The effects of pressure, nozzle diameter and meteorological conditions on the performance of agricultural impact sprinklers

by

Sanchez I.^a, Faci J.M.^a and Zapata N.^b

^a Unidad de Suelos y Riegos (asociada al CSIC), Centro de Investigación y Tecnología Agroalimentaria (CITA), Gobierno de Aragón. Avenida Montañana 930, 50059, Zaragoza, España.

^b Dept. Soil and Water, Estación Experimental de Aula Dei (EEAD), CSIC, Apdo. 202, 50080 Zaragoza (Spain).

Corresponding Author:

Sanchez Marcos I.

Unidad de Suelos y Riegos (asociada al CSIC), Centro de Investigación y Tecnología Agroalimentaria (CITA), Gobierno de Aragón. Avenida Montañana 930, 50059, Zaragoza, España.

Phone: +34 976 71 6324.

Fax: + 34 976 71 6335.

Email: ingancio@gmail.com

Abstract

This study is about the evaluation of agricultural impact sprinklers. The radial curve (Rad), i.e., the water distribution along the wetted radius, was evaluated for an isolated sprinkler using 25 tests corresponding to several combinations of pressures (p) and nozzle diameters (D). The Christiansen's uniformity coefficient (CUC) and the wind drift and evaporation losses (WDEL) were evaluated for a rectangular solid-set system using 52 tests corresponding to several combinations of D and p under an ample range of meteorological conditions.

The Rad constitutes the footprint of a sprinkler and it is the core information to simulate sprinkler irrigation. The CUC is intimately connected with the Rad. The characterization of the Rad must be conducted under calm conditions. This is rather difficult for open-air evaluations. The results illustrate that very low winds, especially those showing a prevailing wind direction, significantly distort the Rad. In this sense, the vectorial average of the wind velocity (V') is recommended as the explanatory variable in the detriment of the widespread arithmetic average (V). We recommend that the characterization of the Rad will be conducted in indoor conditions. In open-air conditions, the characterization must be restricted to conditions that meet $V' < 0.6 \text{ m s}^{-1}$.

The results show that the Rad was mostly affected by the sprinkler model. Consequently, the CUC of the solid-set depended on the sprinkler model. The differences in the CUC between sprinkler models varied with the spacing between sprinklers, the wind and the p . For a sprinkler model, the V' was the main explanatory variable of the CUC, but the p was found significant as well. The V was the main variable explaining WDEL; the T was found significant too.

Sprinkler irrigation simulators make the selection of the solid-set system much easier for farmers, designers and advisors. However, the quality of the simulations greatly depends on the characterization of the Rad. This work provides useful recommendations in this sense.

Keywords

Sprinkler irrigation; evaluation; wind; uniformity; water-losses.

53 **1 Introduction**

54 Sprinkler irrigation depends on many operating, environmental and
55 agronomic factors. The uniformity of the water distribution mainly depends on
56 the sprinkler model, the number and diameter of the nozzles, the sprinklers
57 spacing and arrangement, the operating pressure, the environmental conditions
58 (Carrión et al., 2001; Keller and Bliesner, 1990; Playán et al., 2006) and on the
59 crop irrigated (Sanchez et al., 2010a, 2010b). Among them, those controlled by
60 design are particularly interesting for the irrigation technology. Playán et al.
61 (2005) reported that the wind velocity is the meteorological variable more
62 directly related to the irrigation performance through its effects on the
63 Christiansen's uniformity coefficient (CUC, Christiansen, 1942) and the wind
64 drift and evaporation losses (WDEL).

65 The evaluation of a solid set system ranges from the assessment of the
66 distribution pattern of an isolated sprinkler in no wind conditions (Tarjuelo et al.
67 1999a) to the study of the whole field irrigation in real conditions (Mateos 1998).
68 The operational, atmospheric and agronomical conditions in which sprinkler
69 irrigation can be performed are vast. To study all the cases by field experiments
70 is unaffordable. As a consequence, sprinkler simulators have been developed
71 and used in order to analyze an ample range of conditions with the minimum
72 experimental effort. Most of these models have been developed under the
73 ballistic approach which was mainly developed during the eighties (Fukui et al.,
74 1980; von Bernuth and Gilley, 1984; Vories and von Bernuth, 1987). These
75 models are based on the idea that the superposition of the water distribution by
76 an isolated sprinkler can be an acceptable approximation for simulating the
77 distribution of a group of sprinklers at a field scale when adjustments for wind
78 drift and evaporation losses are correctly made (Carrión et al., 2001).

79 The procedure for the evaluation of an agricultural impact sprinkler
80 conducted to the calibration and validation of an irrigation simulator has been
81 described and followed in numerous studies (Carrión et al., 2001; Dechmi et al.,
82 2004a, 2004b; Playán et al., 2006; Seginer et al., 1991a, 1991b). The radial
83 curve (Rad) for an isolated sprinkler, i.e., the irrigation depth (ID) as a function
84 of the distance from the sprinkler, is the basis for the characterization of the

drop size population from which the irrigation performance of a solid-set can be simulated under different conditions.

This study analyzes the effects of several technical, operational and meteorological factors on sprinkler irrigation. The paper discusses several topics related with common procedures followed to evaluate sprinklers and to calibrate and validate empirical models for the simulation of the irrigation performance.

2 Material and methods

Two experiments oriented to evaluate the irrigation performance with agricultural impact sprinklers were conducted at the experimental farm of the Agricultural and Food Research and Technology Centre in Zaragoza, Spain (41°43' N, 0°48' W, 225 m altitude) during the years 2003 and 2004. One experiment was performed with an isolated sprinkler. The other was performed with a rectangular 15 m x 15 m (R15 x 15) solid-set arrangement.

The isolated sprinkler experiment was oriented to the evaluation of the radial curve (Rad). It was performed under bare soil and seeking calm conditions as specified by the most relevant international standards. The solid-set experiment was oriented to evaluate the irrigation performance through the CUC and the WDEL parameters under different wind conditions. This was conducted above bare soil too in correspondence with the isolated sprinkler experiment. The experiments were designed taking into consideration the recommendations of Merriam and Keller (1978) and the relevant International Standards (Anonymous, 1990, 1995, 2003).

In the isolated sprinkler experiment, the irrigation depth (ID) emitted by a sprinkler model Somlo 30C (Zaragoza, Spain), assembled in a riser tube at 2 m above the ground level (a.g.l), was collected into pluviometers located at 0.25 m a.g.l. along four radii at distances from the sprinkler ranging from 0.75 to 16.75 m, with an increment of 0.5 m (Figure 1). The radii faced north (N), west (W), south (S) and east (E), respectively. The evaluated sprinkler was an agricultural impact sprinkler made of brass and equipped with a drive nozzle including straightening vane (SV). Three diameters of the main nozzle (D) were tested: 4, 4.4 and 4.8 mm. The sprinkler also included a spreader nozzle, 2.4 mm in

diameter (d). An ample range of operating pressures (p) was tested: from 180 to 420 kPa. The combination of D and p resulted in twenty five tests (Table 1), all they performed for 2 hours under low wind conditions. The wind velocity (V) and direction (WD) and the temperature (T) and relative humidity (RH) of the air were monitored by an automatic weather station located in the same plot. The average records every five minutes were collected with a data-logger model CR10X (Campbell Scientific Ltd, UK).

A set-up with 24 sprinklers was used in the solid-set experiment (Figure 1). The distance between laterals was 15 m and the distance between sprinklers along the lateral was 15 m. The sprinklers were arranged according to a rectangular layout (R15x15). The sprinkler model and the combination of nozzles were the same as for the isolated sprinkler test. The experimental area was located between the four central sprinklers. A matrix of 25 pluviometers was installed at 0.25 m a.g.l. according to a 3x3 m grid that covered the experimental area among the four central sprinklers. One manometer was installed at each of the four sprinklers. Three p were evaluated: 240, 320 and 420 kPa. The meteorological factors cannot be controlled but we sought low, medium and strong winds. Fifty two tests were performed accordingly (Table 2). All they lasted 3 hours.

For each test of the solid-set experiment, the Christiansen's uniformity coefficient (Christiansen, 1942) and the wind drift and evaporation losses (WDEL) were assessed from the ID collected in the pluviometers. The WDEL was estimated as the percentage of the water emitted by the sprinklers (ID_e) but not collected inside the pluviometers (Dechmi et al., 2003; Playán et al., 2005; Sanchez et al., 2010a):

$$WDEL = \frac{ID_e - ID}{ID_e} \times 100 \quad (1)$$

$$ID_e = \frac{Q \times t}{15 \times 15} \quad (2)$$

where Q was the water discharge ($l s^{-1}$), t (s) the operating time and 15x15 the area (m^2) assigned to each sprinkler.

Q was assessed by collecting the water emitted by the sprinkler into a tared container. The discharge was calculated dividing the weight of the collected volume by the time of filling. This operation was repeated twice for

each combination of D and p (nine combinations in total). The discharge was estimated using the equation:

$$Q = C_D \times A \times (2gp)^n \quad (3)$$

where C_D is the discharge coefficient, A is the area of the nozzles orifices, g is the gravity acceleration and n is the discharge exponent.

A meteorological station like that used during the isolated-sprinkler test was located at an adjoining plot during the solid-set experiment (Figure 1). The experiment was performed under an ample range of meteorological conditions in an attempt to characterize the CUC and the WDEL resulting from different combinations of D, p and V. The V ranged from 0.4 to 8 m s⁻¹ (Table 2). The variation of the CUC and of the WDEL with several meteorological and technical variables was analyzed using multiple regression analysis.

Traditionally, the average wind velocity during an irrigation event is calculated as the arithmetic mean considering the records as positive rational numbers. This will be called the *arithmetic average* (V). In addition, we assessed the *vectorial average* (V') considering each 5 min record a Euclidean vector endowed with magnitude and direction. Figure 1 shows the Cartesian coordinate systems used for each experiment. The projections of each 5-min vector on the X and Y axes (V_x and V_y , respectively) were calculated and averaged separately. The resultant of the axial components was calculated. Its magnitude was the *vectorial average* (V') and the direction of the resultant was the WD during the irrigation event.

For each isolated sprinkler test, the Rad resulting from each radius were compared. The tests for which the differences between radii were smallest were used to characterize the Rad. For each test, we calculated: the average deviation of the volume collected along the four radii (AD, %); the ratio of the volume of water collected along the leeward radius to the volume collected along the windward radius; the fraction of the water drifted from the leeward radius to the windward radius.

The average Rad was calculated for each test from the four Rad corresponding to each radius. Then, the CUC of the ID was calculated from the average Rad as follows: the ID into each position of the grid of pluviometers was assessed by interpolation through the average Rad as a function of the

distance from each position to each sprinkler. This reckoning was made for a R15x15 solid-set. The values of the CUC evaluated under low winds during the solid-set experiment and the CUC calculated from the Rad were compared.

Four sprinkler models were compared: the Somlo 30C in question, the VYR 70 (VYRSA, Burgos, Spain) and the RC 130 (Riegos Costa, Lleida, Spain) evaluated by Playán et al. (2006), and the VYR 35 evaluated by Zapata et al. (2009). All they are widely used in the Ebro Valley (Spain). The comparison was made both for calm and windy conditions. With respect to calm conditions, we compared the average Rad and the CUC calculated from the average Rad for two solid-sets (R15x15 and R18x15). With respect to windy conditions, we compared the CUC for the same combination of D, p and V evaluated during the solid-set experiment. The latter was assessed with the Ador-sprinkler simulator for the VYR 70, the RC 130 and the VYR 35.

The results from the isolated and solid-set experiments will be used to calibrate and validate Ador-sprinkler with regard to the sprinkler Somlo 30C.

3 Results and discussion

3.1 Isolated sprinkler experiment

The discharge of the evaluated sprinkler increased with the D and the p. With regard to the discharge equation (Eq. 3), several studies applied to agricultural sprinklers interpreted that the C_D is essentially independent of the p for a given nozzle and that the n is constant and equal to 0.5 (Li, 1996; Li and Kawano, 1998; Tarjuelo et al., 1999a). We assumed n equal to 0.5 as well. The discharge coefficient C_D was assessed by nonlinear regression analysis of the evaluated values of Q fitted to a power curve. For D equal to 4, 4.4 and 4.8 mm, the C_D resulted, respectively, 0.952, 0.958 and 0.942. The Eq. 3 and the C_D values allowed calculating Q for every p.

Twenty five tests were performed during the isolated-sprinkler experiment to assess the Rad for different combinations of D and p (Table 1). The Rad must be evaluated under calm conditions. This becomes almost impossible in open-air given that the wind always blows, even imperceptibly. The Rad is calculated as the average between the four radii assuming that the curves must be alike under calm conditions. In contrast, the Rad noticeably

differed between radii for many tests, both in the shape and in the total volume of water collected. Special attention was paid to the differences at the longest distances from the sprinkler; they imply greater differences in the volume collected along each radius because the area watered by the sprinkler increases with the distance.

Figure 2 shows the results for several tests. For the tests I/4/230.a and I/4/230.b, the Rad resulting from each radius were acceptably alike and the tests resulted in similar average Rad; the average deviation of the volume collected at each radius (AD) was 8% for both tests. For the test I/4.4/400, each radius resulted in similar Rad as well (the AD was 8% too). However, for the test I/4.4/420, the Rad from each radius greatly differed and the AD increased to 31%. The former was accepted (suitable) and the latter was rejected.

The wind conditions during the tests explained the results. Prevailing winds, even very low in velocity, drifted an important volume of water. Figure 2 shows that the water collected along the leeward radius exceeded that collected along the other radii. The experiment was limited in this sense because we only used four radii and the wind blew from all the directions.

The distortion of the irrigation pattern by the wind is both connected with the magnitude and the prevalence of the wind (Figure 2). Both features are expressed together by the vectorial average (V'). In this sense, we recommend V' as the explanatory variable in detriment of the widespread use of the arithmetic average (V). The differences between V' and V are greater when the winds are changeable in direction. The reason is that the resultant decreases, thus V' , when the wind blows in opposite directions, while this has no influence in the reckoning of V . Changeable directions are more frequent for low winds because strong winds use to blow from a prevailing direction (Tables 1 and 2, Figure 3).

The water drift was linearly proportional to V' . Let us that we estimate the water drift as the ratio of the volume collected along the leeward radius to the water collected along the windward radius. Then, the drift increased 3.675% for every increase of 0.1 m s^{-1} in V' (Figure 4). This relationship was true for every D and p. This ratio may differ with the riser height of the sprinkler.

$$ratio = 0.3675V' + 1 \quad (4)$$

The water drift can be also estimated in terms of the fraction of the water drifted from the windward radius to the leeward radius (f , %):

$$ratio = \frac{100 + f}{100 - f}$$

and then, f results:

$$f = \frac{0.3675V'}{2 + 0.3675V'} 100 \quad (5)$$

The Table 3 shows the increasing of f with V' . These results can be used to provide recommendations for the evaluation of isolated sprinklers. The authors recommend that the value of f will not exceed 10%, consequently, that the values of V' will not exceed 0.6 m s^{-1} . For the tests I/4/230.a, I/4/230.b and I/4.4/400 (Figure 2), the f resulted 11.1, 11.9 and 10.7% respectively.

The Figure 5 shows the Rad resulting from the tests found suitable according to different combinations of D and p . For every distance from the sprinkler, increasing D and increasing p increased the ID along the curve. In addition, D and p affected the shape of the curve. For D equal to 4.8 mm, the Rad bulged along the final third. This might be related to the atomization process. For the largest diameter of the jet, the complete atomization delayed and the drops achieving the longest distances increased. The curve tended to triangular when the p increased (from the top to the bottom in the central column, Figure 5). According to the previous reasoning, when the p increased, the atomization enhanced and the distribution was more homogenous.

The average Rad resulting from the rejected tests departed in shape and magnitude from the average Rad resulting from the suitable tests (Figure 5). The deformation pattern was not clear. The results demonstrate that it is an error to assess the average Rad from tests performed under unfavorable wind conditions under the assumption that there is a compensatory effect between the windward and the leeward radii.

The suitability of the selected tests was illustrated by bringing together the values of the CUC calculated from the average Rad and the CUC evaluated under very low wind conditions during the solid-set experiment. Figure 6 shows that the selection of the suitable test was according to good sense. Proper Rad can be used to assess the CUC for different arrangements of the sprinklers. We advise evaluating the Rad in indoor conditions with still air. The evaluations

conducted in open-air conditions must pay special attention to the wind, even if the wind is very low. The recommendations in this paper will help to improve the results.

The Figure 7 shows the average Rad for different sprinkler models and combinations of D and p (notice some differences in the p between models). The angle of insertion of the drive nozzle was 26-27° for all the models. The angle of insertion of the spreader nozzle was 20-22° for all the models, excluding the VYR 35 for which it was 26°. All the models included SV.

The Rad noticeably differed between models (Figure 7). Since the sprinklers presented similar configuration of nozzles, we consider that the shape of the Rad was mainly due to the inner design of the sprinklers. Three typical shapes of Rad have been reported: triangular, rectangular and donut. Respectively, they correspond to: a combination of two nozzles, one nozzle without SV, the same with SV and lower pressure (Tarjuelo et al., 1999a). The Rad for the presented models did not match the three typical shapes; they were rather combinations of them.

The Figure 8 shows the CUC calculated from the average Rad (Figure 7) according to two sprinklers arrangements: R15x15 and R18x15. The calculations refer to calm conditions. The CUC ranged between 87% and 92%. The CUC depended on the shape of the Rad, therefore on the sprinkler model. The triangular Rad corresponding to the model VYR 35 yielded the greatest CUC for both arrangements. The VYR 70 and the RC 130 presented similar Rad: rectangular close to the sprinkler and triangular after. They yielded similar CUC. The Somlo 30C presented the most irregular Rad and the CUC was slightly smaller for this model. The arrangement influenced the CUC too. The CUC decreased with the spacing for the VYR 70 and the RC 130; the opposite was true for the Somlo 30C (the arrangement had no relevance for the VYR 35). Consequently, the differences in the CUC between sprinklers decreased for the R18x15 with respect to the R15x15.

Many manufacturers of agricultural sprinklers only provide information about the discharge and the range of their models. According to the results, this information is inadequate because the water distribution closely depends on the shape of the Rad.

So far the analysis has been conducted for calm conditions and very low winds. Next it is introduced the analysis performed under windy conditions.

3.2 Solid-set experiment

Fifty two tests corresponding to different combinations of D, p and wind conditions were performed for the solid-set experiment to analyze their effects on the CUC and on the WDEL (Table 2).

Many studies have shown that the wind is the main environmental factor affecting sprinkler irrigation (Beskow et al., 2008; Dechmi et al., 2003, 2004b; Kincaid et al., 1996; Playán et al., 2005; Sanchez et al., 2010a, 2010b; Seginer et al., 1991a y 1991b; Tarjuelo et al., 1999c; Yu et al., 2009). In accordance with these studies, the wind velocity decreased the CUC (Figure 9) and increased the WDEL (Figure 10).

Sprinkler irrigation has been evaluated using combinations of D and p (Playán et al., 2006; Tarjuelo et al. 1999b, 1999c). Some studies like that by Kincaid (1982) analyzed the combined effect of p and D on the discharge of the sprinklers. However, others analyzed the effects of D and p separately rather than together, as that by Kohl (1974) reporting that the effect of D on the drop size distribution is smaller than the effect of p. At first sight, the relationship between CUC and WDEL with the wind velocity was affected by D and p (Figures 9 and 10). Apparently, these relationships differed depending on p, and the differences owing to p decreased with the D increasing. The effects of the variables on CUC and on WDEL were assessed using multiple regression analysis. The Table 4 shows the steps taken forward towards a satisfactory explanatory function (from the top to the bottom obviating the intermediate steps).

In multiple linear regression it is fundamental to detect the existence of correlation among the prediction variables. The variance inflation factor (vif) was used to detect the multi-collinearity among variables. If the variables are orthogonal to each other, vif equals 1. In contrast, vif greatly increases with the relationship between variables (Bowley, 2004). There are not formal criteria for deciding the cut-off for the vif, but vif resulted sufficiently similar to 1 for the resulting explanatory functions to consider that the independent variables were not correlated (Table 4).

V' was better than V in predicting CUC. V was better than V' in predicting WDEL. This was assessed for each dependent variable by comparing the values of $R^2_{adj.}$ and RMSE corresponding to V' and to V (values not shown). The result makes sense. The CUC is connected with the wind direction as it is proved in the first section. In contrast, the wind increases the evaporation (therefore the WDEL) through the wind intensity and the time of exposure, thus independently of the wind direction.

The variation of CUC was mainly explained by V', and by p to a lesser extent (Table 4, Figure 11). From the multiple regression analysis, the explanatory model for CUC was:

$$CUC = 83.4 - 1.274 V' + 0.019 p \quad (RMSE = 1.98; R^2_{adj.} = 0.75) \quad (6)$$

According to the model, CUC decreased with V' and increased with p. According to our knowledge, this is the first time that experimental results improve the explanation of the CUC considering the prevalence of the wind direction and the operating pressure.

The selection of the predictor variables was more complicated in the case of the WDEL. When all the variables were included, only V and T were found significant (Table 4). Both variables have been previously selected among the predictor variables of the WDEL (Faci et al., 2001; Frost and Schwalen, 1955; Hermsmeier, 1973; Seginer, 1971; Silva and James, 1988; Tarjuelo, 1995; Yazar, 1984;). The D has been included as a predictor variable in former studies (Faci et al., 2001; Frost and Schwalen, 1955; Keller and Bliesner, 1990; Tarjuelo et al., 2000; Trimmer, 1987). An explanatory function considering V and D as the predictor variables, both significant, yielded acceptable results: $RMSE = 5.41$ and $R^2_{adj.} = 0.91$ (not included in the Table 4). However, considering V, D and T, D was not significant and the model improved by considering V and T instead of V and D. The p was not significant although it has been included in many previous studies (Frost and Schwalen, 1955; Keller and Bliesner, 1990; Montero, 1999; Tarjuelo et al., 2000; Trimmer, 1987; Yazar, 1984).

The most suitable model was that comprising V and T as the predictor variables (Table 4). The intercept was not significant and it was deleted from the model (*noint* statement in SAS):

$$WDEL = 2.835 V + 0.433 T \quad (RMSE = 4.75; R^2_{adj.} = 0.93) \quad (7)$$

In addition, the influence of the D on the WDEL was considered by assessing explanatory functions based on V and T for each D. The results show that R^2 adj. increased and RMSE decreased with the D increasing. However, the rates of change assigned to V and T through the partial regression coefficients were not in proportion with the variation of D (Table 4). The empirical model proposed to explain the variation of the WDEL (one function for each D) was statistically satisfactory (Figure 11).

The accuracy in the prediction was greater for the CUC than for the WDEL. For the CUC, the values ranged between 75 and 93% and the RMSE was 1.98% while, for the WDEL the values ranged between 2 and 36% and the RMSE was 4.75%. This trend is recurrent in the bibliography.

The importance of D and p in the performance of the sprinkler irrigation (Eqs. 6 and 7) is explained through their effects on the atomization process. Recent and current investigations are focussed on the atomization of the water jet released by the agricultural sprinklers (Bautista-Capetillo et al., 2009; King et al., 2010; Playán et al., 2010). The presented results prove the suitability of this line of research and point out that, in connection with this matter, D and p must be analyzed together.

Beskow et al. (2008) concluded that the application of empirical models must be limited to working conditions (nozzle size, operational pressure, etc.) similar to the ones in which they were developed. The empirical models proposed in this study are most likely limited to the conditions of the experiment. Discrepancies are expected mostly depending on the solid-set arrangement and spacing and on the surface conditions, especially when tall crops are irrigated (Sánchez et al., 2010b).

The Figure 12 shows the variation of the CUC with the wind velocity for three sprinkler models. The CUC for the Somlo 30C correspond to the tests during the solid-set experiment. The CUC for the VYR 70 and for the RC 130 was simulated with the Ador-sprinkler model (Dechmi et al. 2004a and 2004b, Playán et al., 2006). V was used in this comparison because the Ador-sprinkler simulator has been calibrated and validated according to this variable.

The shape of the curves in the Figure 12 depended on the sprinkler model (as it has been proved in the previous section) and on the p (in accordance with the Eq. 6). According to the results, the choice of the most

suitable sprinkler with regard to the CUC is connected with p , with the solid-set arrangement and with the wind conditions under which irrigation will be conducted.

The presented results prove that the choice of the sprinkler model is very complicated since it depends on many factors of different nature, many of them out of the control of the farmer. Empirical models as Ador-sprinkler are extremely useful tools for decision making as they allow the simulation of the sprinkler irrigation performance under very different conditions. However, thorough investigations are needed to acquire the understanding about the processes involved in the formation and the atomization of the jet and the evaporation and the drift of the resulting water drops. This is the path towards physical models valuable for the manufacturers of agricultural sprinklers, for the farmers and for the whole society that needs and demands an efficient use of the water.

428 **4 Conclusions**

429 The curve of the distribution of the irrigation depth along the wetted
430 radius (Rad) is crucial to characterize the water distribution of a sprinkler. The
431 water distribution closely depends on the shape of the Rad. The discharge and
432 the range of a sprinkler are insufficient by themselves to select a sprinkler
433 adequately. However, this is the only information provided by the manufacturers
434 in most cases. The shape of the Rad is mainly affected by the sprinkler design.
435 The nozzle diameter (D) and the pressure (p) modify the shape too, but to a
436 lesser extent.

437 The characterization of the Rad with isolated-sprinkler tests implies
438 several precautions because the wind, however low it is, significantly distort the
439 Rad. When the tests can not be performed in indoor conditions, the wind must
440 be observed meticulously. The authors recommend to make quite sure that the
441 vectorial average of the wind velocity (V') during the tests does not exceed 0.6
442 m s^{-1} . Otherwise, the resulting Rad will not be suitable and it will conduct to
443 erroneous results. The authors firmly proposed the V' in the detriment of the
444 widespread arithmetic average (V). The V' considers together the wind speed
445 and the prevalence of the wind direction, being both crucial in sprinkler
446 irrigation. Only with regard to the wind drift and evaporation losses (WDEL), the
447 V is preferred to the V' because the wind increases the WDEL irrespective of its
448 direction.

449 For every solid-set system, the Christiansen's Uniformity Coefficient
450 (CUC) can be calculated in calm conditions directly from the Rad. For every
451 wind condition, the CUC can be calculated using sprinkler simulators, but a
452 suitable characterization of the Rad is necessary anyhow. The CUC depends
453 on the Rad, consequently it varies depending on the sprinkler design. The
454 differences in the CUC between sprinkler designs vary with the wind conditions,
455 the solid-set arrangement and the p.

456 As previously reported in many studies, the wind velocity had the
457 greatest relative contribution both to explain the CUC and the WDEL. Moreover,
458 this paper presents new contributions. With regard to a model based on the V ,
459 the assessment of the CUC was noticeably improved including the V' (instead of

the V) and the p as the explanatory variables. With regard to the WDEL, the explanatory variables were the V and the temperature (T). The assessment of the WDEL was improved by assessing a function for each D, but the effect of the D was not found sound. It must be noticed that these functions are restricted to a specific sprinkler design and to a solid-set arrangement.

The presented results prove that the choice of the sprinkler model is very complicated since it depends on many factors of different nature, many of them out of the control of the farmer. Simulators as Ador-sprinkler are extremely useful tools for decision making as they allow the simulation of the sprinkler irrigation performance under very different operational and meteorological conditions. However, thorough investigations are needed to acquire the understanding about the processes involved in the formation and the atomization of the jet and the evaporation and the drift of the resulting water drops. This is the path towards physical models valuable for the manufacturers, advisors, farmers, and for the whole society that needs and demands an efficient use of the water.

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