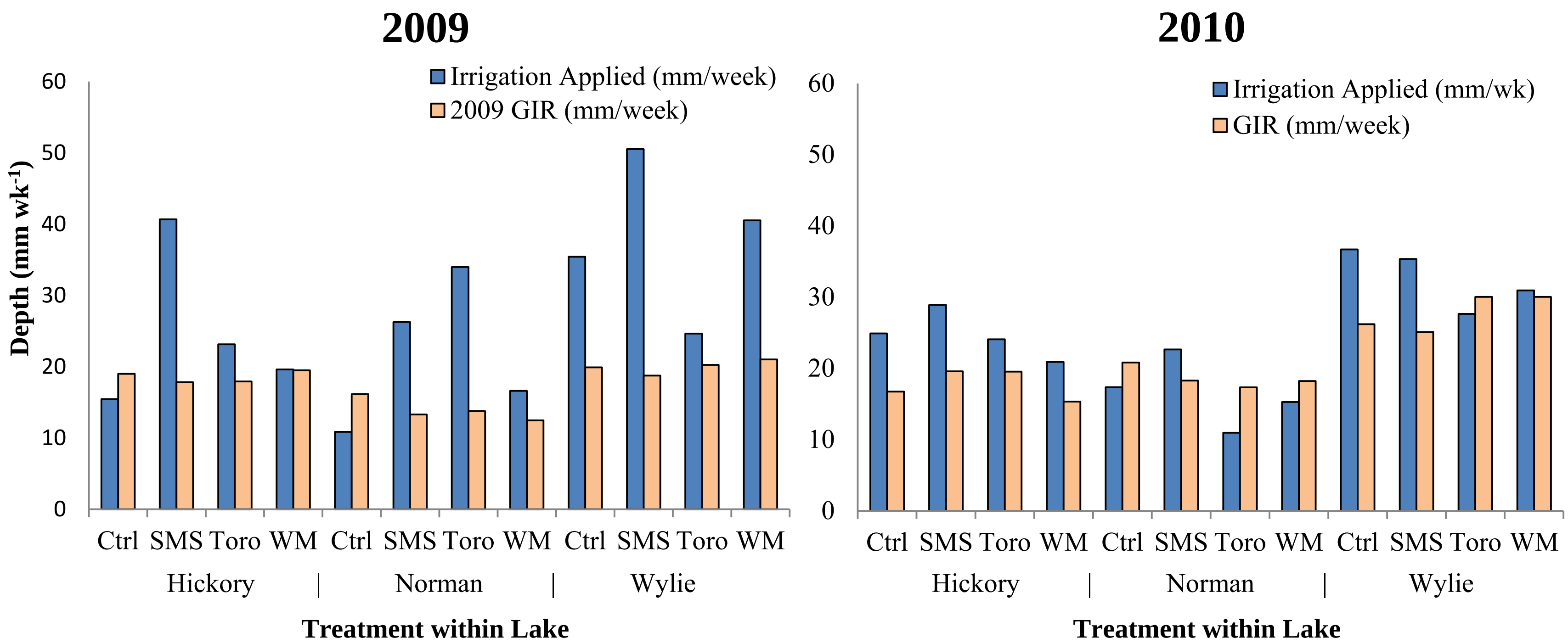

Figure 2.23 Mean weekly irrigation applied (I_{app}) and average weekly gross irrigation requirement (GIR) by lake and treatment for 2009 and 2010. The 2009 plot represents water use behavior before treatment and the 2010 plot represents behavior after treatment.

Treatment	2009* I_{app} (mm/wk)	2009* GIR (mm/wk)	2009* Diff (mm/wk)	2010 I_{app} (mm/wk)	2010 GIR (mm/wk)	2010 Diff (mm/wk)	2009 to 2010 Δ I_{app} (mm/wk)	2009 to 2010 Δ GIR (mm/wk)	2009 to 2010 Δ Diff (mm/wk)
Ctrl	21.1 b	17.1 a	4.5 b	26.4 ab	21.0 a	5.2 ab	5.3	3.8*	0.7
SMS	38.9 a	15.8 a	23.7 a	29.6 a	21.5 a	8.0 a	-9.3*	5.7*	-15.7*
Toro	25.2 b	16.3 a	8.7 b	22.2 b	22.0 a	0.0 c	-2.9	5.8*	-8.7*
WM	24.4 b	16.3 a	7.9 b	22.3 b	20.8 a	2.0 bc	-2.2	4.5*	-5.9*
Overall	*27.4*	*16.4*	*11.2*	*25.1*	*21.3*	*3.8*	*-2.3*	*5.0**	*-7.4**

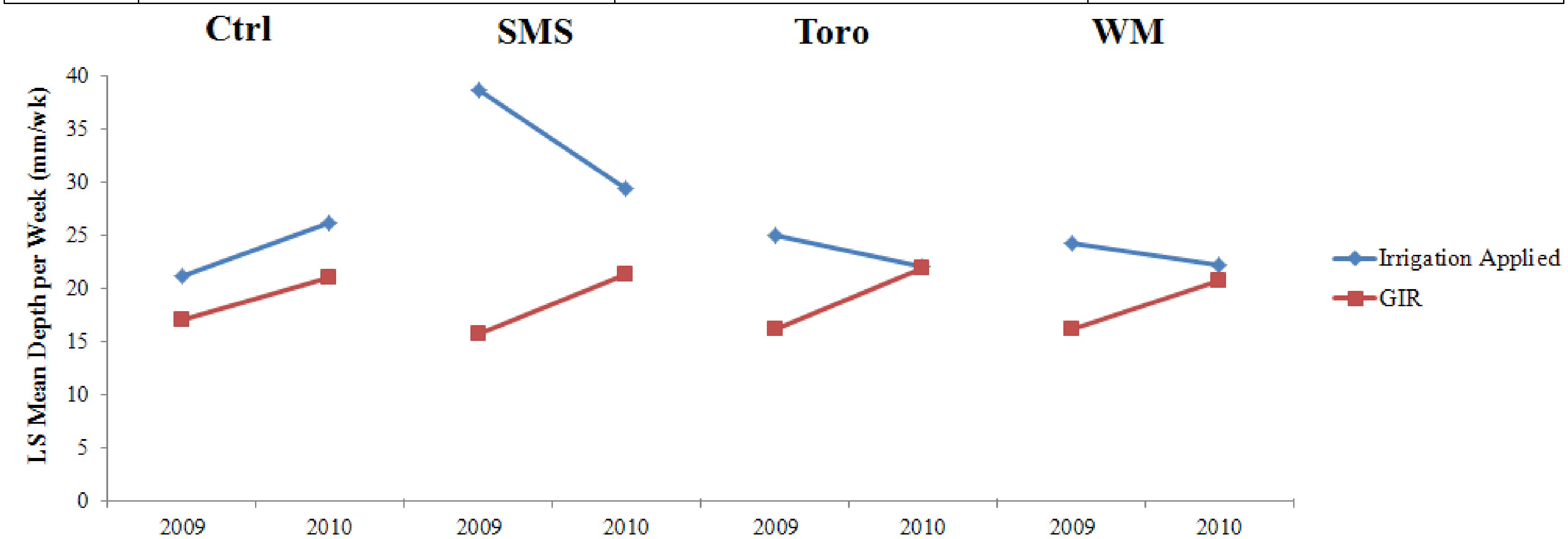

Figure 2.24 Comparison of LS-Means generated from models for I_{app}, GIR, Diff, each with Year, Treatment, and Year*Treatment as fixed affects and Lake as a random effect.

*Note: Data collected between weeks 15 and 26 of both years. Different letters in columns indicate differences between treatments within the year at the α=0.05 level. An asterisk indicates a significant difference within treatment group from 2009 to 2010 at the α=0.05 level. Slight variation between values in this figure and Figure 2.22andFigure 2.23 are the due to being LS-Means versus Arithmetic Means. *Smart technologies not installed in 2009.*

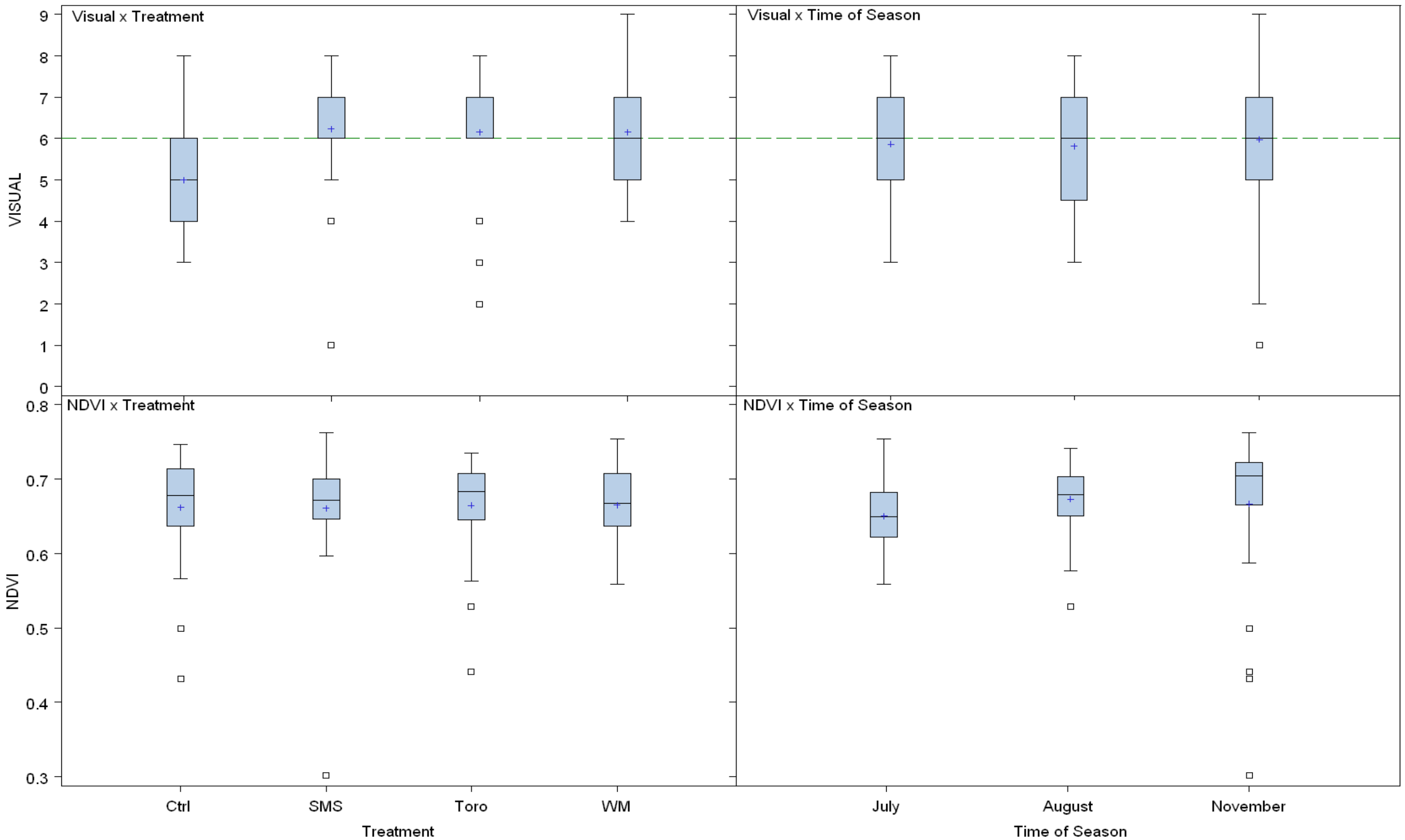

Figure 2.25 Turf quality visual ratings using NTEP standards (Morris and Shearman, 2009) and NDVI ratings by treatment and time of season in 2010. Dashed line in top plots indicates minimum acceptable visual rating (6).

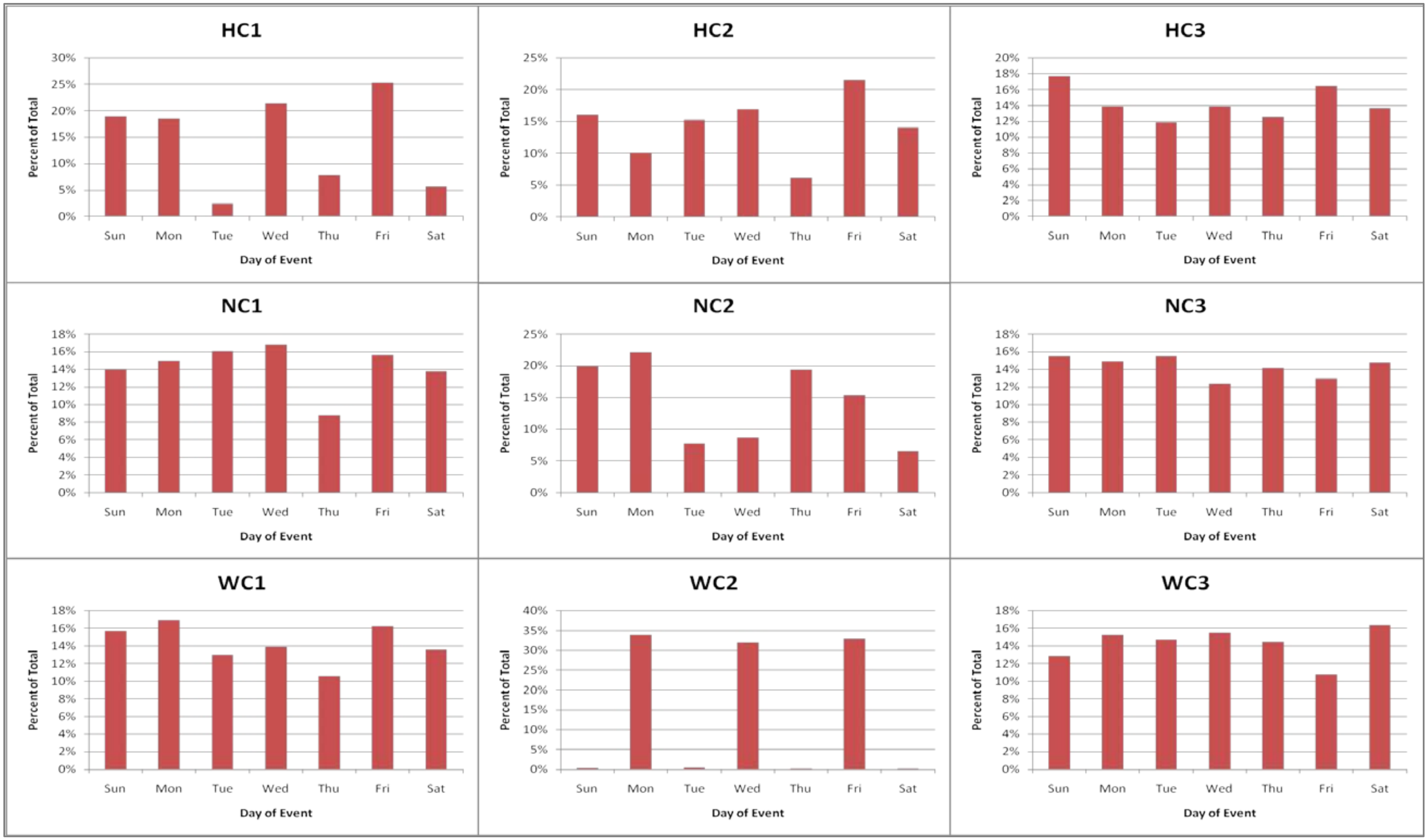

Figure 2.26 Distribution of days of irrigation events for each site in the Ctrl treatment, 2010.
Note: No irrigation day restrictions were imposed on the Ctrl treatment group.

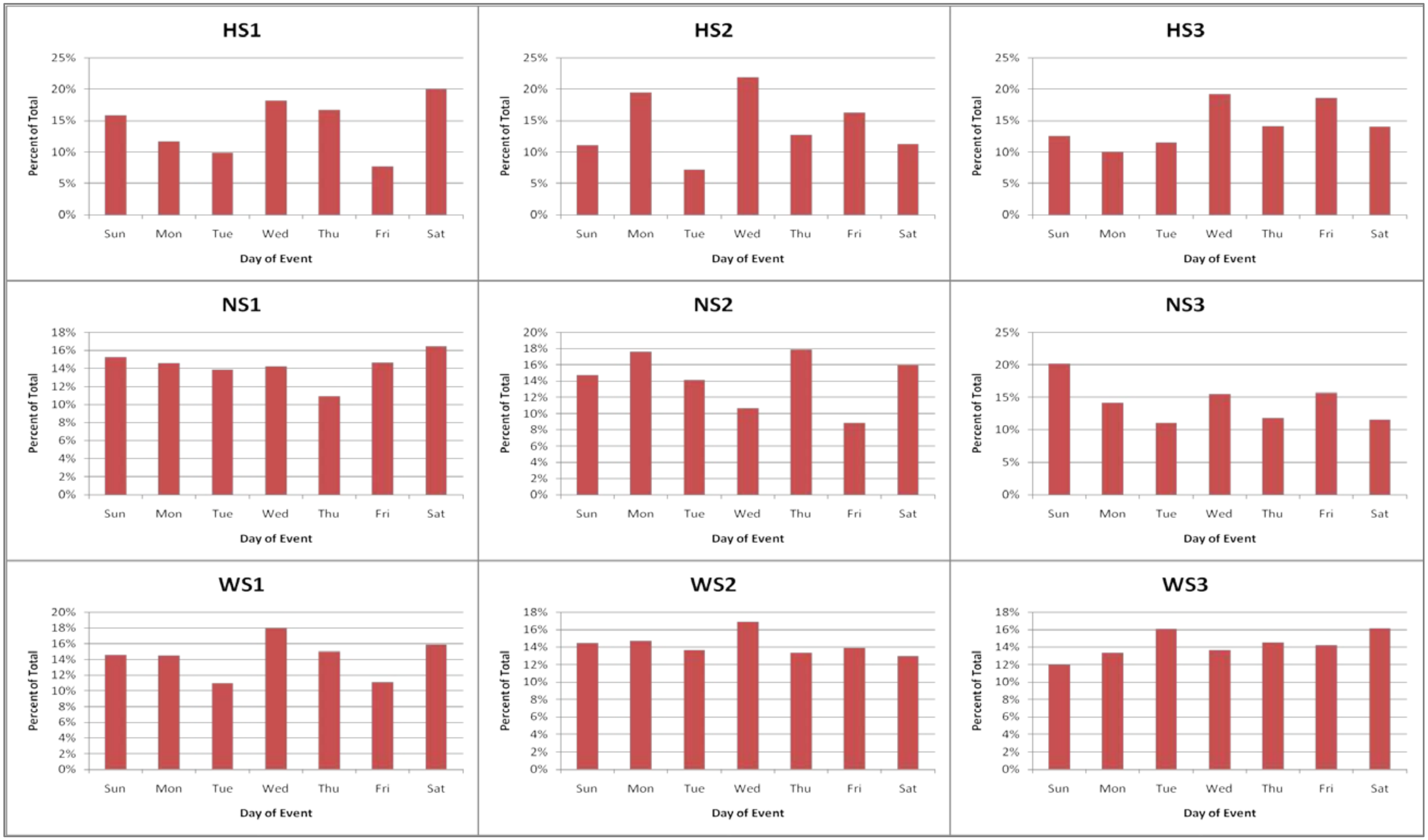

Figure 2.27 Distribution of days of irrigation events for each site in the SMS treatment, 2010.
Note: SMS controllers were programmed to allow for irrigation any day of the week.

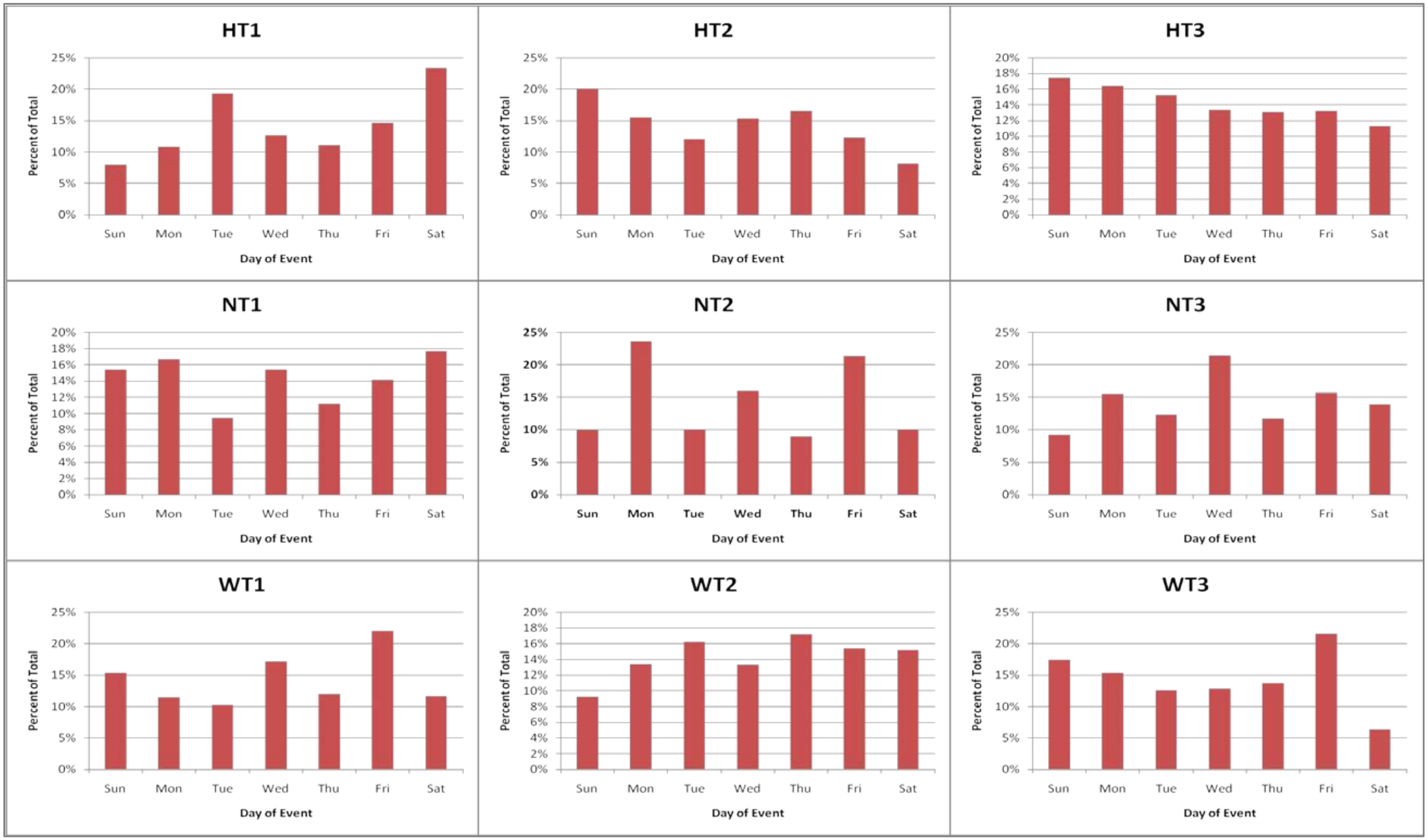

Figure 2.28 Distribution of days of irrigation events for each site in the Toro treatment, 2010.
Note: Toro controllers were programmed to allow for irrigation any day of the week.

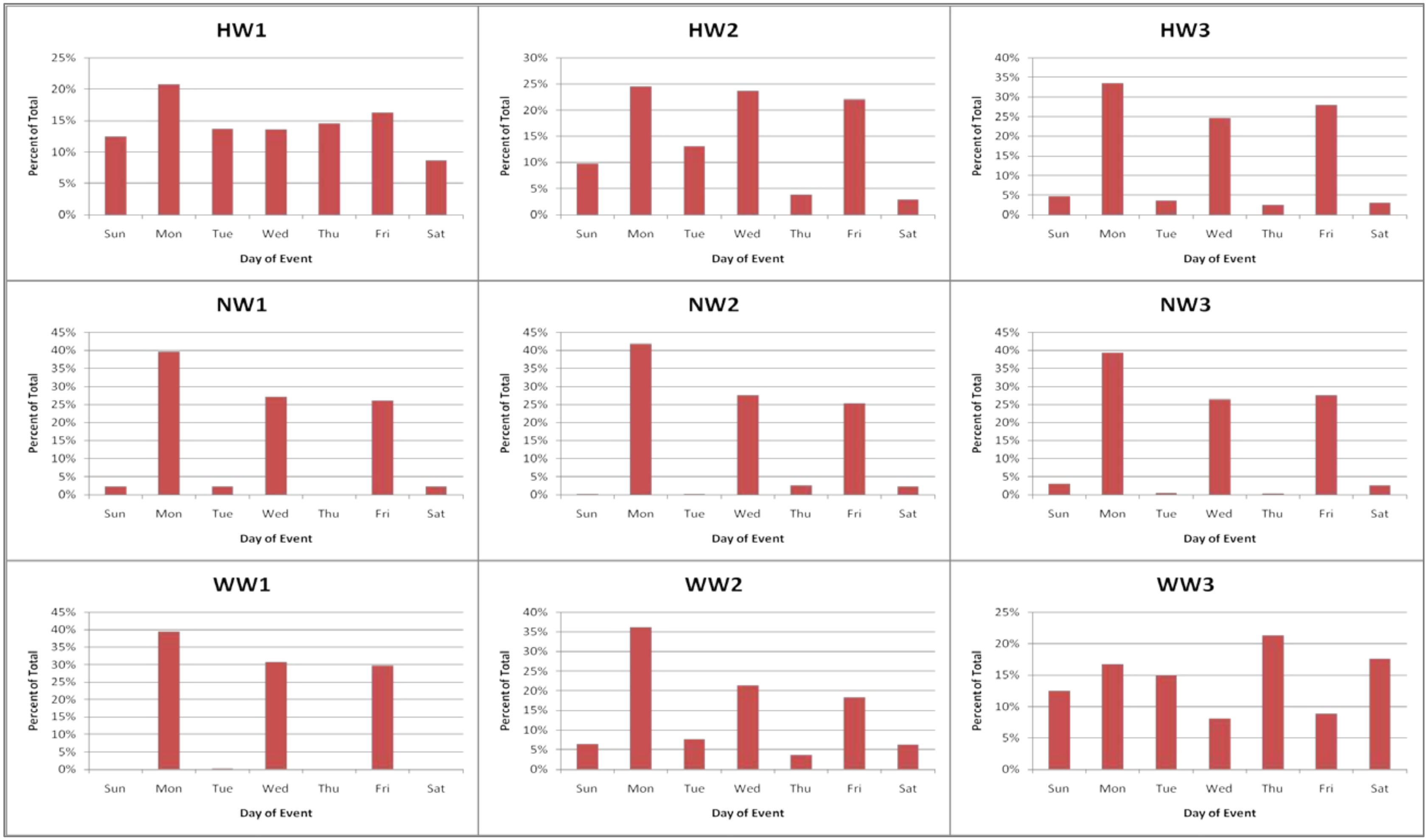

Figure 2.29 Distribution of days of irrigation events for each site in the WM treatment, 2010.
Note: All WM controllers were programmed to run on Mon, Wed, and Fri, except for sites HW1 and HW3, which used day intervals for a portion of the season.

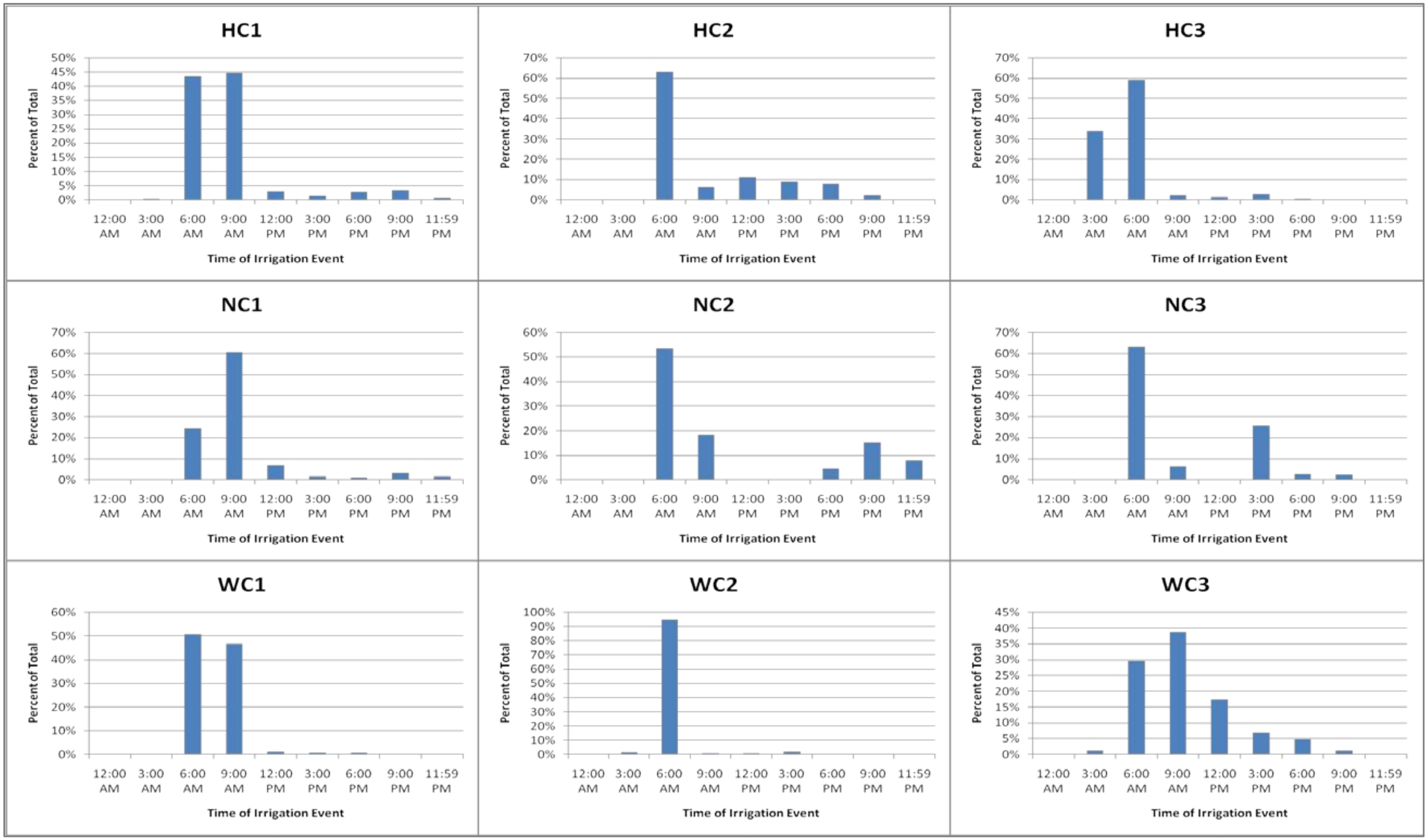

Figure 2.30 Distribution of times of irrigation events for the Ctrl treatment, 2010.
Note: No time restrictions were imposed on the Ctrl treatment group.

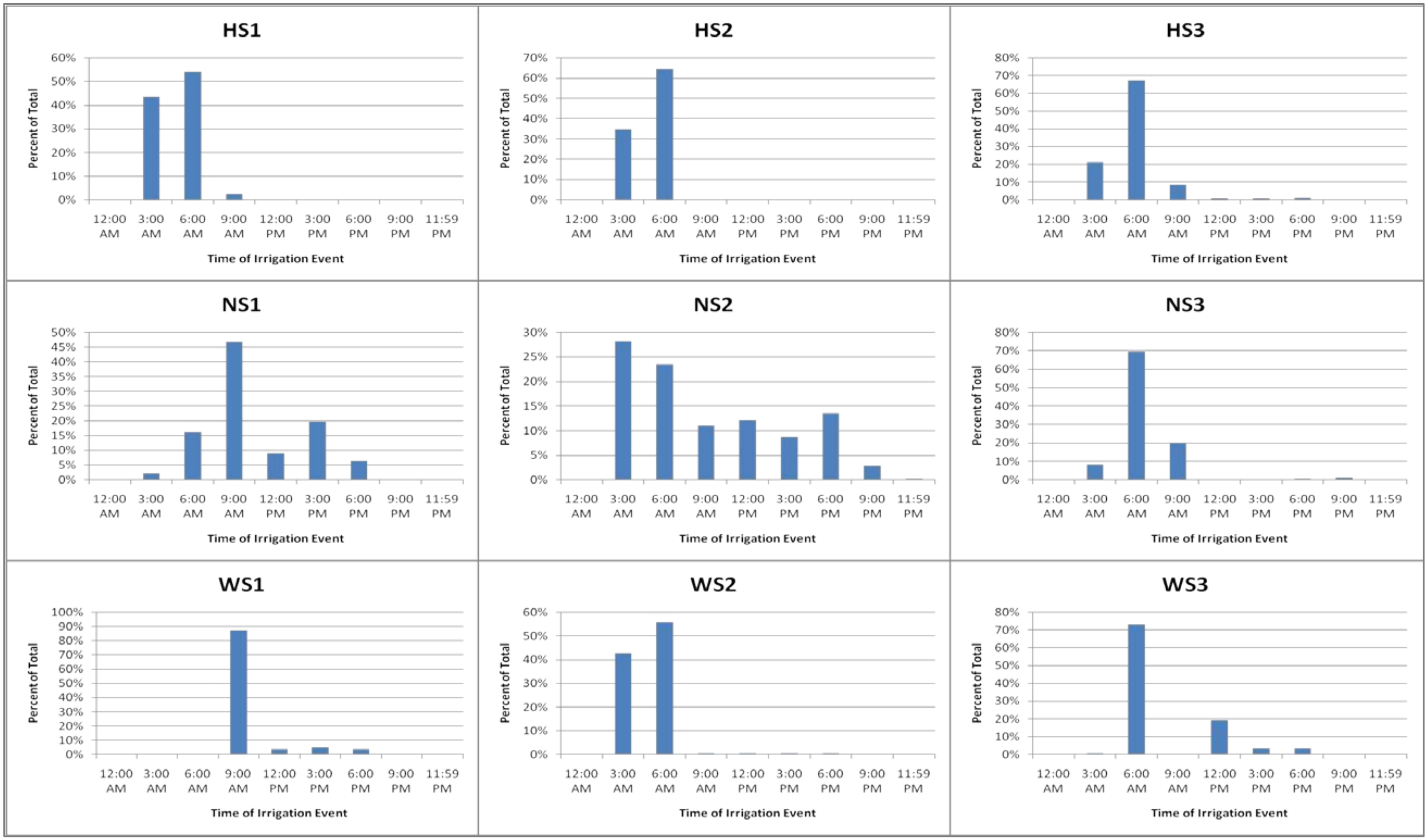

Figure 2.31 Distribution of times of irrigation events in 2010 for the SMS treatment, after technology installations.
Note: All start times were initially programmed between 1:00 and 3:00 AM unless otherwise requested by the homeowner.

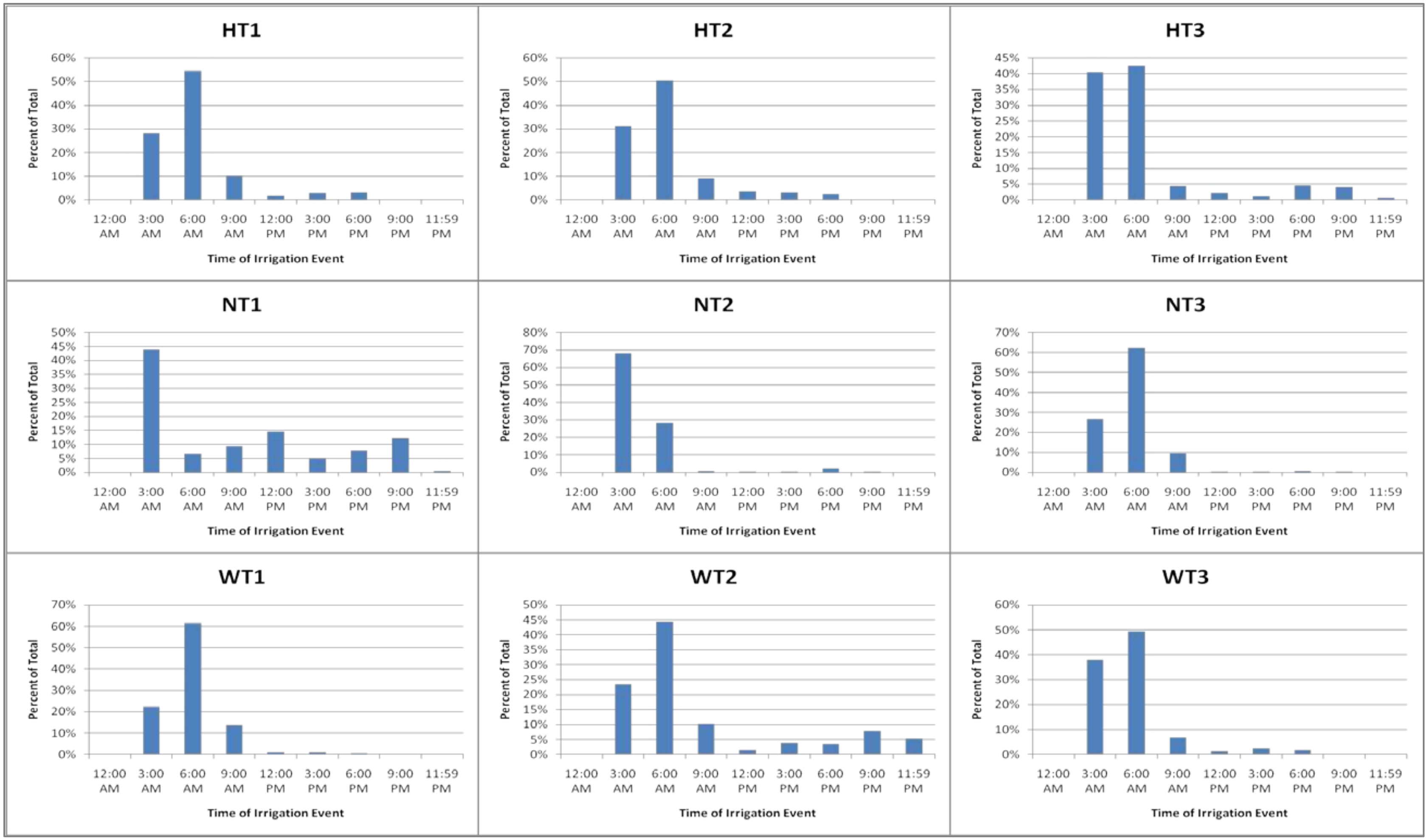

Figure 2.32 Distribution of times of irrigation events in 2010 for the Toro treatment, after technology installations.
Note: All start times were initially programmed between 1:00 and 3:00 AM unless otherwise requested by the homeowner.

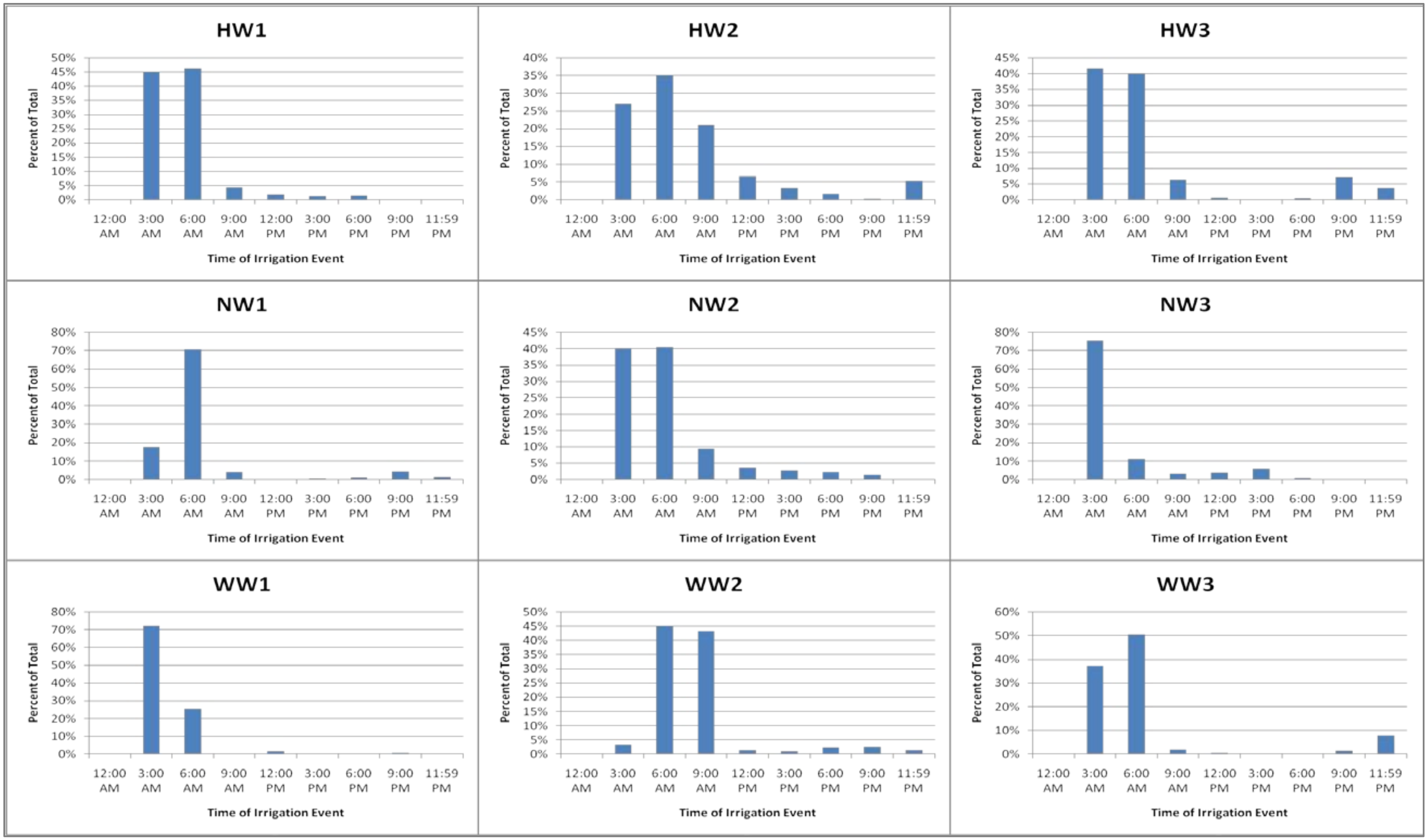

Figure 2.33 Distribution of irrigation event times in 2010 for the WM treatment, after technology installations.
Note: All start times were initially programmed between 1:00 and 3:00 AM unless otherwise requested by the homeowner.

CHAPTER 3. CURRENT IRRIGATION PRACTICES AND SURVEY BASED IRRIGATION WATER USE PREDICTION METHODS

Introduction

The Catawba-Wateree Hydroelectric Project consists of 225 river miles and eleven reservoirs in North and South Carolina (Bruce, 2007). The project has thirteen hydroelectric stations and five steam power plants (including one nuclear station) that are owned and operated by Duke Energy (Duke Energy, 2011; Bruce, 2007). In addition to the role it serves in power generation in the region, the Catawba-Wateree River is also a major source for municipal drinking water and for recreational activity. Duke Energy and other water purveyors in the river basin have a vital interest in preserving the quantity and quality of the Catawba-Wateree River water supply, especially given the population growth and recent droughts in the region.

As operator of a non-federal hydroelectric project, Duke Energy is required to have a license with the Federal Energy Regulatory Commission (FERC) to maintain and operate its reservoirs. Duke Energy's original license with the FERC was obtained in 1958 and expired in 2008 (Duke Energy, 2011). In 2003, Duke Energy began the process of FERC re-licensing and filed a license renewal application on August 31, 2006 (Duke Energy, 2011). The re-licensing process was a collaborative process that included Duke Energy and over 160 stakeholders that benefit from the river (Duke Energy, 2011). As a part of the re-licensing process, the Catawba-Wateree Basin Water Supply Study was conducted to assess current water withdrawals and returns in the project, as well as projections of regional water withdrawals and returns through the year 2058 (Bruce, 2007). The study's final report was published in April of 2006 and included a compilation of all water withdrawals and returns that exceeded 378,541 L d^{-1} (100,000 gal d^{-1}) (Duke Energy, 2006). The study grouped those using the basin for water supply or return into four major categories: Agricultural and Irrigation, Power, Public Water Supplies and Wastewater Utilities, and Direct Industrial (Duke Energy, 2006). Although one of the major categories included irrigation, this group did not include residential systems that directly withdrew water from the Duke Energy reservoirs (Duke Energy, 2006). The study made the assumption that such withdrawals had a negligible impact on reservoir levels. Part of the justification for the assumption was that "since these properties are adjacent, or nearly adjacent to the reservoirs, much of the water withdrawn is likely transferred into the groundwater and feeds back into the reservoirs" (Duke Energy, 2006). This assumption failed to account for the consumptive water use requirement of landscapes (via evapotranspiration), which is the entire reason for landscape irrigation.

There are approximately 19,000 homes that border the Duke Energy reservoirs, many of which have automated irrigation systems that use the lake they border as the water source. Currently, water withdrawals for irrigation are not metered and there is no charge to homeowners for using the lake water. Duke Energy imposes limited watering restrictions when there are periods of drought and reduced lake levels, but typically homeowners are able to withdraw and use lake water without restriction. Given the situation, there was a need for a better understanding of residential irrigation practices within the basin and specifically for a means of quantifying direct water withdrawals from the Duke Energy lakes for residential irrigation. For this study, a survey instrument was chosen as the primary means for assessing irrigation practices of homeowners that live on the reservoirs along the Catawba-Wateree River.

Surveys have been previously used to evaluate landscape irrigation practices. Osmond and Hardy (2004) used data collected in a door-to-door survey in five North Carolina communities to characterize turf practices, specifically related to fertilizer, pesticide, and water use. The surveyors attempted to achieve a sample size of 1% of the population in each of the five communities, and the surveys used in each community had slight differences in questions presented. The water use portion of the surveys addressed when homeowners irrigated (season and time of day), how frequently they irrigated (times per week), how long they irrigated (run times), and what type of system they had (moveable or fixed). It was found that mean watering frequencies did not significantly differ (α=0.05) across the five communities (Osmond and Hardy, 2004). Some variation was found in water durations between communities, which ranged from 5 to 300 minutes and averaged between 49 and 72 minutes for the communities (Osmond and Hardy, 2004).

An interdisciplinary study, including researchers from the fields of plant science, engineering, social science, and policy, conducted in Layton, Utah, by Endter-Wada et al. (2008) used a survey to investigate the effects of various factors that were hypothesized predictors of wasteful watering practices in residential and commercial settings. A water balance was used to determine irrigation requirements for residential and commercial properties within a 13 km^2 (5 mi^2) area, which were compared to measured water use from water bills to determine whether the irrigation practices were “conserving”,” acceptable”, or “wasteful” (Endter-Wada et al., 2008). Surveys conducted for 10% of the household study sites and nearly 50% of the business study sites were designed to gather information specific to landscape water use (irrigation system type, watering practices, and management) and to the conservation-mindedness of the owners. The study found that personal factors, such as demographic characteristics, motivation to conserve, and environmental attitudes, had little impact on water use (Endter-Wada et al., 2008). The more contributing factors were type of irrigation system and whether the site was a business or a household. Business sites tended to over-water more than households and over-watering increased as the amount of labor required to operate systems decreased.

A graduate research project in the Department of Economics at North Carolina State University assessed the effectiveness of non-price water restrictions in reducing residential water use during drought (Wichman et al., 2011). Household-level water billing data for thirty consecutive months were analyzed along with weather data, non-price water restrictions, household income, and survey data from 1726 households in six different North Carolina communities. A forty-three question phone survey explored gardening and irrigation habits, lawn health, lot size, behavioral characteristics, and included participant perceptions of effects (environmental and economic) of water scarcity in North Carolina. The study found that voluntary and mandatory watering restrictions were effective in reducing average monthly household water use, but that the magnitude of the effect varied with household characteristics, including income, family size, and irrigation frequency.

The first goal of this phase of the study was to develop and conduct an online survey to access current irrigation practices within the Catawba-Water River Basin. The second goal was to develop a method for predicting residential irrigation water withdrawals from the Duke Energy lakes based on survey responses. The effectiveness of the prediction method was to be evaluated using measured water use from the thirty-six sites described in Chapter 2.

Materials and Methods

Survey

An online survey was developed by NCSU and administered by Duke Energy in the spring of 2009 to assess the current state of landscape irrigation within the Catawba-Wateree River Basin and to gauge the interest of homeowners in participating in the field study described in Chapter 2. Approximately 19,000 homeowners on nine Duke Energy lakes (Fishing Creek Lake, Lake Hickory, Lake James, Lookout Shoals Lake, Mountain Island Lake, Lake Norman, Lake Rhodhiss, Lake Wateree, and Lake Wylie) were mailed postcards that informed them of the survey and directed them to the website where the survey could be completed. The survey was comprised of twenty-one questions that focused on the landscape (lot size, turf type, etc.), the irrigation system (water source, sprinkler type, percent lot irrigated, etc.), irrigation practices (average months per year irrigated, irrigation frequency, average zone run times, etc.), and interest in participating in an irrigation study to be conducted by NCSU. For most of the questions, categorical bins were provided as possible responses to reduce erroneous or unrealistic responses. A copy of the original survey design is shown in Appendix A - 1. The actual online survey included two additional questions: 1) "Does your irrigation system have a meter that measures the amount of water used?" and 2) "Does your grass turn brown in the winter?"

Duke Energy compiled the data from the 1405 completed surveys and presented it to NCSU in a database format. The survey responses were used to help select thirty-six participants (twelve each on three lakes; Lake Hickory, Lake Norman, and Lake Wylie) for the field portion of the study. Additionally, a water use prediction method was created that used survey responses as inputs to generate estimates of average weekly irrigation depths and volumes for each of the study sites. The survey generated estimates were then compared with measured (actual) weekly water use from 2009 to evaluate the validity of the method. In the process of evaluating the initial prediction results, it was discovered that survey responses for several of the thirty-six study participants did not match the actual site and system characteristics of the cooperators. Information collected during irrigation system audits and from county tax records were used to verify survey responses. Two additional water use prediction methods were created and evaluated, one that replaced incorrect survey responses with the correct categorical responses and the other with measured data for lot size and percent of lot irrigated, both adjustments based on irrigation system audits. The three methods were referred to as "SURVEY," "AUDIT 1," and "AUDIT 2," in the order introduced. The first two methods relied upon discrete values for inputs while AUDIT 2 contained discrete and continuous variables. The goal was to find a method that could be used by Duke Energy to predict average weekly water withdrawals from the Duke Energy Lakes, which could in turn be used to predict overall annual irrigation water use.

Water Use Prediction Methods

A method was created to estimate average weekly water applied (liters per week and millimeters per week) for sites with automated, in-ground irrigation systems using original survey responses. Predicted weekly depth (PWD) was treated as a function of application rate (estimated based on indicated sprinkler type), number of irrigation days per week, and average zone run time. All of the thirty-six study cooperators indicated that their system had either rotor, spray, or both types of sprinklers. Average measured application rates from system audits (see Irrigation System Audits) of 16 mm hr^{-1}, 46 mm hr^{-1}, and 25 mm hr^{-1} were assigned to systems with rotor, spray, and both sprinkler types respectively. PWD was calculated as:

$$\mathrm{PWD_{SURVEY}} = \frac{\mathrm{AR_{SURVEY}} \times \mathrm{DPW} \times \mathrm{RT}}{60} \qquad [3.1]$$

where,

$\mathrm{PWD_{SURVEY}}$ = predicted average weekly depth of irrigation using survey responses, mm wk^{-1}

$\mathrm{AR_{SURVEY}}$ = average application rate for indicated sprinkler type, mm hr^{-1}

DPW = average number of irrigation days per irrigation week, d wk^{-1}

RT = average zone run time, min d^{-1}.

Predicted weekly volume (PWV) was derived from PWD and irrigated area, which was a function of lot size and percent of lot irrigated. The mean value of each bin range was used for calculation of the model, such that a response of "0 – 25%" for percent of lot irrigated was assigned a value of 12.5%. PWV was calculated as:

$$\mathrm{PWV_{SURVEY}} = \mathrm{PWD_{SURVEY}} \times \mathrm{LS_{SURVEY}} \times \mathrm{PLI_{SURVEY}} \times 100 \qquad [3.2]$$

where,

PWV_{SURVEY} = predicted average weekly volume of irrigation using survey responses, L wk^{-1}

PWD_{SURVEY} = predicted average weekly depth of irrigation using survey responses, mm wk^{-1}

LS_{SURVEY} =survey indicated lot size, hectares

PLI_{SURVEY} = survey indicated percent of lot irrigated, %.

While calculating PWD_{SURVEY} and PWV_{SURVEY}, it was recognized that many of the cooperator survey responses for sprinkler type did not match the sprinkler type as determined from the system audits. It also became apparent that irrigated areas (LS_{SURVEY} x PLI_{SURVEY}) were not consistent with measurements taken during audits. Lot size data was obtained from county tax records and percent of lot irrigated was determined using measured irrigated areas (from audits) divided by lot size, to check survey responses to those respective questions. The correct sprinkler type, lot size, and percent of lot irrigated bins were selected as model inputs and the models were recalculated. PWD became:

$$\mathrm{PWD_{AUDIT\ 1}} = \frac{\mathrm{AR_{AUDIT\ 1}} \times \mathrm{DPW} \times \mathrm{RT}}{60} \qquad [3.3]$$

where,

$PWD_{AUDIT\ 1}$ = predicted average weekly depth of irrigation using corrected application rate bins, mm wk^{-1}

$AR_{AUDIT\ 1}$ = average application rate for corrected sprinkler type, mm hr^{-1}

DPW = average number of days irrigated per irrigation week, d wk^{-1}

RT = average zone run time, min d^{-1}.

Actual DPW and RT were recorded only at some sites during irrigation system audits, therefore no corrections were made to those terms for the methods. PWV was calculated using corrected responses as:

$$PWV_{AUDIT\ 1} = PWD_{AUDIT\ 1} \times LS_{AUDIT\ 1} \times PLI_{AUDIT\ 1} \times 100 \qquad [3.4]$$

where,

$PWV_{AUDIT\ 1}$ = predicted average weekly volume of irrigation using corrected bins, L wk^{-1}

$PWD_{AUDIT\ 1}$ = predicted average weekly depth of irrigation using corrected application rate bins, mm wk^{-1}

$LS_{AUDIT\ 1}$ = tax record indicated lot size bin, hectares

$PLI_{AUDIT\ 1}$ = corrected percent of lot irrigated, %.

The AUDIT 1 methods still relied upon median values assigned to bin ranges as with the SURVEY models, but the AUDIT 1 methods had the correct survey response bins selected.

A final set of PWD and PWV methods was created using measured values for LS and PLI as inputs. AR was still assigned an average value based on system sprinkler type because true average AR for each system was not known since not all zones in each system were audited. Therefore, PWD did not change:

$$PWD_{AUDIT\ 2} = PWD_{AUDIT\ 1} \qquad [3.5]$$

But, PWV became:

$$\mathrm{PWV_{AUDIT\ 2}} = \mathrm{PWD_{AUDIT\ 1}} \times \mathrm{LS_{AUDIT\ 2}} \times \mathrm{PLI_{AUDIT\ 2}} \times 100 \qquad [3.6]$$

where,

$\mathrm{PWV_{AUDIT\ 2}}$ = predicted average weekly volume of irrigation using measured data, L wk^{-1}

$\mathrm{PWD_{AUDIT\ 1}}$ = predicted average weekly depth of irrigation using corrected bins, mm wk^{-1}

$\mathrm{LS_{AUDIT\ 2}}$ = tax record specific lot size, hectares

$\mathrm{PLI_{AUDIT\ 2}}$ = specific measured percent of lot irrigated, %.

Analysis of Prediction Methods

Linear regression was used to evaluate the effectiveness of the survey bins (discrete values) at accurately representing the actual values (continuous) for lot size, irrigated area, and percent of lot irrigated for each of the thirty-six study sites. Lot sizes were obtained from county tax records. Irrigated areas were obtained using ArcGIS Software (Esri, Redlands, CA) and aerial imagery from county GIS databases. The percent of lot irrigated for each site was calculated using irrigated area divided by lot size.

Linear regression was also used to compare weekly water use predictions from each of the models with actual average weekly irrigation withdrawals from each of the thirty-six study sites in 2009. Data from the week of July 12, 2009 (date when ten-count circuits were installed on the water meters, as described in Chapter 2) through the end of the year were used for comparison. Only weeks in which irrigation withdrawals totaled 2000 L, which is equivalent to 2 mm wk^{-1} over a 1000 m^2 irrigated area, or more were considered in the comparison. Weeks with lower withdrawals were likely comprised of manual withdrawals data rather than actual automated irrigation, hence they were considered as “non-irrigation weeks.” Since the survey was tailored towards weeks in which automated irrigation took place, the “non-irrigation weeks” were ignored. The linear regression technique paired actual water use with survey method predicted water use for each of the thirty-six study sites, to evaluate the potential of the methods for predicting average weekly water use.

The accuracy of the each prediction method for volume (PWV_{SURVEY}, $PWV_{AUDIT\ 1}$, $PWV_{AUDIT\ 2}$) and depth (PWD_{SURVEY}, $PWD_{AUDIT\ 1}$, $PWD_{AUDIT\ 2}$) was assessed by comparing predicted weekly withdrawal means against measured (actual) weekly withdrawal means from all thirty-six sites. Weekly gross irrigation requirement (GIR) was also evaluated as a prediction method for weekly depth of irrigation. Means separation tests were done using the LSMEANS statement within the Mixed procedure (PROC MIXED) in SAS version 9.2 (SAS Institute, Inc., Cary, NC). Boxplots were used to display the distributions of the different prediction techniques compared to the actual depth and volume values.

PWV_{SURVEY} and PWD_{SURVEY} were calculated for all of the survey respondents that indicated a Duke Energy lake as their irrigation water source, buried system as their irrigation system type, and that provided all of the necessary inputs for the PWV_{SURVEY} and PWD_{SURVEY} methods. The LSMEANS statement within the Mixed Procedure was used to test for differences between the overall survey respondents group and the study participants group in mean PWV_{SURVEY} and PWD_{SURVEY} predictions. Boxplots were used to show the distributions of the predictions for both groups.

Results

Overall Survey Responses

The response rate for the survey was approximately 7.4% (1405 responses out of approximately 19,000 mailed postcards). Unfortunately, 379 of the 1405 surveys submitted were missing answers to questions 5 through 8 (Appendix B - 3 through Appendix B - 8), bringing the response rate down to approximately 5.4% for those questions. Further, only 662 surveys (47.1% of all respondents) had responses for questions 9 through 14 (Appendix B - 9 through Appendix B - 14), reducing the overall response rate for those questions to 3.5%. It was unclear whether these questions were left blank by respondents or if the data was lost in the process of compiling the results. Responses to the question pertaining to average irrigation run times were mistakenly duplicated and the question, "What type of grass is in your lawn?" was unintentionally omitted, but responses to the question, "Does your grass turn brown in the winter?" allowed for the determination of whether or not the respondents had a cool or warm season grass.

Distributions of survey responses by lake are shown in Appendix B - 1 through Appendix B - 16. The majority of the responses came from Lake Norman (61%), Lake Wylie (19%), and Lake Hickory (9%) as shown in Appendix B - 1. The distribution of lot sizes was: 16% less than 0.5 acres, 60% between 0.5 and 1.0 acres, and 24% greater than 1.0 acres (Appendix B - 2). About 88% of the respondents that provided their irrigation water source indicated a Duke Energy lake as source (Appendix B - 3). Most of those same respondents indicated that their irrigation system had either both rotor and spray heads (48%)

or exclusively spray heads (36%) (Appendix B - 8). Surprisingly, 20% of those that said they had buried (in-ground) irrigation systems also responded that a contractor did not install their system. The majority of the 662 that provided a response to the "months of irrigation" question indicated that they irrigated between five and eight months of the year (80%) with the most frequent responses being six months (26%) and seven months (24%) (Appendix B - 11). About 37% responded that they irrigated on average two days per week during the months that their system was running, while 42% indicated three days per week (Appendix B - 12).

Study Participants Survey Responses

The distribution of responses for selected survey questions for the thirty-six field study cooperators are shown in Figures 3.1 – 3.2. Most of the cooperators (58%) responded that their lot size was between 0.2 and 0.3 hectares (0.25 to 0.5 acres) (Figure 3.1). Approximately 58% of study participants said that they irrigated six or seven months out of the year, similar to the 50% that indicated the same from the overall survey. The most frequent responses for days per week irrigation occurred were two and three days with most average zone run times being fifteen, twenty, or thirty minutes.

Survey Response versus Audit Data

Several of the survey responses by various cooperators were found to be inconsistent with data obtained during system audits and from county tax records. Table 3.1 shows survey responses and observed data for three of the survey questions for each of the cooperators. Out of thirty-six study participants, seven indicated the wrong lot size bin on their survey compared to lot sizes obtained from county tax records. Twenty-one of thirty-six selected the wrong bin for percent of lot irrigated compared to the calculated percent irrigated using measured irrigated areas and lot sizes, with seven of the responses being off by more than 25%. Several of the cooperators (ten out of thirty-six) also incorrectly responded regarding the type of sprinklers on their system. The most common mistake was indicating only spray heads when the system actually had rotor and spray heads. This could be attributed to homeowners not knowing the difference between rotor and spray sprinklers, but was probably influenced as well by the fact that the survey bins identified the sprinkler types as "rotors" and "pop-up spray heads." Presumably, using the descriptor "pop-up" for spray heads and not for rotors led some cooperators to incorrectly think that they did not have rotor sprinklers because they knew that all of their sprinklers did "pop-up."

Survey Bin Verification

The average application rates for each site could not be easily determined because not all irrigation zones were audited at each site. Scheduled irrigation days (DPW) and run times (RT) were not recorded for some zones either, which made it difficult to assess the accuracy of DPW and RT responses. Irrigated areas, lot sizes, and percent lot irrigated, however, were known from audits, tax records, and measurements from aerial imagery. These measured parameters were compared with raw and corrected survey responses to evaluate how well the measured data (continuous) could be estimated with the bins (discrete) used in the survey. Figures 3.3 – 3.5 show the linear regressions between original survey responses and corrected survey responses with the measured values for lot size, percent of lot irrigated, and irrigated area. Selecting the correct survey responses improved the coefficient of determination (R^2) for the regression of lot size estimates on actual values from 0.62 to 0.89. Correcting the survey responses for percent of lot irrigated and irrigated area had an even greater impact on the coefficients of determination for the regressions of estimated values on actual values. The R^2 value increased from 0.01 to 0.89 for percent of lot irrigated and from 0.20 to 0.90 for irrigated area. These results suggest that discrete data can be used as an estimate of continuous variables, but show how critical it is that survey questions be answered accurately.

Effectiveness of Water Use Prediction Methods Across Study Sites

The average weekly volume of water applied in 2009 was 22,041 L wk^{-1} with a standard error of 2,379 L wk^{-1}, while the average weekly depth applied was 22.6 mm wk^{-1} with a standard error of 2.8 mm wk^{-1}. Figures 3.6 – 3.8 show the linear regression of actual weekly irrigation volumes versus the SURVEY, AUDIT 1, and AUDIT 2 method predictions for each study site. None of the prediction methods were effective in predicting actual water use for individual study sites. R^2 values were 0.0001, 0.0028, and 0.0017 for actual volumes compared to SURVEY, AUDIT 1, and AUDIT 2 volume predictions, respectively.

Figures 3.9 – 3.11 contain the linear regressions of actual weekly irrigation depths compared to SURVEY, AUDIT 1, and AUDIT 2 method predictions for each study site. As was true for the weekly volume prediction methods, none of the depth prediction methods were effective in predicting actual irrigation depths. R^2 values were 0.0118, 0.0011, and 0.0011 for actual irrigation depths compared to SURVEY, AUDIT 1, and AUDIT 2 depth predictions, respectively. The slopes of each the regression equations were nearly zero, which indicates that there was no correlation between the actual and predicted water withdrawals.

Effectiveness of Water Use Prediction Methods at Estimating Overall Mean Water Withdrawals

The distribution of average weekly irrigation predictions by prediction method is shown in Figure 3.12 for volumes and in Figure 3.13 for depths. LS-means of predicted average weekly water use for each prediction method and actual average weekly water use are presented in Table 3.2. The mean prediction for the PWV_{SURVEY} method (56,910 L wk^{-1}) was different from those for the $PWV_{AUDIT\ 1}$ method (38,242 L wk^{-1}), the $PWV_{AUDIT\ 2}$ method (36,065 L wk^{-1}), and the actual measured weekly withdrawals (22,041 L wk^{-1}) (p = 0.0462, p = 0.0263, p = 0.0004, respectively). There was no statistical difference between the mean prediction of the $PWV_{AUDIT\ 2}$ method and the actual average weekly withdrawal at the $\alpha = 0.05$ level, despite the predicted volume being 64% higher than the actual. The "lack of difference" was probably due to the high standard errors of the means, which ranged from 6514 L wk^{-1} to 7019 L wk^{-1} for the predicted and actual volumes, but suggested that given accurate survey responses, the methods could be used with a correction factor to estimate the overall average volumetric irrigation water withdrawals across all sites that had an automated irrigation system with a Duke Energy lake as the water source.

There was no statistical difference, at the $\alpha = 0.05$ level, between the actual average weekly irrigation depth (22.6 mm wk^{-1}), the $PWD_{AUDIT\ 1}$ method prediction (29.4 mm wk^{-1}), and the $PWD_{AUDIT\ 2}$ method estimate (29.4 mm wk^{-1}) (recall that $PWD_{AUDIT\ 1}$ = $PWD_{AUDIT\ 2}$ according to how they were calculated). The LS-Means of actual average weekly depths (22.6 mm wk^{-1}) and average weekly GIR (17.0 mm wk^{-1}) were not different either; however the mean weekly GIR was significantly less than each of the mean PWD method predictions. The standard error of the means ranged from 3.0 to 3.2 mm wk^{-1} for the predicted and actual depths.

The distributions of PWV_{SURVEY} and PWD_{SURVEY} estimates for all survey respondents that indicated a Duke Energy lake as their irrigation water sources, buried system as their system type, and that provided the necessary inputs for the PWV_{SURVEY} and PWD_{SURVEY} models (n = 542) are shown next to the same distributions for the thirty-six study sites in Figures 3.14 – 3.15. LS-means of the PWV_{SURVEY} and PWD_{SURVEY} models are shown for study participants and overall, qualified survey respondents in Table 3.3. There was no difference between the average PWV_{SURVEY} estimates for study participants and overall respondents ($p = 0.17$) nor was there a difference between the PWD_{SURVEY} estimates for both groups ($p = 0.5042$). The variation in prediction values for overall respondents was higher than the variation in the prediction values for the thirty-six study participants.

Summary, Conclusions, and Recommendations

The results of the survey portion of this study revealed that many homeowners are very unfamiliar with their irrigation system and practices. Multiple study participants were unable to identify the correct sprinkler type for their system, commonly indicating only spray when both spray and rotor sprinklers were actually present. Additional errors were observed in lot size estimates and estimates of percent of lot irrigated. One person even incorrectly selected the county in which they lived. Presumably, there were many more errors throughout the overall survey responses that could not be found because measured site and system data was unavailable. The responsibility for the incorrect survey responses lies in part on the respondents, but there were also flaws in the survey design that if fixed would have likely provided better results. Survey bins should have been of equal size and included all possibilities, such as 5 and 6 for days per week irrigated, instead of simply 1, 2, 3, 4, and 7. Descriptions of irrigation terms such as “run times” and “sprinkler type,” including picture examples of the different sprinkler types, could have reduced respondent confusion. References, such as “An American football field has an area of approximately 0.5 hectares (1.3 acres),” could have assisted respondents in answering the lot size question.

Despite the flaws of the survey and the errors in the responses, the results showed that while the PWV and PWD methods were not good predictors of water use at a single site, they did on average provide a reasonable prediction of overall average weekly water withdrawals per site for a large sample of sites that had buried systems and withdrew water from a Duke Energy lake. In other words, irrigation practices at sites bordering Duke Energy lakes are likely so varied that estimating water withdrawals at a specific site would be almost impossible, but estimating the average water withdrawal across all sites is viable. There were less differences between mean predictions for the PWD methods than for the PWV methods, as was expected since the PWD predictions were not dependent on lot size or percent of lot irrigated, two of the commonly incorrectly answered questions. If the irrigated area estimates could be refined, the PWV methods would improve. The results also suggest that using discrete data does not significantly reduce the accuracy of the models as compared to using continuous inputs, if enough levels (bins) are used.

Finally, the results indicate that the direct water withdrawals from Duke Energy lakes for residential irrigation have more impact on reservoir levels than assumed in the 2006 Water Supply Study (Duke Energy, 2006). The study estimated that the total daily net outflow (consumptive uses) from the Catawba-Wateree River Basin was approximately 643.5 ML d^{-1} (170 MGD) (Duke Energy, 2006). The average PWV_{SURVEY} (56,910 L wk^{-1}) for the thirty-six study sites was 2.58 times greater than the actual average weekly withdrawals (22,041 L wk^{-1}). Assuming this relationship holds true for all sites that use a Duke Energy lake as their irrigation water source, PWV_{SURVEY} (81,719 L $wk^{-}1$) for all 542 such sites that responded to the survey can be adjusted to an estimated "actual" average weekly withdrawal of 31,674 L wk^{-1}. If the 81.1% rate of survey respondents that indicated a Duke Energy lake as an irrigation source and buried system as system type is assumed to be representative of the percentage of such homes across all Duke Energy lake bordering sites (taken to be approximately 19,000 lots), the estimated total weekly direct water withdrawals for residential irrigation would equal 488.1 ML wk^{-1}, or 69.7 ML d^{-1} (18.4 MGD). Note that these values are estimates only for weeks when irrigation occurs. However, these results indicate that during the peak of the irrigation season, direct residential irrigation withdrawals could be removing a volume of water equal to approximately 11% of the study estimated total net outflows (from major users) from the entire Catawba-Wateree River Basin. Based upon these results, it is concluded that direct water withdrawals for residential irrigation may have more of an effect on reservoir levels than previously assumed. In order for that effect to be better quantified, an accurate estimate of total irrigated area along the Catawba-Wateree River shoreline is needed. It is recommended that total irrigated area be assumed as 50% of total shoreline lot area (since this was the average percent of lot irrigated for the study sites and lot size data will be more readily available) and that an estimated weekly irrigation withdrawal of 25 mm be used in determining overall irrigation withdrawals. Any initiatives taken to reduce irrigation withdrawals should be centered on improving system design, maintenance, and scheduling. Efforts to encourage the use of smart irrigation technologies should include provisions that ensure only qualified individuals provide the installation and programming of such controllers. Qualifications should include having been trained to perform irrigation audits to determine accurate zone application rates.

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Tables and Figures

Table 3.1 Survey responses for lot size, percent of lot irrigated, and sprinkler type versus information obtained from tax records, aerial imagery and ArcGIS, and irrigation system audits, respectively.

Label	Lot Size (hectares)		Percent of Lot Irrigated		Sprinkler Type	
	Survey	Tax Records	Survey	Measured	Survey	Audit
HC1	0.3 - 0.4	0.340	50 - 75%	84%*	Both	Both
HC2	0.2 - 0.3	0.239	> 75%	56%*	Spray	Both*
HC3	0.2 - 0.3	0.283	> 75%	60%*	Both	Both
HS1	0.2 - 0.3	0.206	50 - 75%	44%*	Both	Both
HS2	0.2 - 0.3	0.178*	50 - 75%	23%*	Unknown	Spray*
HS3	0.1 - 0.2	0.227*	50 - 75%	42%*	Both	Both
HT1	0.2 - 0.3	0.109*	> 75%	69%*	Both	Both
HT2	0.2 - 0.3	0.202	50 - 75%	63%	Both	Both
HT3	0.3 - 0.4	0.441*	25 - 50%	31%	Both	Both
HW1	0.2 - 0.3	0.267	50 - 75%	89%*	Both	Both
HW2	0.4 - 0.8	0.550	50 - 75%	60%	Spray	Both*
HW3	0.2 - 0.3	0.235	50 - 75%	64%	Both	Both
NC1	0.1 - 0.2	0.186	50 - 75%	88%*	Both	Both
NC2	0.2 - 0.3	0.227	25 - 50%	36%	Spray	Both*
NC3	0.2 - 0.3	0.223	50 - 75%	62%	Both	Both
NS1	0.1 - 0.2	0.158	25 - 50%	53%*	Both	Both
NS2	0.1 - 0.2	0.129	50 - 75%	62%	Both	Both
NS3	0.3 - 0.4	0.336	25 - 50%	46%	Both	Both
NT1	0.2 - 0.3	0.170*	25 - 50%	55%*	Spray	Both*
NT2	0.2 - 0.3	0.275	50 - 75%	58%	Spray	Both*
NT3	0.2 - 0.3	0.263	50 - 75%	56%	Both	Both
NW1	0.1 - 0.2	0.138	25 - 50%	58%*	Both	Both
NW2	0.2 - 0.3	0.223	50 - 75%	49%*	Spray	Both*
NW3	0.2 - 0.3	0.279	> 75%	76%	Spray	Both*
WC1	0.2 - 0.3	0.283	25 - 50%	28%	Both	Both
WC2	0.1 - 0.2	0.214*	> 75%	24%*	Spray	Rotor*
WC3	0.2 - 0.3	0.243	25 - 50%	50%	Both	Both
WS1	0.2 - 0.3	0.223	> 75%	40%*	Both	Both
WS2	0.1 - 0.2	0.129	25 - 50%	30%	Both	Both
WS3	0.2 - 0.3	0.202	> 75%	35%*	Both	Both
WT1	0.2 - 0.3	0.275	25 - 50%	28%	Both	Rotor
WT2	0.3 - 0.4	0.316	> 75%	55%*	Both	Both
WT3	0.3 - 0.4	0.340	50 - 75%	25%*	Both	Both
WW1	0.1 - 0.2	0.174	> 75%	14%*	Both	Rotor
WW2	0.2 - 0.3	0.231	> 75%	41%*	Both	Both
WW3	0.4 - 0.8	0.316*	> 75%	42%*	Spray	Both*

Note: Asterisks indicate sites where survey responses did not match measured data.

Table 3.2 LS-Means of predicted weekly water withdrawals and weekly GIR for 2009 compared to LS-means of actual weekly water withdrawals in 2009 across all 36 study sites (see equation 3.7).

Predictor	Avg. Weekly Volume (L wk^{-1})	Avg. Weekly Depth (mm wk^{-1})
Actual	22,041 c	22.6 bc
SURVEY Models	56,910 a	34.3 a
AUDIT 1 Models	38,242 b	29.4 ab
AUDIT 2 Models	36,065 bc	29.4 ab
GIR	-	17.0 c

Note: Different letters in columns indicate significant differences at the $\alpha = 0.05$ level.

Table 3.3 LS-Means of predicted weekly water withdrawals for the 36 study sites and predicted weekly water withdrawals for all survey respondents that indicated a Duke Energy lake as their water source, a buried system as their system type, and that provided the necessary inputs for the PWV_{SURVEY} and PWD_{SURVEY} models.

Sample Group	PWV_{SURVEY} (L wk^{-1})	PWD_{SURVEY} (mm wk^{-1})
Study Participants (n=36)	56,910 a	34.3 a
Overall Survey Respondents (n=542)	81,719 a	37.7 a

Note: Different letters in columns indicate significant differences at the $\alpha = 0.05$ level.

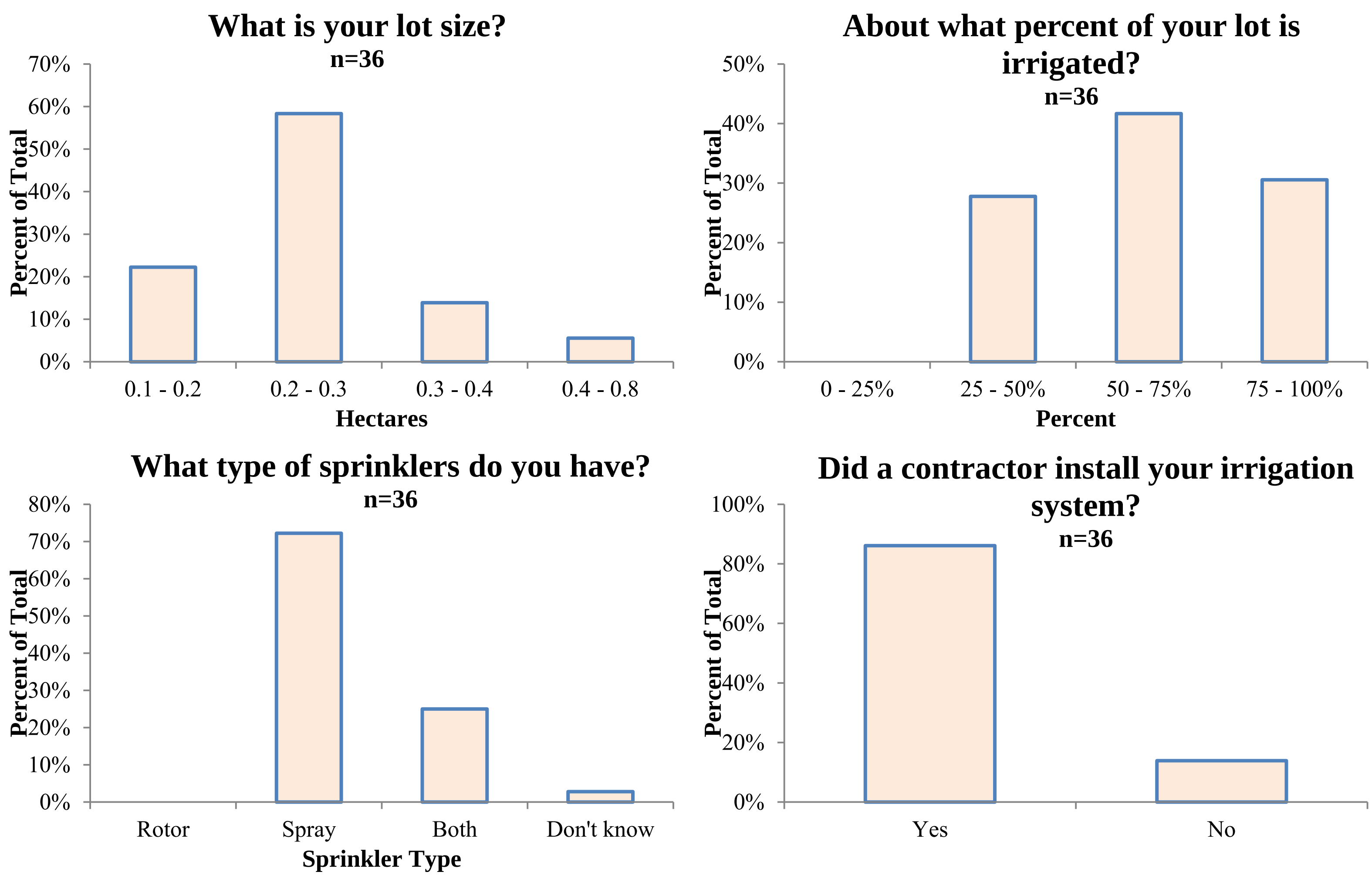

Figure 3.1 Distribution of raw survey responses from the 36 study participants regarding lot and irrigation system characteristics.

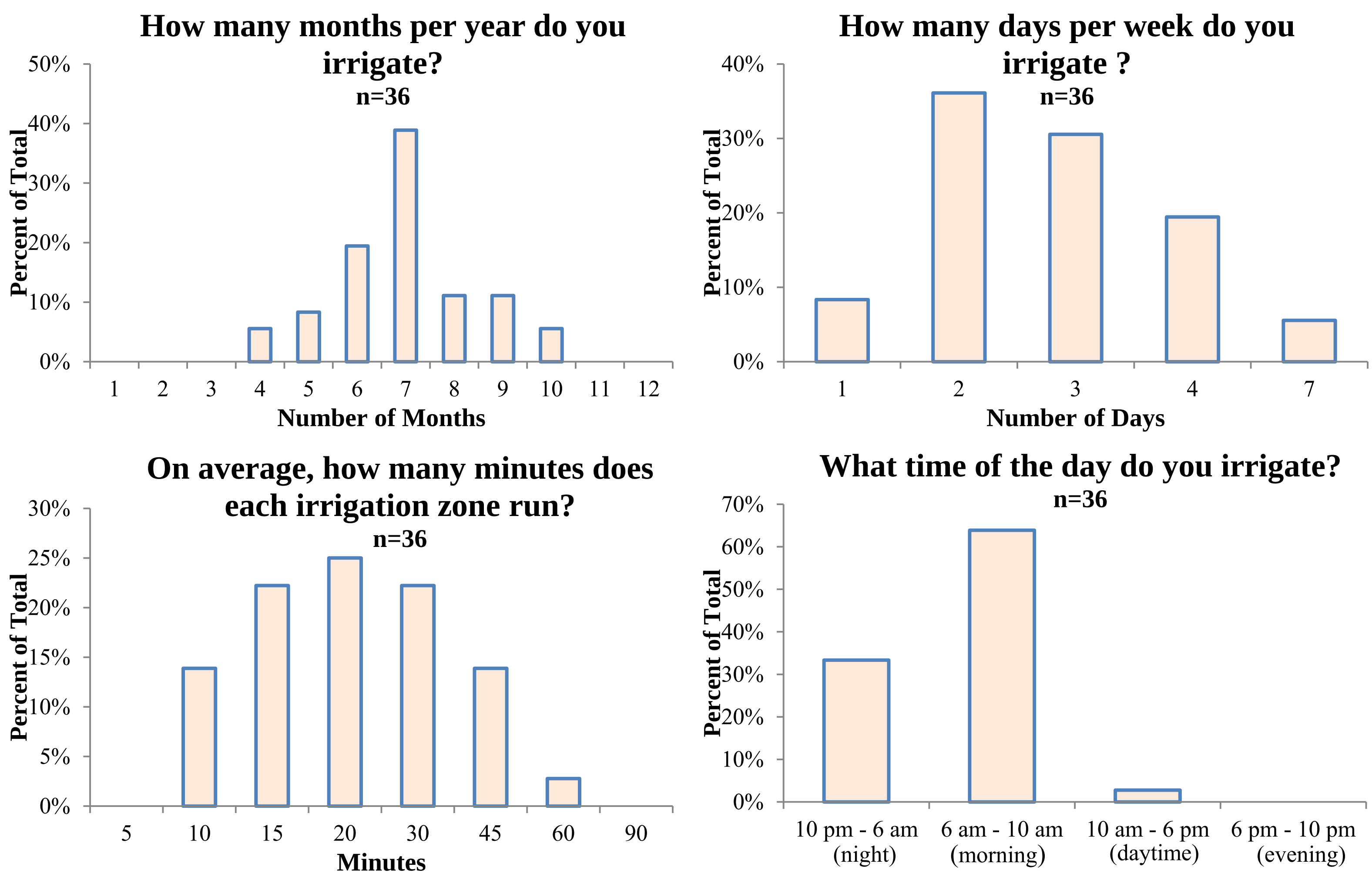

Figure 3.2 Distribution of raw survey responses from the 36 study participants regarding irrigation scheduling.

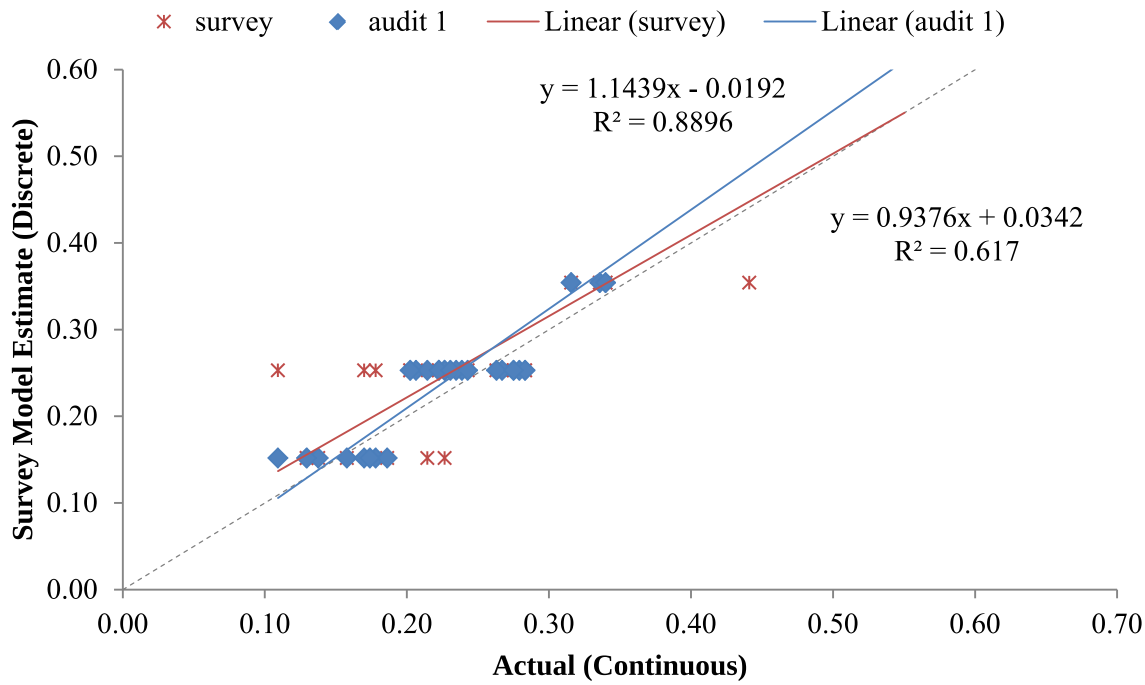

Figure 3.3 Linear regression of Survey and Audit 1 lot sizes (discrete values) versus actual lot sizes (continuous values) for the 36 study sites. Survey lot sizes were those reported by the homeowners and were inaccurate at some sites. Audit 1 lot sizes were the appropriate survey bins based on audit information.

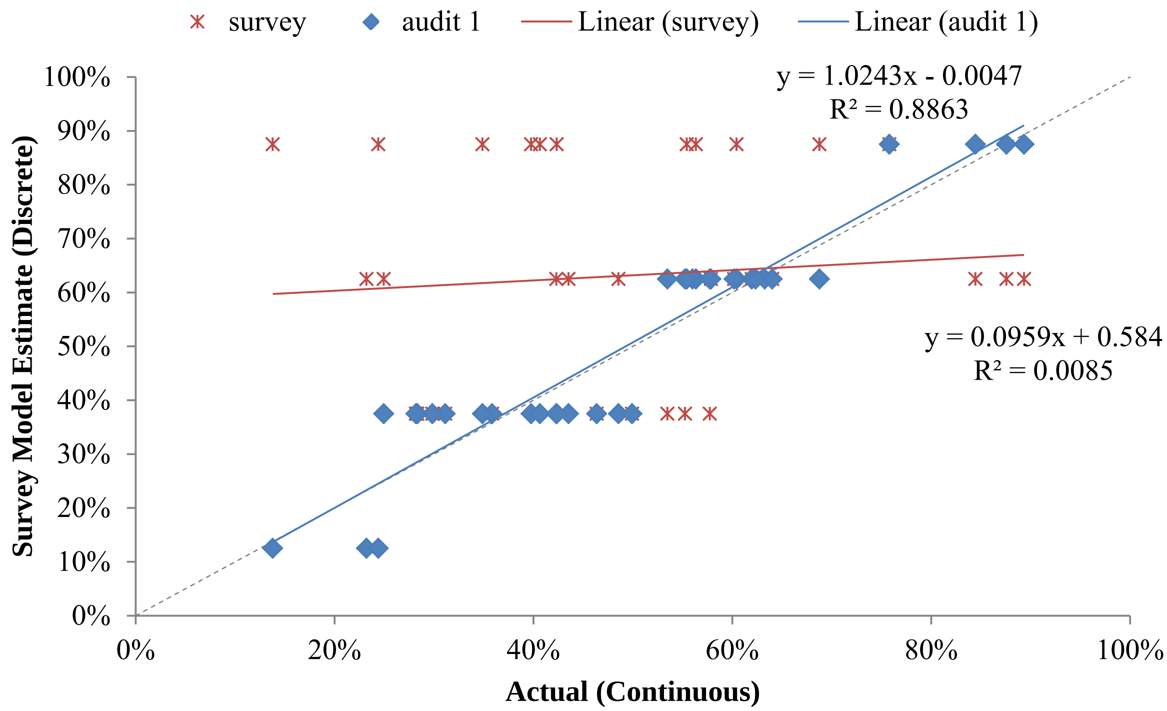

Figure 3.4 Linear regression of Survey and Audit 1 percent of lot irrigated (discrete values) versus actual percent of lot irrigated (continuous values) for the 36 study sites. Survey percent of lot irrigated were those reported by the homeowners and were inaccurate at some sites. Audit 1 percent of lot irrigated were the appropriate survey bins based on audit information.

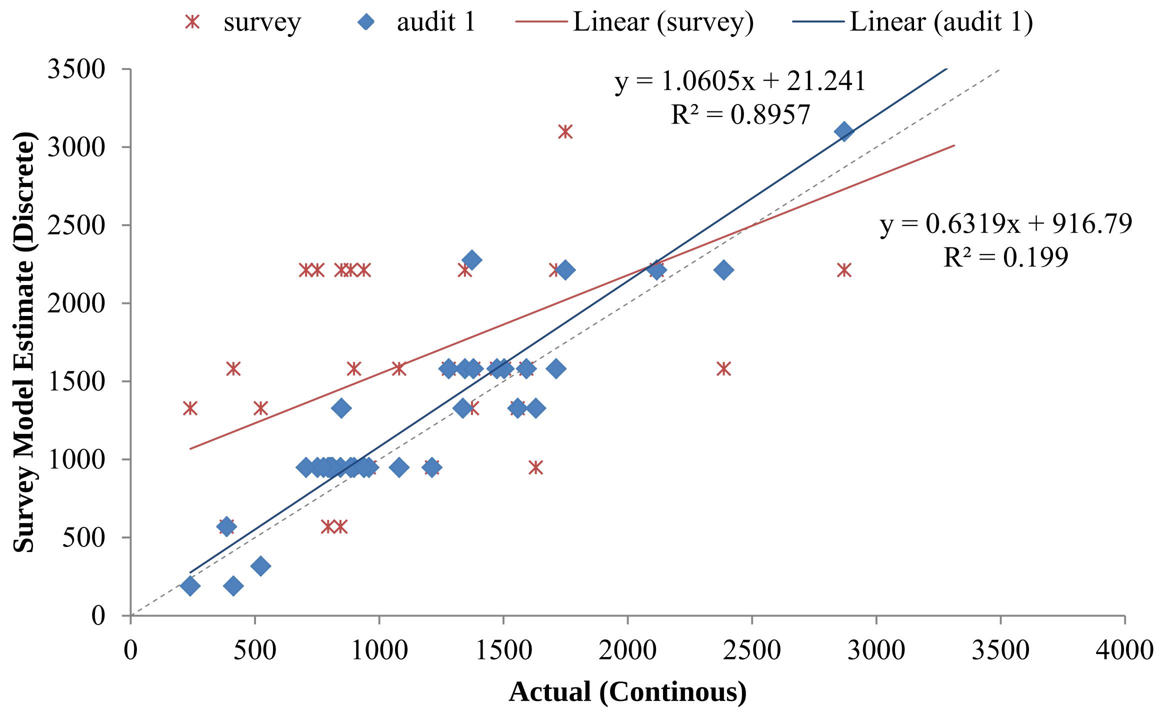

Figure 3.5 Linear regression of Survey and Audit 1 irrigated areas (discrete values) versus actual irrigated areas (continuous values) for the 36 study sites. Survey irrigated areas were those reported by the homeowners and were inaccurate at some sites. Audit 1 irrigated areas were the appropriate survey bins based on audit information.

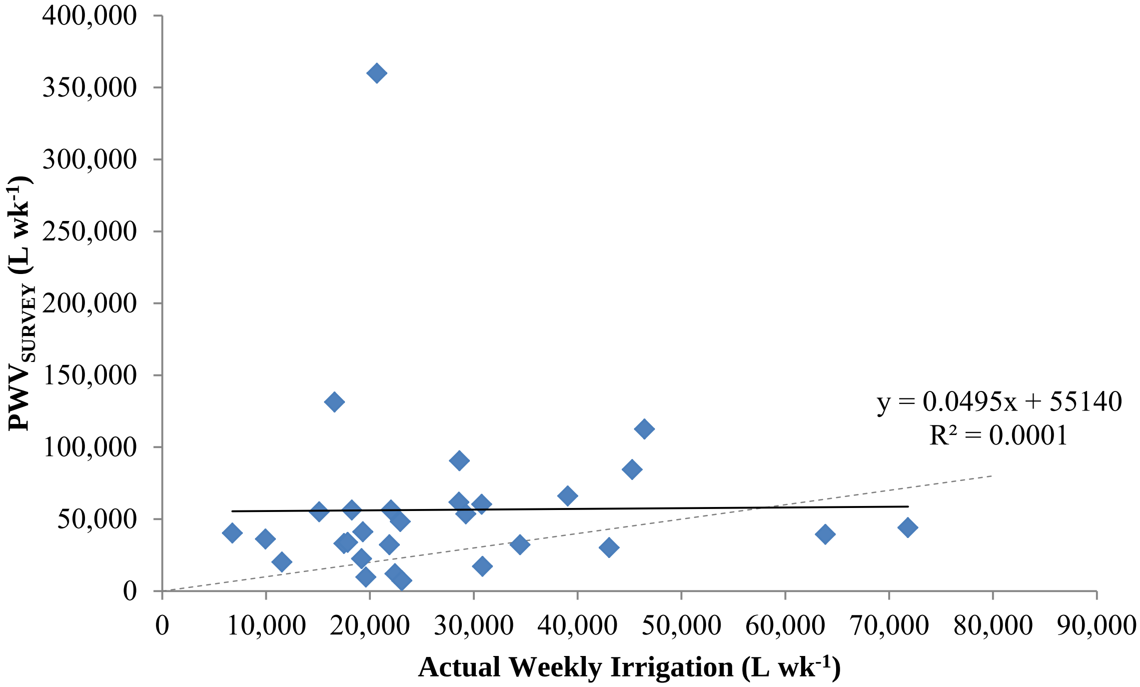

Figure 3.6 Linear regression of PWV$_{SURVEY}$ model estimates versus actual average weekly volumetric irrigation during 2009 for the 36 study sites. Dashed line indicates 1-to-1 line.

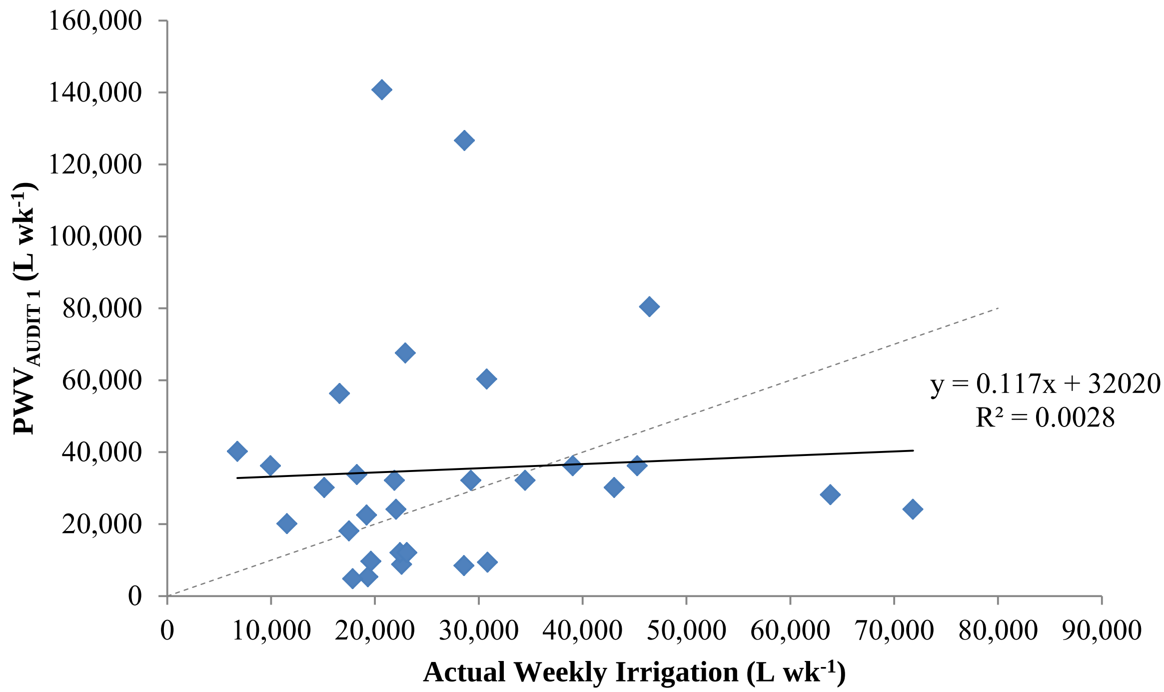

Figure 3.7 Linear correlation of $PWV_{AUDIT\ 1}$ model estimates versus actual average weekly volumetric irrigation during 2009 for the 36 study sites. Dashed line indicates 1-to-1 line.

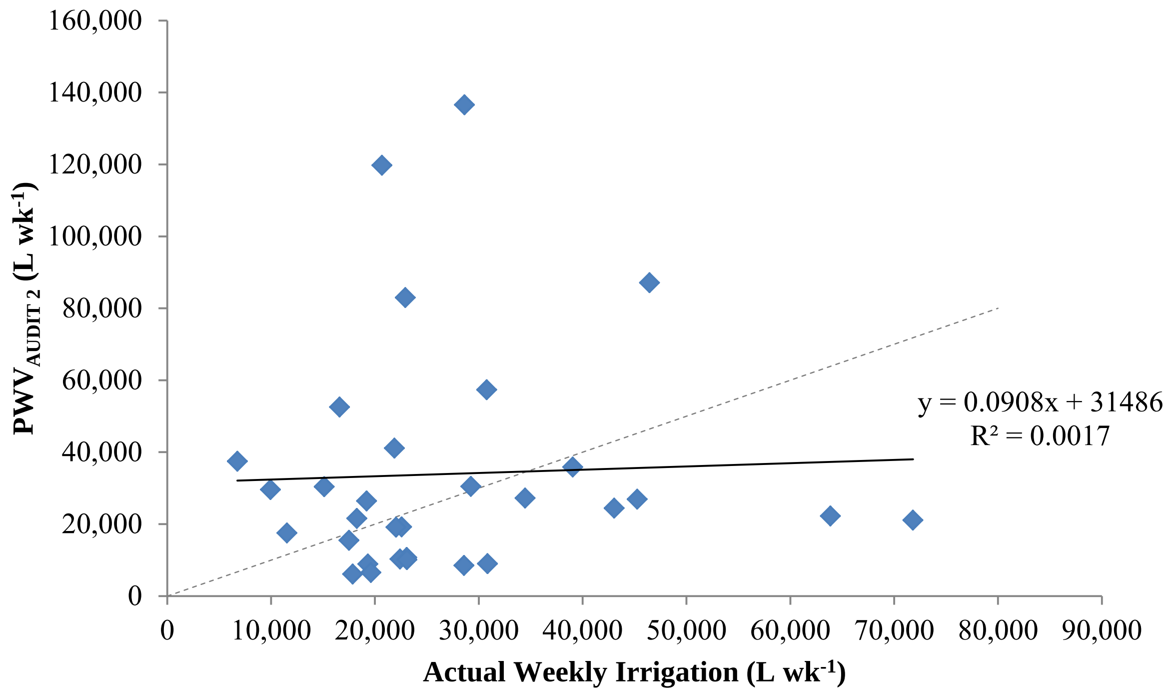

Figure 3.8 Linear regression of $PWV_{AUDIT\ 2}$ model estimates versus actual average weekly volumetric irrigation during 2009 for the 36 study sites. Dashed line indicates 1-to-1 line.

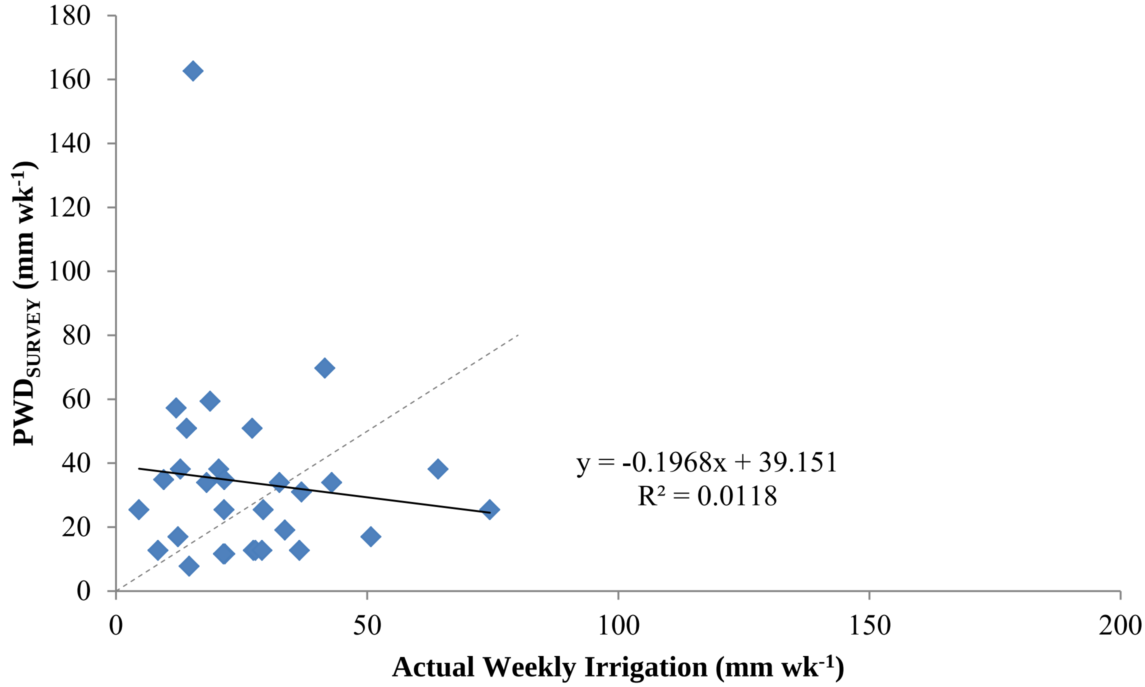

Figure 3.9 Linear regression of PWD$_{SURVEY}$ model estimates versus actual average weekly irrigation depths during 2009 for the 36 study sites. Dashed line indicates 1-to-1 line.

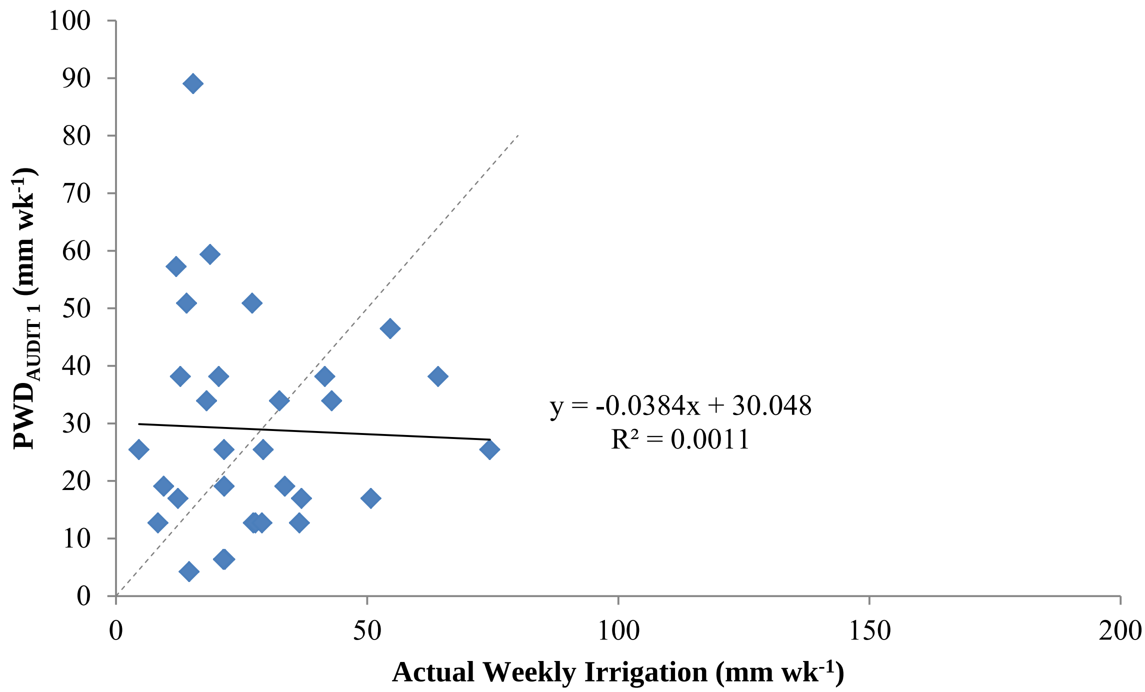

Figure 3.10 Linear regression of $PWD_{AUDIT\ 1}$ model estimates versus actual average weekly irrigation depths during 2009 for the 36 study sites. Dashed line indicates 1-to-1 line.

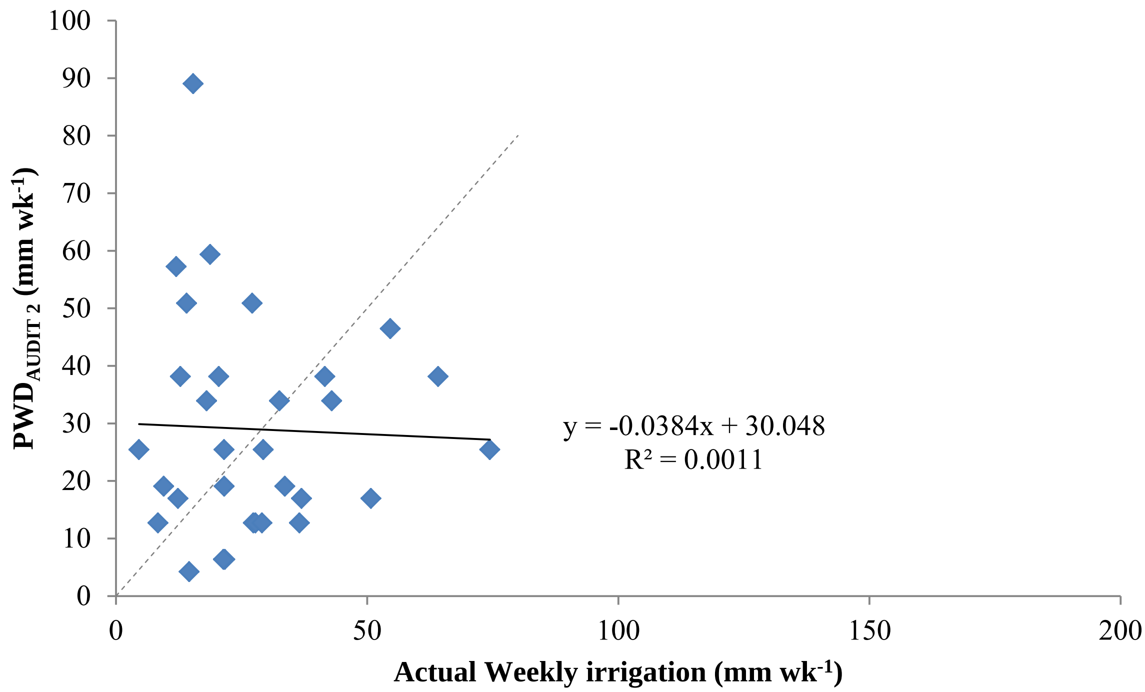

Figure 3.11 Linear regression of $PWD_{AUDIT\ 2}$ model estimates versus actual average weekly irrigation depths during 2009 for the 36 study sites. Dashed line indicates 1-to-1 line.

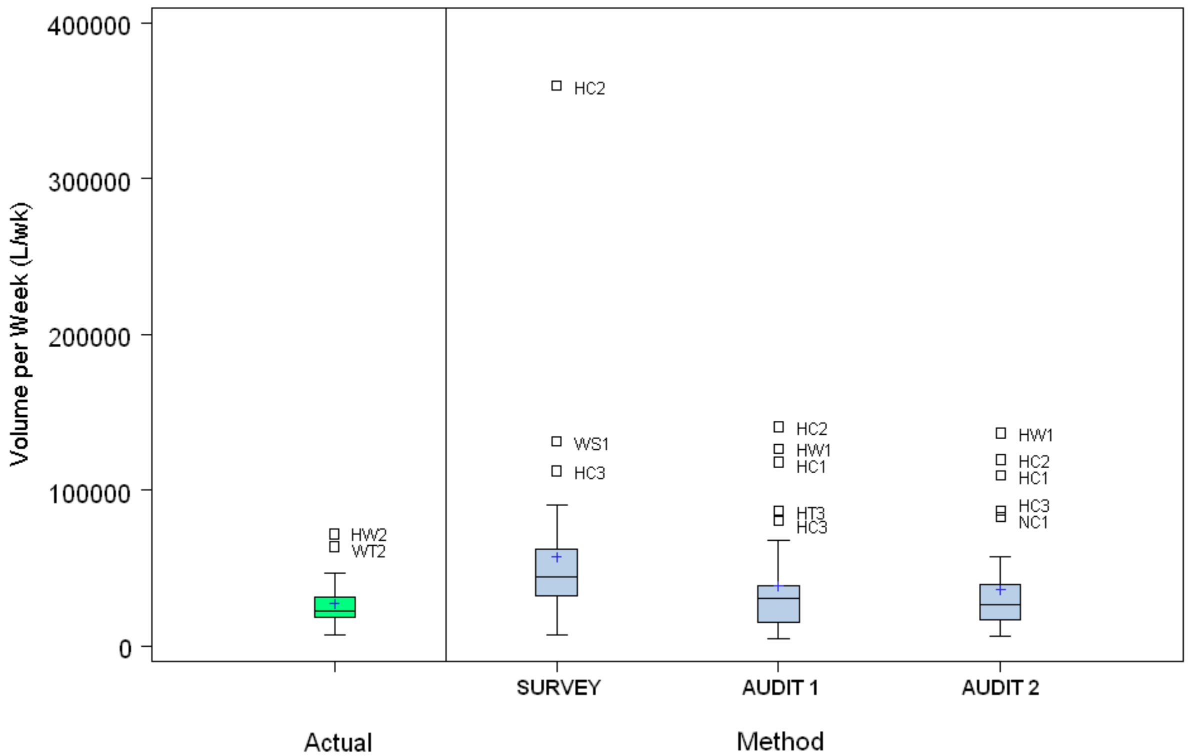

Figure 3.12 Distributions of actual average volumetric water withdrawals from 2009 and predicted weekly water withdrawals using the three prediction models for the 36 study sites.

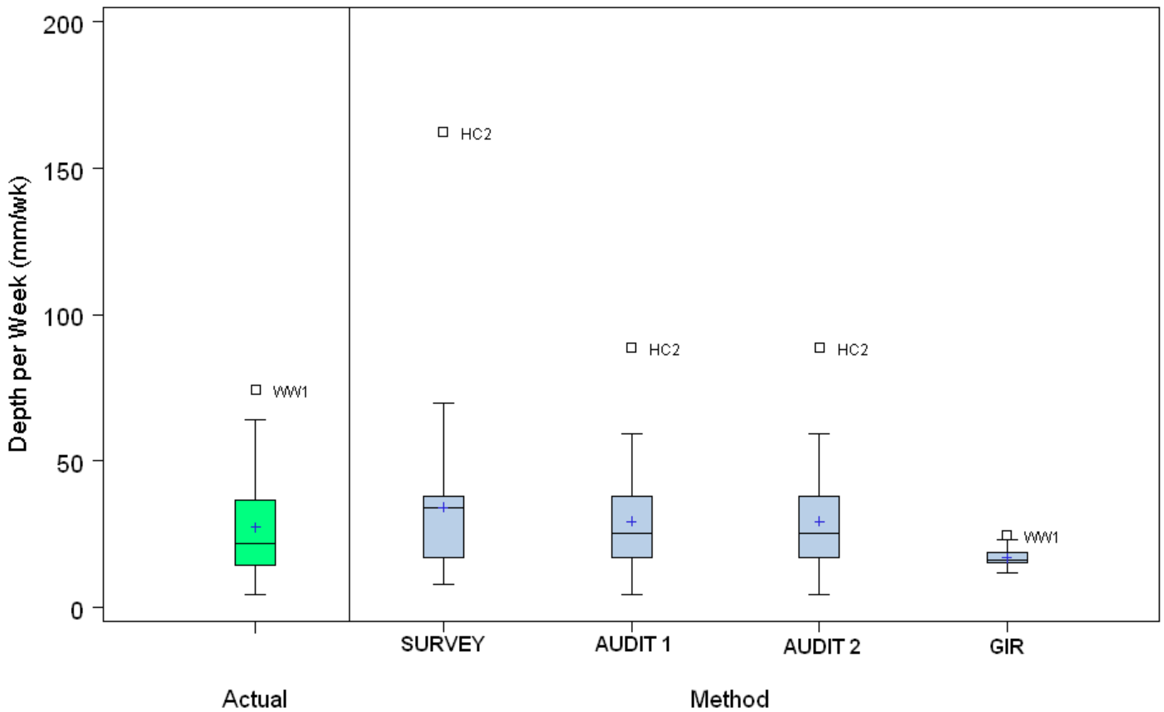

Figure 3.13 Distributions of actual average volumetric water withdrawals from 2009, predicted weekly water withdrawals using the three prediction models, and 2009 average weekly GIR for the 36 study sites.

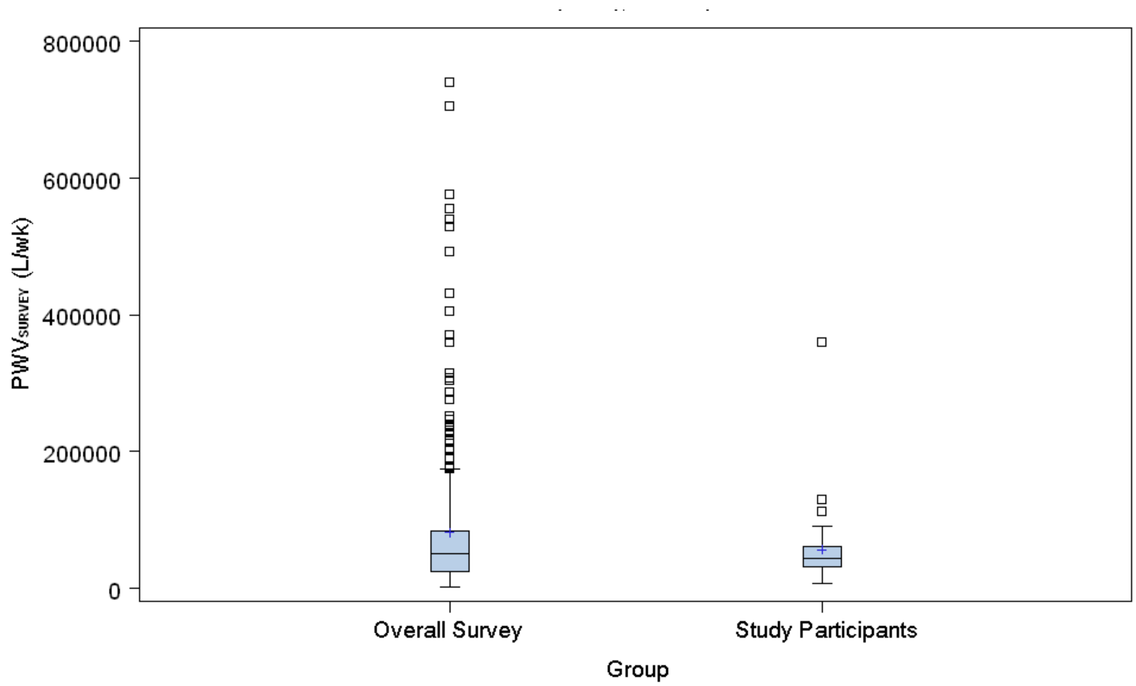

Figure 3.14 Distribution of PWV_{SURVEY} for the 36 study sites and for all survey respondents that indicated a Duke Energy lake as their water source, a buried system as their system type, and that provided the necessary inputs for the PWV_{SURVEY} model.

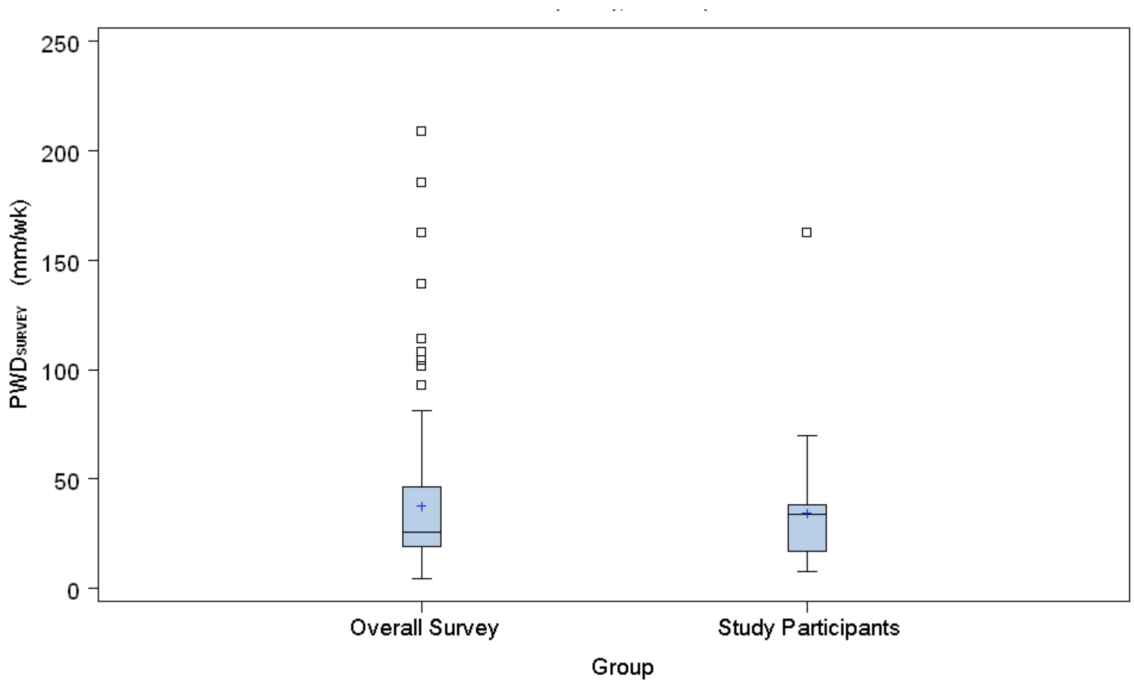

Figure 3.15 Distribution of PWD_{SURVEY} for the 36 study sites and for all survey respondents that indicated a Duke Energy lake as their water source, a buried system as their system type, and that provided the necessary inputs for the PWD_{SURVEY} model.

APPENDIX

Appendix A - 1. Draft of online survey distributed by Duke Energy

NCSU-Duke Energy Water Use Study

Page 1 of 3

LastName:

FirstName:

Address:

Street:

City:

zip:

Lake
- James
- Norman
- Wylie

Do you irrigate? If checked less, skip the rest of this survey. ☐

Water Source
- Lake
- Community Well
- Muncipal
- Don't know

What is your lot size (acres)?
- less than 0.25
- 0.25-0.5
- 0.5-0.75
- 0.75-1.0
- 1.0-2.0
- 2.0-3.0
- greater than 3.0

About what percent of your lot is irrigated?
- Less than 10
- 10-25
- 25-50
- 50-75
- more than 75

Select the type of irirgation system you have
- buried system
- hose (portable)

What type of grass is in your lawn?
- Tall Fescue
- Bermuda
- Zoysia
- Don't know

Do you use a lawn service? ☐

Did a contractor install your irrigation system? ☐

Contractor Name

Select the type of sprinklers you have

- rotors
- pop-up spray heads
- impact sprinklers
- both rotors and spray heads
- hose (portable)
- don't know

Do you irrigate non-turf areas with your system? ☐

If you answered yes to the question above, about what percentage of your total irrigated area is non-turf?

- Less than 10
- 10-25
- 25-50
- 50-75
- 77-90
- 100

How many months per year do you irrigate? (enter a number)

During the months you irrigate, how many days per week on average do you irrigate?

- 1
- 2
- 3
- 4
- 7

On average, how many minutes does each irrigation zone run?

- 5
- 10
- 15
- 20
- 30
- 45
- 60
- 90

What time of day do you irrigate?

- night (10 pm - 6 am)
- morning (6 am - 10 am)
- daytime (10 am -6 pm)
- evening (6 pm - 10 pm)

Would you like to participate in the study by NC State University as decribed in the accompanying letter? ☐

Appendix B - 1. Survey Responses by Lake

Total 1405

Count of Lake	Lake								
	Fishing Creek	Hickory	James	Lookout	Mt Island	Norman	Rhodhiss	Wateree	Wylie
Total	8	125	41	27	56	863	14	7	264
Percent	0.6%	8.9%	2.9%	1.9%	4.0%	61.4%	1.0%	0.5%	18.8%

Appendix B - 2. Lot Size by Lake.

Count of LotSize	LotSize						
Lake	Less than 0.25	0.25 - 0.5	0.5 - 0.75	0.75 - 1.0	1.0 - 2.0	Greater than 3.0	Grand Total
Fishing Creek		1			5	2	8
Hickory		24	31	43	22	5	125
James		2	5	14	12	8	41
Lookout		6	6	6	6	3	27
Mt Island		5	16	19	15	1	56
Norman	1	124	271	301	153	13	863
Rhodhiss					13	1	14
Wateree		1	2	1	3		7
Wylie	3	56	44	80	66	15	264
Total	4	219	375	464	295	48	1405
Percentage	0.3%	15.6%	26.7%	33.0%	21.0%	3.4%	

Appendix B - 3. Irrigation Water Sources by Lake.

Count of What is your irrigation water source	What is your irrigation water source				
Lake	Community Well	Don't know	Lake	Municipal	Grand Total
Fishing Creek	1		2		3
Hickory	5		55	10	70
James	2		7	11	20
Lookout			8	1	9
Mt Island	1	1	30	16	48
Norman	24	6	636	12	678
Rhodhiss		1	1	4	6
Wateree		1	3		4
Wylie	15	4	159	10	188
Total	48	13	901	64	1026
percentage	4.7%	1.3%	87.8%	6.2%	

Appendix B - 4. Percent of Lot Irrigated by Lake.

Count of About What percent of your lot is irrigated? (4)	About What percent of your lot is irrigated?				
Lake	0 - 25%	25 - 50%	50 - 75%	more than 75%	Grand Total
Fishing Creek	1		1	1	3
Hickory	15	20	19	16	70
James	10	6	3	1	20
Lookout	1	4	4		9
Mt Island	14	23	7	4	48
Norman	71	196	233	178	678
Rhodhiss	4	1		1	6
Wateree		1	2	1	4
Wylie	33	73	43	39	188
Totals	149	324	312	241	1026
Percent	14.5%	31.6%	30.4%	23.5%	

Appendix B - 5. Irrigation System Type by Lake.

Count of Select the type of irrigation system you have (2)	Select the type of irrigation system you have		
Lake	Buried system	Hose (portable)	Grand Total
Fishing Creek	3		3
Hickory	58	12	70
James	17	3	20
Lookout	5	4	9
Mt Island	45	3	48
Norman	617	61	678
Rhodhiss	3	3	6
Wateree	4		4
Wylie	175	13	188
Total	927	99	1026
Percent	90.4%	9.6%	

Appendix B - 6. Metered Systems by Lake.

Count of Does your irrigation System have a meter that measures the amount of water used	Does your irrigation System have a meter that measures the amount of water		
Lake	No	Yes	Grand Total
Fishing Creek	3		3
Hickory	68	2	70
James	17	3	20
Lookout	8	1	9
Mt Island	45	3	48
Norman	649	29	678
Rhodhiss	6		6
Wateree	4		4
Wylie	179	9	188
Total	979	47	1026
Percent	95.4%	4.6%	

Appendix B - 7. Contractor Installed System by Lake.

Count of Did a contractor install your irrigation system?	Did a contractor install your irrigation system?		
Lake	No	Yes	Grand Total
Fishing Creek	2	1	3
Hickory	24	46	70
James	7	13	20
Lookout	6	3	9
Mt Island	11	37	48
Norman	172	506	678
Rhodhiss	4	2	6
Wateree	2	2	4
Wylie	53	135	188
Total	281	745	1026
Percentage	27.4%	72.6%	

Appendix B - 8. Sprinkler Type by Lake.

Count of Select the type of sprinklers you have	Select the type of sprinklers you have						
Lake	both rotors and spray heads	Don't know	hose (portable)	impact sprinklers	pop-up spray heads	rotors	Grand Total
Fishing Creek	2				1		3
Hickory	32	6	6	2	23	1	70
James	10	2	2		6		20
Lookout	3	1	1	2	2		9
Mt Island	25	3	1	2	17		48
Norman	332	18	43	12	251	22	678
Rhodhiss		1	1	2	2		6
Wateree	2				2		4
Wylie	89	14	9	5	68	3	188
	495	45	63	25	372	26	1026
	48.2%	4.4%	6.1%	2.4%	36.3%	2.5%	

Appendix B - 9. Indication of Cool or Warm Season Grass.

Count of Does your grass turn brown in winter?	Does your grass turn brown in winter?		
Lake	No	Yes	Grand Total
Fishing Creek		1	1
Hickory	27	16	43
James	8	5	13
Lookout	3	5	8
Mt Island	28	4	32
Norman	312	126	438
Rhodhiss	2		2
Wateree		3	3
Wylie	78	44	122
	458	204	662
	69.2%	30.8%	

Appendix B - 10. Percent of non-turf area irrigated.

Lake	0 - 25%	25 - 50%	50 - 75%	more than 75%	Grand Total
Fishing Creek	1				1
Hickory	23	18	1	1	43
James	4	4	1	4	13
Lookout	6	2			8
Mt Island	26	5	1		32
Norman	316	100	13	9	438
Rhodhiss	2				2
Wateree	2	1			3
Wylie	76	22	18	6	122
Total	456	152	34	20	662
Percent	68.9%	23.0%	5.1%	3.0%	

Appendix B - 11. Number of months per year irrigation occurs.

Count of How many months per year do you irrigate?	How many months per year do you irrigate?											
Lake	1	2	3	4	5	6	7	8	9	10	12	Grand Total
Fishing Creek						1						1
Hickory			5	2	7	12	11	3	1	1	1	43
James	1			2	1	6	2	1				13
Lookout	1			2	3	1	1					8
Mt Island		1	2	1	3	10	5	9	1			32
Norman		3	18	34	51	115	110	84	21	2		438
Rhodhiss				1					1			2
Wateree				2	1							3
Wylie	1	1	4	16	18	29	27	14	10	2		122
Total	3	5	29	60	84	174	156	111	34	5	1	662
Percentage	0.5	0.8	4.4	9.1	12.7	26.3	23.6	16.8	5.1	0.8	0.2	

Appendix B - 12. Number of Days of Irrigation per Week.

Count of During the months you irrigate, how many days per week on average	During the months you irrigate, how many days per week on average					
Lake	1	2	3	4	7	Grand Total
Fishing Creek				1		1
Hickory	4	18	15	4	2	43
James	2	7	3	1		13
Lookout	2	2	3	1		8
Mt Island	3	13	14	1	1	32
Norman	34	158	188	42	16	438
Rhodhiss			1	1		2
Wateree		1	1	1		3
Wylie	13	43	54	8	4	122
Total	58	242	279	60	23	662
Percent	8.8%	36.6%	42.1%	9.1%	3.5%	

Appendix B - 13. Irrigation Zone Run Times.

Count of On average, how many minutes does each irrigation zone run?	On average, how many minutes does each irrigation zone run?								
Lake	5	10	15	20	30	45	60	90	Grand Total
Fishing Creek						1			1
Hickory		7	6	12	4	6	3	5	43
James			4	3	2	3	1		13
Lookout			4		1	1	2		8
Mt Island		8	10	7	3	3	1		32
Norman	5	59	88	104	90	45	28	19	438
Rhodhiss		1				1			2
Wateree			1		1	1			3
Wylie	1	21	24	22	25	15	11	3	122

Total	6	96	137	148	126	76	46	27	662
Percent	0.91	14.5	20.7	22.4	19.0	11.5	7.0	4.1	

Appendix B - 14. Time of Irrigation.

Count of irigtTime	irigtTime				
Lake	morning (6 am - 10 am)	daytime (10 am - 6 pm)	evening (6 pm - 10 pm)	night (10 pm - 6 am)	Grand Total
Fishing Creek				1	1
Hickory	24	2	7	10	43
James	7		2	4	13
Lookout	3	1	3	1	8
Mt Island	17	2	1	12	32
Norman	224	20	34	160	438
Rhodhiss	2				2
Wateree	3				3
Wylie	67	7	10	38	122

Total	347	32	57	226	662
Percentage	52.4%	4.8%	8.6%	34.1%	

Appendix B - 15. Watering Restrictions Awareness.

Count of Are you aware of the lake pump restrictions for your area during	Are you aware of the lake pump restrictions for your area during		
Lake	No	Yes	Grand Total
Fishing Creek	5	2	7
Hickory	25	94	119
James	9	30	39
Lookout	2	25	27
Mt Island	10	44	54
Norman	68	742	810
Rhodhiss	9	5	14
Wateree	2	5	7
Wylie	35	211	246
Total	165	1158	1323
Percentage	12.5%	87.5%	

Appendix B - 16. Desire to Participate in NCSU Study.

Count of Would you like to participate in the study by NC State University	Would you like to participate in the study by NC State University		
Lake	No	Yes	Grand Total
Fishing Creek		2	2
Hickory	6	60	66
James	2	16	18
Lookout	2	7	9
Mt Island	5	41	46
Norman	31	612	643
Rhodhiss	4	2	6
Wateree	1	3	4
Wylie	8	165	173
Total	59	908	967
Percentage	6.1%	93.9%	