Optimization of movable irrigation system and performance assessment of distribution uniformity under varying conditions

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Abstract: The evaluation of the performance of distribution uniformity by linearly moved irrigation system (LMIS) should consider the impacts of non uniformity of the water on crop yield. With increasing pressures to improve water use efficiency, plant productivity and farm profitability, questions continue to be raised concerning the future direction of irrigated agriculture. This study therefore aimed at evaluating water distribution under LMIS newly designed by the National Research Centre of Fluid Machinery Engineering and Technology, Jiangsu University, China. This article reports the real distribution of irrigation water under the LMIS with respect to sprinkler height above the ground surface as well as the consequence of different operating pressures. Water distribution coefficients used in the performance assessment were Christiansen's coefficient of uniformity (*CU*), distribution uniformity (*DU*), scheduling coefficients (*Sc)* and the coefficient of variation (*CV*). The results showed that the mean *CU* ranged from 82.30% to 93.17%, and mean *DU* ranged from 70.39% to 88.44%. Also *Sc* values ranged from 1.13 to 1.42 with *CV* values ranging from 10.3% to 22.5%. The optimum method and results in this study can provide a reference to the operations for saving water and cost in the application of LMIS.

Keywords: movable irrigation system, sprinkler irrigation, distribution uniformity, coefficient of uniformity, coefficient of variation, scheduling coefficient

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1 Introduction

One of the most relevant parameters in sprinkler systems is the water application uniformity. Its effect on crop yield is an important consideration for the design of these systems. The design of a suitable site-specific irrigation system can be complex because of the needs to address the numerous causes of the variation that may exist in each area of the field, the system capabilities that may be needed to achieve the design management level, constraints inherent in the currently existing equipments and the general management policy of the irrigator[1-5]. In agriculture, many ways of conserving water have been investigated and techniques such as partial, deficit or drip irrigation have shown water productivity can be enhanced. Sam-Amoah et al.[6] corroborated that insufficient water may also lead to high soil moisture tension, plant stress and reduced crop yield. According to Darko et al.[7], irrigation systems are the mechanisms that allow water to be diverted from its original place to be applied to the agricultural fields for supplementing water for crop growth and enhancing yields. Sprinkler irrigation under

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which linearly moved irrigation system (LMIS) is categorized, is one of the most commonly used agricultural irrigation methods. Field evaluations of sprinkler performance can include measurements of application uniformity based on measured amounts of water containers referred to as catch cans[8].

Today, LMIS with their automation, large area coverage and high reliability are replacing surface, hand line and wheel line systems. LMIS are not anchored but has both ends of the system moved at constant speed up and down the field. The pump and power source are located at one end of the field and water is supplied to the flat hose, hard hose or open channel. The power supply can be diesel, gen-sets for electric machines and diesel hydraulic power packs for hydraulic machines or mains (electric) via a dragged cable for electric and hydraulic machines (which are rare in most African countries). LMIS consist of a single sprinkler lateral supported by series of towers. Its design enables different types of fixed spray plate sprinklers to be hanged on the span with the help of gooseneck at different points. The type of sprinkler spray head selected for the experiment can be substituted as per the type of pressure needed for the operation, the sprinkler height above the ground can also be varied and the distance between adjacent sprinklers can also be varied per decision of the irrigator[9-13].

However, linearly moved irrigators are designed, installed and operated without much field verification of their performance either initially or overtime. Knowledge about their operation and water applications in the field remains limited. Those who use them only follow the general guidelines provided by the manufacturers and system designers. Ali[14] highlighted that some of the new irrigation systems developed in the industrialized countries are too complex, energy-intensive, dependent on expensive imported equipment and large in scale to be directly applicable to the low-capital, low-technology circumstances of the less-industrialized countries, where farming is often practiced on a small scale and the relative costs of labor and capital are very different.

Issues on uniformity distribution, system efficiency and the application rates have not yet been properly evaluated and assessed[14,15]. Knowing the irrigation systems' application uniformity is critical to make certain that the water applied is spread evenly across the growing zone. In the light of these, this research was conducted to focus on the optimization of irrigation distribution uniformity using a linearly moved irrigation system designed by the National Research Centre of Fluid Machinery Engineering and Technology, Jiangsu University, China. This new system is simple, less expensive, more portable and robust, easily installed and can be used for efficient management of crop-water productivity at farm level.

The objective was to assess the real distribution of irrigation water under the newly designed LMIS with respect to sprinkler height (h) above the ground surface as well as the consequence of different operating pressure (P).

2 Materials and methods

The study on optimization of irrigation distribution uniformity was conducted in the laboratory of the National Research Centre of Fluid Machinery Engineering and Technology, Jiangsu University, China where the ground was bare to avoid interception of applied water by the leaves of plants as shown in Figure 1.

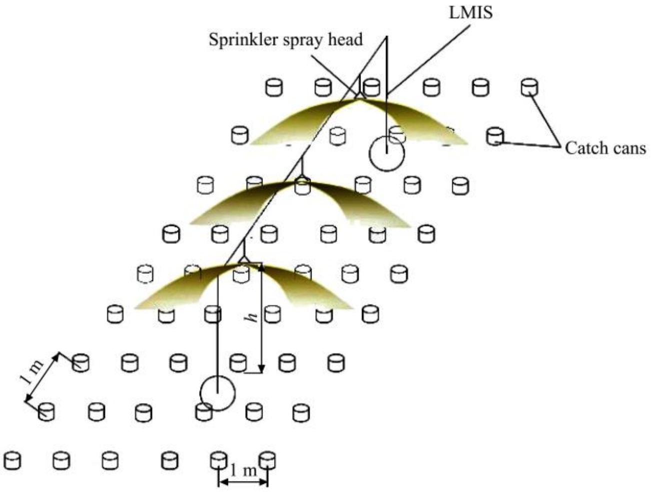
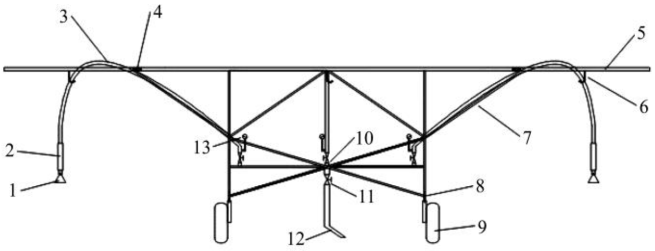


Figure 1 Design of field experiment

A newly designed 12 m long LMIS with one span was used (Figure 2) for the experiment. In this experiment the system was set in a stationary position to sprinkle water over catch can at varying operating pressures and at two different sprinkler heights. However, the system has the potential to move in a linear or straight line path which may cover the entire width designed for its operation and to water the field in one pass if allowed to move. The method of water supply involved the use of a flexible drag hose that was attached to the piping system. The drag hose system utilizes attachments to riser points. Depending on the length of run of the system, the attachment point may need to be moved between two or three supply points (or remain attached to a single point) during one pass. Catch cans with 22 cm height and an inside diameter of 20 cm were used and positioned as shown in Figure 3a.



1. Low pressure nozzle 2. Counterweight 3. Water hose 4. Quick-release connectors 5. Slotted truss 6,7. Pitch means the support bar 8. Height adjustment bolt 9. Sprinkler wheels 10. Water way 11. Supply valve 12. Pipe water supply interfaces 13. Gauge

Figure 2 Schematic view of LMIS used in the experiment

a. Layout of catch cans b. Experiment set up of LMIS c. Sprinkler spray head d. Flip over spray cap

Figure 3 Experiment set up of LMIS

The cans were constructed from standard plastic pipe material and the spacing between catch cans were not varied but set at 1 m apart from each other. According to Cogels[16] and Topak et al.[17], the performance evaluation of sprinkler irrigation is often evaluated based on water uniformity coefficients collected in catch can experiments. There were 6 rows and 9 columns of catch can arrangements resulting in a total of 54 catch cans (Figure 3b). However border catch cans were not computered in data analysis since 99.6% recorded zero catchment of water.

The most commonly used uniformity coefficient (*CU*) is that of Christiansen[18]. It is defined as:

$$CU = \left[1 - \frac{\sum_{i=1}^{n}(X_i - \bar{X})}{n\bar{X}}\right] \times 100\% \tag{1}$$

where, X_i is the water depth collected from the i^{th} catch can, mm/h; $\bar{X}$ is the mean water depth collected in all catch cans within the area, mm/h; n is the total number of catch cans in the area under consideration.

The distribution of uniformity (*DU*) was computed by dividing the mean lowest quarter caught in the cans by the average depth caught in all the cans.

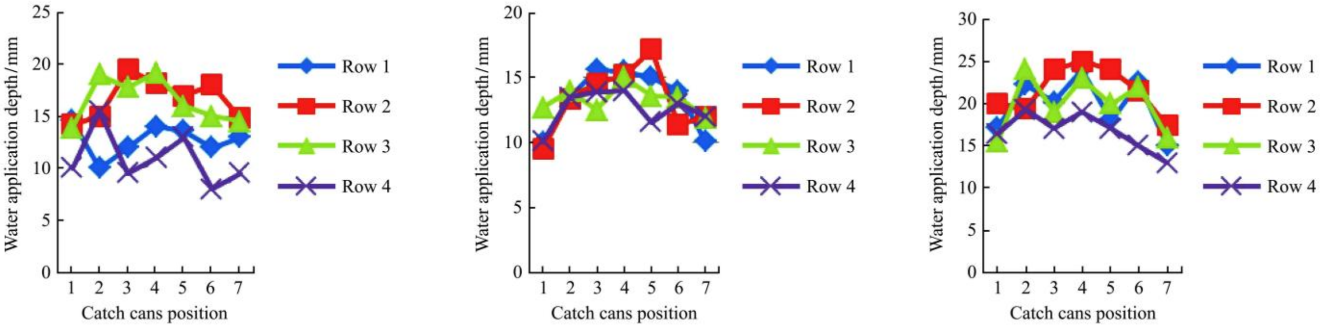
$$DU = 100\left(\frac{Dlq}{\mu}\right) \tag{2}$$

where, *DU* is distribution uniformity, %; *Dlq* is the mean of lowest one-quarter of the measured depths, mm.

The scheduling coefficient (*Sc*) was also determined to represents the ration of area receiving the least amount of water to the average amount of water applied through the irrigation area. This value as cited by Solomon[19] enables us to find the critical area in the water application pattern. Mathematically, *Sc* is:

$$Sc = \frac{1}{DU} \times 100\% \tag{3}$$

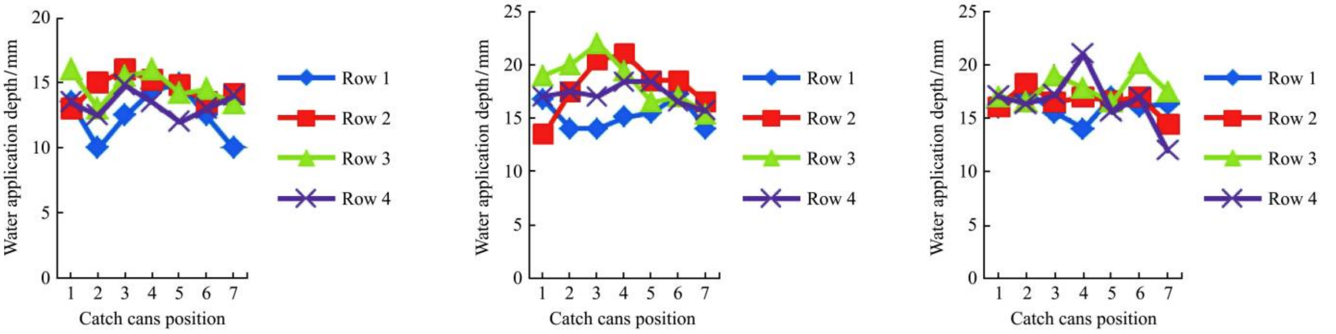
Three different set of Nelson spray heads (Figure 3c) representing P_1-10 psi, P_2-15 psi, and P_3-20 psi were fixed on hose (riser) to aid in the distribution of water over the demarcated area. The spray head is a fixed-spray sprinkler which produces a variety of patterns depending upon the specific spray plate selected. It incorporates a flip-over spray cap (Figure 3d), allowing for a choice of snap-in spray plates to produce a germination, irrigation, or fertigation spray pattern for different seasonal and field needs. In all, three main experiments were carried out at two different sprinkler height (h) above the ground surface (h_1=100 cm, h_2= 150 cm), using three different sprinkler heads (Figure 3c) positioned in the central part of the span of the LMIS as shown in Figure 2. In each case, same kind of sprinkler head was placed on the risers. Each experiment was repeated and their mean values were used in the analysis. The time duration set for each experiment in the collection of water by catch cans at their set positions without moving the LMIS was 15 min after which the valve was closed and readings were taken. Water application depth (cm) captured in each catch can was measured using a volumetric flask, hence, the pattern of distribution as observed in Figure 4.



a. Water distribution pattern in catch cans at h_1 and P_1

b. Water distribution pattern in catch cans at h_2 and P_1

c. Water distribution pattern in catch cans at h_1 and P_2



d. Water distribution pattern in catch cans at h_2 and P_2

e. Water distribution pattern in catch cans at h_1 and P_3

f. Water distribution pattern in catch cans at h_2 and P_3

Figure 4 Water distribution pattern with varying height and different operating pressures

3 Data analysis and representation

Statistical analyses were performed using the Analysis of Variance (ANOVA) and statistical test tools in the Origin (OriginPro 2015 65-bit). Data interpolation and representation of catch can coordinate and water application depths were processed using Microsoft excel program (2010).

4 Results and discussion

The measured sprinkler flow rate ranged from 1.61 m^3/h to 1.82 m^3/h, with average flow rate of 1.74 m^3/h. *CU* values were calculated from the uniformity coefficient formulae by Christensen[18]. From a general perspective, the experimental data presented inherent variability as a result of P and h. The *CU* values ranged from a lower value of 82.30% for h_1 and P_1 to a higher value of 93.17% representing h_2 and P_3 respectively.

4.1 Water distribution pattern

Generally, mean values of water in catch cans increased as P was increased for the two different h positions set for the experiments. However, very low water in catch cans was recorded at height (h_1), pressure P_3 (Figure 4e) compared to that at P_1 (Figure 4c). Mean water distribution in catch cans observed in Figures 4a, 4c and 4e were 14.6 mm, 19.52 mm and 17.23 mm respectively. The decrease in mean value of water at P_3

for h_1 will have resulted from opposing wind force at the time of the experiment leading to a lesser concentration of the sprinkler for the combined effect of P_3 and h_1. These occurrences agree with published results by Dechmi et al.[20] and Evans[21]. It could also be attributed to the relative positions of the catch cans but the effects of these were not quantified in this research. In the case of h_2, mean values of water depth in catch cans recorded for the various operating pressure P_1, P_2 and P_3 were 13.15 mm, 13.16 mm and 16.75 mm respectively (Figures 4b, 4d and 4f). At a range of 5 psi, mean values of *P* recorded at h_2 were not significantly different from each other. Water application intensities are smaller and more uniformly distributed at higher operating pressures. This agrees with Zhang et al.[22] who said that as the sprinkler pressure increases, the magnitude of water application spikes diminishes and more water is distributed to each can along the radial leg. They also postulated that when sprinkler pressure is lower than recommended pressure range, the shape of water distribution curve is dominated by flat segments and bikes, hence most of the water falls within an annular ring around the sprinkler, resulting in a relatively poor overlap pattern as observed in Figures 4a and 4b. As can be observed in the water distribution pattern curves, generally, catch cans in row 2 and row 3 relatively collected more water than that of row 1 and row 4 which could be attributed to their relative positioning closer to the sprinklers.

Table 1 also emphasizes significant influence of *P* and *h* on the coefficient of variation (*CV*). As *P* and *h* decreased, CV values increased. The *CV* (22.5%) value at the lower h_1 and least P_1 was highest during the experiment which indicated that the degree of non uniformity was quite high for this combination as seen in Figure 4a. Combined effect of *P* and *h* resulted in a decreased *CV* values with increasing both *P* and *h*. It must be accentuated that the lowest *CV* mean value, 10.3% occurred at the combined effect of P_3 and h_2 which represents the highest *P* and *h* used in the experiment. The P_1 was found to cause a reduction in throw radius. These reductions may result in sprinkler overlap changing and this will reduce the water distribution uniformity. The reduction in the water distribution uniformity indicated that the LMIS was not too perfect in delivery of irrigation water, hence will affect crops grown under such irrigation as they will not receive more water thereby increasing the energy required as well as the cost involved. Hence for a uniform spread of water distribution, a combined effect of P_3 and h_2 is recommendable. It must also be emphasized that as *P* was set from a lower to a higher value, significant differences occurred in *CV* values for the respective heights used in the experiment.

Table 1 Effect of operating pressure and height of sprinklers on CV (%)

Operating pressure level		Sprinkler height level	
		h_1	h_2
P_1		22.5a	14.4a
P_2		16.98b	11.3b
P_3		12.7c	10.3c
LSD 0.05 at h_1	1.5		
LSD 0.05 at h_2	0.43		

Note: Distinct letters in the column indicate significant differences according to ANOVA test ($p \leq 0.05$).

4.2 Coefficient of uniformity (*CU*)

Table 2 was formulated to establish the effect of different *P* and with respect to two different *h* positions on *CU*.

Table 2 Effect of operating pressure and height of sprinklers on *CU* (%)

Operating pressure level		Sprinkler height level	
		h_1	h_2
P_1		82.30a	88.57a
P_2		85.87b	91.28b
P_3		90.05c	93.17c
LSD 0.05 at h_1	1.5		
LSD 0.05 at h_2	0.43		

Note: Distinct letters in the column indicate significant differences according to ANOVA test ($p \leq 0.05$).

Water application uniformity is an important performance criterion for the design and performance of LMIS. However, the pattern of distribution is usually not uniform across the field as a result of the topography of land, system design and movement, sprinkler design and many other factors. It is clearly seen from Table 2 that *CU* increases significantly for both *P* and *h*. In all experiments at h_1, operating pressures P_1, P_2, and P_3 recorded mean *CU* values of 82.30%, 85.87% and

90.05%, respectively. Also at h_2, mean *CU* values recorded for the different operating pressure were 88.57%, 91.28% and 93.17% for P_1, P_2 and P_3, respectively. Values obtained for the two heights with respect to each pressure were significantly different from each other. These results are in agreement with Kara et al.[23], Sahoo et al.[24] and Moazed et al.[25] in which a direct correlation between *CU* and *P* was recorded. However, according to Michael[26], a satisfactory uniformity coefficient should be 85% or more. Dwomoh et al.,[27] also corroborated uniformity values under low and moderate wind speed conditions as ranging between 80% and 90%. From the experiment, it appears all mean *CU* values at h_2 for the various operating pressures are within the acceptable range. At the combined effect of *P* and *h* on *CU*, there was a direct proportionality. The lowest mean *CU* (82.30%) was observed at P_1 and h_1 and the highest mean *CU* (93.17%) occurred at the extreme conditions of P_3 and h_2 (Table 2). Higher *CU* values were achieved with sprinkler height of 150 cm above ground level. It should be noted that when the *h* was at 100 cm, with pressure at 10 psi, mean *CU* was lowest and not acceptable as per Michael[26] definition for satisfactory *CU*.

4.3 Distribution Uniformity (DU)

The values of *DU* (Table 3) were higher at h_2 and lower at h_1 above ground level.

Table 3 Effect of operating pressure and height of sprinklers on *DU* (%)

Operating pressure level		Sprinkler height level	
		h_1	h_2
P_1		70.39a	81.02a
P_2		78.96b	85.62b
P_3		84.18c	88.44c
LSD 0.05 at h_1	1.5		
LSD 0.05 at h_2	0.43		

Note: Distinct letters in the column indicate significant differences according to ANOVA test ($p≤0.05$).

At h_1, means *DU* for P_1, P_2 and P_3 were recorded as 70.39%, 78.96% and 84.18% respectively. Also, recorded mean *DU* at h_2 for the respective operating pressures ranged from 81.02% to 88.44%. Baum et al.[28] and Rain Bird Corporation[29] found that the mean *DU* ranged from 75% to 85%. All these values with the exception of combined P_1 and h_1 were greater than the minimum acceptable *DU* of (75%) postulated above. Lower *DU* values are associated with high wind speed which might have resulted in the case of the combined effect of P_1 and h_1. Hence the newly designed LMIS could be a very useful tool in uniform distribution of irrigation water to crops in the field.

4.4 Scheduling coefficient (Sc)

The scheduling coefficient depends on *DU*. Irrigation should be scheduled based on soil water levels to avoid undesirable plant stress. This observation is normally carried out to provide time adjustment factor which ensures that under irrigated areas receive the optimum amount of water application. LMIS operates on a lighter frequent water spraying and compounded by evaporative losses from plant canopy and wind drifts, it is very crucial to determine the area receiving least amount of water so that it could be adjusted for optimum application.

Table 4 represents the effect of operating pressure and height on *Sc*. *Sc* ranged from 1.13 at P_3 and h_2 and 1.42 at P_1 and h_1. Connellan[30] and Abdelrahman[31] mentioned that an efficient irrigation system should aim at achieving *Sc* of less than 1.3. From the results in table 4, combined P_1 and h_1 were above this limit. Also, a combination of P_3 and h_2 proved to be lowest hence, the LMIS could be working more effectively at this point.

Table 4 Effects of operating pressure and height of sprinklers on *Sc*

Operating pressure level		Sprinkler height level	
		h_1	h_2
P_1		1.42a	1.23a
P_2		1.27a	1.17a
P_3		1.19a	1.13a
LSD 0.05 at h_1	1.5		
LSD 0.05 at h_2	0.43		

Note: Same letters in the column indicate no significant differences according to ANOVA test ($p≤0.05$).

5 Conclusions

Ideally, an irrigation system would apply water in a completely uniform manner so that each part of the irrigated area receives the same amount of water. Significant effort in sprinkler irrigation system design and management must be directed towards dealing with problems related to irrigation uniformity and management of the system.

1) Water distribution coefficients used in the performance assessment were Christiansen's *CU*, *DU*, *Sc* and *CV*. Values for *CU* ranged from 82.30% to 93.17% and that of *DU* ranged from 70.39% to 88.44%. Also *Sc* values ranged from 1.13 to 1.42 with *CV* values ranging from 10.3% to 22.5%. The best operating conditions was P_3 (20 psi) and h_2 (150 cm) which corresponds to practical situations of high pressure and high sprinkler nozzle height. It is not recommended to operate at low pressures and heights since their coverage area for irrigation will be lessened. It must be emphasized that the optimum values obtained in this study with respect to the varying conditions is not instantly a turning point to successful irrigation but to serve as a platform in providing additional knowledge to the operations and water application trends of LMIS on the field to help save cost.

2) An integrated approach of actual observation and implementation of optimal equipment, design and management factors will be of paramount interest to the system user. The pump supply system, sprinklers and operating conditions must be designed to enable a uniform application of water. Instead of introducing prepackaged hardware systems, developers should use indigenous skills and materials rather than mere transfer of western technology into continents that lack the skills and operational approach to already existing sophisticated systems. It must be re-echoed that the aim should be to adapt or redesign technology flexibly so as to suit the prevailing conditions and requirements of the respective areas.

3) Due to the flexibility and adjustable nature of the newly designed LMIS, it is recommended for vegetable and shallow rooted crops because it produces lighter drops of water per sprinkler selection which do not damage crops.

4) The challenge of this system is that there is some labor requirement to re-orient the system at each end of the field. Further work should be done on other operating conditions of the system for instance moving the LMIS to ensure more efficient distribution uniformity at optimized parameters. The spacing between sprinklers could also be varied to test the efficacy of the newly designed LMIS.

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