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Improving Irrigation Performance in Hose-drawn Traveller Sprinkler Systems

L.L. Silva; R. Serralheiro; N. Santos

Instituto de Ciências Agrárias Mediterrânicas (ICAM), Évora University, Apartado 94, 7002-554 Évora, Portugal; e-mail of corresponding author: llsilva@uevora.pt

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Travelling sprinkler systems usually use a large volume gun-sprinkler that requires high operating pressure. These sprinklers deliver water at high application rates with large drops that can damage plants and destroy soil surface structure and in some cases lead to surface sealing which, in turn, reduces soil infiltration and leads to an increase in runoff. They can also be characterised as having low application uniformity, especially in windy conditions. The use of a line with medium- or low-pressure sprinklers, mounted on the system-moving vehicle, instead of the gun-sprinkler, can be an alternative to the use of traveller systems in some crops and topographic conditions. Smaller sprinklers require less operating pressure, the water drops are smaller and the overlapping of water jets can increase irrigation uniformity. Field tests were used to compare the performance of the traveller machine using a line of four sprinklers (250 kPa) and a gun-sprinkler (350 kPa), at three different travelling speeds, corresponding to three different application depths. The evaluated parameters were: irrigation uniformity, evaporation and wind drift losses, runoff and sediment yield. With wind speeds between 1·4 and 4·0 m/s, the traveller with the line of sprinklers allowed better irrigation uniformity for all travelling speeds. Evaporation and wind drift losses were similar for both system options, presenting significant differences only for the lowest machine velocity. Runoff increased along the irrigation events, with the gun-sprinkler option presenting higher values. However, due to some variations in the soil water content and water depths that occurred in the field tests, it was not possible to prove that the significant differences observed were caused only as a result of the use of a different system option. Sediment yield was higher in the events with the gun-sprinkler due to higher amounts of runoff and more soil detachment by the larger drops of this system option. From these field tests it is possible to state that the line of sprinklers option has some management disadvantages compared to the gun-sprinkler option. It is more labour intensive, and its height from the soil can be a limiting factor for use with some crops. In cases where its use does not interfere with the crop canopy it can allow irrigations with higher performance. It can also be used as an alternative for the first irrigation events, especially in poor-structured soils that present more crust formation problems.

1. Introduction

Hose-drawn travellers are irrigation machines that usually use a large rotating gun-sprinkler, require high operating pressure and can irrigate large areas. This irrigation system can be easily adapted to different soils, crops and topographic conditions, and in addition to presenting a low investment cost per hectare, has great mobility, allowing its use in farms with small and irregular irrigated areas.

However, this system also presents some disadvantages such as: low distribution uniformity, the need for high operating pressure, distribution of water with large water drops and relatively high application rates (Keller & Bliesner, 1990), sometimes incompatible with soil intake capacity which leads to runoff problems. As a result, farmers, who own these systems, show only a partial satisfaction with the system, which is mainly due to its lower cost, when compared to other sprinkler irrigation systems (Sousa *et al.*, 1999).

The distribution uniformity is affected by changes in wind speed and/or its direction, sprinkler characteristics (*e.g.* jet trajectory, nozzle type), and variations in operating pressure and travelling speed (Keller & Bliesner, 1990; Shull & Dylla, 1976).

The impact of large water drops can damage the crop canopy and compact soil surface. Also, it can cause aggregate breakdown and detachment of soil particles, which are the first steps towards crust formation (Morin *et al*., 1981; Chang & Hills, 1993). After the formation of a superficial crust there is a reduction in infiltration (Morin *et al*., 1981; Bosch & Onstad, 1988), increasing runoff problems.

To improve the performance of these systems, the conventional gun-sprinkler can be replaced by a line of low- or medium-pressure sprinklers, mounted on the system-moving vehicle (Braz, 1998). Normally, wind conditions have a lesser effect on these smaller sprinklers, which can generate more uniform irrigation events. The most common option is the use of low-pressure sprinklers. However, in soils with low water intake rate, this can represent a problem. Low-pressure sprinklers have a small wetted diameter, which increases the application rate as well as the runoff problems in soils with low infiltrability. Thus, the use of medium-pressure sprinklers is a better compromise between the need to reduce pressure and, at the same time, have application rates that are more compatible with soil intake characteristics.

The main objective of this study was to compare the performance of a hose-drawn traveller using a line of four medium-pressure sprinklers with that of the same machine equipped with a gun-sprinkler. In addition to the irrigation uniformity, the efficiency of the system was evaluated by examining the resulting water losses due to runoff.

2. Materials and methods

Field tests were done in Southern Portugal, in a field with clay soil on undulated topography. Field slopes ranged from 0% to 3%, and the soil was prepared, using a disc harrow, to a working depth of 20 cm. The hose-drawn traveller had a 63 mm diameter and a 270 m long polyethylene hose, and was tested with two system options: (a) a gun-sprinkler with a 16 mm nozzle and an operating pressure of 350 kPa; and (b) a 25·2 m line of sprinklers, with four 180° rotating sprinklers with 9 mm nozzles and an operating pressure of 250 kPa (*Fig. 1*). The distance between the bottom of the line of sprinklers' structure and the soil was 1·1 m, and the sprinklers were 1·8 m above the soil surface. The sprinklers were spaced approximately 8 m from each other and had a wetted diameter of 34 m, allowing the irrigation of a 59·2 m wide strip using a total flow rate of 19·2 m^3/h. The gun-sprinkler had a wetted diameter of 60 m with a flow rate of 17·9 m^3/h.

The travelling speed of the moving vehicle along the field depends on the reel rotation speed, in this case controlled by a partial flow turbine mechanism that uses part of the flow to make the reel rotate. Since the structure of the line of sprinklers was heavier than that of the gun-sprinkler, it was necessary to increase the flow rate that passed through the turbine mechanism to achieve the same travelling speed. This and the need for higher total flow rate in the line of sprinklers option, to achieve a similar irrigated strip width, made it necessary to have the same water pressure at the reel (785 kPa) in both system options.

The field tests were done in a field with a sunflower crop. The irrigation schedule was determined using the computer program CROPWAT for Windows (Clarke *et al*., 1998) that uses the Penman–Monteith equation for estimating reference crop evapotranspiration.

Applied water depths depend on the machine travelling speed. Thus, irrigation events were done with different machine travelling speeds to achieve the desired water depths according to the scheduling program. The line of sprinklers was used from the beginning of the irrigation season until the crop height was less than 1 m high. After that the gun-sprinkler was used.

Fig. 1. Hose-drawn traveller with a line of four sprinklers

In both system options, two irrigation events with 10, 30 and 40 m/h travelling speeds were evaluated. These events corresponded to three different application depths, in a single pass. The overlapping of two adjacent irrigated strips was simulated according to the methodology presented by Merriam and Keller (1978).

2.1. *Uniformity and evaporation and wind drift losses*

To evaluate uniformity and wind drift losses for each system option a line of catch cans, 3 m apart, was installed in the field across the towpath, in two locations, 50 m apart, using the methodology proposed by Merriam and Keller (1978). The catch containers where chosen according to the ASAE standards (ASAE, 1995), and were positioned above the crop canopy using a 1 m high support.

Uniformity was evaluated using the Christiansen Coefficient of Uniformity C_u (Christiansen, 1942):

$$C_u = \left(1 - \frac{\sum_{i=1}^{n} |D_i - D_c|}{D_c \times n}\right) \times 100 \tag{1}$$

where: C_u is the coefficient of uniformity, in %; D_i is the water depth collected in the individual catch can, in mm; D_c is the average collected water depth, in mm; and n is the total number of catch cans used in the evaluation.

The average applied water depth was calculated by (Keller & Bliesner, 1990):

$$D_a = \frac{Q}{w \times v_t} \tag{2}$$

where: D_a is the average applied water depth, in m; Q is the flow rate, in m^3/h; w is the towpath spacing, in m; and v_t is the travelling speed, in m. Evaporation and wind drift losses were determined by the difference between the average depth of applied water and the average depth of water collected in the catch cans.

2.2. *Runoff and sediment yield*

Runoff water was collected in all evaluated irrigation events. Three metallic rings, in three positions along the machine towpath, positioned approximately 3, 6 and 9 m from the towpath were used. The rings, with a diameter of 50 cm and a height of 25 cm, were buried 5 cm in the soil, leaving a lateral drain levelled with the soil surface, within the ring. The drain was connected to a plastic bottle with a capacity of 10 *l*, by a flexible pipe. The bottle was used to collect the applied water that did not infiltrate the soil area limited by the ring. The rings were maintained in the field throughout the period of the irrigation events with each system option, avoiding disturbance of the soil surface. After the sequence of irrigation events with the line of sprinklers, the rings were lifted and the area, limited by them, was tilled. Then the rings were installed again. Thus, the soil surface had similar initial conditions for both irrigation event sequences. This was important for verifying the surface compaction level along the sequence of irrigation events with each system option.

To measure soil sediments, the water collected in the plastic bottles was put in glass bottles, weighed and placed in an oven until all the water evaporated. The glass bottle was then weighed again and the difference was used to obtain the sediments' weight.

As stated before, an important factor influencing runoff is surface sealing and compaction, caused by water drop impact on the soil surface. Dry bulk density was used to evaluate the increase in soil surface compaction along the irrigation events. This is one of the most frequently used parameters in characterising soil compaction (Hakansson & Lipiec, 2000). Prior to each evaluated irrigation event, undisturbed soil samples from the first 1·5 cm of the top soil layer, where the effect of water drop impact is greatest, were collected, using metallic rings, 1·5 cm high and 3 cm in diameter. A soil sample was collected near each runoff collector, resulting in a total of nine soil samples. These samples were used to measure gravimetric soil water content, another factor that can influence infiltration and runoff.

3. Results and discussion

The collected data was statistically analysed using analysis of variance and post-hoc comparison of means with the LSD test (Statsoft, 1995).

The irrigation schedule was determined as to maximise crop production. It had to be adjusted in real time, based on soil water content, to prevent plant water stress on one hand and avoid excessive runoff on the other. Due to these restrictions, it was not possible to evaluate irrigation events with the three different travelling speeds, and thus different irrigation depths, in the same order with both system options, as shown in Table 1.

3.1. *Evaporation and wind drift*

The differences in the applied water depth between the two system options for each individual travelling speed were very small, but there were some differences in the collected water depths (Table 1). These differences were due to wind speed variations in each irrigation event and their effect on the water application characteristics of each system option.

Table 1
Irrigation events data

System option	*Irrigation number*	*Wind speed, m/s*	*Travelling speed, m/h*	*Average applied water, mm*	*Average collected water, mm*	*Losses, mm*	*Collected water near runoff collectors, mm*
Line of sprinklers	1	1·8–2·6	40	8·1	6·5	1·6	7·5
	2	2·6–3·2	10	32·4	19·4	13·0	29·7
	3	1·8–2·1	40	8·1	9·0	−0·9	11·4
	4	1·4–2·1	30	10·8	11·4	−0·6	14·8
	5	3·6–4·0	10	32·4	14·8	17·6	22·1
	6	2·4–3·0	30	10·8	9·0	1·8	12·6
Gun sprinkler	1	2·7–3·5	30	10·1	9·3	0·8	14·5
	2	3·0–3·2	10	29·8	19·1	10·7	38·2
	3	2·8–3·0	30	10·1	11·2	−1·1	16·4
	4	1·6–1·9	10	29·8	21·4	8·4	25·4
	5	2·7–2·8	40	7·5	9·8	−2·3	19·7
	6	2·0–2·5	40	7·5	8·8	−1·3	15·5

Evaporation and wind drift losses were higher for the lower travelling speeds because these were affected by the wind over a longer period of time. Water applied by the gun-sprinkler was less affected by the wind because it was applied with larger drops that have higher resistance to wind drift. However, the collected water between the two system options showed significant differences ($P<0{\cdot}05$) only for the lowest machine velocity (10 m/h). Evaporation and wind drift losses obtained in this study are within the interval, 2%–40%, referred by Kohl *et al.* (1987) for this type of losses. In both system options it is possible to observe irrigation events with higher average collected water values than average applied water values. This can be due to: (i) the wind effect, that increases the application wetted diameter, making the catch cans receive more water than they would receive with a normal application wetted diameter; (ii) variations in the surface soil water content, producing variations in the machine's travelling speed, and leading to an applied water depth different from the one determined with a regular travelling speed. Higher surface soil water content makes it more difficult for the machine to move along the towpath, thus decreasing travelling speed and increasing the applied water depth.

The values for the collected water near the runoff collectors (last column in Table 1) were higher than the average collected water values because the collectors were near the machine towpath, and since there was no overlapping between adjacent irrigated field strips, the central part of the irrigated strip received more water.

3.2. *Irrigation uniformity*

Most of the irrigation events were subject to very windy conditions, with wind speeds over 2·0 m/s (Table 1), which can also explain the low uniformity values obtained (Table 2). Comparing the average uniformity of all irrigation events it is possible to conclude that the line of sprinklers option allowed better irrigation uniformity for all travelling speeds. The wind speeds that affected the individual irrigation events did not present significant differences ($P>0{\cdot}05$) in the events with the same travelling speed for the two system options, which means that the type of sprinklers used in the system has a greater effect on the irrigation uniformity than the wind speed.

Irrigation uniformity in the events with the line of sprinklers was very similar for all travelling speeds, but with the gun-sprinkler it decreased with the increase in travelling speed. The coefficient of uniformity (CU) values did not show significant differences ($P>0{\cdot}05$) for different travelling speeds within each system option, but the differences between the two systems were significant ($P<0{\cdot}05$) for the higher speeds.

The obtained CU values were within the range of values presented in other studies (Braz, 1998; Madeira, 2000). Keller and Bliesner (1990) have reported typical CU values of only 70% to 75% in the central sections of the field, in irrigation events with a gun-sprinkler traveller system with wind speeds near 4 m/s, when the recommended towpath spacing was used. The values presented in Table 2 were obtained with only a single pass, *i.e.* without any overlapping of adjacent irrigated strips, and it was possible to observe that the boundaries of the irrigated strip received a significantly less amount of water, thus producing a lower CU value.

Overlapping of adjacent irrigated strips can be a solution for increasing irrigation uniformity (Table 3). The increases in all travelling speeds were similar in both system options, with an average increase of 6% and

Table 2
Coefficient of uniformity (CU), values for both systems options in a single pass

System option	*Travelling speed, m/h*	Coefficient of uniformity, %			*Std.dev.*	*Wind speed, m/s*
		Max	*Min*	*Avg*		
Line of sprinklers	10	0·75	0·53	0·64	0·107	2·6–4·0
	30	0·72	0·58	0·64	0·068	1·4–3·0
	40	0·80	0·61	0·69	0·081	1·8–2·6
Gun-sprinkler	10	0·75	0·28	0·51	0·237	1·6–3·2
	30	0·50	0·42	0·46	0·041	2·7–3·5
	40	0·37	0·34	0·36	0·013	2·0–2·8

Table 3
Average coefficient of uniformity values (CU) for both systems options with different overlapping percentages

System option	*Travelling speed, m/h*	Coefficient of uniformity, %		
		0	*15*	*25*
Line of sprinklers	10	0·64	0·71	0·77
	30	0·64	0·70	0·77
	40	0·69	0·75	0·81
Gun-sprinkler	10	0·51	0·55	0·61
	30	0·46	0·54	0·63
	40	0·36	0·40	0·47

13% in uniformity, for 15% and 25% overlapping, respectively.

3.3. *Runoff*

Figure 2 shows that, in general, there was an increase in runoff along the irrigation events with a decrease in the last irrigation event, that was done with less applied water, for both system options. The runoff values were always greater with the gun-sprinkler option, although only the values measured in the 4th and 6th irrigation events presented statistically significant differences ($P<0{\cdot}05$).

A first explanation for the higher amount of runoff with the gun-sprinkler option could be the higher amount of water that reached the soil with this system option (last column in Table 1). However, in irrigation event number 5 there was less collected water with the gun-sprinkler option and still there was a higher amount of runoff.

This means that, apart from the different irrigation depths, there could be other factors that influence runoff in these irrigation events by reducing soil infiltration capacity, that is, the soil water content and surface sealing and crust formation.

Figure 3 shows that the soil water content in the first centimetre of the soil was higher before the irrigation events with the gun-sprinkler option. This could be a cause for the higher amounts of runoff verified. However, the water content of the top soil layer was still far from the soil water content at field capacity (46% by volume), which means that the soil still had some storage capacity in the top layer, giving the idea that other factors could have also interfered in the runoff process.

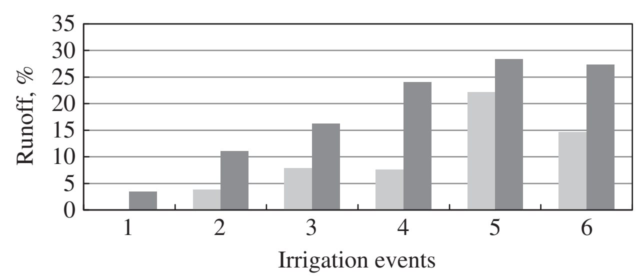

Fig. 2. Average measured runoff; ▪, *sprinklers;* ▪, *gun*

Clay soils in this region have frequent surface sealing and compaction problems, and the different size of the drops from each system option could produce different impact energy on the soil surface, causing superficial crust formation and influencing infiltration. *Figure 4* shows that the bulk density values for both system options did not present significant differences ($P>0{\cdot}05$), which by itself does not necessarily mean the inexistence of surface sealing. McIntyre (1958) found a 0·1 mm thick 'skin seal' that decreased soil permeability. However, with the field data obtained in this study, it was not possible to verify the assumption of reduced infiltration due to surface sealing or crust formation.

3.4. *Sediment yield*

Runoff will not only cause water losses but also soil erosion. Flowing water can transport soil particles detached by droplet impact on the soil surface, and higher amounts of runoff water have more transport capacity, increasing soil erosion. The amount of soil particles transported by runoff water is presented in *Fig. 5*, where the measured sediment is plotted against the amount of runoff water. The two system options produced similar amounts of sediment yield for the same runoff, although, the correlation between transported sediments and runoff for the gun-sprinkler option showed a lower value for the coefficient of determination ($R^2 = 0{\cdot}40$). For runoff values greater than 4 mm, it is, sometimes, possible to observe higher values for sediment yield with the gun-sprinkler option compared to the line of sprinklers option, as observed in *Fig. 5*. These higher values of sediment yield indicate that the bigger drops of the gun-sprinkler option can produce more soil detachment, facilitating sediment transport. Bubenzer and Jones (1971) verified that larger water drops caused a higher splash effect, detaching more soil particles, than smaller drops.

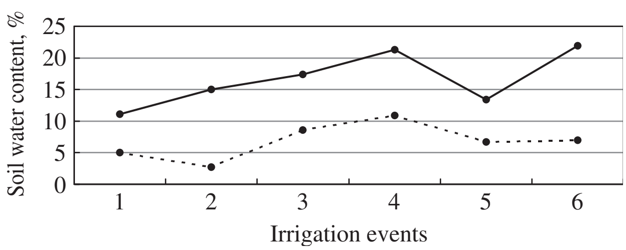

Fig. 3. Average soil water content (% by volume), in the soil top centimetres, before each irrigation event: ——●——, gun; - - ● - -, sprinklers

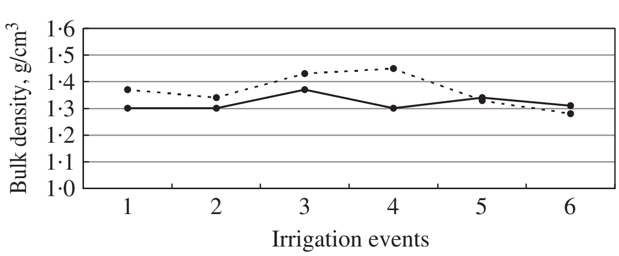

Fig. 4. Average bulk density values in the soil top centimetres before each irrigation event: ——●——, gun; - - ● - -, sprinklers

4. Conclusions

The results obtained in this study indicate that, with wind speeds from 1·4 to 4·0 m/s, the traveller with a line of sprinklers allowed better irrigation uniformity for all travelling speeds. Evaporation and wind drift losses were similar for both system options, presenting significant differences only for the lowest machine velocity.

Runoff increased along the irrigation events and the gun-sprinkler option presented higher values, although not always with statistically significant differences. However, since it was not possible to perform both sequences of irrigation events under the exact same conditions, there were other factors, such as soil water content, that could have indirectly influenced the runoff results.

The higher amounts of runoff with the gun-sprinkler led to more sediment yield. For runoff values lower than 4 mm, sediment yield was similar for both system options. For greater runoff amounts, the gun-sprinkler option sometimes produced more sediment yield, which was due to the larger drops of this system option that

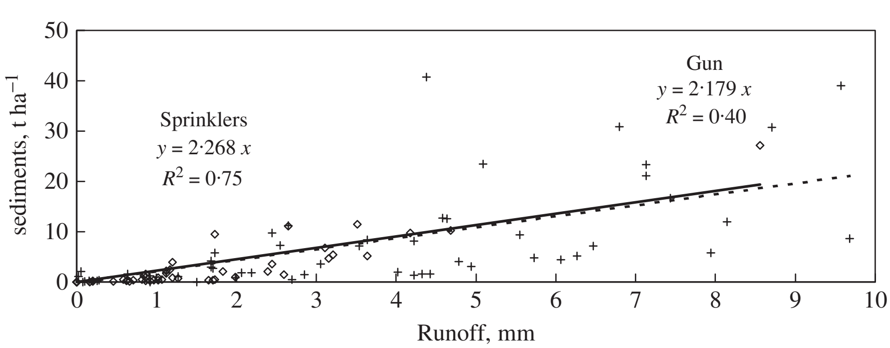

Fig. 5. Sediment yield vs. Runoff: ◇, ————, sprinklers; +, - - - - - -, gun; R^2, coefficient of determination

could produce more soil detachment, thus increasing the sediment yield.

From the field experience obtained through this study, it is possible to state that the line of sprinklers option has some management disadvantages compared to the gun-sprinkler option: it requires more labour to move the equipment and put it to work, since it has a heavier structure; also its height from the soil can be a limiting factor for use with tall crops. However, it can be used with higher performance, for small horticultural crops, or as an alternative to the first irrigation events of taller crops, especially in poor structured soils, that tend to form superficial crusts, due to water droplet impact when the soil surface is unprotected.

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