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A comparison of fixed and rotating spray plate sprinklers

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Keywords

Pivot, Linear Move, Irrigation Uniformity, Spray, Overlapping Spacing, Evaporation losses, Wind drift, Drop size.

Abstract

A comparative study of two types of spray sprinklers was performed. Rotating spray plate sprinklers (RSPS) and fixed spray plate sprinklers (FSPS) were evaluated individually in open field conditions. The water distribution, wind drift and evaporation losses during the evaluations were measured under low, medium and high wind speed conditions with three nozzle diameters and two nozzle heights above the soil surface.

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Individual spray sprinkler water distributions were mathematically overlapped to simulate the water distribution resulting from sprinkler machines. The water distribution of RSPS had a conical shape, while the FSPS concentrated the water application in a circular crown. The uniformity coefficient (CU) of the simulated water application in sprinkler machines fitted with RSPS or FSPS was higher than 93 % in all cases.

However, the RSPS could attain higher CU at higher spacing along the lateral. For the nozzle diameters of 6.7 and 7.9 mm, the wetted width produced by the RSPS was larger than that of the FSPS. Also, the peak instantaneous precipitation rate of the RSPS was smaller than that of the FSPS.

Introduction

Sprinkler irrigation is characterized by a high potential irrigation efficiency (Clemmens and Dedrick, 1994). However, in dry environments and under wind conditions, evaporation and wind drift water losses can be very high, decreasing the irrigation efficiency of sprinkler systems (Tarjuelo et al., 1999). These water losses depend mainly on wind speed, evaporative demand, type of sprinkler, nozzle height and drop size distribution (Keller and Bliesner, 1990). Wind speed also affects the distribution uniformity of sprinkler systems.

Center-pivot and linear-move sprinkler machines are commonly used in new irrigation developments all over the world. The actual trend in sprinkler machines is to use low pressure spray plate sprinklers instead of high pressure impact sprinklers in order to decrease energy costs (Musick et al., 1988). Commonly these sprinkler machines are fitted with fixed spray plate sprinklers (FSPS) in which the water jet hits a

fixed deflector plate that sprays water at a small angle with the horizontal plane. In new machines the nozzles are located closer to the soil to decrease the wind drift and evaporation losses. However, this results in a reduction of the wetted width and therefore increases the instantaneous precipitation rate of the lateral.

In the middle of the 1990's the Nelson Irrigation Company developed a new rotating spray plate sprinkler (RSPS) called "RotatorTM" (use of trade marks in this work does not imply endorsement). This type of spray sprinklers has been successfully introduced in irrigation machines in the recent years (Hanson and Orloff, 1996). One of the features of this new sprinkler (as reported by the manufacturing company) is that the wetted diameter is higher (in comparison with the FSPS) and therefore the instantaneous precipitation rate of a lateral fitted with this type of sprinkler could be reduced. Hanson and Orloff (1996) compared fixed and rotating spray plate sprinklers in a center-pivot machine and found a higher distribution uniformity for the RSPS. Hills and Barragán (1998) performed experiments in a linear-move sprinkler machine and found that rotating plate sprinklers attained higher uniformity than fixed plate sprinklers (94.6% vs. 93.7%). Both studies lead to the conclusion that a high irrigation uniformity can be attained with both FSPS and RSPS, if a proper design is used. As for the effects of wind intensity on irrigation uniformity, both studies seem to differ in their conclusions. Hanson and Orloff (1996) reported that in the presence of wind, the uniformity of FSPS slightly increases, while the uniformity of RSPS slightly decreases. On the contrary, Hills and Barragán (1998) reported that wind speeds up to 6.2 m s^{-1} had little effect on the uniformity of both types of spray sprinklers.

In the present study we compare the water distribution of individual fixed and rotating spray plate sprinklers in open air conditions. The individual pattern of water distribution of nozzles of different diameters was determined using a catch can set up under two nozzle elevations and different wind conditions. Simulations were performed to estimate the distribution uniformity resulting from the overlapping of individual sprinklers at different spacings. Results were used to determine the effect of these factors on the performance of both types of sprinklers.

Material and methods

Spray sprinklers

Fixed and rotating spray plate sprinklers of the series 3000 of the Nelson Irrigation Company were used in this study. The selected FSPS was the "D3000 Sprayhead", while the selected RSPS was the "R3000 RotatorTM". The main difference between the FSPS and the RSPS is that the RSPS is equipped with a deflector plate that rotates when hit by the water jet. Three nozzle diameters of 3.8, 6.7 and 7.9 mm were used for each type of sprinkler. These nozzle diameters are often installed by Valmont Industries, Inc. in their center-pivots with a 2.7 m overlapping at distances of 45, 170 and 235 m (respectively) from the pivot point. The design operating pressure is 140 kPa (Valmont Industries, 2000).

The characteristics of the deflector plate have a direct effect on the pattern of water distribution. The deflector plate chosen for the RSPS produces 6 streams of water at an angle of 12° over the horizontal plane. Each RSPS had only one deflector plate. The deflector plate chosen for the FSPS had 33 grooves at very low angle from the horizontal plane. The 3.8 mm nozzle had one deflector plate, the 6.7 mm nozzle had two deflector plates and the 7.9 mm nozzle had three deflector plates. Under these conditions, flow in the FSPS was divided in 33, 66 and 99 streams for the 3.8, 6.7 and 7.9 mm nozzles, respectively. In general, when the number of grooves in the deflector plate increases the drop size decreases for a given nozzle diameter and working pressure (Kincaid et al. 1996).

Experimental setup for individual spray sprinkler evaluation

An experimental test stand to evaluate the water distribution of a single spray sprinkler was set up at the Agricultural Research Service of the Diputación General de Aragón in Montañana (Zaragoza). It consisted in a support structure and a hydraulic system. The support structure was an inverted U shape frame designed to support a spray sprinkler at different heights. The hydraulic installation supplied pressurized water to the spray sprinklers. Figure 1 presents a diagram of the experimental setup.

Figure 1

The structure, built with three metal cylindrical bars 50 mm in diameter, was 3.2 m high and 4.0 m wide. The frame corners were anchored to the soil with four steel wires. Two additional horizontal wires were installed within the frame to avoid spray sprinkler vibrations and to fix the spray sprinkler at a 1.0 or 2.5 m height above the soil surface. The water source was a reservoir with a capacity of 30 m³. A 1.94 kW electric centrifugal pump was connected to a 2.54 mm (1”) external diameter polyethylene pipe supplying water to the spray sprinkler. Sand and mesh filters were used to avoid nozzle clogging. Discharge was measured using a volumetric water meter with an accuracy of 1 L. Evaluations were performed at a constant pressure of 140 kPa, obtained with a pressure regulator installed immediately upstream from the spray sprinkler. Manometers and valves were installed as required to control water supply during the evaluations (See Fig. 1).

Catch cans were used to collect the applied water. They were constructed in transparent plastic, with an inverted conical shape. The catch can opening was 80 mm in

inside diameter and the can height was 200 mm. The can capacity was 40 L m^{-2} , with 1 L m^{-2} divisions. The top part of the catch cans was placed at 200 mm over the soil surface. The spray sprinkler and the catch cans were installed in a plot with bare soil.

Evaluation of the spray sprinklers

Thirty five evaluations were performed in the fall of 1998. In these evaluations the water distribution resulting from irrigation with individual spray sprinklers was measured for different combinations of the following factors:

- Type of spray sprinkler: RSPS or FSPS.
- Height of the spray sprinkler above soil surface: 1.0 m or 2.5 m.
- Nozzle diameter: 3.8 mm, 6.7 mm or 7.9 mm.
- Range of wind speed: low ($< 2.5 \text{ m s}^{-1}$), medium (between 2.5 and 5.0 m s^{-1}) or high ($> 5.0 \text{ m s}^{-1}$).

The duration of each evaluation varied between 40 and 120 minutes, depending on the type of spray sprinkler and the nozzle diameter. Catch cans were measured immediately after the irrigation. The total measurement time did not exceed 15 minutes. Wind speed and direction, air relative humidity and air temperature were measured during the evaluations using an automatic weather station located at the same experimental farm.

Design of the catch can setup

In preliminary tests we observed that the water distribution patterns of rotating and fixed plate spray sprinklers were completely different. RSPS's presented a conical water distribution pattern very similar to the distribution pattern created by impact sprinklers, with the maximum depth applied at the sprinkler location and decreasing linearly with distance to the water source. However, FSPS's concentrated most of the applied water in a circular crown of about one meter in width. The distance from the water source to the crown depended on the experimental conditions. Water application within the crown was not uniform: we could appreciate alternate radii with very different depths of water applied, corresponding to the grooves of the deflector plates. The volume of water applied outside the crown was negligible.

According to the different patterns of water application characteristic of the two types of spray sprinklers, different methodologies were used in the setup of the catch can network and in the analysis of the experimental data. In both cases, catch can data are considered representative of a portion of the field. This hypothesis may lead to experimental errors, particularly in the borders of the irrigated area and in the vicinity of abrupt changes in precipitation.

Rotating spray plate sprinklers

The RSPS evaluation was based on a square network of 169 catch cans at 2.0 m by 2.0 m spacing, with the spray sprinkler located at the center (Figure 2a). The catch can lines were oriented in the N-S and E-W directions. We found that the catch can

located in the center of the net, just below the spray sprinkler, collected all the drops formed by the impact of the water jets with the three arms supporting the deflector plate. Therefore, this can reflected an unrealistically high water application. To avoid this problem, water application below the spray sprinkler was characterized by the average value of four catch cans located at 0.75 m from the spray sprinkler in the NE, NW, SE and SW directions. Additional experiments revealed that this average value was an adequate estimation of water application at the central 2.0 by 2.0 m tile of the catch can network.

The observed wind drift and evaporation losses (OWDEL) were determined for each evaluation as the percentage of the discharged volume that was not collected in the catch can network, assigning an area of 4 m² to each catch can. The possible evaporation losses from the catch cans during the irrigation evaluation and data collection were not considered in this procedure. OWDEL was computed using the following equations:

$$OWDEL = \left(\frac{Vd - Vc}{Vd} \right) 100 \quad [1]$$

where:

Vd = Volume of water discharged (m³), as obtained from the water meter.

Vc = Volume of water collected in the catch cans (m³), determined from:

$$Vc = \sum_{i=1}^{i=169} D_i \times \frac{4}{1000} \quad [2]$$

where:

D_i = Water application at catch can i (L m^{-2})

Fixed spray plate sprinklers

The location of the catch cans in the evaluation of the FSPS was adapted to the special characteristics of the water distribution pattern. The square network used for the RSPS proved very inadequate to characterize the water application pattern of the FSPS, since the crown width was smaller than the network spacing. A finer square network would require a very large number of catch cans, rendering the experiment unmanageable. To overcome these problems, two lines of 41 catch cans each, with a 0.5 m spacing were installed in the N-S and E-W directions, with the spray sprinkler located at the crossing of the two lines (Figure 2b).

With this setup, an area of 20.0 by 20.0 m was monitored by the catch cans. The variation of water application along the radii was addressed by the 0.5 m catch can spacing. However, to address the variability between the radii, additional catch cans were required. Therefore, 8 lines of 6 to 12 catch cans were added at both sides of each catch can line at a distance of 0.3 m, covering the crown area (Figure 2b). The number of extra catch cans and its location depended on the nozzle diameter, the wind speed and the spray sprinkler height. At each catch can line, where three catch cans were used to measure water application at the same radial distance (at the crown area), the average of these three values was used. Therefore, each experiment was characterized by 81 catch can values.

Interpolation was used to estimate water application in a square net of 41 x 41 points at 0.5 by 0.5 m distance, with the FSPS located at the center. The interpolation procedure used at each unknown network point followed four steps. First, the distance from the unknown point to the spray sprinkler was computed. Second, the two field observations located in the axes of the quadrant of the unknown point, at a radius similar to the distance computed in the first step were identified. These two catch can readings are the basis for the interpolation. Third, the angles formed by the radius through the unknown point and the axes were computed. Fourth, an inverse angle square interpolation was performed to estimate water application at the unknown point.

OWDEL in the FSPS was computed using Eq. 1. However, relevant differences appear in the estimation of the volume of water collected by the catch cans (V_c). This volume was calculated by adding the volumes of water collected in all the 0.5 m width circular crowns in the area covered by the spray sprinkler. The following equation was used to calculate V_c :

$$V_c = \frac{D_1}{1000} \pi 0.25^2 + \sum_{i=2}^{i=21} \left[\left(\frac{D_{Ni} + D_{Si} + D_{Ei} + D_{Wi}}{4} \times \frac{1}{1000} \right) \left(\pi (0.5i - 0.25)^2 \right) - \left(\pi (0.5(i-1) - 0.25)^2 \right) \right] \quad [3]$$

Where:

i = ordinal of catch cans from the spray sprinkler in the four directions

D_{Ni} , D_{Si} , D_{Ei} and D_{Wi} = Water application at the i_{th} catch cans in the N, S, E and W direction, respectively ($L m^{-2}$)

The experimental procedures could result in small errors in the determination of the water application during the evaluation and therefore in the determination of OWDEL. This is particularly important in the case of FSPS, due to the uneven water application resulting from individual spray sprinklers.

Figure 2

Drop size distribution

The drop size distributions resulting from the fixed and rotating spray plate sprinklers were determined using the empirical model proposed by Li et al. (1994). This model calculates the percentage of drops smaller than a given diameter. The equation used for this purpose is:

$$P_v = \left(1 - e^{-0,693 \left(\frac{d}{d_{50}} \right)^n} \right) 100 \quad [4]$$

Where:

P_v = Percentage of total discharge in drops smaller than d

d = Drop diameter (mm)

d_{50} = Average drop diameter (mm)

n = empirical exponent

Additional equations are required to obtain d_{50} and n from empirical parameters:

$$d_{50} = a_d + b_d R \quad [5]$$

$$n = a_n + b_n R \quad [6]$$

Where:

a_d , b_d , a_n and b_n are empirical coefficients

R = Ratio of nozzle size to pressure head (mm kPa^{-1})

Kincaid et al. (1996) presented an experimental study based on drop size measurement using a laser-optical method in which values for the empirical coefficients used in Eqs. 5 and 6 are supplied for a number of spray sprinklers. The RSPS used in this work was characterized by Kincaid et al. (1996), while the FSPS used in this work was not. In order to characterize the FSPS drop distribution, the empirical coefficients derived for the similar Nelson Spray I (with 30 grooves), were used.

Figure 3 presents the drop size distribution of the evaluated RSPS and FSPS. The x axis represents the drop diameter, and the y axis represents the corresponding P_v . Drop size distributions are very different for the two types of spray sprinklers. Drops emitted by the FSPS are, on the average, smaller than those emitted by the RSPS. The steep slope of the drop distribution curves of the FSPS indicate that the range of drop diameter variation is much smaller for fixed than for rotating spray plate sprinklers. Drop distribution for the three nozzle diameters of the FSPS is very similar to each other. However, the drop distributions obtained for the RSPS show a large variability between nozzle diameters. The P_v corresponding to 1.5 mm for the 7.9 mm diameter

nozzle is 72% for the FSPS and 46 % for the RSPS, while for the nozzle diameter of 3.8 mm, the P_v corresponding to 1.5 mm is 86 % for the FSPS and 63 % for the RSPS.

Figure 3

The differences in drop size distribution among types of spray sprinklers are due to the characteristics of the drop formation process. In the FSPS the water jet hits a variable number of grooved deflector plates. The stream reaching each groove remains approximately independent of the nozzle diameter. In the RSPS the water jet hits a deflector plate with 6 grooves. A larger nozzle diameter will result in higher flows in each groove, increasing drop diameter and therefore the wetted radius of the rotator nozzle.

Estimation of the wind drift and evaporation losses

Different empirical equations were used in this work to estimate the wind drift and evaporation losses (EWDEL, %) during the evaluations. These estimates were compared with the experimental OWDEL. The models used for comparison were : Keller and Bliesner (1990), Trimmer (1987) and Montero et al. (1997). The first two approaches are based on the pioneer work by Frost and Schwallen (1955).

Keller and Bliesner (1990) developed an equation in which EWDEL is expressed as a function of potential evapotranspiration, wind speed and an index of drop diameter. The following equations are used in this model:

$$EWDEL = \left[1 - 0.976 - 0.005 PET + 0.00017 PET^2 - 0.0012 U + CI (0.00043 PET + 0.00018 U + 0.000016 PET U) \right] 100 \quad [7]$$

Where:

PET = Potential evapotranspiration (mm day⁻¹).

U = Wind velocity (km h⁻¹).

CI = Coarseness index, obtained from:

$$CI = \frac{0.032 p^{1.3}}{D} \quad [8]$$

Where:

p = Nozzle working pressure (kPa)

D = Nozzle diameter (mm).

Equation 8 is subjected to the following rules: if $CI < 7$ (big drops) CI is set to 7 in Eq.

7. If $CI > 17$ (small drops) CI is set to 17.

Trimmer (1987) developed an equation for $EWDEL$ as a function of nozzle diameter, working pressure, wind speed and vapor pressure deficit. The following equations are used in this model:

$$EWDEL = \left[1.98 D^{-0.72} + 0.22 (e_s - e_a)^{0.63} + 3.6 \cdot 10^{-4} p^{1.16} + 0.4 V^{0.7} \right]^{4.2} \quad [9]$$

Where:

V = Wind velocity (m s⁻¹).

$e_s - e_a$ = Water vapor pressure deficit (kPa), obtained from:

$$e_s - e_a = 0.61 e^{\left(\frac{17.27 T}{237.3 + T} \right)} \left(1 - \frac{RH}{100} \right) \quad [10]$$

Where:

T = Air temperature (°C).

RH = Air relative humidity (%).

Montero et al. (1997) developed an empirical equation from experimental data obtained under field conditions in solid set irrigation systems based only on climatic parameters. The following equations are used in this model:

$$EWDEL = 1.059 (e_s - e_a) + 1.438 V \quad [11]$$

Overlapping of the spray sprinklers

The individual water distributions obtained for the RSPS and FSPS evaluations were mathematically overlapped in order to simulate the water application pattern produced by a section of a center-pivot or a linear-move sprinkler machine.

At the end of the irrigation evaluation process, the individual water distribution of each RSPS was represented by a square 21 by 21 matrix with observations spaced at 2 by 2 m. However, the individual water distribution of the FSPS was represented by a 41 by 41 matrix with a data spacing of 0.5 by 0.5 m. In order to have comparable data

sets for both types of spray sprinklers, the RSPS 21 by 21 matrix of water distribution was converted to a 41 by 41 matrix using an interpolation process based on the inverse distance square. The last step in data processing was to standardize the wind direction. In each evaluation, the resultant wind direction was determined and the data set was rotated to represent three wind directions: North, Northeast and East. Unless otherwise stated, the North wind data set will be used. The result of this interpolation process is a new 41 by 41 matrix with axes in the N-S and E-W directions.

We assumed that the irrigation lateral was oriented in the E-W direction. Therefore, the water application resulting from each individual spray sprinkler is represented by a row vector whose elements are computed as the sum of the elements of the water application matrix in the same column. The next step is to overlap the vectors resulting from neighboring spray sprinklers (Figure 4). Our goal was to obtain a 20.5 m section of fully overlapped water application in the irrigation lateral. This section is characterized by a 41 element vector whose elements (denoted z_i) are calculated by addition of the water applied by each of the spray sprinklers. Four spray sprinkler spacings were considered: 2.5, 3.0, 3.5 and 5.5 m. A relevant limitation of the overlapping procedure is that the spacing must be a multiple of the data spacing in the water application matrix (0.5 m). Figure 4 presents the procedure used to overlap water application between spray sprinklers. The required number of spray sprinklers varied with the spacing, ranging between 7 (for a spacing of 5.5 m) and 17 (for a spacing of 2.5 m).

Figure 4

The Coefficient of Uniformity (CU, %), developed by Christiansen (1942) was calculated in the fully overlapped section of the lateral using the following equation:

$$CU = \left(1 - \frac{\sum_{i=1}^{41} |z_i - m|}{41 m} \right) 100 \quad [12]$$

Where m is the average value of water application (z_i). This CU reproduces the uniformity of the irrigation lateral traveling over a parallel line of 41 catch cans at a 0.5 m spacing (Figure 4). It should be noted that this expression of the coefficient of uniformity is not adequate for the characterization of a complete pivot lateral (Keller and Bliesner, 1990).

Statistical significance

The levels for statistical significance adopted in this work were: *** for $P < 0.001$; ** for $0.001 < P < 0.01$; * for $0.01 < P < 0.05$; and ^{ns} for $0.05 < P$.

Results and discussion

Water distribution pattern of individual spray sprinklers

As an illustrative example of the individual water distribution pattern of the RSPS and FSPS, Figure 5 presents the results of the evaluations for the 3.8 mm nozzle, at 1.0 m and 2.5 m height above the soil surface under low and medium wind velocity. This figure represents, in a grey color intensity scale, the water application in mm h^{-1} , collected at each point of the soil surface during the evaluation of the spray sprinklers. The x and y axes represent the coordinates of the soil surface in m. The point with coordinates (0,0) corresponds to the nozzle location. In all figures, wind direction has been adjusted to represent a North direction (from the positive extreme of the y axis).

Figure 5

It can be observed that the individual water distribution patterns of the RSPS and FSPS are very different. In the RSPS precipitation is maximum at the center and decreases gradually as we move away from the center. In the FSPS precipitation is maximum at a circular crown of variable width located around 6 m from the spray sprinkler. This distance resulted quite invariable with respect to nozzle diameter. In the rest of the wetted area, precipitation is almost negligible. The different behavior of the RSPS and the FSPS can be explained by the different drop size distribution of both types of sprinklers (Figure 3). The ample grading in drop diameter characteristic of RSPS results in drops landing at variable distances along each radius. However, most drops emitted by a FSPS have diameters ranging between 1 and 2 mm. These drops of

uniform diameter land in a narrow range of distances along the radius, resulting in the experimentally observed circular crown of precipitation.

Influence of sprinkler height on the wetted diameter of individual sprinklers

Sprinkler height has a considerable effect on water distribution (Subfigures 5a to 5d). An increase in sprinkler height produces a smoothing and a spread of the water distribution. The wetted area of both sprinklers is larger for the 2.5 m height than for the 1.0 m height. Drops are emitted by both types of spray sprinklers at an angle close to the horizontal. Therefore, as the sprinkler height increases drops travel a longer distance. At the same time, the opportunity time for the wind to evaporate and drift the drops increases as the drop trajectory gets longer. Since the same amount of water is distributed in a small area when the sprinkler is located at a low height, the maximum precipitation is higher at 1.0 m than at 2.5 m height. This can result in runoff problems in soils with low infiltration rates.

Figure 6 presents the relationship between the wetted diameters of the RSPS and FSPS at 1.0 and 2.5 m height. For each nozzle the wetted diameter is higher at 2.5 m height than at 1.0 m height. The wetted diameters of the 6.7 mm and 7.9 mm diameter nozzles were considerably higher for the RSPS than for the FSPS at both 1.0 and 2.5 m height. However, the wetted diameters of the RSPS were slightly lower than the FSPS diameters for the 3.8 mm nozzle diameter at both heights. For large nozzle diameters, the relative advantage of the RSPS (large wetted diameter) is more relevant when the spray sprinkler height is low.

Figure 6

Influence of wind on the water distribution of individual sprinklers

Wind speed is one of the most important environmental factors affecting the quality of sprinkler irrigation (Trimmer, 1987; Vories et al., 1987). The influence of wind speed is related to the type of spray sprinkler, the nozzle diameter, the working pressure and the nozzle height above the soil surface (Tarjuelo et al., 1999).

Wind produced a displacement of the water distribution of RSPS (Subfigures 5c and 5e). This displacement was proportional to the wind speed and increased with nozzle height. However, the shape of the water distribution did not change drastically. In the FSPS wind produced a displacement of the water distribution, and a change in the shape of the crown was also apparent (Subfigures 5d and 5f). Under medium and high wind conditions water application in FSPS often resulted smoothed by the random drift produced by wind blows. Under these conditions the irrigation uniformity could even be improved in the presence of wind.

Overlapped water distribution of RSPS and FSPS

The spacing of the spray sprinklers is a key decision in the design of center-pivot and linear-move sprinkler machines. Usually the desired precipitation rates along the lateral are obtained by choosing adequate nozzle diameters and spacings. For the nozzle diameters considered in the present study, the commercial spacings vary between 2.5 m and 5.5 m.

Figure 7 presents the water distribution of a lateral equipped with RSPS and FSPS with a 7.9 mm nozzle diameter and an spacing of 2.5 m, under low wind conditions at 1.0 and 2.5 m height. The overlapped water distribution patterns of both types of spray sprinklers were very different. The maximum water application in RSPS is obtained just below the irrigation lateral. In the overlapped distribution resulting from the FSPS, two rows of maximum precipitation are formed in the outer parts of the wetted area. These two rows are formed by superposition of the circular crowns of maximum precipitation observed in individual FSPS. For both types of spray sprinklers the wetted width of the lateral increases when the nozzle height is increased from 1.0 m to 2.5 m. Increasing the nozzle height also resulted in a smoothing of the water application. For both nozzle heights the wetted width is larger in the RSPS than in the FSPS (about 3 to 4 m in this particular case).

Figure 7

Figure 8 presents the simulated cross-sectional average water distribution of a lateral fitted with both types of spray sprinklers, 3 m spacing, the three studied nozzle diameters, a nozzle height of 1.0 m and low wind speed. The differences in the shape of the overlapped water distribution are evident. The RSPS is characterized by a bell shape, while the FSPS presents two peaks of maximum water application which are clearly visible for the 6.7 and 7.9 mm nozzle diameters.

Figure 8

When a lateral fitted with FSPS is in motion, the precipitation rate at a given point of the field suddenly increases at the beginning of the irrigation. After reaching a peak the precipitation rate decreases to form a plateau until a second precipitation peak arrives just before the end of the irrigation. This profile of water application can produce runoff in soils with low infiltration rates because the second peak of high precipitation occurs when the soil is already wet and infiltration rate is far from maximum. Considering all simulated spacings, the peak of maximum precipitation is higher in FSPS than in RSPS for the same nozzle diameter. Therefore, it can be presumed that in soils with low infiltration rates a sprinkler machine fitted with RSPS would produce less runoff than if it was fitted with FSPS.

Effect of wind speed and direction on the water distribution of overlapped spray sprinklers

Figure 9 illustrates the effect of wind speed on water distribution. In this particular case, the figure presents the simulated cross-sectional average water distribution of a lateral fitted with both types of spray sprinklers with 3.8 mm nozzle diameter, 2.5 m spacing and under low, medium and high wind speeds of N direction. When the wind direction is perpendicular to the sprinkler lateral (N wind), wind produces a displacement of the water application in both types of sprinklers that is proportional to its speed. In the RSPS high wind resulted in a general displacement of around 9 m. The displacement in FSPS was lower than in RSPS (about 3-4 m). This trend was confirmed for the other two nozzle diameters. It can also be observed that wind speed decreases the peak of maximum precipitation and changes the water application pattern. In the RSPS, as wind speed increases the slope of the upwind side

of the water distribution pattern decreases. In the FSPS high wind produces a decrease of the upwind precipitation peak.

Figure 9

Figure 10 presents the simulated cross-sectional average water distribution of a sprinkler lateral fitted with RSPS and FSPS, 6.7 mm nozzle diameter, at a nozzle height of 1.0 m, at 3.5 m spacing and under high wind speed of N, NE and E directions. The N wind direction (perpendicular to the irrigation lateral) results in a higher displacement of the water distribution than in the other two cases. When the wind direction is from the E (parallel to the sprinkler lateral, blowing from the right side), the resulting simulated water distribution is almost symmetrical to the irrigation lateral. For the NE wind direction the displacement of the water distribution is intermediate. With the E wind direction the water application pattern of the FSPS changes, showing the maximum application rate just below the lateral, in a pattern similar to the RSPS. In all cases the wetted width of the sprinkler lateral was not significantly affected by the wind direction.

Figure 10

Uniformity of the overlapped water distribution

The uniformity of water application for a lateral with 3.0 and 5.5 m spacing was simulated for all the individual evaluations. Winds from the N direction (perpendicular to the lateral), the NE direction (at a 45° angle in relation to the lateral) and the E direction (parallel to the lateral) were also simulated in each case. Table 1 presents the

average values of CU for the different studied management variables. At a spacing of 3.0 m, the average values of CU for the different nozzle diameters, sprinkler height, wind speed and direction are very large for the RSPS (larger than 98.6 %) and relatively large for the FSPS (larger than 93.2 %). The average CU at a spacing of 5.5 m remains high in all cases with the RSPS (larger than 95.1 %), but decreases when the FSPS is used (values of CU between 83.2 and 90.5 %).

Table 1

The influence on CU of each management factor was studied using multiple linear regression. Table 2 presents the regression coefficients and the significance levels obtained for the two types of spray sprinklers. Nozzle diameter, nozzle height over the soil surface and spacing significantly affected CU in both types of spray sprinklers. Increasing the nozzle diameter results in an increased CU with RSPS. The contrary trend was observed with FSPS. Increasing the nozzle height increases CU in both types of spray sprinklers. This is due to the smoothing of the water distribution as the nozzle height increases. However, wind drift and evaporation losses can increase as nozzle height increases. Wind speed and direction did not significantly affect CU neither for RSPS nor for FSPS. Spacing significantly affected CU in both types of sprinklers. Increasing the spacing always resulted in a reduced CU. A higher regression coefficient was found for the FSPS ($-3.3 \% \text{ m}^{-1}$) than for the RSPS ($-0.8 \% \text{ m}^{-1}$).

Table 2

Results indicate that FSPS can be successfully used when the spacing is kept below a certain value. However, the spacing in RSPS can be higher than in FSPS without compromising CU. Frequently, commercial pivot designs with FSPS maintain constant a spacing along the lateral of 2.7 m, varying the nozzle diameter. The same pivot designed with RSPS would use different nozzle diameters but it would also include different spacings (2.7 m and 5.5 m) (Valmont Industries, 2000).

Wind drift and evaporation losses

Figure 11 presents the relationship between wind speed and OWDEL for all the evaluations on RSPS and FSPS. A simple linear regression showed a larger determination coefficient for RSPS ($R^2 = 0.83^{***}$) than for FSPS ($R^2 = 0.32^*$). The slope of both curves is positive, indicating an increase in the OWDEL as the wind speed increases. However, the slope of the RSPS curve ($\text{OWDEL} = 3.61 V - 0.86$) is more than twice the slope of the FSPS curve ($\text{OWDEL} = 1.51 V + 6.95$). The low value of the coefficient of determination obtained for FSPS seems to be related to the experimental difficulties associated with the determination of OWDEL in this type of spray sprinklers.

Figure 11

Linear regression was used to explain the EWDEL obtained with the Keller and Bliesner (1990), Trimmer (1987) and Montero et al. (1997) models using the OWDEL as the independent variable. The results of these regressions are presented in Eq. [13].

$$\begin{aligned}
EWDEL_{Keller\ and\ Bilesner} &= 0.147\ OWDEL ; \quad R^2 = 29\% ** \\
EWDEL_{Trimmer} &= 0.176\ OWDEL ; \quad R^2 = 54\% *** \\
EWDEL_{Montero\ et\ al.} &= 0.829\ OWDEL ; \quad R^2 = 38\% ***
\end{aligned}
\tag{13}$$

In all cases the regression intercept did not significantly differ from zero. Results indicate that the Keller and Bliesner (1990) and the Trimmer (1987) equations systematically underestimate the values of the OWDEL. The lack of agreement between OWDEL and EWDEL could be due to the fact that these equations incorporate the nozzle working pressure. The experimental pressure was very low in all evaluations (140 kPa), considering that these equations were primarily developed for impact sprinklers. Our results suggest that these equations can not be used in spray sprinklers without further study. The Montero et al. (1997) equation satisfactorily predicted the OWDEL. The slope of the regression line was 0.83, indicating some underestimation. However, there was some scatter in the data and the resulting determination coefficient was only 38 %.

The multiple linear regression analysis performed with the OWDEL as the dependent variable and type of spray sprinkler, nozzle diameter, nozzle height, wind speed, air relative humidity and temperature as independent variables, indicated that the best adjustment equation was:

$$EWDEL = -0.74 D + 2.58 V + 0.47 T ; \quad R^2 = 69\% *** \tag{14}$$

The resulting determination coefficient was 69 %. Only nozzle diameter, wind speed and air temperature proved to have an effect on wind drift and evaporation losses. The rest of the variables did not result statistically significant in the regression. We

believe that a more elaborated and intense experimental protocol would unveil the effect of variables like type of spray sprinkler, nozzle height and air relative humidity, which have been included in other equations. In the case of nozzle height, it would probably be necessary to experiment with higher nozzles in order to find a relevant quantitative effect.

General discussion and conclusions

The results of the individual RSPS and FSPS evaluations indicated that the behavior of both types of sprinklers is drastically different. The FSPS result in a more uniform drop size than the RSPS. This drop diameter uniformity in the FSPS is maintained for the different nozzle diameters considered in this study. However, the drop size distribution was affected by the nozzle diameter in the RSPS. The average drop diameter is in general smaller in the FSPS than in the RSPS. As a consequence, the water distribution pattern of both types of sprinklers differs completely. Under low wind conditions, FSPS concentrate most of the applied water in a narrow circular crown at around 6 m from the location of the sprinkler, while the RSPS produce a conical shape water distribution with the peak located just underneath the nozzle. The average wetted diameter in the 3.8 mm FSPS and RSPS was very similar. However, the wetted diameter in the 6.7 and 7.9 mm nozzle diameters was significantly higher in the RSPS than in the FSPS.

Wind speed affected the water distribution pattern of the FSPS and RSPS. In both cases a displacement in the wind direction and a deformation of the water distribution were observed. Under high wind conditions the displacement of the water distribution is more important in the RSPS, while the deformation of the water distribution pattern is more evident in the FSPS. Displacement and deformation of the water distribution were more relevant at 2.5 m than at 1.0 m nozzle elevation. The 2.5 m nozzle height produced a smoothing of the precipitation rate and an increase of the wetted diameter in both types of spray sprinklers.

The results of the simulations of overlapping the individual water distribution in an irrigation lateral indicated that the cross-sectional water application in the FSPS is characterized by two peaks of maximum precipitation. The RSPS produces a triangular (or bell-shaped) cross-sectional water distribution, with the maximum precipitation just under the lateral. The simulated CU for a 3.0 m spacing with both types of sprinklers was in general very high. For a spacing of 5.0 m, the simulated CU for FSPS resulted clearly lower than for the RSPS. This fact does not affect the CU of commercial sprinkler machines because the FSPS are not generally overlapped at spacings over 3.0 m.

Wind speed significantly affected the observed wind drift and evaporation losses (OWDEL) in the individual spray sprinkler evaluations. A better relation between OWDEL and wind speed was found for the RSPS ($R^2 = 83 \%$) than for the FSPS ($R^2 = 32 \%$) evaluations. Only the Montero et al. (1997) equation predicted reasonably well the OWDEL that occurred in the evaluation of these type of sprinklers. The OWDEL was related linearly with the nozzle diameter, wind speed and air temperature with an R^2 of 69 %.

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Appendix I. References

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Appendix II: Notation

The following symbols were used in this paper:

a_d	Empirical coefficient;
a_n	Empirical coefficient;
b_d	Empirical coefficient;
b_n	Empirical coefficient;
CI	Coarseness index;
CU	Christiansen uniformity coefficient;
d	Drop diameter;
d_{50}	Average drop diameter;
D	Nozzle diameter;
D_i	Water application at catch can i ;
D_{Ei}	Water application at the i_{th} catch cans in the E direction;
D_{Ni}	Water application at the i_{th} catch cans in the N direction;
D_{Si}	Water application at the i_{th} catch cans in the S direction;
D_{Wi}	Water application at the i_{th} catch cans in the W direction;
$e_s - e_a$	Water vapour pressure deficit;
$EWDEL$	Estimated wind drift and evaporation losses;
$FSPS$	Fixed spray plate sprinkler;
I	Ordinal of catch cans from the spray sprinkler in the four directions;
m	Average value of water application;
n	Exponent in equation 4;
$OWDEL$	Observed wind drift and evaporation losses;

p	Nozzle working pressure;
P_v	Percentage of drops with diameter smaller than d ;
PET	Potential evapotranspiration;
R	Ratio of nozzle size to pressure head;
RH	Air relative humidity;
$RSPS$	Rotating spray plate sprinkler;
T	Air temperature;
U	Wind speed, expressed in km h^{-1} ;
V	Wind speed, expressed in m s^{-1} ;
V_c	Volume of water collected in the catch cans;
V_d	Volume of water discharged; and
Z_i	Water application at the i_{th} location.

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Table 1. *Average Coefficients of Uniformity (%) for the FSPS and RSPS, under different spacings, nozzle diameter, spray sprinkler height and wind speed and direction.*

		Overlapping distance			
		3.0 m		5.5 m	
		RSPS	FSPS	RSPS	FSPS [†]
Nozzle diameter (mm)	3.8	98.6	96.8	95.1	90.5
	6.7	99.1	94.6	98.0	87.8
	7.9	99.2	94.6	98.2	83.2
Spray sprinkler height (m)	1.0	98.7	93.3	96.3	83.8
	2.5	99.2	97.5	97.9	90.5
Wind speed (m s ⁻¹)	Low	98.9	93.2	97.3	87.0
	Medium	99.1	96.5	97.0	85.5
	High	98.8	96.3	97.0	88.9
Wind direction	N	99.0	95.8	97.2	89.7
	NE	99.0	94.9	96.5	85.1
	E	98.9	95.2	97.5	86.2

[†] The 5.5 m spacing is not commercially used in FSPS.

Table 2. *Multiple linear regression coefficients of CU as a function of nozzle diameter, spray sprinkler height, wind speed, wind direction and overlapping spacing for the RSPS and FSPS.*

	Regression Constant	Nozzle Diameter (mm)	Sprinkler Height (m)	Wind Speed	Wind Direction	Overlapping Spacing (m)
RSPS	97.2***	0.5***	0.6***	ns	ns	-0.8***
FSPS	104.9***	-0.9**	3.3***	ns	ns	-3.3***

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Figure 11. *Wind speed effects on the OWEDL for the FSPS and RSPS.*

Figure 1. *Structure and components of the experimental setup for the evaluation of water distribution of individual spray sprinklers.*

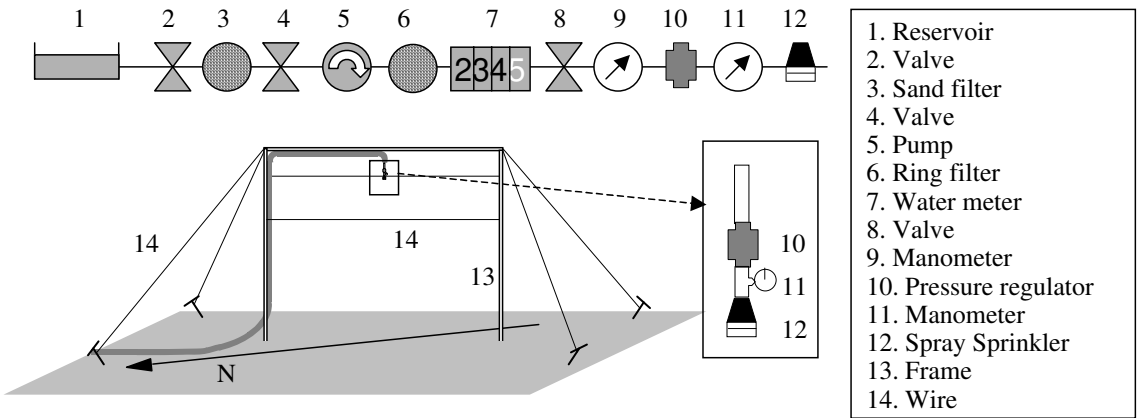


Figure 2. *Catch can network used for the evaluation of rotating (a) and fixed (b) plate spray sprinklers. Catch cans are denoted by fine dots, and the spray sprinkler is represented by a thick dot. The gray areas represent the wetted area. Darker gray in fig. b represents the area of intense water application.*

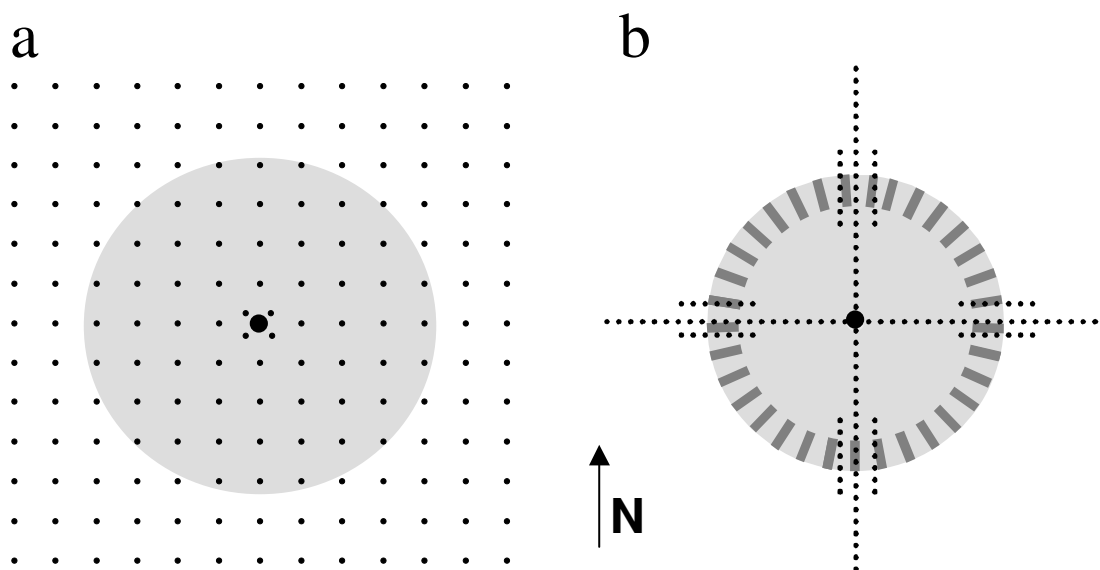


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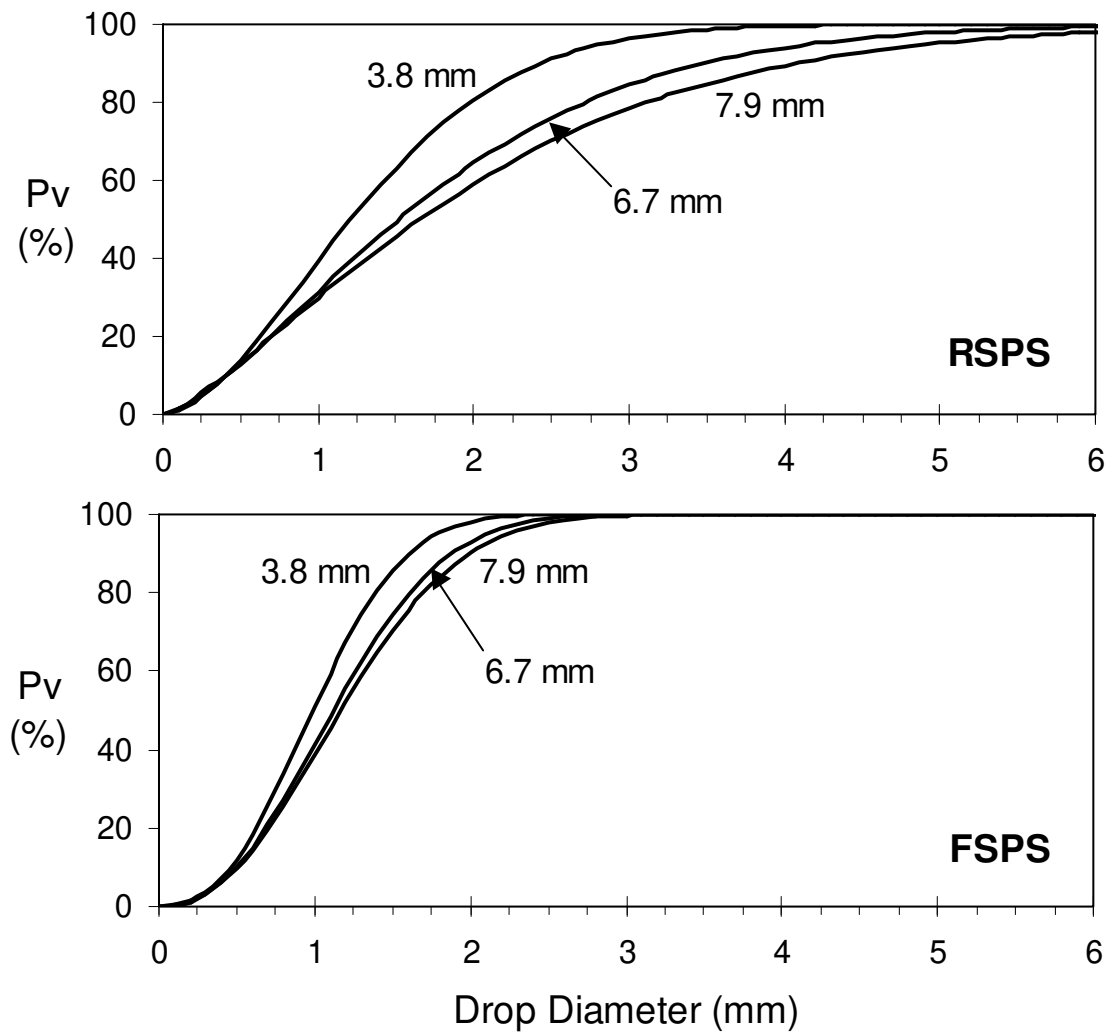


Figure 4. *Scheme of the mathematical procedure used for the simulation of the overlapping of spray sprinklers at different spacings.*

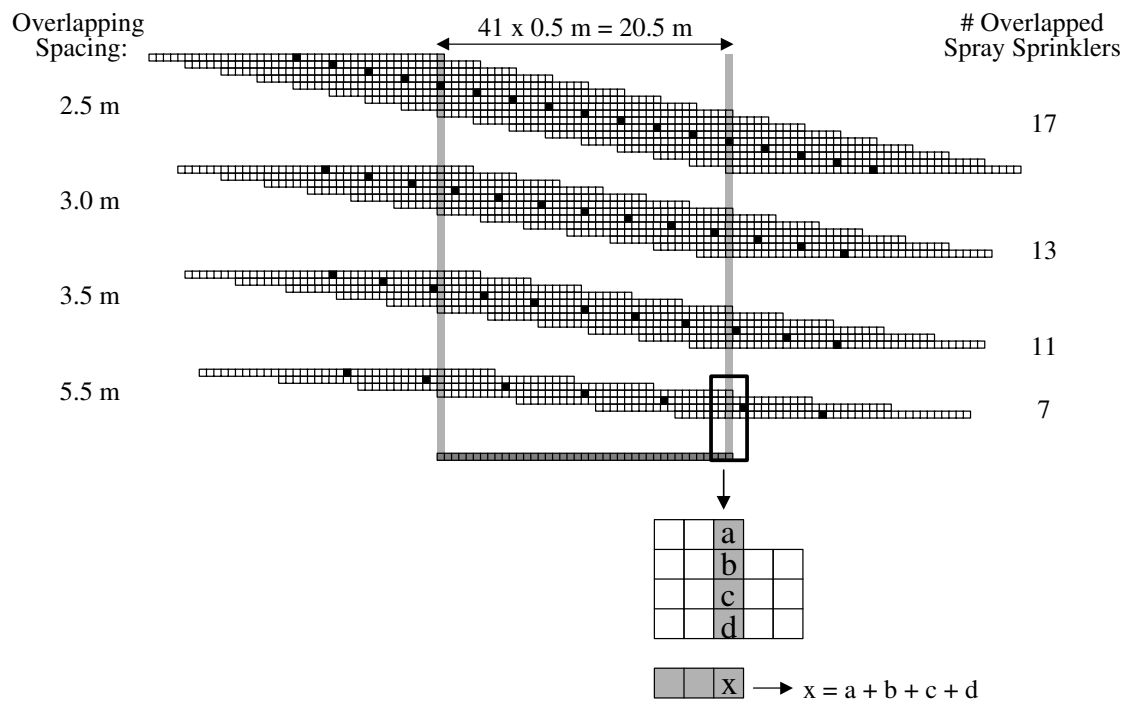


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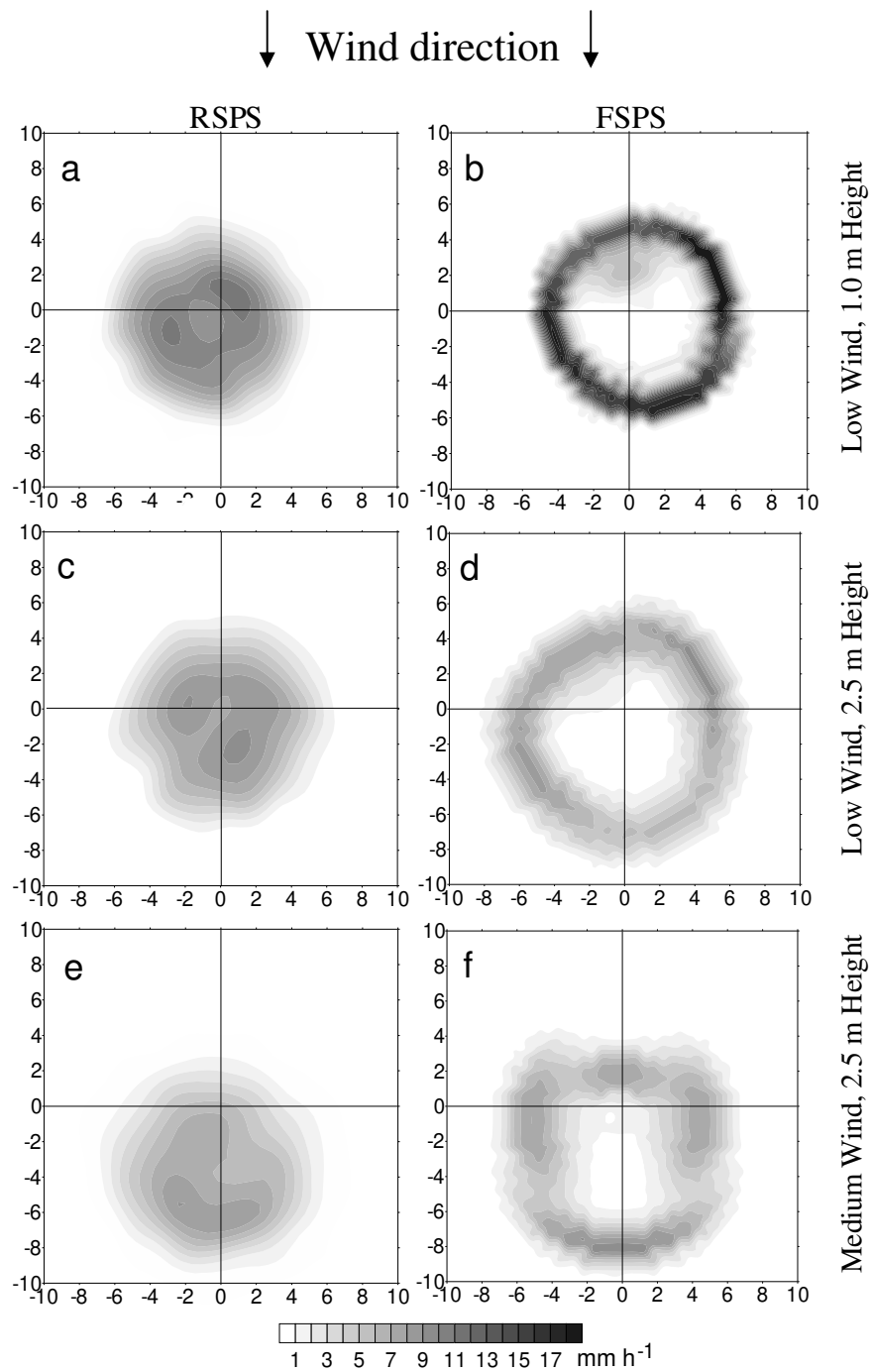


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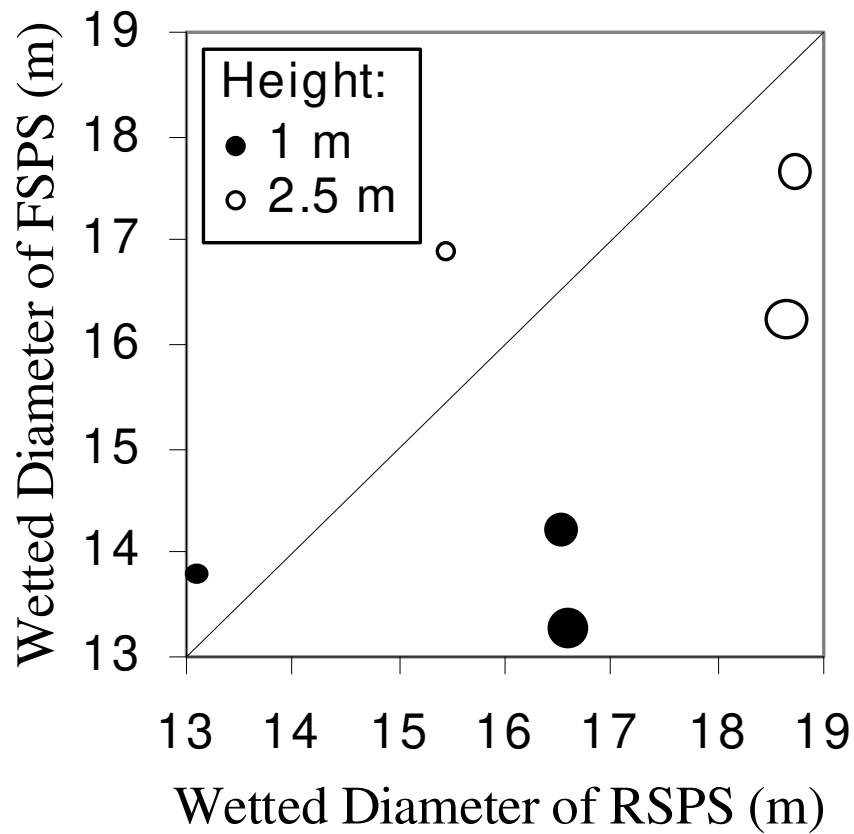


Figure 7. *Two-dimensional representation of the water distribution of a lateral with rotating (a and c) and fixed spray plate (b and d) sprinklers of 7.9 mm diameter installed at 1.0 m (a and b) and 2.5 m of height (c and d) under low wind speed. The spacing of spray sprinklers in all cases is 2.5 m. The irrigation lateral is denoted by the dotted line. Axes coordinates are in m.*

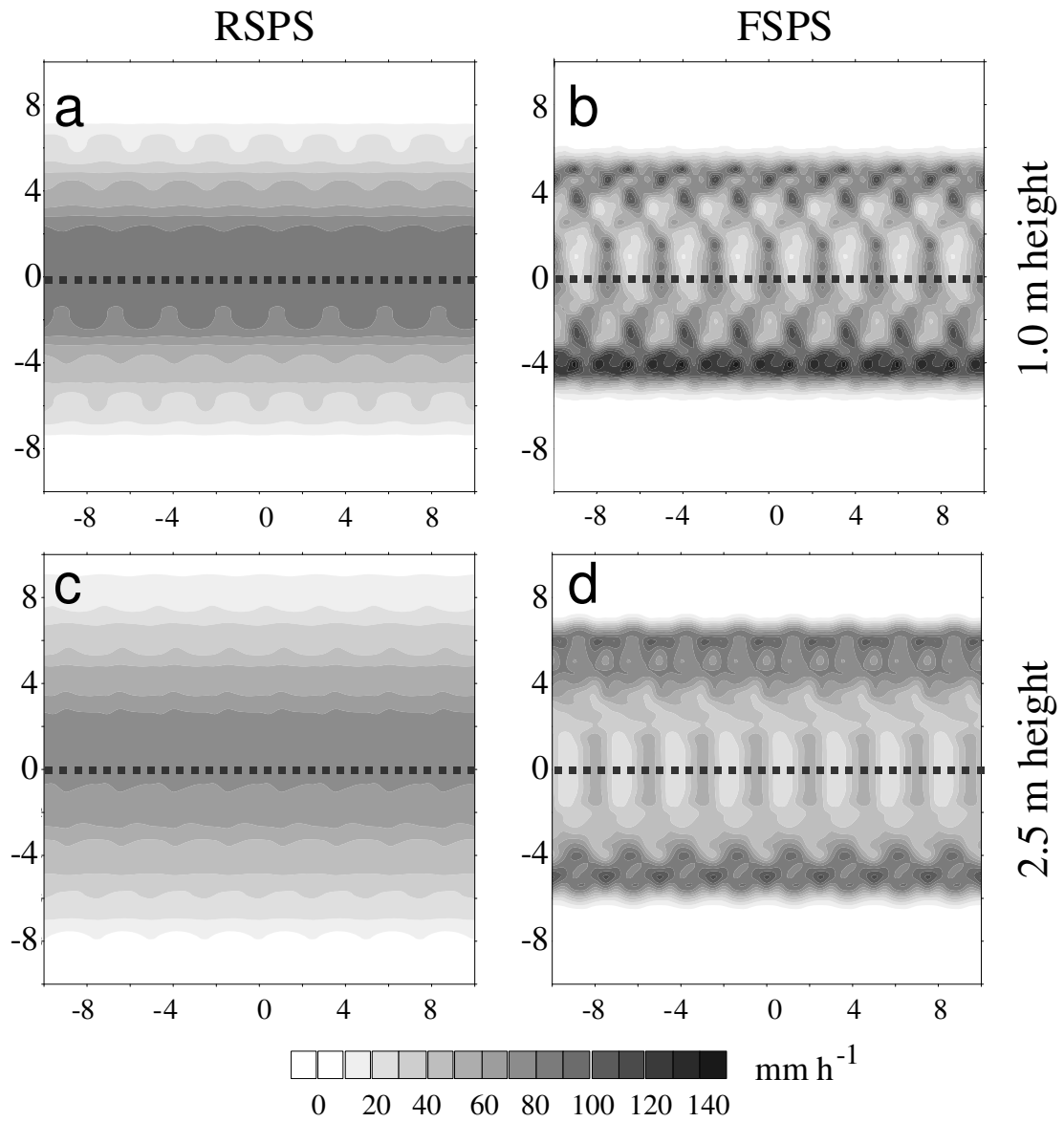


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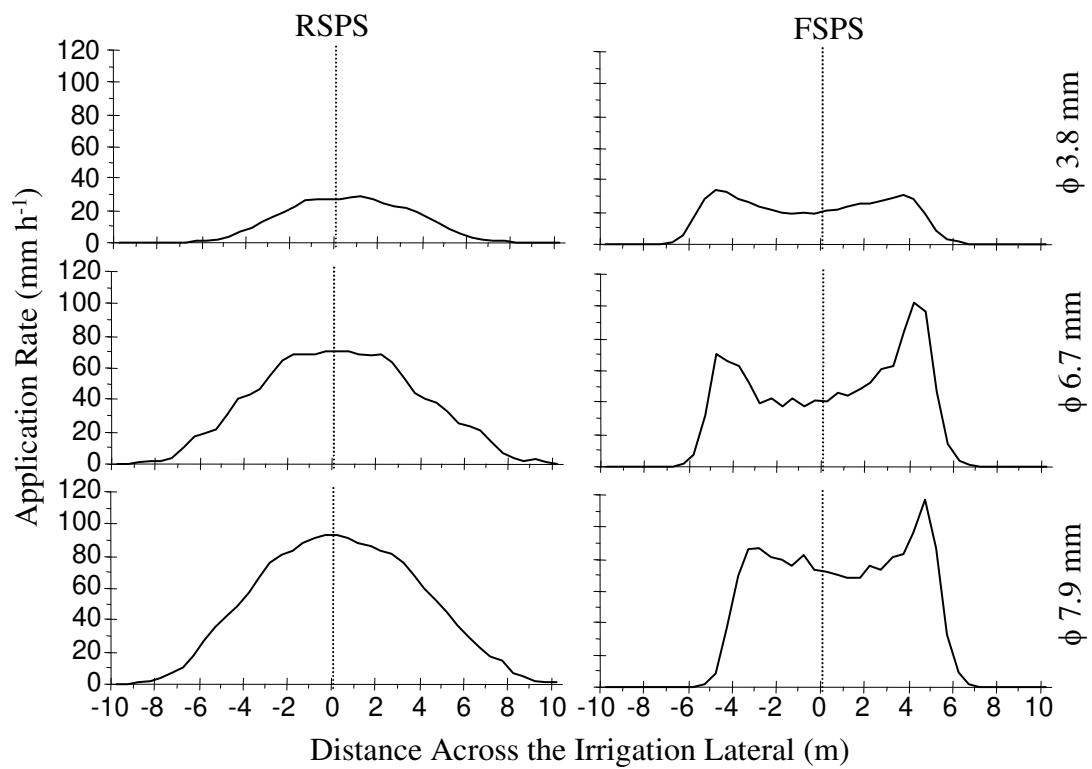


Figure 9. *Simulated cross-sectional water distribution (mm h^{-1}) of an irrigation lateral with 2.5 m spacing, a nozzle diameter of 3.8 mm and a spray sprinkler height of 2.5 m, for RSPS and FSPS, under low, medium and high wind speeds.*

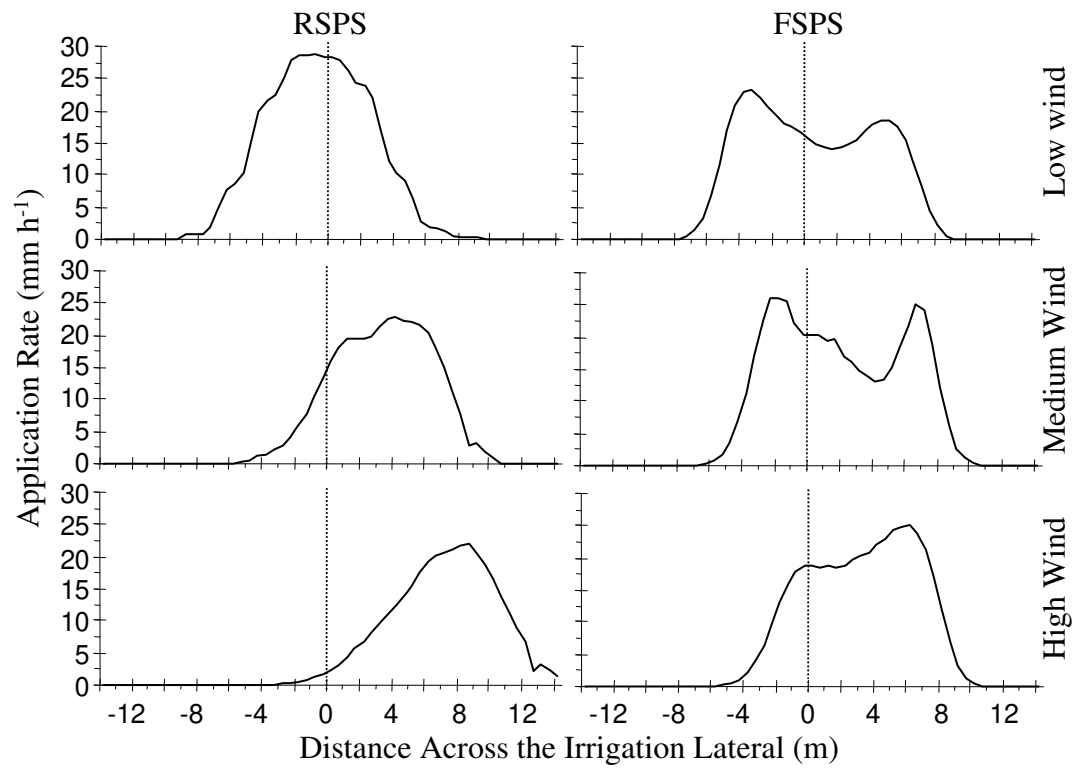


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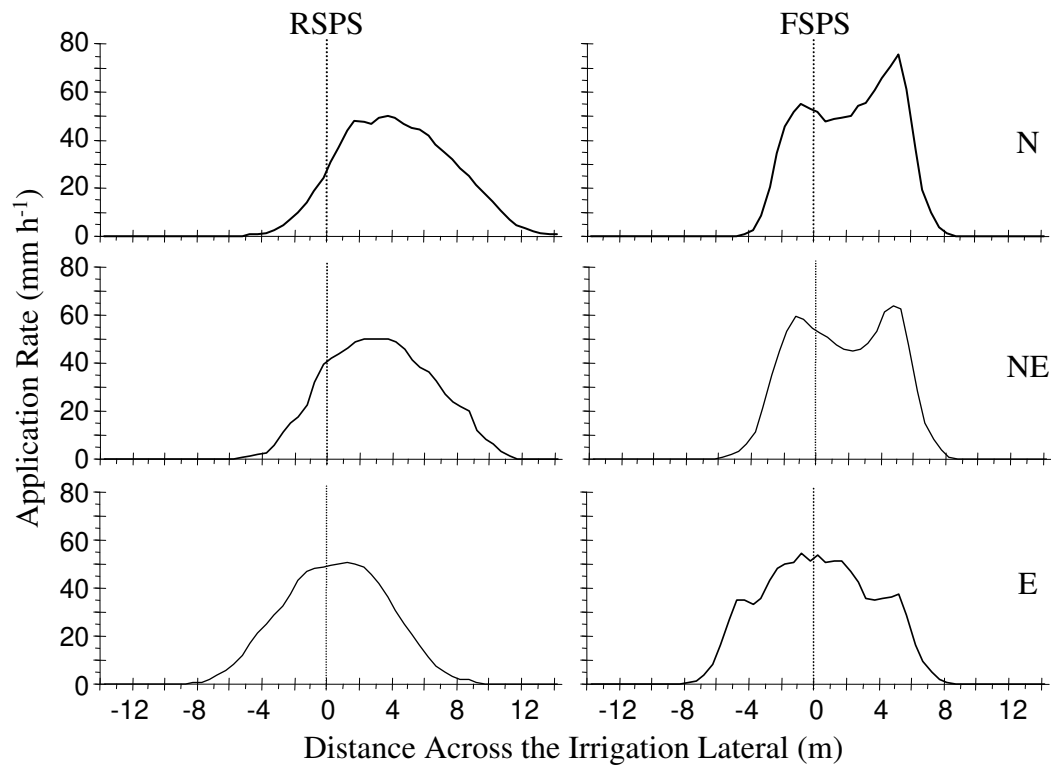


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