EFFECT OF WIND SPEED AND PRESSURE ON LINEAR MOVE IRRIGATION SYSTEM UNIFORMITY

M. D. Dukes

ABSTRACT. *Use of center pivot and linear move sprinkler irrigation systems is becoming popular in the Southeastern United States. As these systems are used to irrigate increasing acreage, quantitative data are needed on sprinkler performance under local conditions. Two types of low pressure sprinkler nozzles were tested under field conditions, stationary grooved plate (LDN) and off-center wobbling diffuser sprinklers (IWOB). Replicated uniformity measurements were conducted along the axis of a linear move irrigation system at low (<1.7 m/s), medium (3.3-3.9 m/s), and high (5.0-6.6 m/s) wind speeds and at two pressure levels of at least 200 kPa, which was in excess of the pressure regulator discharge pressure and less than 97 kPa, a pressure below nominal regulator discharge pressure. Also, the normal probability distribution was investigated to determine how well it represented the sprinkler field data. The IWOB sprinklers coefficient of uniformity (CU) was consistently 10% to 16% higher than the LDN sprinklers over all conditions and ranged from 87% to 93% and 70% to 85%, respectively. The coefficient of uniformity of the LDN sprinklers was significantly improved at higher wind speeds (5.0-6.6 m/s) under low pressure (<97 kPa) operation from 70% to 85%, while other sprinkler/pressure combinations were not affected by wind speed. It was hypothesized that this improvement was due to the formation of larger drops falling in a more random pattern due to inadequate pressure. Finally, the IWOB sprinklers produced a more uniform application of water compared to the LDN sprinklers under all of the testing conditions in this project and the normal distribution adequately represented the field data except for LDN sprinklers at <97 kPa.*

Keywords. *Sprinkler, Irrigation, Center pivot, Uniformity, Low pressure.*

Sprinkler irrigation accounts for 71,400 ha of irrigation in Florida and 349,600 ha in the Southeastern United States (NASS, 2004). Agricultural self-supply is the largest component of freshwater use in Florida accounting for 45% of the total withdrawals (Marella, 1999), mostly from groundwater sources. Sprinkler irrigation with center pivot (CP) or linear move (LM) systems is popular in the Southeastern United States with 277,800 ha irrigated (79% of sprinkler irrigation) by these systems (NASS, 2004). Crops irrigated with sprinkler irrigation in the Southeast United States consist primarily of corn (grain and silage), soybeans, tobacco, cotton, and assorted vegetables (NASS, 2004). In Florida, crops such as sweet corn, potato, bare ground vegetables (i.e. not drip irrigated) and sod are increasingly irrigated with CP and LM systems due to the convenience and relatively higher water use efficiency than other forms of sprinkler irrigation. Many of the systems used in the Southeastern United States are low pressure systems (<206 kPa) with a variety of nozzles available.

Several types of low pressure spray nozzles commonly used include fixed plate, grooved plate low drift nozzles (LDN), rotating plate nozzles and wobbling diffuser nozzles (IWOB). The LDN sprinklers were developed to resist stream dispersion under windy conditions that can occur due to larger droplets with less kinetic energy (relative to impact sprinklers) produced by low pressure nozzles (Kohl, 1974). These particular sprinklers emit distinct streams of water depending on the number of grooves in the non-moving plate (fig. 1). Wobbling diffuser nozzles were developed to produce higher uniformity of water application compared to grooved plate nozzles by creating wetting patterns that do not depend on streams of water and result in a lower instantaneous application rate. The IWOB nozzles use a diffuser that rotates off center to produce a random pattern of droplets (fig. 2). Both LDN and IWOB sprinklers have become popular in North Florida on LM and CP irrigation systems.

In a study to evaluate the uniformity of center pivot systems with fixed plate and rotator nozzles, Hanson and Orloff (1996) found that under both windy conditions (2.2 to 4.5 m/s) and no-wind conditions that rotating plate sprinklers resulted in more uniform water application than grooved plate spray sprinklers (distribution uniformity of 0.85 to 0.95 vs. 0.59 to 0.80, respectively). In addition, they found that under windy conditions the application uniformity of grooved plate spray nozzles was higher than rotating plate nozzles. Clark et al. (2003) found that application uniformity of grooved plate LDN sprinkler nozzles tended to decrease as operating pressure decreased from 138 to 41 kPa. Tarjuelo et al. (1999) determined for a solid set sprinkler system that coefficient of uniformity decreased as wind speed increased and that uniformity remained nearly constant beyond 6 m/s. They also showed that there is a linear relationship between

---

Submitted for review in August 2005 as manuscript number SW 6020; approved for publication by the Soil & Water Division of ASABE in March 2006.

Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the University of Florida and does not imply approval of a product or exclusion of others that may be suitable. This research was partially supported by Senninger Irrigation, Inc., the Florida Agricultural Experiment Station, and approved for publication as Journal Series No. R-11052.

The author is **Michael D. Dukes, ASABE Member Engineer,** Assistant Professor, Agricultural and Biological Engineering Department, University of Florida, P.O. Box 110570, Gainesville, Florida 32611; phone: 352-392-1864 ext 107; fax: 352-392-4092; e-mail: mddukes@ufl.edu.

ISSN 0883−8542

Figure 1. Single pad grooved plate low drift nozzle (LDN) sprinkler.

coefficient of uniformity and distribution uniformity (CU and DU_{lq}). Sprinkler uniformity has been shown to influence nutrient concentrations in the soil (Li et al., 2005); however, a system with a coefficient of uniformity ranging from 72% to 84% did not result in differences in yield of winter wheat. The higher the sprinkler system uniformity, the less chance that crop nutrients will be leached from the root zone (Brito and Willardson, 1982). In addition to the rationale presented earlier that support the idea of maximizing sprinkler application uniformity, crop yields could be reduced under nonuniform application of water. It is also important to understand the performance of sprinkler packages since other factors such as variable rate control systems have the potential to influence uniformity as well (Perry and Dukes, 2004).

The probability distribution of irrigation water application has been compared with analytical techniques (Warrick, 1983) and compared to field data (Heermann et al., 1992). Warrick (1983) related the DU_{lq} and CU parameters to application depth coefficient of variation (CV) for the normal, log normal, uniform, specialized power, beta, and gamma probability distributions. Heermann et al. (1992) surveyed 60 center pivot catch can tests to determine the best statistical distribution among the normal, log normal, uniform, and the specialized power distributions and found the normal distribution fit the measured data better than the other probability distributions. Testing conditions included both spray nozzles and impact sprinklers and tests were conducted in the afternoon, which led to wind speeds as high as 11.5 m/s. The CV was 20%, 24%, and 30% for wind speeds less than 2.2 m/s, 2.2 to 4.5 m/s, and greater than 4.5 m/s, respectively. Hanson and Wallender (1986) found that the probability distribution of application depth on two towers of a linear move was log normal.

Figure 2. Wobbling diffuser (IWOB) sprinkler nozzle.

The objectives of this research project were 1) to determine the application uniformity of grooved plate and wobbling diffuser type sprinklers for center pivot and linear move irrigation systems in climatic conditions found in the humid Southeastern United States, under adequate and relatively low system operating pressure scenarios and 2) to test the fit of the normal distribution to catch can data from field tests.

MATERIALS AND METHODS

Linear move nozzle uniformity tests were conducted at the University of Florida Plant Science Research and Education Unit, near Citra, Florida. The LM system is a 375-m, 6-span Valley system (Valmont Industries, Inc., Omaha, Nebr.) fitted with Senninger (Senninger Irrigation, Inc., Orlando, Fla.) single pad #14 low drift nozzle (LDN; 5.6-mm diameter orifice, 33 grooves, flat plate, 23.0 L/min at 138 kPa) sprinklers (fig. 1) on the three south spans (from the center) and Senninger #17 i-Wob sprinkler (fig. 2) nozzles (IWOB; 6.9-mm orifice diameter, 29.3 L/min at 103 kPa) on the three north spans. All sprinklers were on flexible drop hoses that set the LDN and IWOB sprinklers approximately 1.5 and 1.8 m, respectively, above the soil surface. The LDN sprinklers, spaced 2.3 m apart, were fitted with 138-kPa pressure regulators, and the IWOB sprinklers, spaced 3 m apart, had 103-kPa regulators according to the sprinkler package specified by the linear move manufacturer in the case of LDN nozzles and nozzle manufacturer in the case of IWOB nozzles. The LM operated at approximately 3.8 m^3/min at 206 kPa under normal operating conditions.

UNIFORMITY TESTING

The uniformity testing consisted of three lines of collectors (plastic paint buckets, 16 cm diameter, 20 cm tall) placed on the ground along the travel path of the LM system (fig. 3). Thus, the distance from the sprinklers and the collectors was approximately 1.3 and 1.6 m for the LDN and the IWOB sprinklers, respectively. This size catch can was chosen since it has been shown that catch cans with less than 15-cm diameter result in biased results with fixed plate nozzles that have distinct streams, such as the LDN sprinklers in this experiment (Dogan et al., 2003). Collector spacing was approximately 3-m parallel to the system and 15-m perpendicular to the system where the catch cans were aligned such that they did not fall under a sprinkler. To facilitate data collection, two north spans of the linear move system were used for the IWOB testing and two south spans were used for the LDN testing. Since there were multiple experiments on the linear move system, the two spans closest to the center were used in seven of the tests, while the two outer spans on each half were used for the other 12 uniformity tests. There were 35 to 40 collectors per line for a total of 105 to 120 collectors in the three lines for each test. One irrigation application across the three lines represented one replication of a test. All tests occurred at a system movement speed of 11% setting (approximately 24-mm application depth) on the control panel.

Catch can tests were conducted under a variety of wind conditions from nearly no wind to wind speeds exceeding the 5 m/s limit according to *ASAE Standards* (2001). In addition to wind speed, the system pressure was varied between adequate (>200 kPa), which was higher than the pressure regulators on the LDN sprinklers of 138 kPa, and a lower setting (<97 kPa) that was lower than the pressure regulators for both nozzle packages (138 kPa and 103 kPa, LDN and IWOB, respectively). Pressure ranged from 200 to 290 kPa over all adequate pressure tests while the lower setting pressure ranged from 62 to 97 kPa. The most expedient way to adjust the pressure of the system was partial closure of the supply valve to the system. Each wind speed/pressure combination was tested at least three times, where each test was treated as a replicate. A 500- or 1000-mL graduated cylinder was used to measure catch can volumes depending on volume caught. All tests were conducted on a permanent bahiagrass (*Paspalum notatum*) cover crop that was mowed 15 to 20 cm tall so as not to interfere with catch can placement or water entry into the catch cans. Collector volumes were measured as soon as the system had moved past a line. A weather station within 500 m of the LM system was used to measure temperature, relative humidity, and wind speed every minute and output the average every 15 min.

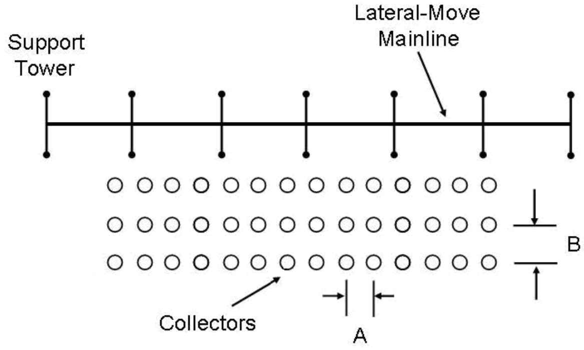

Figure 3. Schematic of linear move irrigation system uniformity testing showing three rows of catch cans in the direction of travel. Dimension A was 3 m and B was 15 m.

DATA ANALYSIS

Several quantitative measurements of uniformity were calculated. The low quarter Distribution Uniformity (DU_{lq}) was calculated as:

$$DU_{lq} = \frac{\overline{V}_{lq}}{\overline{V}_{tot}} \qquad (1)$$

where

$\overline{V}_{lq}$ = average of the lowest one-fourth of catch-can measurements (mL)

$\overline{V}_{tot}$ = average depth of application over all catch can measurements (mL)

DU_{lq} is expressed as a decimal as suggested by Burt et al. (1997) and the Christiansen Uniformity Coefficient (Christiansen, 1941; *ASAE Standards*, 2001) was calculated as:

$$CU = 100 \times \left[1 - \frac{\sum_{i=1}^{n} \left| V_i - \overline{V} \right|}{\sum_{i=1}^{n} V_i} \right] \qquad (2)$$

where

V_i = individual catch can measurement (mL)

$\overline{V}$ = average volume of application over all catch can measurements (mL)

In addition, the coefficient of variation (CV) in application volume for each test was computed as the standard deviation of all catch can measurements in that test divided by the average catch can volume for a test.

Data were analyzed with an analysis of variance using the general linear models procedure in SAS (SAS, 2001) with nozzle type, wind speed, system pressure, and span tested as main effects on DU_{lq}, CU, CV, and application depth.

The application depth data were compared to the normal, triangular, log normal, uniform, Weibull, beta, gamma, logistic, pareto, and extreme value distributions. The tests to determine the goodness-of-fit with the field data were the Chi-square, Kolmogorov-Smirnov, and Anderson-Darling statistics. A significantly good fit was determined as Chi-square p-value > 0.5, Kolmogorov-Smirnov value < 0.03, and Anderson-Darling value < 1.5 (Crystal Ball, 2004). Based on the mean and standard deviation for each test, a Monte Carlo analysis was used to generate application depths for 100 simulated catch cans 1000 times with a probability distribution that best described the field measured data. A normal distribution was also generated for sprinkler type and sprinkler type in each pressure category since Heermann et al. (1992) found the normal distribution adequately represented center pivot sprinkler distributions.

The DU_{lq}, CU, and CV were calculated for the simulated catch can tests and the mean values for each set of 1000 simulations were determined. Uniformity statistics were compared between probability distributions best describing experimental data to the generated normal distributions.

Results and Discussion

A total of 19 catch can tests were conducted, with six under low wind conditions (< 1.7 m/s), seven under medium wind conditions (3.3 to 3.9 m/s), and six under high wind conditions (5.0 to 6.6 m/s). According to *ASAE Standards* (2001) wind speeds greater than 5 m/s are not recommended due to the potential to negatively impact distribution uniformity. Wind direction was monitored; however, a low correlation coefficient between DU_{lq} and wind direction ($r = -0.0019$) indicated that wind direction did not influence uniformity. The average temperature during testing was 18.6°C and ranged from 9.3°C to 28.4°C. The average relative humidity was 61% and ranged from 31% to 99%. One potential source of error in this project is differences in evaporative conditions across the time period of the various tests. However, due to the relatively high humidity and low wind conditions, this particular error was minimized. Catch cans with a known amount of water were set out on tests during high potential evaporative conditions (i.e. warm and windy) and there was not any measurable evaporation from these cans during the test due to the weather conditions and the limited time of each test (typically less than 2 hours). In addition, Schneider (2000) points out that previous studies on evaporation from center pivot systems resulted in no more than 2% losses, although many of the studies on evaporation during sprinkler irrigation were conducted under conditions optimal for evaporation. For example, Kohl et al. (1987) measured evaporation as 0.8% of total sprinkler discharge under an average temperature of 26°C, relative humidity of 64%, and wind speed of 6.4 m/s.

Analysis of Variance

Using the different spans over the uniformity testing did not result in a statistically significant effect on uniformity parameters or application depth. This result is in contrast to a study by Hanson and Wallender (1986) that found application uniformity along a linear move system depended on the span that was tested. They attributed the higher uniformity span to its close proximity to the guide tower. The LM system was supplied by water in the center, thus the farthest guide tower was the third span from the center; whereas, the system tested by Hanson and Wallender (1986) had nine spans that were supplied from one end.

There was a significant interaction between wind speed and system pressure ($p = 0.013$) for DU_{lq} and application depth CV ($p = 0.036$). Once the analysis of variance was run for pressure groups, nozzle type resulted in significantly different DU_{lq} ($p = 0.032$), CU ($p = 0.014$), CV ($p = 0.017$), and application depth ($p = 0.044$) at adequate pressure. At low pressure, there was a trend toward interaction between wind speed and nozzle type for DU_{lq} ($p = 0.072$), CU ($p = 0.064$), and CV ($p = 0.084$). It was therefore decided to perform the statistical analysis on the depth and uniformity statistics within nozzle type and pressure category. Table 1 presents the uniformity and depth statistics across all tests.

Uniformity Comparison

The IWOB had higher uniformity than the LDN nozzles by all statistical measures. Over all testing conditions the average DU_{lq}, CU, and application depth CV were 0.81, 90%, and 13% for the IWOB nozzles, respectively. The same respective uniformity parameters were 0.67, 80%, and 26% for the LDN sprinklers (table 1). Under normal operating pressure, the LDN sprinklers had an average CU of 82% across all wind speeds (not significant) compared to 71% to 85% along most systems summarized by Schneider (2000). Thus, the IWOB sprinklers produced a more uniform application of water along the linear move system. This result can be attributed to the more random pattern of water distribution (fig. 4) due to the off-center rotating diffuser on the IWOB sprinklers that tends to create a pattern more like rainfall compared to the grooved plate in the LDN sprinklers that produced distinct streams of water (fig. 5).

Coefficient of uniformity was consistently higher than DU_{lq} and both are inversely related to application depth CV (fig. 6). According to the mathematical relationship between DU_{lq} and CU, CU will always be larger (when both are decimals or a percentage) since positive and negative deviations from the mean application volume are used in the calculation of CU; whereas, only negative deviations are used in the calculation of DU_{lq} (Keller and Bliesner, 2000). This relationship between DU_{lq} and CU has been reported for residential sprinkler uniformity (Baum et al., 2005). Warrick (1983) showed similar relationships in an analytical analysis

Table 1. Uniformity and variability statistics of catch can data as affected by wind speed and linear move system pressure (n = 3 except where noted).

Nozzle	Wind Speed (m/s)	System Pressure[a] (kPa)	DU_{lq}[b]		CU (%)		CV (%)	Depth (mm)
IWOB	5.0–6.6	>200	0.81	NS	90	NS	13	24
IWOB[c]	3.3–3.9	>200	0.82	NS	88	NS	15	22
IWOB	<1.7	>200	0.82	NS	93	NS	9	24
Avg.			0.81		90		12	23
IWOB	5.0–6.6	<97	0.80	NS	87	NS	16	14
IWOB	3.3–3.9	<97	0.79	NS	87	NS	18	16
IWOB	<1.7	<97	0.80	NS	92	NS	9	16
Avg.			0.80		89		14	15
LDN	5.0–6.6	>200	0.66	NS	80	NS	26	22
LDN	3.3–3.9	>200	0.78	NS	85	NS	19	21
LDN	<1.7	>200	0.66	NS	82	NS	23	22
Avg.			0.70		82		22	22
LDN	5.0–6.6	<97	0.77	a	85	a	19	13
LDN	3.3–3.9	<97	0.62	ab	74	ab	32	14
LDN	<1.7	<97	0.53	b	70	b	36	16
Avg.			0.64		77		29	14

[a] Pressure for the tests >200 kPa ranged from 200 to 290 kPa and from 62 to 97 kPa for the <97-kPa tests.

[b] NS indicates not significant and numbers followed by different letters are significantly different at the 95% confidence level within nozzle type and pressure category.

[c] Four replications of this test.

Figure 4. Wobbling diffuser (IWOB) sprinkler nozzles in operation.

Figure 5. Single pad grooved plate low drift nozzle (LDN) sprinklers in operation.

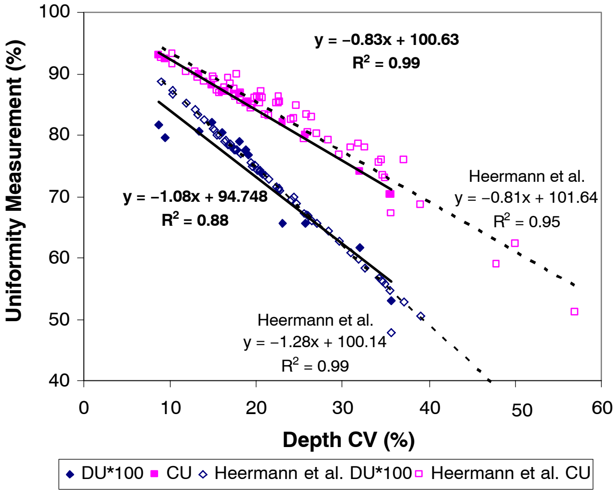

Figure 6. Relationships between DU_{lq} and CU with application depth coefficient of variation (CV) from the present study (bold) and Heermann et al. (1992).

of DU_{lq}, CU, and CV. Since both DU_{lq} and CU in figure 6 are linearly related to CV, then they are linearly related to one another; similar to results reported by Tarjuelo et al. (1999). Thus, trends in DU_{lq} and CU are similar but DU_{lq} changes are greater than CU.

Averaged across all wind speeds and under normal operating pressure where the pressure regulators on each sprinkler provided the proper pressure, the IWOB sprinklers had a CU that was 10% (90% vs. 82%; table 1) higher than the LDN sprinklers, with an example in figure 7. However, under high wind conditions (5.0 to 6.6 m/s) IWOB sprinklers had similar uniformity characteristics to the LDN sprinklers (fig. 8). From table 1, IWOB sprinklers under low pressure and wind conditions, resulted in similar uniformity to normal pressure and low wind (CU = 92% and 93%, respectively), but LDN sprinkler CU degraded 15% (82% vs. 70%) under similar conditions. This trend in decreasing uniformity of grooved plate sprinklers with pressure was also shown by Clark et al. (2003). Figure 9 shows an example of IWOB and LDN performance under low pressure and low wind conditions. Poorer uniformity from LDN sprinklers is likely due to the fixed grooved plate that produces distinct streams (fig. 5) compared to the rotating plate IWOB sprinklers that result in a distribution of droplets. The grooved streams resulted in a recommendation by Dogan et al. (2003) to use sufficiently large catch containers to reduce the bias associated with distinct streams and small (<15-cm diameter) catch containers. Low pressure and high wind conditions degraded IWOB uniformity slightly in some tests but not significantly on average (table 1). In contrast, low pressure operation under higher wind speed resulted in significantly higher LDN uniformity where on average CU improved from 70% to 85%

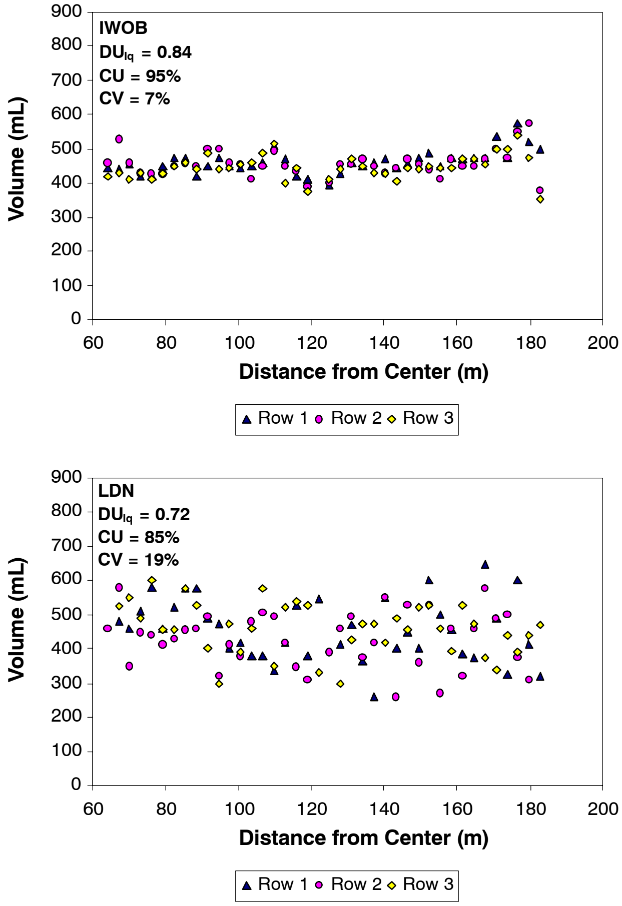

Figure 7. Example of distribution of catch can volume collected on a linear move irrigation system with wobbler nozzles (IWOB) and grooved plate spray nozzles (LDN) under adequate system pressure (221 kPa) and low wind conditions (0.45 m/s).

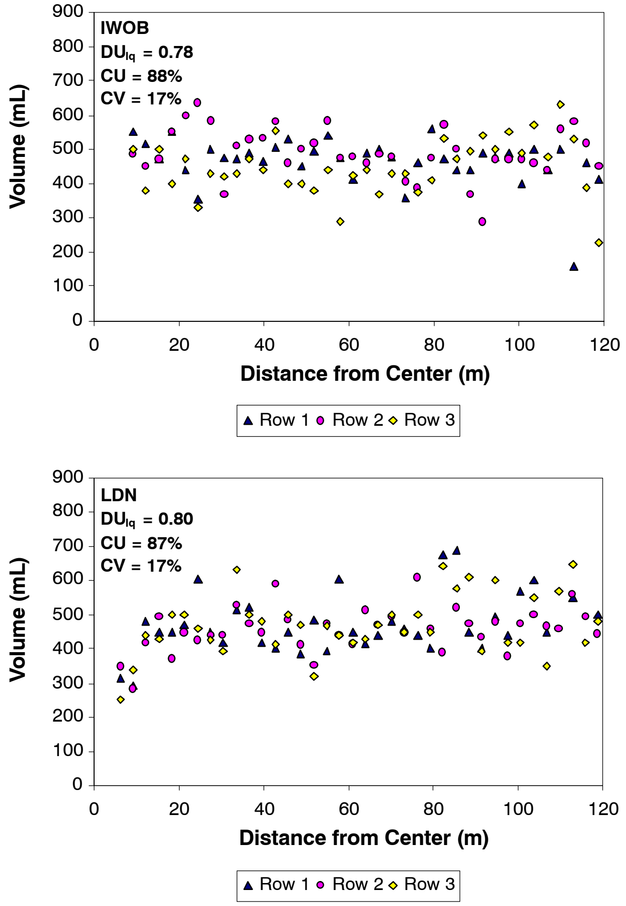

Figure 8. Example of distribution of catch can volume collected on a linear move irrigation system with wobbler nozzles (IWOB) and grooved plate spray nozzles (LDN) under adequate system pressure (290 kPa) and high wind conditions (5.7 m/s).

as wind speed increased from <1.7 m/s to 5.0-6.6 m/s (table 1). An example of this phenomenon is shown in figure 10. Catch can depth was reduced 35% and 36% for IWOB and LDN sprinklers, respectively, as a result of low pressure operation (table 1).

The IWOB sprinklers in this experiment have a rated wetted radius of 7.8 m at 103 kPa (Senninger, 2006a); whereas, the LDN sprinklers have a radius of 6.0 m at 138 kPa according to manufacturer data (Senninger 2006b). When the pressure was lowered to the <97-kPa category, the IWOB nozzles did not have sufficient pressure and the LDN nozzle pressure was at the low end of acceptable pressure. Decreasing pressure on the IWOB nozzles from 103 to 69 kPa would result in a radius of throw reduction of 7.8 to 7.4 m. Comparatively, the LDN radius of throw would be reduced from 6.0 m at 138 kPa to 4.3 m at 69 kPa. These reductions in radius of throw would result in sprinkler overlap changing from 260% and 261% for the IWOB and LDN sprinklers to 247% and 187%, respectively. Actual pressure reductions ranged from 62 to 97 kPa across all lower pressure tests. The reduction in overlap was much larger for the LDN sprinklers relative to the IWOB although the LDN sprinklers still had overlap in excess of 150% recommended by the manufacturer (Senninger, 2006b). The greater overlap reduction for the LDN versus the IWOB sprinklers likely contributed to the higher uniformity of IWOB compared to LDN sprinklers under low wind conditions (table 1).

It is unknown specifically why uniformity of LDN sprinklers increased with higher wind speeds under lower pressure operation. However, during testing it seemed as though the distinct streams of water emitted by the LDN sprinklers (fig. 5) tended to disperse quicker when the pressure was toward the low end of the range in this experiment. This consequence of low pressure operation likely resulted in a more random distribution of droplets that approached the uniformity of the IWOB sprinklers. Hanson and Orloff (1996) also found that grooved plate spray nozzles had higher uniformity under wind increasing from no-wind to windy (2.2 to 4.5 m/s) conditions.

PROBABILITY DISTRIBUTION OF FIELD DATA

The normal distribution has been used to describe the distribution of application depths for solid set (Mantovani et al., 1995; Li and Rao, 2003) and center pivot/linear move (Heermann et al., 1992) sprinklers. The measured distributions of sprinkler application fit the logistic, extreme value, and the beta distributions best, although the goodness of fit tests were not always significant (table 2). In practical terms, however, when the normal distribution was used to represent the application data in the Monte Carlo analysis, the DU$_{lq}$,

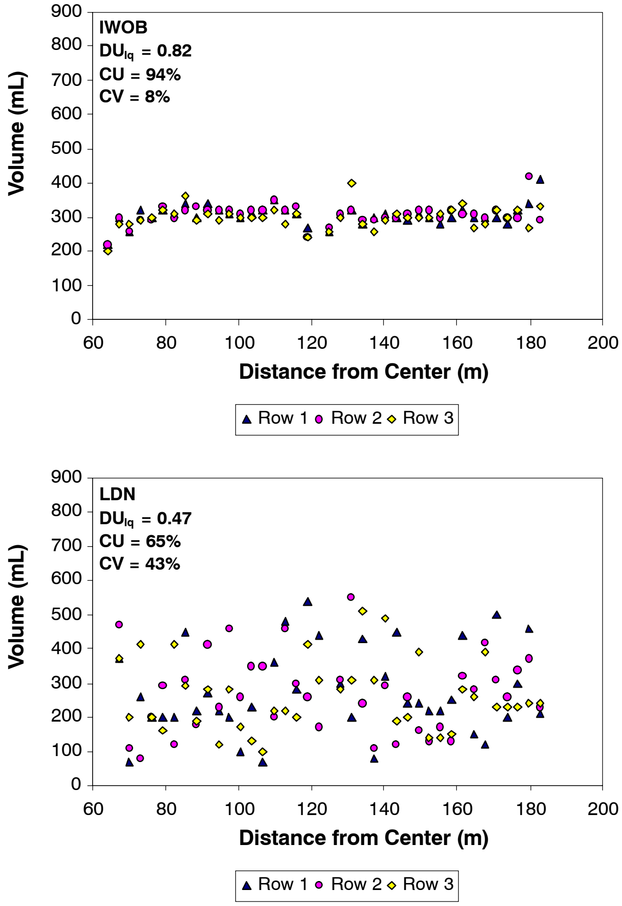

Figure 9. Example of distribution of catch can volume collected on a linear move irrigation system with wobbler nozzles (IWOB) and grooved plate spray nozzles (LDN) under low system pressure (76 kPa) and low wind conditions (1.5 m/s).

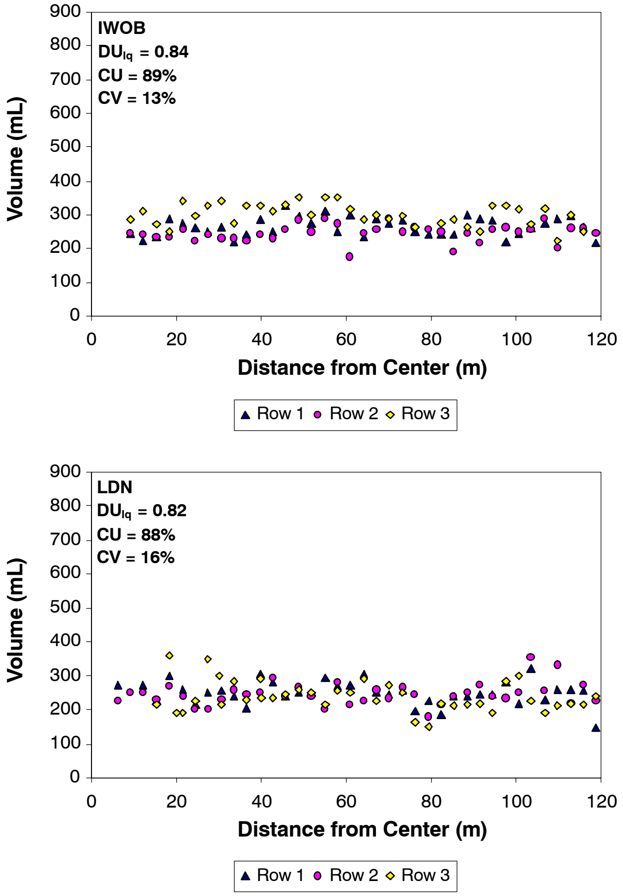

Figure 10. Example of distribution of catch can volume collected on a linear move irrigation system with wobbler nozzles (IWOB) and grooved plate spray nozzles (LDN) under low system pressure (62 kPa) and high wind conditions (5.6 m/s).

CU, and CV did not differ more than a few percentage points from the "best fit" probability distributions except in the case of the LDN sprinklers at low pressure where the normal distribution resulted in 0.41, 63%, and 46%, DU_{lq}, CU, and CV, respectively (table 2). The extreme value distribution (0.61, 72%, and 36%; table 2) better approximated the field data (0.64, 77%, and 29%; table 2).

Warrick (1983) analytically confirmed that CU and DU_{lq} could be approximated as follows:

$$CU = 1 - 0.8\ CV,\ CV < 50\% \quad (3)$$

$$DU_{lq} = 1 - 1.3\ CV,\ CV < 25\% \quad (4)$$

where DU_{lq}, CU, and CV are all expressed as decimals. The DU_{lq} and CU data from the present study and from Heermann et al. (1992) were graphed against CV in figure 6. The regression equations fit the field data well in most cases ($R^2 > 0.95$) and adequate in one other case ($R^2 > 0.88$). When the regression equations in the present study are rearranged such that DU_{lq}, CU, and CV are expressed as decimals they become the following:

$$CU = 1.00 - 0.83\ CV,\ R^2 = 0.99 \quad (5)$$

$$DU_{lq} = 0.95 - 1.08\ CV,\ R^2 = 0.88 \quad (6)$$

Table 2. Probability distributions fit to experimental catch can tests compared to the normal distribution using the mean and standard deviation from the same tests.

Nozzle	System Pressure[a] (kPa)	Probability Distribution	Significance Test[b]	DU_{lq}	CU (%)	CV (%)
IWOB	<97	Logistic	NS	0.70	82	24
IWOB	>200	Logistic	AD	0.80	88	16
LDN	<97	Extreme value	NS	0.61	72	36
LDN	>200	Beta	KS AD	0.72	82	22
IWOB	All	Beta	NS	0.65	78	27
LDN	All	Beta	NS	0.56	70	38
IWOB	<97	Normal	--	0.70	81	23
IWOB	>200	Normal	--	0.79	87	17
LDN	<97	Normal	--	0.41	63	46
LDN	>200	Normal	--	0.71	82	22
IWOB	All	Normal	--	0.65	78	27
LDN	All	Normal	--	0.51	70	38

[a] Pressure for the tests >200 kPa ranged from 200 to 290 kPa and from 62 to 97 kPa for the <97-kPa tests.

[b] NS = not significant.
AD = Anderson-Darling.
KS = Kolmogorov-Smirnov.
"--" = significance test not performed since the normal distribution was fitted to the field data.

and the data from Heermann et al. (1992) become:

$$CU = 1.02 - 0.81\ CV,\ R^2 = 0.95 \qquad (7)$$

$$DU_{lq} = 1.00 - 1.28\ CV,\ R^2 = 0.99 \qquad (8)$$

When equations 5 to 8 are rounded off to the same significant digits as the equations developed by Warrick (1983), except for equation 6 they are identical to the analytical relationships despite the fact that CV in the DU_{lq} relationship approached 40% which exceeds the limit of 25% recommended by Warrick (1983). The slope in equation 6 is slightly smaller than the relationship by Warrick (1983) at 1.1 versus 1.3. Overall, the relationships from the current experiment are remarkably close to relationships found by Heermann et al. (1992) and analytical relationships given by Warrick (1983) despite sprinkler differences and variation in testing conditions over wind speed and pressure.

SUMMARY AND CONCLUSIONS

The uniformity of grooved plate (LDN) and wobbling diffuser (IWOB) low pressure sprinkler nozzles were tested along the length of a linear move irrigation system under a range of wind conditions and two operating pressure scenarios in a humid environment. The IWOB sprinklers resulted in 16% to 25% higher DU_{lq} and 10% to 16% higher CU, as well as a corresponding lower CV of the application depth under the low (<1.7 m/s), medium (3.3 to 3.9 m/s), and high (5.5 to 6.0 m/s) wind conditions in North Florida either at normal operating pressure or at an operating pressure less than the sprinkler regulators. Reducing pressure resulted in 35% to 36% lower application depth on both types of sprinklers. When operating at low pressure, the uniformity of LDN nozzles was significantly better as wind speed increased. Thus, for the best uniformity under a range of conditions IWOB sprinklers would outperform LDN sprinklers under most conditions in North Florida. In addition, for most practical applications the normal distribution approximates the sprinkler distributions adequately.

ACKNOWLEDGEMENTS

The author acknowledges the following for their contributions to the success of this project: James Boyer, Clay Coarsey, Jason Icerman, Stephen Hanks, Mary Shedd, and Kristen Femminella.

REFERENCES

ASAE Standards, 48th ed. 2001. S436.1. Test procedure for determining the uniformity of water distribution of center pivot and lateral move irrigation machines equipped with spray or sprinkler nozzles. St. Joseph, Mich.: ASAE.

Baum, M. C., M. D. Dukes, and G. L. Miller. 2005. Analysis of residential irrigation distribution uniformity. *J. of Irrigation and Drainage Engineering* 131(4): 336-341.

Brito, R. A. L., and L. S. Willardson. 1982. Sprinkler irrigation uniformity requirements for the elimination of leaching. *Transactions of the ASAE* 25(5): 1258-1261.

Burt, C. M., A. J. Clemmons, and K. H. Strelkoff. 1997. Irrigation performance measures: Efficiency and uniformity. *J. of Irrigation and Drainage Engineering* 123(6): 423-442.

Christiansen, J. E. 1941. Uniformity of application of water by sprinkler systems. *Agricultural Engineering* March: 89-92.

Clark, G. A., K. Srinivas, D. H. Rogers, R. Stratton, and V. L. Martin. 2003. Measured and simulated uniformity of low drift nozzle sprinklers. *Transactions of the ASAE* 46(2): 321-330.

Crystal Ball. 2004. Crystal Ball User Manual. Denver, Colo.: Decisioneering, Inc.

Dogan, E., G. A. Clark, D. H. Rogers, and V. L. Martin. 2003. Evaluation of collector size for the measurement of irrigation depths. ASAE Paper No. 032007. St. Joseph, Mich.: ASAE.

Hanson, B. R., and S. B. Orloff. 1996. Rotator nozzles more uniform than spray nozzles on center pivot sprinklers. *California Agriculture* 50(1): 32-35.

Hanson, B. R., and W. W. Wallender. 1986. Bidirectional uniformity of water applied by continuous-move sprinkler machines. *Transactions of the ASAE* 29(4): 1047-1053.

Heermann, D. F., H. R. Duke, A. M. Serafirm, and L. J. Dawson. 1992. Distribution functions to represent center-pivot water distribution. *Transactions of the ASAE* 35(5): 1465-1472.

Keller, J., and R. D. Bliesner. 2000. *Sprinkler and Trickle Irrigation*. Caldwell, N.J.: The Blackburn Press.

Kohl, K. D. 1974. Drop size distribution for medium-sized agricultural sprinklers. *Transactions of the ASAE* 17(4): 690-693.

Kohl, K. D., R. A. Kohl, and D. W. DeBoer. 1987. Measurement of low pressure sprinkler evaporation loss. *Transactions of the ASAE* 30(4): 1071-1074.

Li, J., and M. Rao. 2003. Field evaluation of crop yield as affected by nonuniformity of sprinkler-applied water and fertilizers. *Agricultural Water Management* 59: 1-13.

Li, J., B. Li, and M. Rao. 2005. Spatial and temporal distributions of nitrogen and crop yield as affected by nonuniformity of sprinkler fertigation. *Agricultural Water Management* 76: 160-180.

Mantovani, E. C., F. J. Villalobos, F. Orgaz, and E. Fereres. 1995. Modeling the effects of sprinkler irrigation uniformity on crop yield. *Agricultural Water Management* 27: 243-257.

Marella, R. L. 1999. Water withdrawals, use, discharge, and trends in Florida, 1995. Water-Resources Investigations Report 99-4002, U.S. Geological Survey, Reston, Va.

NASS. 2004. 2003 Farm and Ranch Irrigation Survey, 2002 Census of Agriculture. National Agricultural Statistics Service, United States Department of Agriculture, Washington, D.C. Available at http://www.nass.usda.gov/census/census02/fris/fris03.htm, last accessed 15 July 2005.

Perry, C., and M. D. Dukes. 2004. Effects of variable rate sprinkler cycling on irrigation uniformity. ASAE Paper No. 041117. St. Joseph, Mich.: ASAE.

SAS. 2001. SAS User's Guide: Statistics. Ver. 8.02. SAS Institute, Inc., Cary, N.C.

Senninger. 2006a. IWOB brochure. Clermont, Fla.: Senninger Irrigation, Inc. Available at http://www.senninger.com/pdfs/iWob%20brochure%2005.pdf. Last accessed 4 February 2006.

Senninger. 2006b. IWOB brochure. Clermont, Fla.: Senninger Irrigation, Inc. Available at http://www.senninger.com/pdfs/ldn.pdf. Last accessed 4 February 2006.

Schneider, A. D. 2000. Efficiency and uniformity of the LEPA and spray sprinkler methods: A review. *Transactions of the ASAE* 43(4): 937-944.

Tarjuelo, J. M., J. Montero, P. A. Carrion, F. T. Honrubia, and M. A. Calvo. 1999. Irrigation uniformity with medium size sprinklers part II: Influence of wind and other factors on water distribution. *Transactions of the ASAE* 42(3): 677-689.

Warrick, A. W. 1983. Interrelationships of irrigation uniformity terms. *J. of Irrigation and Drainage Engineering* 109(3): 317-332.