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Performance Evaluation of Sprinkler Irrigation in a Semi-arid Area

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Abstract: The objective of this study was to evaluate the performance of handmoved sprinkler irrigation systems under semi arid climate conditions by means of field tests conducted in Çumra-Konya (Turkey). The study was done in the sugar beet and dry bean fields irrigated by sprinkler irrigation. Catch can tests were performed to determine the performance of irrigation applied with sprinkler irrigation systems in field conditions. The main factors affecting water application and evaporation and drift losses with these systems were analysed. A set of performance guidelines and recommendations for the design and management of sprinkler irrigation is presented to attain the highest uniformity and efficiency in water application in arid and semi arid areas. In evaluation of performance was considered Christiansen Coefficient of Uniformity (CU) and the potential application efficiency of the low quarter (PAE_{1q}). The results of field tests indicated that the average CU for 10×10 m and 10×15 m sprinkler spacing was 86.7 and 80.6%, respectively. For the same spacings, the average PAE_{1q} was 70.6 and 62.4%.

Key words: Arid areas irrigation, handmoved sprinkler system, irrigation uniformity, potential application efficiency

INTRODUCTION

In many areas of the world, the performance of sprinkler irrigation systems must be improved in order to save water and energy. This generally requires an improvement in the process of management and application of water[1]. Using sprinkler systems with easier operation and automation that, in addition, have the capacity to attain highly uniform and efficient irrigation results in water saving and farm profitability. This is a major issue for the present and future of irrigable lands in arid and semi arid areas, where high application rates are required.

Portable systems are used extensively throughout the world. Portable sprinklers are one of the most popular systems and are used to irrigate a wide range of field and orchard crops[2,3] .

Two terms which describe the performance of sprinkler irrigation system are uniformity and application efficiency. If the water necessary for plant growth is not applied uniformly, yields will be affected. Stern and Bresler[4], Mantovani *et al.*[5], Mateos *et al.*[6] and Li[7] incorporated the effect of sprinkler irrigation uniformity on crop yield through model simulations and field experiments.

One of the standard practices to characterize water use in an irrigated area is to conduct irrigation evaluations. In sprinkler irrigation, the most valuable outcome of evaluation process is irrigation uniformity. Sprinkler irrigation system performance is often evaluated based on uniformity coefficients from water collected in an array of measuring devices (catch cans). The Christiansen Uniformity coefficient (CU) has been used extensively to characterize irrigation uniformity of sprinkler irrigation systems[8]. The measurement is generally made during once test and the determined value of CU becomes the basis for evaluating the system performance. A high uniformity is required to attain a satisfactory level of irrigation efficiency. Several uniformity measures have been proposed, with CU being the most used for sprinkler irrigation[9]. A sprinkler irrigation water distribution pattern depends on system design parameters (such as sprinkler spacing, operation pressure and nozzle diameter) and on environmental variables (wind speed and direction)[1,2,10]. Wind speed affects not only uniformity, but also evaporation and wind drift losses. Sprinkler irrigation evaporation and drift losses have been the subject of numerous field, laboratory and analytical studies[11-15]. The suppression of the evaporation in catch cans during field tests is difficult to achieve. To overcome this, peripheral collectors surrounding the pattern can be used to estimate collector evaporation during the test. Kohl[16] reported that the evaporation in catch cans is influenced by the test time

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(morning, noon, mid-afternoon and night), the composition of the catch cans and sprinkler application rate.

Water application efficiency is an irrigation concept that is very important in both system design and irrigation management. It can be divided into two components, water losses and uniformity of application. When either the water losses are large, or uniformity is poor, efficiency will be low. The primary losses associated with sprinkler irrigation (other than those due to overwatering) are evaporation from droplets and wet soil surfaces, transpiration from unwanted vegetation, wind drift, field border losses, leaks and system drainage[2,17].

In arid and semi-arid areas of the world, agricultural production depends upon efficient irrigation[18]. Sprinkler irrigation systems can attain irrigation efficiencies of greater than 80% if adequately designed and managed[2,19]. Keller and Bliesner[2], Burt *et al.*[20] reported that the gross irrigation water required for an irrigation event could be computed by using the potential application efficiency of the low quarter (PAE_{lq}).

Several articles have been published describing application uniformity and the application efficiency as well as evaporation and drift losses from field evaluations of sprinkler irrigation systems[21-25].

This research presents additional data to study the influence of the main factors on water distribution in arid and semi-arid areas. The objective of this study was to estimate and quantify the effect of the main factors influencing the water distribution at field level in handmoved sprinkler systems; to evaluate the uniformity and the potential application efficiency of the low quarter (PAE_{lq}) of the handmoved sprinkler systems.

MATERIALS AND METHODS

During the irrigation season in 2002 and 2003, 21 portable, handmoved sprinkler system catch can tests were conducted in 21 farmer's field in the area of collective irrigation in Çumra (Turkey), in order to identify possible factors influencing both irrigation uniformity and potential application efficiency.

The geographical location of the Çumra Plain is 37°55′ N latitude, 32°47′ E longitude and 1010 m elevation. Çumra has a semi-arid climate with an average annual rainfall of 315 mm and potential evaporation of 1180 mm. All set sprinkler systems used in the collective irrigation area are handmoved and as most of the sprinklers have double nozzles with a diameter of 4.5+4.8 mm, this type was used in the experiments. The characteristics of the sprinkler (reported by the manufacturer, Arili, Turkey) are: working pressure range, 200-350 kPa; diameter of wetted circle, 26-30 m; flow, 1.96-2.75 m^3 h^{-1} and the trajectory angle, 27°. The sprinkler nozzles are plastic, the main nozzle 90 mm in length and the secondary nozzle 40 mm in length. The internal design of the main nozzle is divided into three parts: the first conic part at the inlet, of about 10 mm in length and 13 mm inlet in diameter; a cylindrical part at the outlet of about 25 mm in length and 4.8 mm in diameter and cylindrical part between them of about 55 mm in length and 7.0 mm in diameter.

Field evaluations were conducted by adopting the methodology of Merriam and Keller[9], Merriam *et al.*[26], following ASAE standard S330.1[27] and ASAE standard S398.1[28]. In the evaluations, the field tests were performed as single-lateral tests. The spacing between the sprinklers in the laterals tested was taken to be 10 m, representing sprinkler spacing practiced by local farmers. In this irrigation district, the sprinklers are located 0.60 to 0.80 m above the ground. The field tests were carried out in covered areas with sugar beet and dry beans. In field tests, plastic and white catch cans with a 16 cm opening diameter and a 15 cm height were used. Concerning the field procedure, first a sprinkler position on lateral line was chosen, where the existing pressure is the most similar to that of the system average pressure. An approximate 1 m square grid of catch cans was located within the space wetted by three consecutive sprinklers on the tested lateral. By overlapping the right and left hand catch can data, the total catch between adjacent lateral positions was simulated. The water distribution patterns obtained with single-lateral tests were overlapped for the 10 and 15 m lateral position spacing, calculating the performance parameters. Previous to the test, both discharge and operational pressure of the sprinklers in the test site was measured. Environmental conditions during test (wind speed and direction, air temperature, relative humidity) were recorded every 15 min. During the evaluations, farmers performed their normal irrigation practices. Sprinkler systems were tested under farmer's working conditions. The experiments were completely conducted with the sprinkler systems designed and operated by local farmers.

In all cases, the duration of the test (2 h in our cases) was shorter than a regular event and tests were performed on clear, sunny days and between 10 am and 5 pm during July and August. After test completion, the amounts collected in the catch cans were measured. The water collected in the catch cans was measured volumetrically with a calibrated test tube. The reading process at the catch cans took approximately between 15 and 20 min. Furthermore, some catch cans were placed outside the testing area with the approximate average amount of water expected to be collected by catch cans, in order to estimate the volume of water lost by evaporation in catch cans, both during the field test and during the reading process. Losses were considered as the difference between the volume discharged by sprinklers and that the measured in all the catch cans after the test. The volume of water lost by evaporation in the catch cans was added to the volume measured in the catch cans after the test. The evaporation in the catch cans was taken into account to determine the potential application efficiency of the low quarter.

For the analysis of performance parameters, the sprinkler spacing was taken as 10×10 and 10×15 m as practiced by local farmers. The first number indicates the spacing between sprinklers in tested lateral (m) and the second number indicates the spacing between lateral positions (m).

The parameters used in the analysis performance were:

Christiansen's coefficient of uniformity, CU (%)

$$CU = \left[1 - \frac{\sum_{I=1}^{N} |X_i - \bar{X}|}{N \times \bar{X}}\right] \times 100 \quad (1)$$

where:

X_i = The individual depth of catch observations from uniformity test (mm)

$\bar{X}$ = The average water depth collected in all catch cans (mm)

N = The number of observations.

Keller and Bliesner[2] defined the system coefficient of uniformity, CUS as:

$$CUS = CU \times \frac{1}{2}\left[1 + \sqrt{\frac{P_n}{P_a}}\right] \quad (2)$$

where:

P_n = The minimum sprinkler pressure (kPa)

P_a = The average sprinkler pressure (kPa)

Distribution uniformity, DU (%)

$$DU = \frac{d_q}{d} \times 100 \quad (3)$$

where:

d_q = The average low-quarter depth of water received (mm)

d = The average depth of water received on the test area (mm)

Discharge efficiency E_d: it shows the relationship between water collected by catch cans and water discharged by sprinkler. The difference between them is intended to be evaporation and wind drift losses during the irrigation event, mainly due to environmental conditions.

$$E_d = \frac{d_o}{d_d} \times 100 \quad (4)$$

where:

d_o = The average water depth observed (mm)

d_d = The average water depth discharged (mm).

In determining PAE_{lq}, the net water losses were computed as the difference between the evaporation and wind drift losses during test and the water lost by evaporation in catch cans during test. The evaporation from catch cans was not considered as a loss. Following Burt *et al.*[20], PAE_{lq} was determined as:

$$PAE_{lq} = \frac{d_c}{d_{lq}} \times 100 \quad (5)$$

where:

d_c = The average depth of irrigation water contributing to target (mm)

d_{lq} = The low quarter irrigation water target depth (mm).

RESULTS AND DISCUSSION

Analysis of uniformity: Uniformity indicators were sorted into different interval of wind speed (low: $w<2$ m s^{-1}; high: $2<w<4$ m s^{-1}) and working pressure range (low: $p<200$ kPa; high: $200<p<355$ kPa) under two sprinkler spacings.

The CU values were always higher than those of DU. In the 10×10 m sprinkler spacing (Table 1), the CU variability was large, ranging from 76.4 to 95.2%, with an average value of 86.8% (Table 1). All the evaluations presented CU's higher than the threshold established by Keller and Bliesner[2] for moderately low uniformity (CU=75%). The values of DU were minimum, 63.4%; maximum, 91.9 and average, 79.9%. The lowest value of DU (63.4%) is higher than the threshold (DU=60%) established by Keller and Bliesner[2]. The highest CU value (95.2%) was recorded in 10×10 m sprinkler spacing, with low pressure (170 kPa) and wind speed of 1.1 m s^{-1}.

Under the 10×15 m sprinkler spacing conditions, the uniformity indicators variability was large. The value of CU ranged from 66.1 to 90.2%, with an average value of 80.6%. In the same sprinkler spacing, DU value varied between 54.7 and 83.9%. The 76% of tests presented CU's higher than the threshold established by Keller and

Table 1: Computed uniformity indicators for handmoved system evaluations

			CU (%)			CUs (%)			DU (%)		
		No. tests	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
10×10 m spacing											
Pressure (kPa)	110-200	15	76.41	95.20	86.97	75.26	94.40	85.80	63.44	91.99	74.65
	200-355	6	78.40	90.89	86.22	75.83	89.95	84.08	70.31	90.14	80.67
Wind speed (m s^{-1})	0-2	12	86.26	95.20	90.34	83.76	94.40	89.08	79.77	91.99	85.06
	2-4	9	76.41	90.74	81.99	75.26	87.76	80.27	63.44	81.94	73.08
Total		21	76.41	95.20	86.77	75.26	94.40	85.31	63.44	91.99	79.93
10×15 m spacing											
Pressure (kPa)	110-200	15	66.13	90.17	81.09	95.55	89.08	79.79	55.56	83.95	71.61
	200-355	6	69.19	88.43	79.46	68.00	87.51	77.85	54.72	81.80	71.20
Wind speed (m s^{-1})	0-2	12	80.98	90.17	85.34	80.16	89.08	83.97	70.25	83.95	77.17
	2-4	9	66.13	82.94	74.34	65.55	80.22	72.92	54.72	77.40	63.92
Total		21	66.13	90.17	80.63	65.55	89.08	79.23	54.72	83.95	71.49

Table 2: Computed efficiency indicators for handmoved systems

			PAE_{lq} (%)		
		No. tests	Min.	Max.	Avg.
10×10 m spacing					
Pressure (kPa)	110-200	15	51.73	81.91	70.69
	200-355	6	54.94	81.60	70.32
Wind speed (m s^{-1})	0-2	12	65.04	81.91	76.54
	2-4	9	51.73	75.84	62.63
Total		21	51.73	81.91	70.58
10×15 m spacing					
Pressure (kPa)	110-200	15	45.19	75.52	62.44
	200-355	6	43.91	76.95	62.37
Wind speed (m s^{-1})	0-2	12	59.64	76.95	68.36
	2-4	9	43.91	68.27	54.50
Total		21	43.91	76.95	62.42
E_d (%)					
Pressure (kPa)	110-200	15	80.43	95.81	88.45
	200-355	6	75.16	93.65	86.81
Wind speed (m s^{-1})	0-2	12	80.43	95.81	89.75
	2-4	9	75.16	92.37	85.62
Total		21	75.16	95.81	87.98

Bliesner[2] for moderately low uniformity (CU=75%). In the rest of the evaluations, CU ranged from 66.1 to 73.9%.

The low CU values were attained from tests performed with high wind speeds. During these tests, wind speed ranged from 1.5 to 5.1 m s^{-1}, with an average value above of 3.0 m s^{-1}. For example, the lowest CU value (66.1%) was attained in the 10×15 m spacing, at the average wind speed of 3.4 m s^{-1}, which was changing in a range of 2.5 to 5.1 m s^{-1}.

The mean CUS value achieved from the entire set of tests was 85.3% for 10×10 m and 79.2% for 10×15 m sprinkler spacing.

In the each type of sprinkler spacings, average CU was lower with a wind speed between 2 and 4 m s^{-1} than with wind speeds below 2 m s^{-1}. In previous an experimental study, Hills and Barragan[29] did not find to the effect of low wind speeds on CU. For wind speeds ranging from 2 to 4 m s^{-1}, average CU value was 81.9% for 10×10 m and 74.3% for 10×15 m sprinkler spacing.

In all tests conducted with low wind speeds, in the 10×10 m spacing the CU values were obtained as a value higher than 84%, the value recommended by Keller and Bliesner[2] for this type of sprinkler systems. For 10×15 m sprinkler spacing, the 66.66% of the same tests could reached above this threshold value. In the rest of tests, CU values presented to ranging between 80.9 and 83.1%.

When the sprinkler spacing is considered, the 10×10 m spacing performed much better than the 10×15 spacing (CU =86.7%, 6.14 points higher than the average CU). In low pressure class, average CU value was 86.9% for 10×10 m spacing and 81.1% for 10×15 m spacing. For the same sprinkler spacings, the average CU values were 86.2 and 79.4% for high pressures, respectively. In the same sprinkler spacing, there was no difference between average CU values for each working pressure class. As expected, the average CU obtained with low wind speeds is higher than the one obtained with high wind speeds, with a difference of about 8.3% in 10×10 m spacing and 8.8% in 10×15 m spacing.

Figure 1 shows the relationship between CU values and wind speed as a function of operating pressure according to sprinkler spacing. In general, when sprinkler spacing or wind speed increased, the CU values decreased. The large spacing and the high wind speed appear to be the main causes of low CU (Fig. 1).

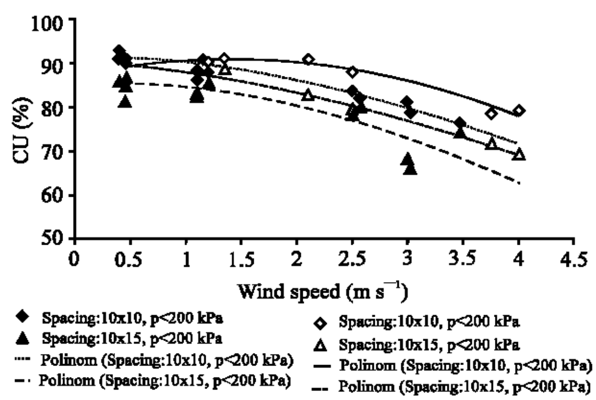

Fig. 1: Relationship between CU (%) and wind speed w (m s^{-1}) for handmoved sprinkler systems as affected by the working pressure according to sprinkler spacing

Results show that the CU predictive capability is better for the high working pressure (R^2=0.96; 0.97) than for low operating pressure (R^2=0.72; 0.87). This case can be explained by the fact that the sprinkler working pressure recommended by manufacturer firm is the between 200 and 350 kPa.

The CU values attained in different fields with similar working pressure have shown a dispersion (Fig. 2). Under these conditions, the CU values become more affected by other factors (wind speed, irrigation layout, variable winds). In the tests performed with low pressure, most of CU values concentrated between 80 and 92% independently of the sprinkler spacing (Fig. 2). This case is mostly relevant to low wind speed.

Existing pressures in different places of the evaluated sprinkler lateral were measured and determined the lowest and highest pressures. It is normally accepted that the limit of discharge variation in the different points of the lateral is about 10% of average discharge in order to obtain an acceptable uniformity. For this to happen, the pressure difference limit must not exceed 20% of mean working pressure. With excessive pressure variations there will be areas receiving more irrigation water than others will. This problem may occur when the hydraulic design of the installation is not correct, that is, when pipe diameters are small in relation to the flow to be delivered. In 47.6% of evaluations pressure variation exceeded 20% of average working pressure.

Analysis of efficiency: The potential application efficiency of the low quarter, PAE_{lq} values were sorted into different intervals of wind speed and working pressure under two sprinkler spacings (10×10 and 10×15 m).

Discharge efficiency (E_d) variability was relatively large, ranging from 75.2 to 95.8%, comparison to an average value of 87.9% (Table 2). When these data examined, the wind drift and evaporation losses varied between 4.2 and 23.8%, with an average of 12.0% of the water discharged by sprinkler. During the field tests, wind speed, temperature and relative humidity ranged from 0.4 to 5.1 m s^{-1}, 20 to 35°C and 36 to 50%, respectively (Table 2).

The highest PAE_{lq} value (81.9%) was attained in the 10×10 m sprinkler spacing, with low pressure (115 kPa) and wind speed of 1.5 m s^{-1}. In the 10×15 m sprinkler spacing the PAE_{lq} was 75.5% for the same sprinkler system. The lowest PAE_{lq} values were attained with the 10×15 m sprinkler spacing especially under high wind speed conditions. The lowest value of PAE_{lq} (43.9%) was recorded in 10×15 m spacing, a pressure of 350 kPa and a high wind speed (3.75 m s^{-1}) (Table 2).

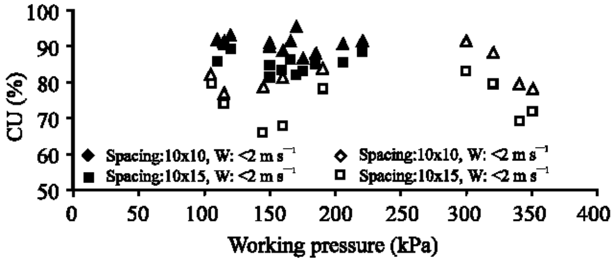

Fig. 2: Relation ship between CU (%) and working pressure P (kPa) for handmoved systems as affected by the wind speed according to sprinkler spacing

In the 10×10 m spacing, the average PAE_{lq} was 70.5%. Only four evaluations presented a particularly low PAE_{lq} more than 60%. In the rest of the evaluations, PAE_{lq} ranged from 63.4 to 81.9%, with an average of 74.1%. These values are higher than the threshold (PAE_{lq}=60%) established by Keller and Bliesner[2] for this type of sprinkler systems.

For the 10×15 m sprinkler spacing, PAE_{lq} values ranged from 43.9 to 76.9%, with an average value of 62.4%. In 14 evaluations the PAE_{lq} values varied between 61.7 and 76.9%. In the remaining seven evaluations (under high wind speed conditions) the PAE_{lq} was obtained in between 43.9 and 59.6%.

In general, the dependence of PAE_{lq} on the sprinkler spacing, pressure and wind speed is similar to that found for CU. Some PAE_{lq} values are lower than 60%. This is partly due to the relevance of wind drift and evaporation losses in the Çumra. In some evaluations, water losses amounted to 20% of the applied water. The second considered factor affecting PAE_{lq} is that the spatial variability of the applied water is high. In sprinkler irrigation, most of this variability is associated to the high wind speed.

When the sprinkler spacing is considered, the 10×10 m spacing performed much better than the 10×15 m spacing (PAE_{lq}=70.5%, 8.16 points higher than the average PAE_{lq}). The second considered factor affecting PAE_{lq} is the wind speed. The average PAE_{lq} obtained with low wind speeds is higher than the one obtained with high wind speeds, with a difference of about 14% for the both sprinkler spacing.

Figure 3 shows the relationship between PAE_{lq} values and wind speed as a function of working pressure according to sprinkler spacing.

The test results show that the PAE_{lq} predictive capability is higher for the high working pressure (R^2=0.92; 0.97) comparison to low operating pressure (R^2=0.70; 0.72). When the wind speed increased, especially in wind speed above of 2 m s^{-1}, PAE_{lq} value sharply decreased (Fig. 3).

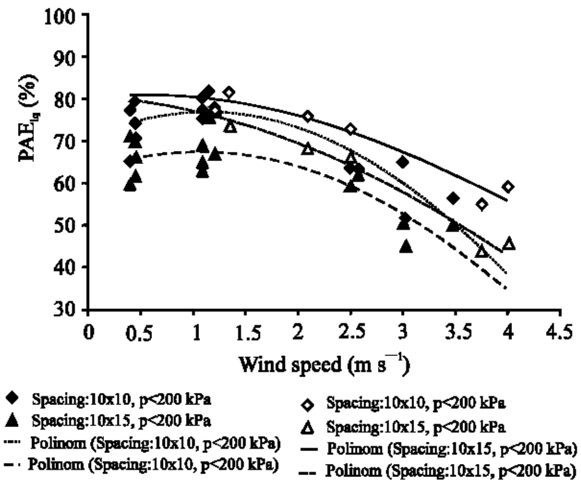

Fig. 3: Relationship between PAE_{1q} (%) and wind speed, w (m s^{-1}) for handmoved sprinkler systems as affected by the working pressure according to sprinkler spacing

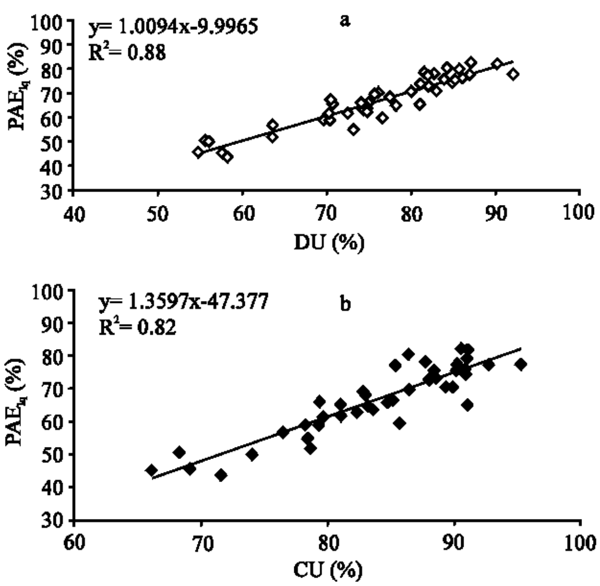

Fig. 4: Linear regression between PAE_{1q} and DU (a), PAE_{1q} and CU (b)

The relationship between PAE_{1q} and CU, PAE_{1q} and DU is shown in Fig. 4. There is a linear relationship between them.

The relationship between PAE_{1q} and DU (R^2=0.88) is higher than the relationship between PAE_{1q} and CU (R^2=0.82). The potential application efficiency of the low quarter, PAE_{1q} may be adequately estimated in the range of observed values.

Results from this study show that the PAE_{1q} was affected negatively when CU was influenced negatively by parameters such as wind speed, sprinkler spacing and operating pressure. Results also show that under windy conditions, the narrow sprinkler spacing has the higher performance when compare to 10×15 m spacing.

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