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Controlling Sprinkler Rotation Speed to Optimize Water Distribution Uniformity of Travelling Rain Guns

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Abstract. *Big travelling rain guns irrigate the field according to a typical bell-shaped pattern having a potentially negative effect on distribution uniformity, irrigation efficiency and working capacity. Field experiences demonstrate that old travelling sprinklers do not allow good distribution of water, unless large wetted areas overlap. Recent big sprinkler models take advantage of improved hydraulic and mechanical characteristics, and under normal field operations, overlapping of wetted areas is about 15% of sprinkler diameter (SD). Irrigation performance of big travelling rain guns can be improved by flattening the water distribution curve. This condition can be achieved through accelerating the sprinkler rotation speed while irrigating the central sector of the wetted area. A mechanical device, named Uniform, was designed and manufactured to this end. A big rain gun was equipped with the device, and compared to an identical rain gun (Explorer), according to the same nozzle/pressure setting resulting in 56 m sprinkler radius. A field test under no wind conditions was carried out in two experimental fields, bare and flat, arranged in parallel according to ISO 8224-1 n. 584, in order to assess the effectiveness of the device both in absolute and comparative terms, according to Christiansen's uniformity coefficient, CU, and low-quarter distribution uniformity coefficient, DUlq. Under test conditions, when adjacent travel lanes of the cart were spaced from about 75% to 90% of sprinkler diameter, average DUlq of Uniform ranged from 0.88 to 0.80, and CU varied from 92% to 88%. In the same spacing interval, DUlq of Explorer ranged from 0.86 to 0.70, and CU from 90% to 82%. The highest average DUlq and CU values for Uniform occurred when adjacent travel lanes were around 85% of SD, for Explorer when spacing was 80% of SD. Acceptable values of DUlq and CU over the irrigation strip were allowed by Uniform for travel lanes spacing about 90% and 95% of SD, respectively. The same values decrease to 88% and 92% of SD without the rotation speed controller. Compared to Explorer, we found that a 5% wider area can be irrigated by Uniform when given the same uniformity, and potential water saving due to uniformity is about 15%. It should be noted that quite a simple mechanical device enabled appreciable potential water saving, proving that irrigation performance can benefit from relatively small investments.*

Keywords. Hose reel, travelling rain guns, sprinkler irrigation, distribution uniformity, water saving.

Introduction

In time of increasing water scarcity, the need to improve the efficient use of irrigation water is of paramount importance. Application efficiency (AE) is a performance indicator defined as the ratio of the volume of irrigation water beneficially used to the volume of irrigation water applied (Pereira,1999). It is affected by a number of water losses that are difficult to measure, and is also strongly affected by the distribution uniformity (DU) of the irrigation system (Pereira, 1997). In spite of uniformity not being an efficiency indicator (Burt et al., 1997), observed DU values can be used as the upper limits of the AE (Pereira et al., 2002), for practical purposes as is traditionally done. Pressurized water application (e.g., sprinkler and micro irrigation) is said to be more efficient than traditional surface irrigation, due to reasons such as minor losses thanks to better DU. The self-propelled traveller irrigation systems are widely used worldwide for irrigation of most field crops. They are available in two types (Evans and Sneed, 1996): the cable-tow and the hose-pull or drum traveller. The hose-pull traveller is widespread, and consists of a hose-drum and a polyethylene (PE) hose. One end of the PE hose is attached to the hose drum and the other end attached to a sprinkler cart or a boom. The hose is used to supply water to the water distribution device and also pull the cart toward the drum. Until the beginning of the early '90s, the major problems of travelling rain guns were application depths which were different from those expected, and low DU. The consequence is that the present design value of AE is 75% (Reinders, 2011), and the prevailing opinion of people involved in the irrigation sector worldwide, is that hose reel sprinkler irrigation is water wasting due to low efficiency. The main causes for poor irrigation performance were attributed to excessive spacing of travel lanes, asymmetric wetted angle, and variable advance velocity (Dubalen, 1993). Big rain guns supply irrigation water according to a typical bell-shaped distribution pattern, resulting in low DU values. This characteristic is accentuated in old rain gun models, as shown in figure 1 (Ghinassi, 2008). To overcome such condition, normal spacing between two adjacent hose travel lanes (e.g., the irrigation strip width) should be 70-80 percent of sprinkler diameter (SD) (Smith et al., 2003; Mathieu et al., 2007; Capra and Scicolone, 2007).

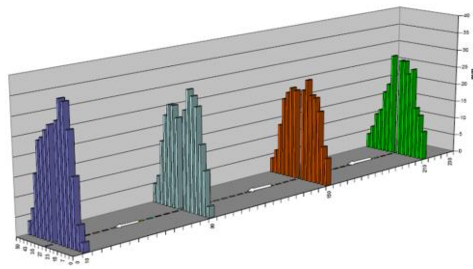

Figure 1. Typical bell-shaped distribution pattern of old travelling rain guns. Measured DU of the figure is low, and increased overlapping of wetted areas (e.g., progressive reduction of travel lane spacing) results in limited increase of DU.

Recent big sprinkler models benefit from improved hydraulic and mechanical performance. The result is that under normal field operations, the irrigation strip width is around 85 percent of SD (Taglioli, 2007), i.e. 1.7 the sprinkler radius (R). Irrigation performance can be improved further by flattening the water distribution curve by varying the instantaneous irrigation time over the irrigated sector. This condition can be achieved by accelerating the sprinkler rotation speed while irrigating the central sector of the wetted area.

Materials and methods

A mechanical device, named Uniform, was designed and manufactured to this end by SIME Idromeccanica, a sprinklers Manufacturer operating in Guastalla, Reggio Emilia province, Italy. Uniform was assembled on a SIME big rain gun, Explorer, and compared to a second Explorer not equipped with the speed regulating device. The objective of the comparison was to assess the effectiveness of the device, both in absolute and comparative terms, according to Christiansen's uniformity coefficient, CU (Christiansen, 1942):

$$CU = 100 * \left(1 - \frac{\sum Y_i}{\sum h_i}\right) \quad (1)$$

where: $\sum Y_i$ = sum of the difference of individual depths against the average depth;

$\sum h_i$ = sum of the total collected depths.

and the distribution uniformity of the lower quarter, DUlq (Burt et al., 1992):

$$DU_{lq} = \frac{h_{lq}}{h_{avg}} \quad (2)$$

where: h_{lq} = average low quarter depth;

h_{avg} = average depth of water accumulated in all elements.

The CU is an uniformity indicator for design, while the DUlq is used when evaluating existing systems. An acceptable value for CU is 80% (ARC, 2010), for DUlq it is 0.75 (IAA, 2006).

Experimental fields

A field test was carried out in September 2012 in two identical experimental fields, bare and flat, arranged in parallel (fig. 2) on a farm located in North Italy, 40 km NE from Bologna. The longer side of both fields was separated by a strip of land 70 m in width. Each field was 227 m long and 121 m wide, equipped with 3 lines of catch cans (L1, L2, L3), perpendicular to the hose travel lane. Each line was made up of 28 collectors, spaced every 4.5 m according to ISO 8224-1 n. 584 (ISO, 2003) and secured on the soil surface by iron pickets. The distance between consecutive lines was 60 m. the stop position of the sprinkler carts was set at 74 m behind the last line (L3). A meteorological station for wind monitoring and rainfall measurement was placed close to the fields.

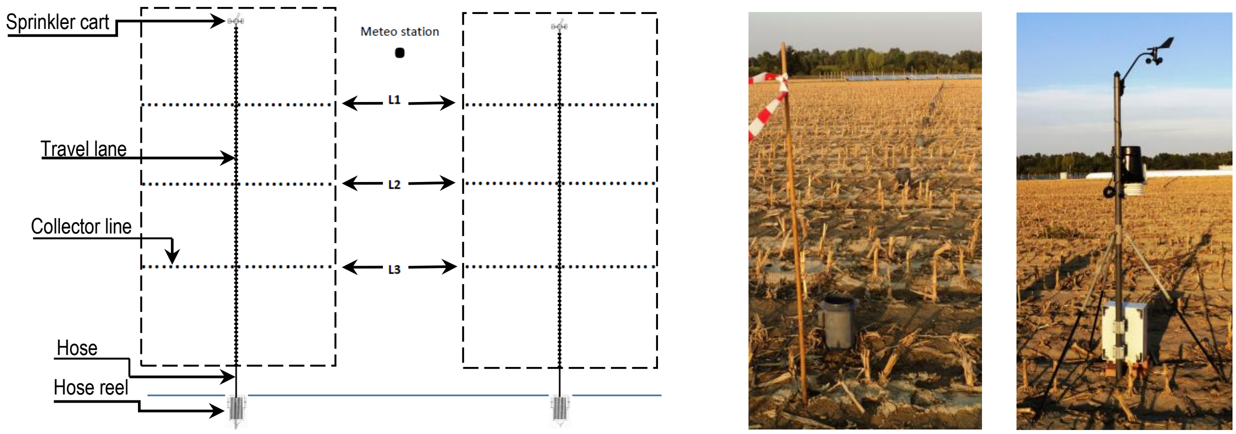

Figure 2. Left to right: layout of the experimental fields (not in scale); one line of collectors; the meteo station.

Wind and rainfall

Wind was absent during the first and the third test, while it just blew sporadically from 22:00 to 03:30 h at a speed ranging between 0.4 and 0.9 m/s (0.3÷1.5 m/s: *waft or breath of wind* according to the Beaufort scale) during the second test. No rain fell during field activity.

Rotation speed controller

The Uniform device consists of two parts, one of which is fixed on the riser and the other which rotates with the sprinkler. The core is a locked cam-shaped ring, over which a pulley rotates. Rain guns used for the test are in figure 3.

Figure 3. Explorer (left) and Uniform (right). Uniform device, with pulley in the low part of the cam, is detailed in the sketch. Braking force is adjusted by the external screw pin.

The pulley is coupled with a circular brake through a brake adjuster. The up-and-down motion of the pulley during rotation over the ring, leads to variable clamping force on the brake. When the pulley approaches the lower part of the cam, the braking force diminishes. As the pulley moves towards the upper part of the ring during the ascending phase, the brake clamps onto the brake lining with increasing force and rotation speed decreases to a rate depending on the adjuster position regulated by the external screw pin. The angle regulated by the cam is 60° and corresponds to the wetted sector over which the water jet moves faster. Wetting sector can vary ranging from 60° to 240°. The ring diameter passing through the lowest part of the cam is perpendicular to the hose travel lane. Sprinkler rotation can vary considerably, depending on the combination of water pressure, braking force and the setting of the oscillating arm.

Results

Data collection

Wetted sectors were set for 180°, since Uniform was primarily designed for such a wetting angle. Sprinkler nozzles were 28 mm Ø, and under 500 kPa working pressure at the nozzle (900 kPa pressure at reel inlet), measured flow rate was 17 l/s and R was 56 m. Sprinklers were regulated at the beginning of the first test. Rotation speed was measured for 180° round trip over three sectors, 60° each one. Coverage times of each sector are given in table 1.

Table 1. Time for 180° round trip under sprinkler working setting. Wetting angle was split into three sub sectors 60° each, left (L), central (C) and right (R).

	Average Time to Cover 60° Sector (s)							
	Uniform				Explorer			
Sprinkler Rotation	L	C	R	Total	L	C	R	Total
Clockwise	32	19	32	**83**	18	18	18	**54**
Anticlockwise	24	17	24	**65**	19	19	19	**57**
Round Trip	**56**	**36**	**56**	**148**	**37**	**37**	**37**	**111**

Rotation times over the sectors highlights the effect of Uniform device on coverage during irrigation. Under the test setting, Uniform spent 55% more time on external sectors than on the central one.

Collector lines were wetted in pairs (e.g., L1-L1, L2-L2, L3-L3), since the travelling rain guns worked simultaneously being coupled with two identical modern machines, each one equipped with a control unit, a pressure gauge and a water meter (fig. 4). The hose size was 110 mm Ø external diameter.

Figure 4. Left: the hose reel machines. A water meter is in the foreground. Right: sprinkler carts on travel lane at start position.

Depths of water application for lines of collectors

The test was replicated three times (8, 10 and 17 September 2012), and irrigations lasted from 20:00 to 7:15 h. Measurement of the water applied during the irrigation event was completed before the rising of the sun. All depths of water application are reported in table 2.

Table 2. Water depths (mm) collected during test events (8, 10, 17 September) by the 28 catch cans (Cc n.) of the three lines (L1, L2, L3) placed along the sprinkler radius [R (m)] on the left (Ln.) and right (Rn.) side of the hose travel lane .

Cc n.	L14	L13	L12	L11	L10	L9	L8	L7	L6	L5	L4	L3	L2	L1	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	Machine	Date
R (m)	**60**	**56**	**52**	**47**	**43**	**38**	**34**	**29**	**25**	**20**	**16**	**11**	**6.5**	**2**	**2**	**6.5**	**11**	**16**	**20**	**25**	**29**	**34**	**38**	**43**	**47**	**52**	**56**	**60**		
L1	0	0.5	8.9	17	24	28	32	37	41	38	39	39	39	39	33	38	34	35	35	38	38	37	34	33	28	15	2.5	0	**Uniform**	**8 September**
L2	0	0	4.8	14	21	25	32	33	37	38	39	38	39	38	34	36	32	32	36	39	39	39	40	33	27	20	6.5	0	**Uniform**	**8 September**
L3	0	0.3	8.3	16	24	29	34	35	35	36	38	36	38	36	33	36	32	32	36	35	34	34	29	30	23	13	1.7	0	**Uniform**	**8 September**
L1	0	0	6.8	17	23	29	33	34	34	34	34	35	40	43	41	45	39	36	36	37	34	33	32	26	19	11	1.6	0	**Explorer**	**8 September**
L2	0	0	5.5	16	24	27	32	36	37	39	39	41	44	50	44	46	39	36	37	36	36	33	30	26	21	13	2.7	0	**Explorer**	**8 September**
L3	0	1	8.5	21	26	31	35	38	40	41	42	43	46	46	44	43	38	37	36	35	33	30	28	26	18	10	2.8	0	**Explorer**	**8 September**
L1	0	2.8	9.5	16	21	26	31	34	37	38	39	38	43	37	36	38	36	35	37	38	36	36	34	29	24	17	8.5	0	**Uniform**	**10 September**
L2	0	3.5	11	20	26	29	32	34	37	37	38	37	39	39	35	38	36	35	37	35	34	32	30	27	24	15	5.4	0	**Uniform**	**10 September**
L3	0	5.5	16	23	26	29	33	35	38	39	38	40	42	39	46	44	41	43	40	38	34	30	26	23	16	9.5	1.5	0	**Uniform**	**10 September**
L1	0	1.5	9.5	16	21	27	32	34	37	38	39	42	45	46	45	44	40	37	36	37	34	32	26	21	15	9.8	2.5	0	**Explorer**	**10 September**
L2	0	3.4	12	25	31	33	36	36	36	35	36	35	40	39	42	37	33	34	36	33	29	27	22	17	12	5.9	0	0	**Explorer**	**10 September**
L3	0	4.4	17	27	32	33	37	39	39	42	41	45	52	48	49	45	42	37	35	32	31	24	18	13	8.1	1.5	0	0	**Explorer**	**10 September**
L1	0	9.8	11	21	26	33	38	39	43	44	44	46	45	45	41	43	38	40	40	40	40	38	36	32	24	11	2.5	0	**Uniform**	**17 September**
L2	0	2	9.8	21	22	26	30	33	33	34	34	36	38	36	36	36	34	33	37	38	38	35	35	31	27	14	2.4	0	**Uniform**	**17 September**
L3	0	1	7.5	16	22	27	32	37	39	38	39	38	41	40	38	37	33	32	35	35	33	35	30	29	26	19	4.5	0	**Uniform**	**17 September**
L1	0	0	6	21	29	33	38	39	42	43	42	42	45	47	43	45	41	39	37	36	36	32	30	26	21	9.6	2.3	0	**Explorer**	**17 September**
L2	0	1.6	10	23	27	32	34	33	36	36	38	38	42	43	41	40	35	34	35	34	31	30	28	21	17	8	2.4	0	**Explorer**	**17 September**
L3	0	1	9.5	18	26	30	33	37	41	42	42	43	48	48	45	45	40	37	36	35	33	30	27	24	19	12	3.2	0	**Explorer**	**17 September**

During each event, the water jet did not reach the edge of the field, i.e., the catch cans L14 and R14, and measurements were done on 26 catch cans in each line, resulting in 78 values per sprinkler. Max depth supplied by Explorer exceeded max depth of Uniform also in all pairs of lines. The mean application depth for each line of collectors, the mean application depth over the strip, the maximum and minimum application depth for the strip, and the total amount of water supplied, are reported in Table 3.

Table 3. Mean depth of water in collector lines (L1, L2, L3), mean (h_{mean}), maximum (h_{max}) and minimum (h_{min}) application depth for the strip, and total water supplied (WS).

Water measurement	8 September		10 September		17 September	
	Sprinkler model		Sprinkler model		Sprinkler model	
	Explorer	*Uniform*	*Explorer*	*Uniform*	*Explorer*	*Uniform*
L1 (mm)	28.9	30.1	29.4	29.9	31.7	33.3
L2 (mm)	30.3	29.6	27.8	29.3	28.8	28.8
L3 (mm)	30.7	28.1	30.4	30.5	30.8	29.2
h_{mean} (mm)	30.0	29.2	29.2	29.9	30.4	30.4
h_{max} (mm)	50.4	40.5	51.6	45.9	48.3	45.5
h_{min} (mm)	1.0	0.3	1.5	1.5	1.0	1.0
WS (m^3)	668	655	671	694	684	670

In spite of the mean application depths being almost coincidental, water distribution is different, particularly in the central part of the wetted area, resulting in a less pronounced bell shaped pattern. An example of measured water application depths for one transverse line of collectors is shown in figure 5.

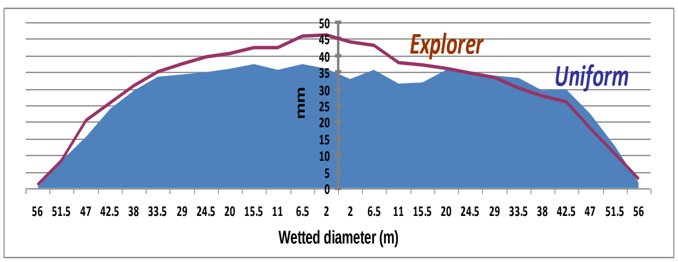

Figure 5. Example of water distribution of Uniform and Explorer for L3 line of collectors (8 September).

Uniformity for irrigation strips

The measured water depths of table 2 were used to assess DUlq and CU for irrigation strips (figure 6 and figure 7). For water distribution system operating in adjacent travel lanes, application depths include those in areas of overlap. Calculation is made by translating to the irrigation strip the out-of-strip data by a distance corresponding to the irrigation strip width, i.e., by adding the values that fall outside the right part of the strip to the values in the left part of the strip and vice versa (ISO, 2003).

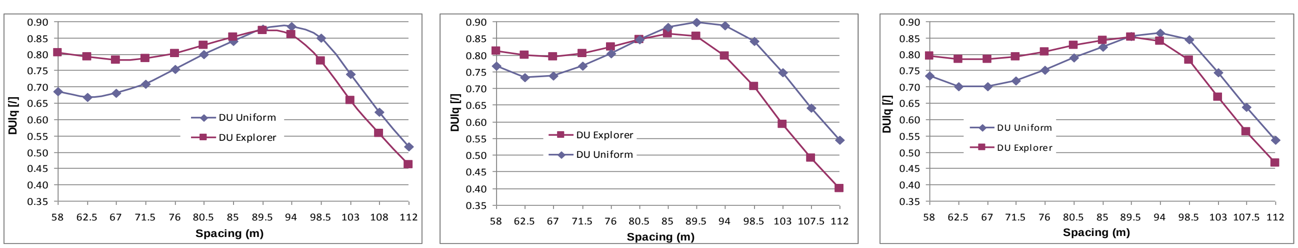

Figure 6. DUlq values for irrigation strips originated by different overlapping during 8, 10 and 17 September 2013 (left to right)

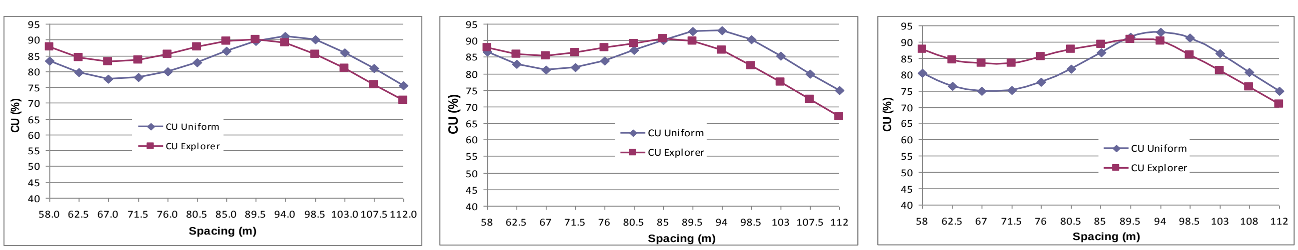

Figure 7. CU values for irrigation strips originated by different overlapping during 8, 10 and 17 September 2013 (left to right).

The width of the irrigated strip corresponds to the spacing between adjacent travel lanes, i.e., from 58 to 112 m, according to the progressive overlapping of wetted areas, 4.5 m each step, corresponding to collectors spacing. DUlq and CU values refer to the first, second and third irrigation event (from left to right), as reported in figure 6 and figure 7 respectively. Each value is calculated from 78 measured water application depths (L1+L2+L3) using *ISO 8224-1 n. 584* procedure. DUlq and CU patterns look quite similar. Explorer performed better than Uniform when overlap increased (spacing less than 85 m or 1.5 R), while effectiveness of the speed rotation controller increased with spacing. For strip widths exceeding 1.5 R (about 75% of SD), the advantage of Uniform under the same uniformity value was about 5% the irrigated width. Under the same spacing, the difference of DUlq and CU increased up to about 10% and 5% respectively. Since radial distribution pattern of Uniform was flatter than that of Explorer, it permitted better uniformity performance with minimal overlapping of wetted areas in all comparisons (e.g., line of collectors, irrigation strip). On average, and under test conditions, when adjacent hose travel lanes were spaced from about 75% to 90% the SD (1.5 R to 1.8 R), DUlq of Uniform ranged from 0.80 to 0.88, and CU varied from 88% to 92%. In the same spacing interval, DUlq of Explorer ranged from 0.70 to 0.86, and CU from 82% to 90%. The highest average DUlq and CU values for Uniform occurred when adjacent travel lanes were around 85% of SD, for Explorer when spacing was 80% of SD. For Uniform, maximum spacing allowing acceptable values of DUlq and CU was about 92% and 97% of the SD (more than 1.8 R and 1.9 R), respectively. For Explorer, maximum spacing declined to 88% and 92% of the SD for DUlq and CU, respectively. Under test conditions, both Explorer and Uniform were over the acceptable threshold of DUlq and CU in a wide range of spacing. Compared to Explorer, potential water saving due to better uniformity ranged from 6% to 14% as the irrigated strip width increased from 94 to 103 m, that is from 69 to 212 m^3 of water saved every 1000 m^3 of net irrigation requirement.

Conclusion

Test results showed appreciable improvement in water distribution uniformity of a modern big rain gun in comparison with older models. Further improvement is given by the speed rotation controller, that proved effectiveness in flattening the radial distribution pattern, resulting in some practical advantages. The first being that uniformity values were higher than those performed by the normal model, and achieved under minimal overlapping. This condition resulted in both potentially higher irrigation efficiency and increased working capacity. It should be noted that quite a simple mechanical device enabled appreciable potential water saving, proving that irrigation performance can benefit from relatively small investments. Improvements of the rotating speed controller are in progress, and further benefits on water use and farm economy are expected.

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