RESIDENTIAL IRRIGATION WATER USE IN THE CENTRAL FLORIDA RIDGE

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF ENGINEERING

UNIVERSITY OF FLORIDA

2005

To my husband, Patrick E. Haley.

ACKNOWLEDGMENTS

I thank the following individuals for their help: Danny Burch, Clay Coarsey, Jeff Williams, Brent Addison, Justin Gregory, Kristen Femminella, and Mary Shedd. I would also like to thank my graduate committee members (Dr. Dorota Z. Haman and Dr. Grady L. Miller) for guidance and patience. Lastly, a most special “thank you” goes to Dr. Michael D. Dukes, for being a wonderful guru! This research was supported by the Florida Agricultural Experiment Station and a grant from St. Johns River Water Management District.

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LIST OF ABBREVIATIONS

ASAE	American Society of Agricultural Engineers
CU	Coefficient of Uniformity
DU_{lq}	Distribution Uniformity
ET	Evapotranspiration Rate
ET_o	Reference Evapotranspiration
GLM	General Linear Model
MIL	Mobile Irrigation Lab
NRCS	Natural Resource Conservation Service
NTEP	National Turfgrass Evaluation Procedure
SJRWMD	St. Johns River Water Management District
T1	Treatment One
T2	Treatment Two
T3	Treatment Three
TDR	Time Domain Reflectometry
UF	University of Florida
USDA	United States Department of Agriculture
VWC	Volumetric Water Content

Abstract of Thesis Presented to the Graduate School
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May 2005

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Major Department: Agricultural and Biological Engineering

Automatic in-ground irrigation is almost a standard for residential homeowners desiring high-quality landscapes in Florida. The goal of this study was to document irrigation water use (T1) and system uniformity in the Central Florida Ridge region under typical irrigation practices, and to quantify distribution uniformity of residential sprinkler equipment under controlled conditions. The other major goal was to determine if scheduling irrigation by setting controllers based on historical evapo-transpiration (ET) (T2) and reducing the percentage of turf area combined with setting the controllers based on historical ET (T3) would lead to reductions in irrigation water use.

The time frame of this study was 29 months beginning in 2002. Most of the homes in the study tended to over-irrigate. Irrigation system analysis for each home included irrigation water distribution uniformity tests, recorded water use, visual observation of the turf quality, and pressure testing across all zones in the system. Of the 27 houses in this study, average annual irrigation accounted for 62% of the residential water use volume. The T1 homes had an average monthly water use of 146 mm. Compared to the

T1 homes, T2 had a 21% reduction, and T3 had a 41% reduction in average monthly water use. Over-irrigation was a result of a lack of understanding of the run times based on equipment type and seasonal evapotranspiration rates. In many cases, homeowners did not decrease irrigation water use in the winter months.

To test the distribution uniformity of the irrigation systems, a catch-can test was used. From these tests, the overall low quarter distribution uniformity (DU_{lq}) value was calculated as 0.45. Rotor sprinklers resulted in significantly higher DU_{lq} compared to fixed pattern spray heads (0.49 compared to 0.41, respectively). The spray heads had higher uniformity (DU_{lq} value) when fixed quarter-circle nozzles were used, as opposed to adjustable nozzles. Uniformity was higher in the tests where the manufacturer recommended pressure was maintained rather than tests performed at low pressure. For the control tests, the spacing was set according to manufacturer guidelines for head to head coverage. In contrast, the residential systems had less-than-ideal spacing, and thus had a decreased DU_{lq} value. Residential irrigation system, uniformity can be improved by minimizing the occurrence of low pressure in the irrigation system and by ensuring that proper spacing is used in design and installation.

The use of time domain reflectometry (TDR) probes is an effective nondestructive method of measuring soil moisture content. The study compared irrigation distribution uniformity evaluated by TDR in the upper 12 cm of the soil versus catch-can tests. The calculated DU_{lq} determined from a TDR device tended to be 0.15 to 0.20 points higher than the DU_{lq} value determined by the catch-can method. The TDR moisture content DU_{lq} did not correlate with catch-can DU_{lq}.

CHAPTER 1
INTRODUCTION

Irrigation has become nearly a standard option for residential homeowners desiring high quality landscapes in Florida. Turfgrass is a key landscape component, and normally the most commonly used single type of plant in the residential landscape. Although Florida has a humid climate (the average precipitation rate is greater than the evapotranspiration rate), the spring and winter are normally dry. The average annual precipitation for the Central Florida ridge is approximately 1320 mm, with most of this in the summer months (June through August). The spring months (March through May) are typically the hottest and driest (USDA, 1981). This region is also characterized by sandy soils with a low water-holding capacity; therefore, storage of water is minimal. The dry spring weather and sporadic large rain events in the summer (coupled with the low water-holding capacity of the soil) make irrigation necessary for the high-quality landscapes desired by homeowners.

Residential water use comprises 61% of public-supply water withdrawals (Fernald and Purdum, 1998). Public supply is responsible for most (43%) of the groundwater withdrawn in Florida. Between 1970 and 1995, public-supply water withdrawals increased 135%(Fernald and Purdum, 1998). Florida consumes more fresh water than any other state east of the Mississippi River (Solley al. (1998).

Florida's current population of 16 million is projected to exceed 20 million by 2020 (USDC, 2001). With the average residential irrigation cycle consuming 2000 to 2500 gallons of water per cycle (Hayes, 2000), water conservation has become a state concern.

In 1972 (in the Florida Water Resources Act, Chapter 373) the Florida Legislature created the five water management districts. In 1997, Chapter 97-160 of the Laws of Florida was ratified; this overruled Chapter 373 of the Florida Statutes, the previous water law. The revision included delegating responsibilities to the water management districts. Each district was assigned primary responsibility for conducting water resource development.

This study focused on the Central Florida ridge in the St. Johns River Water Management District (SJRWMD). Due to drought conditions in the past few years, the SJRWMD has limited residential irrigation to 2 times per week. Residential irrigation is prohibited between 10 a.m. and 4 p.m., whether the water is from public supply, domestic self-supply (i.e., wells), or surface water (SJRWMD, 2002). Irrigation outside of these hours reduces evaporative and wind losses. Residential irrigation water is thought to be 50% of total irrigation water use, although, no literature confirmed this.

Irrigation efficiency defines how well an irrigation system supplies water to a given crop or turf area. Efficiency is the ratio between water used beneficially and water applied, and is expressed as a percentage. There are three concepts of irrigation efficiency: water conveyance efficiency (E_c) (Eq. 1-1); water-application efficiency (E_a) (Eq. 1-2); and reservoir storage efficiency (E_s) (Eq. 1-3).

$$E_c = 100 \cdot \frac{W_d}{W_i} \quad [1\text{-}1]$$

$$E_a = 100 \cdot \frac{W_s}{W_d} \quad [1\text{-}2]$$

$$E_s = 100 \cdot \frac{W_p}{W_{rs}} \quad [1\text{-}3]$$

where W_d is the water delivered to the area being irrigated, W_i is the water introduced into the distribution system, W_s is the irrigated water stored in the root zone, W_p is the water pumped from the reservoir, and W_{rs} is the water stored in the reservoir (Smajstrla al. (1991).

Water conveyance efficiency is calculated from the point of discharge (pump), while water application efficiency is calculated over an entire field (or lawn). Reservoir storage efficiency is the ratio of water pumped from the reservoir and water stored in the reservoir. Factors that lower efficiency are evaporation, wind drift, improper equipment adjustment, drainage below the root zone, and runoff. Reservoir storage efficiency is varies depending on site conditions. The lowest values can be attributed to surface reservoirs due to evapotranspiration (ET) and seepage. Since most residential irrigation water in Florida is derived from groundwater, reservoir storage efficiency is thought to be as high as technically possible. In pressurized sprinkler irrigation systems, water conveyance efficiency is nearly 100%, unless there is a leak in the pipeline or distribution equipment. Thus, application efficiency is the only component that may vary in residential irrigation systems. To achieve relatively high application efficiency, it is necessary to maintain even distribution of irrigated water over the target area.

To determine if the water is used beneficially, it is necessary to determine the overall quality of the lawn. The assessment of turfgrass is a subjective process using the National Turfgrass Evaluation Procedures (NTEP) (Shearman and Morris, 1998). This evaluation is based on visual estimates such as color, stand density, leaf texture, uniformity, disease, pests, weeds, thatch accumulation, drought stress, traffic, and quality.

Turfgrass quality is a measure of functional use and aesthetics (i.e., density, uniformity, texture, smoothness, growth habit, and color).

Irrigation systems used by the households typically include stationary spray heads and gear driven rotor sprinklers for the turf and landscape. Water conservation oriented designs include microirrigation for the landscape bedding.

Uniformity of water distribution measures the relative application depth, over a given area. This concept can be valuable in system design and selection, and can assign a numeric value to quantify how well a system is performing. The term uniformity refers to the measure of the spatial differences between applied or infiltrated waters over an irrigated area. Two methods have been developed to quantify uniformity: distribution uniformity (DU) and Christiansen's coefficient of uniformity (CU).

The low-quarter irrigation distribution uniformity (DU_{lq}) can be calculated with the following equation (Merriam and Keller, 1978):

$$DU_{lq} = \frac{\overline{D}_{lq}}{\overline{D}_{tot}} \qquad [1\text{-}4]$$

where $\overline{D}_{lq}$ is the lower quarter of the average of a group of catch-can measurements, and $\overline{D}_{tot}$ is the total average of a group of catch-can measurements.

Distribution uniformity is usually represented as a ratio, rather than a percent (Burt et al. (1997), to signify the difference between uniformity and efficiency. This method emphasizes the areas that receive the least irrigation by focusing on the lowest quarter.

Burt et al. (1997) defined common irrigation performance measurements, standardized and clarified of irrigation definitions, and quantified irrigation measurements. Distribution uniformity is not considered efficiency. Although a system may have even distribution, over-irrigation can occur because of mismanagement. Low-quarter distribution uniformity uses a definable minimum range (lowest quarter) rather than the absolute minimum value (zero). The Irrigation Association (2003), recommended the following distribution of the lower half (DU_{lh}) for scheduling residential irrigation systems,

$$DU_{lq} = \frac{\overline{D}_{lh}}{\overline{D}_{tot}} \qquad [1\text{-}5]$$

$$DU_{lh} = 0.386 + .614 \times DU_{lq} \qquad [1\text{-}6]$$

where $\overline{D}_{lh}$ is the lower half of the average depth of the water irrigated, and $\overline{D}_{tot}$ is the total of the average depth of water irrigated in a given area. Determining distribution uniformity helps to reduce excess water used for irrigation purposes. DU_{lh} is suggested over DU_{lq} because the lower quarter overestimates the effect of non-uniformity for landscapes (IA, 2003).

The coefficient of uniformity treats over-irrigation and under-irrigation equally as compared to the mean, and can be calculated by the Christiansen (1942) formula (Eq. 1-7),

$$CU = 1 - \frac{\sum_{i=1}^{n} \left| V_i - \overline{V} \right|}{\sum_{i=1}^{n} V_i} \qquad [1\text{-}7]$$

where V_i equals the volume in a given catch-can, and $\overline{V}$ refers to the mean volume. In addition to the coefficient of uniformity and the distribution uniformity, there are other important factors in evaluation of a system. Application rates, system pressure variability, runoff, wind, amount of water applied, pump performance, and overall system management must be considered when evaluating total system performance.

Several studies have used these concepts to determine efficiency and uniformity of irrigation systems used in urban and agricultural settings. In Utah, a model for estimating turf water requirements was created (Aurasteh, 1984). Urban irrigation was studied with the irrigation use measured weekly by 20 homeowners. The objectives of the study were to measure residential distribution uniformities, assess potential application efficiencies, and to compare water use to ET rate. The sprinkler uniformity tests were conducted using catch-cans. The ET rate was calculated, and an empirical model for determining urban irrigation needs was created. Residential solid set and movable systems were compared; analysis of the application efficiency these systems showed that the average water application was about 30% for hand-move and 37% for solid set systems (Aurasteh et al. (1984). It was also noted that these homeowners used approximately 61% of their total water supply for irrigation. Utah receives less average annual precipitation, 207 mm (8.2 in) (NRCS, 1990), compared to the 1320 mm (52 in) received in Florida.

Due to the wide use of sprinkler irrigation as an irrigation method on sloping lands, the effects of surface slope on sprinkler uniformity were studied in Brazil. It was found that distribution uniformity has a direct correlation to nozzle and riser angle, increasing as the nozzle angle is varied from vertical to horizontal, perpendicular to the ground. However, the DU decreases with an increase in ground slope. The DU was improved with a triangular precipitation pattern for all ground slopes and nozzle angles (Soares al. (1991).

A number of computer models have been created to aid in uniformity testing of sprinkler systems. In Brazil, a data acquisition system for sprinkler uniformity testing was created (Zanon et al., 2000). The system was designed to test a two radii precipitation pattern (head-to-head) for low to medium pressure sprinklers under no wind conditions. In Japan, a method was developed for evaluating water application rate and the coefficient of uniformity, CU, of sprinklers with head to head coverage. The tests were under realistic conditions, including monitoring the effect of wind drift (Fukui al. (1980).

Numerous modeling studies have been conducted with regard to residential irrigation uniformity and efficiency. In Spain, the SIRIAS software was developed. This model for sprinkler irrigation uses the ballistic theory to predict the path of drops discharged, obtaining wind-distorted water distribution, and formulation for the air drag coefficient. To consider actual environmental conditions, the program has three options for evaporation and drift losses within the irrigation process (Carrion et al., 2000). The simplification and comparison of models has also been explored. At Oregon State University, a widely used model based on numerical solutions was modified for simplicity of use. Accurate analytical approximations for DU, CU, application efficiency, deficiently irrigated volume, and the average deficit over the deficiently irrigated area were developed. The approximations proved to be more accurate than earlier approximations and introduced negligible error when used for practical applications (Smesrud and Selker, 2001). At Colorado State University, the use of the normal distribution function in describing sprinkler irrigation uniformity was simplified for evaluation of irrigation system performance in terms of economic and environmental decisions (Walker, 1979). Colorado State University and Louisiana Technical University compared statistical models to approximate sprinkler patterns with various coefficients of uniformity, calculation of water volume needed, and irrigation efficiency. It was found that for uniformity coefficients the normal distribution was a better fit than the linear model. However, at uniformities below 0.65 the linear model fit best (Elliott al. (1980).

In Colorado, granular matrix soil moisture sensors were used to control the irrigation for urban landscapes. The objective of the study was to evaluate the effectiveness and reliability of soil moisture sensors for irrigation control. The soil moisture systems proved to be very reliable and reduced the irrigation application below theoretical requirements. The calculated theoretical irrigation requirement was 726 mm, while the actual water applied, as allowed by the sensor system, was 533 mm (Qualls et al., 2001).

According to the residential irrigation system audits conducted by the University of Georgia Water Resources Team (Thomas et al., 2003) the operating time was improperly set on many homes tested, therefore the systems were set to run too long applying more water than necessary. Of the systems audited, the spray heads distributed three to five times the water application rate per given area as compared to rotary sprinklers.

To increase water conservation, a national sub-metering and allocation billing study found , more multi-family dwellings are being converted to billing systems where the water and wastewater charges are paid separately, as opposed to including these charges as part of the total rent. Data suggested that sub-metering irrigation water use would further increase the outdoor water use efficiency and management. Sub-metering on multifamily apartment units and billing based on actual consumption resulted in water savings of 15% or 8,000 gallons per unit per year. Reduction of irrigation in the winter months resulted in a statistically significant impact on the overall water use ($p<0.001$). The percent of total property which was irrigated did not have a significant ($p=0.150$) affect on the total water use. However, water billing practices based on the allocation methods (ratio utility billing method) did not affect water savings (Mayer et al., 2004).

The American Water Works Association (AWWA) Research Foundation funded a study on residential end uses of water (Mayer al. (1999). The study concluded the following homes with: in-ground irrigation systems used 35% more water than houses without these systems, automatic timer controls incorporated into the system led to 47% more water used, drip irrigation systems used 16% more water than homes which did not irrigate the area with in-ground irrigation, homes which only hand (hose) watered used 33% less water than those with in-ground systems, and homes which included a consistently maintained garden used 30% more outdoor water. The samples which were grouped into the low-water-use treatment applied an average of 20.3 gal/ft^2 per year for the irrigated area. The standard landscape treatment applied 22.8 gal/ft^{2}per year. However, there was not a significant difference (at the 95 percent confidence interval) between these two treatments. One of the conclusions as to why there was an inconclusive finding was that the low-water-use landscaping required an initial establishment period of additional water.

In Florida, Mobile Irrigation Labs (MILs) were established as a public service in 1992 as part of a water conservation program. Funding for this program comes from the United States Department of Agriculture (USDA) and the individual water management districts. The Florida MILs were modeled after those operating in California and Texas. They evaluate irrigation systems in both agricultural and urban areas by conducting a series of tests over a two-hour period, measuring pump flow rates, sprinkler pressures and flow rates, and application uniformities (Micker, 1996).

While overall uniformity of irrigation systems has been measured in Florida in the past, most of the MILs no longer conduct actual system distribution uniformity tests; therefore, there is a lack of information regarding current residential irrigation system performance and water use. In some MILs distribution uniformity results that were judged to be low were discarded (anonymous MIL source).

In field assessments of irrigation system performance in California, Pitts et al. (1996) found a mean DU_{lq} of all systems tested as 0.64. The average DU_{lq} for non-agricultural turfgrass sprinklers (large turfgrass areas) was 0.49. Greater than 40% of the tested systems had a DU_{lq} of less than 0.40. This study concluded that the low DU_{lq} values were based on the following reasons (listed in order of frequency): maintenance and faulty sprinkler heads, mixed zones (spray and rotor), excessive pressure variations, and poor head-to-head coverage. Many of the cooperators in this study were unaware of importance of scheduling based on potential evapotranspiration and uncertain about the application rates of their systems. It was found that scheduling was usually based on the appearance of the turfgrass. To the “trained” eye this would be acceptable, however typical homeowners do not know what signs are indicative of over-watering or drought related stress.

Linaweaver et al. (1967) found that the amount of water used for residential lawns is effected by the total number of consumers, the economic level of the residential area, the area of turfgrass and bedding requiring irrigation, the evapotranspiration rate, and the quantity of effective rainfall. In Wyoming, from the summer 1975 through spring 1977, a study was conducted on actual lawn water application rates for residential households and evaporation rates of lawn turfgrass. The application rates found were between 122 and 156% above calculated seasonal evapotranspiration rates (Barnes, 1977).

Evapotranspiration (ET) is the rate at which water may be removed from soil and plant surfaces to the atmosphere by a combination of evaporation and transpiration (Allen al. (1998). Evaporation (E) is the conversion of water into its vapor phase. The main factors influencing evaporation are the supply of energy by solar radiation and the transport of vapor away from the surface (e.g., by wind). Transpiration (T) refers to the water used by plants and is affected by plant physiology and environmental factors. The evapotranspiration process is climate controlled. Researchers at Texas A&M University (White et al., 2004) looked at using potential ET, a landscape coefficient (L_c), and the landscape size, to develop water budgets for residential landscapes. It was determined that potential ET irrigation budgeting with an L_c of 1.0 would account for substantial irrigation water savings, especially in the summer months.

A time domain refectometry (TDR) device can be used to measure soil water content by measuring the time needed for an electrical signal to travel along wave guides. As opposed to the measurement of irrigation application, soil moisture is measured as the volume of water within a volume of soil. A TDR device can be used to estimate the amount of water stored in a profile. It also can help to eliminate how much irrigation is required to reach a desired moisture content.

The Northern Colorado Water Conservancy District compared catch-can tests and soil moisture sensor measurements in turfgrass irrigation auditing. When calculating DU_{lq}, it was found that the soil moisture uniformity was higher than the catch-can uniformity. From the tests in the study, the soil moisture DU_{lq} was 0.15-0.20 (maximum value of 1.00) higher than the DU_{lq} determined by the catch-can method (Mecham, 2001). Although the catch-can DU_{lq} could help determine the overall system performance, these uniformity values did not properly express the distribution of the water through the thatch or as affected by the soil properties. Estimating irrigation run times based on the catch-can DU_{lq} would lead to over-irrigation, due to the low nature of these DU_{lq} values (Mecham, 2001).

In Florida, a study compared microirrigation (drip) uniformity determined by both time domain reflectometry and the conventional volumetric method. The study concluded that the TDR can be a useful tool for quick determination of uniformity. Inversely in this study, for the drip systems the TDR DU_{lq} was lower than the DU_{lq} calculated by the conventional method. Differences were assumed to be a result of soil properties and point measurement locations (Dukes and Williams, 2002).

CHAPTER 2
RESIDENTIAL IRRIGATION WATER USE

Homeowners in Florida desire a year-round lush landscape; consequently, irrigation is required. Florida is reputed as the "Sunshine State" with lush foliage and beautiful weather. The population is steadily increasing and new housing developments are constantly being built. New Floridians expect a manicured and lush landscape around their homes. Unfortunately, this has resulted in excessive water used for irrigation purposes. Since the price of groundwater is not yet particularly high most homeowners would rather pay the price for a green lawn.

As of 2000 Florida had a population of nearly 16 million and is projected to exceed 20 million people by 2020 (USDC, 2001), which has led to the consumption of more fresh water than any other state east of the Mississippi River (Solley al. (1998). Between 1970 and 1995 there was a 135% increase in groundwater withdrawals in Florida (Fernald and Purdum, 1998). Public supply is responsible for the largest portion, 43%, of groundwater withdrawn in Florida. Residential water use comprises 61% of the public supply category (Marella, 1999). Since irrigation is so widely used and the number of in-ground irrigation systems is increasing across the state, it is necessary to observe the residential irrigation water use trends. The objective of this project was to measure residential irrigation water use in the Central Florida Ridge across three landscape and irrigation scheduling treatments.

Materials and Methods

This study was conducted within the Central Florida ridge (Figure 2-1), which included eight homes in Marion County, nine homes in Lake County, and ten homes in Orange County. The homes were categorized into three treatments. Treatment one (T1) consisted of existing irrigation systems and typical landscape plantings, where the homeowner controlled the irrigation scheduling. Treatment two (T2) also consisted of existing irrigation systems and typical landscape plantings, but the irrigation scheduling was based on historical evapotranspiration (ET) rates from the Central Florida area over 30 years. Treatment three (T3) consisted of an irrigation system designed according to specifications for optimal efficiency including a landscape design that minimized turfgrass and maximized the use of native drought tolerant plants as classified by the SJRWMD. To further achieve water savings in T3, the landscape plants were irrigated by microirrigation (micro-spray heads, bubblers, and drip tubing) as opposed to standard spray and rotor heads. The T3 landscape designs and modifications to irrigation systems were installed as part of this project. The newly planted landscape in T3 required an establishment period of one to two months, with increased irrigation. This additional water use data has been omitted in water use analysis. Water use was included for analysis after the andscape material had been established for two months. Mayer et al. (1999) also found that new landscapes required an initial establishment period of additional water.

The average annual precipitation in this area ranges from 1275 to 1400 mm, with the maximum rainfall in the summer months and the minimum rainfall from late fall through spring (USDA, 1981). The soils are excessively to moderately well drained sandy Quartzipsamments (USDA, 1981). The prevalent soil series in the Marion and

Lake County sites is Astatula sand, which allows for rapid permeability, has a very low available water capacity, and little organic matter content (USDA, 1975). The dominant soil series in the Orange County site location is Urbanland-Tavares-Pomello, which is a moderately well drained soil that is sandy throughout (USDA, 1989). The Marion and Lake County sites included in this study are on the hills that were previously citrus farms, and have been built upon a layer of sand fill. The irrigation systems used by the households typically include stationary spray heads and gear driven rotor sprinklers for the turf and landscapes. The lawn areas of the yards all consisted of St. Augustine turfgrass, which is a warm season turfgrass and a common sod in new construction in Florida.

The residences for this study where chosen if an in-ground automatic irrigation system was used and the irrigation system was supplied by potable city water (not well-drawn or reclaimed water). The homeowners were recruited at garden club or area community association meetings. All of the residences included in this study obtained water from local utilities. The utility water meter was used to determine the amount of water consumed by the household. For domestic water systems, positive displacement meters are used, which are relatively inexpensive and accurate (Munson al. (1998). To determine the volume of irrigation water used, a second flow meter was installed after the irrigation pipeline diverged from the main water line to the house, before distribution to the solenoid valves. The meters were installed with no obstruction within approximately ten diameters of the inlet and outlet of the meter. This was to ensure minimal turbulence in flow through the meter to maintain accuracy (Baum et al., 2003). Water use data was collected from January 2002 through May 2004. However, additional homes were incorporated into T1 and T2 until May 2003, and the last of the T3 homes was added in July 2003.

The area of each yard was calculated from a scale drawing of the house, turf, and landscape beds. The irrigated area was necessary for calculating depth of irrigation applied from the volume data measured by the meters.

Weather stations in Marion and Lake Counties were installed in late February 2002 and one was installed in Orange County in May 2002 to enable calculation of reference evapotranspiration (ET_o). The weather stations were located in flat-grassed areas so that the nearest obstruction was at least 61 m away from the station. Irrigated areas were chosen when possible; however, this resulted in one of the stations collecting irrigation water in the precipitation bucket. A separate rain bucket and data logger (Davis Instruments Corp., Hayward, CA and Onset Computer Corp., Bourne, MA) was installed in a non-irrigated area to separate precipitation events from irrigation events. The residential home sites were located within 1 km of the weather stations. Date, time, temperature, relative humidity and temperature (model HMP45C, Vaisala, Inc., Woburn, MA), soil heat flux (model HFT3, Radiation Energy Balance Systems, Bellevue, WA), solar radiation (model LI200X, Li-Cor, Inc., Lincoln, NE), wind speed and direction (model WAS425, Vaisala, Inc., Sunnyvale, CA) and, precipitation (model TE525WS, Texas Electronics, Inc., Dallas, TX), were recorded in 15 minute intervals via a CR10X data logger (Campbell Scientific, Inc., Logan UT).

The Penman-Monteith equation is a widely used combination method for calculating ET_o. As outlined in FAO-56 this equation takes the following form (Allen al. (1998):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad [2\text{-}1]$$

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2} \qquad [2\text{-}2]$$

$$R_n = R_{ns} - R_{nl} \qquad [2\text{-}3]$$

$$R_{nl} = \sigma\left[\frac{T^4_{\max,K} + T^4_{\min,K}}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}} - 0.35\right) \qquad [2\text{-}4]$$

$$R_{ns} = (1 - \alpha)R_s \qquad [2\text{-}5]$$

$$R_{so} = (0.75 + z(2 \times 10^{-5}))R_a \qquad [2\text{-}6]$$

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r \left[\omega_s \sin(\varphi)\sin(\delta) + \sin(\omega_s)\cos(\varphi)\cos(\delta)\right] \qquad [2\text{-}7]$$

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \qquad [2\text{-}8]$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \qquad [2\text{-}9]$$

$$\omega_s = \arccos\left[-\tan(\varphi)\tan(\delta)\right] \qquad [2\text{-}10]$$

$$e_s = \frac{e^o(T_{\max}) + e^o(T_{\min})}{2} \qquad [2\text{-}11]$$

$$e_a = \frac{e^o(T_{\min})\frac{RH_{\max}}{100} + e^o(T_{\max})\frac{RH_{\min}}{100}}{2} \qquad [2\text{-}12]$$

$$e^o(T) = 0.6108\exp\left[\frac{17.27T}{T+237.3}\right] \qquad [2\text{-}13]$$

where ET_o = Potential evapotranspiration, mm/day
Δ = slope of the vapor pressure curve, kPa $^oC^{-1}$
R_n = net radiation of the turf surface, MJ m^{-2} day^{-1}
R_{nl} = net outgoing longwave radiation, MJ m^{-2} day^{-1}
R_{ns} = net solar or shortwave radiation, MJ m^{-2} day^{-1}
R_{so} = clear sky solar radiation, MJ m^{-2} day^{-1}
R_s = measured solar radiation W/m^2 x 0.0864, MJ m^{-2} day^{-1}
R_a = extraterrestrial radiation, MJ m^{-2} day^{-1}
G = measured soil heat flux density, MJ m^{-2} day^{-1}
G_{sc} = solar constant, 0.0820 MJ m^{-2} min^{-1}
T = measured air temperature at a 1.5 m height, ^oC
u_2 = measured wind speed at a 2 m height, m s^{-1}
e_s = saturation vapor pressure, kPa
e_a = actual vapor pressure, kPa
$e^o(T)$ = saturation vapour pressure at air temperature, kPa
RH = relative humidity at 1.5 m height, %
d_r = inverse relative distance Earth-Sun
ω_s = sunset hour angle, rad
δ = solar declination, rad
γ = psychrometric constant, 0.067 kPa $^oC^{-1}$
σ = Stefan-Boltzmann constant, 4.903 x 10^{-9} MJ K^{-4} m^{-2}
J = Julian day
φ = latitude, radians

Effective rainfall is the portion of rainfall that is beneficial to the plants, and does not include that rainfall that produced runoff. Effective rainfall was estimated by the SCS method, presented by the following equation (Schwab al. (1993):

$$P_e = f(D)[1.25P_m^{0.824} - 2.93][10^{0.000955ET_o}] \quad [2\text{-}14]$$

$$f(D) = 0.53 + 0.0116D - 0.894\times10^{-5}D^2 + 2.32\times10^{-7}D^3 \quad [2\text{-}15]$$

where P_e = estimated effective rainfall for soil water deficit depth, mm

P_m = mean monthly rainfall, mm

ET_o = average monthly evapotranspiration, mm

f(D) = adjustment factor for soil water deficits or net irrigation depths

D = soil water deficit or net irrigation depth, mm (used 25 mm)

To determine if the water is used beneficially, it is necessary to determine the overall quality of the lawn. The assessment of turfgrass is a subjective process following the National Turfgrass Evaluation Procedures (NTEP) (Shearman and Morris, 1998). This evaluation is based on visual estimates such as color, stand density, leaf texture, uniformity, disease, pests, weeds, thatch accumulation, drought stress, traffic, and quality. Turfgrass quality is a measure of functional use and aesthetics (i.e., density, uniformity, texture, smoothness, growth habit, and color).

The statistical analysis of the collected data was analyzed using the general linear model (GLM) function of the SAS software for the anova tables. The means are reported as weighted means. All significance was at the 95% confidence interval, unless otherwise noted. Interactions, such as year or season with treatment were observed, and the three locations were nested for proper data analysis.

Results and Discussion

Overall, the average household used 63% of total water consumed for irrigation. Treatment 1 averaged 75% of the total water use for irrigation (Table 2-1), Treatment 2 used 66% (Table 2-2), and Treatment 3 used 49% (Table 2-3), which were statistically different ($p<0.001$).

Many of the homeowners, particularly in Marion and Lake Counties, would leave town for extended periods of time in the summer months (June-August). Although the homeowner was not in town, irrigation of the landscape continued. Three of the T3 homes were vacant for part of the data collection period because the irrigation system was installed prior to the sale of the house. This lack of occupancy did not affect the irrigation water use for the homes because the homes were part of T3, where the controller settings were adjusted as part of the study. The lack of occupancy did however have and effect on the percentage of water used for irrigation by the household, so the months in which the percentage of water use was 100% were omitted.

Treatment 1 (user controller setting with typical irrigation system) had the highest average monthly irrigation water use, 146 mm. Treatment 2 (60% historical ET replacement with typical irrigation system) consumed 116 mm for irrigation purposes. Treatment 3 (adjusted controller setting incorporating microirrigation) used the least water for irrigation, 86 mm. The average monthly irrigation depth was significantly different ($p<0.001$) across all treatments. The T2 homes consumed 21% less water than T1, and T3 consumed 41% less than T1.

The evapotranspiration and rainfall data is reported in Table 2-4. The comparison of the effective rainfall plus the applied irrigation compared to ET_o can be found in Figure 2-2. Across all three years, T1 had a higher water input than ET_o. The T2 water use was very similar to T1, especially in the summer months. There was a decrease in water input during the first winter; this is when the controller adjusting began for the T2 homes. The reasons the T2 water input did not decrease as much during the later part of 2003 and early 2004 was because: the homeowners would periodically re-adjust their controller; the controller settings was based on historical ET and during this time there was more rain than expected; and sometimes rain events occurred after scheduled irrigation. The T3 water input was much lower after the first year, this is probably because during the first year there was an initial establishment period for the landscapes. Although this period was removed, there were residual effects.

Year two, 2003, was the only full year of data collection where the irrigation run times were seasonally adjusted. During this cycle of seasons, there were significant differences between treatment and season, there was not however an interaction between treatment and season. The T1 homes applied 141 mm of irrigation water, which was significantly more that T2 and T3, which applied 94 mm and 85 mm respectively during this year.

Across the 29 months of data collection, all three treatments combined used significantly the least water in the winter months, 78mm. The summer months accounted for significantly the second lowest amount, 117 mm. There was not a significant difference between the fall and spring months, and during these the most water was used for irrigation purposes.

Turf quality was rated seasonally (Table 2-5). In the winter months (December-February), when the turfgrass is typically dormant, T3 used the least water, 55 mm, primarily because the microirrigation zones result in a smaller effective irrigated area and turfgrass irrigation could be stopped or greatly reduced. In the spring months (March-May) T1 applied the most irrigation water, 179 mm, T2 used 132 mm, and T3 consumed the least, 94 mm. This is due to monthly adjustments of irrigation times and because the microirrigated areas in T3 homes required less water than if those areas were sprinkler irrigated. However, there was not a statistical difference between the treatments. During the spring months, ET_o was the highest and the adjusted controller run time settings were similar to that of typical user set run times. In the fall months (September-November), T1 and T2 resulted in similar application amounts of 155 mm and 148 mm, and T3 significantly less at102 mm.

The minimum turf quality rating for acceptable quality is 6. Lower ratings do not necessarily imply drought stress. The lawns in T1 and T2 maintained minimum or better quality during the project data collection period. The T2 turfgrass had no significant differences in quality from T1 under a decreased irrigation schedule. The T3 lawns did have lower quality ratings as compared to T1 and T2 in the winter (Table 2-5).

The homes in T1 and T2 were irrigated solely by either rotary or spray irrigation heads. The homes in T3 incorporated a portion of the irrigated area covered by microirrigation. The landscape designs for T3 homes also included larger bedding and decreased turfgrass areas. The typical T1 or T2 landscape averaged 75-78% turfgrass (Table 2-6). The turfgrass portion of the T3 homes ranged from 66% to 5%, and averaged 35%. The remaining percentage of the landscaped area was considered bedding and irrigated with the microirrigation. In some sections of the T3 homes the bedded areas included the use of ground covers.

The homes in Orange County had the highest average water use, 130 mm/month. This water use is directly correlated with the irrigation system design. The yards in Orange County had the smallest turfgrass area, which is typically irrigated by a greater percentage of spray zones versus rotary zones heads (a ratio of 5:1). The ratios of spray heads to rotor zones for Marion and Lake Counties were 4:1 and 4:3 respectively. Spray zones have a higher precipitation rate and the water output is more sensitive to the scheduled run time compared to rotor zones. For all treatments, the homes in Lake County used the greatest percentage of water for irrigation because the yards in this area were the largest, primarily composed of turfgrass (Table 2-6). The irrigation water use difference between the three counties was marginally significant (p-value of 0.06).

Summary and Conclusions

The average household in this study used, for irrigation, 63% of the total. Substantial over-irrigation occurred on all treatments when compared to ET_o. Over-irrigation resulted from poor uniformity and improper scheduling.

Irrigation water use was greatest on the homes with typical irrigation systems where the homeowner set their own controller run times (T1). At the homes where the irrigation system still consisted of a typical design, but the controller run times were adjusted based on historical evapotranspiration rates (T2), the irrigation water consumption was decreased by 21% as compared to T1. The homes with both the adjusted controller run time settings and the incorporation of microirrigation in the bedding areas (T3) consumed the least amount of irrigation water, 41% water savings as compared to T1.

From the figure comparing the water use by treatment including effective rainfall to ET_o, it was observed that T3 had the lowest water input, which was similar to the evapotranspiration. The water input for the T1 homes was always much higher than ET_o. Irrigation application with respect to ET_o for T2 fluctuated, over-irrigation still occurred, the scheduling could be improved to maintain lower water input.

In Florida, rainfall supplies a significant portion of the plant water requirements but since rain events are often intense and water holding capacity is low, high rainfall values will not supply crop water needs over time.

Turfgrass quality did not vary significantly across treatments 1 and 2. The T3 lawns did have lower quality ratings as compared to T1 and T2 in the winter. The T3 ratings were below the NTEP acceptable rating of 6, but never lower than 5. In the fall and winter months there was a decrease in turf quality, because turfgrass went into partial dormancy. During dormancy, which is the normal state of turfgrass in the winter months, irrigation run times can be decreased because the plant has decreased water needs. When the turfgrass goes into dormancy, the turfgrass color changes to tan from green. The decreased turf quality was color related and not due to drought stress or winter injury. In the spring months, after “green-up”, when the grass comes out of dormancy, the T3 turf quality was better than T1.

Table 2-1. Monthly water use for Treatment 1 homes for all three locations combined.

	Treatment 1		
Month	Water Use (mm)	% of Total Water Use	No. of Homes
Mar-02	124	85	5
Apr-02	144	87	5
May-02	186	89	5
Jun-02	124	76	5
Jul-02	90	75	5
Aug-02	154	69	8
Sep-02	148	83	8
Oct-02	158	82	8
Nov-02	135	83	8
Dec-02	106	60	8
Jan-03	135	78	8
Feb-03	97	80	8
Mar-03	142	79	8
Apr-03	184	85	8
May-03	162	91	8
Jun-03	177	90	8
Jul-03	117	31	8
Aug-03	123	31	8
Sep-03	177	81	8
Oct-03	158	57	8
Nov-03	110	75	8
Dec-03	104	67	8
Jan-04	83	77	8
Feb-04	102	77	8
Mar-04	245	80	8
Apr-04	157	71	8
May-04	214	68	8
Average*	146	75	
Median	142	78	
Std. Dev.	39	15	
Total	3856		

Water use indicated as depth applied per month, the fraction of the total water consumed by the home which was used for irrigation purposes, and the number of homes included in the sample.
*The average is a weighted average by the number of homes included in the treatment.

Table 2-2. Monthly water use for Treatment 2 homes for all three locations combined.

	Treatment 2		
Month	Water Use (mm)	% of Total Water Use	No. of Homes
2-Mar	164	74	6
2-Apr	154	90	6
2-May	173	31	6
2-Jun	85	31	6
2-Jul	116	81	7
2-Aug	129	57	8
2-Sep	168	81	9
2-Oct	155	80	9
2-Nov	172	61	9
2-Dec	97	65	9
3-Jan	31	46	9
3-Feb	42	47	9
3-Mar	66	56	9
3-Apr	100	67	9
3-May	133	73	9
3-Jun	167	64	9
3-Jul	72	63	9
3-Aug	85	71	9
3-Sep	157	76	9
3-Oct	162	76	9
3-Nov	115	69	9
3-Dec	81	61	9
4-Jan	74	64	9
4-Feb	107	69	9
4-Mar	124	69	9
4-Apr	154	75	9
4-May	175	63	9
Average*	116	66	
Median	124	67	
Std. Dev.	43	14	
Total	3258		

Water use indicated as depth applied per month, the fraction of the total water consumed by the home which was used for irrigation purposes, and the number of homes included in the sample.

*The average is a weighted average by the number of homes included in the treatment.

Table 2-3. Monthly water use for Treatment 3 homes for all three locations combined.

	Treatment 3		
Month	Water Use (mm)	% of Total Water Use	No. of Homes
2-Mar	128	66	2
2-Apr	168	76	2
2-May	173	68	2
2-Jun	173	58	2
2-Jul	186	58	2
2-Aug	178	35	3
2-Sep	114	36	3
2-Oct	201	37	3
2-Nov	150	38	4
2-Dec	110	39	4
3-Jan	58	20	4
3-Feb	67	32	4
3-Mar	119	48	7
3-Apr	143	65	7
3-May	80	89	7
3-Jun	101	88	10
3-Jul	75	59	10
3-Aug	58	31	10
3-Sep	90	52	10
3-Oct	89	55	10
3-Nov	76	32	10
3-Dec	47	31	10
4-Jan	37	34	10
4-Feb	58	43	10
4-Mar	74	57	10
4-Apr	61	47	10
4-May	97	48	10
Average*	86	46	
Median	97	48	
Std. Dev.	48	18	
Total	2911		

Water use indicated as depth applied per month, the fraction of the total water consumed by the home which was used for irrigation purposes, and the number of homes included in the sample.

*The average is a weighted average by the number of homes included in the treatment.

Table 2-4. Evapotranspiration, rainfall, and effective rainfall calculated per month.

		Evapotranspiration	Rainfall		Effective Rainfall
Month	Year	ET_o (mm)	Total Depth (mm)	Events (#)	Total Depth (mm)
Mar	2002	123	98	7	56
Apr	2002	134	45	6	28
May	2002	156	184	10	102
Jun	2002	129	354	21	168
Jul	2002	139	389	23	186
Aug	2002	134	246	19	125
Sep	2002	124	111	13	62
Oct	2002	112	101	13	56
Nov	2002	91	50	15	29
Dec	2002	81	175	25	83
Jan	2003	86	16	11	9
Feb	2003	88	107	12	55
Mar	2003	109	129	23	68
Apr	2003	131	45	14	28
May	2003	151	112	19	66
Jun	2003	131	256	20	128
Jul	2003	139	84	11	50
Aug	2003	125	185	21	96
Sep	2003	107	103	14	56
Oct	2003	97	51	10	29
Nov	2003	75	52	15	29
Dec	2003	61	57	10	30
Jan	2004	59	64	10	33
Feb	2004	76	106	5	53
Mar	2004	112	50	6	30
Apr	2004	130	59	8	36
May	2004	155	78	5	49
	Average*	113	122	14	64
	Median	123	101	13	55
	Std. Dev.	28	94	6	44
	Total	3055	3307	366	1741

This data is the average from all three weather stations, one at each location.
*The average is a weighted average by the number of homes included in the treatment.

Table 2-5. Seasonal water use, fraction of total water use, and turf quality rating with letter notations referring to the significant difference between treatments for each season.

Season	Treatment	Water Use (mm)	Fraction of Total Water Use (%)	Turf Quality Rating
	T1	103a	75	5.7a
	T2	73b	63	6.4a
Winter	T3	55b	37	5.4b
	T1	179a	77	5.9a
	T2	132b	74	6.6a
Spring	T3	94c	42	6.4a
	T1	139a	82	5.8a
	T2	110ab	66	5.6a
Summer	T3	96b	63	5.1a
	T1	155a	62	6.6ab
	T2	148a	61	6.9a
Fall	T3	102b	55	5.8b
	T1	142	75	6.0
	T2	119	66	6.3
Average	T3	87	46	5.7

Table 2-6. Percentage if irrigated area which is turfgrass or landscaped bedding as well as the total irrigated area for each home.

	Treatment 1			Treatment 2			Treatment 3		
House	Turfgrass (%)	Bedding (%)	Area (m^2)	Turfgrass (%)	Bedding (%)	Area (m^2)	Turfgrass (%)	Bedding (%)	Area (m^2)
1	66	33	2165	60	40	497	5	95	495
2	70	30	1709	66	33	2434	10	90	1636
3	74	26	495	74	26	495	15	85	1059
4	80	20	351	74	26	743	20	80	775
5	82	18	655	75	25	822	40	60	1050
6	85	15	3198	76	24	611	50	50	450
7	85	15	697	78	22	1059	50	50	400
8	88	12	1505	85	15	701	59	41	1737
9	.	.	.	85	15	1328	60	40	450
10	.	.	.	.	.	.	66	34	448
Average*	78	21	1347	74	25	966	35	65	850

* The average is a weighted average based on area.

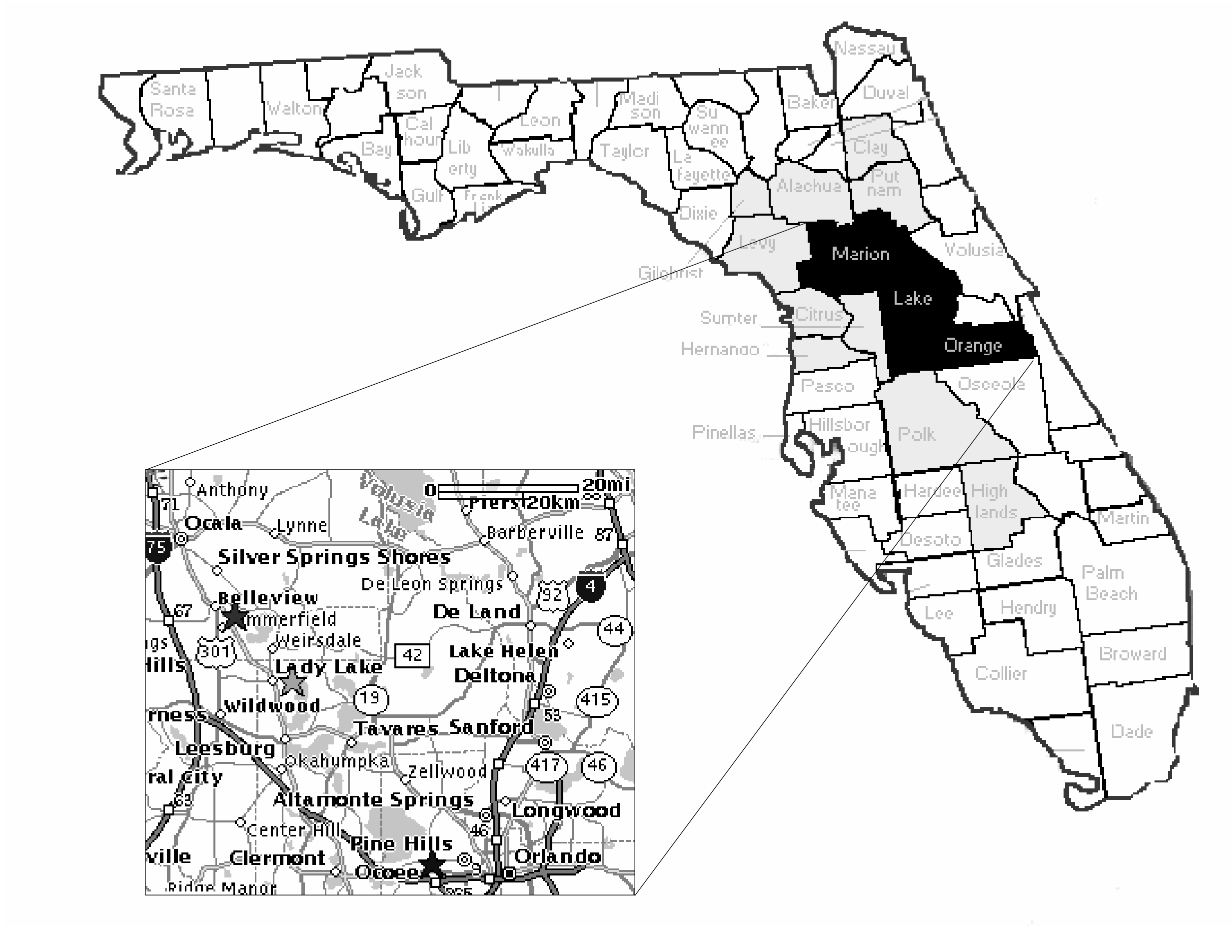

Figure 2-1. Map of site locations.

Grey counties encompassing the Central Florida Ridge and the dark counties encompassing the cooperator homes. Inset map shows the geographic location of the cities closest to the three residential locations, marked by stars.

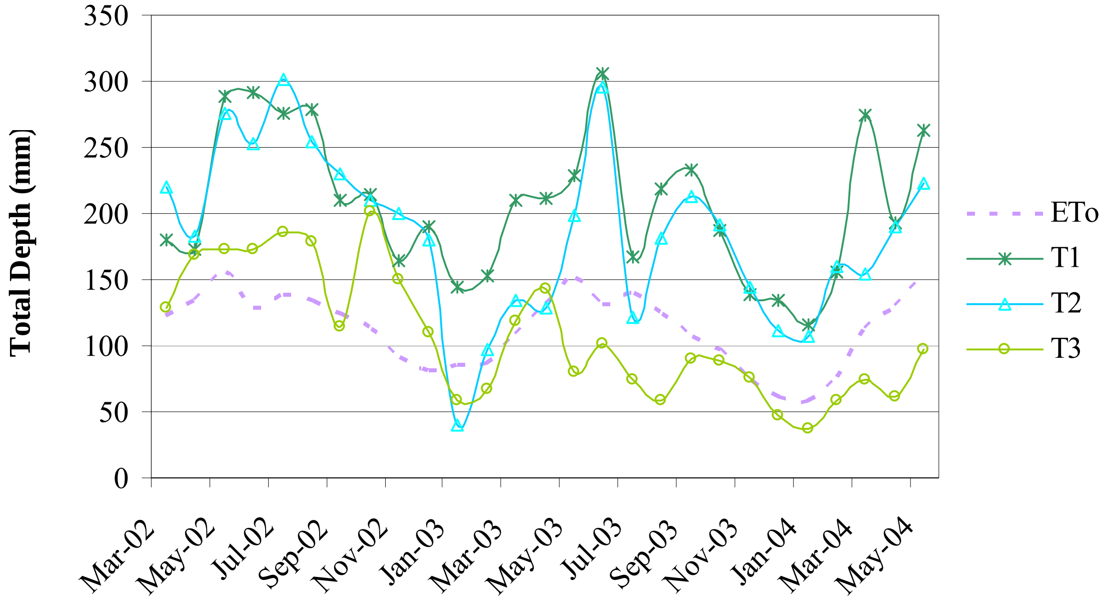

Figure 2-2. Effective rainfall plus applied irrigation for each treatment compared to reference evapotranspiration.

CHAPTER 3
RESIDENTIAL IRRIGATION DISTRIBUTION UNIFORMITY

Irrigation efficiency defines how effectively an irrigation system supplies water for crop or turfgrass beneficial use. Application efficiency can be computed as the ratio between water used beneficially and water applied and is expressed as a percentage. Irrigation efficiency is difficult to quantify; therefore, distribution uniformity is often measured for sprinkler irrigated areas. Irrigation can be uniform and inefficient due to mismanagement; however, irrigation can not be non-uniform and efficient. As a result, irrigation uniformity can be a good indication of potential irrigation efficiency. Uniformity of water distribution measures the variability in application depth over a given area. Two methods have been developed to quantify uniformity: distribution uniformity (DU) and the coefficient of uniformity (CU).

The low-quarter irrigation distribution uniformity (DU_{lq}) (Merriam and Keller, 1978) can be calculated with the following equation

$$DU_{lq} = \frac{\overline{D}_{lq}}{\overline{D}_{tot}} \qquad [3\text{-}1]$$

where $\overline{D}_{lq}$ is the lower quarter of the average of a group of catch-can measurements, and $\overline{D}_{tot}$ is the total average of a group of catch-can measurements.

Distribution uniformity is usually represented as a ratio, rather than a percent (Burt al. (1997), to signify the difference between uniformity and efficiency. This method emphasizes the areas that receive the least irrigation, by only focusing on the lowest quarter. Burt et al. (1997) defined common irrigation performance measurements, which discussed standardization and clarification of irrigation definitions and quantified irrigation measurements. Although an irrigation system may have even distribution, over-irrigation can occur due to mismanagement.

The coefficient of uniformity treats over-irrigation and under-irrigation equally as compared to the mean, and can be calculated by the Christiansen formula as

$$CU = 1 - \frac{\sum_{i=1}^{n} \left| V_i - \overline{V} \right|}{\sum_{i=1}^{n} V_i} \qquad [3\text{-}2]$$

where, V_i refers to the volume in a given catch-can and $\overline{V}$ refers to the mean volume (Christiansen, 1942).

As part of a conservation program, in 1992 the Mobile Irrigation Labs (MILs) were established as a public service in Florida. The program is funded by the USDA and the individual water management districts. The Florida MILs were modeled after those operating in California and Texas. They evaluate irrigation systems conducting a series of tests over a two-hour period, measuring pump flow rates, sprinkler pressures and flow rates, and application uniformities (Micker, 1996). The MIL procedure requires 16 to 24 cans to be used, in selected irrigation zones, which is usually the largest turf area for residential tests. Table 3-1 shows the average DU_{lq} ratios from residential irrigation systems of turf in various counties in Florida acquired from annual reports within the last decade. While uniformity of irrigation systems has been measured in Florida, many of the MILs no longer measure irrigation system uniformity by catch-can tests determining DU_{lq}; therefore, there is a lack of information regarding current residential irrigation system performance and water use in the state.

The purpose of these tests was to evaluate residential irrigation system uniformity in the South Central Florida ridge, and determine typical residential equipment uniformity under controlled conditions.

Materials and Methods

The homes included in this study were located within the South Central Florida ridge. The study included 8 homes in Marion County, 9 homes in Lake County, and 10 homes in Orange County. The irrigation systems at the homes typically included stationary spray heads and gear driven rotary sprinklers for the turf and landscape areas. Spray heads and rotors were tested in this experiment since they are commonly used on turfgrass and designed to apply irrigation water as uniformly as possible. In most of the tested systems, the irrigation zones were not separated based on plant material. That is, an irrigation zone would commonly be installed to irrigate turfgrass and ornamental plants at the same time. Uniformity testing was only performed on turfgrass areas. An onsite weather station was in place to monitor wind speed, relative humidity, and temperature during testing.

In residential testing, the catch-cans were distributed around the residential turf area in either a 1.5 or 3 m square grid depending on the irrigated area size (3 m grid for lawns with an area greater than 750 m^2 and 1.5 m grid otherwise). To minimize edge effects, the grid was positioned 0.8 m from property boundaries. This resulted in 100 to 500 cans used in each test. Pressure at the two furthest points in each zone was tested with a pitot tube and pressure gauge on rotors or with a in-line pressure gauge just beneath a spray head emitter.

The control test site was located at the University of Florida (UF) Agricultural and Biological Engineering department in Gainesville, Florida. These test plots were set up to test the irrigation equipment from three different manufacturers. The tests were performed in a mowed turfgrass area without slope. The plot area for rotary sprinklers was 11.3 m x 11.3 m or 12.8 m x 12.8 m depending on equipment type and according to the manufacturer recommended spacing. The plot area for the spray heads was 4.6 m x 4.6 m according to manufacturer recommendations based on the equipment selected. Sprinklers were installed at each of the four corners of the plot area to insure spacing at 50% of manufacturers rated diameter at recommended pressure (Table 3-2). Pressure gages were installed before and after the pressure regulator entering the grid piping as well as at each nozzle.

To quantify irrigation uniformity, the catch-can method of uniformity testing was used. The catch-can method of uniformity testing is described by both the ASAE and the NRCS (ASAE, 2000 and Micker, 1996). However, the procedure used in this project differs because it tests residential sprinkler irrigation systems rather than linear move, and center pivot sprinkler systems as in the ASAE Standard and is more detailed than that of the NRCS Mobile Irrigation Lab.

For all test conditions (residential and control), 30 cm wire stem flags were used to mark the grid and were bent so as to level the catch-cans and prevent movement. The cans had an opening diameter of 15.5 cm and a depth of 20.0 cm. The irrigated area of each zone was recorded and the system was set to run for 25 min on spray zones and 45 min on rotor zones, to ensure that the average water application depth was at least 1.3 cm. At the residential test sites a sketch of the house and landscape beds was drawn to scale with the location of each can marked. Also, the type and location of each nozzle was recorded.

According to the ASAE standards (ASAE, 2000) the wind speed was measured every 30 min during the test. The standard allows testing up to 5 m/s; however, if the wind speed was above 2.5 m/s or if the distribution was affected by the wind at lower speeds, the test was discontinued. If practical, the test was performed at night to minimize evaporative losses. If night time operation was impractical. (i.e., due to homeowner concerns or storms), the test was run during early morning hours when ET was lowest. Catch-can volumes were measured immediately following the test using a 500 or 1000 mL graduated cylinder depending on catch-can volume. These procedures were followed in both the residential testing and the control testing.

Data analysis was performed using the Statistical Analysis System software (SAS Institute, Inc., 2003, version 8.02) using the GLM procedure to perform an analysis of variance. The GLM procedure enables the specification of any degree of interaction (i.e., crossed effects) and was designed for fixed effects models. The estimation of the fixed effects was based on ordinary least squares. Mean differences were determined using Duncan's Multiple Range Test at the 95% confidence level.

For the control tests at UF under ideal conditions, the cans were placed in either a 0.9 or 1.5 m square grid for spray or rotor heads, respectively and with a 0.3 m inset from the edge. The heads were all adjusted or fitted with appropriate nozzles to irrigate quarter circle arcs. The spray and rotary heads tested under ideal conditions were labeled as brand A, B, and C. For professionally installed irrigation systems in Central Florida, these three products comprise the most commonly used equipment. The spray heads with an adjustable arc (the coverage pattern is variable from part circle up to full circle) were denoted by "adj." following the letter reference. All rotors had an adjustable arc by design. As shown in Table 3-2, the spray heads were tested at low pressure (69 kPa), high pressure (414 kPa), and manufacturer recommended pressure (207 kPa). The rotor heads were tested at low pressure (207 kPa) and manufacturer recommended pressure (345 kPa or 379 kPa). Each head test was replicated 5 times at each pressure. To maintain ideal testing pressure, gages were installed in the system piping immediately following an adjustable pressure regulator and at each irrigation head. Pressure varied less than 5% between the most distant two nozzles, indicating that pressure variations were not a source of non-uniformity.

Results and Discussion

Residential Testing

The low-quarter distribution uniformities can be classified by the overall system quality ratings in Table 3-3 (IA, 2003). The uniformities of the residential systems tested in this study (Table 3-4) would be considered in the "fair" to "fail" range, with the exception of one "good". When looking at the DU_{lq} of the spray and rotor zones individually, it can be noted that the ratings of the spray zones were much lower, with half of the spray zone uniformities receiving a "fail" rating. The ratings of the rotor zones were normally distributed about the mean within the "good" to "fail" range. The mean DU_{lq} (Table 3-4) of the rotor zones was 0.49 and the mean DU_{lq} of the spray zones was 0.41, which was statistically different ($p = 0.034$).

The overall low DU_{lq} values for this study were lower than values reported by the MILs. The MIL DU_{lq} values in Table 3-1 were significantly higher, averaging 0.53 ($p = 0.02$) than the overall DU_{lq} values in Table 3-4 of 0.43. According to the overall system quality ratings in Table 3-2, two of the regions surveyed by the MIL result in an irrigation system quality rating of "good" or "very good", one other as "fair", one as "poor" and two others as “fail”. The DU_{lq} value differences were in part due to testing procedure. As stated in the previous section, the catch-can tests performed for this study were a combination of the testing methods of both the ASAE standards and the NRCS MIL guidelines. The MIL catch-can test procedure requires only 16-24 cans to be distributed centrally within one of the largest zones. The procedures performed in this study used a grid with 100-500 cans distributed evenly across the entire irrigated turf area. Consequently, edge effects and challenging design areas, such as side lawns, were included in the tests of this study. Due to the greater number of catch-cans, a larger percentage of the under-irrigated areas were also included. Despite this difference in methodologies, it is thought that the procedures used in this study provided a more realistic determination of the variation in irrigation water application depth for the entire irrigation system. If the turfgrass edges of an irrigation zone in a residential setting begin to become stressed and turf quality declines, the homeowner will likely increase the irrigation volume applied to that area. As such, it is important to include the edge areas in uniformity testing. Table 3-4 compares DU_{lq} determined with the catch-cans placed in the grid formation versus the DU_{lq} determined by using only 16-24 can samples simulating the MIL procedure on the largest turfgrass area. The uniformity results are consistently significantly higher when following the MIL method.

As previously mentioned, the MIL guidelines specify that the can placement should be in the largest area of the yard. Typically, rotar heads irrigate the largest area of the yard. Based on equipment alone, rotary heads tend to have greater uniformity (note Table 3-4). Therefore can location (i.e., center of zone vs. near edge of zone) will increase the DU_{lq} value. Since the testing in this study was more representative of actual conditions, the IA table may be unrealistic for the conditions of this study.

Mathematical calculation methods also affected the uniformity values. The coefficient of uniformity (CU) method (Table 3-4) produced higher values than the DU_{lq} method. This is because CU takes into account both over and under-irrigation, while DU_{lq} only considers the lowest quarter on the under-irrigated area. Including both the over- and under-irrigated areas resulted in an amount of mathematical equalizing.

Pressure differences across residential irrigation zones did not vary more than 10%, which is considered acceptable (Pair, 1983). As a result it was concluded that pressure variations did not substantially impact uniformity.

Control Testing

Statistical analysis of the spray and rotor head uniformities tested under ideal circumstances was compared to results from the residential system tests. The difference in uniformity between residential and control tests was mostly due to design (i.e., spacing). There was a significant difference between uniformities ($p = 0.001$) based on testing condition. The overall mean DU_{lq} of the tests performed under ideal circumstances was 0.53 compared to 0.45 on the residential systems. For the control tests, there was not a significant difference in uniformity between the rotor and spray heads. Although for the test under the ideal conditions, the rotors still performed better with a uniformity of 0.56 (Table 3-5), while the spray heads had a uniformity in 0.51 (Table 3-6)

Spray head DU_{lq} values were significantly lower at 69 kPa (low pressure) compared to the 207 kPa and 414 kPa tests. However, high pressure (407 kPa), above the pressure recommended by the manufacturers, did not result in significantly different DU_{lq}

compared to recommended pressure tests. There was an interaction between brand and pressure. From the spray head tests, brand C performed the best at recommended and high pressure with a mean DU_{lq} of 0.68 at these two pressures. The next highest Duncan letter grouping for DU_{lq} was measured under brands B at recommended (0.55) and high (0.54) pressures and A at the recommended (0.53) pressure. Low pressure significantly degraded spray head uniformity, across all brands. The poorest DU_{lq} at high pressure was measured under brand B-adj. This brand consistently had the lowest DU_{lq}, averaging 0.37 across all pressures.

The statistical analysis of the rotor head test showed significant differences in DU_{lq} between brands ($p = 0.004$); while pressure resulted in a difference at the 90% confidence level ($p = 0.090$). The spray head test statistical analysis showed that both pressure ($p = 0.001$) and brand ($p = 0.001$) had significant influence on the DU_{lq} values. The rotor heads showed moderate statistical differences across brand regardless of pressure with brand A producing the highest DU_{lq} of 0.66 and C yielding the least uniform distribution of water with a DU_{lq} of 0.46. Brand B was statistically similar to brands A and C at both pressure levels; however, differences were pronounced enough such that brands A and C were not similar.

Summary and Conclusions

The DU_{lq} values reported in this study were lower than the Irrigation Association (2003) quality ratings and the historical average MIL findings. When examining the differences between the catch-can testing procedures employed in this study to the MIL guidelines, it can be inferred that one difference was in the testing methodologies.

For the residential systems tested in this study, the low-quarter distribution uniformities classified by the overall system quality ratings would be considered in the fair to fail range, with the exception of one good. However, it should be noted that any degradation in turfgrass or plant quality on the edges of a residential site will likely result in the homeowner increasing irrigation volume to that area. Therefore, testing of the entire irrigated site including edges and irregular areas is important to define the variability in the overall irrigation system. When the uniformity of the spray and rotor zones were individually examined, the ratings of the spray zones were lower (0.41) than the ratings of the rotor zones (0.49).

Overall, the control tests under ideal conditions still resulted in poor uniformity compared to the IA (2003) ratings. Rotary sprinklers DU_{lq} averaged higher at 0.56 while spray heads averaged 0.51. The spray heads have closer spacing and a higher precipitation rate. Therefore, over-irrigation may be exacerbated in some areas, thus decreasing uniformity. The spray heads had the better uniformity when fixed quarter circle nozzles were used as opposed to adjustable arc nozzles.

Distribution uniformity is a mathematical means for explaining how evenly a system is irrigating an area. According to the IA quality ratings, the DU_{lq} values determined in this study were considered unacceptable or since the testing in this study was more representative of actual conditions, the IA table may be unrealistic for the conditions of this study. As determined from the results of this study, the DU values are subject to the testing procedure.

Sprinkler brand and pressure also affected the uniformity values. For the rotor head control tests there was a significant difference between the brands, however there was not one based on pressure at the 95% confidence level. The pressure variation was only between high and the recommended setting. The equipment will still function properly under excessive pressure conditions, however the arc and through of the nozzle may not present the correct pattern. For the spray head control tests, there was an interaction between pressure and brand and the pressure. The results from these tests concurred with the assumption that the equipment can withstand higher pressure while still providing a comparable uniformity. Low pressure had an adverse affect on the equipment functionality regardless of brand.

The trend which remained constant was that the rotary sprinkler heads create more uniform distributions than fixed spray heads. In addition, spacing the heads properly under controlled conditions resulted in higher uniformities compared to the actual residential sites. Therefore, irrigation system design is important to achieving higher irrigation uniformity distribution.

Table 3-1. Mobile Irrigation Lab turf DU_{lq} results for five counties in Florida.

County	Distribution Uniformity (DU) Average	Minimum	Maximum	Sample Size
Fort Myers (2002)	0.59	0.40	0.82	173
Hillsborough (1993)	0.48	0.11	0.71	68
Lake (2001)	0.38	0.12	0.74	64
St. Johns (2001)	0.39	0.12	0.74	64
South Dade (1993-94)	0.71	0.34	0.89	25
St. Lucie (2000)	0.64	0.38	0.8	75
St. Lucie (2001)	0.67	0.13	0.85	88
Average	0.55	0.23	0.79	80
CV	25	59	8	57

Table 3-2. Recommended pressure and radii for tested spray and rotor heads under ideal conditions according to manufacturer guidelines.

Head Type	Brand	Recommended Pressure (kPa)	Low Pressure (kPa)	High Pressure* (kPa)	Distance of Throw (m)
	A	345	207		12.8
	B	379	207		11.3
Rotary	C	345	207		11.3
	A	207	69	414	4.6
	A-adj.	207	69	414	4.6
	B	207	69	414	4.6
	B-adj.	207	69	414	4.6
Spray	C	207	69	414	4.6

*High pressure tests were only performed on the spray heads

Table 3-3. Irrigation Association overall system quality ratings, related to distribution uniformity

Quality of Irrigation System	Irrigation System Rating (ISR)	Distribution Uniformity (DUlq)
Exceptional	10	> 0.85
Excellent	9	0.75 – 0.85
Very Good	8	0.70 - 0.74
Good	7	0.60 - 0.69
Fair	5	0.50 - 0.59
Poor	3	0.40 – 0.49
Fail	< 3	< 0.40

Table 3-4. Residential system distribution uniformity catch-can test results

		CU	DU_{lq}			
County	Rep	Overall System	Overall System	Spray Head	Rotor Head	MIL Style (16-24 cans)
	1	0.60	0.44			0.54
	2	0.59	0.39	0.12	0.45	0.51
	3	0.72	0.60	0.57	0.63	0.70
	4	0.60	0.46			0.58
	5	0.65	0.47	0.51	0.49	0.54
	6	0.55	0.35	0.35		0.64
	7	0.54	0.50	0.50	0.47	0.60
Marion	8	0.55	0.39	0.39		0.45
	1	0.57	0.39	0.15	0.45	0.64
	2	0.68	0.58	0.67	0.55	0.63
	3	0.61	0.50	0.49	0.48	0.50
	4	0.60	0.42	0.16	0.49	0.42
	5	0.55	0.40		0.41	0.50
	6	0.64	0.50	0.66	0.47	0.64
	7	0.71	0.54	0.52	0.59	0.65
	8	0.52	0.33	0.41	0.32	0.82
Lake	9	0.60	0.54	0.45	0.64	0.70
	1	0.60	0.48	0.42	0.49	0.64
	2	0.57	0.38	0.33	0.50	0.51
	3	0.50	0.32	0.31	0.34	0.48
	4	0.57	0.44	0.47	0.50	0.49
	5	0.54	0.36	0.32	0.39	0.42
	6	0.50	0.34	0.23	0.44	0.65
	7	0.62	0.56	0.43	0.63	0.68
Orange	8	0.63	0.47	0.47		0.67
Mean		*0.59*	*0.45*	*0.41*	*0.49*	*0.58*

Table 3-5. Control system distribution uniformity catch-can test results for these brands of rotor heads at recommended and low pressures.

Brand of Rotor Head	Pressure[a]					
	Rec.			Low		
	DU_{lq}		Sample Size	DU_{lq}		Sample Size
A	0.68	a[b]	5	0.6	a	5
B	0.57	a	5	0.5	b	5
C	0.51	a	5	0.4	c	5
Average	0.58			0.52		

[a] High pressure tests only performed on spray heads.
[b] Duncan letters show significant difference between brands at each pressure and are head type specific (i.e., spray or rotor).

Table 3-6. Control system distribution uniformity catch-can test results for these brands of spray heads at recommended, low, and high pressures.

Brand of Spray Head	Pressure[a]								
	Rec.			Low			High		
	DU_{lq}		Sample Size	DU_{lq}		Sample Size	DU_{lq}		Sample Size
A	0.48	b[b]	5	0.39	b	5	0.50	b	5
A-adj.	0.52	b	5	0.41	ab	5	0.52	b	5
B	0.55	b	5	0.44	ab	5	0.53	b	5
B-adj.	0.38	c	5	0.37	b	5	0.37	c	5
C	0.70	a	5	0.48	a	5	0.65	a	5
Average	0.53			0.42			0.52		

[a] High pressure tests only performed on spray heads.
[b] Duncan letters show significant difference between brands at each pressure and are head type specific (i.e., spray or rotor).

CHAPTER 4
COMPARISON OF UNIFORMITY MEASUREMENTS

As competition for limited water supplies increase, irrigation must become more efficient. Irrigation efficiency defines how effectively an irrigation system supplies water to a given crop or turf area. Application efficiency can be computed as the ratio between water used beneficially and water applied and is expressed as a percentage (Burt al. (1997). In an efficient residential irrigation system, the components that must be considered are: design, scheduling, and equipment. The design of a system (i.e., spacing) will affect the uniformity of the water distribution. It is important that irrigation systems are designed to apply water evenly across a target area such as turfgrass. Even with good design, scheduling will affect how much water is applied. Residential and commercial irrigation systems typically use stationary spray heads and gear driven rotor sprinklers for the turf and landscapes.

Uniformity of water distribution measures the relative application depth over a given area. This concept can be valuable in system design and selection, and can quantify system performance. The term uniformity refers to the measure of the spatial differences between applied (or infiltrated) waters over an irrigated area. A common method which has been developed to quantify uniformity is distribution uniformity.

A time domain refectometry (TDR) device can be used to measure soil volumetric water content (VWC), by relating the time needed for an electrical signal to travel along wave guides. As opposed to the measurement of irrigation application, soil water volume is measured as a function of the volume of the bulk soil. A TDR device can be used to measure the amount of stored water in a profile or how much irrigation is required to reach a desired amount of water. The use of TDR probes is an effective nondestructive method of measuring soil moisture content.

The catch-can test requires a grid of cans to be placed across the desired testing location. When the system completed the irrigation cycle, the volume of water collected in the cans is measured and related to uniformity. The catch-can method, although not destructive, does necessitate recently mowed turfgrass and is subject to the slope of the area.

This experiment compared irrigation distribution uniformity evaluated by the use of a TDR device to the catch-can test method. The uniformities of both residential irrigation systems and controlled equipment testing were evaluated.

Materials and Methods

The tests for this study included both residential lawns and a turfgrass area used for the control irrigation testing. The residential tests were conducted with the cooperation of homeowners within the Central Florida Ridge as discussed in Chapter 1. Only spray and rotor heads (as opposed to the micoirrigated areas) were tested in this part of the experiment since they are most commonly used on turfgrass and designed to apply irrigation water as uniformly as possible. In many of the tested systems, the irrigation zones were not separated based on plant material. That is, an irrigation zone would commonly be installed to irrigate turfgrass and ornamental plants.

The control system test site was located at the University of Florida Agricultural and Biological Engineering department in Gainesville, Florida as part of a study to determine residential irrigation equipment performance parameters. These tests were performed in a mowed and maintained field without slope. The plot area for the rotor sprinklers was 11.3 m x 11.3 m or 12.8 m x 12.8 m depending on equipment type and according to the manufacturer recommended square spacing. The plot area for the spray heads was 4.6 m x 4.6 m. Nozzles were installed at each of the four corners of the plot area to insure spacing at 50% of manufacturers rated diameter at recommended pressure.

To quantify the uniformity of the irrigation systems described previously, the low-quarter distribution uniformity (DU_{lq}) value was calculated for each system test. The catch-can method of uniformity testing used for this study is a modified combination of both the ASAE and the NRCS methods (ASAE, 2000 and Micker, 1996). The modifications from the ASAE method resulted from testing residential systems rather than agriculture systems, while it is more detailed than the procedures of the NRCS Mobile Irrigation Labs. The procedure used in this project differed because residential sprinkler irrigation systems were tested rather than linear move, and center pivot sprinkler systems as in the ASAE Standard and is more detailed than that of the NRCS Mobile Irrigation Lab.

To test the irrigation systems, a grid was marked with 30 cm wire stem flags which were bent so as to level the catch-cans and prevent movement. The cans had an opening diameter of 15.5 cm and a depth of 20.0 cm. The systems were set to run for 25 min on spray zones and 45 min on rotor zones, this ensured the average water application depth was at least 1.3 cm within the catch-cans.

In the residential tests, catch-cans were distributed around the turf area in either a 1.5 or 3 meter square grid depending on the irrigated area size (3 m grid for lawns with an area greater than 750 m^2 and 1.5 m grid otherwise). To account for edge effects the grid was positioned 0.8 meters from property boundaries. For the control system tests, the cans were placed in either a 0.9 or 1.5 m square grid for spray or rotor heads respectively, and with a 0.3 m inset from the edge. The heads were all adjusted or fitted with appropriate nozzles to irrigate quarter circle arcs.

According to the ASAE standards (ASAE, 2000) the wind speed was measured every 30 min during the test. The standard allows testing up to 5 m/s; however, if the wind speed was above 2.5 m/s or if the distribution was affected by the wind at lower speeds, the test was discontinued.

TDR measurements were performed at the time of catch-can tests. Catch-can volumes were measured immediately following the test using a 500 or 1000 mL graduated cylinder depending on catch-can volume. The TDR VWC percentage was taken within 0.5 m of each catch-can to ensure similarity in measurement point and grid location. TDR measurements were taken immediately after each irrigation run cycle.

For this study the TDR device used was the Field Scout TDR 300 Soil Moisture Probe (Spectrum Technologies, Inc., Plainfield, Illinois) with 20 cm rods. The TDR device was used to determine irrigation distribution uniformity for turfgrass. The device was easy to operate and relatively nondestructive to the turfgrass area. Typically, irrigation uniformity is determined by the catch-can method, where DU_{lq} is calculated based on the volume collected in the cans. When calculating the uniformity with the TDR, the DU_{lq} was based on the soil moisture readings after irrigation.

To determine the VWC percentage, the probes of the device must be inserted into the ground. The probes were checked when inserted into the ground each time because after multiple measurements the metal probes tended to splay outward if inserted too aggressively. This movement of the probes can give a false low soil moisture reading.

Results and Discussion

The soil moisture measurements collected by the TDR ranged from 0-45% VWC. The measurements collected by the catch-cans ranged from 0-1500 mL. The methods were compared by calculating dimensionless DU_{lq}. The uniformity calculated by the soil moisture method was higher than the uniformity calculated by the catch-can method (Table 4-1). Overall the, the DU_{lq} calculated from the TDR measurements was 0.74, where the DU_{lq} from the catch-can volumes was 0.51, with an average difference of 0.22. This concurs with the findings from a similar study in Colorado (Mecham, 2001). To compare the two methods, the coefficient of variation (CV) was calculated. The smaller the CV, the smaller the scatter of data about the mean, signifying smaller variability in the data. When considering all the tests in this study, the CV of the TDR DU_{lq} was 11, where the CV of the catch-can volume DU_{lq} was 25 (Table 4-2).

The higher the DU_{lq} in the catch-can tests, the smaller the difference was between the TDR and catch-can volume uniformities. This was because the TDR uniformity was higher on average (Table 4-1) with a smaller standard deviation (0.08). The smaller standard deviation would be expected due to the smaller range of values.

There were significant differences between the uniformity values determined from the residential versus the control systems. The uniformity values for the residential locations determined from the catch-can tests averaged 0.45, and from the TDR measurements the uniformity was 0.68. For the control locations the uniformity values from the catch-can and TDR measurements were 0.54 and 0.78 respectively. The only apparent difference was with the control system equipped with rotor heads. The average rotor DU_{lq} for the catch-can volumes and TDR measurements were 0.65 and 0.75, respectively.

The TDR and catch-can volume uniformities were plotted against each other in Figure 4-1. The TDR measured moisture content DU compared to volume based DU is essentially horizontal, meaning that soil moisture content does not change predictably with a change in catch-can volume. If there were better correlation between the data, the points would surround the 1:1 line. The data however, was above this line due to the higher TDR VWC DU_{lq} values.

Table 4-2 lists the average catch-can volume and soil moisture measurements. Overall, the average volume collected per can was 271 mL, with a standard deviation of 180 mL. The average soil moisture reading was 24, with a standard deviation of only 6. The increase in variation between the measurements had an effect on the uniformity. Additionally, there were occurrences of volume measurement at or near 0 mL, where the soil moisture readings were not below 7%. It can be observed, in Figure 4-2, that there is not a strong correlation between increased soil moisture VWC measurements and catch-can volume measurements.

The effects of the irrigation event were taken into consideration. The average soil moisture uniformity calculated prior to the irrigation event was 0.55, and after the irrigation event was 0.64.

Summary and Conclusions

This study compared irrigation distribution uniformity values determined by the catch-can test to those determined by soil moisture measurements. The TDR device would allow for a quick and easy method for calculating system uniformity, as there is no significant set up time as with the catch-can tests.

One of the major differences between the uniformity results calculated by the two methods was from the scale of the measurements. The catch-can scale was larger than the

TDR scale, which can account for a great deal of variation due to an increase in standard deviation. The methods were compared in the DU_{lq} values to help diminish the range dissimilarity. It must be noted that in addition to the scales differing, only the catch-can volume measurements actually included the minimum (0 mL) and maximum (1500 mL) values. Although the soil moisture measurements could range from 0-45%, the actual measurement range was typically from 7-35%. When collecting the measurements, a large volume of water collected in a catch-can was typically correlated with a high TDR VWC reading.

Ultimately, there was not enough correlation between the DU_{lq} values determined by the TDR device and the catch-can method. Therefore the TDR device can not be used in place of the catch-cans to determine the uniformity of a system. However, perhaps the uniformity values determined from the catch-can tests are not the most important measure of uniformity, because the measurements ignore the effects of the soil properties, which do in turn affect the turfgrass. The TDR equipment may not be sensitive enough to detect the soil water changes. The soil properties affect the uniformity results. The redistribution of the soil water may lead to a higher DU from the soil water measurements compared to catch-can measurements.

Table 4-1. Uniformity values from both the catch-can tests and the TDR values.

Sample	Method	Average	Standard Deviation	Coefficient of Variation	Point Difference
	Vol. DU_{lq}	0.45	0.09	20	
Residential	VWC DU_{lq}	0.68	0.08	12	0.20
	Vol. DU_{lq}	0.54	0.14	25	
Control	VWC DU_{lq}	0.77	0.07	9	0.22
	Vol. DU_{lq}	0.51	0.13	25	
Overall	VWC DU_{lq}	0.74	0.08	11	0.22

Table 4-2. Measurement results from both the catch-can and the TDR tests.

Sample	Method	Average	Standard Deviation	Coefficient of Variation
	Volume (mL)	294	108	37
Residential	VWC %	22	4	19
	Volume (mL)	259	207	80
Control	VWC %	25	6	25
	Volume (mL)	271	180	66
Overall	VWC %	24	6	24

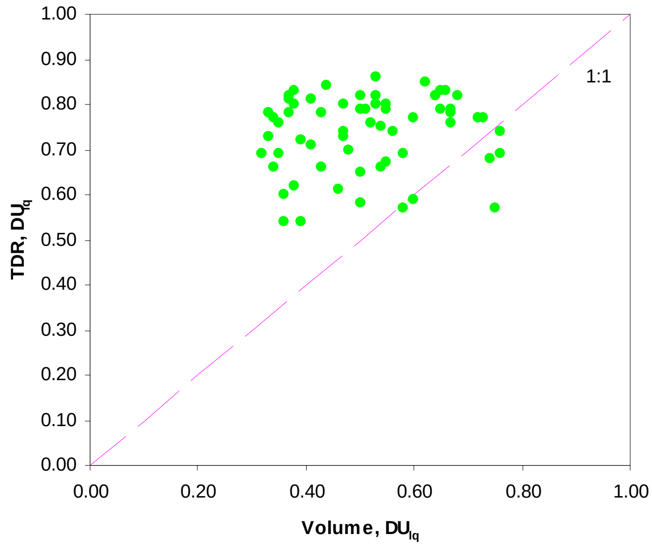

Figure 4-1. Comparison of DU_{lq} values calculated from both the TDR soil moisture and catch-can tests.

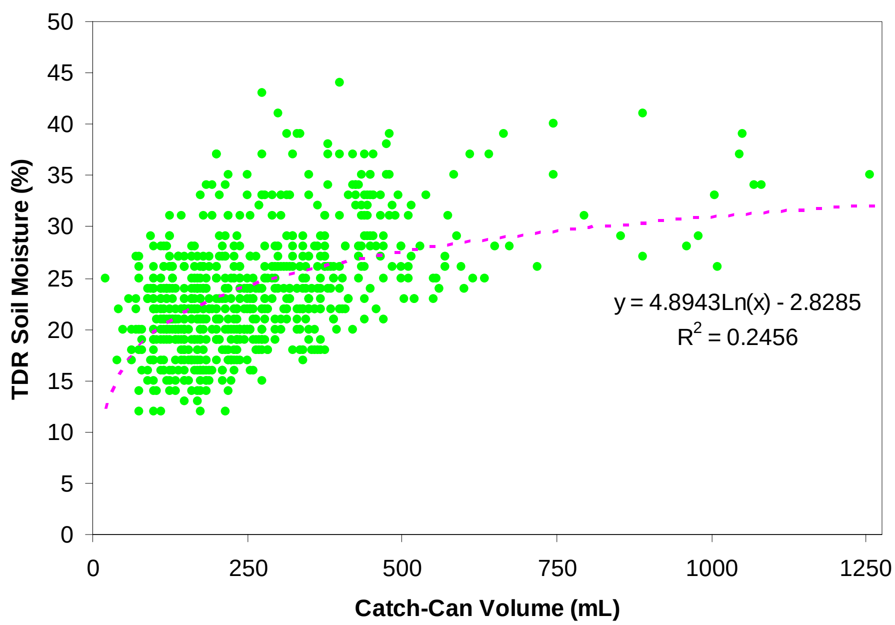

Figure 4-2. Comparison of soil moisture to can volume measurements taken during uniformity tests.

CHAPTER 5
CONCLUSIONS

The goal of this project was to evaluate residential irrigation water use and uniformity. The research conducted for this study assessed residential irrigation water use and total water input, taking rainfall and evapotranspiration (ET) into account from January 2002 through May 2004. Both residential systems and individual equipment distribution uniformities were measured. These tests were used to compare catch-can volume to soil moisture uniformity testing methods.

To determine water use for residential irrigation systems, irrigation water consumption was monitored on a monthly basis. The homes were separated into three treatments, each relating to the type of system (typical or designed) and the controller settings (homeowner controlled or adjusted based on historical evapotranspiration rates). T1 consisted of existing irrigation systems and typical landscape plantings, where the homeowner controlled the irrigation scheduling. T2 also consisted of existing irrigation systems and typical landscape plantings, but the irrigation scheduling was adjusted based on historical ET. T3 consisted of an irrigation system designed according to specifications for optimal efficiency and scheduled based on historical ET. T3 also included a landscape design that minimized turfgrass and maximized the use of native drought tolerant plants. To further achieve water savings in T3, the landscape plants were irrigated by microirrigation as opposed to the standard spray and rotor heads.

The average residential irrigation system consumed 63% of the total water used in the home. The average monthly irrigation water depths for T1, T2, and T3 were 146 mm, 116 mm, and 86 mm respectively.

Adjusting the controller run times and incorporating microirrigation into the bedding areas (T3) did result in less water use. In the summer months, all the treatments required similar water amounts. However, in the winter months, when the turfgrass went dormant, very little irrigation was necessary. In spring months, T1 consumed the most irrigation water 179 mm, and T3 consuming the least, 94 mm. This was due to the monthly adjustments of irrigation times and because the microirrigated areas on T3 homes used much less volume than if those areas were sprinkler irrigated. In the fall months, T1 and T2 consumed similar amounts, 155 mm and 148 mm, while T3 consumed significantly less (102 mm).

Most of the homes still tended to over-irrigate. The over-irrigation resulted from poor uniformity and unnecessarily high irrigation run times. In this study, the amount of over irrigation was determined by comparing the amount of water applied (irrigation and effective rainfall) to the amount of water required (ET). The amount of over irrigation was especially high in the winter months. Irrigation alone was consistently higher than the crop water requirements.

Water use could also be affected by the functionality and setting of rain sensors. Irrigation during periods of rainfall implies malfunctioned or improperly adjusted rain sensors connected to the irrigation controllers. However, rainfall could occur immediately after an irrigation event. In efforts to increase irrigation efficiency, the irrigation amounts should be adjusted seasonally, the system must be properly maintained, and should be designed to achieve acceptable distribution uniformity (DU_{lq}).

The measured residential and control irrigation system uniformity values were lower than industry recommendations. The average overall system residential DU_{lq} was 0.45. When the uniformity of the spray and rotor zones were individually examined, the ratings of the spray zones (0.41) were lower than the ratings of the rotor zones (0.49). Although the tests under controlled conditions yielded results better than the residential tests, the uniformities were still low. The rotary sprinklers DU_{lq} averaged higher than spray heads with average DU_{lq} of 0.56 and 0.51 respectively. The spray heads had better uniformity when fixed quarter circle nozzles were used as opposed to adjustable arc nozzles.

Sprinkler brand and pressure also affected the uniformity values. Low pressure had an adverse affect on the equipment functionality regardless of brand. However, there was an interaction between brand and pressure in spray head controlled testing, but certain brands tended to perform better regardless of pressure. Both rotor and spray heads, performed similarly when tested at the recommended and high pressures. The controlled tests resulted in higher uniformity, regardless of pressure (0.51) versus the residential tests (0.45). Thus irrigation design and spacing of the heads, positively affects the uniformity.

Distribution uniformity values are subject to the testing procedure. The methods for testing uniformity were compared by determining the DU_{lq} from the catch-can volume measurements and the soil moisture at each measurement point. A Time Domain Reflectometry (TDR) device was used to determine the soil moisture. The TDR, which can be easily inserted into the ground at each measurement point, is is much quicker than catch can tests for determining uniformity. Overall, the uniformities calculated by the soil moisture measurements were higher (0.74) than those calculated by the catch-can volumes (0.51). The uniformity values determined from the catch-can tests may not be a proper representation of actual soil uniformity. The volume measurements ignore the effects of the soil properties, which have an impact on the turfgrass quality. The TDR equipment may not be sensitive enough to detect the soil water redistribution. The actual soil water movement may lead to a higher DU than the catch-can measurements predicts.

In the future, residential irrigation system audits may not rely solely on catch-can tests to measure distribution uniformity. The surface distribution seems to differ from the actual soil moisture. The MIL procedure tended to yield higher uniformities, but the procedure ignores edge effects and uses less measurement samples. However, the grid formation outlined in the procedures of this study may be too stringent, and suggest DU values lower than the actual uniformity.

Microirrigation increased irrigation water savings. Many contractors and homeowners are reluctant to install microirrigation components. The microirrigation required more maintenance and was more costly to install. However, the majority of the homeowners with the microirrigation incorporated into their systems (T3) were quite pleased with the results. Additionally, once the landscape plants became established the microirrigation equipment was almost unnoticeable.

The observations and results found from this research will lead to a better understanding of residential irrigation uniformity and water use, which will aid in determining efficient residential irrigation. Upon interaction with the homeowners cooperating in this research, there were vast misconceptions about irrigation water use and scheduling. Changing the irrigation controller run times based on season was vaguely understood and the concept of significantly reducing the water in the winter time was initially met with some confusion. Some of the homeowners in the treatments 2 and 3 are now avid water conversationalists after becoming aware of the excessive over-irrigation that can be avoided.

APPENDIX A
PHOTOGRAPHS

The following groups of photographs were taken during the period of data collection for this study, from January 2002 through May 2004.

Figure A-1. Flow meter

Figure A-2. Weather station

Figure A-3. Control system spray head with pressure gage

Figure A-4. Control system catch-can test

Figure A-5. Residential system catch-can test

Figure A-6. Setup of catch-can grid formation

Figure A-7. Catch-can grid formation around bedded area

Figure A-8. Measure catch-can volume with graduated cylinders

Figure A-9. Turfgrass area with high turf quality rating

Figure A-10. Turfgrass area with low turf quality rating

A

B

Figure A-11. Sample cooperator homes from each treatment in Marion County. A) T1. B) T2. C) T3. D) Another T3.

C

D

Figure A-11. Continued

A

B

Figure A-12. Sample cooperator homes from each treatment in Lake County. A) T1. B) T2. C) T3. D) Another T3.

C

D

Figure A-12. Continued

A

B

Figure A-13. Sample cooperator homes from each treatment in Orange County. A) T1. B) T2. C) T3. D) Another T3.

C

D

Figure A-13. Continued

APPENDIX B
STATISTICAL ANALYSIS

The following is the SAS output text files for the statistical analysis performed.

```
                    OVERVIEW OF WATER USE STATISTICS
                            The GLM Procedure
                         Class Level Information
             Class         Levels    Values
             tmt                3    T1 T2 T3
             season             4    Fall Spring Summer Winter
             year               3    Y1 Y2 Y3
             loc                3    HH OC SC
                   Number of Observations Read         708
                   Number of Observations Used         581
Dependent Variable: mm
                                        Sum of
 Source                      DF        Squares     Mean Square    F Value    Pr > F
 Model                       23     1290736.388       56118.973      13.78    <.0001
 Error                      557     2269192.814        4073.955
 Corrected Total            580     3559929.201
               R-Square     Coeff Var      Root MSE       mm Mean
               0.362574      53.88991      63.82754      118.4406
 Source                      DF     Type III SS     Mean Square    F Value    Pr > F
 tmt                          2     140934.3261      70467.1631      17.30    <.0001
 season                       3     248629.7489      82876.5830      20.34    <.0001
 year                         2     121068.6074      60534.3037      14.86    <.0001
 tmt*season                   6      48040.4748       8006.7458       1.97    0.0687
 tmt*year                     4      80888.7765      20222.1941       4.96    0.0006
 tmt(loc)                     6     344599.2220      57433.2037      14.10    <.0001

                        Duncan's Multiple Range Test for mm
       NOTE: This test controls the Type I comparisonwise error rate, not the
                             experimentwise error rate.
                        Alpha                            0.05
                        Error Degrees of Freedom          557
                        Error Mean Square            4073.955
                        Harmonic Mean of Cell Sizes  189.8242
                           NOTE: Cell sizes are not equal.
                        Number of Means          2          3
                        Critical Range       12.87      13.55
             Means with the same letter are not significantly different.
              Duncan Grouping          Mean      N    tmt
                          A         146.005    198    T1
                          B         116.866    224    T2
                          C          86.333    159    T3
```

Alpha	0.05
Error Degrees of Freedom	557
Error Mean Square	4073.955
Harmonic Mean of Cell Sizes	142.5793

NOTE: Cell sizes are not equal.

Number of Means	2	3	4
Critical Range	14.85	15.63	16.16

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	season
A	138.071	140	Fall
A	137.227	176	Spring
B	116.967	120	Summer
C	77.903	145	Winter

Alpha	0.05
Error Degrees of Freedom	557
Error Mean Square	4073.955
Harmonic Mean of Cell Sizes	175.4245

NOTE: Cell sizes are not equal.

Number of Means	2	3
Critical Range	13.39	14.09

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	year
A	155.185	135	Y1
B	107.352	162	Y3
B	107.299	284	Y2

WATER USE SORTED BY SEASON (Fall)

The GLM Procedure

Class Level Information

Class	Levels	Values
tmt	3	T1 T2 T3

Number of Observations Read 162

Number of Observations Used 140

Dependent Variable: mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	68119.0104	34059.5052	7.41	0.0009
Error	137	629962.2753	4598.2648		
Corrected Total	139	698081.2857			

R-Square	Coeff Var	Root MSE	mm Mean
0.097580	49.11263	67.81051	138.0714

Source	DF	Type III SS	Mean Square	F Value	Pr > F
tmt	2	68119.01037	34059.50519	7.41	0.0009

Duncan's Multiple Range Test for mm

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	137
Error Mean Square	4598.265
Harmonic Mean of Cell Sizes	45.6846

NOTE: Cell sizes are not equal.

Number of Means	2	3
Critical Range	28.06	29.53

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	tmt
A	155.38	48	T1
A	147.85	54	T2
B	102.32	38	T3

WATER USE SORTED BY SEASON (Spring)

The GLM Procedure

Class Level Information

Class	Levels	Values
tmt	3	T1 T2 T3

Number of Observations Read 219

Number of Observations Used 176

Dependent Variable: mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	197383.354	98691.677	15.47	<.0001
Error	173	1103675.555	6379.627		
Corrected Total	175	1301058.909			

R-Square	Coeff Var	Root MSE	mm Mean
0.151710	58.20459	79.87257	137.2273

Source	DF	Type III SS	Mean Square	F Value	Pr > F
tmt	2	197383.3542	98691.6771	15.47	<.0001

Duncan's Multiple Range Test for mm

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	173
Error Mean Square	6379.627
Harmonic Mean of Cell Sizes	57.83185

NOTE: Cell sizes are not equal.

Number of Means	2	3
Critical Range	29.32	30.86

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	tmt
A	179.17	59	T1
B	132.30	67	T2
C	94.34	50	T3

WATER USE SORTED BY SEASON (Summer)

The GLM Procedure

Class Level Information

Class	Levels	Values
tmt	3	T1 T2 T3

Number of Observations Read 162

Number of Observations Used 120

Dependent Variable: mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	35434.9238	17717.4619	3.08	0.0499
Error	117	673766.9429	5758.6918		
Corrected Total	119	709201.8667			

R-Square	Coeff Var	Root MSE	mm Mean
0.049965	64.87835	75.88604	116.9667

Source	DF	Type III SS	Mean Square	F Value	Pr > F
tmt	2	35434.92381	17717.46190	3.08	0.0499

Duncan's Multiple Range Test for mm

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	117
Error Mean Square	5758.692
Harmonic Mean of Cell Sizes	38.47328

NOTE: Cell sizes are not equal.

Number of Means	2	3
Critical Range	34.27	36.06

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	tmt
	A	139.02	42	T1
B	A	110.75	48	T2
B		96.03	30	T3

WATER USE SORTED BY SEASON (Winter)

The GLM Procedure

Class Level Information

Class	Levels	Values
tmt	3	T1 T2 T3

Number of Observations Read 165

Number of Observations Used 145

Dependent Variable: mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	54047.1816	27023.5908	8.66	0.0003
Error	142	442937.4666	3119.2779		
Corrected Total	144	496984.6483			

R-Square	Coeff Var	Root MSE	mm Mean
0.108750	71.69194	55.85050	77.90345

Source	DF	Type III SS	Mean Square	F Value	Pr > F
tmt	2	54047.18164	27023.59082	8.66	0.0003

Duncan's Multiple Range Test for mm

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	142
Error Mean Square	3119.278
Harmonic Mean of Cell Sizes	47.634

NOTE: Cell sizes are not equal.

Number of Means	2	3
Critical Range	22.62	23.81

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	tmt
A	102.88	49	T1
B	72.98	55	T2
B			
B	54.66	41	T3

WATER USE SORTED BY YEAR (Y2)

The GLM Procedure

Class Level Information

Class	Levels	Values
tmt	3	T1 T2 T3
season	4	Fall Spring Summer Winter

Number of Observations Read	324
Number of Observations Used	284

Dependent Variable: mm

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	256997.215	23363.383	6.72	<.0001
Error	272	945824.345	3477.295		
Corrected Total	283	1202821.560			

R-Square	Coeff Var	Root MSE	mm Mean
0.213662	54.95711	58.96860	107.2993

Source	DF	Type III SS	Mean Square	F Value	Pr > F
tmt	2	156270.7198	78135.3599	22.47	<.0001
season	3	54353.6781	18117.8927	5.21	0.0016
tmt*season	6	20698.8448	3449.8075	0.99	0.4309

Duncan's Multiple Range Test for mm

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	272
Error Mean Square	3477.295
Harmonic Mean of Cell Sizes	93.23741

NOTE: Cell sizes are not equal.

Number of Means	2	3
Critical Range	17.00	17.90

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	tmt
A	140.573	96	T1
B	94.380	108	T2
B	84.813	80	T3

Alpha	0.05
Error Degrees of Freedom	272
Error Mean Square	3477.295
Harmonic Mean of Cell Sizes	70.22526

NOTE: Cell sizes are not equal.

Number of Means	2	3	4
Critical Range	19.59	20.62	21.31

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	season
A	124.303	66	Spring
A	112.556	81	Fall
A	107.453	75	Summer
B	82.145	62	Winter

WATER USE SAS CODE

```
options nodate nonumber center formdlim="*"linesize=85;
data mm;
input tmt$ year$ month$ season$ loc$ mm @@;
cards;
/* Data is inputted here */
;
data mm; set mm;
proc glm data=mm;
title 'OVERVIEW OF WATER USE STATISTICS';
class tmt season year loc;
model mm = tmt season year season*tmt year*tmt tmt(loc)/ss3;
test h=loc e=tmt(loc);
means tmt/duncan;
means season/duncan;
means year/duncan;
means loc/duncan e=tmt(loc);
run;
data mm3; set mm;
proc sort data=mm3; by season;
proc glm data=mm3; by season;
title 'WATER USE SORTED BY SEASON';
class tmt;
model mm = tmt/ss3;
means tmt/duncan;
run;
data mm4; set mm (where=(year='Y2'));
proc glm data=mm4; by year;
title 'WATER USE SORTED BY YEAR';
class tmt season;
model mm = tmt season season*tmt/ss3;
means tmt/duncan;
means season/duncan;
run;
```

DIFFERENCE BETWEEN ZONES FOR BOTH RESIDENTIAL AND CONTROL TESTS AT REGULAR PRESSURE

The GLM Procedure

Class Level Information

Class	Levels	Values
study	2	control resident
rep	6	1 2 3 4 5 6
zone	2	R S

Number of Observations Read	92
Number of Observations Used	82

Dependent Variable: du

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	12	0.55746706	0.04645559	3.11	0.0014
Error	69	1.03058172	0.01493597		
Corrected Total	81	1.58804878			

R-Square	Coeff Var	Root MSE	du Mean
0.351039	24.69554	0.122213	0.494878

Source	DF	Type III SS	Mean Square	F Value	Pr > F
study	1	0.28393850	0.28393850	19.01	<.0001
rep(study)	9	0.23677843	0.02630871	1.76	0.0917
zone	1	0.10334447	0.10334447	6.92	0.0105
study*zone	1	0.00373972	0.00373972	0.25	0.6184

Tests of Hypotheses Using the Type III MS for rep(study) as an Error Term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
zone	1	0.10334447	0.10334447	3.93	0.0788

Duncan's Multiple Range Test for du

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	9
Error Mean Square	0.026309
Harmonic Mean of Cell Sizes	40.97561

NOTE: Cell sizes are not equal.

Number of Means	2
Critical Range	.08106

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	study
A	0.54800	40	control
B	0.44429	42	resident

Alpha	0.05
Error Degrees of Freedom	69
Error Mean Square	0.014936
Harmonic Mean of Cell Sizes	40.12195

NOTE: Cell sizes are not equal.

Number of Means	2
Critical Range	.05444

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	zone
A	0.52857	35	R
B	0.46979	47	S

DIFFERENCE BETWEEM ZONES AND LOCATION FOR RESIDENTIAL STUDY AT REGULAR PRESSURE

The GLM Procedure

Class Level Information

Class	Levels	Values
zone	2	R S
rep	6	1 2 3 4 5 6
loc	3	l m o

Number of Observations Read 92

Number of Observations Used 42

Dependent Variable: du

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	19	0.39627950	0.02085682	1.54	0.1643
Error	22	0.29774907	0.01353405		
Corrected Total	41	0.69402857			

R-Square	Coeff Var	Root MSE	du Mean
0.570984	26.18494	0.116336	0.444286

Source	DF	Type III SS	Mean Square	F Value	Pr > F
zone	1	0.07399772	0.07399772	5.47	0.0289
loc	2	0.02185570	0.01092785	0.81	0.4588
zone*loc	2	0.00376647	0.00188324	0.14	0.8709
rep(loc)	14	0.30645415	0.02188958	1.62	0.1516

Tests of Hypotheses Using the Type III MS for rep(loc) as an Error Term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
loc	2	0.02185570	0.01092785	0.50	0.6174

Duncan's Multiple Range Test for du

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	22
Error Mean Square	0.013534
Harmonic Mean of Cell Sizes	20.95238

NOTE: Cell sizes are not equal.

Number of Means	2
Critical Range	.07454

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	zone
A	0.48650	20	R
B	0.40591	22	S

Alpha	0.05
Error Degrees of Freedom	14
Error Mean Square	0.02189
Harmonic Mean of Cell Sizes	13.84615

NOTE: Cell sizes are not equal.

Number of Means	2	3
Critical Range	.1206	.1264

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	loc
A	0.46750	12	m
A	0.45200	15	l
A	0.41800	15	o

DIFFERENCE BETWEEN ZONES FOR CONTROL STUDY AT REGULAR PRESSURE

The GLM Procedure

Class Level Information

Class	Levels	Values
brand	8	H HA HS R RQ RV T TQ
rep	5	1 2 3 4 5
zone	2	R S

Number of Observations Read 92

Number of Observations Used 40

Dependent Variable: du

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	0.39931000	0.03630091	3.71	0.0025
Error	28	0.27433000	0.00979750		
Corrected Total	39	0.67364000			

R-Square	Coeff Var	Root MSE	du Mean
0.592765	18.06247	0.098982	0.548000

Source	DF	Type III SS	Mean Square	F Value	Pr > F
zone	1	0.03226667	0.03226667	3.29	0.0803
brand(zone)	6	0.34385333	0.05730889	5.85	0.0005
rep	4	0.02319000	0.00579750	0.59	0.6714

Tests of Hypotheses Using the Type III MS for brand(zone) as an Error Term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
zone	1	0.03226667	0.03226667	0.56	0.4814

Duncan's Multiple Range Test for du

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	6
Error Mean Square	0.057309
Harmonic Mean of Cell Sizes	18.75

NOTE: Cell sizes are not equal.

Number of Means	2
Critical Range	.1913

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	zone
A	0.58467	15	R
A	0.52600	25	S

DIFFERENCE BETEWEEN BRANDS AND PRESSURE FOR CONTROL TESTS - ROTOR ZONES

The GLM Procedure

Class Level Information

Class	Levels	Values
brand	3	H R T
pressure	2	L R
rep	5	1 2 3 4 5

Number of Observations Read 56

Number of Observations Used 30

Dependent Variable: du

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	0.28491000	0.03165667	3.63	0.0078
Error	20	0.17442667	0.00872133		
Corrected Total	29	0.45933667			

R-Square	Coeff Var	Root MSE	du Mean
0.620264	16.84692	0.093388	0.554333

Source	DF	Type III SS	Mean Square	F Value	Pr > F
brand	2	0.20444667	0.10222333	11.72	0.0004
pressure	1	0.02760333	0.02760333	3.17	0.0904
brand*pressure	2	0.00580667	0.00290333	0.33	0.7207
rep	4	0.04705333	0.01176333	1.35	0.2868

Duncan's Multiple Range Test for du

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	20
Error Mean Square	0.008721

Number of Means	2	3
Critical Range	.08712	.09145

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	brand
A	0.65800	10	H
B	0.54900	10	R
C	0.45600	10	T

Alpha	0.05
Error Degrees of Freedom	20
Error Mean Square	0.008721
Number of Means	2
Critical Range	.07113

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	pressure
A	0.58467	15	R
A	0.52400	15	L

Least Squares Means

brand	pressure	du LSMEAN	LSMEAN Number
H	L	0.63800000	1
H	R	0.67800000	2
R	L	0.52800000	3
R	R	0.57000000	4
T	L	0.40600000	5
T	R	0.50600000	6

Least Squares Means for effect brand*pressure
Pr > |t| for H0: LSMean(i)=LSMean(j)
Dependent Variable: du

i/j	1	2	3	4	5	6
1		0.5060	0.0773	0.2632	0.0008	0.0370
2	0.5060		0.0195	0.0824	0.0002	0.0086
3	0.0773	0.0195		0.4852	0.0521	0.7135
4	0.2632	0.0824	0.4852		0.0116	0.2914
5	0.0008	0.0002	0.0521	0.0116		0.1060
6	0.0370	0.0086	0.7135	0.2914	0.1060	

NOTE: To ensure overall protection level, only probabilities associated with pre-planned comparisons should be used.

DIFFERENCE BETEWEEN BRANDS AND PRESSURE FOR CONTROL TESTS - SPRAY ZONES

The GLM Procedure

Class Level Information

Class	Levels	Values
brand	5	HA HS RQ RV TQ
pressure	3	H L R
rep	5	1 2 3 4 5

Number of Observations Read 101

Number of Observations Used 75

Dependent Variable: du

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	18	0.69422667	0.03856815	9.56	<.0001
Error	56	0.22584000	0.00403286		
Corrected Total	74	0.92006667			

R-Square	Coeff Var	Root MSE	du Mean
0.754540	13.08478	0.063505	0.485333

Source	DF	Type III SS	Mean Square	F Value	Pr > F
brand	4	0.44870667	0.11217667	27.82	<.0001
pressure	2	0.17817867	0.08908933	22.09	<.0001
brand*pressure	8	0.06434133	0.00804267	1.99	0.0639
rep	4	0.00300000	0.00075000	0.19	0.9448

Duncan's Multiple Range Test for du

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	56
Error Mean Square	0.004033

Number of Means	2	3	4	5
Critical Range	.04645	.04886	.05045	.05161

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	brand
A	0.61000	15	TQ
B	0.50533	15	RQ
B	0.48400	15	HA
B	0.45667	15	HS
C	0.37067	15	RV

Alpha	0.05
Error Degrees of Freedom	56
Error Mean Square	0.004033

Number of Means	2	3
Critical Range	.03598	.03785

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	pressure
A	0.52600	25	R
A	0.51320	25	H
B	0.41680	25	L

Least Squares Means

brand	pressure	du LSMEAN	LSMEAN Number
HA	H	0.52000000	1
HA	L	0.40800000	2
HA	R	0.52400000	3
HS	H	0.49600000	4
HS	L	0.39000000	5
HS	R	0.48400000	6
RQ	H	0.53400000	7
RQ	L	0.43600000	8
RQ	R	0.54600000	9
RV	H	0.36600000	10
RV	L	0.36800000	11
RV	R	0.37800000	12
TQ	H	0.65000000	13
TQ	L	0.48200000	14
TQ	R	0.69800000	15

Least Squares Means for effect brand*pressure
Pr > |t| for H0: LSMean(i)=LSMean(j)
Dependent Variable: du

i/j	1	2	3	4	5	6	7	8
1		0.0072	0.9210	0.5525	0.0020	0.3739	0.7287	0.0410
2	0.0072		0.0055	0.0326	0.6558	0.0636	0.0027	0.4886
3	0.9210	0.0055		0.4886	0.0015	0.3236	0.8043	0.0326
4	0.5525	0.0326	0.4886		0.0107	0.7662	0.3482	0.1408
5	0.0020	0.6558	0.0015	0.0107		0.0229	0.0007	0.2570
6	0.3739	0.0636	0.3236	0.7662	0.0229		0.2184	0.2371
7	0.7287	0.0027	0.8043	0.3482	0.0007	0.2184		0.0179
8	0.0410	0.4886	0.0326	0.1408	0.2570	0.2371	0.0179	
9	0.5201	0.0011	0.5860	0.2184	0.0003	0.1283	0.7662	0.0083
10	0.0003	0.3002	0.0002	0.0020	0.5525	0.0048	0.0001	0.0868
11	0.0004	0.3236	0.0003	0.0024	0.5860	0.0055	0.0001	0.0960
12	0.0008	0.4582	0.0006	0.0048	0.7662	0.0107	0.0003	0.1543
13	0.0020	<.0001	0.0027	0.0003	<.0001	0.0001	0.0055	<.0001
14	0.3482	0.0707	0.3002	0.7287	0.0258	0.9605	0.2007	0.2570
15	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.0001	<.0001

i/j	9	10	11	12	13	14	15
1	0.5201	0.0003	0.0004	0.0008	0.0020	0.3482	<.0001
2	0.0011	0.3002	0.3236	0.4582	<.0001	0.0707	<.0001
3	0.5860	0.0002	0.0003	0.0006	0.0027	0.3002	<.0001
4	0.2184	0.0020	0.0024	0.0048	0.0003	0.7287	<.0001
5	0.0003	0.5525	0.5860	0.7662	<.0001	0.0258	<.0001
6	0.1283	0.0048	0.0055	0.0107	0.0001	0.9605	<.0001

i/j	9	10	11	12	13	14	15
7	0.7662	0.0001	0.0001	0.0003	0.0055	0.2007	0.0001
8	0.0083	0.0868	0.0960	0.1543	<.0001	0.2570	<.0001
9		<.0001	<.0001	0.0001	0.0122	0.1167	0.0004
10	<.0001		0.9605	0.7662	<.0001	0.0055	<.0001
11	<.0001	0.9605		0.8043	<.0001	0.0063	<.0001
12	0.0001	0.7662	0.8043		<.0001	0.0122	<.0001
13	0.0122	<.0001	<.0001	<.0001		0.0001	0.2371
14	0.1167	0.0055	0.0063	0.0122	0.0001		<.0001
15	0.0004	<.0001	<.0001	<.0001	0.2371	<.0001	

DIFFERENCE BETEWEEN BRANDS FOR CONTROL TESTS -SPRAY ZONES AT EACH PRESSURE (High)

The GLM Procedure

Class Level Information

Class	Levels	Values
brand	5	HA HS RQ RV TQ
rep	5	1 2 3 4 5

Number of Observations Read 25

Number of Observations Used 25

Dependent Variable: du

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	0.21620800	0.02702600	9.93	<.0001
Error	16	0.04353600	0.00272100		
Corrected Total	24	0.25974400			

R-Square	Coeff Var	Root MSE	du Mean
0.832389	10.16430	0.052163	0.513200

Source	DF	Type III SS	Mean Square	F Value	Pr > F
brand	4	0.20578400	0.05144600	18.91	<.0001
rep	4	0.01042400	0.00260600	0.96	0.4571

Duncan's Multiple Range Test for du

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	16
Error Mean Square	0.002721

Number of Means	2	3	4	5
Critical Range	.06994	.07334	.07547	.07692

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	brand
A	0.65000	5	TQ
B	0.53400	5	RQ
B	0.52000	5	HA
B	0.49600	5	HS
C	0.36600	5	RV

DIFFERENCE BETEWEEN BRANDS FOR CONTROL TESTS -SPRAY ZONES AT EACH PRESSURE (Low)

The GLM Procedure

Class Level Information

Class	Levels	Values
brand	5	HA HS RQ RV TQ
rep	5	1 2 3 4 5

Number of Observations Read 25

Number of Observations Used 25

Dependent Variable: du

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	0.04148800	0.00518600	1.31	0.3074
Error	16	0.06345600	0.00396600		
Corrected Total	24	0.10494400			

R-Square	Coeff Var	Root MSE	du Mean
0.395335	15.10945	0.062976	0.416800

Source	DF	Type III SS	Mean Square	F Value	Pr > F
brand	4	0.03898400	0.00974600	2.46	0.0877
rep	4	0.00250400	0.00062600	0.16	0.9566

Duncan's Multiple Range Test for du

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	16
Error Mean Square	0.003966

Number of Means	2	3	4	5
Critical Range	.08444	.08854	.09111	.09287

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	brand
	A	0.48200	5	TQ
B	A	0.43600	5	RQ
B	A	0.40800	5	HA
B		0.39000	5	HS
B		0.36800	5	RV

DIFFERENCE BETEWEEN BRANDS FOR CONTROL TESTS -SPRAY ZONES AT EACH PRESSURE (Recommended)

The GLM Procedure

Class Level Information

Class	Levels	Values
brand	5	HA HS RQ RV TQ
rep	5	1 2 3 4 5

Number of Observations Read	51
Number of Observations Used	25

Dependent Variable: du

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	0.28036000	0.03504500	5.79	0.0014
Error	16	0.09684000	0.00605250		
Corrected Total	24	0.37720000			

R-Square	Coeff Var	Root MSE	du Mean
0.743266	14.79046	0.077798	0.526000

Source	DF	Type III SS	Mean Square	F Value	Pr > F
brand	4	0.26828000	0.06707000	11.08	0.0002
rep	4	0.01208000	0.00302000	0.50	0.7369

Duncan's Multiple Range Test for du

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	16
Error Mean Square	0.006052

Number of Means	2	3	4	5
Critical Range	.1043	.1094	.1126	.1147

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	brand
A	0.69800	5	TQ
B	0.54600	5	RQ
B	0.52400	5	HA
B	0.48400	5	HS
C	0.37800	5	RV

DIFFERENCE BETEWEEN BRANDS FOR CONTROL TESTS -ROTOR ZONES AT EACH PRESSURE (Low)

The GLM Procedure

Class Level Information

Class	Levels	Values
brand	3	H R T
rep	5	1 2 3 4 5

Number of Observations Read 15

Number of Observations Used 15

Dependent Variable: du

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	0.14170667	0.02361778	7.31	0.0065
Error	8	0.02585333	0.00323167		
Corrected Total	14	0.16756000			

R-Square	Coeff Var	Root MSE	du Mean
0.845707	10.84881	0.056848	0.524000

Source	DF	Type III SS	Mean Square	F Value	Pr > F
brand	2	0.13468000	0.06734000	20.84	0.0007
rep	4	0.00702667	0.00175667	0.54	0.7090

Duncan's Multiple Range Test for du

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	8
Error Mean Square	0.003232

Number of Means	2	3
Critical Range	.08291	.08640

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	brand
A	0.63800	5	H
B	0.52800	5	R
C	0.40600	5	T

DIFFERENCE BETEWEEN BRANDS FOR CONTROL TESTS -ROTOR ZONES AT EACH PRESSURE (Recommended)

The GLM Procedure

Class Level Information

Class	Levels	Values
brand	3	H R T
rep	5	1 2 3 4 5

Number of Observations Read 41

Number of Observations Used 15

Dependent Variable: du

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	0.14014667	0.02335778	1.51	0.2884
Error	8	0.12402667	0.01550333		
Corrected Total	14	0.26417333			

R-Square	Coeff Var	Root MSE	du Mean
0.530510	21.29630	0.124512	0.584667

Source	DF	Type III SS	Mean Square	F Value	Pr > F
brand	2	0.07557333	0.03778667	2.44	0.1491
rep	4	0.06457333	0.01614333	1.04	0.4432

Duncan's Multiple Range Test for du

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	8
Error Mean Square	0.015503

Number of Means	2	3
Critical Range	.1816	.1892

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	brand
A	0.67800	5	H
A	0.57000	5	R
A	0.50600	5	T

UNIFORMITY SAS CODE

```
options nodate nonumber center formdlim="*"linesize=85;
data du;
input study$ loc$ rep zone$ brand$ pressure$ du;
cards;
/* Data is inputted here */
;
data du2;
set du(where=(pressure = 'R'));
proc glm data=du2;
title 'DIFFERENCE BETWEEN ZONES FOR BOTH RESIDENTIAL AND CONTROL
TESTS AT REGULAR PRESSURE';
class study rep zone;
model du = study rep(study) zone study*zone/ss3;
test h=zone e=rep(study);
means study/duncan e=rep(study);
means zone/duncan;
run;
data du3; set du2; if study=control then delete;
proc glm data=du3;
title 'DIFFERENCE BETWEEM ZONES AND LOCATION FOR RESIDENTIAL STUDY
AT REGULAR PRESSURE';
class zone rep loc;
model du = zone loc zone*loc rep(loc)/ss3;
test h=loc e=rep(loc);
means zone/duncan;
means loc/duncan e=rep(loc);
data du4; set du2; if study= residential then delete;
proc glm data=du4;
title 'DIFFERENCE BETWEEN ZONES FOR CONTROL STUDY AT REGULAR
PRESSURE';
class brand rep zone;
model du = zone brand(zone) rep/ss3;
test h=zone e=brand(zone);
means zone/duncan e=brand(zone);
run;
data du5; set du; if study=residential then delete;
proc sort data=du5; by zone;
proc glm data=du5; by zone;
title 'DIFFERENCE BETEWEEN BRANDS AND PRESSURE FOR CONTROL TESTS -
SPRAY AND ROTOR ZONES';
class brand pressure rep;
model du = brand pressure brand*pressure rep/ss3;
means brand/duncan;
means pressure/duncan;
lsmeans brand*pressure/pdiff;
run;
data du6; set du5 (where=(zone = 'S'));
proc sort data=du6; by pressure;
proc glm data=du6; by pressure;
title 'DIFFERENCE BETEWEEN BRANDS FOR CONTROL TESTS -SPRAY ZONES AT
EACH PRESSURE';
class brand rep;
model du = brand rep/ss3;
means brand/duncan;
run;
data du7; set du5 (where=(zone = 'R'));
```

```
proc sort data=du7; by pressure;
proc glm data=du7; by pressure;
title 'DIFFERENCE BETEWEEN BRANDS FOR CONTROL TESTS -ROTOR ZONES AT
EACH PRESSURE';
class brand rep;
model du = brand rep/ss3;
means brand/duncan;
run;
```

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BIOGRAPHICAL SKETCH

My name is Melissa C. Baum and I am attending the University of Florida. I am studying in the department of Agricultural and Biological Engineering, focusing on land and water engineering, researching residential irrigation water use. In 2002, I obtained my B.S. from the department of Agricultural and Biological Engineering, at the University of Florida (UF). During my undergraduate study, I had many research experiences. I worked with the Engineering Research Center and Dupont Mining, on a water quality project. I also spent 4 months at the Universite de Technologie in Compiegne, France, working on a hydrophobicity project. As a student I was very active in clubs and organizations. I was president of the UF student chapter of the American Society of Agricultural Engineers and vice-president of the UF Alpha Epsilon Agricultural Engineering Honor Society. I also conducted water-lab demonstrations for undergraduate classes and touring high-school students. I enjoyed my teaching and research experience during my time at the University.