A simplified method to improve water distribution and application uniformity for sprinkler irrigation on sloping land: adjustment of riser orientation

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ABSTRACT

To improve the water application uniformity for sprinkler irrigation on sloping land, indoor tests were conducted on an artificial slope (slopes of 0, 0.05, 0.10 and 0.15) to evaluate the effects of two riser orientations, vertical (VO) and perpendicular (PO) to the slope, on the uniformity of sprinkler rotation, radius of throw, water distribution of an individual sprinkler and the overlapped water application uniformity (WAU). Compared with the VO, the PO could effectively improve the water distribution on sloping land and minimize the risk of soil erosion. Additionally, the PO was superior in the WAU, and a rectangular arrangement could dramatically enhance the WAU at smaller sprinkler spacing, while larger acceptable sprinkler spacing was accepted in a triangular arrangement. The riser orientation and sprinkler spacing had the most significant effect on the WAU, followed by the slope and sprinkler arrangement, suggesting that the adjustment of riser orientation or sprinkler spacing was helpful in improving the WAU. However, from the aspects of investment cost and installation convenience for irrigation projects, the method of PO was recommended. Therefore, when designing the sprinkler irrigation systems on the slope, choosing PO is the simplest and most effective way to achieve good irrigation uniformity.

Key words | overlapped application uniformity, radius of throw, riser orientation, sprinkler rotation uniformity, water distribution

HIGHLIGHTS

- Riser perpendicular to the slope can obviously improve the water distribution on sloping land and minimize the risk of soil erosion.
- The overlapped water application uniformity is superior for riser perpendicular to the slope than for a vertical riser.
- Both the riser orientation and sprinkler spacing have the most significant effects on the overlapped water application uniformity.
INTRODUCTION

China has 135 million ha of cultivated land, of which slope cultivated land accounts for 33.33 million ha, approximately 1/4 of the total cultivated land area. Sloped farmland is the food production base for the survival and development of people in China's hilly or mountainous areas. Due to the long-term influence of terrain slope, the soil on sloping farmland is sensitive to drought, which drastically reduces crop yield and quality (Zhang et al. 2018). Thus, it is of great importance to determine a reasonable irrigation method for crops on sloping land. Compared with traditional irrigation methods, sprinkler irrigation on sloping land has been shown to have both higher efficiency and better adaptability to the terrain (Elwadie et al. 2013).

Sprinkler distribution is an important parameter in the design of irrigation engineering, and a key indicator for evaluating the water application uniformity of irrigation systems (Zhu et al. 2012). There are many factors that affect water distribution, including the sprinkler head, distribution system, and climatic and management factors (Mateos 1998). Because of the terrain slope, the water distribution of a single sprinkler on sloping land is quite different from that on flat land. When no wind is present, the curves of water distribution on flat ground approximate a set of concentric circles centred on the location of the sprinkler, and the water application rates at the same distance from the sprinkler are almost equal. However, when the sprinkler is used on sloping land, the water distribution patterns approximate a set of eccentric circles, and at the same distance from the sprinkler, the water application rate for uphill is greater than that for downhill, thereby resulting in poor water application uniformity (Zhang et al. 2018).

Extensive research has been conducted on sprinkler water distribution patterns and their application uniformity on sloping land. Montazar & Moridnejad (2008) revealed that soil moisture uniformity was more sensitive to the water application uniformity than to terrain slope. Ben-Hur et al. (1995) found that soil water contents were higher for downhill areas because of runoff. Cisneros Espinosa et al. (2007) performed an experimental assessment of the sprinkler application rate for steep sloping fields and determined the maximum application rates that caused zero runoff for slopes above 0.16 with a NAAN sprinkler. Additionally, due to the difficulty in measuring the sprinkler water distribution on sloping land, calculation models for the water distribution on sloping land were established using dynamics theory, ballistic theory and the water balance principle (Zhang et al. 2016).

Many previous research results have provided the basis for the design and application of sprinkler irrigation systems on sloping land (Hasebe & Mizunoe 1970; Keller & Bliesner 1990; Cisneros Espinosa et al. 2007). However, these results mainly aimed at determining the characteristics of water distribution and soil water infiltration, and few studies have been performed to determine how to effectively improve the water application uniformity on sloping farmland. As one of the effective methods to improve the...
uniformity of slope irrigation, adjusting the orientation of the sprinkler riser has been gradually applied in recent years, due to its simple operation and low investment cost. A preliminary analysis on the effects of sprinkler riser orientation on rotation uniformity and throw radius was investigated by Li (1988), but the effects on water distribution and application uniformity were not analysed. Soares et al. (1991) established a model to evaluate the sprinkler water distribution under different slopes and riser orientations and found that the riser perpendicular to the soil surface could maximize the uniformity of water application. However, this model was developed using water data collected on flat ground combined with ballistic theory, and there were differences from the actual water distribution of the slope. Accordingly, the effects of the riser orientation on the sprinkler water distribution and application uniformity on sloping land still requires further investigation.

In this study, an experiment on water distribution patterns was conducted under two commonly used riser orientations (vertical (VO) and perpendicular (PO) to the slope) and four slopes (0, 0.05, 0.10, and 0.15). The objectives were (1) to evaluate the effects of the two riser orientations on the sprinkler rotation uniformity, radius of throw and the water distribution of individual sprinklers on sloping land; (2) to investigate the overlapped water application uniformity (WAU) of multiple sprinklers with various riser orientations, sprinkler arrangements, spacings and slopes; and (3) to further propose a new method to improve the water application uniformity for sprinkler irrigation on sloping land. The flowchart of research methodology for this study is shown in Figure 1.

MATERIALS AND METHODS

Experimental setup

The experiment of sprinkler irrigation on sloping land was conducted indoors under no wind conditions. The experimental slope surface was artificially constructed using
height-adjustable brackets and steel channels. There were a total of 11 rows of steel channels of 12 m in length. The horizontal distance between the two adjacent rows was 1 m. The brackets were installed under the steel channels, and their heights were adjustable according to the test slope. To obtain the sprinkler water distribution on sloping land, catch cans with an opening diameter of 10.6 cm and a height of 15 cm were placed in the steel channels and arranged in a grid pattern. The grid size on the ground was 1 \times 1 \text{ m}. In the experiment, 11 catch cans were arranged on each row of steel channels, so there were 121 catch cans in 11 rows of steel channels (Figure 2).

An LF1200 rotating sprinkler (Rain Bird Corp., Azusa, California, USA), commonly used in agricultural irrigation, was selected for this study. The sprinkler has a 2.18 mm nozzle diameter and 17° jet angle, with a recommended operating pressure ranging from 210 to 410 kPa. In addition, a pressure transducer (Xi’an Xinmin model CYB, accuracy of \pm 0.1%) with a range from 0 to 500 kPa was installed at the sprinkler inlet and connected to a data logger. The pressure was recorded at 5 s intervals during each 1 h sprinkler test, and the average value was calculated for each test.

**Experimental design**

The sprinkler was tested with two riser orientations of VO and PO and four terrain slopes of 0, 0.05, 0.10, and 0.15. This setting was selected mainly because when the riser was PO, the riser angles (inclination of the riser from the vertical) corresponding to the various slopes (0, 0.05, 0.10 and 0.15) were 0°, 2.86°, 5.71°, and 8.53°, respectively, in accordance with the requirements of ISO 7749-1 (ISO standards 2004) that the riser angle should not exceed 10°. In total, there were seven trials in the overall experiment, and each of them were performed with three replicates in order to obtain reliable experimental data. During the sprinkler test, the working pressure of the sprinkler was stabilized at the designed pressure of 300 kPa, indoor air and water temperature were approximately 30°C and 26°C, respectively, and relative humidity was 60%. The test indicators included sprinkler rotation speed, radius of throw, as well as water distribution on sloping land.

**Test of rotation speed of an individual sprinkler**

Sprinkler rotation speed tests were conducted indoors for different riser orientations and slopes. The sprinkler has a full circle spray pattern and a clockwise rotation. Every 1/4 turn was regarded as a quadrant, that is, the uphill right quadrant and uphill left quadrant were defined as the first and second quadrants, respectively, and the downhill left quadrant and downhill right quadrant were defined as the third and fourth quadrants, respectively. The rotation times of four quadrants were recorded consecutively using a TF307 electronic stopwatch (Timestar Electronic Corp., Shenzhen, China) with an accuracy of 0.01 s. To comply with the ISO 7749-1 (ISO standards 2004), the rotation time for each combination of riser orientation and slope was taken as the average of five replications.

**Test of water distribution and throw radius of an individual sprinkler**

A full grid collector array method was used to test the sprinkler water distribution on sloping land. For convenience of the test, the sprinkler was installed at the bottom and the top of the slope surface, respectively. The height of the sprinkler riser was 30 cm, according to the manufacturer’s recommendation. At the given operating pressure of 300 kPa, the sprinkler was first installed at the top of the slope, and the water distribution on the downhill was recorded. After a 1 h test, the sprinkler was installed at the bottom of the slope, and the water distribution on the uphill was recorded under exactly the same experimental conditions. The combination of the water distribution on the downhill and uphill...
was the water distribution on the whole slope surface. Additionally, according to the ISO 15886-3 (ISO standards 2022), the radii of throw on the slope was determined by measuring the distances to the farther points with the minimum effective water application rate of 0.26 mm h⁻¹.

Data analysis

The maximum relative sprinkler rotation deviation (MRD) (Li & Kawano 1996) was used to evaluate the uniformity of the sprinkler rotation. A higher MRD value means a lower rotation uniformity. The water distribution patterns of the individual sprinklers under different riser orientations and terrain slopes were assessed using surface maps produced with SURFER software (Golden Software Inc., Colorado, USA). Meanwhile, Catch 3D software (Merkley 2004) was used to simulate the overlapped water distribution of multiple sprinklers with various sprinkler arrangements and spacings. Additionally, the WAU was evaluated using the Christiansen uniformity coefficient (CU) (Christiansen 1942) and the distribution uniformity coefficient (DU) (Hart & Reynolds 1965). Additionally, the effects of riser orientations, sprinkler arrangements, spacings and slopes on the CU and DU values were each subjected to multi-way analysis of variance (ANOVA). Means were separated using Fisher’s Protected LSD at the 0.05 level with SPSS 20.0 analytical software (IBM Corp., Armonk, NY, USA).

The MRD can be calculated by Equation (1):

\[
MRD = \frac{\max |T_j - \bar{T}|}{\bar{T}} \quad (j = 1, 2, 3, 4)
\]

where \(T_j\) is the sprinkler rotation times of \(j\)th quadrant, s, and \(\bar{T}\) is the average sprinkler rotation time of four quadrants, s.

The CU can be calculated by Equation (2):

\[
CU = \left(1 - \frac{\sum_{i=1}^{n} |h_i - \bar{h}|}{\sum_{i=1}^{n} h_i}\right) \times 100\%
\]

where \(h_i\) is the measured water depth from an individual catch can, mm; \(\bar{h}\) is the average measured water depth of all catch cans, mm; and \(n\) is the number of catch cans.

The DU can be calculated by Equation (3):

\[
DU = \frac{\bar{h}_m}{\bar{h}} \times 100\% 
\]

where \(\bar{h}_m\) is the average of the lowest 1/4 of ranked catch can measurements, mm.

RESULTS AND DISCUSSION

Uniformity of individual sprinkler rotation

Sprinkler rotation uniformity is a key factor affecting the quality of sprinkler irrigation systems (Li & Kawano 1996). Generally, when the riser was VO, the sprinkler had uniform rotation speed, whereas the actual rotation speed varied when the riser was inclined from the vertical (Soares et al. 2014). The sprinkler rotation period per quadrant and MRD value versus terrain slope when the riser was PO are presented in Table 1. Overall, sprinkler rotation periods among the four slopes were basically the same, whereas a large variation was found in the MRD values. For instance, the rotation periods under the slopes of 0, 0.05, 0.10 and 0.15 all remained at approximately 18.08 s, but the corresponding MRD values were 0.96%, 3.19%, 6.81% and 9.21%, respectively (Table 1). This finding indicated that when the riser was PO, the increase in terrain slope caused the sprinkler rotation uniformity to decrease, regardless of the minimal effect on the sprinkler rotation period, which was consistent with the findings of Nderitu & Hills (1993) and Li & Kawano (1996).

Further analysis showed that the rotation times of \(T_1\) and \(T_4\) were always less than that of \(T_2\) and \(T_3\) at the slopes of 0.05, 0.10 and 0.15, which meant that when the
riser was not vertical, the rotation speed slowed down when the sprinkler nozzle was moving in the uphill direction, whereas it accelerated when it was moving in the downhill direction, as previously reported by Soares et al. (1991). One possible explanation for this performance was that the riser inclined from the vertical led the gravity centre of the sprinkler to shift, so that the sprinkler rotating torque changed inevitably during the full circle spraying process. The sprinkler slowed down due to the reduction in the rotational torque when the nozzle turned towards the uphill direction, while the nozzle turned towards the downhill direction, a reverse result was observed.

In addition, from the analysis, the maximum MRD value appeared at the slope of 0.15, reaching 9.21%. This value was lower than the maximum allowed MRD value of 12% stipulated in Agricultural Irrigation Equipment-Rotating Sprinklers (ISO 7749:2004), suggesting that in this study, as the riser was perpendicular to a slope not exceeding 0.15, the uniformity of the sprinkler rotation could be guaranteed.

**Throw radius of an individual sprinkler**

The throw radius of a sprinkler plays an important role in the optimal selection of sprinkler spacing and lateral spacing (Ge et al. 2020). Table 2 presents the throw radii for the uphill (RU) and downhill (RD) under the two riser orientations and four slopes. It was clear that when the riser was VO, increasing the slope resulted in a gradually decreased RU and a gradually increased RD, thereby enlarging the difference between the RU and RD (ΔR), consistent with the results reported by Li (1988). Taking the slope of 0.15 as an example, the RU decreased by 9.53% and the RD increased by 10.10% compared to the slope of 0. Furthermore, the ΔR value reached a maximum of 2.02 m at the slope of 0.15. This occurred because, under the vertical orientation of the riser, the landing time of the water jet on sloping land was different from flat ground because of the terrain slope. When the sprinkler nozzle sprayed in the uphill direction, the water jet landed earlier than that for the flat ground, and a greater slope would result in earlier landing and a shorter throw radius. When the nozzle sprayed in the downhill direction, the result was reversed (Zhang et al. 2018).

Further analysis of Table 2 indicated that when the riser was PO, the impact of the slope on the throw radius appeared to be weakened. Both the measured RU and RD values at the slopes of 0.05, 0.1, and 0.15 were very close, and the ΔR values for any slope did not exceed 0.17 m. This finding was partly because this kind of riser orientation changed the initial jet angle of the nozzle, making the uphill and downhill jet trajectories similar to that of flat ground. As a result, the PO could effectively minimize the influence of terrain slope on the sprinkler throw radius and reduce the difference between the uphill and downhill throw radii, which was conducive to the design of these sprinkler irrigation projects.

**Water distribution of an individual sprinkler**

The riser orientation affects not only the rotation uniformity and throw radius of a sprinkler but also the trajectory of spray jet towards different directions, thereby affecting the sprinkler water distribution (Seginer et al. 1992). Figure 3 presents the water distribution patterns of individual sprinklers under the two riser orientations and four terrain slopes. The coordinate (0, 0) marks the location of the sprinkler. When the riser was VO, the water distribution on sloping land differed drastically from that on flat ground. From the perspective of water distribution shape, it was similar to a ‘heart-shape’ for the slopes of 0.05, 0.10 and 0.15, whereas it resembled a ‘circle-shape’ for the slope of 0 (Figure 3(a)), consistent with the results reported by Zhang et al. (2018). This result was primarily caused by the change in water jet landing time due to the influence of terrain slope, as in the aforementioned analysis. In contrast, when the riser was PO, the influence of the terrain slope on the water jet

| Riser orientation | Slope | RU (m) | RD (m) | ΔR (m) |
|-------------------|-------|--------|--------|--------|
| VO                | 0     | 10.40  | 10.40  | 0.00   |
|                   | 0.05  | 10.28  | 10.90  | 0.62   |
|                   | 0.10  | 9.77   | 11.21  | 1.44   |
|                   | 0.15  | 9.43   | 11.45  | 2.02   |
| PO                | 0     | 10.40  | 10.40  | 0.00   |
|                   | 0.05  | 10.40  | 10.52  | 0.12   |
|                   | 0.10  | 10.35  | 10.50  | 0.17   |
|                   | 0.15  | 10.30  | 10.34  | 0.04   |
trajectory was greatly reduced. It was clear that as the slope increased, the water distribution curve on sloping land was gradually transformed from a ‘heart-shape’ to a more circular shape, and it finally approximated the water distribution curve on flat ground (Figure 3(b)).

Additionally, from the perspective of water application rate (WAR) on sloping land, the higher WAR was closer to the sprinkler and the lower WAR was further away from the sprinkler, regardless of whether the riser was VO or PO (Figure 3). Similar trends have been observed in the rotating spray plate sprinkler tests conducted by Sourell et al. (2003) on flat ground. Further analysis of Figure 3 indicated that, when the riser was VO, the applied water had a trend of concentrating on the uphill with the increase of the slope, while the opposite result was observed when the riser was PO. For instance, when the riser was VO, the average WAR values on the uphill were 0.02 mm h$^{-1}$, 0.19 mm h$^{-1}$ and 0.22 mm h$^{-1}$ higher than that on the downhill for the slopes of 0.05, 0.10 and 0.15, respectively. In contrast, when the riser was PO, the uphill WAR values for various slopes (0.05, 0.10 and 0.15) averaged 0.1 mm h$^{-1}$, 0.25 mm h$^{-1}$ and 0.3 mm h$^{-1}$ lower than that on the downhill, respectively (results not presented). These outcomes signified that the PO could effectively solve the problem of the concentration of irrigation water on the uphill. The greater the slope, the more pronounced was the improvement effect observed.

In an attempt to quantitatively study the water distribution of individual sprinklers on sloping land, the distribution proportions of water application rates ($P_{WAR}$) under the two riser orientations and four terrain slopes are presented in Figure 4. It was notable that most WAR values were below 1.5 mm h$^{-1}$ for the different combinations of riser orientation and terrain slope, covering more than 83%. This finding demonstrated that the overall WAR values were relatively uniform, although the water distribution shape was affected by the riser orientation and slope, which might be attributed to the spray pattern of a single jet rotating sprinkler. From the aforementioned analysis, the WAR values on the slope were mainly distributed within 1.5 mm h$^{-1}$, but the applied water in the range of 1.5–4.0 mm h$^{-1}$ must also be considered, because high WAR values are prone to cause soil erosion (Levy et al. 1992). Further investigation of Figure 4 revealed that, in terms of the WAR values within 1.5–4.0 mm h$^{-1}$, the $P_{WAR}$ of the PO was lower than that of the VO. Using the three slopes (0, 0.05 and 0.15) selected in this study as an example, the $P_{WAR}$ within 1.5–4.0 mm h$^{-1}$ was 13.0%, 13.9% and 16.7%.
for the VO, respectively, whereas they were 12.0%, 13.5% and 13.2% for the PO, respectively. In summary, the PO could not only improve the water distribution of an individual sprinkler on sloping land but also minimize the risk of soil erosion, resembling the results obtained by Soares et al. (1991) through a ballistic trajectory model.

**Overlapped water application uniformity of multiple sprinklers**

**Effect of riser orientations, sprinkler arrangements, spacings and slopes on overlapped water application uniformity**

Statistical analysis of the WAU is usually of significant interest because, in practice, sprinklers are always overlapped (Playán et al. 2006). Since the radius of throw on flat ground was 10.4 m at the designed pressure of 300 kPa, seven different sprinkler spacings (8 × 8 m, 8 × 10 m, 10 × 10 m, 10 × 12 m, 12 × 12 m, 12 × 14 m, 14 × 14 m) and two sprinkler arrangements (rectangular and triangular) were considered for simulating the WAU values at the selected two riser orientations and four terrain slopes, as shown in Table 3. Overall, the VO resulted in lower WAU values compared to those with the PO, consistent with results reported by Soares et al. (1991). For instance, under the rectangular arrangement, the mean CU and DU values at various sprinkler spacings and slopes were 69.0% and 55.4% for the VO and 73.0% and 60.9% for the PO, respectively, whereas they were 66.7% and 51.4% for the VO, and 71.7% and 57.9% for the PO under the triangular arrangement,

![Figure 4](http://iwaponline.com/ws/article-pdf/21/6/2786/932966/ws021062786.pdf)

**Figure 4** Distribution proportions of water application rates under two riser orientations and four terrain slopes: (a) 0, (b) 0.05, (c) 0.10, (d) 0.15.
respectively. It was not difficult to find that, with the rectangular arrangement, the CU and DU values for the PO were on average 4.0 and 5.5 percentage points higher than those for the VO, while with the triangular arrangement, the values were 5.0 and 6.5 percentage points higher. One possible explanation for this performance was that when the riser was VO, the sprinkler produced a more irregular profile on the slope than that of the PO (Figure 3), and this consequently influenced the overlapped distribution pattern, as previously reported by Nderitu & Hills (2006).

Further analysis of Table 3 indicated that the WAU differed drastically between the rectangular and triangular arrangements, whether VO or PO. Among them, the CU and DU values for the rectangular arrangement mainly varied from 62.5% to 84.6% and 42.2% to 77.4%, respectively, whereas they varied from 52.4% to 82.1% and 32.6% to 73.1% for the triangular arrangement, respectively. This finding revealed that the overall WAU of the rectangular arrangement was superior to that of the triangular arrangement; despite the close upper limits of the uniformity coefficients observed under the two arrangements, their lower limits varied significantly, with differences of the lower limits of the CU and DU values attained of 10.1 and 9.6 percentage points, respectively. This finding was consistent with the results reported by Fukui et al. (2012) but contrasted with the results reported by Dechmi et al. (2000).

Additionally, the maximum values of the WAU under different slopes and riser orientations were often found to occur at 8 × 8 m for the rectangular arrangement, and the WAU values gradually decreased with the increase in sprinkler spacing (Figure 5), resembling the previous findings by Nderitu & Hills (2006) for different riser heights and sprinkler spacings. For 8 × 8 m, 10 × 12 m and 14 × 14 m spacings, the average CU and DU values of the various slopes were 73.1%, 67.9%, 63.5% and 64.3%, 51.7%, 47.3%, respectively, when the riser was VO. The corresponding values were 80.2%, 72.8%, 66.9% and 70.0%, 58.8%, 51.7%, respectively, when the riser was PO. These data suggested that for the rectangular arrangement, if high uniformity was required, reducing the sprinkler spacing might

| Table 3 | Overlapped water application uniformities (%) for rectangular and triangular arrangements with various sprinkler spacings under two riser orientations and four terrain slopes |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Riser orientation | Slope | CU | DU | CU | DU | CU | DU | CU | DU | CU | DU | CU | DU | CU | DU |
| Rectangular arrangement | VO | 0 | 82.1 | 77.4 | 77.8 | 66.3 | 74.2 | 61.4 | 69.8 | 54.0 | 66.0 | 65.7 | 67.1 | 56.1 | 64.1 | 49.1 |
| | 0.05 | 73.2 | 65.1 | 74.1 | 66.3 | 72.5 | 58.0 | 68.2 | 54.0 | 65.7 | 51.8 | 65.8 | 51.1 | 64.0 | 49.0 |
| | 0.10 | 72.1 | 57.4 | 73.6 | 63.1 | 72.3 | 56.7 | 67.2 | 49.6 | 65.4 | 49.5 | 62.5 | 46.2 | 63.4 | 48.9 |
| | 0.15 | 72.2 | 57.2 | 73.0 | 60.0 | 71.4 | 54.6 | 66.3 | 49.1 | 64.3 | 48.0 | 62.5 | 42.3 | 62.5 | 42.2 |
| | Mean | 75.1 | 64.3 | 74.6 | 63.9 | 72.6 | 57.7 | 67.9 | 51.7 | 65.1 | 53.8 | 64.0 | 48.9 | 63.5 | 47.3 |
| PO | 0 | 82.1 | 77.4 | 77.8 | 66.3 | 74.2 | 61.4 | 69.8 | 54.0 | 66.0 | 65.7 | 67.1 | 56.1 | 64.1 | 49.1 |
| | 0.05 | 84.6 | 77.2 | 81.8 | 73.9 | 82.1 | 73.1 | 77.9 | 66.5 | 75.3 | 65.1 | 73.6 | 61.9 | 68.2 | 55.1 |
| | 0.10 | 76.8 | 64.0 | 75.9 | 64.1 | 74.2 | 61.2 | 72.3 | 57.9 | 68.4 | 53.5 | 70.2 | 55.8 | 69.8 | 54.1 |
| | 0.15 | 77.3 | 61.4 | 76.4 | 60.9 | 74.2 | 58.6 | 71.0 | 56.6 | 64.1 | 49.2 | 64.5 | 55.6 | 65.4 | 48.3 |
| | Mean | 80.2 | 70.0 | 78.0 | 66.3 | 76.2 | 63.6 | 72.8 | 58.8 | 68.5 | 58.4 | 68.9 | 57.4 | 66.9 | 51.7 |
| Triangular arrangement | VO | 0 | 57.2 | 49.0 | 68.9 | 51.4 | 74.2 | 63.1 | 75.1 | 66.0 | 70.9 | 58.3 | 68.3 | 56.0 | 56.5 | 44.2 |
| | 0.05 | 68.6 | 53.3 | 67.3 | 48.9 | 72.5 | 61.4 | 73.7 | 59.6 | 69.9 | 54.4 | 66.8 | 50.0 | 56.0 | 44.0 |
| | 0.10 | 66.9 | 48.9 | 65.4 | 48.2 | 72.3 | 58.0 | 70.6 | 63.4 | 68.8 | 50.6 | 64.4 | 46.2 | 52.9 | 36.8 |
| | 0.15 | 59.6 | 36.2 | 60.9 | 42.1 | 71.4 | 56.7 | 69.9 | 55.2 | 66.4 | 47.4 | 62.5 | 44.6 | 52.4 | 34.2 |
| | Mean | 67.3 | 49.4 | 65.6 | 47.7 | 72.6 | 59.8 | 72.3 | 61.1 | 69.0 | 52.7 | 65.5 | 49.2 | 54.5 | 39.8 |
| PO | 0 | 74.2 | 59.0 | 68.9 | 51.4 | 74.2 | 63.1 | 75.1 | 66.0 | 70.9 | 58.3 | 68.3 | 56.0 | 56.5 | 44.2 |
| | 0.05 | 71.5 | 55.8 | 71.3 | 51.2 | 82.1 | 73.1 | 79.1 | 67.2 | 76.3 | 66.0 | 77.2 | 67.9 | 63.9 | 46.8 |
| | 0.10 | 74.2 | 61.2 | 75.9 | 64.1 | 78.8 | 69.5 | 70.3 | 58.4 | 70.4 | 53.3 | 72.8 | 56.0 | 62.3 | 49.0 |
| | 0.15 | 74.2 | 58.6 | 76.4 | 60.9 | 80.1 | 72.7 | 71.3 | 57.1 | 67.5 | 50.5 | 66.3 | 50.2 | 56.9 | 32.6 |
| | Mean | 73.5 | 58.7 | 73.1 | 56.9 | 78.8 | 69.6 | 74.0 | 62.2 | 71.3 | 57.0 | 71.2 | 57.5 | 59.9 | 43.2 |
be a good choice, in addition to the riser perpendicular to the slope. With very close spacings, however, the cost of hardware or labour would increase. The spacings, moreover, could be such that the instantaneous rates during the irrigation interval might become too high for the soil (Chen & Wallender 1984; Nderitu & Hills 1993). Hence, it was critical for determining the proper sprinkler spacing.

Compared to the rectangular arrangement, the WAU of the triangular arrangement had an initial increase and then tapered off as the sprinkler spacing increased, of which the highest WAU values at various slopes all mainly focused on the $10 \times 10$ m or $10 \times 12$ m spacings, regardless of the VO and PO (Figure 6). Moreover, it was notable that the WAU values of some triangular arrangements exceeded that of the rectangular arrangements under the three spacings of $10 \times 12$ m, $12 \times 12$ m and $12 \times 14$ m. Among these three sprinkler spacings and four different slopes, the mean CU and DU values of the triangular arrangement were 3.3% and 2.8% higher than that of the rectangular arrangement for the VO, respectively, and the above values changed to 2.1% and 0.8%, respectively, for the PO. These findings signified that the overall WAU values of the rectangular arrangement were better than that of the triangular arrangement, but the triangular arrangement seemed to improve the WAU at large sprinkler spacing in this study.

From the perspective of acceptable sprinkler spacing (ASS) ($CU \geq 75\%$, $DU \geq 60\%$) (Nderitu & Hills 1993), almost no ASS occurred in the VO in either the rectangular
or triangular arrangement, suggesting that the VO indeed had poor WAU values. When the riser was PO, the maximum ASS values of the rectangular arrangement at various slopes was $8 \times 10 \text{ m}$ except for $12 \times 12 \text{ m}$ at the slope of 0.05. However, the maximum ASS values of all slopes were increased when switching from the rectangular to the triangular arrangement, especially for the slope of 0.05. The corresponding ASS values at the four slopes (0, 0.05, 0.10 and 0.15) increased to $10 \times 12 \text{ m}$, $12 \times 14 \text{ m}$, $10 \times 10 \text{ m}$ and $10 \times 10 \text{ m}$, respectively. From the analysis, the rectangular and triangular arrangements had their own advantages for the PO. Among them, the rectangular arrangement played an important role in improving the uniformity under the small sprinkler spacing, while the triangular arrangement had a larger ASS value that could minimize the investment cost and risk of soil erosion.

Taken together, in the design of sprinkler irrigation projects on sloping land, both of these arrangements should be used in combination; it is recommended to select the rectangular arrangement for small sprinkler spacing and the triangular arrangement for large sprinkler spacing when the riser is PO. This finding differs somewhat from those of previous studies, which suggested that either the rectangular or the triangular arrangement could be chosen in practice (Fukui et al. 1980; Dechmi et al. 2004).

Furthermore, the influence of the slope on the WAU also cannot be ignored. When the riser was VO, the WAU increased with the higher slope at the same sprinkler spacing, while for the PO, the variability of the WAU became less sensitive as the slope increased due to the reduction in the slope effect on water jet trajectory. Surprisingly, when the riser was PO, the overall WAU at the slope of 0.05 was highest compared to the other slopes, and the mean CU and DU values at different sprinkler spacings were at least 5.1 and 8.8 percentage points higher than that of the other slopes for the rectangular arrangement, as they were 2.4 and 2.3 percentage points for the triangular arrangement, respectively. Perhaps the water distribution pattern of a single sprinkler at a slope of 0.05 was more conducive to the water overlapping under the different sprinkler arrangements.

### Analysis of variance of the effect of various factors on overlapped water application uniformity

To further investigate and compare the effect of different factors (riser orientation, sprinkler arrangement, spacing and slope) on the WAU, Tables 4 and 5 presented the ANOVA results of the effect of each factor on the CU and DU values, respectively. Notably, the riser orientation and sprinkler spacing had the most significant effect on the CU and DU values ($P = 0.000$) followed by the slope ($P = 0.081$ and 0.002 for CU and DU, respectively), and the sprinkler arrangement had the smallest effect ($P = 0.130$ and 0.040 for the CU and DU, respectively). This outcome suggested that, regardless of the sprinkler arrangement and slope, adjusting the riser orientation or sprinkler spacing was very helpful to improve

| Factor                  | Sum of square of deviation | Degree of freedom | Mean square deviation | F value | P value |
|-------------------------|---------------------------|------------------|----------------------|---------|---------|
| Riser orientation       | 572.413                   | 1                | 572.413              | 15.926  | 0.000   |
| Sprinkler arrangement   | 93.623                    | 1                | 93.623               | 2.323   | 0.130   |
| Sprinkler spacing       | 2,235.437                 | 6                | 372.573              | 17.079  | 0.000   |
| Slope                   | 272.262                   | 3                | 90.754               | 2.304   | 0.081   |

| Factor                  | Sum of square of deviation | Degree of freedom | Mean square deviation | F value | P value |
|-------------------------|---------------------------|------------------|----------------------|---------|---------|
| Riser orientation       | 1,006.201                 | 1                | 1,006.201            | 13.751  | 0.000   |
| Sprinkler arrangement   | 343.350                   | 1                | 343.350              | 4.335   | 0.040   |
| Sprinkler spacing       | 3,137.884                 | 6                | 522.981              | 9.280   | 0.000   |
| Slope                   | 1,192.567                 | 3                | 397.522              | 5.460   | 0.002   |

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the WAU values on the slope as previously analysed, but from the aspects of investment cost and project convenience, changing the sprinkler spacing generally required a high level of manpower and material resources, and therefore the method of PO was recommended.

CONCLUSIONS

Compared with the vertical riser, the maximum relative sprinkler rotation deviation within the slope of 0.15 did not exceed 9.21%, indicating that the uniformity of sprinkler rotation could be guaranteed for the riser erected perpendicular to the slope. Again, the PO could effectively reduce the difference between uphill and downhill throw radii ($\Delta R$). The $\Delta R$ values for slopes of 0.05, 0.1, and 0.15 did not exceed 0.17 m.

Despite the water distribution shape of individual sprinklers was affected by the riser orientation and slope, the overall WAR on sloping land was relatively uniform for both the VO and PO, and their WAR values below 1.5 mm h$^{-1}$ all covered more than 83% at different combinations of riser orientation and terrain slope. Additionally, the distribution frequency of the high WAR values within 1.5–4.0 mm h$^{-1}$ was observed to be lower for the PO than for the VO, suggesting that the PO was conducive to minimizing the risk of soil erosion.

The PO had an absolute superiority in overlapped WAU compared to the VO. Its mean CU and DU coefficient with rectangular arrangement were 4.0 and 5.5 percentage points higher than those for the VO, while with the triangular arrangement, the above values were changed to 5.0 and 6.5 percentage points. Moreover, for the PO, the rectangular arrangement could dramatically enhance the WAU at smaller sprinkler spacing, while the triangular arrangement had larger acceptable sprinkler spacing (CU $\geq$ 75%, DU $\geq$ 60%); thus, both arrangements should be used in combination for the design of sprinkler irrigation projects on sloping land.

From the ANOVA results of the effect of various factors on the WAU, the riser orientation and sprinkler spacing were found to have the most significant effect on the CU and DU values, followed by the slope and sprinkler arrangement, revealing that the adjustment of the riser orientation or sprinkler spacing was important in improving the WAU values, regardless of the sprinkler arrangement and slope. However, in view of investment cost and installation convenience for irrigation projects, the method of PO is a worthy recommendation. In summary, in order to obtain a good irrigation uniformity when designing the sprinkler irrigation system on slopes, choosing PO is undoubtedly the simplest and most effective way.

This paper presented the comparison results of the water distribution and application uniformity for the two riser orientations using a Rainbird LF1200 rotating sprinkler on an artificial slope. These results provided a basis for the design of sprinkler irrigation systems on sloping land, but there were still some limitations. In this paper, a rotating sprinkler with a unique structure was selected for experimental research. The water collected in catch cans were not weighed timely during the tests; this might lead to the measurement errors due to water evaporation. This study was conducted under indoor conditions, ignoring the influence of external factors such as wind speed and temperature, which might affect the design of sprinkler irrigation systems in the field. In addition, this study did not involve the soil water movement on sloping land, and further research is therefore required.

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DECLARATION OF CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.
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