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Effect of Catch-Can Spacing on Calculation of Sprinkler Irrigation Application Uniformity

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Sprinkler irrigation application uniformity is an important indicator for sprinkler irrigation system design, which can be expressed by the Christiansen uniformity coefficient (CU). The calculated accuracy of CU is closely related with catch-can spacing and grid size. In theory, the smaller the catch-can spacing and grid size are, the more accurate the calculation of CU is. However, smaller catch-can spacing needs more labor in water distribution measurement, and smaller grid size needs more computer runtime to calculate CU. In order to recommend the proper catch-can spacing and grid size, an experiment is carried out to obtain four different water distribution patterns, and data characteristics for water distribution with various catch-can spacing and the effect of catch-can spacing and grid size on CU are studied in the paper. The results show that CU is overestimated for the larger catch-can spacing, especially when the distribution of water for the pattern is non-uniformity. CU changes very little within a certain catch-can spacing and grid size for all the four patterns. Considering the accuracy of CU calculation, labor cost, and the computational runtime, the recommended catch-can spacing is 1.96 m for pattern I, 0.92 m for patterns III and IV, and the recommended grid size in the calculation of CU is 1.25, 1.0, and 0.5 m for patterns I, III, and IV, respectively.

1. Introduction

Sprinkler irrigation, which can reduce groundwater seepage and pollution, plays an important role in agricultural water management. Sprinkler irrigation water application uniformity refers to the uniformity of water distribution on the ground surface.[1–3] It is an important indicator of the quality of sprinkler irrigation systems, and is an important parameter of sprinkler irrigation system design.[4–6] There are many factors affecting sprinkler irrigation water application uniformity, such as the structure of sprinklers, operating pressure, sprinkler spacing and combinations, wind, slope, and so on. All the above factors influence sprinkler irrigation water application uniformity by influencing water distribution.

Sprinkler irrigation water distribution data are the basis and precondition for analyzing and calculating sprinkler irrigation water application uniformity. Catch-can measurement is the most common method for obtaining the data of sprinkler irrigation water distribution. However, catch-can measurement can only obtain a finite number of data of water depth in water distribution, but sprinkler irrigation water distribution is continuous in the space. Therefore, it is required that the data of water depth obtained by catch cans should accurately reflect the continuous water distribution of sprinkler irrigation in the space. The accuracy of the reflection is related to catch-can spacing. In theory, the smaller the catch-can spacing, the more accurate the reflection of the continuous water distribution of sprinkler irrigation. Moreover, the more accurate reflection results in the more accurate calculation of sprinkler irrigation application uniformity. However, smaller catch-can spacing needs more labor and other resources for water distribution measurement.

For catch cans, previous research has mainly focused on reducing water losses due to evaporation, water clinging to the wall of catch can, and splashing. Christensen showed that evaporation losses from cylindrical catch cans were comparatively high.[7] Kohl found that evaporation losses from a separatory funnel precipitation gage were insignificant in several types of catch cans.[8] The accuracy of three different types of catch cans, including separatory funnel, fuel funnel, and oil can was evaluated by Marek, and the results showed that separatory funnel was the most accurate for water distribution measurement. To reduce water losses, a good catch can should not only separate water droplet striking the part of catch can, but also prevent splash-out and splash-in once the droplet is below the plane of catch can lip.[9]

Heermann and Kohl found that, compared to losses due to wind effects or evaporation from catch cans, sprinkler irrigation water losses from evaporation of the spray are comparatively small.[10] Livingston et al. carried out wind-tunnel research on the performance of catch cans. Comparing catch-can depths with

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known precipitation depths at different catch-can heights, surface roughness and speed of wind, an inverse relationship between percent catch and speed of wind was found.[11]

Clark et al. evaluated field measured data related to the catch accuracy of IrriGage collectors for measuring water depths and application uniformities using low pressure sprinklers. It was indicated that the current standard catch-can size criteria are inappropriate for the low-pressure sprinklers providing distinct water streams with little pattern breakup.[12,13] Fischer et al. studied the effect of test duration and catch-can size on the measurement of sprinkler water distribution. Large catch can is recommended to reduce test number and duration, and maintain accuracy.[14] Moreover, six different types of catch cans were employed to evaluate catch-can characteristic effect on sprinkler water depths measurement. It was also found the variation in catch depths is less for catch cans with a large opening diameter.[15]

Previous research is very helpful to improve the accuracy of catch-can measurements. However, there is lack of the effect of catch-can spacing on the calculation of sprinkler irrigation application uniformity in the studies of sprinkler catch-cans, which may influence the accuracy of the design of sprinkler irrigation system. Thus, the paper is to study the effect of catch-can spacing and grid size on the calculation of sprinkler irrigation application uniformity, recommend the proper catch-can spacing in water distribution measurement to save the labor, and provide the proper grid size in the calculation of sprinkler irrigation application uniformity to save computer runtime.

2. Experimental Section

2.1. Experimental Setup

The experiment on sprinkler irrigation water distribution was carried out at Utah State University. The experimental setup was composed of sprinklers, a centrifugal pump, a water storage tank, pipe, pressure sensor, flow rate meter, valves, a sprinkler screen, catch cans, and so on. The testing apparatus is shown in **Figure 1**.

The Nelson R33 Rotator sprinkler and Rainbird Mini Paw/LG-3 sprinkler were selected for the experiments. Each sprinkler was tested at six various pressures, including low pressure and recommended pressure. The information for the two sprinkler types is shown in **Table 1**.

Figure 1. The indoor experimental setup: 1) screen, 2) sprinkler, 3) catch can, 4) tank, 5) pump, 6) flow meter.

The pump was employed to provide the sprinkler the desired working pressure. By setting a manual valve before starting to collect data, the desired working pressure was produced for each test. The 475 L plastic water tank was held full during each test. Therefore, it can provide the pump a constant pressure. The pressure sensor was a Rosemount model. The magnetic flow rate meter was a Siemens model. The flow rate meter and the pressure sensor were connected to a data logger (Campbell Scientific CR800). The flow rate and pressure were recorded at 5 s intervals by the data logger during each 1 h test. Then the average flow rate and pressure were calculated for each test. In order to prevent water from splashing on the electronic instruments, the wooden posts, wire mesh and clear plastic sheets were used to make a sprinkler screen, which can keep water jet in the scope covered by the radial leg of catch cans.

Two radial legs of catch cans were employed, and there were two cans at each distance from the sprinkler, and the measured values of catch cans from each pair were averaged. The opening diameter and height of the catch can were 0.115 and 0.07 m, respectively. As presented by Figure 1, the catch cans were put on two radial legs at 0.115 m intervals, and they were touching each other. The distance from the sprinkler location to the center of the first catch can was 0.22 m. In the experiment there were 280 catch cans in total, and 140 catch cans for each radial leg. The graduated cylinders were used to measure water volume from each catch can. Catch cans must be emptied and dried before being returned to the appropriate location on the floor for the next test. To easily obtain the water distribution curve with different catch-can spacing, some values of water depths of 280 catch cans were deleted according to the desired catch-can spacing, and the distance between the first catch can and the sprinkler was the desired catch-can spacing. Thus, it can be ensured that the water distribution curves with different catch can spacing were obtained under exactly the same experimental conditions.

2.2. Calculation of the Coefficient of Uniformity

The Christiansen uniformity coefficient (CU) is a most commonly used indicator which assesses sprinkler irrigation water application uniformity in agriculture. CU can be calculated by Equation (1)[7]:

Table 1. Basic information for tested sprinklers.

Sprinkler type	Nozzle [mm]	Nominal tested sprinkler pressure [kPa]	Recommended pressure range [kPa]	Riser height [m]
Nelson R33 Rotator	4.8	103, 172, 241, 310, 379, 448	276–448	0.65
Rainbird Mini Paw/LG-3	3.2	155, 172, 241, 310, 379, 448	172–345	0.20

$$\mathrm{CU} = 100\left[1 - \frac{\sum_{i=1}^{n}\left|V_{\mathrm{i}} - \overline{V}\right|}{\sum_{i=1}^{n} V_{\mathrm{i}}}\right] \quad (1)$$

where V_{i} is the measured volume from an individual catch can and $\bar{V}$ is the average measured volume of all catch cans. In addition, volumes can be replaced by depths in Equation (1).

Catch3D is a mathematical model which can be used to analyze the measured performance data for sprinklers in agriculture, emphasizing water application uniformity calculation.[16] It was used in this paper for some calculations of the results presented herein, and the natural cubic spline method was employed in the radial leg interpolation for Catch 3D.

3. Results and Discussion

3.1. Water Distribution Pattern

The degree of water application uniformity obtainable with a set sprinkler system depends largely on the water distribution pattern and spacing of the sprinklers.[17,18] As shown in **Figure 2**, the following four sprinkler water distribution patterns were evaluated: 1) pattern I: the Nelson R33 sprinkler operating at recommended pressure; 2) pattern II: the Nelson R33 sprinkler operating at severely below recommended pressure; 3) pattern III: the Rainbird sprinkler operating at recommended pressure; and 4) pattern IV: the Rainbird sprinkler operating at slightly below recommended pressure. The coordinate (0, 0) in Figure 2 is the location of the sprinkler. To accurately represent water distribution within the pattern, water application profiles were measured with the catch-can spacing of 0.115 m. As seen in Figure 2, for pattern I, most of the water fell within a circular area with a certain radius around the sprinkler. The water application rate changed little while the distance from sprinkler increased. The water application rate decreased gradually when the distance was larger than the radius of circular area. Pattern I was good for the water overlap, resulting in a good uniformity. For pattern II, there was much water falling in an annular ring far from the sprinkler, because the water distribution curve was mainly composed of spikes and flat segments. For pattern III, the water application rate decreased very fast from the sprinkler to about 1 m, so there was much water falling in a small circular area around the sprinkler. For pattern IV, most of the water concentrated in a small circular area around the sprinkler and an annular ring far from the sprinkler. The above four patterns can represent water distribution for most types of sprinkler, according to sprinkler water application profile types generalized by Christiansen.[7]

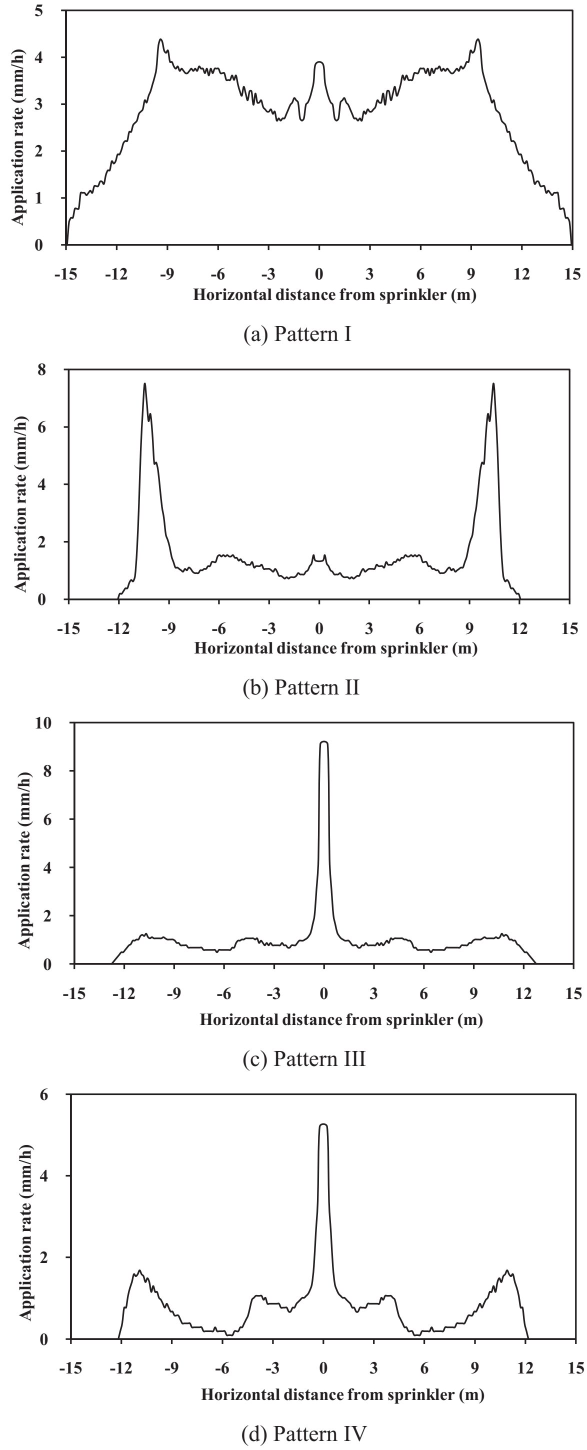

Figure 2. a–d) Water distribution patterns for Nelson R33 and Rainbird.

3.2. Data Characteristics of Water Distribution With Various Catch-Can Spacing

The calculated average value, standard deviation and the range of water application rate with different catch-can spacing for all the four patterns were summarized in **Table 2**. Because the catch-can spacing of 0.115 m was an extremely small spacing, it was assumed that the data with this spacing accurately represented the water distribution within the pattern and that the calculated average value, standard deviation and the range of water application rate shown in Table 2 for the spacing of 0.115 m

Table 2. The range, average, and standard deviation of measured values of water application rate with different catch-can spacing.

	Pattern I			Pattern II			Pattern III			Pattern IV		
Catch can spacing [m]	Min to Max [mm h^{-1}]	Average [mm h^{-1}]	SD [mm h^{-1}]	Min to Max [mm h^{-1}]	Average [mm h^{-1}]	SD [mm h^{-1}]	Min to Max [mm h^{-1}]	Average [mm h^{-1}]	SD [mm h^{-1}]	Min to Max [mm h^{-1}]	Average [mm h^{-1}]	SD [mm h^{-1}]
0.115	0.48–4.38	2.83	0.10	0.19–7.51	1.63	1.53	0.10–9.10	0.96	0.09	0.10–5.20	0.82	0.69
0.230	0.58–4.38	2.82	0.10	0.19–6.93	1.60	1.52	0.10–9.10	1.01	0.12	0.10–5.20	0.84	0.79
0.345	0.48–4.33	2.77	0.11	0.29–6.93	1.62	1.56	0.29–4.33	0.93	0.06	0.10–3.37	0.78	0.63
0.460	0.58–4.14	2.74	0.11	0.19–6.55	1.57	1.63	0.29–3.08	0.89	0.05	0.10–2.60	0.76	0.57
0.575	0.77–4.14	2.76	0.11	0.39–6.93	1.57	1.53	0.10–2.02	0.83	0.04	0.10–1.78	0.73	0.52
0.690	0.77–4.14	2.73	0.11	0.29–6.93	1.53	1.63	0.29–1.64	0.82	0.03	0.10–1.59	0.71	0.48
0.805	0.77–3.90	2.69	0.12	0.67–7.51	1.68	1.88	0.48–1.30	0.79	0.03	0.10–1.59	0.68	0.49
0.920	1.06–4.14	2.72	0.11	0.19–6.45	1.39	1.55	0.48–1.16	0.79	0.03	0.10–1.59	0.67	0.47
1.035	0.77–4.33	2.62	0.13	0.58–6.93	1.58	1.81	0.29–1.11	0.75	0.03	0.19–1.40	0.69	0.48
1.150	1.06–4.14	2.67	0.12	0.39–6.93	1.58	1.87	0.10–1.11	0.73	0.04	0.10–1.40	0.67	0.47
1.265	1.11–3.90	2.64	0.12	0.58–6.45	1.53	1.79	0.10–1.06	0.73	0.04	0.19–1.40	0.68	0.50
1.380	1.06–3.75	2.64	0.12	0.82–4.48	1.32	1.25	0.29–1.16	0.73	0.04	0.10–1.59	0.67	0.53
1.495	1.11–4.14	2.69	0.13	0.19–7.50	1.68	2.26	0.58–1.06	0.74	0.03	0.19–1.49	0.60	0.45
1.610	0.77–3.75	2.51	0.14	0.67–4.48	1.34	1.34	0.48–1.11	0.75	0.04	0.29–1.59	0.66	0.51
1.725	1.06–3.80	2.57	0.13	0.77–6.93	1.80	2.31	0.48–1.11	0.69	0.03	0.19–1.40	0.54	0.49
1.840	1.35–4.14	2.65	0.14	0.72–2.26	1.06	0.71	0.67–1.16	0.74	0.04	0.10–1.59	0.65	0.57
1.955	1.11–3.66	2.46	0.13	0.82–4.72	1.35	1.57	0.58–1.06	0.67	0.03	0.19–1.16	0.59	0.44

SD, standard deviation.

could be used as a comparison standard. As seen in Table 2, catch-can spacing has a significant influence on the range of the measured values of water application rate. For the four patterns, the low value of the range increased and the high value decreased as the catch-can spacing increased. When catch-can spacing increased from 0.115 to 1.955 m, the low values of the range of water application rate increased from 0.48 to 1.11, 0.19 to 0.82, 0.10 to 0.58, and 0.10 to 0.19 mm h^{-1} for patterns I, II, III, and IV, respectively, whereas the high values of the range of water application rate decreased from 4.38 to 3.66, 7.51 to 4.72, 9.10 to 1.06, and 5.20 to 1.16 mm h^{-1} for patterns I, II, III, and IV, respectively. Therefore, the range of measured values of water application rate was decreased. Especially for patterns III and IV, the range decreased severely because some of the high values of water application rate near the sprinkler could not be sampled as the catch-can spacing increases.

The average measured values of water application rate tend to become smaller as the catch-can spacing increases for all the patterns. When catch-can spacing increased from 0.115 to 1.955 m, the average measured values of water application rate decreased from 2.83 to 2.46, 1.63 to 1.35, 0.96 to 0.67, and 0.82 to 0.59 mm h^{-1} for patterns I, II, III, and IV, respectively. Additionally, an increased spacing which samples a smaller range of measured values of water application rate might thus result in a lower standard deviation for all the patterns except for pattern I. This is because the standard deviation is not only mainly dependent on the range of measured values, but also is related with the water distribution pattern.

As shown in **Figure 3**, both the catch-can spacing and the water distribution pattern have an impact on the relative differences between the average water application rates for the spacing of 0.115 m and those for other spacing (from 0.230 to 1.955 m at 0.115 m intervals). Generally, the relative difference increases as the catch-can spacing increases for all the patterns. The effect of water distribution pattern on the relative difference followed the sequence as: patterns III, IV, II, and I. Most of the relative differences were <15% for patterns I and II, whereas for patterns III and IV, most of the relative differences were >15%. It was mainly because water application rates for patterns III and IV were concentrated in a very narrow area near the sprinkler. An increased catch-can spacing cannot sample the high value of water application rate near the sprinkler, resulting in a lower average and higher relative difference.

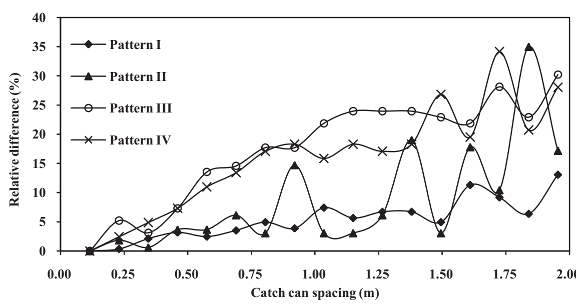

Figure 3. Relative difference between average values of water application rate for the spacing of 0.115 m and other spacing.

3.3. Effect of Catch-Can Spacing on CU

The relationship between CU and catch-can spacing for all the patterns is shown in **Figure 4**. CU was calculated by the recommended sprinkler spacing of 10 m × 10 m for patterns I and II, and 8 m × 8 m for patterns III and IV. Grid size used in the calculation of CU for all the patterns was 0.125 m. As seen in Figure 4, for each pattern, because increased catch-can spacing may result in a lower standard deviation of water application rates, most of the CU values for the larger catch-can spacing are overestimated compared with the true value of CU (CU value for the catch can spacing of 0.115 m). This result was consistent with the finding by Han et al., who reported that the value of CU with the spacing of 2.0 m was 1.3–3.4% higher than that with the spacing of 1.0 m for Nelson sprinkler at the operating pressure of 350 kPa.[19] Furthermore, the poorer the water distribution uniformity and the larger the catch-can spacing are, the greater the overestimated value and the probability of being overestimated for CU are. For example, for pattern II, because most water was concentrated in an annular ring area far from the sprinkler due to low operating pressure, particularly after water distribution overlap, water distribution is poor, thus, the value of CU with the spacing of 1.84 m was 25.7% higher than that with the spacing of 0.115 m. Additionally, the true value of CU for pattern II was very low (62.9%), which is not accepted in practice because the minimum CU used by many designers is 80%.[20]

For pattern I, the change of CU value was fairly small as the catch-can spacing increased. The maximum difference of CU value between the spacing of 0.115 m and other spacing was 1.5%, and most of the differences were <1.0%, indicating the effect of catch-can spacing on CU is small for pattern I. Thus, the larger catch-can spacing can be used in the measurement of water distribution to save the labor cost. Considering the accuracy of CU calculation and labor cost, the recommended catch-can spacing used in the measurement of water distribution was 1.96 m for pattern I.

For patterns III and pattern IV, compared with the true value of CU, the changed value of CU was <1% when the spacing increased from 0.115 to 0.92 m. When the catch-can spacing was >0.92 m, the changed value of CU is a little greater as the catch-can spacing increased. The maximum difference was 3.9% and 5.6% for patterns III and IV, respectively. Thus, to attain the accurate water distribution data, the recommended catch-can spacing used in the measurement of water distribution was 0.92 m for patterns III and IV.

The recommended catch-can spacing as related to sprinkler radius of throw was specified for full grid catch-can array method and radial catch-can array method in International Standard (ISO 15886-3) and National Standard of the People's Republic of China (GB/T 19795.2).[21,22] As these two standards depicted, for radial catch-can array method, the recommended maximum catch-can spacing is 2 m when sprinkler effective radius of throw ranges from 12 to 17 m (ISO 15886-3) or when sprinkler effective radius of throw is >10 m (GB/T 19795.2). The above standard is suitable for pattern I, but is not good for patterns III and IV. Because most of the water is concentrated in a small circular area around the sprinkler for patterns III and IV, some high values of water application rate near the sprinkler cannot be sampled if catch-can spacing was >0.92 m. Consequently, CU values for patterns III and IV were overestimated compared with the true value of CU. Therefore, for the recommended catch-can spacing, not only does sprinkler radius of throw need to be considered, but also sprinkler water distribution pattern should be further considered.

3.4. Effect of Grid Size on CU

Grid size is closely related to the run time of computer and the accuracy for the calculation of CU. The smaller the grid size is, the more accurate the calculation of CU is, but the more time computer needs to calculate CU. The relationship between CU and grid size for all the four patterns is shown in **Figure 5**. The catch-can spacing measuring water application rates for all the four patterns was 0.115 m. CU was calculated by the recommended sprinkler spacing of 10 m × 10 m for patterns I and II, and 8 m × 8 m for patterns III and IV.

As seen in Figure 5, for pattern I, CU was really stable when grid size increased from 0.125 to 1.429 m, and compared with the true value of CU (CU value for the grid size of 0.125 m), the magnitude of the change was only about 0.5%. However, CU began to fluctuate when the grid size was over 1.429 m, but the magnitude of the change was within 2.5%, indicating the effect of grid size on the calculation of CU is small for pattern I.

For pattern II, the true value of CU was 62.9%, which is usually not accepted in practice, especially as a design criterion. For pattern III, CU was also quite stable when grid size increased from 0.125 to 1.14 m, and compared with the true value of CU, the magnitude of the change was only about 0.6%. However, CU began to fluctuate strongly when the grid size exceeded 1.14 m,

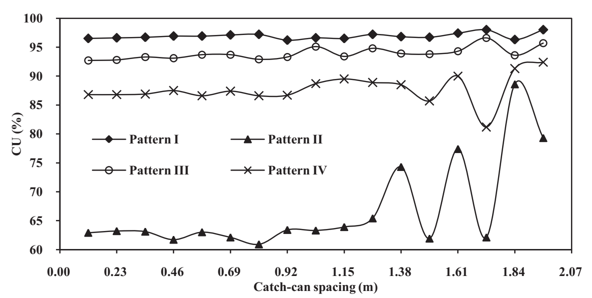

Figure 4. Relationship between CU and catch-can spacing.

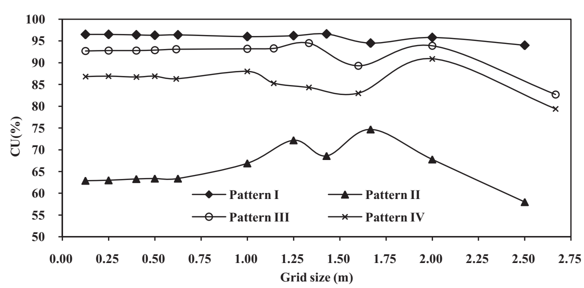

Figure 5. Relationship between CU and grid size.

and compared with the true value, the maximum difference in CU was 10.0%.

For pattern IV, CU was very stable when grid size increased from 0.125 to 0.615 m, and compared with the true value of CU, the magnitude of the change was only about 0.5%. However, CU began to fluctuate strongly when the grid size was over 0.615 m, and compared with the true value, the maximum difference was 7.4%. These results indicate that the effect of catch-can grid size on the calculation of CU is significant for patterns III and IV.

Therefore, considering the computer runtime and the accuracy of CU calculation, the grid sizes of 1.25, 1.0, and 0.5 m are recommended in the calculation of CU for patterns I, III, and IV, respectively.

4. Concluding Remarks

Although the conditions including the sprinkler, operating pressure, and riser height were exactly the same, using different catch-can spacing to measure water application depths resulted in varying water distribution profiles and different calculation results of CU. An experiment was conducted for two types of sprinkler at different pressure to obtain four different types of water distribution patterns. The data characteristics for water distribution with various catch-can spacing and the effect of catch-can spacing and grid size on CU were analyzed for all the four patterns. It was found that CU is overestimated for larger catch-can spacing, particularly if the distribution of water for the pattern is non-uniformity. As the catch-can spacing increased, the average value decreased, and the range of measured water depth narrowed, resulting in a lower standard deviation of water depths. CU changed very little within a certain catch can spacing and grid size for all the four patterns. Considering the accuracy of CU calculation, labor cost and the computer runtime, the recommended catch-can spacing used in water depths measurement was 1.96 m for pattern I, 0.92 m for patterns III and IV, and the recommended grid size in the calculation of CU was 1.25, 1.0, and 0.5 m for patterns I, III, and IV, respectively.

It should be noted that these results are valid under windless condition without crop canopy interception water. However, the case for the sprinkler system operating under wind condition sometimes occurs in practice, and the crop canopy interception water is unavoidable in the cultivated field. Thus, the effect of catch-can spacing on the calculation of sprinkler irrigation water application uniformity considering the wind and crop canopy interception water needs to be researched further.

Abbreviation

CU, Christiansen uniformity coefficient.

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Conflict of Interest

The authors have declared no conflict of interest.

Keywords

coefficient of uniformity, grid size, water application rate, water depth, water distribution patterns

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