Analysis of Residential Irrigation Distribution Uniformity

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Abstract: Irrigation has become commonplace for residential homeowners desiring high quality landscapes in Florida. The goal of this project was to document irrigation system uniformity in Central Florida and to quantify distribution uniformity of residential sprinkler equipment under controlled conditions. The catch-can testing procedure used was a modified version of both the American Society of Agricultural Engineers standard and Florida Mobile Irrigation Laboratory (MIL) procedures. The modified version included a larger sample size to ensure complete sample collection over the entire irrigated area. The standard MIL procedure may overestimate the uniformity for residential systems. From the tests on residential irrigation systems, the average low quarter distribution uniformity (DU_{lq}) value was calculated as 0.45. Rotary sprinklers resulted in significantly higher DU_{lq} compared to fixed pattern spray heads with 0.49 compared to 0.41, respectively. From uniformity tests performed on rotor and spray heads under ideal conditions, rotor heads had more uniform distributions than the spray heads of 0.55 compared to 0.49, respectively. Spray heads had better uniformity when fixed quarter circle nozzles were used as opposed to adjustable nozzles. Both residential irrigation system and controlled tests resulted in (DU_{lq}) at the low end of industry guidelines. Residential irrigation system uniformity can be improved by minimizing the occurrence of low pressure in the irrigation system and by ensuring proper spacing is used in design and installation.

DOI: 10.1061/(ASCE)0733-9437(2005)131:4(336)

CE Database subject headings: Irrigation; Residential location; Water use; Landscaping; Florida.

Introduction

Automatic in-ground irrigation systems are found in most residential construction in Florida. Homeowners desiring high quality landscapes need irrigation to maintain these landscapes during dry periods. Turfgrass is normally the most commonly used single type of plant in the residential landscape. Residential water use comprises 61% of the public supply category. The mostly groundwater derived public supply is responsible for the largest portion, 43%, of groundwater withdrawn in Florida. Between 1970 and 1995 there was a 135% increase in public supply water withdrawals (Fernald and Purdum 1998). Florida consumes more fresh water than any other state east of the Mississippi River (Solley et al. 1998). From a recent study in Florida, it was determined that the average household used 71% of the total water consumption for irrigation (Baum et al. 2003). With continual withdrawals of water for irrigation purposes, competition is increasing between agricultural, municipal, and industrial users. One potential area of water conservation is residential irrigation water use.

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Note. Discussion open until January 1, 2006. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on April 12, 2004; approved on August 24, 2004. This paper is part of the ***Journal of Irrigation and Drainage Engineering***, Vol. 131, No. 4, August 1, 2005. ©ASCE, ISSN 0733-9437/2005/4-336–341/$25.00.

There have been district water restrictions enforced by St. Johns River Water Management District (SJRWMD) since 1991 in the South Central Florida ridge. Due to drought conditions in the past few years, in some locations residential irrigation has been limited to twice a week and is prohibited between the hours of 10:00 a.m. and 4:00 p.m. district wide, 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.

Irrigation efficiency defines how effectively an irrigation system supplies water to a given crop or turf area. Efficiency can be computed as the ratio between water used beneficially and water applied and is expressed as a percentage (Burt et al. 1997). Irrigation efficiency is difficult to quantify; therefore, distribution uniformity is often measured as an indicator of potential efficiency for sprinkler irrigated areas. Irrigation can be uniform and inefficient due to mismanagement (i.e., overirrigation); however, irrigation cannot be nonuniform and efficient. As a result, irrigation uniformity can be a good indication of potential irrigation efficiency. Uniformity of water distribution is a measure of 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}) can be calculated with the following equation (Merriam and Keller 1978):

$$DU_{lq} = \frac{\overline{D}_{lq}}{\overline{D}_{tot}} \tag{1}$$

where $\overline{D}_{lq}$ = lowest quarter of the average of a group of catch-can measurements and $\overline{D}_{tot}$ = 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 which receive the least irrigation by focusing on the low quarter.

Burt et al. (1997) defined common irrigation performance measurements, which discussed standardization and clarification of irrigation definitions and quantified irrigation measurements. Low quarter distribution uniformity uses a definable minimum range (lowest quarter) rather than the absolute minimum value (zero). It is important to focus on underirrigation in reference to residential landscaping because homeowners are typically more concerned with turfgrass quality and aesthetics than water conservation.

The coefficient of uniformity treats overirrigation and underirrigation equally compared to the mean, and can be calculated by the Christiansen formula as

$$\mathrm{CU} = 1 - \frac{\sum_{i=1}^{n} |V_i - \overline{V}|}{\sum_{i=1}^{n} V_i} \quad (2)$$

where V_i refers to the volume in a given catch-can and $\overline{V}$ refers to the mean volume (Christiansen 1942). Both over- and underirrigation occurring in the same system could could cancel each other out, which would result in a relatively high CU value.

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 developed (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 the evapotranspiration rate. Sprinkler uniformity tests were conducted using catch-cans. The evapotranspiration rate was calculated and an empirical model for determining urban irrigation needs was developed. Residential solid set and movable systems were compared; analysis of the application efficiency of these systems showed that the average DU_{lq} was about 0.30 for hand-move and 0.37 for solid set systems (Aurasteh et al. 1984). It was also noted that in this arid climate, where annual precipitation averages 207 mm, the homeowners used approximately 61% of their total water supply for irrigation (NRCS 1990).

The Univ. of Georgia Water Resources Team (Thomas et al. 2002) conducted residential irrigation system audits. It was found that the irrigation time on many homes tested was set too high, which resulted in overapplication of water. The largest problem discovered from the auditing was that the selection of nozzle type for the rotary sprinklers was not appropriate for the coverage area, resulting in poor water distribution uniformity. For example, full circle sprinklers often had the same nozzle as part circle rotary sprinklers. The writers determined that there could be a 24% irrigation water use savings if proper nozzles were used.

In assessments of irrigation sprinkler system performance in California, Pitts et al. (1996) found a mean DU_{lq} of all systems tested of 0.64. The average DU_{lq} for nonagricultural turfgrass sprinklers (residential lawns) was 0.49. More 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 equipment types in zones (spray and rotor), excessive pressure variations, and poor head-to-head coverage. Many of the cooperators in this study were unaware of the 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.

Table 1. Florida Mobile Irrigation Lab Turf DU_{lq} Results

	Low quarter distribution uniformity (DU_{lq})			
Location	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	0.80	75
St. Lucie (2001)	0.67	0.13	0.85	88
Average	*0.55*	*0.23*	*0.79*	*80*

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 is from the U.S. Department of Agriculture (USDA) and 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 2 h period, measuring pump flow rates, sprinkler pressures and flow rates, and application uniformities (Micker 1996). The MIL procedure requires 16–24 cans to be used, in selected irrigation zones, which is usually the largest turf area for residential tests. Table 1 presents 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, resulting in a lack of information regarding current residential irrigation system performance and water use in the state.

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

Materials and Methods

The residential systems included in this study were located within the South Central Florida ridge. The study included eight homes in Marion County, nine homes in Lake County, and eight homes in Orange County. The residences for this study where chosen if they were willing to cooperate and had an in-ground automatic irrigation system which used potable city supplied water (not well-drawn or reclaimed water). The homeowners were recruited at garden club or area community association meetings. Of the homeowners who expressed interest, a subset were randomly selected by the Univ. of Florida.

The irrigation systems at the residences typically included stationary spray heads and gear-driven rotary sprinklers for the

Table 2. Recommended Radii for Spray and Rotary Heads According to Manufacturer Guidelines and Tested under Controlled Conditions

Head type	Brand	Recommended pressure (kPa)	Low pressure (kPa)	High pressure (kPa)	Distance of throw[a] (m)
Rotary	A	345	207	—[b]	12.8
	B	379	207	—	11.3
	C	345	207	—	11.3
Spray	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
	C	207	69	414	4.6

Note: adj.=adjustable.

[a]At recommended pressure.

[b]Test not performed.

turf and landscape areas. Spray heads and rotors were tested in this experiment because they are commonly used on turfgrass and are also 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.

A control test site was established at the University of Florida Agricultural and Biological Engineering Dept. in Gainesville, Fla. The 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 × 11.3 m or 12.8 m × 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 × 4.6 m according to manufacturer recommendations based on the nozzles selected. Nozzles were installed at each of the four corners of the plot area to ensure spacing at 50% of manufacturer published diameters at recommended pressure (Table 2). Pressure gages were installed before and after the pressure regulator entering the piping network as well as just before each nozzle.

To quantify the uniformity of the irrigation systems described previously, the catch-can method of uniformity testing was used. The catch-can method of uniformity testing is described by both the American Society for Agricultural Engineers (ASAE) and the National Resources Conservation Service (NRCS) (Micker 1996 and ASAE 2000). However, the procedure used in this project differed because residential sprinkler irrigation systems were tested rather than large agricultural irrigation systems as in the ASAE Standard and is more detailed than the procedures of the NRCS MIL guidelines.

For both test locations (residential or control), 300 mm wire stem flags were used to mark the catch-can grid and were bent so as to level the catch-cans and prevent movement. The cans had an opening diameter of 155 mm and a depth of 200 mm. 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 13 mm. A sketch of the house and landscape beds was drawn to scale with the location of each can marked. Additionally, 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 in wind speeds 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 evapotranspiration 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.

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 account for edge effects the grid was positioned 0.8 m from property boundaries. This resulted in 100–500 cans used in each test. Pressure across the two furthest points in each zone was measured with a pitot tube and pressure gage on rotors or with an in-line pressure gage just beneath the spray head nozzle.

For the control tests 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 three brands of spray and rotary heads tested under ideal conditions were labeled as A, B, and C. These three brands are the most popular for professionally installed irrigation systems in Central Florida. 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 brand reference. All rotors had an adjustable arc by design. As shown in Table 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 the manufacturer recommended pressure (345 or 379 kPa). Each head test was replicated five times at each pressure.

Data analysis was performed using the Statistical Analysis System software (SAS Institute, Inc. *version 8.02*) (SAS 2003) using the general linear models (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.

Results and Discussion

The low-quarter distribution uniformities can be classified by the overall system quality ratings published by the Irrigation Association (IA 2004). The uniformities of the residential systems tested in this study (Table 3) would be considered in the "fair" (0.50–0.59) to "fail" (<0.40) range, with the exception of one "good" (0.60–0.69). 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) of the rotor zones was 0.49 and the mean DU_{lq} of the spray zones was 0.41, which was

Table 3. Residential Distribution Uniformity Catch-Can Test Results

		Coefficient of uniformity	Low quarter distribution uniformity			
County	Report	Overall system	Overall system	Spray head	Rotor head	MIL style (16–24 cans)
Marion	1	0.60	0.44	—[a]	—[a]	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	—[a]	—[a]	0.58
	5	0.65	0.47	0.51	0.49	0.54
	6	0.55	0.35	0.35	—[b]	0.64
	7	0.54	0.50	0.50	0.47	0.60
	8	0.55	0.39	0.39	—[b]	0.45
Lake	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	—[b]	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
	9	0.60	0.54	0.45	0.64	0.70
Orange	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
	8	0.63	0.47	0.47	—[b]	0.67
Average		*0.59*	*0.45*	*0.41*	*0.49*	*0.58*

Note: MIL=Mobile Irrigation Laboratory.

[a]Separation of zones not possible due to small yard.

[b]Irrigation system comprised of all rotary sprinklers or all spray heads.

statistically different at the 95% confidence level ($p=0.043$). Pressure differences across residential irrigation zones varied by less than 10% which is considered acceptable (Pair 1983). As a result it was concluded that pressure variations did not negatively impact uniformity.

The average DU_{lq} values from the residential irrigation systems tested in this study were lower than values reported by the MILs. The mean MIL DU_{lq} values in Table 1 were significantly higher, averaging 0.55 ($p=0.0004$) than the overall DU_{lq} values in Table 3 of 0.45. According to the Irrigation Association overall system quality ratings, two of the regions surveyed by the MIL resulted in an irrigation system quality rating of "good" or "very good" (0.70–0.74), one other as "fair," one as "poor" (0.40–0.49), and two others as "fail" (IA 2004). The DU_{lq} value differences were in part based on 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. This modified testing methodology included a larger sample size to ensure complete coverage. 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, are included in the tests of this study. Due to the greater number of catch-cans, a larger percentage of the underirrigated areas are 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 shows a comparison between the DU_{lq} determined with the catch-cans placed in the grid formation, as specified in the discussed procedure, as well as 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 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, the largest area of the yard is irrigated by rotor heads. Based on equipment alone, rotor heads tend to have greater uniformity (see Table 3). Therefore, can location will increase the DU_{lq} value. For the tests performed in this study, to employ the IA system quality ratings, a multiplier of 1.3 should be used to account for procedural differences, which may have caused the exceptionally low uniformity values. This was determined by dividing the residential DU_{lq} data with only 16–24 catch-cans in the largest zone by the overall residential average DU_{lq} that incorporated edges of the yard and difficult to irrigate areas. Even with an adjusted DU_{lq} of 0.58 (Table 3), the residential systems tested would rate as "fair" (0.50–0.59).

Mathematical calculation methods also affected the uniformity values. The CU calculations (Table 3) produced higher values than the DU_{lq} calculations. This is because CU takes into account both over and underirrigation, while DU_{lq} only considers the lowest quarter on the underirrigated area. Including both the over- and underirrigated areas resulted in high and low deviations from the mean, canceling each other to some extent.

Statistical analysis of the control test spray and rotor head uniformities tested under ideal conditions was compared to results from the residential home tests. There was a significant difference between uniformities ($p=0.0004$) based on testing condition. The overall mean DU_{lq} of the tests performed under ideal conditions was 0.55 compared to 0.45 on the residential systems. Similar to the differences in uniformity between rotor and spray heads found on the residential systems, these two types of equipment were found to have uniformities that were mildly statistically different ($p=0.08$) under ideal testing conditions of 0.58 for rotary sprinklers and 0.53 for spray nozzles at manufacturer recommended pressure.

The control spray and rotor heads were tested individually at different pressure ranges as stated previously. The statistical analysis of the rotor head tests showed significant differences in DU_{lq} between brands ($p=0.0004$); while pressure resulted in a difference at the 90% confidence level ($p=0.090$) as can been seen in Table 4. The spray head test statistical analysis showed that there was a mild interaction ($p=0.0639$) between pressure and brand. Spray head DU_{lq} values were significantly lower at 69 kPa (low pressure) compared to the 207 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. The influences on the DU_{lq} values from this interaction can be

Table 4. Distribution Uniformity Catch-Can Test Results under Controlled Conditions

(a) Rotor heads

Brand	Pressure[a] Recommended: Low quarter distribution uniformity (DU_{lq})	Recommended: Sample size	Low: DU_{lq}	Low: Sample size
A	0.68a[b]	5	0.64a	5
B	0.57 a	5	0.53b	5
C	0.51 a	5	0.41c	5
Average	0.58		0.52	

(b) Spray heads

Brand	Pressure Recommended: DU_{lq}	Recommended: Sample size	Low: DU_{lq}	Low: Sample size	High: DU_{lq}	High: Sample size
A	0.48b	5	0.39 b	5	0.50b	5
A-adj.	0.52b	5	0.41ab	5	0.52b	5
B	0.55b	5	0.44ab	5	0.53b	5
B-adj.	0.38c	5	0.37 b	5	0.37c	5
C	0.70a	5	0.48 a	5	0.65a	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).

observed by the Duncan letters in Table 4. 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 brand B at recommended (0.55) and high (0.54) pressures and brand 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}, which averaged 0.37 across all pressures.

The rotor heads showed mild statistical differences across brands regardless of pressure, with brand A producing the highest DU_{lq} of 0.66 and brand C yielding the least uniform distribution of water with a DU_{lq} of 0.46. These DU_{lq} values are the average of low and recommended pressure tests. 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. Pressure for both spray head and rotary sprinkler testing varied less than 5% between the most distant two nozzles, indicating that pressure variations were not a source of nonuniformity.

Summary and Conclusions

The DU_{lq} values reported in this study were lower than expected, especially with respect to the Irrigation Association quality ratings and the historical 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 systems tested in this study, the low-quarter distribution uniformities classified by the overall system quality ratings would be considered in the "fair" (0.50–0.59) to "fail" (<0.40) range, with the exception of one "good" (0.60–0.69). When the testing results in this study were adjusted to match the MIL methodologies, the ratings of the residential systems tested in this study were improved to the "fair" to "very good" (0.70–0.79) ratings. However, it should be noted that any degradation in turfgrass or plant quality on the edges of a residential home 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 DU_{lq} of the spray zones (0.41) was lower than the DU_{lq} of the rotor zones (0.49).

Overall, the control tests under ideal conditions resulted in poor uniformity. The rotary sprinkler DU_{lq} was significantly higher (0.55) than the spray head DU_{lq} (0.49). The spray heads have closer spacing and a higher precipitation rate. Therefore, overirrigation 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.

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. There was not a significant difference with respect to pressure because the pressure testing was over a narrow range. For the spray head control tests, there was an interaction between pressure and brand. 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. The implications of these findings emphasizes the need for properly designed residential irrigation systems.

Acknowledgments

The writers would like to thank the cooperators for participating in this work, and the following individuals for technical support: Danny Burch, Clay Coarsey, Jeff Williams, Brent Addison, and Justin Gregory. This research was supported by the Florida Agricultural Experiment Station and a grant from St. Johns River Water Management District and approved for publication as Journal Series No. R-10115.

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