COLLECTOR SIZE EFFECT ON THE MEASUREMENT OF APPLIED WATER DEPTH FROM IRRIGATION SYSTEMS

by

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Abstract

Center pivot irrigation systems are used in crop production across the state of Kansas. The American Society of Agricultural and Biological Engineers (ASABE) standard on uniformity testing of a center pivot system calls for collectors to be used to measure the water depth emitted by the irrigation system. The standard was designed without specially considering the low pressure sprinklers now commonly used on center pivot systems; the recommended collectors may not accurately measure the applied depth from these sprinklers. The collector size effect on measured water depth and measured depth variability was studied for spinning plate, fixed plate, and wobbling plate sprinkler systems.

Five different collector sizes (C2 (5.5 cm), C4 (10.0 cm), C6 (14.8 cm), C8 (20.0 cm), and C10 (27.4 cm)) were studied using four 5x5 Latin squares. Each collector's water depth was measured and statistically analyzed. Two analysis of variance (ANOVA) tests of the collector size effect were reported. Past experimental results were compared to this experiment's results.

The ANOVA for the measured water depth reported no collector size effect for the spinning plate and wobbling plate systems. The ANOVA of the variability of measured depths showed significant differences between collector sizes for the spinning plate system but not for the wobbling plate system. Previous studies of spinning plate and wobbling plate systems reported acceptable variability for all collector sizes. Although some collector sizes measured significantly different mean depths, the numerical difference in mean depths was small. Any studied collector size could be used to measure the water depth of wobbling plate systems, but the C4 collector is ideal. C4 and C6 collectors are ideal for measuring spinning plate systems.

Significant differences between measured depths were reported for the fixed plate system. The C10 measured significantly lower water depths than all other collectors, and the C4 collector measured lower depths than the C2 and C8 collectors. The variability of mean depths was similar and high for all collector sizes. Previous experiments also indicated that different collector sizes measured different depths and had high variability of depth measurements for the fixed plate sprinkler systems. The distinct stream pattern provides a challenge for accurately measuring the water depth with these collector sizes; other methods of measuring uniformity should be considered for fixed plate sprinklers.

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CHAPTER 1 - Literature Review

The uniformity of water application by sprinkler systems is an important characteristic of irrigation system design. Uniformity provides a measurement of system performance by characterizing how consistent is water applied across the entire irrigation system. High uniformity center pivot systems apply the same amount of water at all parts of the system. Potential water conservation and efficiency improvements made possible by sprinkler technology depend on the sprinkler system's ability to accurately and evenly apply water across the entire field. Christiansen (1942, p. 75) states that, "the purpose of a sprinkler is to distribute the water to the soil in the form of a sprinkle or spray so that it can be absorbed without running off". Uneven water distribution patterns can lead to overwatering which lowers crop yields, wastes water, and increases irrigation costs. A uniform water application along a center-pivot system is maintained by controlling the pressure, nozzle orifice diameter, sprinkler spacing, and sprinkler device to regulate the application intensity delivered to the soil. The soil's infiltration rate, surface storage, and crop residue cover influences the appropriate water application rate. An added challenge for uniform water application from center pivot systems is that each subsequent sprinkler requires more water to adequately irrigate the increased area watered by each successive sprinkler (Heermann & Hein, 1968). Center pivot systems should be designed to achieve the proper balance between soil water infiltration rate, crop water requirements, and center pivot capabilities (Dillon et al., 1972). The first significant work in testing the uniformity of water application from sprinkler systems was done by Christiansen (1942) as he studied how to improve sprinkler system performance.

Christiansen's Pioneering Work

Christiansen (1942) noted that sprinkler irrigation applied water to the soil better than surface irrigation because runoff and water ponding, water wastes caused by elevation differences, were minimized. Sprinkler systems eliminated the land grading requirements needed for surface irrigation systems and created less erosion than flood systems (Christiansen, 1942). Christiansen (1942) noted that sprinkler systems could reduce the overall irrigation expense by using less water than flood irrigation systems, although the per unit water cost may be greater for sprinkler systems than flood irrigation systems. He cited the need for irrigation managers to ensure that the soil water content in the field is never overdrawn because of the difficulty of applying enough water to satisfy an initial soil water deficit. Manufacturers had tested the distribution uniformity of their sprinklers to rate the sprinkler performance before Christiansen's study, but never had uniformity tests been used to describe the water application characteristics in the field.

Christiansen (1942) used a grid pattern of collectors to measure the water distributions of single, stationary sprinklers. Over 130 tests using no. 2½ tin cans as collectors measured the distribution of water from slow-rotating sprinklers. The tests showed that low pressures produce uneven water distributions; the under-pressured sprinklers delivered uneven, high-intensity water applications both close to the center of the system and at the outside edge of the sprinkler's radius of throw. Lower operating pressure caused the irrigated area to decrease proportionate to the pressure reduction but did not change the average application rate over the watered area. Uneven sprinkler rotation rates caused low uniformity by watering different parts of the irrigated area for varied durations of time. Christiansen (1942) noted that a triangular arrangement of sprinklers can lead to more uniform water applications than square arrangements for permanent sprinkler systems.

Coefficient of Uniformity Equations

Many different equations have been developed to describe the uniformity of center pivot systems. "Efficiency can be measured in a myriad of ways, and efficiency by one measure may not be efficient by another measure" (Heermann & Solomon, 2007, p.108). A lasting contribution of Christiansen's work was the development of an equation describing the water application uniformity of a sprinkler system. Labeled as the *uniformity coefficient* or *coefficient of uniformity* and abbreviated as CU, the equation is given by

$$CU = 100 * \left[1 - \left(\frac{\sum \left(V_i - V_{mean} \right)}{\left(n * V_{mean} \right)} \right) \right] \qquad (1.1)$$

where CU is the coefficient of uniformity in percent, n is the number of collectors, V_i is the individual collector depth and V_{mean} is the mean collected water depth. Christiansen's CU equation is used to calculate the water application uniformity of a linear move system for the

American Society of Agricultural and Biological Engineers (ASABE) standard (ASABE S436.1, 2007).

Another equation for the water application uniformity that assumes a normal distribution of sprinkler precipitation is

$$UCH = 100 * \left(1 - \frac{0.798s}{\bar{x}} \right) \tag{1.2}$$

where s is the standard deviation of the sample and $\bar{x}$ is the mean of the sample (Seniwongse et al., 1972). This equation was created for its ease of computation compared to Christiansen's CU equation and its ability to predict an irrigation system's performance. This concept was an early precursor of using a uniformity equation to characterize the quality of water application from irrigation systems. The UCH and CU are not significantly different when the uniformity is over 70 percent.

The sum of the squares of errors can be used to define the uniformity coefficient as

$$UCW = 100 * \left(1 - \frac{s}{\bar{x}} \right) \tag{1.3}$$

where s is the standard deviation of the sample and $\bar{x}$ is the sample mean (Seniwongse et al., 1972).

The Christiansen equation has been adapted over the years by different researchers, including most significantly by Heermann and Hein. Heermann & Hein (1968, p. 13) adapted Christiansen's coefficient of uniformity (CU) equation for center pivot systems by weighting the application depth by the area receiving water

$$CU_{HH} = 100 * \left[1.0 - \left(\frac{\Sigma_S S_S * \left| D_S - \frac{\sum_S D_S S_S}{\sum_S S_S} \right|}{\Sigma_S D_S S_S} \right) \right] \tag{1.4}$$

where CU_{HH} is Heermann and Hein's coefficient of uniformity, S_s is the distance from the central axis of the center pivot system to point S, and D_s is the application depth at a distance S from the central axis of the center pivot system. The Heermann and Hein revision of

Christiansen's CU equation has been adopted as the ASABE standard for measuring the water application uniformity of center pivot irrigation systems (ASABE S436.1, 2007).

Other methods of measuring the uniformity of water application have been developed. All equations for uniformity must address the scatter within the data set; two methods of addressing the measurement variability are the mean deviation approach and the standard deviation approach (Marek et al., 1986). The standard deviation approach is more sensitive to outlier values and reports lower CU values than the higher-CU-yielding mean deviation method which reduces the effect of extreme measurement deviations. Unlike Christiansen’s CU equation, the Heermann and Hein CU equation, and most other equations which use the mean deviation approach to measure the uniformity, Marek et al. (1986) created a CU equation that uses both areal-weighting and a standard deviation approach

$$CU_{WSD} = 100 * \left[1 - \frac{\sqrt{\dfrac{\sum^{N} \left[r_i x_i - \left(r_i * \dfrac{\sum^{N} r_i x_i}{\sum^{N} r_i} \right) \right]^2}{N - 1}}}{\dfrac{\sum^{N} r_i x_i}{N}} \right] \tag{1.5}$$

where r_i is the distance from the system's pivot point to the catch collector i, x_i is the depth observation at point i, and N is the number of catch collectors. The CU_{WSD} equation was compared to the Heermann and Hein equation for 190 center pivot evaluations and scored an average of 16 percent lower than the CU_{HH} score which led Marek et al. (1986) to recommend the CU_{WSD} as a highly sensitive equation useful for identifying specific errors, such as nozzle failure, that can lower the CU. A highly uniform sprinkler application with a CU_{HH} value of 93 percent was measured at 91 percent with the CU_{WSD} equation. The CU_{WSD} is most useful for measuring the uniformity of high-performing irrigation systems.

The uniformity of a system is also reported occasionally as the distribution uniformity. Distribution uniformity (DU) is defined as

$$DU = \frac{\left(\frac{\sum r_i * x_i}{\sum r_i}\right)_{lq}}{\left(\frac{\sum r_i * x_i}{\sum r_i}\right)} \tag{1.6}$$

where r_i is the distance from the pivot point to the catch collector i, x_i is the water depth measurement at point I, and $\left(\frac{\sum r_i * x_i}{\sum r_i}\right)_{lq}$ is the low water depth applied to one fourth of the field (Cook, 1990). The low quarter depth represents the average depth of the one fourth of the field receiving the least water and is calculated by identifying the smallest depth measurements and summing the distance between the pivot point and each measurement's corresponding location along the center pivot system until the running total of radii length equals one-fourth of the total summed radius length (Cook, 1990).

ASABE Standards

Uniformity testing and collector sizing are important in two ASABE standards. The ASABE S398.1 *Procedure for Sprinkler Testing and Performance Reporting* (2007) specifies how sprinklers should be tested to determine performance specifications for pressure, flow rate, and radius of throw. The protocol was developed by manufacturers to standardize the reporting of sprinkler performance. This standard does not specify a minimum diameter or height for collectors used in sprinkler testing except that all collectors should be identical, prevent water from splashing into or out of the collector, and the container opening must not be greater than 0.9 m (3 ft) above the ground (ASABE S398.1, 2007). The maximum wind velocity allowable during sprinkler testing is 2.2 m/s (7.9 km/h), and the average wind velocity must be less than 1.3 m/s (4.7 km/h) when measuring the sprinkler's rotation speed, collector precipitation rate, and radius of throw.

ASABE 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* specifically focuses on uniformity measurements of traveling irrigation systems. The standard describes how to measure the application uniformity of center pivot and linear move systems and was designed for high pressure impact sprinkler systems. The ASABE S436.1 standard was written before the development and widespread adoption of low pressure spinning plate, fixed plate, and wobbling plate sprinklers on irrigation systems. Unlike ASABE S398.1, ASABE S436.1 specifies several characteristics of proper collectors and correct collector spacing for measuring the center pivot uniformity. Adequate collectors should prevent water from splashing in or out and the minimum height and diameter must be 120 mm and 60 mm, respectively. Ideally, the diameter should be one half to one times its height (ASAE S436.1, 2007). Collectors should be arranged in two straight lines that extend radially outward from the central axis of the center pivot system like spokes on a wheel with a maximum spacing between the arcs of 50 m; the maximum distance between collectors is 5 m for impact sprinklers and 3 m for spray devices (ASAE S436.1, 2007). The distance between the height of the sprinkler and the top opening of the collector must be at least 1 m (ASAE S436.1, 2007) and the collector opening should be within 0.3 m of the ground surface. The applied water depth during uniformity testing must be at least 15 mm and the center pivot must completely pass over all of the collectors being measured (ASAE S436.1, 2007). Notably, ASABE S436.1 does not recommend or specify what collector diameters are appropriate for specific irrigation sprinkler technologies. Specific uniformity testing methods for low pressure sprinkler technologies like fixed plate, spinning, and wobbling plate sprinklers are not given.

Collector Guidelines

The uniformity of a system has been measured using several different methods. Collectors are the most common method of measuring irrigation depths for uniformity testing (Schneider, 2000). Recommendations of collector properties used in uniformity testing have been made to improve the quality of depth measurements. Due to the challenges of accurate water depth measurements with small catch cans, Schneider (2000) cautioned that small collectors not be used in uniformity studies of spray irrigation systems. Kohl (1972) reported that four characteristics of a good collector include a minimized inner surface area to reduce droplet evaporation, reduction of splashing droplets, white collector walls to minimize the absorption of solar radiation, and easy transporting and measuring capabilities. Increased collector wall heights have been used to limit evaporation and minimize splash-in and splash-out of water droplets (Kohl, 1972). Tipping bucket rain gages were found to not satisfactorily measure high intensity application rates from various sprinkler types such as fixed plate sprinklers (Kelso & Gilley, 1986). Marek et al. (1985) identified several qualities of a good collector including a sharp lip to separate falling water droplets, prevention of splash effects, and droplet evaporation suppression.

Studies of Irrigation System Uniformity

Tarjuelo et al. (1999b, p.666) listed three approaches used to evaluate the irrigation system uniformity:

"The procedures to determine sprinkler water distribution can be grouped into three types:

- Apply the catch can grid to the existing irrigation system: evaluation of the system.
- Place a catch can grid around a single sprinkler head in no-wind conditions and establish the corresponding overlapping for any sprinkler spacing.
- Reduce the catch cans grid to a single-leg in a radial pattern, in no-wind and with high relative humidity conditions. The application rate can be calculated by rotating the radial pattern around the sprinkler."

Past irrigation system studies have measured the water application uniformity with a variety of collector types, sizes, and arrangements in the field. The range of reported uniformity levels from these past studies is high. Several significant studies are reported below.

Kohl (1972) used a separatory funnel in sprinkler precipitation measurements and compared the separatory funnel with metal one-quart oil cans, a frustum can (a frustum can's top and bottom sides have different areas), a 7.6 cm (3 in.) rain gage with 2.5 cm (1 in.) measuring tube, and a plastic wedge-shaped rain gage. The top of the 250-mL separatory funnel was removed above the maximum diameter and the edge was sharpened to separate falling water droplets (Kohl, 1972). Kohl (1972) used diesel fuel as evaporation-suppressing oil for additional tests of all collectors except the 7.6 cm rain gage. Kohl (1972, p. 265) noted that "the slightest wind caused small droplets to swirl into contact with the inner walls and provide opportunity for evaporation loss". The separatory funnel measured the greatest water depth of any collector during the daytime measurements regardless of the application rate. Lower intensity application rates recorded lower catch percentages of applied water, causing Kohl to speculate that CU measurements are affected by the rate of water application. The water application rate varies depending on the distance from the sprinkler. Kohl (1972) stated that most evaporation losses attributed to sprinkler irrigation systems should be credited to collector evaporation.

Marek et al. (1985) evaluated an oil can with a diameter of 10.3 cm (4.1 in) and height of 14.1 cm (5.6 in), a glass separatory funnel with a diameter of 9.0 cm (3.55 in) which curved inward at the top to prevent splash-out and was filled with oil to prevent evaporation, and a fuel funnel with a diameter of 4.9 cm (1.98 in) and height of 4.4 cm (1.75 in). The oil can was found to measure 5.3 percent more than the separatory funnel and the fuel funnel measured 16.7 percent more than the separatory funnel (Marek et al., 1985). The separatory funnel overestimated the water depth by 0.19 percent when compared to the average of 25 rain gauges (Marek et al., 1985). The coefficient of variation (CV) of the separatory funnel's measured water depths was 4.4 percent, the CV of the oil can's measurements was 4.5 percent, and the CV of the fuel funnel's measurements was 12.4 percent (Marek et al., 1985). Both the separatory funnel and the oil can performed consistently in the test, and although the oil can overestimated the water application depth compared to the separatory funnel, Marek et al. (1985) remarked that it could be useful for CU measurements. The fuel funnel should not be used for depth or CU measurement (Marek et al., 1985). In culminating this work, Marek et al. stated, "The use of different collectors for sprinkler measurements can have a significant impact on the estimation of efficiency values" (p.1195, 1985).

Marek and Howell (1987) used previous research detailing the accuracy of the glass separatory funnel to compare the separatory funnel with seven other collector types including: 203 mm (8 in.) diameter rain gage; 76.8 mm (3 in.) diameter No. 303 vegetable can; 102.3 mm (4 in.) diameter 946 mL metal oil can; 102.3 mm (4 in.) diameter 946 mL metal oil can with a rolled lip; 49.7 mm (1.96 in.) diameter fuel funnel and bottle; 99 mm (3.9 in.) diameter 0.45 kg (1 lb) coffee can; and the 80.6 mm (3.17 in.) droplet counting rain gage. These containers were compared to an 84.3 mm (3.32 in.) diameter separatory funnel gage. The study showed that larger collector sizes measured water depths with less variability than smaller collectors (Marek and Howell, 1987). Marek and Howell (1987) stated that the effect of the collector wall on water depths decreases as the collector diameter increases. The minimum collector diameter should be 75 mm (3 in.) to accurately measure water within +/-2 percent of the separatory funnel gage and the collector diameter should be at least 100 mm (4 in.) to measure the water depth within +/-1 percent of the separatory funnel when water is emitted from a flat spray sprinkler without serrations at an elevation of 3.05 m (10 ft).

Clark et al. (2004) used PVC sewer pipe and PVC drain caps to create catch cans for uniformity testing. The pipe edges were sharpened at the collector opening by beveling the top lip to meet the ASABE standard. Testing of collectors made of capped PVC pipe found the water evaporation rates for the exposed PVC collectors to be equal to the atmometer-based grass reference ET amounts of 6.6 to 9.3 mm/day (0.26-0.37 in./day) (Clark et al., 2004). To reduce evaporation, a bottle was mounted to the bottom of the collector barrel and connected through a screw-top lid to allow water caught by the collector to drain into the bottle. A residual water film test revealed that no more than 3 percent of the water would stick to the collector walls during water measurement if the applied application depth was at least 15 mm (0.59 in.) as per rule 5.1.4 of the ASAE Standard S436.1 (2007). These collector devices were titled IrriGages (Clark et al., 2004).

Clark et al. (2006a) used 100 mm (4 in.) IrriGage collectors to measure the application uniformity of fixed plate, wobbling plate, and spinning plate sprinkler packages on low pressure center pivot irrigation systems. Clark et al. (2006a) found that, for fixed plate sprinkler packages during 1999, the 100 mm IrriGages were not acceptable and significantly underreported the water depth by 39 percent, 20 percent, and 18 percent for system pressures of 41, 104, and 138 kPa (6, 15, and 20 psi) when compared to depths measured by 430 mm (17 in.) diameter large pans. The same test of fixed-plate sprinklers was repeated the next year with the only difference that the IrriGage collectors were moved from within the crop area to a bordering grass buffer zone. The second year results revealed that the IrriGages collected significantly more water than the pans (Clark et al., 2006a). The variability of the IrriGage measurements was extremely large for the fixed plate sprinkler package (Clark et al., 2006a). Clark et al. (p. 68, 2006a) concluded that the 100 mm collector diameter is “probably too small to adequately measure average irrigation depths and patterns from sprinklers with fixed plate (FP), coarse-grooved deflector pads”. Combinations of multiple IrriGages were tested to determine the mean depth and variance in an irrigation study in 2002. A 150 mm (5.9 in.) collector measured lower irrigation depths than both the single 100 mm collector and averaged water depths of two 100 mm collectors stacked side-by-side or front-and-back (Clark et al., 2006a). Application depths of spinning plate sprinkler packages using 100 mm IrriGages were found to overestimate water depths when compared to 150 mm collectors, but the differences were relatively small (between 5 percent and 11 percent increase in application depth) (Clark et al., 2006a). The increased collector accuracy is likely due to the smaller droplets and the more dispersed droplet pattern of the spinning plate sprinklers compared to the distinct water streams released by the fixed plate sprinklers. The mean application depth collected was not different in three of the four tests comparing the 100 mm and the 150 mm collectors during the wobbling plate sprinkler test, although the variance of the 100 mm collector was greater (Clark et al., 2006a). Clark et al. (2006a) concluded that lower pressure sprinkler packages, and particularly the fixed plate coarse-grooved sprinklers, should be studied to determine the necessary collector diameter to ensure accurate water depth measurements.

A lab study to determine the minimum collector size for accurate measurements of fixed plate sprinkler systems used collectors similar to the IrriGage (Clark et al., 2004) with diameters of 5.2 cm (2.0 in.), 10.1 cm (4.0 in.), 14.8 cm (5.8 in.), and 19.8 cm (7.8 in.) and compared them with a square collector with a 19.8 cm by 21.1 cm (7.8 in. by 8.3 in.) opening (Clark et al., 2006b). The irrigation depth measurements were highly variable as the square collectors typically measured larger volumes than the 4.8, 10.1, and 19.8 cm collectors but less than the 14.8 cm collectors (Clark et al., 2006b). Six different types of fixed plate sprinklers were studied in this research, and the four fixed plate sprinklers that provided the coarsest, most distinct water streams experienced more variability of measured water depths between the collector sizes (Clark et al., 2006b). The two fixed plate sprinklers that produced the most dispersed water distribution patterns experienced less variability of depth measurements for larger collector sizes. Clark et al. (2006b) concluded that consistently measuring water application depths is difficult even with the 19.8 cm diameter collector size.

Dogan et al. (2003) reported that the 10.2 cm diameter IrriGages collected smaller water application depths than 43 cm diameter pans (8.3-10.3 mm (0.33-0.41 in.) compared to 12.5-13.7 mm (0.49-0.54 in.), respectively) from fixed plate LDN (low discharge nozzle) sprinklers when measured at a variety of pressure settings; the CU was much higher for the large pans than for the 10 cm IrriGages. In a repeat test, the IrriGage collectors overestimated the depth of water application compared to the large pans (17.1-20.2 mm (0.67-0.80 in.) compared with 13.8-14.5 mm (0.54-0.57 in.), respectively) and again experienced lower CU values (though at the lowest pressure the CU_{HH} of both collectors were similar). A 15.2 cm diameter IrriGage collector and a 30.5 cm (12 in.) diameter bucket were not statistically different in depth or uniformity measurements for the fixed plate sprinklers but both collector sizes were different from the 10 cm IrriGage. Averaging two 10 cm IrriGages did not change the depth measurements of the fixed-plate sprinkler system (Dogan et al., 2003). Dogan et al. (2003) concluded that one row of 10 cm diameter IrriGages is sufficient for measuring the uniformity and applied water depth of spinning-plate sprinklers. The 10 cm IrriGage was not different from the 15 cm IrriGage in wobbling-plate measurements and could be used to accurately measure sprinkler system application depth and uniformity (Dogan et al., 2003). Fixed-plate sprinkler systems should be measured by a collector with a diameter of at least 15 cm for accurate depth measurements.

Both 10 cm and 15 cm IrriGages were found to have slightly higher water depth measurements compared to a black pan (43 cm diameter). The 10 cm IrriGage had a lower uniformity measurement than the pan for one spinning plate sprinkler system (Rogers et al., 2009). In tests of spinning plate and fixed plate spray sprinklers, the 15 cm IrriGage had more variability in depth measurements than the 10 cm IrriGage, but both collectors measured more variability than large troughs (12 cm x 48 cm) (Rogers et al., 2009). The 10 cm IrriGage, 15 cm IrriGage, and the 43 cm black pans measured similar uniformity values from a wobbling plate system (Rogers et al., 2009). Collector spacing did not greatly affect CU values leading Rogers et al. (2009) to conclude that collector spacing should be chosen according to the overall objective of the center pivot evaluation (possible objectives might include documenting individual nozzle characteristics or estimating system performance) (Rogers et al., 2009). Rogers et al. (2009) concluded that determining the appropriate collector size for specific irrigation technologies is challenging because of contradictions in laboratory and literature reviews.

Six catch cans were evaluated by Winward and Hill (2007) including the 8.3 cm (3.3 in.) diameter, 19.0 cm (7.48 in.) height separatory funnel; the 8.2 cm (3.2 in.) diameter, 13.0 cm (5.12 in.) height PVC reducer can; the 15.1 cm (5.94 in.) diameter, 17.3 cm (6.81 in.) height metal can; the 6.4 cm by 5.9 cm (2.5 in. by 2.3 in.) rectangular opening, 33.6 cm (13.2 in.) height wedge rain gauge; the 14.6 cm (5.75 in.) diameter, 19.0 cm (7.48 in.) height plastic bucket; and the 10.0 cm (3.94 in.) diameter, 8.5 cm (3.35 in.) height plastic funnel rain gauge. Both the separatory funnel and the PVC reducer were filled with diesel fuel to act as evaporation suppressants (with an accompanying drainage bucket for overflow fuel) but the fuel reduced the collector depth so much that the two collectors violated the ASABE standard for minimum collector depth (Winward & Hill, 2007). Measurements taken from groups of collectors placed at five different distances from a line-source sprinkler recorded that the separatory funnel collected the greatest water depth of all collectors at every distance except for the metal can at the third and fifth levels, the wedge rain gauge at the third level, and the funnel rain gauge and PVC reducer at the first level (the levels were ordered from lowest to highest starting with the farthest collector group from the line-source sprinkler). Larger collectors measured less variable water depths; the variability in measured depths was greatest for the lowest irrigation intensity (the farthest from the sprinkler) and decreased for the higher irrigation intensities (Winward & Hill, 2007). Statistical tests showed no difference in water depths between any of the collectors and the separatory funnel except for the metal can and the white bucket at the lowest water application intensity. The depth measurement variability was highest for small collector sizes and low water depth irrigations. The wedge rain gauge, which was the smallest collector, had the greatest variability in depth measurements while the metal can, with the largest collector opening, had the lowest variability of water depths (Winward & Hill, 2007).

Dogan et al. (2008) used 20 collectors of 10.2 cm (4.0 in.) diameter and 20.0 cm (7.9 in.) height to study the effect of the collector opening height on uniformity measurements by placing collector openings at 30, 60, 90, and 120 cm (12, 24, 35, and 47 in.) above the land surface. The uniformity increased at the higher collector heights but the measured water depths decreased significantly (Dogan et al., 2008). Differences in collector height could lead to measured irrigation depths being 10 mm (0.4 in.) lower and CU values increasing by 6 percent (Dogan et al., 2008). Dogan et al. (2008) found that sprinkler system speed was not significant for determining either uniformity or water depth measurements.

Dukes (2006) found that wind speed and pressure have a significant effect on the CU of spinning plate and wobbling plate sprinklers. When the operating pressure exceeded the pressure regulator set pressure, regardless of wind speed, the CU values were 8 percent greater for the wobbling plate sprinkler than the spinning plate sprinkler. Wind did not significantly affect the wobbling plate sprinklers but during low wind speed conditions the spinning plate sprinklers experienced about 15 percent lower uniformity values than during higher wind speed conditions. Greater uniformity values for the wobbling plate sprinklers were attributed to its consistent wetted area compared to the reduced wetted area formed by the spinning plate sprinklers. If the spinning plate system is under-pressured then high wind speeds improve the uniformity by increasing the breakup of water streams released from the sprinkler.

Hanson and Orloff (1996) used 15.2 cm (6 in) catch cans that were spaced 61 cm (24 in.) apart under two spans of a center pivot system to compare the uniformity of spinning plate and fixed plate sprinkler systems. Single sprinkler analysis was also used to measure the water distribution. The discontinuous jet pattern of the grooved, fixed plate sprinkler resulted in extremely variable collector results while the spinning plate sprinkler produced much more uniform depths. Wind increased the uniformity of the fixed plate sprays due to increased stream breakup and droplet dispersion (Hanson & Orloff, 1996). The coefficient of variation (CV) of depth measurements from fixed plate sprinklers was between 0.154-0.379 during windy conditions and 0.192-0.339 during no wind conditions; these compare to water depth CVs of 0.037-0.128 during no wind conditions and 0.097-0.126 during windy conditions on the spinning plate sprinkler. Uniformity results showed that the spinning plate sprinklers reported higher CU measurements (92-93 percent for wind and 90-97 percent for no wind conditions) compared to the fixed plate sprinklers (84-87 percent for wind conditions and 74-85 percent for no wind conditions).

Faci et al. (2001) studied individual fixed plate and spinning plate sprinklers to describe water distribution, wind drift, and evaporation losses. Using fixed plate and spinning plate sprinklers and 8 cm (3 in.) diameter, 20 cm (7.9 in.) height collectors made of transparent plastic, Faci et al. (2001) noted that the fixed plate sprinklers concentrated the flow in a doughnut-shaped pattern of high application at a constant radius around the sprinkler but the spinning plate sprinkler applied water in a linearly-decreasing pattern from the center of the wetted radius toward the perimeter. Fixed plate sprinklers emit smaller droplet diameters with a much narrower range of droplet sizes than spinning plate sprinklers (72 percent of the applied water volume was in droplets smaller than a 1.5 mm droplet for the fixed plate spray compared to only 46 percent of the applied volume of the spinning plate spray). The distance a droplet travels from the sprinkler is dependent on the droplet mass. Because the fixed plate sprays produce droplets of similar size the droplets fly approximately the same distance. This causes fixed plate sprinklers to distribute water primarily to a narrow band around the sprinkler (Faci et al., 2001). Wind was noted to widen the band of high intensity water application because the gusts varied the droplet travel distances but did not significantly change the overall water application pattern. The maximum application intensity of fixed plate sprinklers is higher than spinning plate sprinklers which can lead to more surface runoff from fixed plate systems; soils with low infiltration rates and high slopes are especially susceptible (Faci et al., 2001). Simulated uniformity measurements based on individual sprinkler performance were reported to be high for all combinations of sprinkler size and height for both fixed plate and spinning plate sprinklers when the sprinkler spacing was 3 m; when the sprinkler spacing increased to 5.5 m the fixed plate sprinkler theoretically indicated lower uniformity measurements than the spinning plate spray for a stationary sprinkler system (83.2-90.5 percent compared to >95.1 percent) (Faci et al., 2001).

Fischer and Wallender (1988) found that the coefficient of variation (CV) of depth measurements from a stationary irrigation sprinkler decreased for larger water depths because the water depth increased more than the standard deviation of the depths. Larger collector sizes measured water depths with less variability than smaller collector sizes during tests conducted for the same length of time (Fischer & Wallender, 1988). Limiting the variability of the water depth measurements is dependent on the distance between the sprinkler and the collector. More collectors were required to reach an acceptable CV at distances very close or very far from the sprinkler (Fischer & Wallender, 1988). Fischer and Wallender (1988) concluded that large diameter collectors operated for short time durations experienced the same variability of water depths as small collectors operated for long time periods. Liang and Wu (1970) state that the goal of a sprinkler system should be to limit variation in application uniformity to 20 percent or less; this requires a CU uniformity of at least 80 percent.

Dukes and Perry (2006) used containers with 16 cm (6.3 in.) diameters and 20 cm (7.9 in.) heights to measure the uniformity of spinning plate, fixed plate, and wobbling plate sprinklers. Thirty catch cans were placed in each of six collector lines for the spinning plate center pivot system. Six lines of 18 catch cans were used for the linear move system with wobbling plate and fixed plate sprinklers. Dukes and Perry (2006) found that the spinning plate sprinklers had a CU of 95 percent. The fixed plate sprinkler CU rating was 78 percent and the wobbling plate sprinkler had a CU rating of 91 percent. All three uniformities are the average of separate CU measurements and were conducted in low wind conditions. In a test of the effect of irrigation system movement speed, variable sprinkler rate, and sprinkler type on system uniformity, Dukes and Perry (2006) found that sprinkler type was the only significant factor affecting application uniformity.

The effects of wind speed, operating pressure, sprinkler height, sprinkler type, and area of irrigation on application uniformity were studied by Montero et al. (1998) using collectors of 16 cm (6.3 in.) diameter and 15 cm (5.9 in.) height. 58 center pivots were tested with a 2 m (6.6 ft) catch can spacing from the pivot point to the end of the lateral. Higher CU values were reported when the sprinkler height was raised (78.1 percent, 83.6 percent, and 86.7 percent at sprinkler heights of 1.5 m (4.9 ft), 2.5 m (8.2 ft), and 4.0 m (13.1 ft), respectively) and were significantly different at the 90 percent significance level (Montero et al., 1998). Increasing the sprinkler height improved the uniformity of the fixed plate sprinklers because the additional droplet travel distance allowed the distinct water streams to completely break apart. Wind helped to improve the uniformity of sprinklers mounted at a one meter height by causing additional water stream breakup. The average CU of 20 impact sprinkler tests was 86.8 percent compared to an average CU of 85.0 percent from 38 fixed plate sprinkler tests. Low pressure systems (55-150 kPa) averaged 87.2 percent CU, medium pressure (150-250 kPa) averaged 86.5 percent CU, and high pressure (250-375 kPa) averaged 84.3 percent CU in this test.

Hanson and Wallender (1986) used collectors of 11 cm (4.3 in.) height and 7.8 cm (3.1 in.) diameter to study the effect of tower movement on the application uniformity of linear move and center pivot systems. Collectors oriented parallel to the direction of travel reported CU values of 89 percent near the guide tower but only 75 percent in the middle of the linear move system; the center pivot system had CU values of 90 percent near the guide tower and 76 percent in the middle of the pivot (Hanson & Wallender, 1986). The calculated uniformity of measured depths taken from collectors oriented parallel to the irrigation system lateral pipe was 73 percent for the linear move and 77 percent for the center pivot. Hanson and Wallender (1986) gave several factors that determine the severity of low application uniformity's impact on crop performance, including the movement of water in the soil, the degree of low uniformity, the seasonal total of low uniformity, the volume of applied water, and the crop's sensitivity to water stress caused by reduced irrigation uniformity.

Although CU is measured above ground with catch cans, a uniform water application is valuable because it leads to a consistent distribution of water throughout the crop root zone. Hart (1972) studied how non-uniform water applications infiltrate and move through the soil profile by investigating factors including: initial soil water content; application rate; surface application uniformity; areal extent of surface application; soil properties; total applied water; and initial water distribution in the soil. Water moves through wet soil quicker that through dry soil. Within 36 hours after water application, an irrigation event that had a surface uniformity of 60 percent was calculated to have reached 85 percent uniformity in subsoil moisture measurements (Hart, 1972). Within 26 hours of irrigation, a surface-measured CU of 70 percent was measured in the sub-surface at 85 percent and was still increasing in uniformity. Hart (1972, p. 659) argues that "such a measurement [referring to surface-measured CU uniformity] may not be as important as originally supposed", indicating that high uniformity of water application may not be critical for good crop performance because the water can redistribute in the soil. Large water irrigations distribute in the soil quicker than small water irrigations. Hart (1972) showed that increased collector spacing diminishes the detail of the uniformity analysis and results in an inflated estimation of system uniformity by reducing the number of data points; the uniformity tests overestimate the CUs from low uniformity systems the most. Hart (1972) concluded that lateral and vertical soil moisture gradients are responsible for the distribution of water in the subsoil. Pair (1973) found that water applied at CU values of 87.2 percent yielded 18.06 metric tons/hectacre, 86.8 percent yielded 18.24 metric tons/hectacres, 63.0 percent yielded 18.24 metric tons/hectacre, and 16.0 percent yielded 16.94 metric tons/hectacres.

In a study to measure differences between high, medium, and low pressure sprinklers, DeBoer et al. (1992) found that increasing the sprinkler pressure decreased the application rate intensity and expanded the sprinkler's wetted diameter. The lowest pressure sprinklers (two different types of fixed plate sprinklers) produced surface runoff amounts averaging about 20 percent of applied water over the four year study compared to 10 percent or less for the two high-pressure impact sprinklers (DeBoer et al., 1992).

Henggeler and Vories (2009) hypothesized that center pivot uniformity testing is more accurately represented by data points created by averaging neighboring collectors than single collector data points because the applied water will redistribute in the soil. They conducted 60 field evaluations of center pivots using catch cans with a 9.2 cm (3.6 in.) opening diameter and 15 cm (5.9 in.) depth (Henggeler & Vories, 2009). They discovered that by reporting each measured depth as the average of three surrounding depth measurements (the preceding collector, the collector at the position, and the next collector) the CU increased by 4 percent. The overall water distribution uniformity in the soil is usually 10 percent greater than the uniformity indicated by catch cans measurements (Seginer, 1978).

Li and Rao (2001) used 36 catch cans (11.3 cm (4.45 in.) diameter) to measure the water application uniformity at the soil surface and 16 catch cans to measure the CU in the crop canopy to compare the CU of surface water distribution with the soil water content uniformity calculated from soil moisture measurements. Li and Rao (2001) also studied the effect of surface CU on crop yield. Soil moisture uniformity was greater than 90 percent for all tests at both 50 cm (19.7 in.) and 100 cm (39.4 in.) depths while the surface CU ranged between 67-89 percent at the ground level and 57-84 percent in the canopy for the two plots (Li & Rao, 2001). Increased winter wheat yields were noted for the higher uniformity water applications, but the grain yield increases were statistically significant. Grain yields were more uniform than either of the collector measurements. Li and Rao (2001) concluded that the uniformity of applied irrigation is not critical for sustaining high winter wheat yields when the field receives 15 cm (5.9 in.) of precipitation throughout the year.

Cook (1990) used 10 cm (3.9 in.) diameter containers spaced at 4.5 m (14.8 ft) intervals to measure the application uniformity of one center pivot system using spinning plate sprinklers; requirements of ASABE S436.1 (2007) were followed for this study. Collectors were placed in four collector rows in the field and each pair of two rows was separated by five degrees. The center pivot system had a swing arm corner system and end gun; one pair of collector rows was designed to catch water with the swinging corner system fully extended while the other pair of rows measured the water depths when the corner system was retracted. The collectors were not moved over the course of the summer; all measurements were conducted during the normal operation of the center pivot system. The CU uniformity of 28 separate collector row calculations of the system averaged 85.6 percent and ranged between 92.7 percent and 78.4 percent. Fifteen CU measurements were made when the corner system was fully extended and averaged 87.3 percent. The average CU of the 13 tests with the corner system retracted was 83.6 percent (Cook, 1990). The application depth of the center pivot system varied between 1.8 cm and 2.5 cm (0.71 – 0.98 in.). The center pivot system was noted as operating at a pressure 14 percent below the design specifications.

According to Duke et al. (1992), the prevailing wisdom for determining the correct irrigation depth to apply to fields in situations of cheap water, fuel, and fertilizer has been to excessively irrigate 85-90 percent of the field to ensure that the water applied to the least watered 25 percent of the field is sufficient for all plant needs. Although noting that uniformity typically increases when averaged over a period of events, Duke et al. (1992) claimed that improvements in crop yields were caused by increased uniformity of low pressure, in-canopy spray sprinklers and not by reduced evaporation and wind drift losses. Low uniformity water applications require greater volumes of water to satisfy the crop's water demands (Paz et al., 1998). Seginer (1978) stated that, in conditions of cheap water, the optimum irrigation target is to maximize yield per unit area, but when water prices increase the optimum irrigation indicator is found by maximizing yield per volume of water.

Other Factors Affecting Uniformity

Accurate measurement of irrigation system uniformity is highly dependent on the collector properties, irrigation system, and external factors that can produce errors during testing. Several of these other factors include droplet sizes, wind characteristics, collector placement, and random sources of error such as wind and evaporation.

Droplet Diameter

Larger droplets (from droplets with larger diameters) can have a significant effect on the soil surface. The speed of falling water droplets will approach terminal velocity in the vertical direction and the prevailing wind velocity in the horizontal direction (Kincaid, 1996). The kinetic energy is determined by the mass and velocity of a droplet. The kinetic energy of fixed plate sprinkler water droplets does not change even if the sprinkler height changes, but wind can increase the kinetic energy of droplets by 2 to 3 times (Kincaid, 1996). Falling water droplets, by following directly on bare soil, can create surface seals which lower the soil's infiltration rate (DeBoer & Monnens, 2001). Higher kinetic energy droplets are more likely to create these surface seals. Sprinkler properties affect the distribution pattern of water by controlling droplet size and velocity. In a study of spinning plate sprinklers, DeBoer and Monnens (2001) found that the D50 droplet diameter (the droplet diameter corresponding to 50 percent of the applied water volume) increased from 0.6 mm at a radius of 2 m (6.6 ft) from the sprinkler to 3.5-5.5 mm at radiuses of 8-10 m (26.2-32.8 ft). Longer droplet travel distances improve uniformity levels (Vories & von Bernuth, 1986).

The droplet diameter is controlled by several different factors such as the irrigation technology, operating pressure, and nozzle size. Larger nozzle sizes produce larger water droplets and increased droplet kinetic energy, while higher sprinkler pressures decrease the droplet size and reduce kinetic energy (Kincaid, 1996). DeBoer and Monnens (2001) observed that higher operating pressures caused the water droplet diameter to decrease. Nozzle pressure affects droplet sizes for spinning plate sprinklers and rotating plate sprinklers more than fixed plate sprinklers. Droplet sizes from fixed plate sprinklers are determined by the nozzle diameter (Kincaid, 1996). Larger nozzles and lower pressures created larger drop sizes (Solomon et al., 1985). Flooding nozzles produce a wide distribution of drop sizes and larger droplet sizes overall than other nozzles (Solomon et al., 1985). Fixed-plate sprinklers were noted to produce droplet diameters within a narrow band concentrated around a central size (Solomon et al., 1985; Kincaid et al., 1996). Kincaid et al. (1996) created an extensive index of common droplet sizes produced by a variety of sprinkler types currently used in the irrigation industry. The more grooves used in a fixed plate sprinkler, the smaller the resulting droplet size for a given pressure and nozzle size. The droplet size of spray sprinklers is more affected by the nozzle size than by operating pressure but impact sprinkler's droplet size is determined more by pressure than nozzle size. Spray sprinklers operated at pressures above 103.5-138 kPa (15-20 psi) emit very fine water droplets that are susceptible to evaporation or wind drift (Burks, 2010).

Rainfall diameters are commonly between one and two mm for almost all storm events except heavy thunderstorms (Mueller & Kidder, 1972). Ocampo et al. (2003) reported that water losses are high for those systems that produce small water droplets and/or suspend the water droplets in the air for a long period of time. During wind speeds of 9.1-15.2 m/s (30-50 ft/s), between 40-90 percent of 1 mm drops are missed by an eight inch diameter rain gauge and at 12.2 m/s (40 ft/s) over 20 percent of 2 mm drops are missed by the rain gauge (Mueller & Kidder, 1972). About 10 percent of the 1 mm diameter drops are missed by the rain gauge for 6.1 m/s (20 ft/s) wind speeds (Mueller & Kidder, 1972). Neither 3 mm nor 5 mm drops were affected by the higher wind speeds (<5 percent catch disturbance) (Mueller & Kidder, 1972). The water droplet size controls the extent of wind drift and evaporation loss (Solomon et al., 1985). Wind drift affects catch can effectiveness and spray pattern disturbance. Droplet diameter influences the evaporation rate because small droplets evaporate more than large droplets, thus affecting the water depth measured by a collector (Kohl, 1972).

Higher operating pressures caused the D50 to decrease but larger nozzles caused the D50 diameter to increase (Kohl, 1974). Distinct water streams emitted by a sprinkler break into individual droplets because turbulent eddies within the water stream pull apart the water droplets into a constantly expanding mass of water (Kohl, 1974). Wind resistance is important for stream breakup because wind alters the flight path of individual droplets more than the distinct water stream (Kohl, 1974). Stream breakup is proportional to the stream velocity and the cross-sectional area of the water stream (Kohl, 1974).

Wind

Livingston et al. (1985) noted that wind affects the accuracy of catch-can measurements by altering how water droplets are collected by the can. Wind changes the water application of a sprinkler by carrying water droplets farther in the wind direction and concentrating water in the directions perpendicular to the wind direction (Christiansen, 1942). The uniformity of impact sprinklers in properly spaced stationary systems was not affected by wind because all sprinklers were equally affected (Christiansen, 1942). Colombo et al. (2009) found that wind lengthened the wetted radius by +1 percent per 1 m/s (3.3 ft/s) (wind velocity) in the downwind direction and -7 percent and -0.6 percent per 1 m/s (wind velocity) in the upwind and crosswind directions, respectively. Wind shifts the gravity center of water application 1 m (3.3 ft) in the wind direction for every 1 m/s of wind speed, reduces the radius of throw in directions perpendicular to the wind direction, reduces the total wetted area, and increases the application rate near the sprinkler center with a rapid reduction of application rates in the direction into the wind and gradual application rate reductions in the direction that the wind is blowing towards (Tarjuelo et al., 1999a). Higher wind speeds and smaller droplet sizes increase the collection rate error (Hendawi et al., 2005). Wind tunnel experiments revealed that higher wind speeds decreased the percent of rainfall caught for three different-sized collectors; the largest collector was most affected (Livingston et al., 1985). Larger nozzles and/or lower pressures, which both produce large droplets, are less affected by wind (Vories & von Bernuth, 1986).

Wind affects both the distribution of water around the sprinkler and the air flow pattern around the collectors, which impacts how a collector intercepts water droplets. The localized airflow around a funnel collector with an upper cylindrical opening of 25.0 cm (9.84 in.) diameter and 10 cm (3.9 in.) height was impacted by windy conditions. The airflow over the top of the collector accelerated by 1.3 m/s (4.3 ft/s) for wind speeds of 8 m/s (26.2 ft/s) (Hendawi et al., 2005). Smoke tests demonstrated that an upward air draft formed over the can, explaining why collectors measured lower catch percentages during high wind conditions. Falling raindrops hit the upward draft and were channeled around the catch can instead of falling into the collector

(Livingston et al., 1985). Wind swirl velocities between 2-3 m/s (6.6-9.8 ft/s) inside the collector caused by 8 m/s wind speeds caused some measurement error. Water droplets smaller than 2 mm experienced much greater losses (in terms of catch percentage) than larger water droplets; an 8 percent reduction of collected water was seen for water droplets of 0.5 mm at wind speeds of 4 m/s (13.1 ft/s) (Hendawi et al., 2005). This test emitted water droplets over a range of sizes and measured the catch percentage at four different wind speeds (Hendawi et al., 2005). The collectors measured catch percentages of at least 95 percent for droplets at least 1.5 mm in diameter. Wind-exposed rain gages were found to measure water depths between 5-15 percent less than rain gages located in pits or protected by side barriers that reduced the air drafts around the collector (Neff, 1977). The measured depths of the exposed rain gages ranged between 0-70 percent of the total catch depending on the magnitude and timing of winds. Neff (1977) commented that error levels of 5-10 percent might not affect large-scale precipitation projects but could extremely complicate localized studies, such as a center pivot uniformity study.

Winds can both decrease and increase the water application uniformity of an irrigation system. Kincaid (2005) used metal cans of 150 mm (5.9 in.) diameter and 150 mm (5.9 in.) height for testing spray pattern widths; the research used rotating plates, spinning plates, and wobbling plate sprinklers but avoided fixed-plate sprinklers because “they [meaning fixed plate sprinklers] produce ‘point applications’ which are difficult to measure with catch cans” (Kincaid, 2005, p. 607). Wind reduced the irrigated area regardless of the angle of incidence between wind direction and the irrigation system (Kincaid 2005). Kincaid (2005) noted that greater pattern widths, and therefore lower application rates, can be achieved by using two-staged sprinkler nozzle heights. The higher sprinkler height experiences more evaporation and drift losses but also expands the wetted area of the system. Increased wind speed intensity decreased the CU values and the wetted area (Tarjuelo et al., 1999a).

Wind exerts a greater influence on water droplet distribution as the sprinkler height increases (wind moved the gravity center of water application 1.53 m (5 ft) when the sprinkler height was 2 m (6.6 ft) but only 1.07 m (3.5 ft) when the sprinkler height was 0.6 m (2 ft)) and the sprinklers installed at high heights had increased CU during winding conditions (Tarjuelo et al., 1999a). The increase in uniformity was attributed to increases in radius of throw for the higher sprinkler heights (Tarjuelo et al., 1999a). The sprinkler system design, working pressure, and the nozzle number, size, and configuration determines the water distribution ability of the system (Tarjuelo et al., 1999a). Using catch cans of 16 cm diameters and 15 cm heights, Tarjuelo et al. (1999a) found that a square grid network of catch cans measured similar CU values during windy conditions compared to no-wind and high relative humidity conditions. Wind's effect on the uniformity of irrigation application is heavily dependent on the size of the water droplets emitted by the irrigation system.

Evaporation

Another major source of collection error comes from the evaporation of water caught by the collector. Evaporation that occurs between the sprinkler and the ground is not measured during CU testing. Sunshine has a significant impact on evaporation of spray droplets (Christiansen, 1942). Evaporation rates are controlled by climate, time of exposure, and water droplet surface area (Smajstrla & Zazueta, 1994). Average evaporation losses are affected by wind speed and vapor pressure deficit which vary according to geographic location and time of day (Dylla & Shull, 1983). Christiansen (1942) indicated that only a very small part of the discharged water is in the form of droplets that would be lost due to evaporation or wind drift and that the maximum evaporation loss of the applied water is two percent. Christiansen (1942) stated that the evaporation of rain drops was insignificant compared to evaporation from wet soil and vegetation. Evaporation from wet soil occurs in the first five days after irrigation, with most losses from water stored in the upper one foot of soil (most losses are from the top four inches of the soil). Fields of growing crops have much less evaporation from wet soil than bare fields due to crop shading and rapid plant transpiration of water at the soil surface (Christiansen, 1942). Collector measurements taken during high relative humidity conditions recorded about 10 percent more water than measurements taken during low relative humidity conditions (Ocampo et al., 2003). If certain sections of a field are watered at the same time for every irrigation cycle of continuous operation irrigation systems (i.e. a part of a field is always watered in the afternoon) different water depths will be applied to the field because evaporation will reduce the effective water depth applied during the daylight hours. For this reason most center pivot systems are timed to operate in 84 hour (3.5 day) cycles (though some systems are timed for 60 hour, 2.5 day rotations) so that the timing of water application is variable. The maximum evaporation rate of nine tests of low pressure sprinklers was 1.4 percent and the average evaporation loss was 0.8 percent (Kohl et al., 1987). Kohl et al. (1987) commented that errors in accurate collection of water and evaporation of water from catch cans have often been falsely credited to droplet evaporation between the sprinkler and the ground.

Evaporation of collected water from the collector lowers the accuracy of water depth and uniformity measurements. Several different strategies have been employed to reduce the evaporation of collected water. Marek et al. (p. 1192, 1985) used lightweight oil in separatory funnels to “provide an overburden for splash effects, maintain a constant surface area, and prevent evaporation”. Displaced oil was allowed to freely drain from the collector into a receptacle for later disposal. The separatory funnel had the lowest CV value of any collector in the study and measured the water depth within 0.19 percent of the averaged mean of 25 oil cans leading Marek et al. (1985) to conclude that the separatory funnel with evaporation-suppressing oil accurately measured irrigation levels. Clark et al. (2004) attached a storage bottle to reduce evaporation losses from IrriGages. In a four-week comparison of the evaporation rate of IrriGage collectors, the standard grass-reference ETo, and a commercial rain gauge the IrriGage demonstrated only one instance of measureable evaporation loss (which was 0.1 mm/d) (Clark et al., 2004). The average grass-reference ETo was 49.3 mm per week, the rain gage recorded average ET losses of 16.2 mm per week, and the IrriGage lost only 0.13 mm per week. Clark et al. concluded that “the IrriGage can be a useful tool for in-field measurement of rainfall or irrigation amounts without the concern for substantial evaporation of collected water” (p. 466, 2004). In measuring evaporation rates of the six collectors, Winward and Hill (2007) found that, without evaporation-suppressing oil, the separatory funnel and PVC reducer had evaporation rates of 1.81 mm/hr and 0.71 mm/hr. The funnel rain gauge was similar to the IrriGage design in that water was stored in a container connected to the water collection device by a narrow diameter funnel; the standing evaporation rates for the funnel rain gauge were 0.04 mm/hr (Winward & Hill, 2007). Standing evaporation tests found that evaporation loses more water than splash effects which led to a recommendation for determining a maximum collector diameter to minimize evaporation (Winward & Hill, 2007). Evaporation from the collector sidewalls was greater than evaporation from water collected and stored in the bottom of the collector (Winward & Hill, 2007). Hodges et al. (1990) observed that one advantage of using a tipping bucket rain gage is that evaporation losses are not incurred during data measurement; however, the cost of a tipping bucket gage can be prohibitive for a complete uniformity test.

Collector Spacing and System Movement

Uniformity measurements can also be affected by the collector spacing used in the test. Using a simulated model of water application from a center pivot system, Bremond and Molle (1995) concluded that uniformity calculations using two rows of collectors are not statistically different from calculations using one row if the distances between the central axis of the center pivot system and each collector are the same for collectors in both rows. If two collector rows are used and the collector spacing is the same for both rows but the collectors in each row are placed at different distances from the system's central axis, the uniformity measurement is improved. The maximum spacing between measurements should be no more than 5 m (Bremond & Molle, 1995). Pragada (2008) found that CU calculations using either 33 percent or 50 percent subsets of a dataset of measured depths were not significantly different from CU calculations made using the entire dataset. Using CU values from linear-move systems, center pivot systems, and simulated data, Clark et al. (2003) recommended that the maximum sprinkler spacing should be 20 percent of the wetted diameter of the fixed plate sprinklers. A correlation between increased fixed plate sprinkler spacing and lower CU values was demonstrated. For low pressure center pivot systems the maximum fixed plate sprinkler spacing should be 1.8 m (Clark et al., 2003). Vories and von Bernuth (1986) noted that smaller sprinkler spacings typically increased both CU and equipment cost.

In an experiment on how lateral move speed impacts system uniformity, Hills et al. (1988) found that collectors placed in a line parallel to the irrigation system (which measures the uniformity of applied water depths along the center pivot system) had higher CU values than collector rows perpendicular to the system (which measures the uniformity of water depths along the travel path). The system was installed with drop tube sprayers. Systems that use boom sprayers had higher CU values on collectors arranged perpendicular to the irrigation system lateral (the difference between parallel and perpendicular measurements was low). Spray booms are most effective when the sprinklers are spaced at 70 percent of the distance of sprinkler throw (Kincaid, 2005). Smaller sprinkler spacings produce higher uniformity ratings, and high wind speeds and double nozzle sprinklers increase the need for small sprinkler spacings (Tarjuelo et al., 1999a). As the spacing of fixed plate sprinklers increases the CU decreases rapidly (Hills et al., 1988).

Other Factors

The uniformity of irrigation systems can also be affected by other less-studied causes. Low energy precision application (LEPA) has a very high water application rate and the uniformity is determined by the intermittent tower movement of the system (Buchleiter, 1992). Measured water applications demonstrate that water uniformity was greatest at the guide tower because the system movements were most uniform; the CU of LEPA near the guide tower was similar to the uniformity of low pressure fixed plate sprinkler systems but the CU in the middle of the LEPA pivot was much lower than the fixed plate sprinkler system uniformity (Buchleiter, 1992). Stationary irrigation system uniformity can be affected by individual sprinkler rotation differences. Inconsistent sprinkler rotation speeds increase the variability of measured water depths (i.e., the sprinkler does not rotate at a constant rate) (Li & Kawano, 1996). Li and Kawano (1996) found that the CU decreased when the sprinkler rotation speeds fluctuated by more than 20 percent for riser-mounted sprinklers, though total reductions in CU were no more than 3 percent.

A potential error source in catch-can uniformity testing is leaking overhead pipes or drips from trusses, sprinkler drops, and other system structures that are caught by collectors and impact the measured water depth (Heermann & Solomon, 2007).

Application uniformity can be maintained at satisfactory levels during low flow conditions until flow is reduced to 50 percent, after which the uniformity drops rapidly (King et al., 2009). Turbulence in the main nozzle reduced nozzle discharge (between 7-10 percent) and maximum wetted radius (0.5 m of a radius of 16 m) but did not affect the uniformity of throw (Tarjuelo et al., 1999b). Double nozzles attached to impact sprinklers improved the irrigation uniformity (Tarjuelo et al., 1999b). Vane-straightening nozzles reduced the CU (Tarjuelo et al., 1999b). Double nozzle sprinklers were found to demonstrate higher uniformity at low wind speeds but single nozzle sprinklers had greater uniformity at high wind speeds (Tarjuelo et al., 1999a).

Sprinkler that produce ‘triangular’ distribution patterns (those sprinklers that emit the most water at the sprinkler and linearly less water at farther radii of throw) apply water more uniformly with tighter sprinkler spacings and low wind speed conditions (Tarjuelo et al., 1999a). Rectangular sprinkler patterns (those that emit the same water depth over the entire irrigated area) produce high uniformity applications even during high wind speeds and with wider sprinkler spacings (Tarjuelo et al., 1999a). Gohring and Wallender (1987) used a radial leg test to describe the water distribution from a single sprinkler at different nozzle and pressure settings. The water distributions were used to theoretically calculate the uniformity of different sprinkler spacings. Water distribution patterns that resemble a donut shape with large water depths applied at the center and edges of the irrigated area have varying CU values determined by how the water application patterns align. Changing the spacing of sprinklers that produce triangular water distributions (those with the greatest water application at the center of the irrigated area) minimally changes the uniformity as long as the spacing is less than the sprinkler's wetted diameter (Gohring & Wallender, 1987).

Study Objective

Conflicting results have been noted in the published studies about the minimum collector diameter required for accurate measurement of water depths from low pressure sprinklers such as fixed plate, spinning plate, and wobbling plate sprinklers. This study will evaluate the accuracy and variability of depth measurements recorded by different collector sizes from spinning plate, fixed plate, and wobbling plate sprinkler systems. The objectives of this research are to:

1. Identify the ideal collector size for measuring the application depth of spinning plate, fixed plate, and wobbling plate sprinkler systems.
2. Determine the accuracy of using a given number of collectors to estimate the true application depth of spinning plate, fixed plate, and wobbling plate sprinkler systems.

CHAPTER 2 - Methods and Materials

This study measured the water depth applied by three different sprinkler types with collectors of five different diameters. Field evaluations were conducted at three farms around Garden City, KS including Gigot Farms (spinning plate), Alexander Farms (fixed plate), and the Southwest Research and Extension Center Research Farm (wobbling plate). The spinning plate sprinklers at Gigot Farms were Nelson A3000 Accelerators with Nelson 69 kPa (10 psi) Integral Series pressure regulators (low flow) with sprinkler heights approximately 1.5 m (5 ft) above the ground surface. Nozzle sizes at the collector site were Nelson #28, #28, and #29; the sprinkler spacing along the center pivot system was 3.05 m (10 ft). The field had a rolling slope and was planted in alfalfa. The fixed plate sprinklers at Alexander Farms were 1.8 m (6 ft) above the ground surface and spaced at 1.5 m (5 ft) intervals along the center pivot lateral. Sprinklers were Senninger LDN sprays with D3000 blue plates and #29 nozzle sizes and were operated with Senninger 104 kPa (15 psi) regulators. The field was planted into alfalfa and had large slopes throughout the field but the ground surface was level at the collector study site. The wobbling plate sprinklers were Senninger I-Wobs with LA9 pads and used the 33/128th in. nozzle size; Senninger 83 kPa (12 psi) pressure regulators were attached. The collectors were placed in a harvested soybean field of very little slope for the wobbling plate system. The wobbling plate sprinklers were spaced every 2.3 m (7.5 ft) and were 2.3 m (7.5 ft) above the ground surface.

Twenty collectors each of five different sizes were constructed for this study. All collectors were 20.3 cm (8 in.) tall. Collector diameters were 5.5 cm (2.19 in.), 10.0 cm (3.92 in.), 14.8 cm (5.81 in.), 20.0 cm (7.87 in.), and 27.4 cm (10.8 in.) and are referenced throughout the paper as C2, C4, C6, C8, and C10, respectively. The surface areas of the C2, C4, C6, C8, and C10 collectors were 23.8 cm^2 (3.77 $in.^2$), 78.5 cm^2 (12.1 $in.^2$), 170.9 cm^2 (26.5 $in.^2$), 314.2 cm^2 (48.6 $in.^2$), and 589.7 cm^2 (91.6 $in.^2$), respectively. The C2, C4, C6, and C8 collectors were made from PVC drainage pipe. The C10 collector was modified from an existing 18.9 liter (5 gallon) bucket. The collector construction details are given below.

Construction of the C2, C4, C6, and C8 collectors began by cutting the PVC pipe into twenty 20.3 cm (8 in) sections. The radial arm saw used for this step could only cut a maximum depth of 9.53 cm (3.75 inch) in one stroke so the C4, C6, and C8 collectors required multiple cuts to separate the pipe. The top of each collector barrel was planed to a smooth level around the collector barrel lip. The outside of the barrel lip was then beveled to create a sharp-edge inner lip used to separate falling water droplets during water collection. Each 18.9 liter (5 gallon) bucket was cut to the 20.3 cm (8 in.) height by a band saw. Because the buckets' sides were tapered to a smaller bottom diameter from the larger bucket top diameter, a special support bracket was used to position the bottom of the bucket parallel to the band saw blade for cutting. A sander made the sharp-edged inner lip on the top of each C10 collector. Pipe end caps were glued onto the bottom of the C2, C4, C6, and C8 collectors; after the glue had dried the outside joint between of the collector and the end cap was glued again to ensure that the glue joints were sealed. Each collector was tested for leaks in the lab before being used in the field. Side mounting tubes were added to the C2, C4, and C6 collectors so that ground stakes could be attached to support the collectors during field testing.

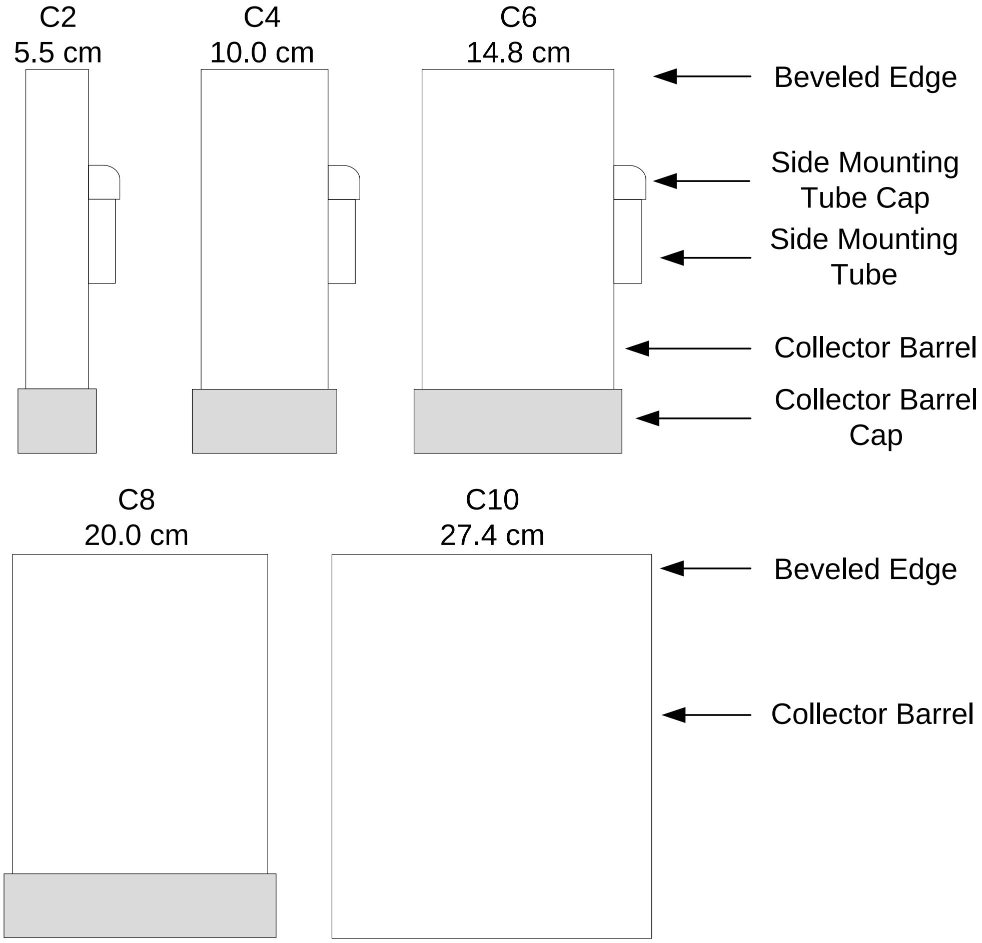

Figure 2.1. C2, C4, C6, C8, and C10 Collector Construction.

The design of the collector arrangement in the field was created using SAS 9.2. Four Latin squares were developed for each sprinkler type tested. The 5 x 5 Latin square was replicated four times so that twenty collectors of each size were measured for each irrigation system studied. SAS 9.2 was used to assign the collectors within each Latin square. To ensure that the Latin squares were random, the SAS 9.2 code for each Latin square was seeded with a random five digit number. The resulting Latin square diagrams were used to arrange the collectors in the field. The Latin squares were designed to partition error resulting from differences in water application due to sprinkler pattern overlap to the columns and error due to time effect differences (including climatic factors such as changing winds, sunlight, and temperature as well as changing field elevation of the irrigation system) to the rows. The first Latin square received water from the irrigation system and had the water depths measured first. The first row received water from the moving center pivot system before the other rows; the first column was closest to the wheel track used as the field benchmark for Latin square placement.

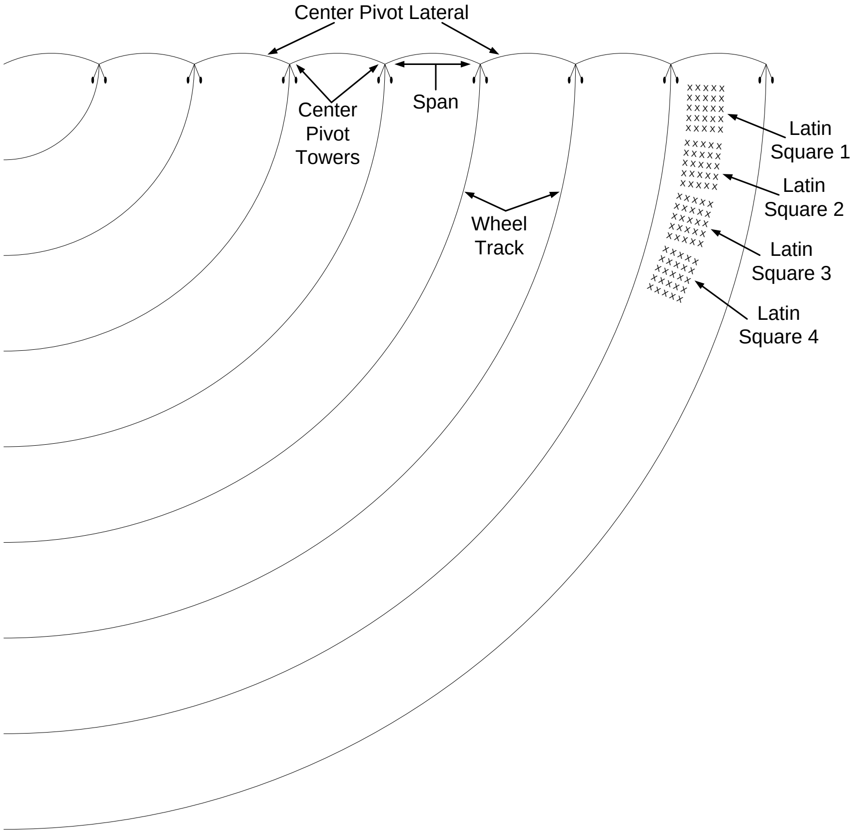

Figure 2.2. Center pivot lateral system and location of Latin square field sites.

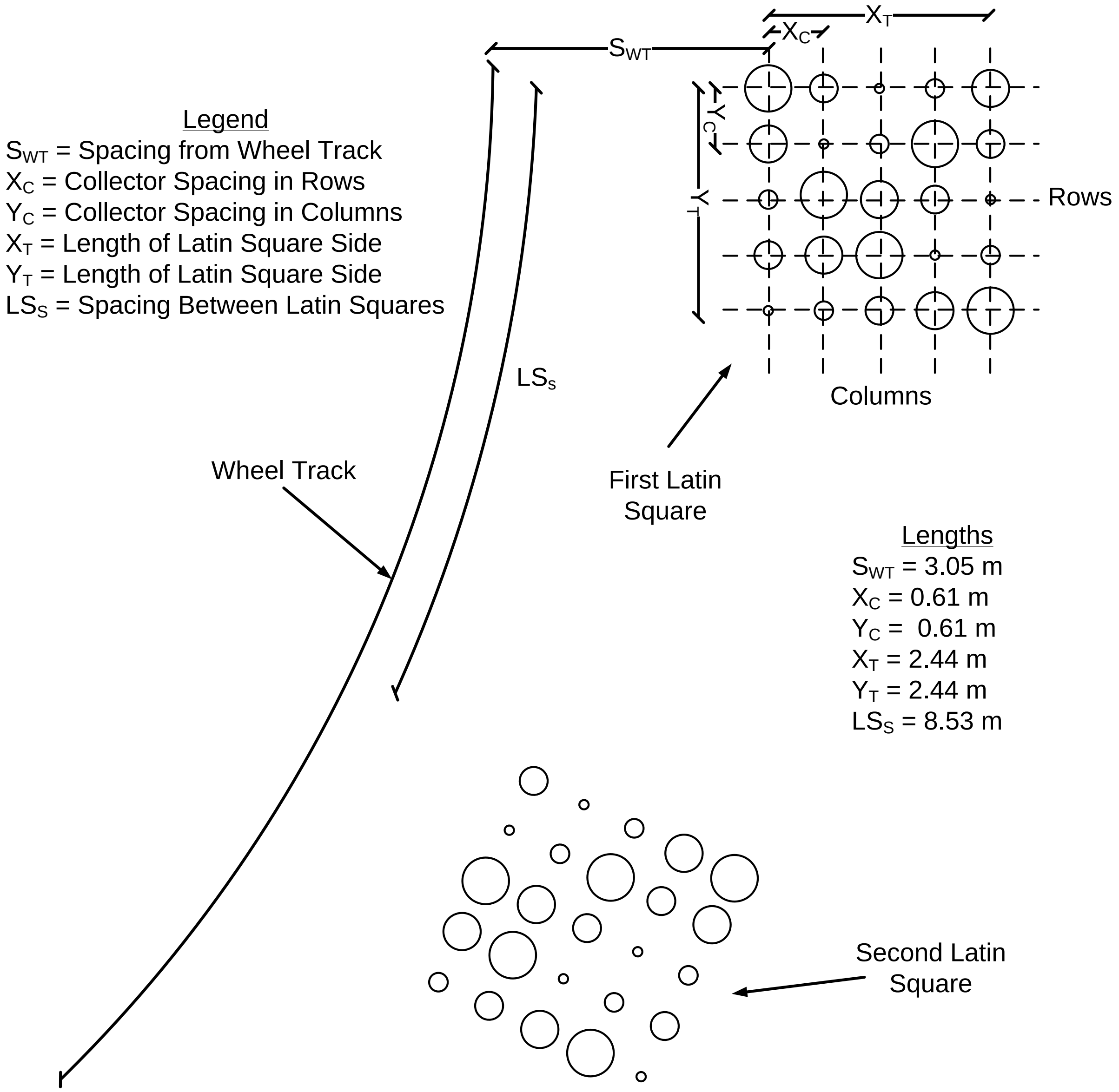

Figure 2.3. Two Latin squares with the collector spacing, columns, and rows labeled.

The experimental procedure was the same for all three systems. The field site for the collector study was selected by considering the site slope and the center pivot system's present location and rotational direction. It was critical that the water volume be measured immediately after the irrigation system moved past the collectors to limit the evaporation of water from the collectors. Preference for site selection was given to the outer part of the center pivot system because the short water application time limited potential evaporation losses. The outside spans also more heavily influence the center pivot system performance because the outer spans irrigate larger areas than the inner spans. A wheel track was used as the benchmark for each Latin square setup. The spinning plate and wobbling plate systems were tested with the collectors placed outside of the wheel tracks away from the central axis of the center pivot system (pivot point). The collectors for the fixed plate sprinkler test were positioned inside the wheel track toward the central axis of the center pivot system.

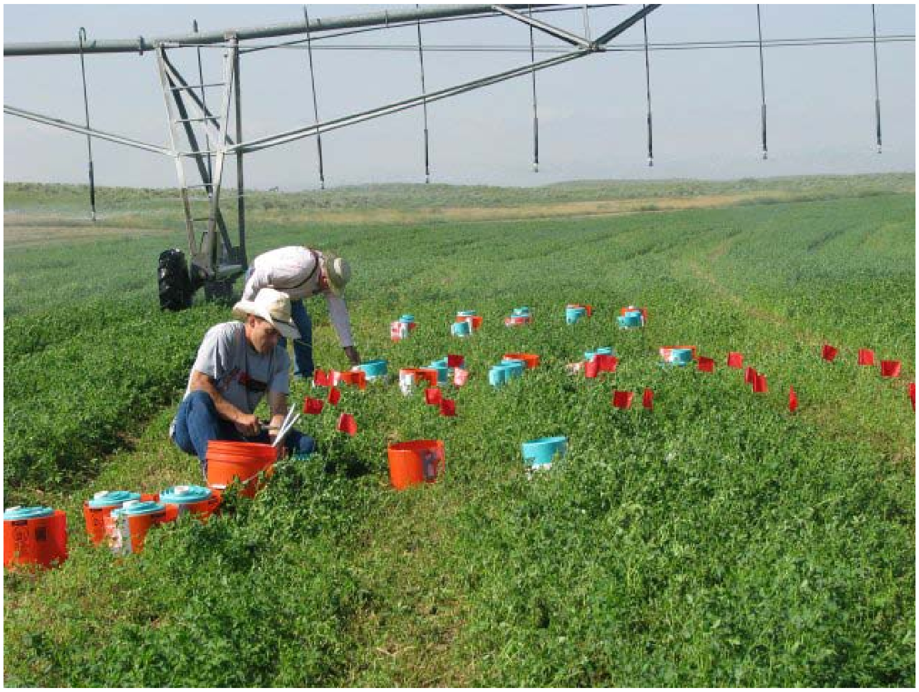

Figure 2.4. Field setup of collectors in the Latin squares. Flags were placed to plot the future locations of the collectors.

A transit and rod were used to mark the first collector row of each Latin square by shooting a straight line from outside the collection site to the pivot point. Flags were used to mark the first row. Each block of collectors was installed 3.05 m (10 ft) from the rim of the wheel track along the marked row; the collector in the first row and first column was centered at this position. Each collector in the first row was separated by 0.61 m (2 ft). Collectors were placed 3.05 m (10 ft), 3.66 m (12 ft), 4.27 m (14 ft), 4.88 m (16 ft), and 5.49 m (18 ft) from the wheel track edge. The columns were placed perpendicular to the first row and separated by 0.61 m (2 ft) intervals. The specific collector size used at each position within the grid was determined by the Latin square diagram created from SAS. All vegetation over 20.3 cm (8 in.)

within the Latin square site was removed so that the plants did not interfere with water collection. Each collector was visually inspected to ensure that the collector openings were parallel to the ground. The total distance between the first and fifth collectors in a row or column was 2.44 m (8 ft). Each Latin square was separated by 6.10 m (20 ft). The first row of the second Latin square was marked by using the same procedure. This procedure of laying out the collectors was repeated for the second, third, and fourth Latin squares.

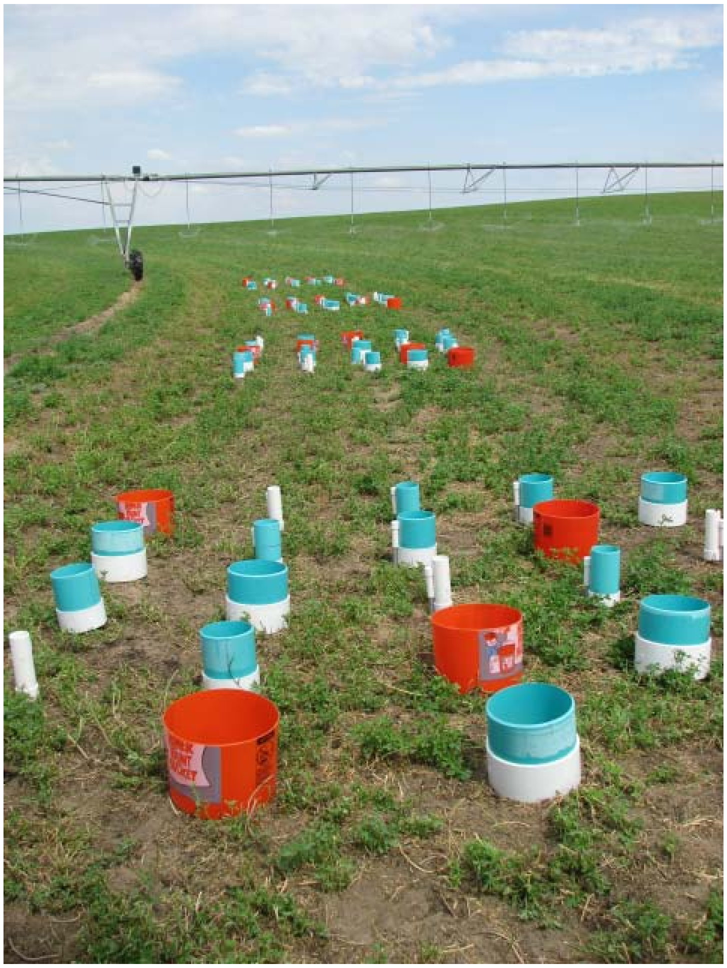

Figure 2.5. Four Latin squares positioned in the field.

Collected water amounts were measured as soon as the collectors stopped receiving water to limit the evaporation of collected water. The C2 collector's water volume was measured by a 100 mL graduated cylinder read to the nearest 1 mL. The C4, C6, C8, and C10 collectors were measured using a 500 mL graduated cylinder read to the nearest 5 mL. The catch volume was converted to a water application depth by dividing the measured water volume by the collector's surface area.

SAS 9.2 analyzed the measured water depth data. The means and standard deviations of the water depth measurements from the different collectors, columns, and squares were calculated using the *"Proc Means"* command. The coefficient of variation (CV) was computed for each factor by dividing the standard deviation by the mean. The *"Proc Mixed"* command created an analysis of variance (ANOVA) of the measured water depths for the different collector sizes. The *"Proc Mixed"* command was chosen to accommodate both the fixed effect and random effect factors in the model. The collector size (often called the treatment), column, and row were fixed effects and the Latin squares were a random effect. The ANOVA reported the significance of the collector size effect on the measured mean depths (whether each collector size measured the same depth). If the ANOVA showed that the collector size effect was significant then the collector size measurements were compared. No comparisons were analyzed if the ANOVA showed that the collector size effect was not significant.

Another ANOVA examined the variability of the measured water depths of each collector size. First, the significance of the column factor on measured water depths was determined for each sprinkler test. If the column effect was significant then the measured depths were adjusted to eliminate the column effect. By adjusting the data the variability in measured depths caused by the column effect was eliminated. The standard deviation of each collector size's adjusted measured depths was calculated. The ANOVA of the standard deviations reported whether collector size had a significant effect on the variability of measured depths. If the collector size effect was significant then comparisons between collector sizes were analyzed.

The estimated standard deviation of each collector size was also used to create the 95 percent confidence interval of the mean depth reported by a given number of collectors. The equation

$$95\%\, Confidence\ Interval = Mean\ Depth \pm \frac{2 * Std.Deviation}{\sqrt{Number\ of\ Collectors}} \tag{2.1}$$

determines the accuracy of the mean depth reported by a given number of collectors. Small standard deviations and large numbers of collectors produce narrow confidence intervals that are highly accurate in measuring the true mean depth of the irrigation system. The quality of a water depth estimated by any number of collectors (up to 20) of any size was calculated and reported. The confidence intervals calculated by this test cannot be applied to any other system because these 95 percent confidence interval estimates are highly dependent on the standard deviation of the measured water depths. The variability of depth measurements might change between different fields and/or different water application depths for the same sprinkler type. The overall variability of a sprinkler type cannot be estimated from the analysis of one system, therefore these results can only be applied to the center pivot system studied.

CHAPTER 3 - Results and Discussion

Three different center pivot systems were analyzed to study the effect of collector size on the measured water depth. Weather conditions during each field test are reported below (table 3.1) and are typical for southwestern Kansas during the summer months. The wobbling plate system was tested early in the morning when the air temperature was cool and the humidity was high. Both the spinning plate and fixed plate systems were tested in the afternoon. Wind speeds were particularly high for the spinning plate sprinkler test but were determined to be acceptable for this study using water depth measurements.

Table 3.1. Weather conditions of the 2009 field tests.

System	Date	T* (^oC)	Heat Index (^oC)	RH* (%)	Wind Speed Max (km/h)	Wind Speed Avg. (km/h)
Spinning Plate	July 15, 2009	31.9	44	81	23.	14.
Fixed Plate	August 5, 2009	34.8	45.5	66	13.	2.6
Wobbling Plate	July 15, 2009	24.0	27.1	100	12.	4.5

* T = air temperature, RH = relative humidity

The nominal application depth was 1.5 cm (0.60 in.) for the spinning plate system, 5.1 cm (2 in.) for the fixed plate system, and 2.5 cm (1 in.) for the wobbling plate system. The nominal water application depth of the spinning plate system was the minimum depth (1.5 cm) specified by the ASABE S436.1 standard for uniformity measurements of center pivot irrigation systems. The mean water depth of each system was calculated by combining the depth measurements of all collectors regardless of size. Large differences in standard error between the sprinkler types correspond to the mean water depth of each system (table 3.2). The fixed plate system has much larger standard deviations than the spinning plate and wobbling plate systems but a comparable amount of variability in depth measurements because the applied water depth was so much larger. The coefficient of variation (CV) normalized the level of variability to compare the different sprinkler types. The CVs of the three sprinkler types were similar. The fixed plate system has the highest CV, followed by the wobbling plate and the spinning plate systems, but the differences between CVs were small. It was expected that the fixed plate and wobbling plate sprinkler systems would be more different in terms of water depth measurement variability than what was observed in this study.

Table 3.2. Means and standard deviations of each sprinkler system, combining across collector diameter sizes.

System	Applied Depth (cm)	Nominal Depth (cm)	Lower 95% Mean Confidence Level	Upper 95% Mean Confidence Level	St. Dev. (cm)	CV
Spinning Plate	1.49	1.52	1.46	1.51	0.108	0.07
Fixed Plate	5.11	5.08	5.01	5.21	0.510	0.10
Wobbling Plate	2.27	2.54	2.23	2.31	0.208	0.09

Collector Size, Column, and Square Mean Depths

Spinning Plate Sprinkler System

The mean depths of all collector sizes, columns, and squares from the spinning plate sprinkler test are recorded in Table 3.3. The difference between the highest and lowest mean depths from the collector sizes was only 0.05 cm, which is very small. The measured depth standard deviations of the C2, C4, C8, and C10 collector sizes were acceptable but the C6 collector's standard deviation of the measured depths was approximately one half of the other standard deviations. The C6 collector size measured the application depth from spinning plate systems with the lowest variability.

Column and squares were noted to have statistically different water depth measurements. Column 5 recorded a different mean depth than columns 1, 2, and 3, column 1's and 3's measured depth is different from column 4's measured depth. The overlapping sprinkler patterns formed from the sprinklers spaced along the center pivot system caused the differences between columns. Although center pivot systems are designed to apply the same water depth to the entire field area, localized variations in water depth will occur based on the overlapping application patterns from sprinklers. Each column, representing a specific position along the center pivot lateral, receives a unique water depth depending on the number and proximity of the surrounding sprinklers. Each successive square of collectors caught smaller water depths than the preceding square. It is not known why the successive squares measured lower water depths. The variability of the mean depth measurements within each square was consistent across all squares.

Table 3.3. Proc Means results for the spinning plate sprinkler.

Treatment	Mean (cm)	Grouping*	St. Dev. (cm)	CV
C2	1.51	A	0.127	0.08
C4	1.48	A	0.108	0.07
C6	1.51	A	0.0598	0.04
C8	1.47	A	0.115	0.08
C10	1.46	A	0.121	0.08
Column	**Mean (cm)**	**Grouping***	**St. Dev. (cm)**	**CV**
1 (Inner)	1.45	A	0.0861	0.06
2	1.47	AB	0.0983	0.07
3	1.42	A	0.0850	0.06
4	1.53	BC	0.145	0.09
5 (Outer)	1.55	C	0.0537	0.03
Square	**Mean (cm)**	**Grouping***	**St. Dev. (cm)**	**CV**
1	1.54	A	0.101	0.07
2	1.52	AB	0.107	0.07
3	1.47	B	0.0864	0.06
4	1.41	C	0.0925	0.07

* Treatments with the same letter are not different at the 95 percent significance level.

Fixed Plate Sprinkler System

The largest range of measured water depths between collector sizes was recorded from the fixed plate sprinkler study (table 3.4). The range between the highest and lowest measured depths was 0.38 cm (7.3 percent of the maximum water depth). The C2, C8, and C6 collectors measured the larger mean water depths. The C4 collector measured 0.19 cm less water than the C6 collector; the C10 collector recorded the lowest mean depth. The different collector sizes had similar levels of variability for this study.

Significant differences were seen between columns and squares in the fixed plate sprinkler results. Column 5 was significantly different from columns 1, 2, and 3. Column 4 was significantly different from columns 1 and 2. Columns 2 and 3 were significantly different. The measured water depth for squares 3 and 4 was significantly less than for squares 1 and 2. What caused the significant differences in measured water depth between the squares is not known. It was unexpected that the squares would measure different water depths. The variability decreased for each successive square.

Table 3.4. Proc Means results for the fixed plate sprinkler.

Treatment	Mean (cm)	Grouping*	St. Dev. (cm)	CV
C2	5.23	A	0.539	0.10
C4	5.04	AB	0.476	0.09
C6	5.19	A	0.549	0.11
C8	5.22	A	0.486	0.09
C10	4.85	B	0.435	0.09
Column	Mean (cm)	Grouping*	St. Dev. (cm)	CV
1 (Outer)	4.91	AB	0.340	0.07
2	4.77	A	0.362	0.08
3	5.12	BC	0.486	0.10
4	5.26	CD	0.537	0.10
5 (Inner)	5.48	D	0.501	0.09
Square	Mean (cm)	Grouping*	St. Dev. (cm)	CV
1	5.45	A	0.541	0.10
2	5.37	A	0.410	0.08
3	4.78	B	0.357	0.07
4	4.82	B	0.311	0.06

* Treatments with the same letter are not different at the 95 percent significance level.

Wobbling Plate Sprinkler System

The C6 collector measured the highest water depth from the wobbling plate system; the smallest depth was measured by the C10 collector (table 3.5). The total range of the water depth measured was 0.13 cm (5.5 percent of applied water). The C2 collector measured depth variability was 2.5 times larger than the C4, C8, and C10 measured variability. A slight trend of decreasing variability for increased collector diameters was recorded. The high variability of the C2 collector reduces the confidence of its water depth measurements. The C4, C6, C8, or C10 collector sizes are acceptable collector sizes for measuring depth measurements from the wobbling plate sprinkler system.

Significant differences between columns and squares were observed. The column effect is expected and caused by the positions of the sprinklers along the center pivot system. The squares showed an interesting pattern of measured depths as the first and third squares measured larger water depths than the second and fourth squares. This indicates variability in the depth measurements. It is expected that each square would collect similar depth measurements.

Table 3.5. Proc Means results for the wobbling plate sprinkler.

Treatment	Mean (cm)	Grouping*	St. Dev. (cm)	CV
C2	2.30	AB	0.340	0.15
C4	2.23	A	0.136	0.06
C6	2.35	B	0.214	0.09
C8	2.26	AB	0.134	0.06
C10	2.22	A	0.122	0.06
Column	Mean (cm)	Grouping*	St. Dev. (cm)	CV
1 (Inner)	2.20	AB	0.365	0.17
2	2.18	A	0.105	0.05
3	2.35	C	0.0687	0.03
4	2.32	BC	0.112	0.05
5 (Outer)	2.31	BC	0.197	0.09
Square	Mean (cm)	Grouping*	St. Dev. (cm)	CV
1	2.33	A	0.136	0.06
2	2.21	B	0.139	0.06
3	2.39	A	0.300	0.13
4	2.16	B	0.130	0.06

* Treatments with the same letter are not different at the 95 percent significance level.

Proc Mixed Tests of the Measured Mean Depths

Collector size did not significantly affect the measured water depths for the spinning plate system (table 3.6). Any collector size used in this analysis (C2, C4, C6, C8, and C10) measured the same water depth. The rows were not significant but the columns were significant.

It is unexpected that the row effect would be significant as this factor combined the depth measurements from the same row of every Latin square to compare the measured depths. The column factor was expected to be significant for determining measured depths for all sprinkler types due to sprinkler system characteristics such as the sprinkler placement and overlapping sprinkler pattern that create the differences in measured mean water depths between the columns.

The collector size's effect on measured depths was highly significant for the fixed plate sprinkler system. The significant difference indicates that at least two collector sizes measured significantly different water depths. The comparisons between the collector sizes are given in the *Collector Size Comparison Using the Measured Mean Depths* section. The column factor was highly significant for influencing the measured water depths as was the row effect. That the rows and collector size factors were significant is hard to explain. This indicates the difficulties in consistently measuring the water depths from these sprinkler systems with a high degree of confidence.

The collector size and row factors are not a significant factor in determining the measured water depth from wobbling plate sprinkler systems. The column factor is significant.

The wobbling plate system and the spinning plate system had identical results (the column factor was significant but the row and collector size factors are not significant). This indicates that the water distribution patterns from sprinklers using moving parts in the sprinkler design behave similarly and have increased water application uniformity. The fixed plate sprinkler, which emits controlled streams of water that do not move, had significant effects from both the collector size and row for the measured water depth. The column factor was significant for all three systems, confirming that, indeed, overlapping sprinkler patterns create localized differences in water depth along the center pivot.

Table 3.6. Proc Mixed results for the collector size effect on measured depth for the spinning plate, fixed plate, and wobbling plate systems.

Sprinkler Type	Source	Degrees of Freedom	F Value	p-Value	Significance
Spinning Plate	Row	84	1.12	0.3528	NS
	Column	84	8.87	<0.0001	***
	Collector Size	84	1.47	0.2187	NS
Fixed Plate	Row	84	2.62	0.0405	**
	Column	84	18.66	<0.0001	***
	Collector Size	84	6.17	0.0002	***
Wobbling Plate	Row	84	0.34	0.8518	NS
	Column	84	3.63	0.0089	***
	Collector Size	84	1.79	0.1386	NS

* NS indicates collectors are not significantly different, * indicates collectors different at 90 percent significance, ** indicates collectors different at 95 percent significance, and *** indicates collectors different at 99 percent significance.

Collector Size Comparison Using the Measured Mean Depths

Comparison tests between the collector sizes' measured depths were conducted for each sprinkler type that showed significant collector size effects. Only the collector sizes from the fixed plate sprinkler were compared because the collector size effect was not significant for the spinning plate and wobbling plate sprinkler systems.

Differences between measured mean depths from collector sizes were recorded for the fixed plate sprinkler system (table 3.7). The C2 and C4 collectors measured significantly different water depths. The C10 collector measured a significantly different water depth from all other collectors. It was hypothesized that the C2 and C4 collectors would perform similarly and the C8 and C10 collectors would perform similarly because of the comparable sizes. These hypotheses were not validated by this research. The C10 collector measured almost 0.37 cm less water than the C8 collector and the C4 collector recorded a mean depth that is 0.19 cm lower than the C2 collector's measured depth. It is not known what caused the fluctuations in mean measured depths or why a trend of increasing or decreasing measured depth was not seen between the collector sizes.

One assumption often used in analyzing water depths from irrigation systems is that larger collectors measure water depths with greater accuracy. This assumption would lead to selecting 4.85 cm as the true depth applied by the irrigation system. This assumption leads to an accepted water depth that is different from the measurements of sixty collectors (twenty each of C2, C6, and C8 collectors) that reported mean depths within a range of 0.04 cm. The C8 collector would also be considered a larger collector size. The correct collector size for measuring the water depth from fixed plate sprinklers cannot be determined because the actual water depth applied by the irrigation system is unknown.

Table 3.7. Proc Mixed comparison test of the measured depths for the fixed plate sprinkler system.

Treatment	Mean (cm)	95% Significance Grouping
C2	5.23	A
C4	5.04	B
C6	5.19	AB
C8	5.22	AB
C10	4.85	C

* Treatments with the same letter are not significantly different at the 95 percent level.

Proc Mixed Test of the Measurement Variability

The *"Proc Mixed"* test of the level of variability of the measured depths from the different collector sizes tested the standard deviation of the collected water depths. The model adjusted the raw data for column effects and therefore only the significance of the collector size effect was calculated (table 3.8). Significant differences exist between different collector sizes in the variability of measured depths for the spinning plate system. The collector size effect was not significant for the variability of measured depths from the fixed plate sprinkler system. Even though the variability of depth measurements was higher, there existed sufficient variability in depth measurements for all collector sizes that differences between collector sizes were not significant. The collector size effect was not significant for the measured depth variability of the wobbling plate sprinkler system. It is interesting that the spinning plate system and the wobbling plate system did not perform similarly since both sprinkler types have moving splash plates.

Table 3.8. Proc Mixed Test of the collector size effect on variability of measured depth.

Sprinkler Type	Degrees of Freedom	F Value	p-Value	Significance
Spinning Plate	12	3.43	0.0432	**
Fixed Plate	12	0.10	0.9817	NS
Wobbling Plate	12	1.09	0.4061	NS

* NS indicates collectors are not significantly different, * indicates collectors different at 90 percent significance, ** indicates collectors different at 95 percent significance, and *** indicates collectors different at 99 percent significance.

Collector Size Comparison Using the Variability of the Measured Depths

The *"Proc Mixed"* command compared the different collector sizes' estimated variability from the spinning plate system to determine which collectors were significantly different (table 3.9). The fixed plate and wobbling plate systems were not tested because the collector size effect was not significant for those tests. At a 99 percent significance level the C6 collector had lower variability than the C2 and C10 collectors. At 90 percent significance level the C2 and C4 collectors measured significantly different variability levels, the C6 and C8 collectors measured significantly different variability levels, and the C4 and the C10 collectors measured significantly different water depth variability. The variability of the measured depths demonstrated a trend of decreasing variability between the C2 to C6 collectors but increasing variability between the C6 and C10 collectors. What caused this increase in measured depth variability for the larger collector sizes is not known. It is interesting that the C2 and C10 collectors measured the same level of variability in the data. An assumption often employed when using collectors to measure water depths is that larger collector sizes will measure the water depth with less variability in the measured depths. The results of the spinning plate system refute that assumption.

Table 3.9. Proc Mixed comparison test of the measured depth variability for the spinning plate system.

Collector Size	Estimated Standard Deviation	99% Significance Grouping	90% Significance Grouping
C2	0.100	A	A
C4	0.0687	AB	BC
C6	0.0477	B	B
C8	0.0785	AB	AC
C10	0.0997	A	A

* Treatments with the same letter are not significantly different at the noted significance level.

Accuracy of Water Depth Measurement for a Given Number of Collectors

The accuracy of the measured mean water depth reported by a given number of collectors was calculated using the standard deviation estimates of each collector size for each sprinkler type. The 95 percent confidence intervals surrounding the estimated water depth were given to indicate the range needed to contain the true applied depth. The collector sizes that have less measured depth variability are more accurate (and have narrower confidence intervals) than the collector sizes with more measurement variability. Additional collectors improved the estimated mean depth accuracy, as a percentage, equally for all sprinkler types. The estimates of the collector size accuracy cannot be applied to all fields using the same sprinkler type. The estimates are dependent on the standard deviation of the water depths applied by the sprinkler type. Because only one system was tested for each sprinkler type the measured standard deviation may not reflect the overall standard deviation of the sprinkler type but only a single system's standard deviation of applied water depth. The standard deviation of the measured depths may be influenced by the water depth level applied, weather, and field conditions for the system tested.

The spinning plate system's mean depth estimates begin over a wide range of values for the different collector sizes (figures 3.1 and 3.2). Interestingly, the C2 and C10 collectors had identical levels of variability. The mean depth reported by five collectors of either C2 or C10 size would have the same measurement accuracy. A mean depth reported by a group of C6 collectors is twice as accurate as the mean depth reported by the same number of C2 or C10 collectors. The reduced depth variability of the C6 collector for the spinning plate system results in greater measurement accuracy as compared with the other collector sizes. It seems unlikely that four C6 collectors measure the water depth as accurately as eight C10 collectors but this is what was observed in the study.

The water depth measurement accuracy of the fixed plate system was very similar for all collector sizes studied (figures 3.3 and 3.4). The C6 collector was slightly more accurate than the other collector sizes. The mean depth estimates are more similar for the different collector sizes than either of the spinning plate or wobbling plate systems. The distinct water streams produced by fixed plate sprinkler systems are measured with the same level of variability of depth measurements for the different collector sizes.

The estimates of the water depths of the wobbling plate system demonstrated that larger collector sizes measure the water depth more accurately than small collector sizes (figures 3.5 and 3.6). The C2 collector's water depth estimate was three times less accurate than the C8 and C10 collector's estimated water depth. The "larger is better" assumption that larger collectors measure water depths more accurately was confirmed for this sprinkler system. It was unexpected that the C6 collector would have less accurate water depth estimates than the C4 collector. Another unexpected finding was that the accuracy of the C4 collector's estimate is almost identical to the C8 and C10 collectors' accuracy. Collector sizes can measure the water depth with high accuracy for the wobbling plate sprinklers. The diffused water application pattern of the wobbling plate sprinkler contributes to a large decrease in measurement variability from larger collectors.

The collector sizes in the fixed plate system produced the most similar confidence interval estimates but the estimates were higher than the confidence interval estimates of some collector sizes for the spinning plate and wobbling plate systems. The normalized estimates of the spinning plate and wobbling plate systems are similar, with the collector sizes that measured low variability having water depth estimates that are within 6 percent accurate with one collector and the high variability estimates that are within 14-20 percent accurate for one collector. The C2 collector measured the highest variability for both wobbling plate and spinning plate systems and the C6 collector measured high variability in the wobbling plate system and low variability in the spinning plate system. Conversely, the C10 collector measured low variability in the wobbling plate system and high variability in the spinning plate system. The consistently high variability measurements of the C2 collector indicate the challenges in accurately measuring the mean depth. The changing variability levels of the C6 and C10 collectors indicate that all collector sizes can experience fluctuating levels of variability of depth measurements for moving sprinkler types like the spinning plate and wobbling plate sprinklers. That all collector sizes behaved similarly for the fixed plate system indicates that the collector sizes studied in this research were not able to detect differences in measurement variability. The range of collector sizes studied was not large enough to significantly reduce the water depth measurement variability.

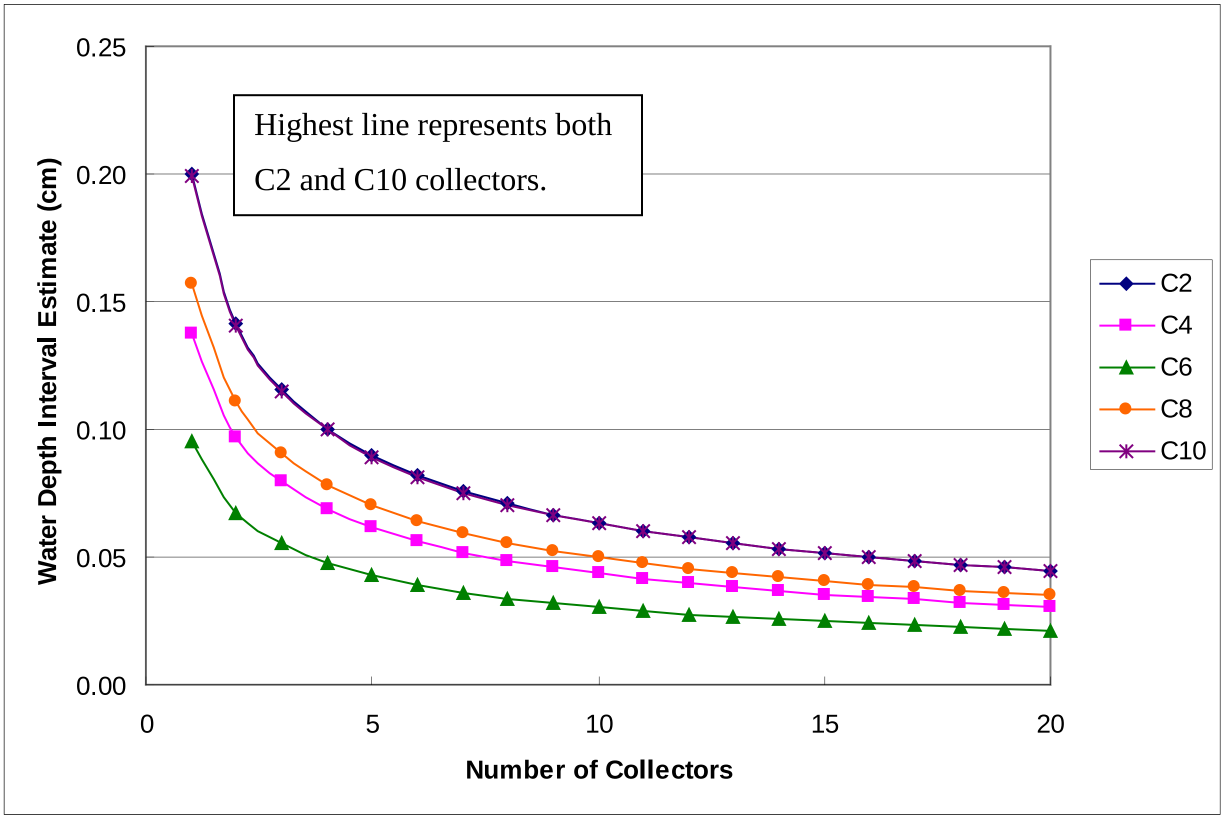

Figure 3.1. Accuracy of the measured mean depth reported by a given number of collectors for the spinning plate sprinkler system based on this study's mean water depth measurement of 1.49 cm.

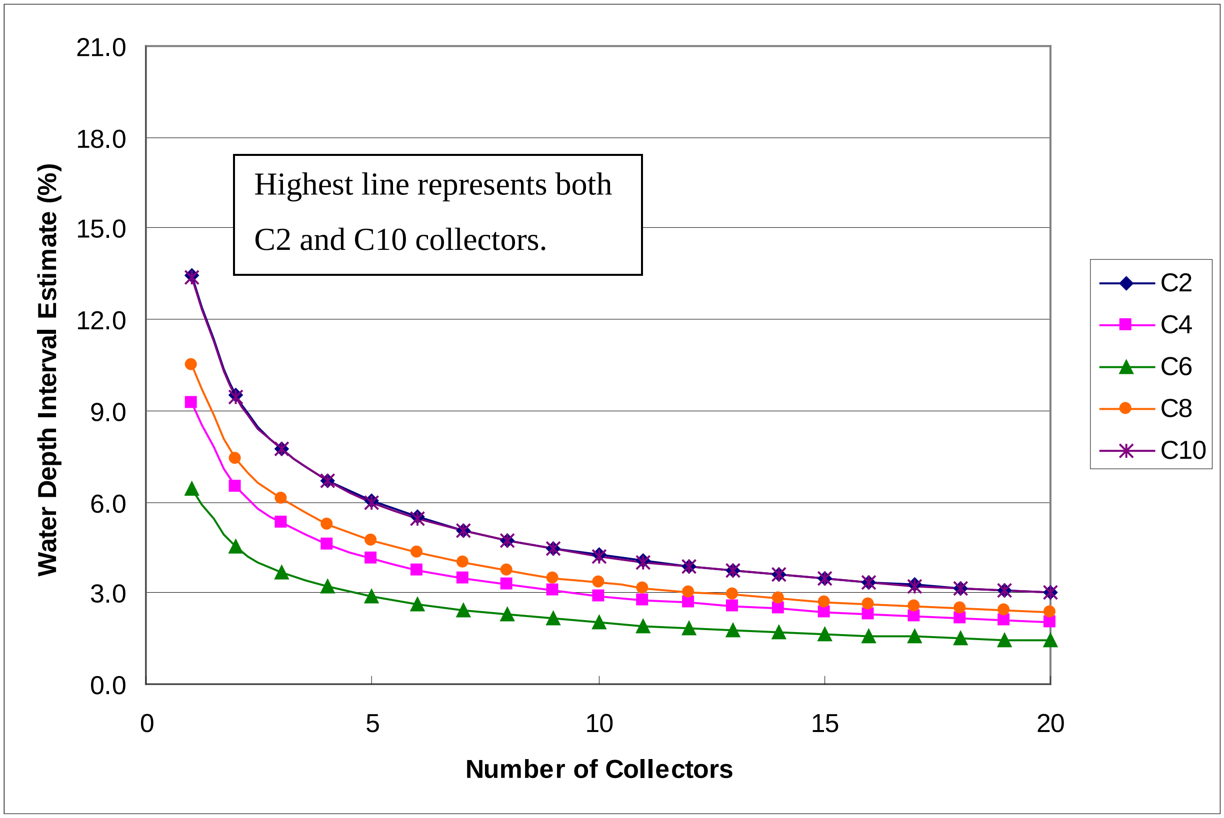

Figure 3.2. Normalized estimate of measurement accuracy (%) based upon collector size and number of collectors for the spinning plate system.

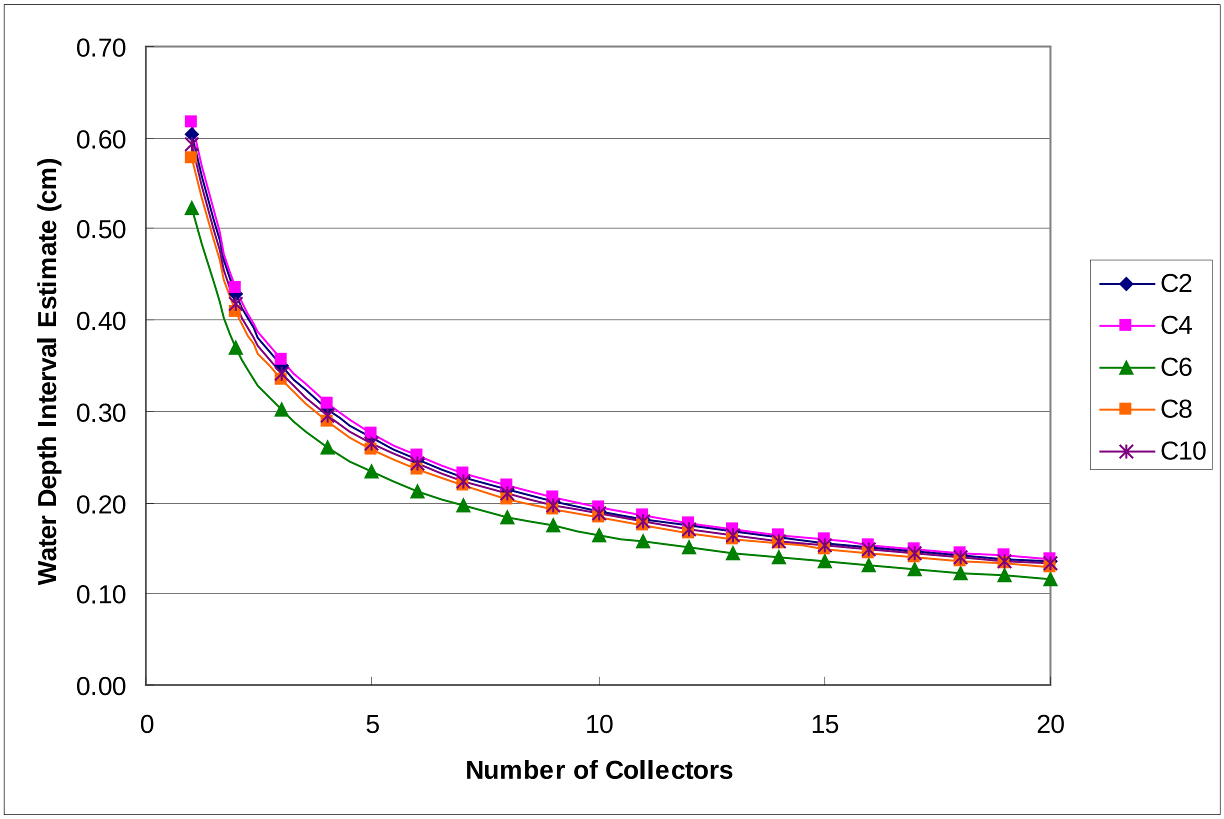

Figure 3.3. Accuracy of the measured mean depth reported by a given number of collectors for the fixed plate system based on this study's mean water depth measurement of 5.11 cm.

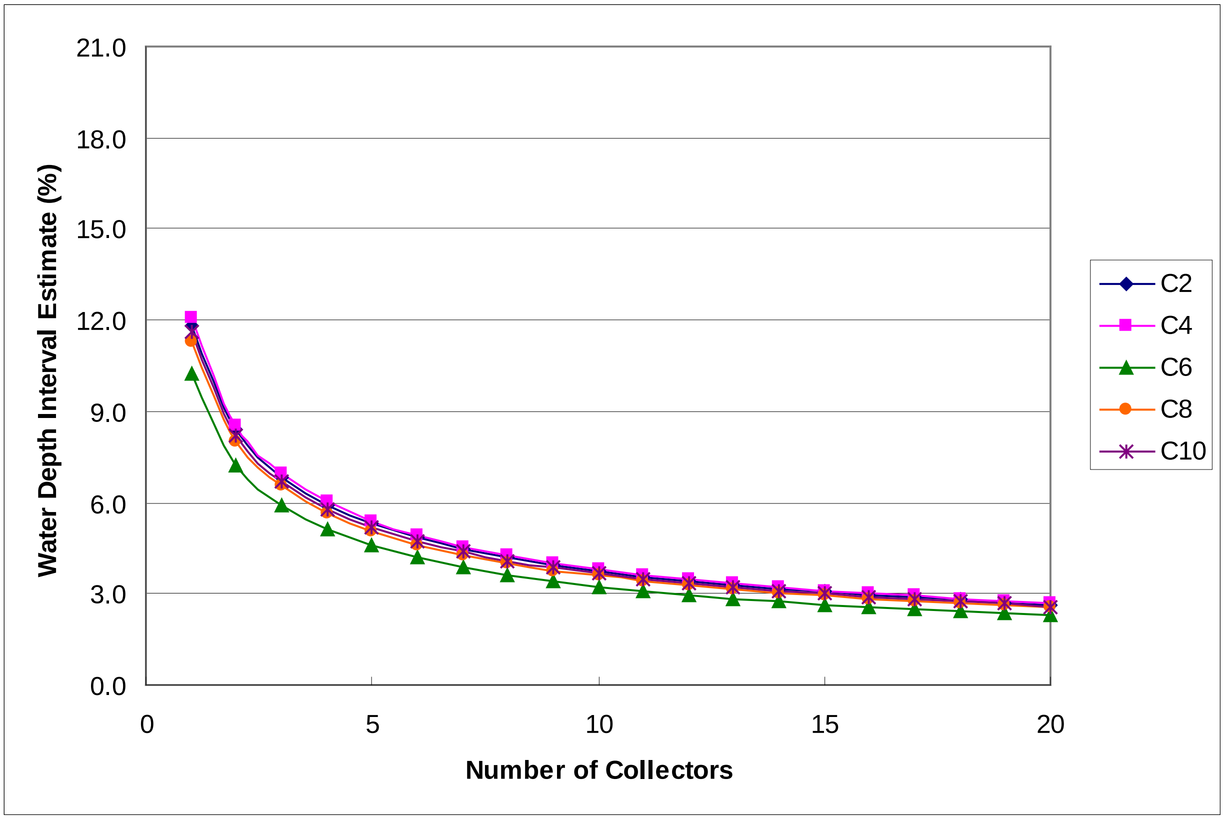

Figure 3.4. Normalized estimate of measurement accuracy (%) based upon collector size and number of collectors for the fixed plate system.

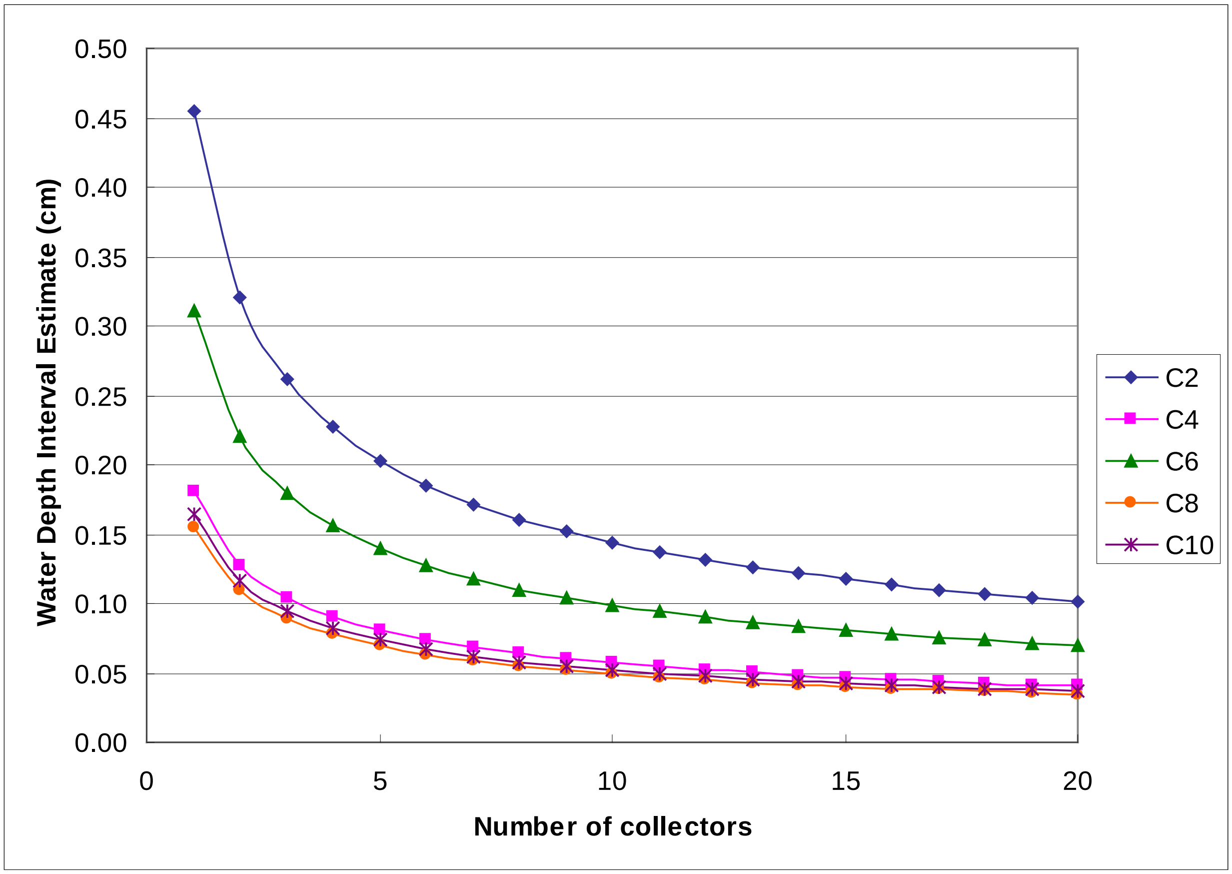

Figure 3.5. Accuracy of the measured mean depth reported by a given number of collectors for the wobbling plate sprinkler system based on this study's mean water depth measurement of 2.27 cm.

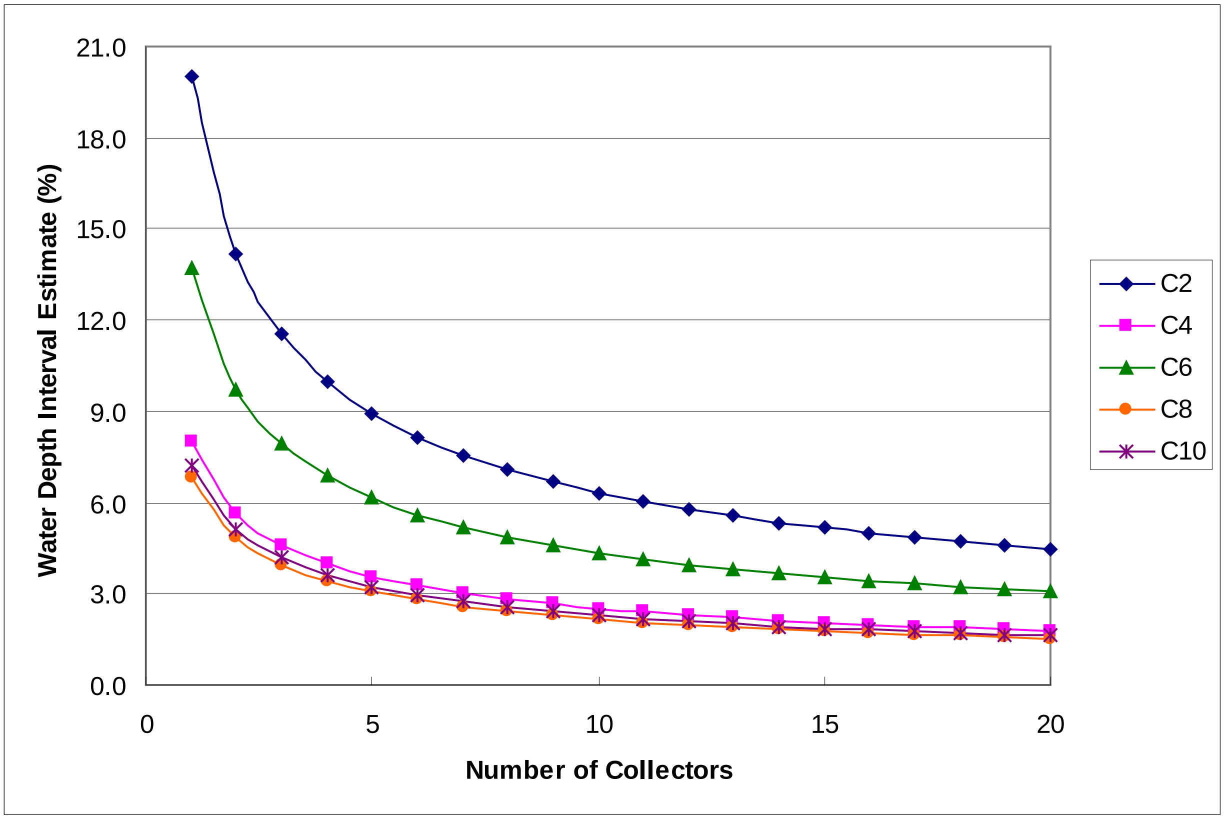

Figure 3.6. Normalized estimate of measurement accuracy (%) based upon collector size and number of collectors for the wobbling plate system.

CHAPTER 4 - Past Collector Size Studies

The collector size effects on measured mean depth and measurement variability observed in the 2009 study were compared to several past studies conducted in the Biological and Agricultural Engineering Department at Kansas State University under the direction of Dr. Gary Clark and Dr. Danny Rogers. The Cart Study, Nozzle Study, and Irrigage Study are summarized below, with a focus on the variability of measured depths. The results of these tests cannot be compared directly with each other or the 2009 study because of differences in experimental design. Within each study the results are compared to capture the trends in collector size performance; these trends can be compared between different studies. The qualitative performance of the collector sizes can be compared between different experiments but not the quantitative values of measurement variability.

Cart Study

Tests of the collector size effect on the measured water depth were conducted in the Biological and Agricultural Engineering labs during the summer of 2005 using a small stationary irrigation system. The stationary system consisted of three sprinklers suspended on drops below an elevated lateral. Two tests used flexible drops to mount the sprinklers (all sprinklers in the 2009 study were installed on flexible drops), two other tests used sprinklers mounted on rigid drops, and two additional tests compared trough collectors (surface area of 954 cm^2 (148 in^2)) with C6 and C8 collectors. To replicate a moving system with the stationary sprinkler system, a cart loaded with collectors was pulled underneath the irrigation system at a constant rate. Senninger #16 (6.35 mm orifice) fixed plate sprinklers were used and the sprinkler system was operated at 41.4 kPa (6 psi) pressure. The collectors used in the Cart Study were equivalent to the C2, C4, C6, and C8 collectors used in this research. Six collectors of each size were randomly arranged in a six by four matrix on the cart for the first four tests. The mean, coefficient of variation (CV), and standard deviation of the water depths for the collector sizes were analyzed using Microsoft Excel. Microsoft Excel t-Tests compared the measured depths of the collector sizes to determine if significant differences existed between the collector sizes.

The C4 collectors recorded smaller water depths than the C2, C6, or C8 collectors in the first two tests (tables 4.1 and 4.2). The CVs were high for all collectors in both tests. It is interesting that the C2 and C6 collectors had lower variability of measured depths in the first test but higher measurement variability in the second test. This observation, coupled with the range of CV values for the different collector sizes, indicate the difficulty in measuring water depths accurately from the highly variable fixed plate sprinkler water application patterns. The fact that CV's are consistently high, regardless of collector size indicates that the problem may be associated to a greater extent with the inherent spray pattern from the sprinklers and not the collector size. Both tests showed that significant differences existed between the C8 and C4 collectors but not between the C8 collector and the C2 and C6 collectors. The 2009 study also reported that the C4 was different from the C8 collector, but no differences existed between the C2, C6, and C8 collector sizes. Why the C2, C6, and C8 collector sizes performed similarly is unknown. The C2 and C8 collectors were not significantly different even though the measured mean depths were 10-11 percent different for both tests.

Table 4.1. Senninger Nozzle #16, 41.4 kPa, 6-16-05, flexible drops.

Collector Diameter	Depth (cm)	St. Dev. (mm)	CV	T-Test compared to C8*
C2	3.09	3.63	0.12	NS
C4	2.84	5.61	0.20	**
C6	3.30	4.48	0.14	NS
C8	3.40	7.06	0.21	

* NS indicates collectors are not significantly different, * indicates collectors different at 90 percent significance, ** indicates collectors different at 95 percent significance, and *** indicates collectors different at 99 percent significance.

Table 4.2. Senninger Nozzle #16, 41.4 kPa, 6-20-05, flexible drops.

Collector Diameter	Depth (cm)	St. Dev. (mm)	CV	T-Test compared to C8*
C2	2.98	9.26	0.31	NS
C4	2.81	5.73	0.20	***
C6	3.49	9.01	0.26	NS
C8	3.31	5.10	0.15	

* NS indicates collectors are not significantly different, * indicates collectors different at 90 percent significance, ** indicates collectors different at 95 percent significance, and *** indicates collectors different at 99 percent significance.

Two additional tests were conducted on the same three-sprinkler irrigation system after replacing the flexible drops with rigid drops. The mean depths of the first test were similar (table

4.3) but the second test had a much greater range of reported depth values (table 4.4). The C4 collector measured some of the smallest water depths for both tests. The C2 collector measured smaller water depths in the flexible drop tests but measured the largest water depths in the rigid drop tests. The variability of measured depths is high for all collector sizes in both tests. It was expected that the variability of measured depths from small collectors would be high for fixed plate sprinklers because the distinct water streams emitted could affect the measured depths. A noticeable decrease in the variability of measured depths was noted for the larger collector sizes, particularly for the C8, but the variability is still high. The measured depth variability of all collector sizes studied is unacceptable for measuring the water depth. The measured depths were not significantly different in these two tests even though the measured mean depths varied by 14 percent between the C6 and C8 collectors and by 12 percent between the C2 and C8 collectors. The high variability of measured depths does not allow the collector sizes to be significantly different.

One hypothesis for the higher variability of depth measurements in the rigid drop tests than in the flexible drop tests is that the random swinging of sprinklers on flexible drops increases the water application uniformity. The rigid drops reduce the sway of the sprinkler which may lower the application uniformity by eliminating the random movements of sprinklers on flexible drops. These random sprinkler movements could be especially important for fixed plate sprinklers to disperse the distinct streams of water emitted by the sprinkler. By reducing the sprinkler movement the water streams emitted by the sprinkler can only apply water to certain areas. The random motion of swinging sprinklers allowed by flexible drops could increase the area receiving the distinct streams of water.

Table 4.3. Senninger Nozzle #16, 41.4 kPa, 6-21-05, rigid drops.

Collector Diameter	Depth (cm)	St. Dev. (mm)	CV	T-Test compared to C8*
C2	2.90	11.51	0.40	NS
C4	2.87	12.53	0.44	NS
C6	2.78	10.30	0.37	NS
C8	2.81	5.31	0.19	

* NS indicates collectors are not significantly different, * indicates collectors different at 90 percent significance, ** indicates collectors different at 95 percent significance, and *** indicates collectors different at 99 percent significance.

Table 4.4. Senninger Nozzle #16, 41.4 kPa, 6-21-05, rigid drop.

Collector Diameter	Depth (cm)	St. Dev. (mm)	CV	T-Test compared to C8*
C2	2.30	7.00	0.30	NS
C4	1.93	5.73	0.30	NS
C6	2.35	5.32	0.23	NS
C8	2.06	3.75	0.18	

* NS indicates collectors are not significantly different, * indicates collectors different at 90 percent significance, ** indicates collectors different at 95 percent significance, and *** indicates collectors different at 99 percent significance.

The C6 and C8 collectors were compared with a rectangular trough in the last two tests. The trough was laid with the long axis perpendicular to the direction of travel of the irrigation system. The difference in collector shape was ignored because the trough collector's surface area was much greater than the C8 and C6 collectors' surface area. The trough collectors measured 0.26 cm (almost 10 percent) more water than the C6 and C8 collectors (table 4.5). The trough's mean depth was different at the 90 percent significance level from the C6 and C8 collectors. The trough's variability of measured depths was lower than both C6 and C8 collectors' variability. The measured depth variability of all three collectors was high.

The C8 collector's depth measurements were compared with measurements from five troughs (table 4.6). The trough tests were conducted over two days at different times including both morning and evening tests. Though not statistically different, the C8 collector measured a water depth at least as low as all of the trough's measured depths. The range of measured water depths for the five trough tests was 0.37 cm, although morning and evening tests had similar depth measurements (the trough water depths from the morning tests were within 0.10 cm and the afternoon tests were separated by 0.14 cm). The C8 collector had much less measured depth variability than any of the trough collectors. This observation is contrary to the earlier conclusion that the trough collector measurements have less variability (table 4.5). That only one of the five troughs was significantly different from the C8 collector indicates the variability of measured mean depths from fixed plate sprinklers. The trough collector variability was similar for all five measurements. The trough CVs increased slightly between the two tests but the C8 CV reduced dramatically from 0.28 to 0.06 (table 4.5 compared to table 4.6). The extreme fluctuations of C8 collector variability measurements indicate the difficulty of obtaining consistent depth measurements from fixed plate sprinklers regardless of the collector size used.

These tests reveal that these collector sizes are not acceptable for measuring the water depth from fixed plate sprinklers.

Table 4.5. Senninger Nozzle #16, 6-21-05.

Collector Diameter	Depth (cm)	St. Dev. (mm)	CV	T-Test compared to Trough*
C6	2.79	8.88	0.32	*
C8	2.81	7.94	0.28	*
Trough	3.16	5.53	0.17	

* NS indicates collectors are not significantly different, * indicates collectors different at 90 percent significance, ** indicates collectors different at 95 percent significance, and *** indicates collectors different at 99 percent significance.

Table 4.6. Senninger Nozzle #16, Comparison of C8 and trough collectors.

Collector Diameter	Depth (cm)	St. Dev. (mm)	CV	T-Test compared to C8*
C8	3.10	1.83	0.06	
Trough - 6/17	3.33	5.84	0.18	NS
Trough – 6/20 am	3.20	7.02	0.22	NS
Trough – 6/20 am	3.10	6.84	0.22	NS
Trough – 6/20 pm	3.33	7.04	0.21	NS
Trough – 6/20 pm	3.47	5.12	0.15	**

* NS indicates collectors are not significantly different, * indicates collectors different at 90 percent significance, ** indicates collectors different at 95 percent significance, and *** indicates collectors different at 99 percent significance.

IrriGage Study

A series of collector size experiments were conducted in 2002 at several different center pivot and linear move irrigation systems across the state of Kansas. C4, C6, and C12 collectors (the C12 collector diameter was 30.5 cm (12.0 in.)) were used to evaluate spinning plate, fixed plate, and wobbling plate sprinkler types. The collectors were arranged in groups of 12 collectors in the field. The twelve C6 collectors were spaced at equal intervals and placed directly in front of a row of twelve C4 collectors. Four tests were conducted for each of the three sprinkler systems, but extreme winds during the third test of the fixed plate and spinning plate systems caused those results to be removed. The fixed plate system and the spinning plate system have 36 depth measurements per collector size. The wobbling plate study used all four tests and has 48 depth measurements per collector size. The variability of the depth measurements from this experiment will be higher than the 2009 study's depth measurement variability because the collectors in this study were placed at varying positions along the center pivot system instead of at the same position along the irrigation system. The collector placement in this test increases the effect of overlapping sprinkler patterns on the measured water depths (the column effect in the 2009 study). The high levels of variability of measured depths obtained in this study are partly caused by the experimental design.

Spinning Plate Sprinkler System

The collector size test for the spinning plate system reported that the collector sizes measured numerically similar depths and had moderate to high variability (table 4.7). The C6 collector measured a significantly different water depth than the C4 and C12 collectors, which measured similar water depths. The variability of depth measurements was lower for the C12 and the C6 collectors than the C4 collector. The C4 collector's measured depth variability is high, and the C12's and C6's variability are moderate. The variability of the depth measurements was low enough to allow the measured mean depth difference of 0.1 cm (7 percent of the applied water) to be significantly different. The C4 collector's high variability of depth measurement is a concern for using the C4 collector to measure water depths from spinning plate systems.

Table 4.7. Comparison of C4, C6, and C12 collectors for the spinning plate sprinkler system.

Collector Diameter	Average (cm)	St. Dev. (cm)	CV	T-Test with C6*	T-Test with C4*
C12	1.51	0.156	0.103	***	NS
C6	1.42	0.157	0.110		
C4	1.52	0.321	0.211	**	

* NS indicates collectors are not significantly different, * indicates collectors different at 90 percent significance, ** indicates collectors different at 95 percent significance, and *** indicates collectors different at 99 percent significance.

Fixed Plate Sprinkler System

The C4 and C6 collectors' measured water depths were significantly different at the 99 percent significance level (table 4.8). The C6 collector measured 0.30 cm (21 percent) less water than the C4 collector. Both the C4 and C6 collectors have particularly high CVs of 0.46 and 0.40, respectively. Neither collector is acceptable for measuring the water depths of fixed plate sprinklers because of the extremely high variability. The true applied water depth is not known.

Without the actual water depth, neither collector can be chosen as acceptable for measuring the water depth. The variability of water depths for both collectors was extremely high and is unacceptable for collectors used to measure water depths.

Table 4.8. Comparison of C4 and C6 collectors for the fixed plate sprinkler system.

Collector Diameter	Average (cm)	St. Dev. (cm)	CV	T-Test with C6*
C6	1.44	0.577	0.40	
C4	1.74	0.792	0.46	***

* NS indicates collectors are not significantly different, * indicates collectors different at 90 percent significance, ** indicates collectors different at 95 percent significance, and *** indicates collectors different at 99 percent significance.

Wobbling Plate Sprinkler System

The C6 collector's measured water depth was 4 percent lower than the C4 collector (table 4.9). The variability of the C6 collector measurements is acceptable for measuring the mean water depths but the C4 collector's variability is high. The T-Test reported that the C4 and C6 collectors are different at 90 percent significance. Unlike the 2009 results of the wobbling plate systems, this data indicates that different collector sizes measured different mean water depths, but the actual difference between the two collector sizes was only 4 percent. Although the collectors are slightly significantly different, the small numerical difference between the measured depths, coupled with the moderate variability of water depths, indicates that both collector sizes could be used in uniformity studies.

Table 4.9. Comparison of C4 and C6 collectors for the wobbling plate sprinkler system.

Collector Diameter	Average (cm)	St. Dev. (cm)	CV	T-Test with C6*
C6	1.96	0.16	0.08	
C4	2.04	0.32	0.16	*

* NS indicates collectors are not significantly different, * indicates collectors different at 90 percent significance, ** indicates collectors different at 95 percent significance, and *** indicates collectors different at 99 percent significance.

Nozzle Study

Six types of fixed plate sprinklers were studied in 2005 at the Biological and Agricultural Engineering Department at Kansas State University. Five collector sizes were studied in this test, including the C2, C4, C6, C8, and square collectors (with dimensions of 19.8 by 21.1 cm).

Coarse, medium, and fine spray patterns of both Senninger and Nelson fixed plate sprinklers were tested. The spray pattern of the Senninger sprinklers was determined by the number of plates installed on the sprinkler. The coarse Senninger sprinkler used one plate, the medium Senninger sprinkler used two plates, and the fine Senninger sprinkler used three plates. Each Nelson sprinkler was installed with only one plate. The coarseness of the Nelson fixed plate sprinkler was determined by the number of grooves on the fixed plate. Senninger #16 (6.35 mm orifice) and Senninger #20 (7.94 mm orifice) nozzles were used for this study, as well as Nelson #32 (6.35 mm orifice) nozzles.

The results of the study are shown graphically in Figure 4.1. It was expected that the larger collector sizes would measure less variability of depth measurements. Only the water depth measurements for the fine Senninger sprinkler demonstrated this trend as the C2 collector recorded the highest variability and the depth measurement variability decreased as the collector size increased. Interestingly, the collector sizes did not measure similar depth variability for the sprinklers that have the same type of spray pattern. Even the square collector had a high variability of depth measurements for the Nelson coarse sprinkler. The extremely high variability of the coarse Nelson sprinkler indicates that the mean depth variability can be very high for fixed plate systems that emit distinct streams of water (between 0.30-0.50 CV). The high variability of the coarse Nelson sprinkler illustrates the challenges in measuring the water depth with these collector sizes. The very coarse fixed plate sprinklers cannot be accurately measured by these collector sizes.

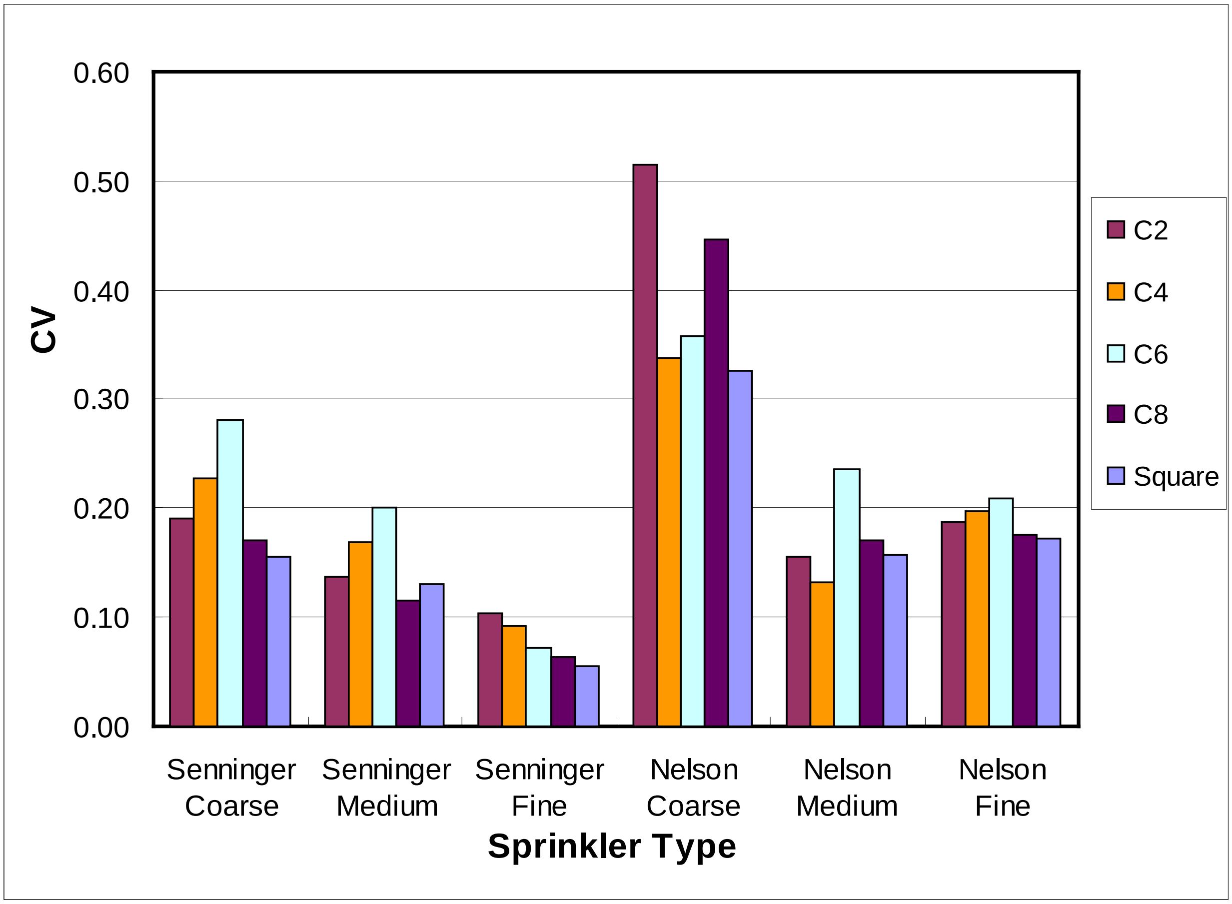

Figure 4.1. The calculated variability of water depth measurements for five collector sizes from six different fixed plate sprinkler types.

CHAPTER 5 - Summary and Conclusion

Summary of 2009 Results

The effect of collector size on the measured water depths from spinning plate, fixed plate, and wobbling plate sprinkler systems was studied during the summer of 2009. The collector sizes included C2, C4, C6, C8, and C10 collectors with diameters of 5.5 cm (2.19 in.), 10.0 cm (3.92 in.), 14.75 cm (5.81 in.), 20.0 cm (7.87 in.), and 27.4 cm (10.8 in.), respectively, and were 20.3 cm (8 in.) tall. A replicated Latin square experiment was used to study the collector size effect. Weather conditions were acceptable for all three experiments.

The mean statistics calculated for each irrigation system indicated several interesting conclusions. For all three sprinkler systems, the C10 collector measured the lowest water depth. The C6 collector measured the largest water depths for the spinning plate and the wobbling plate systems, but the C2 collector measured the greatest depth measurements for the fixed plate system. The larger collector sizes measured the same variability of measured depths as the smaller collector sizes for the spinning plate and fixed plate systems. The wobbling plate system did show a trend of decreasing measured depth variability as the collector size increased but the C4, C8, and C10 collectors measured similar levels of variability. The larger collector sizes were expected to record lower measured depth variability for the fixed plate system but the variability was consistent across all collector sizes.

The ANOVA of the measured depths showed that collector size was not a significant factor in determining the mean water depth for the spinning plate and wobbling plate systems but was significant at the 95 percent level for the fixed plate system. The comparison test of the collector sizes for the fixed plate system revealed that the C2 and C4 collectors measured significantly different depths and the C10 collector was significantly different from all other collectors. What caused the C4 collector to measure significantly different water depths from the C2 collector is unknown. The actual water depth must be known to determine the ideal collector size for measuring water depths. The correct collector size for measuring fixed plate sprinkler systems cannot be chosen because the actual applied water depth is not known.

The ANOVA of the variability of the measured depths reported significant differences for the spinning plate system but not for the fixed plate or wobbling plate systems. The C6 collector had lower depth measurement variability (90 percent significance) than the C2, C8, and C10 collectors and the C4 collector's measured variability was significantly lower than the C2 and C10 collectors' measured depth variability. The ideal collector size to minimize the variability of depth measurements is either the C6 or C4 collectors (the C6 collector's measurement variability was numerically lower than the C4 collector's variability though not significantly different). Though not significant, the C4, C8, and C10 collectors had the lowest variability of measured depths for the wobbling plate system. All collector sizes measured similar levels of variability of depth measurements for the fixed plate system.

Summary of Past Collector Size Studies

Previously conducted lab and field tests from the Department of Biological and Agricultural Engineering focusing on the effect of collector size on measured water depths were analyzed. C2, C4, C6, C8, C12, trough, and square collectors were all analyzed at least once. The Cart Study used collectors mounted on a rolling cart that was pulled under a stationary irrigation system equipped with fixed plate sprinklers to simulate a linear move system. Spinning plate, fixed plate, and wobbling plate sprinkler types were studied in field tests for the IrriGage Study. The Nozzle Study calculated the variability of measured depths for five different collector sizes from coarse, medium, and fine fixed plate sprinklers.

The range of mean depths recorded for the different collector sizes was high in the Cart Study. All collector sizes recorded high variability of water depth measurements in at least one test. Collector sizes in one test had low variability of water depth measurements but then recorded very high variability measurements in the next test. The results of this study indicate that the variability of collected water depths from the fixed plate sprinkler system is too great for accurate measurement.

The IrriGage Study measured water depths using C4, C6, and C12 collectors for the spinning plate system and the C4 and C6 collectors for the fixed plate and wobbling plate system. The C4 collector's variability of depth measurements was greater than the C6 and C12 variability for all three systems. The C6 and C12 collectors were acceptable for collector measurements for the spinning plate and wobbling plate sprinklers based on the low measurement variability and similar measured mean depths. The C4 collector's CV was about twice the C6 collector's CV for these two systems. The C4 and C6 collectors' CVs for the fixed plate system were very large, indicating unacceptable variability of depth measurements. The measured mean depths were also significantly different. These collector sizes are unacceptable for measuring the applied depth from the fixed plate sprinkler systems. The C6 and C4 collectors can acceptably measure the water depth of the spinning plate and wobbling plate systems.

The Nozzle Study compared the variability of depth measurements for five different collector sizes from six different types of fixed plate sprinklers. The C8 and square collectors recorded similar variability levels for all sprinklers except the Nelson #32 coarse sprinkler. The variability of the measured depths was high for most of the sprinklers except the fine Senninger sprinkler, which measured lower levels of variability. The coarse Nelson sprinkler had very high variability measurements (between 0.32 and 0.52) for all collector sizes. The square collector measured low CVs (comparatively) for all six sprinkler types tested. The variability of water depths was unacceptable for all collector sizes for the coarse Nelson sprinkler. The Nozzle Study illustrated the high level of measured water depth variability for these collector sizes from fixed plate sprinkler systems.

Conclusion

The results of the 2009 study and the past collector size studies indicate that measuring the applied water depth of center pivot systems with these collector sizes is challenging. Differences between measured depths were reported for the spinning plate and wobbling plate systems in the past studies; the fixed plate system reported significant differences between collector sizes in both the 2009 study and the past studies.

Any collector size used for spinning plate systems will measure the same water depth. To limit the variability of measured depths, the C6 or C4 collectors should be used. The C6 measured less variability than the C4 collector for all studies.

Collector size was not a significant factor in determining the measured water depth for the wobbling plate systems in the 2009 study. The 2009 study revealed no significant differences in variability between collector sizes but the variability of depth measurements of the C2 collector was over two times greater than the variability of the C4, C8, and C10 collectors. Though all collector sizes are acceptable, the much higher depth measurement variability of the C2 collectors indicates that the C4 collector should be chosen. The C4 collector is the ideal collector size because of its measurement accuracy and smaller size.

The fixed plate sprinkler system in the 2009 study indicated that collector size was a significant factor for measuring water depths. This test, combined with the other studies, documented that depth measurements are often significantly different between different collector sizes. The measured depth variability for the fixed plate sprinkler system was not significantly different between collector sizes in the 2009 study. The previous studies illustrated that the measured water depths from fixed plate sprinkler systems had higher mean variability levels than measurements from spinning plate and wobbling plate sprinklers.

Fixed plate systems emit distinct streams of water which are challenging to accurately measure with these collector sizes. The actual applied water depth is not known for the 2009 study and the IrriGage Study which prevents the correct collector size from being chosen. Two different assumptions can be used to determine the actual applied depth. One, the assumption that “bigger is better” for collector surface area argues that the biggest collector is the most accurate measurement of water depths. The other assumption is “more is better”, and concludes that the correct mean depth measured in the field is revealed by the similar mean depths reported from different collector sizes. A definitive conclusion based on these assumptions cannot be obtained because neither assumption can be proven correct. The significantly different water depth measurements from the fixed plate sprinkler systems, coupled with the large variability of the measured depths, indicate that fixed plate sprinklers cannot be accurately measured by the C2, C4, C6, C8, or C10 collectors.

A different method of measuring the application uniformity of fixed plate sprinklers that does not use collectors but is still based on actual field performance is needed. One method is to measure the water flow and pressure along the center pivot system to characterize the performance of a fixed plate sprinkler system. Visual inspection of the sprinkler performance would also be conducted. The flow rate of each sprinkler drop along the length of the center pivot system could be measured. By comparing the flow rate and pressure of each sprinkler drop with the center pivot system design specifications, a reasonable assurance that the irrigation system is performing adequately is provided. While measuring each sprinkler drop, the researcher should evaluate the pressure regulator, nozzle orifice size, and sprinkler spray plates installed on the sprinkler. If the water properties and sprinkler equipment at each drop along the system are correct it is highly likely that the system is performing to design specifications.

CHAPTER 6 - Bibliography

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Appendix A - SAS 9.2 Code

The code used in SAS 9.2 for the analysis of the data is given below. The identical code was used to analyze each sprinkler system. The *"Proc Means"* section reports the 95 percent confidence level of the means, standard error, standard deviation, *t* Test and p-Value of the water depths for each variable included in the class that is studied. This code created the results used in Tables 3.3, 3.4, and 3.5. The first *"Proc Mixed"* ANOVA modeled the measured water depth of each collector size. The second *"Proc Mixed"* ANOVA modeled the variability of the measured depths of each collector size.

Proc Means SAS 9.2 Code

```
proc print data= spinning;
run;
proc means N mean clm stderr stddev t prt;
class square;
var water;
run;
proc means N mean clm stderr stddev t prt;
class column;
var water;
run;
proc means N mean clm stderr stddev t prt;
class treatment;
var water;
run;
proc means N mean clm stderr stddev t prt;
class square treatment;
var water;
run;
```

Proc Mixed Code for Measured Depths

```
proc mixed data = spinning;
class square row column treatment;
model water=treatment column row;
random square row;
lsmeans treatment/pdiff;
lsmeans column/pdiff;
run;
```

Proc Mixed SAS 9.2 Code for Variability of Measured Depths

Spinning Plate System Column Adjustment

```
data one;set one;if Column=4 or Column=5 then
adjWater=Water*(1.4469/1.54265);
if Column=1 or Column=2 or Column=3 then  adjWater=Water;
keep Square Row Column Treatment adjWater;
run;
```

Fixed Plate System Column Adjustment

```
data one;set one;if Column=5 then  adjWater=Water*(5.1889)/(5.4786);
if  Column=1 or Column=2 then  adjWater=Water*(5.1889)/(4.8377);
if Column=3 or Column=4  then  adjWater=Water;
keep Square Row Column Treatment adjWater;
run;
```

Wobbling Plate System Column Adjustment

No column adjustment was completed for the wobbling plate sprinkler system.

General Code

```
/*************Treatment 2*********************/
data two;set one;where Treatment=2;run;
PROC SORT data = two;
BY square; run;
PROC MEANS DATA = two;

BY square;
VAR adjWater;
OUTPUT OUT = smpmeans std(adjwater)=sdwater;
proc print data=sdwater;
TITLE 'Adjusted data for treatment 2';
run;
goptions reset=all;
symbol1 i = join v=circle l=32  c = black;
PROC GPLOT data=smpmeans;
TITLE 'Adjusted data for treatment 2';
PLOT sdwater*square;
RUN;
goptions reset=all;
symbol1 v=circle l=32  c = black;
/**************Treatment 4*******************/
data four;set one;where Treatment=4;run;
PROC SORT data = four;
BY square; run;
PROC MEANS DATA = four;
BY square;
VAR adjWater;
OUTPUT OUT = smpmeans std(adjwater)=sdwater;
proc print data=sdwater;
TITLE 'Adjusted data for treatment 4';
run;
goptions reset=all;
symbol1 i = join v=circle l=32  c = black;
PROC GPLOT data=smpmeans;
TITLE 'Adjusted data for treatment 4';
```

```
PLOT sdwater*square;
RUN;
goptions reset=all;
symbol1 v=circle l=32  c = black;
/***************Treatment 6*******************/
data six;set one;where Treatment=6;run;
PROC SORT data = six;
BY square; run;
PROC MEANS DATA = six;
BY square;
VAR adjWater;
OUTPUT OUT = smpmeans std(adjwater)=sdwater;
proc print data=sdwater;
TITLE 'Adjusted data for treatment 6';
run;
goptions reset=all;
symbol1 i = join v=circle l=32  c = black;
PROC GPLOT data=smpmeans;
TITLE 'Adjusted data for treatment 6';
PLOT sdwater*square;
RUN;
goptions reset=all;
symbol1 v=circle l=32  c = black;
/***************Treatment 8*******************/
data eight;set one;where Treatment=8;run;
PROC SORT data = eight;
BY square; run;
PROC MEANS DATA =eight;
BY square;
VAR adjWater;
OUTPUT OUT = smpmeans std(adjwater)=sdwater;
proc print data=sdwater;
TITLE 'Adjusted data for treatment 8';
run;
goptions reset=all;
symbol1 i = join v=circle l=32  c = black;
PROC GPLOT data=smpmeans;
TITLE 'Adjusted data for treatment 8';
PLOT sdwater*square;
RUN;
goptions reset=all;
symbol1 v=circle l=32  c = black;
/***************Treatment 10*******************/
data ten;set one;where Treatment=10;run;
PROC SORT data = ten;
BY square; run;
PROC MEANS DATA = ten;
BY square;
VAR adjWater;
OUTPUT OUT = smpmeans std(adjwater)=sdwater;
proc print data=sdwater;
TITLE 'Adjusted data for treatment 10';
run;
goptions reset=all;
symbol1 i = join v=circle l=32  c = black;
PROC GPLOT data=smpmeans;
TITLE 'Adjusted data for treatment 10';
```

```
PLOT sdwater*square;
RUN;
goptions reset=all;
symbol1 v=circle l=32  c = black;

proc import out= work.stdadjust
  datafile = "G:\tingting song from computer\ttsong\study\945\scotte\std3-
adjust.xls"
  dbms = excel replace;
     SHEET="sheet1";
     GETNAMES=YES; MIXED=NO; SCANTEXT=YES; USEDATE=YES; SCANTIME=YES;
run;
proc mixed;
class treat square;
model stdadjust=treat;
random square;
lsmeans treat/ pdiff;
run;
      ods rtf close;
```

Appendix B - Raw Data

The raw data collected from the spinning plate, fixed plate, and wobbling plate systems are reported belong.

Spinning Plate System Data

Table B.1. Spinning plate sprinkler system measured water depth data.

Square	Row	Column	Collector Size Diameter (inch)	Water Depth (cm)
1	1	1	10	1.49
1	2	1	2	1.57
1	3	1	4	1.50
1	4	1	6	1.52
1	5	1	8	1.29
1	1	2	8	1.64
1	2	2	4	1.50
1	3	2	6	1.58
1	4	2	10	1.49
1	5	2	2	1.57
1	1	3	2	1.36
1	2	3	6	1.49
1	3	3	10	1.60
1	4	3	8	1.46
1	5	3	4	1.44
1	1	4	4	1.69
1	2	4	10	1.59
1	3	4	8	1.61
1	4	4	2	1.78
1	5	4	6	1.61
1	1	5	6	1.58
1	2	5	8	1.59
1	3	5	2	1.49
1	4	5	4	1.57
1	5	5	10	1.49
2	1	1	6	1.40
2	2	1	8	1.50
2	3	1	10	1.50
2	4	1	2	1.49
2	5	1	4	1.44
2	1	2	8	1.37
2	2	2	10	1.46
2	3	2	2	1.49
2	4	2	4	1.50
2	5	2	6	1.52
2	1	3	10	1.31
2	2	3	2	1.44

Square	Row	Column	Collector Size Diameter (inch)	Water Depth (cm)
2	3	3	4	1.44
2	4	3	6	1.49
2	5	3	8	1.51
2	1	4	4	1.69
2	2	4	6	1.58
2	3	4	8	1.59
2	4	4	10	1.67
2	5	4	2	1.78
2	1	5	2	1.53
2	2	5	4	1.57
2	3	5	6	1.58
2	4	5	8	1.70
2	5	5	10	1.54
3	1	1	2	1.57
3	2	1	6	1.58
3	3	1	10	1.46
3	4	1	8	1.43
3	5	1	4	1.38
3	1	2	8	1.37
3	2	2	10	1.55
3	3	2	4	1.38
3	4	2	6	1.46
3	5	2	2	1.57
3	1	3	10	1.27
3	2	3	2	1.53
3	3	3	8	1.38
3	4	3	4	1.44
3	5	3	6	1.46
3	1	4	6	1.49
3	2	4	4	1.44
3	3	4	2	1.40
3	4	4	10	1.39
3	5	4	8	1.42
3	1	5	4	1.63
3	2	5	8	1.53
3	3	5	6	1.55
3	4	5	2	1.57
3	5	5	10	1.46
4	1	1	10	1.36
4	2	1	8	1.40
4	3	1	6	1.43
4	4	1	2	1.32
4	5	1	4	1.32
4	1	2	2	1.36
4	2	2	4	1.50
4	3	2	8	1.40
4	4	2	6	1.49
4	5	2	10	1.22

Square	Row	Column	Collector Size Diameter (inch)	Water Depth (cm)
4	1	3	4	1.32
4	2	3	6	1.43
4	3	3	2	1.40
4	4	3	10	1.40
4	5	3	8	1.29
4	1	4	6	1.46
4	2	4	10	1.31
4	3	4	4	1.38
4	4	4	8	1.40
4	5	4	2	1.36
4	1	5	8	1.53
4	2	5	2	1.53
4	3	5	10	1.59
4	4	5	4	1.50
4	5	5	6	1.55

Fixed Plate System Data

Table B.2. Fixed plate sprinkler system measured water depth data.

Square	Row	Column	Collector Size Diameter (inch)	Water Depth (cm)
1	1	1	4	4.64
1	2	1	6	5.23
1	3	1	8	5.46
1	4	1	10	4.89
1	5	1	2	4.88
1	1	2	8	4.96
1	2	2	4	4.51
1	3	2	10	4.87
1	4	2	2	5.09
1	5	2	6	5.26
1	1	3	6	5.46
1	2	3	2	5.73
1	3	3	4	5.26
1	4	3	8	5.73
1	5	3	10	5.46
1	1	4	10	5.01
1	2	4	8	5.65
1	3	4	2	6.37
1	4	4	6	6.16
1	5	4	4	5.58
1	1	5	2	6.37
1	2	5	10	5.36

Square	Row	Column	Collector Size Diameter (inch)	Water Depth (cm)
1	3	5	6	6.40
1	4	5	4	6.14
1	5	5	8	5.68
2	1	1	8	4.68
2	2	1	2	5.09
2	3	1	10	4.99
2	4	1	4	5.58
2	5	1	6	5.11
2	1	2	6	4.91
2	2	2	4	5.01
2	3	2	8	5.22
2	4	2	10	5.01
2	5	2	2	5.09
2	1	3	2	5.09
2	2	3	10	5.33
2	3	3	6	5.70
2	4	3	8	6.09
2	5	3	4	5.01
2	1	4	4	5.33
2	2	4	8	5.57
2	3	4	2	5.94
2	4	4	6	5.75
2	5	4	10	5.00
2	1	5	10	5.27
2	2	5	6	5.72
2	3	5	4	5.89
2	4	5	2	5.94
2	5	5	8	6.03
3	1	1	6	4.15
3	2	1	4	4.57
3	3	1	2	4.46
3	4	1	8	4.93
3	5	1	10	4.62
3	1	2	10	3.88
3	2	2	2	4.67
3	3	2	8	4.65
3	4	2	6	4.53
3	5	2	4	4.76
3	1	3	8	5.08
3	2	3	10	4.37
3	3	3	4	4.45
3	4	3	2	4.88
3	5	3	6	4.85
3	1	4	4	5.14
3	2	4	8	4.98
3	3	4	6	4.73
3	4	4	10	5.18
3	5	4	2	5.09

Square	Row	Column	Collector Size Diameter (inch)	Water Depth (cm)
3	1	5	2	5.09
3	2	5	6	5.05
3	3	5	10	4.89
3	4	5	4	5.14
3	5	5	8	5.44
4	1	1	6	5.23
4	2	1	2	5.09
4	3	1	10	4.84
4	4	1	8	4.93
4	5	1	4	4.76
4	1	2	2	4.88
4	2	2	8	4.69
4	3	2	6	4.85
4	4	2	4	4.57
4	5	2	10	3.96
4	1	3	10	4.86
4	2	3	6	5.02
4	3	3	4	4.82
4	4	3	2	4.88
4	5	3	8	4.23
4	1	4	8	5.16
4	2	4	4	4.57
4	3	4	2	5.09
4	4	4	10	4.27
4	5	4	6	4.67
4	1	5	4	5.14
4	2	5	10	4.92
4	3	5	8	5.16
4	4	5	6	5.05
4	5	5	2	4.88

Wobbling Plate System Data

Table B.3. Wobbling plate sprinkler system measured water depth data.

Square	Row	Column	Collector Size Diameter (inch)	Water Depth (cm)
1	1	1	6	2.25
1	2	1	10	2.29
1	3	1	8	2.35
1	4	1	2	2.12
1	5	1	4	2.32
1	1	2	4	2.27
1	2	2	8	2.20
1	3	2	2	2.33
1	4	2	6	2.45

Square	Row	Column	Collector Size Diameter (inch)	Water Depth (cm)
1	5	2	10	2.29
1	1	3	10	2.34
1	2	3	2	2.46
1	3	3	6	2.42
1	4	3	4	2.32
1	5	3	8	2.37
1	1	4	8	2.34
1	2	4	6	2.44
1	3	4	4	2.26
1	4	4	10	2.16
1	5	4	2	2.16
1	1	5	2	2.38
1	2	5	4	2.32
1	3	5	10	2.19
1	4	5	8	2.39
1	5	5	6	2.80
2	1	1	4	1.94
2	2	1	10	2.03
2	3	1	2	2.04
2	4	1	8	2.02
2	5	1	6	1.96
2	1	2	2	2.12
2	2	2	6	2.16
2	3	2	10	2.10
2	4	2	4	2.13
2	5	2	8	2.15
2	1	3	10	2.36
2	2	3	8	2.31
2	3	3	6	2.37
2	4	3	2	2.29
2	5	3	4	2.32
2	1	4	8	2.40
2	2	4	2	2.21
2	3	4	4	2.32
2	4	4	6	2.37
2	5	4	10	2.19
2	1	5	6	2.39
2	2	5	4	2.19
2	3	5	8	2.31
2	4	5	10	2.24
2	5	5	2	2.25
3	1	1	8	2.12
3	2	1	10	2.06
3	3	1	6	2.34
3	4	1	2	3.61
3	5	1	4	2.13
3	1	2	2	2.08
3	2	2	4	2.26

Square	Row	Column	Collector Size Diameter (inch)	Water Depth (cm)
3	3	2	8	2.21
3	4	2	10	2.15
3	5	2	6	2.22
3	1	3	10	2.41
3	2	3	6	2.45
3	3	3	2	2.42
3	4	3	4	2.32
3	5	3	8	2.39
3	1	4	4	2.51
3	2	4	8	2.48
3	3	4	10	2.42
3	4	4	6	2.45
3	5	4	2	2.42
3	1	5	6	2.77
3	2	5	2	2.33
3	3	5	4	2.32
3	4	5	8	2.39
3	5	5	10	2.38
4	1	1	4	1.94
4	2	1	8	2.07
4	3	1	6	2.42
4	4	1	10	2.09
4	5	1	2	1.91
4	1	2	2	2.12
4	2	2	10	2.07
4	3	2	4	2.13
4	4	2	6	1.99
4	5	2	8	2.12
4	1	3	6	2.31
4	2	3	2	2.29
4	3	3	10	2.17
4	4	3	8	2.29
4	5	3	4	2.32
4	1	4	10	2.25
4	2	4	4	2.19
4	3	4	8	2.26
4	4	4	2	2.25
4	5	4	6	2.37
4	1	5	8	2.07
4	2	5	6	2.07
4	3	5	2	2.12
4	4	5	4	2.13
4	5	5	10	2.14