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Analysis of water application with semi-portable big size sprinkler irrigation systems in semi-arid areas

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ABSTRACT

Sustainability of irrigated agriculture depends heavily on getting a high efficiency application for the irrigation. It is very important to understand the factors that affect to irrigation uniformity and discharge efficiency, especially using semi-portable big size sprinkler. There are not studies conducted with big size sprinklers which work on high flow rates and big layouts spacing. In this paper, the spray losses (L_s) and water distribution of sprinkler irrigation system with semi-portable big size sprinkler on semi-arid areas have been characterized. The factors affecting on discharge efficiency and irrigation uniformity were analysed (working pressure, irrigation layout and weather conditions). The field tests were conducted in outdoor conditions with a single sprinkler system. Six predictive equations were obtained to estimate drift and evaporation losses. The proposed equations use operating pressure, wind speed and vapour pressure deficit. The results show an increment of 3.26% for Ls for each increment of 1 m s^{-1} of wind speed. Spray losses rise up to 22.7% at 450 kPa operating pressure when wind speed and vapour pressure deficit increased up to 4.2 m s^{-1} and 6 kPa, respectively. A significantly effect of wind is appreciated on the spray losses and water distribution pattern under different conditions with regard for working pressure and sprinkler spacing. This behaviour is very similar to obtained with medium size sprinklers. Technical criteria can be used to optimize irrigation management according to the design factors and the climatic parameters.

1. Introduction

The sustainability of irrigated agriculture in windy and semi-arid areas depends on achieve a proper design and management of the irrigation systems. When the irrigation is applied by sprinkler, water is distributed over the irrigated area by spraying through the air.

Many works have been conducted to understand the main factors affecting on efficiency and uniformity on sprinkler irrigation systems, but mostly, with medium size sprinklers. However, there are not studies conducted with big size sprinklers which work on high flow rates (greater than 3 l s^{-1}) and big layouts spacing (higher than 24 m sprinkler spacing).

The semi-portable big size sprinkler is a very common irrigation system on the irrigated areas with semi-arid climatic conditions. Focused on Iran, 48.7% of the total pressurized irrigation surface and 85% of sprinkler irrigation surface are irrigated with this system (660,000 ha) (Report, 2014). Actually, this irrigation system is the main configuration in certain Iranian regions, such as Khuzestan province, where it represents the 73.1% (22,634 ha) of the total pressurized irrigation area and 99% of sprinkler irrigation area.

Meteorological variables, such as wind speed (W) and direction, are the main factors that influence the water distribution pattern in sprinkler irrigation, playing an important role in wind drift and evaporation losses (Dechmi et al., 2003; Keller and Bliesner, 1990; Tarjuelo et al., 2000). These references have led to two firm conclusions. First, applied water is lost partially by evaporation, particularly through drift out of the irrigated area; second, under windy conditions, the water distribution pattern of an isolated sprinkler is distorted and narrowed. The consequence of this problem could be either over- or under-irrigation of in portions of the field. To get a good operation of any sprinkler, it is very important that it works in the proper pressure range recommended by the manufacturer. The drop size is controlled by pressure and nozzle size.

The range of smaller drops cause that a significant portion of the discharged droplets do not reach the crop canopy. Spray losses (L_s), also known as evaporation and drift losses, can be estimated as the

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Table 1
Empirical equations used for spray losses (L_s) estimation.

Reference	Empirical equation	
Yazar (1984)	$L_s = 0.389 \times e^{0.18 \times W} \times (Es–Ea)^{0.7}$	Moving lateral
Trimmer (1987)	$L_s = [1.98 \times D^{-0.72} + 0.22 \times (Es–Ea)^{0.63} + 0.00036 \times P^{1.16} + 0.14 \times W^{0.7}]^{4.2}$	
Keller and Bliesner (1990)	$L_s = [1 - (0.976 + 0.005 \times ET_0 - 0.00017 \times ET_0{}^2 + 0.0012 \times W-$ $IG \times (0.00043 \times ET_0 + 0.00018 \times W + 0.000016 \times ET_0 \times W))] \times 100$ where $IG = 0.032 \times P^{1.3}/D$ (if $IG < 7 \Rightarrow IG = 7$; if $IG > 17 \Rightarrow IG = 17$)	
Seginer et al. (1991a)	$L_s = 3.22 \times e^{0.075 \times W} \times (T_a - T_w)^{0.69}$	Single sprinkler test
Montero (1999)	$L_s = 7.63 \times (Es–Ea)^{0.5} + 1.62 \times W$	Block irrigation test
Tarjuelo et al. (2000)	$L_s = 18.1 \times (Es–Ea)^{0.5} + 1.41 \times W - 3.43$	Single sprinkler test
Tarjuelo et al. (2000)	$L_s = 0.007 \times P + 7.38 \times (Es–Ea)^{0.5} + 0.844 \times W$	On-farm test
Playán et al. (2005)	$L_s = 20.3 + 0.214 \times W^2 - 0.00229 \times H^2$	Solid-set
Playán et al. (2005)	$L_s = -2.1 + 1.91 \times W + 0.231 \times T$	Moving lateral

where ETo (evapotranspiration, mm day^{-1}), D (nozzle diameter, mm), P (operating pressure, kP_a), W (wind speed, m s^{-1}), Es–Ea (vapour pressure deficit, kP_a), T (air temperature, °C), T_a (dry bulb temperature, °C), T_w (wet bulb temperature, °C), H (relative humidity, %).

difference between the volume of water discharged by sprinklers and the volume of water collected by catch cans.

Furthermore, irrigation uniformity, or uniformity of water distribution, is an important performance characteristic and the most relevant parameter of the sprinkler irrigation systems. Indeed, this design factor affects on important aspects such as water use efficiency, leaching of fertilizers and crop yield (Seginer et al., 1991b). So, field evaluation is an excellent procedure to research the factors affecting on the real irrigation uniformity under different combinations of climate and design factors on sprinkler irrigation systems.

The spray losses effect has been reported on many researches (e.g. laboratory, field tests and analytical studies). The most important work that starts to study this effect was done by Frost and Schwalen (1955, 1960),) in Arizona. In their works, Frost and Schwalen summarized the results of 700 field tests conducted under different climate conditions. These studies allowed them to develop a nomograph to estimate the evaporation losses rate during sprinkler irrigation as function of the sprinkler characteristics, operating pressure, and the climate factors.

The value of spray losses could become very relevant under certain climate conditions. While Frost and Schwalen (1955) found spray losses that reached 45% under full sun conditions with high temperatures and very low humidity, characteristic of Arizona zone, other authors has got maximum values of 30% (Yazar, 1984; Kohl et al., 1987; Kincaid, 1996; Kincaid et al., 1996; Montero, 1999; Tarjuelo et al., 2000). Spurgeon et al. (1983) reported that hot, dry, and windy conditions could cause spray losses at about 30% of the water applied on sprinkler irrigation systems. Other study, based on volume measures collected by rain-gauges, conducted in Kansas by Steiner et al. (1983), show that the average spray losses found under conditions of high evaporation were about 15%.

Edling (1985), Kohl et al. (1987), and Kincaid and Longley (1989) concluded from their experiences that the evaporation of the droplets in sprinkler irrigation was almost negligible for droplet diameters between 1.5–2 mm.

It is well known that the evaporation losses in the air mainly depend on air relative humidity, air and water temperature, drop size and wind speed (Yazar, 1984) and wind drift losses depend on wind speed, drop size and the distance to be covered before landing.

Some studies reported losses of 5–10% under moderate evaporative demand (Keller and Bliesner, 1990). In the average meteorological conditions of Zaragoza (Spain), the seasonal average spray losses measured for the solid-set system were 15.4 and 8.5% during day and night irrigations, respectively (Playán et al., 2005).

Several authors have identified the influence of irrigation system and meteorological variables on spray losses. The predictive equations are presented in Table 1. These equations were obtained for different sprinkler systems and operating parameters. The independent variables shown are: evapotranspiration (ETo, mm day^{-1}), nozzle diameter (D, mm), operating pressure (P, kP_a), wind speed (W, m s^{-1}), vapour pressure deficit (Es–Ea, kP_a), air temperature (T, °C), dry bulb temperature (T_a, °C), wet bulb temperature (T_w, °C), relative humidity (H, %).

A non-uniform distribution not only could leave some parts of the crop on a deficitary water situation, also could over-irrigate other parts causing ponding water, plant damage, soil salinisation, and leaching of chemical substances to ground water (Solomon, 1983). James and Blair (1984) also stated that non-uniform irrigations might waste energy and chemicals. Increasing water application uniformity can improve irrigation efficiency by preventing deep percolation and surface runoff due to over irrigation.

Several authors have argued that, although wind speed is the most important climatic parameter affecting sprinkler irrigation performance (Tarjuelo et al., 1999a,b; Sánchez et al., 2010), its effect is affected by system design parameters such as operating pressure, spacing between sprinklers (Se), nozzle size and sprinkler type (Keller and Bliesner, 1990; Tarjuelo et al., 1992). One of the decisive factors in raising water distribution uniformity is the extent of overlapping of the sprinklers. Sprinkle systems require proper overlapping of spray patterns between lines of sprinklers (Sl) to get good distribution uniformity.

Canessa and Hermanson (1994) described that a correct overlap is the result of a correct combination of sprinkler spacing, pressure and nozzle size. They believe experienced irrigation engineers/specialists should combine manufacturer's recommendations with experience with local conditions to design efficient sprinkle systems.

Burt et al. (1997) indicated that the most influential factors of heterogeneity in water distribution are working pressure variation at the hydrant, sprinkler design, sprinkler layout, as well as climate conditions such as wind speed. In fact, W is the most complicated and uncontrollable parameter so that, wind generates the most important effect on wind drifts, evaporation losses and water distribution uniformity (Sheikhesmaeili, 2003).

Keller and Bliesner (1990) identified that most sprinkle irrigation systems require a minimum value of water distribution uniformity such as Christiansen's coefficient of uniformity (CU) ≥ 80%. Low values of CU are usually indicators of a faulty combination of the number and size of nozzles, working pressure and sprinkler spacing (Tarjuelo et al., 1999a).

Phocaides (2007) from FAO consultants recommended that in order to obtain good CU by overlapping, the Se should not exceed 65% of the sprinkler diameter coverage under low to moderate wind conditions in the square and rectangular patterns. He also stated that in strong wind conditions, the sprinkler spacing should be 50% of the diameter coverage with the lateral direction perpendicular to the wind direction.

The objectives of this paper are: (1) to characterize L_s on different weather conditions and operating pressures on semi-portable big size sprinkler system and to propose predictive equations to estimate L_s using multiple regression; (2) to analyse on irrigation uniformity the combined influence of the climatic parameter such as wind speed, and design characteristics of the system, including operating pressure heads and sprinklers' spacing and layout, and (3) give some recommendations to help on design and manage in sprinkle irrigation system with semi-portable big size sprinkler on semi-arid areas.

2. Material and methods

2.1. Experiment site

The experiments were performed in the south-western area of Iran (Behbahan region, south-eastern of Khuzestan province, 50°17′37″E and 30°30′45″N). The region is characterized by a semi-arid climate with a mild winter and hot summer. Annual evapotranspiration and average rainfall amount to 1717 and 350 mm, respectively. The most important type of sprinkler irrigation system in this area is the semi-portable hand-move (Sheikhesmaeili, 2003). In this system, the whole pipes network is buried and only the sprinklers and the riser are moved manually over the line, which may be extended up to 300 m.

2.2. Single-sprinkler tests

For the analysis of L_s and CU in semi-portable big sprinkler irrigation system, forty trials in outdoor single-sprinkler tests were conducted at 450 and 500 kP_a operating pressures on bare soil and in flat agricultural land in accordance with the standards ISO 15886-3 (2012) and ASAE S398.1 (2001). One type of big size impact sprinkler was used in these tests: A-D-5 (Abyaran Dasht Inc., Tehran, Iran). This sprinkler had three nozzles (11 + 6.3 + 3.2 mm) and is similar to the sprinkler VYR 155 (VYRSA Inc., Burgos, Spain). The A-D-5 is manufactured in Iran under license of the Spanish company. The working pressures used were the normal operating pressures recommended by the manufacturer (450 and 500 kP_a), with a discharge of 3.25 and 3.46 l s^{-1}, respectively. The tests were conducted between April and November 2013, during different hours of a day to cover all weather conditions that may occur.

A grid of 22 × 22 rows and columns catch cans was used in these tests (Fig. 1). Sprinkler-nozzles were placed 1.6 m above catch can openings. Plastic white catch cans with 0.1 m opening diameter and 0.15 m height were placed in a square three-meter grid. Keller and Bliesner (1990) estimated a measurement error of 5% for these tests conditions. The water was pumped from a deep well, where a valve regulated the water pressure, and a calibrated in-line flow meter (with error range <2%) was used to measure the total water pumped. Sprinkler pressure heads were measured by using the Pitot tube pressure gauge in the centre of the sprinkler jet about 1.5 mm from the nozzle. Weather conditions (e.g. dry bulb temperature, wet bulb temperature and speed and direction of the wind at two meters height) were measured in an automatic weather station located 50 m next to the test place at 5 min intervals during test duration. All this information was recorded on a data logger in five-minute intervals time.

The duration of the tests was 1 h, although 45 min may be sufficient with this catch can size (Fischer and Wallender, 1988). Once testing is over, the volume of water collected by the catch cans was measured with a calibrate test tube, with the particularity that same reading order is always followed. In every catch can, the volume of water collected was corrected to quantify evaporation losses during the irrigation time (1 h).

The methodology followed to correct the evaporating water of the catch cans during the tests is similar to that is described in Tarjuelo et al. (1999b).

Evaporation and drift losses were considered as the difference between the total water volume discharged by sprinklers and the volume measured in catch cans after irrigation. Losses include: (1) evaporation and drift losses; (2) evaporation in catch cans, either during the irrigation event or during the reading process; and (3) measurement errors (e.g. flowmeter precision error, the determination of the water volume on the calibrate test tube . . .).

2.3. Characterization of the sprinkler water distribution pattern

In order to characterize the water distribution pattern of the A-D-5 sprinkler several tests were conducted in accordance with the standard ISO 15886-3 (2012) under no-wind conditions at CREA facilities (Castilla-La Mancha University, Albacete, Spain). Only one sprinkler-nozzles was tested (11 + 6.2 + 3.2 mm), at two operating pressure (450 and 500 kP_a). The trajectory angles for each nozzle are 28°–28°–13°. The sprinkler was located 1.5 m above the ground. Two lines of catch cans with a 0.16 m diameter were arranged forming a 90° angle with a 1 m spacing between each catch can. Two repetitions were made for every operating pressure. The volume of water in each catch cans was determined as the average of the two rows of catch cans and for both repetitions. Water distribution pattern is useful for engineers when choosing the type of sprinkler, nozzle, and working conditions in order to achieve high water distribution uniformity (Tarjuelo et al., 1999c). Also is interesting to be applied on ballistic irrigation simulation models (Carrion et al., 2001; Seginer et al., 1991a).

2.4. Drop sizes measurements of the sprinkler

In order to establish the relation between L_s and drop sizes for the sprinkler, an optical disdrometer model ODM 470, manufactured by Eigenbrodt (Königsmoor Inc., Germany), was used. A further description of this equipment can be found in Montero et al. (2006).

The device is based on the attenuation of an infrared light beam when the drops cross through an optical window. The shape of beam detector was circular with a diameter of 20 mm. The disdrometer performed continuous measurements of the drops emitted by the sprinkler. Each drop produces an attenuation of the normal signal. The signal analysis allows estimating the drop diameter and the time spent to cross the light beam (passage time).

Drop size measures were made at the same time as the radial tests. The measure distances to the sprinkler were 4, 8, 12, 16, 20, and 24 m. For each distance, the volumetric mean diameter (VMD) was calculated. VMD is the drop diameter that corresponds the 50% of the accumulated water volume (Montero et al., 2003).

2.5. Statistical analysis to L_s determination

To make the model, a statistical analysis were conducted starting with the relationship existing between the different explanatory variables and the dependent variable. The statistical analysis of evaporation and drift losses was carried out with the software packages SPSS rel. 11.5 (SPSS Inc.) and EXCEL (MicroSoft Inc.).

The main objective is to achieve a predictive model to estimate L_s considering the influence of the operating pressure (i.e. 450 and 500 kP_a) and the climatic conditions. Vapour pressure deficit (Es–Ea) is a measure of the dryness of the air; thus, it is an index of the evaporation rate, and of course, it significantly influences on spray losses. So, it is desirable to consider both air temperature

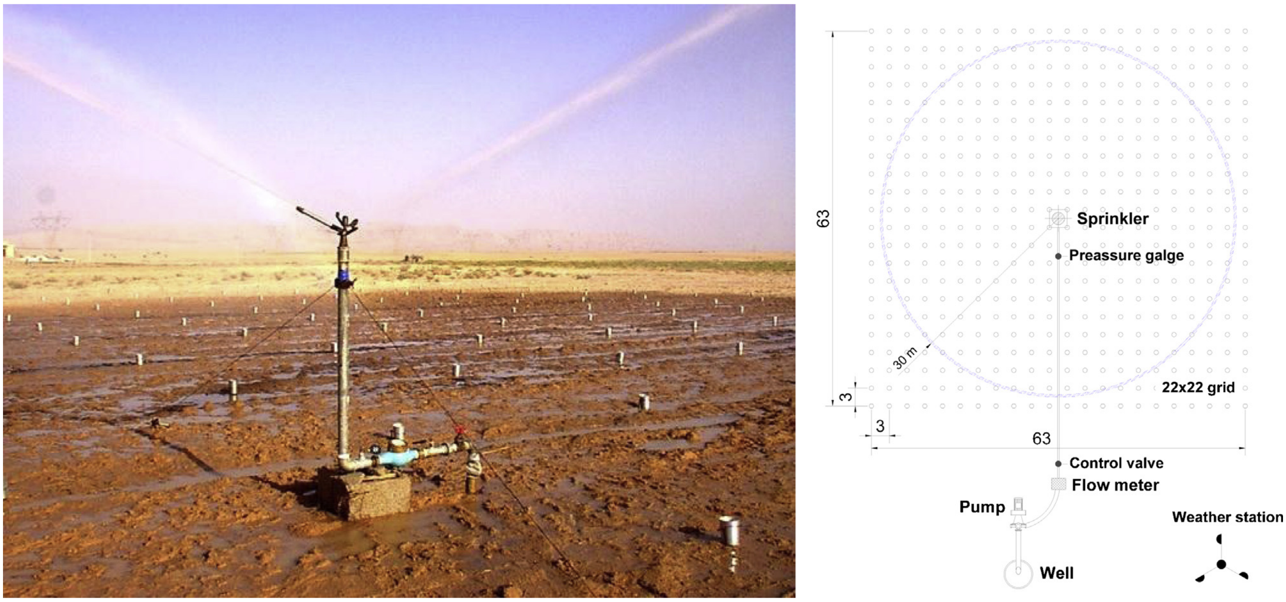


Fig. 1. Schematic of the outdoor single sprinkler test.

and relative humidity through the Es–Ea to get a robust modelling (Murray, 1967).

A multiple regressions analysis were used in order to relate experimental data of L_s with the meteorological (e.g. W and Es–Ea) and hydraulic variables (e.g. P). Then, variables were selected as a function of the ease to obtain them.

In order to create some predictive equations, a variety of regression models with different numbers of independent variables were studied. In each case, the independent variables (X) were considered on different mathematical forms. The procedure to select the best and simplest predictive equations was as follows:

1. The equations were designed in order to get models with a high significance level for all variables used in each equation. In this way, all variables of the model are highly significant (probability $\leq$0.05).
2. Next, the predictive equations with higher coefficient of determination (R^2) were selected.
3. Simplicity criterion: equations involving more than one independent variable were only accepted if their R^2 was better than the simple equations.
4. A Student t-test for coupled samples was applied on pairs of measured and estimated values of L_s. The selected equations for this step surpassed the 95% probability threshold.
5. Predictive capability: three additional statistics were introduced at this point patterns to determine the best fit: the average magnitude of the relative error (AMRE), standard error (SE) and the prediction level 25 (Pred [0.25]) (Dolado, 1999). AMRE can be computed as (Eq. (1)):

$$\mathrm{AMRE} = \frac{1}{n}\sum_{i=1}^{n} \left| \frac{e_i - \hat{e}_i}{e_i} \right| \qquad (1)$$

where e and $\hat{e}$ are the measured and estimated values of L_s, respectively, and n is the number of samples. SE is the standard error of the estimated value for each measured value in the regressive model. The prediction level 25 (Pred [0.25]) is the percentage of the estimated L_s values differing from the measured value by less than 25%.

2.6. Analysis of Christiansen's coefficient of uniformity (CU)

Measured single-sprinkler distribution patterns were then used in an overlapping sequence with all treatments include three sprinklers' spacing (21, 24 and 30 m) and two sprinklers' layout (square and rectangular) at two operating pressure heads (450 and 500 kP_a) to calculate CU. Software packages SPSS rel. 18 (SPSS Inc.) and EXCEL 2010 (MicroSoft Inc.) were used for these analysis. All calculated layouts Se × Sl, where S_e is the spacing between sprinklers in each line and S_l is the spacing between lines of sprinklers, were: 21 × 21, 24 × 24 and 30 × 30 for square layout, and 21 × 24, 21 × 30 and 24 × 30 for rectangular layout.

The Christiansen's coefficient of uniformity (Christiansen, 1942) was utilized to determine CU (Eq. (2)):

$$\mathrm{CU}\ (\%) = \left(1 - \frac{\Sigma_{i=1}^{n} |V_i - \bar{V}|}{n \times V}\right) \times 100 \qquad (2)$$

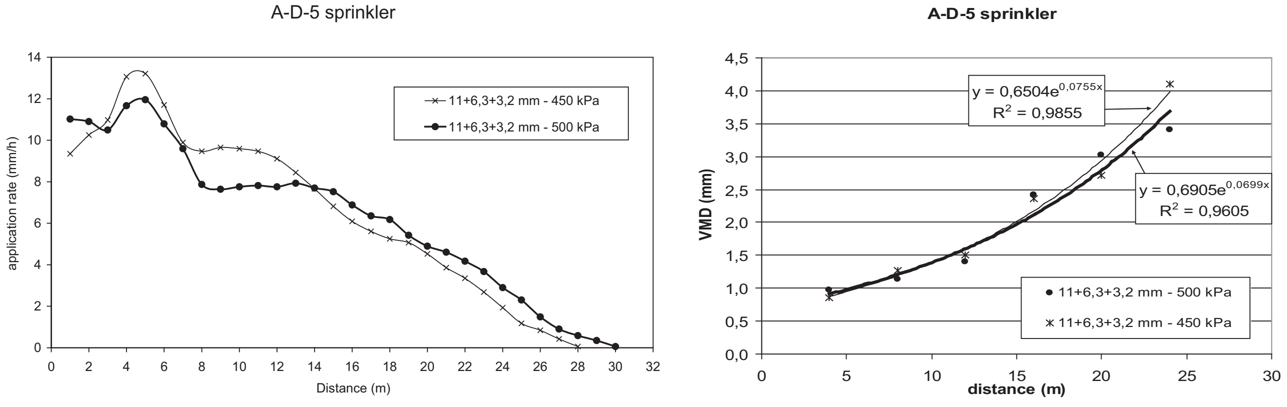
with V_i: the water volume of an individual catch can measurement, $\bar{V}$: the average application volume from all catch can measurements and n: the number of catch cans.

3. Results and discussion

3.1. Radial curves and drop size distributions

A graphic representation of single-radius sprinkler patterns obtained in tests is shown in Fig. 2a. In this, a curve with triangular shape can be observed. Also it can be observed that the application rate is higher near the sprinkler (8–10 m), and then it decreases to the end.

After the measure of the drop sizes for the sprinkler, VMD for every distance was computed. These values are plotted in Fig. 2b. Non-significant differences of drop size distribution between two pressures were observed. In relation with the distance to the sprinkler, the larger the distance was, the higher the drop sizes were, following an exponential trend. For this sprinkler, with large nozzles diameter and high operating pressure (450–500 kP_a), similar drop sizes range (up to 3.5–4 mm) were obtained to those for a medium size sprinkler with smaller nozzles and medium operation pressure (350 kP_a) (Li et al., 1994; Montero et al., 2003).



(a) (b)

Fig. 2. Water radial distribution (a) and drop size distribution (b), at the two operating pressures.

Table 2
Mean measured values for weather parameters (and mini–max range) for experimental tests.

	Number of tests	W (m s^{-1})	T (°C)	H (%)	Es–Ea (kP_a)	Measured Ls (%)
Total	40	1.62 (0 – 6.8)	31.9 (21.4 – 44.9)	41.8 (11.8 – 80.0)	3.14 (0.6 – 8.4)	11.5 (1.1 – 26.8)
450 kP_a	24	1.59 (0 – 6.8)	31.5 (21.4 – 44.9)	42.0 (11.8 – 72.9)	3.16 (0.7 – 8.4)	10.6 (1.9 – 26.8)
500 kP_a	16	1.67 (0 – 4.7)	32.6 (24.8 – 39.8)	41.5 (27.8 – 80.0)	3.09 (0.6 – 4.9)	13.0 (1.1 – 21.2)

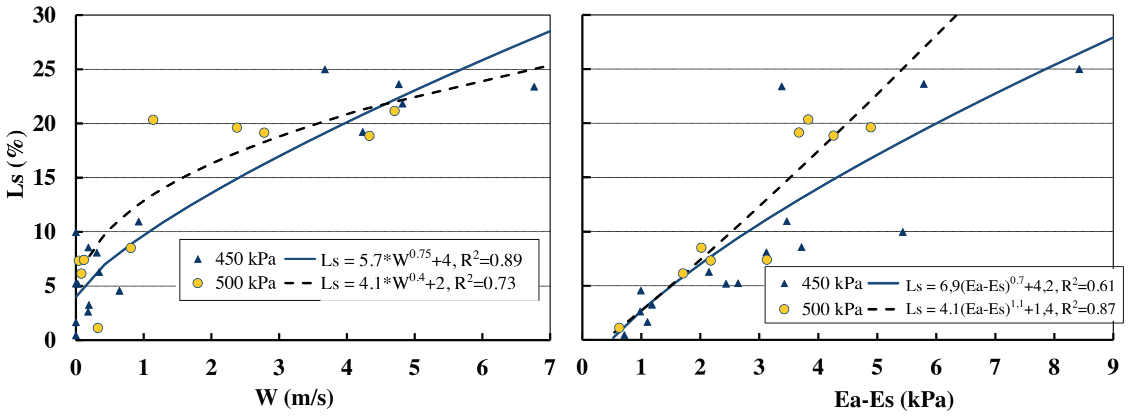


Fig. 3. Spray losses (L_s) measured as a function of wind speed (W) and vapour pressure deficit (Es–Ea).

3.2. *Experimental tests to determinate evaporation and drift losses*

A summary of the experimental results is presented in Table 2. Climate demand for evaporation and wind drift losses (L_s) normally was highest during the early afternoon hours (at 13–15 o'clock), when relative humidity (H) was lowest and air temperature (T), wind speed (W) and vapour pressure deficit (Es–Ea), were highest. So, in these conditions L_s was highest. The worst weather conditions of Khuzestan province (Iran) are in summer. So that the value of L_s reached 26.8%. The opposite effect is attained when irrigated at night, during early morning and early evening hours.

3.3. *Working pressure and climatic conditions effects on* L_s

In order to relate the important relationship between L_s and meteorological variables, Fig. 3 was prepared. The figure shows L_s

Table 3
Predictive equations obtained to estimate spray losses (L_s).

Equation no.	P	L_s (%)	R^2	SE	AMRE	Pred [0.25]
E1	All	$7.1 \times W^{0.6} + 4$	0.83	3.0	0.55	63
E2	All	$10 \times (\text{Es–Ea})^{0.6} - 7.6$	0.66	4.1	0.44	41
E3	All	$5.4 \times W^{0.6} + 7.4 \times (\text{Es–Ea})^{0.45} - 6.1$	0.94	2.0	0.23	63
E4	All	$0.628 \times P^{0.6} + 4.4 \times W^{0.7} + 4.9 \times (\text{Es–Ea})^{0.6} - 28.1$	0.94	1.9	0.23	81
E5	450	$2.9 \times W + 1.6 \times (\text{Es–Ea}) + 0.9$	0.99	1.0	0.11	94
E6	500	$19 \times \text{W}^{0.1} + 21 \times (\text{Ea–Ea})^{0.3} - 34.2$	0.93	2.0	0.14	90

where L_s (spray loses, %), P (operating pressure, kP_a), W (wind speed, m s^{-1}), Es–Ea (vapour pressure deficit, kP_a), R^2 (coefficient of determination), SE (standard error), AMRE (average magnitude of the relative error) and Pred [0.25] (prediction level 25).

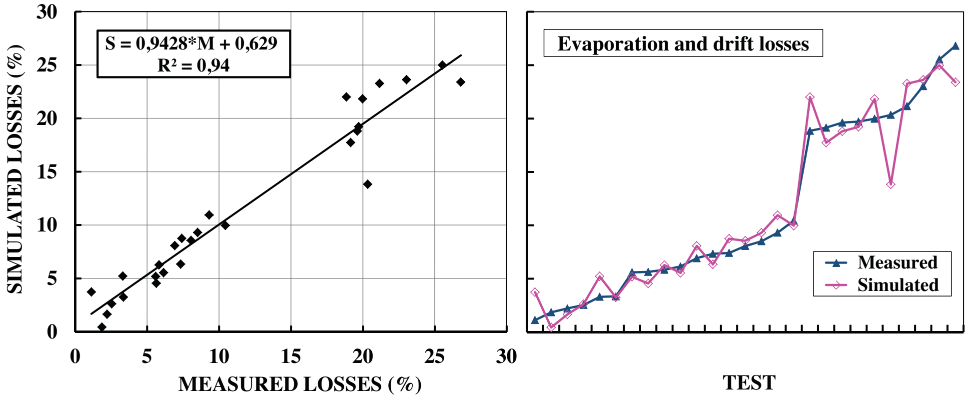


Fig. 4. Representation of the measured-simulated spray losses with the E4.

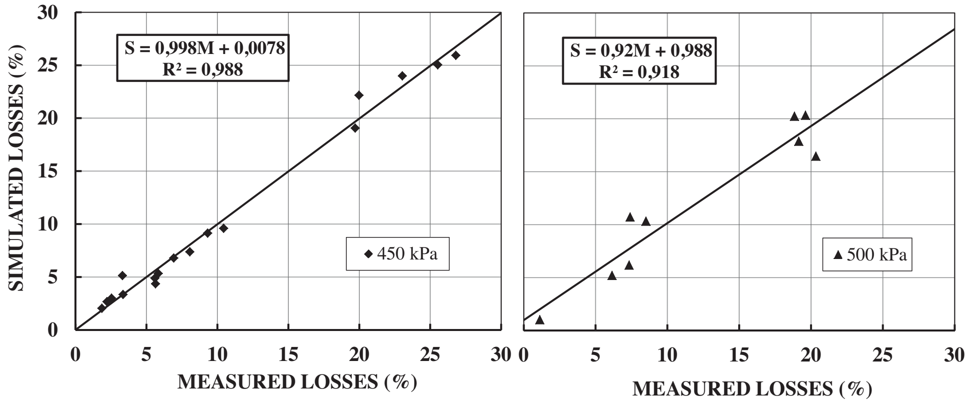


Fig. 5. Representation of the measured-simulated spray losses with the E5 (left) and E6 (right).

Table 4
CU values of the water distribution pattern.

Wind speed	Pressure head	Sprinklers' spacing and layout (m × m)						Mean	
(m s^{-1})	(kP_a)	Square			Rectangular				
		21 × 21	24 × 24	30 × 30	21 × 24	21 × 30	24 × 30	By pressure	Global
0–2	450	90.5	83.3	79.7	87.0	86.9	83.7	85.2	86.1
	500	91.7	86.1	83.2	87.5	87.6	86.1	87.0	
2–4	450	76.0	74.7	66.4	74.0	67.0	68.4	71.1	74.8
	500	79.0	77.5	76.2	79.2	80.5	78.9	78.6	
>4	450	78.2	78.3	61.5	76.9	66.6	68.4	71.6	68.4
	500	72.4	70.0	59.0	69.9	59.6	60.3	65.2	
Mean	450	85.1	80.6	73.1	82.3	78.7	77.5	79.6	80.2
	500	85.9	81.6	77.5	82.8	81.2	80.1	81.5	
	450 & 500	85.3 (A)	81.0 (B)	74.6 (C)	82.5 (AB)	79.5 (B)	78.3 (BC)		

(*) Brackets shows homogeneous groups obtained after performing the analysis of variance (group by rows).

as a function of *W* and Es–Ea for both operating pressures (i.e. 450 and 500 kP_a). On increasing pressure from 450 to 500 kP_a produce an increment of 2.4% in L_s, as shown in Table 2.

Fig. 3 can be used to determine L_s and thus, to modify the irrigation timing considering *W* and Es–Ea. Additionally, the effect of wind speed on irrigation uniformity must always be considered. Phocaides (2007) suggests that sprinkling is not recommended with wind strength over 3.5 m s^{-1}. The single effect of operating pressure on L_s was investigated using an One-Way Anova between 450 and 500 kP_a situations. So, it can be said that significant differences were not found in L_s at two operating pressures (Sig = 0.431). In other words, the difference between 450 and 500 kP_a operating pressures did not influence on the evaporation and wind drift losses. These non-effects could be caused by the small differences obtained in the water distribution for the radial patterns and the drop size distributions that this sprinkler got at the two operating pressures tested (Fig. 2). Therefore, it may be advisable avoided operating pressures higher than 450 kP_a, since higher pressure involves a higher economic cost. For example, an increase in pressure from 450 to 500 kP_a suppose an increase of energy costs of 18%, estimated according to the methodology described by Montero et al. (2004).

3.4. Predictive equations to L_s estimation

A nonlinear multiple regression model was performed to evaluate how the hydraulic and meteorological variables explain L_s. It corresponds to the model with highest regression coefficient. Wind speed and Es–Ea were the most explicative variable. Thus, the model that quantifies the influence of the effect of W and Ea–Es for each operating pressure (i.e. 450 and 500 kP_a) was fitted.

Six predictive equations were obtained to estimate L_s (Table 3). Table 3 compares statistical results of the proposed equations include: coefficient of determination (R^2), standard errors (SE), AMRE and Pred [0.25] for every equation.

First, two predictive equations was performed one based on wind speed and other based on (Es–Ea) singly. Then E1 and E2 parameters (Table 3) were obtained for all rank of operating pressures (i.e. 450 and 500 kP_a).

If E1 is analysed in the wind speed rank of 0 and 6.77 m s^{-1}, an increase of 3.26% L_s for every increment of 1 m s^{-1} of wind speed is observed. The results of this study show if the W is blowing when irrigation occurs, some wind drift loss is unavoidable. So, as recommendation to avoid excessive wind drift loss in this conditions, irrigation systems should not be operated when wind speeds are high (e.g. $W > 3.5$ m s^{-1}).

Secondly, in order to improve the predictive equation, L_s was proposed as constitutive equation that use both wind speed and Es–Ea. This model also works in all rank of operating pressures (i.e. 450 and 500 kP_a).

The analysis with SPSS software showed that all terms for this model result highly significant. Table 3 shows how equation E3 has higher R^2 and Pred [0.25] than the previous equations proposed (i.e. E1 and E2). Also, it has less SE and AMRE than the others. Thus, E3 is clearly better than E1 and E2. Therefore, these results suggest that the contribution of climatic parameters to estimate L_s is essential. Frost and Schwalen (1955) arrived to the same conclusion in their researches.

Equations are presented for: 450, 500 kP_a and two operating pressures together. All the parameters and quality indicators were defined in each equation (i.e. R^2, SE, AMRE and Pred [0.25]) previously.

The next step was to fit the predictive capability of this last equation using different values of pressures. The experimental data are used to adjust L_s equation at these two operating pressures. For this purpose, predictive equation based on W, Es–Ea and P were achieved together at the 450 and 500 kP_a operating pressures using the experimental values.

Fig. 4 shows the values for simulated L_s by E4 and measured L_s on experiments. On this figure, it is proved that the values are distributed on an increasing way around the line 1:1. Moreover, the results in Table 3 show that E4 model has higher Pred [0.25] and less SE than E3. So, E4 is better and more exact than E3.

On a last step, the predictive capability of E4 was improved using the values of 450 and 500 kP_a operating pressures separately, resulting one new equation for each one of them. On analysing the additional statistics parameters that are shown in Table 3, it can be concluded that equations E5 and E6 are the best approaches to simulate the evaporation and drift losses. Fig. 5 shows the values of simulated L_s by E5 and E6 and the experimental values of L_s at 450 and 500 kP_a operating pressures, respectively. The resulting points are situated around the line 1:1.

The results of this study suggest that it would be better to work 450 vs. 500 kP_a operating pressure for semi-portable hand-move sprinkler system whit big size sprinkler to obtain the same results. So, due to the higher economic costs to get the same results (about 18% of energy cost for 500 kP_a), this sprinkler system should not work above 450 kP_a. As a consequence, E5 is used to estimate evaporation and drift losses. E5 shows that L_s increases up to 22.7% when wind speed and Es–Ea increased to 4.2 m s^{-1} and 6 kP_a, respectively. Therefore, sprinkler irrigation is not recommended at early afternoon hours in the summer or in windy conditions according with L_s obtained in Molle et al. (2012).

3.5. Uniformity coefficient analysis

The CU values calculated at different sprinkler and lateral spacings and working pressure under various W conditions were found out and presented in Table 4 and Fig. 6 for management and design purposes. All data were sorted on three different wind intervals (low: 0–2 m s^{-1}, moderate: 2–4 m s^{-1} and high: $W > 4$ m s^{-1}).

3.5.1. Effect of working pressure on CU

An one-way analysis of variance (ANOVA) was conducted to investigate the single effect of operating pressure on CU when it was changed from 450 to 500 kP_a. So, it can be said that there is no significant difference between the CU values at two P (Sig = 0.13, $p > 0.05$) without wind speeds differentiation. This could be caused by the small differences between the water distribution radial patterns at pressures of 450 and 500 kP_a. Therefore, in agreement with Keller (1983), we would rather avoid work with higher P than 450 kP_a, since higher P implies a higher economic cost to get the same CU value.

However, when the influence of P is analyzed with differentiating on wind speed classes, it is observed how the influence of P makes significant differences on CU. According with Table 4, for low and medium winds speeds, CU value is higher for 500 kP_a (87.7–78.6%) than for 450 kP_a (85.9–71.1%), but when wind increases above 4 m s^{-1}, CU is strongly affected by wind effect for $P = 500$ kP_a (65.9%) compared with this effect in 450 kP_a (73.0%).

These results certified the findings of Jiusheng (1997) who demonstrated that droplet size formation, mainly affected by working pressure, and it is an important reason that explaining that the small droplets resulting from a high operating pressure, can severely distort the application pattern and being subject to wind drift and evaporation losses.

3.5.2. Effects of wind speed on CU

The water distribution patterns obtained on the single sprinkler's tests were overlapped for the different irrigation spacing to calculate the CU parameter. A regression analysis was done to relate CU with wind. According with Tarjuelo et al. (1999a), the best coefficient of determination (R^2) was obtained to third-degree polynomial equations, due to wind speed had a negative effect on CU values above a minimum wind speed ($\cong 2$ m s^{-1}) and for strong winds ($W > 4$ m s^{-1}) CU values were remained almost constant. Fig. 6 show the variation of CU values vs. wind speed for the different layout configurations. The effect of W on CU showed on Fig. 6 is not agreed with Sánchez et al. (2010) who said that CU values linearly decreases as W increases, approximately.

In agreement with studies mentioned previously with medium size sprinklers, significant differences in the variation of the uniformity due to W were found (sig 3.0×10^{-9}, $p < 0.01$), so that CU decreases with increasing W, but not linearly.

Results of this research with big size sprinklers showed that CU values slightly increase under low wind speed conditions (<2 m s^{-1}) as working pressure increases from 450 to 500 kP_a according to Table 4. It confirms the results of De Lima and Torfs (1994) who explained that the greater effect of the W impact on smaller drops due primarily to greater drag and lower fall velocity. They are also more time-subjected to the wind action. Due to these effects, the distribution of drop diameters is quite different for still-air and windy conditions.

Also, the relationship between CU and W, as shown in Table 4, portends that CU falls under 75% when W exceeds 3.5–4 m s^{-1}, that

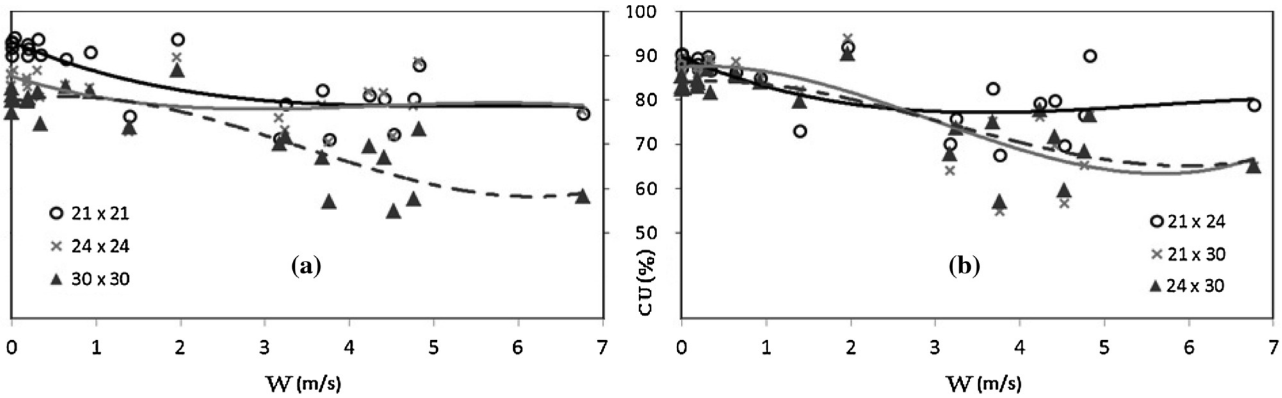


Fig. 6. Uniformity coefficient versus wind speed for different layouts of square (a) and rectangular (b) at 450 kP_a operating pressure.

Table 5
Homogeneous groups of CU obtained for the different layouts, differentiating on global situation, by operating pressures and wind range.

Layout	Global		By pressure (P)				By wind speed range (W)					
Type	All P & W		450 kP_a		500 kP_a		<2 m s^{-1}		2–4 m s^{-1}		>4 m s^{-1}	
	Mean	Group	Mean	Group	Mean	Group	Mean	Group	Mean	Group	Mean	Group
30 × 30	74.6	C	73.1	C	77.5	B	80.9	D	69.7	A	60.8	B
24 × 30	78.3	CB	77.5	CB	80.1	B	84.5	C	71.9	A	66.1	B
21 × 30	79.5	B	78.7	B	81.2	BC	87.2	B	71.5	A	64.6	B
24 × 24	81.0	B	80.6	BA	81.6	BC	84.3	C	75.1	A	75.9	A
21 × 24	82.5	BA	82.3	BA	82.8	BC	87.2	B	75.8	A	74.9	A
21 × 21	85.3	A	85.1	A	85.9	C	90.9	A	77.0	A	76.5	A

Table 6
Recommendation sprinklers' spacing (Se × Sl) under various wind speed, working pressure and conditions of overlapping.

Wind (m s^{-1})	Se × Sl (m × m)	P (kP_a)	Wetted diameter Dw (m)	Se/Dw	Sl/Dw
0–2	30 × 30	500	60	0.50	0.50
	25 × 30	450	56	0.45	0.54
2–4	25 × 25	450	56	0.45	0.45
>4	25 × 25	450	56	0.45	0.45

which FAO consultant Phocaides (2007), recommended as the critical velocity for application of sprinkler irrigation. In agreement with Yacoubi et al. (2012), it is visible in Table 4 to assert that CU (76.3%) was significantly affected by higher wind speed than 4 m s^{-1}, regardless of the sprinkler and lateral spacings and working pressure according to Table 4.

Table 4 approves the findings of Seginer et al. (1991a) that water distribution was largely distorted by wind speed higher than 4 m s^{-1}, especially when the pressure is increased to 500 kP_a, due to the aforementioned effect of the distortion on the pattern of drops, is not as obvious at the pressure of 450 kP_a.

3.5.3. *Effects of irrigation spacing on CU*

The result of ANOVA statistical test showed that there are no-significant differences between CU values in square or rectangular layouts analysed (sig = 0.791, $p > 0.05$). So, for the analysed sprinkler system and for this configuration of nozzles on the analysed sprinkler, it is not possible to conclude which one layout is better, square or rectangular. As is showed in the next point, it will depend on the S_e and S_l selection for each case.

As it can be seen in Table 4, the square layout induces the highest CU (85.1% and 85.9%) at the two working pressure, averagely, but also have the smallest mean value 73.1%. The rank for CU in rectangular layout is 82.7% and 77.5%.

It is clearly resulted that the single effect of Se and Sl on CU has significant differences (sig = 5.75 × 10^{-5}, $p < 0.01$). In other words, operating sprinklers close enough together induces the water distribution more uniform over the field.

It can confirm the conclusion of Montero et al. (2004), who stated that the most important design parameter is sprinkler spacing after analysing the influence of design and performance parameters, such as subunit arrangement, lateral spacing, pressure, average application rate and application efficiency of water application cost, in a permanent set sprinkler irrigation system.

With the objective to determine the effect of Se and Sl on CU, a Tukey HSD test have been performed. Table 5 shows the homogeneous groups for each layout type, differentiating on global tests, by operating pressures, or by wind classes.

According with results showed in Table 5, how it is reasonable, CU mean values decrease in according Se and Sl increases, resulting three homogeneous groups and highlighting that layouts 21 × 24, 24 × 24, 21 × 30 and 24 × 30 are included in the same group, so there are non-significant differences between the value of CU obtained for this layouts, even differentiating by pressure.

Focussing on the CU analysing by wind speed classes, when CU is analysing with low winds, results show that an increase from 24 m up to 30 m the sprinkler spacing has no significant differences in the CU value when lateral spacing is 21 m (Group B) or 24 m (group C), so it would be important in the design of the irrigation system with big size sprinklers since an increase on the sprinklers' spacing suppose more economical solutions, and even, in this particular semi-portable hand-move system, implies decrease the time required to change all sprinklers and, in consequence, decreasing the time out in the irrigation.

However, select a high sprinkler spacing (30 m) could bring an important decreasing on the CU value when wind speed increases over 4 m s^{-1}, obtaining values of CU 10–15% lower than for sprinkler spacing of 21 m and 24 m, as shown in Table 5. In this way, a careful examination of Tables 4 and 5 reveals that the all layouts satisfied the acceptable CU (80%) under low wind conditions, but when wind exceeds this value, CU decrease below 80%, obtaining CU ≈ 75% for $S_e < 30$ m.

So, it would be conclude that, a good technique-economic situation will be square 24 × 24 or rectangular 21 × 24 layouts working at 450 kP_a, depending on the predominant wind speeds for the irrigated area of the system.

Nowadays, the most frequently used Se in semi-portable big size sprinkler irrigation system is 25 m × 30 m in Iran (Sheikhesmaeili, 2003) for conditions recommended in this study such as working pressure up to 450 kP_a and wind speed below 4 m s^{-1}. It has noticed that facility of implementation and maintenance cause to select the S_e multiple of 5 m as 25 × 30 instead of 24 × 30. In the other hand, a good propriety of S_e = 21 m (or 20 m due to practical problem) is that it can be applied on W above 4 m s^{-1} with an acceptable CU (CU = 79.4%) in accordance with the Table 4.

This note should be consider that soil water content uniformity is about 20% higher than water application uniformity in no wind conditions (Montazar and Sadeghi, 2008) due to effects of the low W, surface runoff flow and horizontal seepage through soil.

So, as abbreviated result, Table 6could be used to select the best sprinklers' spacing in semi-portable hand-move big sprinkler irrigation system.

4. Conclusions

Water distribution in sprinkle irrigation system with semi-portable big size sprinkler, is very similar to that obtained with medium size sprinklers.

The difference between 450 and 500 kP_a operating pressures did not have a clear influence over evaporation and wind drift losses. This may be caused by the small differences observed on the water distribution radial patterns and the drop size distribution of the tested sprinkler at the two operating pressures.

In the worst experimental conditions tested the value of L_s was 26.8%; the spray losses increase 3.26% for every increment of 1 m s^{-1} of wind speed.

A nonlinear multiple regression model has been fitted using factors and co-variables, by analysing the effect of the operating pressure and weather conditions in the spray losses. The air temperature and relative humidity through the vapour pressure deficit have been considered to get robust estimated model.

One important consequence of this study is the six predictive equations to estimate spray losses. The best proposed equations use operating pressure, wind speed and vapour pressure deficit. Spray losses increases up to 22.7% at 450 kP_a operating pressure when wind speed and vapour pressure deficit increased up to 4.2 m s^{-1} and 6 kP_a, respectively. Therefore, sprinkler irrigation is not recommended at early afternoon hours or windy conditions. The results switching irrigation from day to night reduced L_s strongly. The amount of L_s would be very small (mainly 1–2%) for operation during night time, early morning and early evening hours even in summer of semi-arid area such as Iran.

The effect of working pressure (increasing from 450–500 kP_a) on CU, has no significant effect under low wind conditions. A significantly action of wind, especially for speeds higher than 2 m s^{-1}, is appreciated on the water distribution pattern under different conditions with regard for sprinkler and lateral spacing and operating pressure. So, the night time irrigation can be very useful and advised to obtain high CU, with low wind drift and evaporation losses due to lower wind speed during the night time than during the day time. In this case, the highest sprinkler layout (24 × 30 and 30 × 30) could be used on the design of these irrigation systems.

As a consequence, technical criteria (Tables 5 and 6) can be used to optimize irrigation management with big size sprinklers in response to the design factors (P, Se and Sl) and the climatic parameter (W). These tables could be implemented in advanced irrigation programmers, whose primary objective would be to guarantee minimum irrigation uniformity in all irrigation events under these conditions.

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Appendix A.

Abbreviations

AMRE	average magnitude of the relative error
CU	Christiansen's coefficient of uniformity, %
D	nozzle diameter, mm
D_w	wetted diameter
e	measured value of Ls, %
$\hat{e}$	estimated value of Ls, %
Es–Ea	vapour pressure deficit, kP_a
ETo	evapotranspiration, mm day^{-1}
H	relative humidity, %
L_s	spray losses, %
n	number of samples
P	operating pressure, kP_a
p	significance
Pred [0.25]	prediction level
R^2	coefficient of determination
SE	standard error
Se	sprinkler spacing in each line, m
Sl	lateral spacing between lines, m
T	air temperature, °C
T_a	dry bulb temperature, °C
T_w	wet bulb temperature, °C
V_i	water volume of an individual catch can measurement, ml
$\bar{V}$	average application volume from all catch can measurements, ml
VMD	volumetric mean diameter, mm
W	wind speed, m s^{-1}

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