Assessing sprinkler irrigation uniformity using a ballistic simulation model

by

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Abstract

Experiments were performed in the Ebro Valley of Spain to provide the basis for the calibration and validation of a ballistic simulation model of sprinkler irrigation. The experiments included evaluations of isolated sprinklers and solid-sets. Two different sprinklers, two principal nozzle diameters and three operating pressures were

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considered in the experiments, which also covered the usual range of wind speeds in the study area. Model calibration served the objectives of predicting the Christiansen Coefficient of Uniformity (*CU*) and the water application pattern. The resulting standard error of *CU* estimation was 3.09 %. Tables of simulated uniformity were produced for the two sprinklers using different nozzle diameters, sprinkler spacings, operating pressures and wind speeds. These tables can be used for design and management purposes, identifying options leading to adequate irrigation uniformity. A simple simulation software has been produced and disseminated to assist irrigation professionals and farmers in decision making.

Introduction

The uniformity of sprinkler irrigation depends on a number of factors, including the sprinkler and nozzle type, the irrigation layout and the environment (Keller and Bliesner, 1990). The combination of these factors greatly complicates the assessment of irrigation uniformity for a given on-farm irrigation system and a set of environmental conditions. As a consequence, sprinkler irrigation design and management rules are very site specific, change with the irrigation materials, and often rely on unstructured experiments and life-long professional experience.

Sprinkler irrigation has only limitedly benefited from modelling approaches. Ballistics constitute the most common modelling approach to sprinkler irrigation. While the theory behind this approach has been available for decades (Fukui et al., 1980), its application is progressing quite slowly. The main problem for the generalization of ballistic models is that model calibration is currently required for every combination of sprinkler type, nozzle type and diameter, operating pressure, nozzle elevation and wind speed (Montero et al., 2001). As a consequence, an intense experimental work is required for the applicability of ballistic models for a particular situation. Once the model is calibrated and validated, it can yield information leading to improved irrigation design and management. Dechmi et al. (2004b) calibrated a ballistic model for a particular irrigation layout under variable wind conditions. These authors reported on a number of model applications for successful sprinkler irrigation in the central Ebro Valley of Spain, a region where the yearly average of wind speed can exceed 2.4 m s^{-1}.

In this paper we present the experimental and computational process required to calibrate and validate a ballistic simulation model for two sprinklers, each with two nozzle diameters, operating under a wide range of pressures and wind speeds, and covering a large set of sprinkler spacings. The results permit to establish a comparison between the two sprinklers, and to highlight their respective strengths and weaknesses. Beyond the regional relevance of this comparison, the presented methodology represents a contribution to the applicability of ballistic models to sprinkler irrigation practice.

Materials and Methods

Model description

Fukui et al. (1980) presented the basic equations and procedures for ballistic simulation of sprinkler irrigation. Their work was followed by a number of contributions which improved the original approach in different aspects (Vories et al., 1987; Seginer et al., 1991). Recently, Carrión et al. (2001) and Montero et al. (2001) presented the SIRIAS software, which further developed ballistic theory and presented it in a user-friendly environment. The SIRIAS model was calibrated and validated for a number of cases involving different sprinklers and nozzle configurations, layouts and operating conditions. The mean absolute error in the estimation of the Christiansen Coefficient of Uniformity (*CU*) (Burt et al., 1997) was 2.7 %. Dechmi et al. (2004a; 2004b) presented a ballistic sprinkler irrigation model which was used in combination with a crop model. They showed that the sprinkler irrigation model could successfully reproduce the water distribution pattern observed in the field ($R^2 = 0.871^{***}$). Moreover, a crop simulation model using the simulated water distribution pattern as input resulted in simulated values of yield reduction which could explain the field observed values ($R^2 = 0.378^{***}$).

The main characteristics of the ballistic model used in this work are presented in the following paragraphs. Additional specifications can be found in Dechmi et al. (2004a), who presented an early version of this model. General details the construction and testing of ballistic models can be found in Carrión et al. (2001) and Fukui et al. (1980).

A sprinkler is simulated as a device emitting drops of different diameters. It is assumed that drops are formed at the sprinkler nozzle, and travel independently until reaching the soil surface (or the crop canopy, or the experimental catch can). In the absence of wind, and for a given sprinkler configuration, the horizontal distance between the drop landing point and the sprinkler nozzle is a function of the drop diameter. Ballistic theory is used to determine the trajectory of each drop diameter subjected to an initial velocity vector and a wind vector ($\boldsymbol{U}$, parallel to the ground surface). The action of gravity (acting in the vertical direction) and the resistance force (opposite to the drop trajectory) complete the analysis of forces acting on the water drop. The drop velocity with respect to the ground ($\boldsymbol{W}$) is equal to the velocity of the drop in the air ($\boldsymbol{V}$) plus the wind vector ($\boldsymbol{U}$).

According to Fukui et al. (1980) the three directional components of the movement of each drop can be expressed as:

$$A_x = \frac{d^2x}{dt^2} = -\frac{3}{4}\frac{\rho_a}{\rho_x}\frac{C}{D}V(W_x - U_x) \qquad [1]$$

$$A_y = \frac{d^2y}{dt^2} = -\frac{3}{4}\frac{\rho_a}{\rho_W}\frac{C}{D}V(W_y - U_Y) \qquad [2]$$

$$A_z = \frac{d^2z}{dt^2} = -\frac{3}{4}\frac{\rho_a}{\rho_W}\frac{C}{D}VW_z - g \qquad [3]$$

Where x, y, z are coordinates referring to the ground (with origin at the sprinkler nozzle), t is the time, ρ_a is the air density, ρ_W is the water density, A is the acceleration of the drop in the air, D is the drop diameter, and C is a drag coefficient, which can be expressed as a function of the Reynolds number of a spherical drop and the kinematic viscosity of the air (Fukui et al., 1980; Seginer et al., 1991):

Equations [1] to [3] are solved in the model using a fourth order Runge-Kutta numerical integration technique (Press et al., 1988). The main result of each drop trajectory solution is constituted by the x and y coordinates of the drop when the z coordinate equals 0 (the soil surface), or the crop canopy elevation, or the catch can elevation. In order to reproduce the water application pattern resulting from an isolated sprinkler, these equations must be solved for a number of horizontal sprinkler angles (due to the sprinkler rotation) and for a number of drop diameters. The model typically uses 180 horizontal sprinkler angles and 180 drop diameters, evenly distributed between 0.0002 and 0.007 m. When the landing coordinates of each drop diameter are combined with the fraction of the sprinkler discharge which is emitted in this drop diameter, the water application pattern can be simulated.

The measurement of sprinkler drop size has been performed using a variety of indirect methods. It is only recently that optical spectropluviometers have been used for sprinkler drop size characterization (Montero et al., 2003). These devices result in accurate and automated measurements. An alternative procedure consists on using the ballistic model to simulate the landing distance of different drop diameters resulting from a given sprinkler model, nozzle elevation and operating pressure in the absence of wind. The percentage of the irrigation water collected at each landing distance can be used to estimate the percentage of the irrigation water emitted in drops of a given diameter.

Li et al. (1994) proposed the following empirical model to fit the drop diameter distribution curve:

$$P_V = \left(1 - e^{-0.693 \left(\frac{D}{D_{50}} \right)^{n}} \right) 100 \qquad [4]$$

Where: Pv is the percent of total sprinkler discharge in drops smaller than D; D_{50} is the mean drop diameter, and n is a dimensionless exponent. Equation [4] permits to establish a functional relationship between the drop diameter and the sprinkler discharge. The estimation of the parameters of this equation permits to characterize the drop diameter distribution resulting from a given sprinkler, nozzle diameter and operating pressure.

A significant part of the water emitted by a sprinkler does not reach the soil surface, because it either evaporates of drifts away. This water constitutes the Wind Drift and Evaporation Losses (*WDEL*), which are expressed as a percentage of the emitted discharge. Salvador (2003) and Playán et al. (2005) presented a number of empirical equations aiming at the prediction of *WDEL* using meteorological variables. These authors used 37 solid-set experiments to formulate predictive equations. The following equation, obtained for daytime operation, was introduced in the model:

$$WDEL = 24.1 + 1.41\,U - 0.216\,RH \qquad [5]$$

where U is the wind speed (m s^{-1}) and RH is the relative humidity of the air (%). According to Montero et al. (2001) the magnitude of *WDEL* was used to adjust the drop size distribution curve. Option B, as presented by these authors, was used for this purpose.

Seginer et al. (1991) reported on the need to correct the drag coefficient in order to reproduce the deformation of the circular water application area produced by the wind. Tarjuelo et al. (1994) further refined these corrections, arriving to the following expression:

$$C' = C\left(1 + K_1 sin\beta - K_2 cosa\right) \qquad [5]$$

Where: α is the angle formed by vectors $\boldsymbol{V}$ and $\boldsymbol{U}$, β is the angle formed by the vectors $\boldsymbol{V}$ and $\boldsymbol{W}$, and K_1 and K_2 are empirical parameters. According to Montero et al. (2001) K_2 is much less relevant than K_1. This extreme was confirmed by the findings of Dechmi et al. (2004a). In order to maintain the generality of their model, Montero et al. (2001) recommended fixed values for K_1 and K_2 for different sprinkler materials and environmental conditions. To maximize the model predictive capability, Dechmi et al. (2004a) used wind-dependent values of both parameters for their particular experimental sprinkler set-up.

In order to simulate solid-set irrigation, the model overlaps a number of sprinklers located at coordinates reproducing a given sprinkler spacing. For this purpose, 16 sprinklers are used in rectangular layouts and 18 in triangular layouts. The central sprinkler spacing is divided into a number of rectangular cells, with a default 5 x 5 arrangement. The resulting number of cells (25 in this case) must be equal to the number of catch cans used in the field experiments.

Each drop landing in this central sprinkler spacing is assigned to one of the cells, according to the landing co-ordinates. The simulated water application in each cell is computed from the number of drops of each diameter and the percent of the sprinkler discharge corresponding to that particular drop diameter. Water application in the cells is further used to determine the simulated coefficient of uniformity. The process of sprinkler overlapping is therefore performed following a mathematical rationale, and is not subjected to any additional model parameter. This is why, once the model is calibrated and validated, it can be used in sprinkler spacings different from the experimental ones.

Catch can size experiments

A plastic commercial catch can (a rain gauge) with a diameter of 79 mm was found to be well suited for the experiments, since it was marked in mm for direct readout (up to 40 mm), and it was mounted on a plastic stick for quick installation at 0.35 m over the soil surface. The catch can was conical in its lower part (145 mm), and cylindrical in its upper part (30 mm).

According to the relevant International Standards (Anonymous, 1987; Anonymous, 1990; Anonymous, 1995), the catch can diameter should exceed 85 mm. This criterion was not met by the abovementioned catch can. The principle behind this diameter requirement is that small catch cans can result in an underestimation of CU: the larger the catch can, the higher the uniformity estimate. Taking the issue to a limit, if the catch can size was equal to the sprinkler spacing, the *CU* estimate would always be 100%. When uniformity is low (for instance, due to a high wind) this issue becomes particularly important: small catch cans may artificially increase the existing variability. While for practical purposes it is convenient to use small catch cans, this choice should not compromise the quality of the uniformity estimations.

An experiment was devised to: 1) establish the effect of catch can size on *CU* and *WDEL* under the windy, dry conditions of the Ebro valley of Spain; and 2) assess the validity of the small catch can (79 mm in diameter). The experimental set-up and the effect of catch can size on *WDEL* were reported by Playán et al. (2005). In this work, the experimental set-up is summarily described, and the results for *CU* are presented and discussed. The experiment involved the comparison of the small catch can (S) with two larger, cylindrical catch cans with diameters of 130 and 210 mm (medium and large, M and L, respectively).

The experiment was performed on a solid-set field with a R15x15 sprinkler spacing. The sprinklers were VYR-70, and the nozzle diameters were 4.4 and 2.4 mm. The nozzle height was 2 m, and the operating pressure was 380 kPa. 25 catch can locations were evenly distributed within a central sprinkler spacing (5 rows by 5 columns, with a 3 m spacing). Three catch cans (S, M and L) were installed at each location, separated 0.3 m in a triangular arrangement. The location of each catch can at the vertices of this triangle was randomised. The upper part of all catch cans was located 0.50 m over the soils surface. A total of thirteen 3-hour irrigation experiments were performed. The operating pressure, the meteorological conditions and the catch can readings (3 x 25) were recorded in every experiment. The *CU* was determined in each experiment for each type of catch can.

The statistical analysis was based on the relationship between the differences in CU estimated with the different catch cans and the wind speed. At low wind speeds CU was very high (typically about 95 %), and the differences in CU among the three catch cans were non-relevant. If a regression line can be statistically established between the wind speed and the differences in CU estimation between two types of catch cans, then both catch cans perform differently, with the large one being potentially more accurate under windy conditions

Water application experiments

Field experiments were designed taking into consideration the recommendations of Merriam and Keller (1978), and the relevant international standards (Anonymous, 1987; Anonymous, 1990; Anonymous, 1995).

Two different sprinklers, frequently installed in the Ebro Valley of Spain, were used in this research: the RC-130H from Riegos Costa (Lleida, Spain) and the VYR-70 from VYRSA (Briviesca, Burgos, Spain) (the citation of commercial trademarks does not imply endorsement). Both sprinklers were analysed with their principal nozzles of 4.0 and 4.4 mm, and an auxiliary nozzle of 2.4 mm. The principal nozzles were equipped with the straightening vanes provided by the manufacturer. The nozzle elevation was 2.0 m above the soil surface. This nozzle elevation is widely used in the study area since corn is a very common crop.

Each combination of sprinkler and principal nozzle diameter was tested at three nozzle operating pressures: 200, 300 and 400 kPa. The experimental tests were performed in isolated sprinklers and in a rectangular 18 x 15 m (R18x15) solid-set arrangement. The gross application rate ranged from 4.4 to 7.2 mm h-1.

In the isolated sprinkler experiments precipitation was recorded along four radii, at distances from the sprinkler ranging from 0.5 to 15.5 m, with an increment of 0.5 m. The results of the four radii were averaged to produce the radial water application pattern. All the experiments performed with isolated sprinklers lasted for 2 hours and were performed under low wind conditions. A total of 12 isolated sprinkler experiments were performed (2 sprinklers x 2 principal nozzle diameters x 3 operating pressures).

A rectangular 4 x 4 sprinkler set-up was used for the solid set, with the experimental area located between the four central sprinklers. A matrix of 5 x 5 catch cans was installed at a spacing of 3.6 x 3.0 m, covering the experimental sprinkler spacing. Each solid-set experiment was repeated under different wind speed conditions, in an attempt to characterize the water distribution pattern resulting from different combinations of sprinkler, principal nozzle diameter, operating pressure and wind speed. All solid-set experiments lasted for 3 hours. Table 1 presents the average wind speed and the *CU* resulting from all solid-set experiments. Of the 43 solid-set experiments, 36 were used for model calibration and 7 for model validation. The number of experiments performed for each combination of sprinkler, principal nozzle diameter and operating pressure varied from 3 to 5. This variability resulted from the difficulties in obtaining uniform wind speed and direction during the whole experiment, from the replications needed to obtain adequate coverage of the usual wind speed range, and from the need for validation experiments in the same conditions. Tolosa (2003) presented further details on this set of field experiments.

Additional experiments were performed to further validate the model in other sprinkler spacings. 50 experiments were performed with sprinklers RC-130H and 4.4+2.4 mm nozzles using triangular spacings of 18 x 18 m (T18x18) and 18 x 15 m

(T18x15). 37 experiments were performed on a R15x15 solid set equipped with VYR-70 sprinklers and 4.4+2.4 mm nozzles.

An automated weather station located in the experimental field recorded air temperature, relative humidity and wind speed and direction at 5 min intervals.

Model calibration

The first step of the validation process consisted on determining the parameters D_{50} and n that result in best agreement between the model results and the experimental radial water application pattern obtained from isolated sprinklers in the absence of wind. The following procedure was repeated for each sprinkler, nozzle diameter and operating pressure.

A range of D_{50} and n pairs of values were explored (D_{50} from 0.0014 to 0.0023 m, with an increment of 0.0001 m; n from 1.9 to 2.8, with an increment of 0.1). The resulting 100 simulations were sorted in decreasing order of the ratio $r/RMSE$, where r is the correlation coefficient between observed and simulated radial precipitation, and $RMSE$ is the root mean square error. High values of this ratio ensure a high correlation and a low estimation error.

The next step was to simulate the experimental solid set at zero wind speed using different combinations of D_{50} and n, and starting from the top of the list. Typically, the upper parameter values in the list resulted in lower CU than the closest experimental values (the lowest wind experiments). A sensitivity analysis showed that the simulated CU very much depended on the value of n. As a consequence, the irrigation event was simulated with the optimum D_{50} and lower than optimum values of n. The procedure was repeated till a pair of parameters was found that resulted in an adequate CU

estimation, while still reproducing the radial water application pattern in a satisfactory way (with adequate values of *r* and *RMSE*).

The next step was the calibration of K_1 and K_2. For each of the 36 solid-set experiments devoted to model calibration, simulations were performed using values of K_1 from 0.0 to 2.8 (with increments of 0.2), and values of K_2 from 0.0 to 0.95 (with increments of 0.05). Each of the 266 resulting simulations was confronted with the experimental results of catch can irrigation depth and *CU*. Out of this comparison, three indexes were determined: *r*, *RMSE* and the absolute difference between observed and simulated *CU* (CU_d). The simulation results were again sorted by decreasing values of *r/RMSE*, and pairs of K_1 and K_2 values were selected that ranked in the upper 10 % of the list and had values of CU_d typically lower than ±1%. This procedure ensures that the model will produce an adequate prediction of CU, and at the same time, the spatial distribution of irrigation water within the sprinkler spacing will be reproduced. Obtaining both goals simultaneously leads to sacrificing some accuracy in each of them. On the positive side, the resulting model will be fit for irrigation engineering and agronomic applications (Dechmi et al., 2004b).

The resulting values of D_{50}, *n*, K_1 and K_2 were built into the calibrated model, and linear interpolation among the parameters was introduced to simulate values of operating pressure and wind speed not considered in the calibration phase.

Model validation

The first step of model validation consisted on simulating the seven irrigation events which were not used for calibration purposes, and comparing the model simulated and experimental values of CU.

In a second step, the 87 additional solid-set validation experiments were used. The experimental conditions were introduced in the model. Simulated and experimental values of CU were compared for the three different sprinkler spacings. This validation experiment served to evaluate the capacity of the model to reproduce irrigation events in solid-set spacings and operating pressures different from the ones used for calibration.

Model application

The validated model was used to estimate *CU* in different conditions. The simulations included the two sprinklers, the two nozzle diameters, five operating pressures (200, 250, 300, 350 and 400 kPa), 9 wind speeds (from 0 to 8 m s^{-1}, with an increment of 1 m s^{-1}), two types of sprinkler spacings (triangular and rectangular), and four sprinkler spacings (15x12, 18x15, 18x18 and 21x18). The results of these 1,440 simulations were organized in a tabular form in order to provide for a comparison of the relative performance of each sprinkler under different irrigation set-ups, operational and environmental conditions.

Results and discussion

Effects of catch can size on irrigation uniformity

Differences in *CU* between the three considered catch cans were found to be minimal when the wind speed was between 0 and 2 m s^{-1}, as presented in Figure 1. Statistical relationships between wind speed and the differences in *CU* could be established between the large catch can (210 mm in diameter) and the other two. The resulting regression equations and the coefficients of determination are presented in Figure 1.

No statistical differences were found between the small catch can (S, 79 mm in diameter), and the medium catch can (M, 130 mm in diameter), which is way larger than required by the International Standard (minimum diameter of 85 mm). It could therefore be concluded that using the experimental catch can (S) does not result in significant errors in *CU* estimation respect to the minimum diameter requirement.

However, the comparison with the large catch can does cast some doubts, since at large wind speeds (6-8 m s^{-1}) the small and medium catch cans resulted in lower estimates of *CU*. It is reasonable to assume that the large catch can produces better estimates of *CU* than the other two. However, the issue of catch can size (and shape) will require additional research.

With these precautions in mind, the small catch can was retained for use in all the experiments described in this paper. The regression equation L-S could be used to estimate the *CU* corresponding to the large catch can from the *CU* obtained with the small catch can.

Calibration of *d50* and *n*

The results of the calibration procedure are presented in Table 2. Dechmi et al. (2004a) analysed one of the cases presented in this table: sprinkler VYR-70 with 4.4 + 2.4 mm nozzles at an operating pressure of 300 kPa. For this particular case, our results show that the parameter combination ranking highest in terms of *r/RMSE* is D_{50} = 0.0017 m and n = 2.45 (r = 0.83; *RMSE* = 1.08 mm h^{-1}). Dechmi et al. (2004a) found an optimum combination of D_{50} = 0.0013 m and n = 2.50 (r = 0.79; RMSE = 0.48 mm h^{-1}). For a generic medium-sized impact sprinkler, Kincaid et al. (1996) measured drop size distribution an arrived to D_{50} = 0.0021 m and n = 1.82. The differences between our results and those of Dechmi et al. (2004a) are not particularly relevant in practical terms. For instance, the comparison of the simulation results using the optimum parameters found by Dechmi et al. (2004a) with the experiments reported in this paper would result in r = 0.87 and $RMSE$ = 2.35 mm h^{-1}; a very good correlation and a somewhat large error. The optimum experimental results still need to be adjusted to perform in terms of uniformity estimation. The CU obtained at the lowest wind speed (U = 1.4 m s^{-1}) was 93.6 % (Table 1). Simulations performed at zero wind speed should therefore result in a uniformity higher than 93.6 %. This was first obtained for D_{50} = 0.0017 m and n = 1.90 (CU = 95.0%). As a consequence, this set of parameters was retained.

The values of D_{50} decrease with the operating pressure and, in the case of the RC-130H, with the nozzle diameter (Table 2). For sprinkler VYR-70 operating at a pressure of 400 kPa, D_{50} decreases as the nozzle diameter increases. This may be explained by the fact that, as previously discussed, different parameter combinations result in adequate simulation of the water application pattern. The values of RMSE ranged from 1.09 to 3.64 mm h^{-1}. The coefficient of correlation remained in the range of 0.50 to 0.83.

Calibration of K_1 and K_2

Table 1 presents the optimum values of K_1 and K_2 for each of the calibration experiments, together with the resulting values of $RMSE$ and r. The correlation coefficients ranged from 0.18 to 0.84, with an average of 0.65. The lowest correlation coefficients correspond to high uniformities (CU > 85%). In these irrigation events the variability in irrigation depth is small and the experimental error may account for a large part of the variability. The $RMSE$ ranged from 0.41 to 2.11 mm h^{-1}, with an average of 0.96 mm h^{-1}. These figures of $RMSE$ amount to between 3 and 19 % of the gross irrigation depth applied by each combination of nozzle diameter and operating pressure in the experimental R18x15 sprinkler spacing.

The goal of the calibration was to maintain low values of *RMSE* and high values of *r*, while producing accurate predictions of *CU*. Figure 2a presents a plot of experimental *vs.* calibration values of *CU*. A regression line was established with R^2 = 0.977***. The regression slope and the intercept were not significantly different from 1 and 0, respectively, at the 95 % probability level. Uniformity was accurately predicted, with a standard error of the linear regression model of 1.48 %.

Model validation

In a first step, the model was validated with data from the same series of experiments as the calibration data set. Figure 2b shows a scatter plot of experimental *vs.* simulated *CU* for the seven validation experiments. A regression analysis proved significant (R^2 = 0.855**), and revealed that the regression slope and the intercept were not significantly different from 1 and 0, respectively (95 % probability level). The standard error of *CU* estimation was 3.09 % .

Figure 3 presents the results of the second validation step. Experimental values of *CU* were plotted against wind speed for the three different sprinkler spacings. A series of simulated data corresponding to the experimental conditions and wind speeds at increments of 1 m s^{-1} was added to the three subplots. The simulated data reproduced the basic features of the experimental data set, although the variability was larger than in the first step. The simulation model showed predictive capacity at sprinkler spacings and operating pressures different from the experimental ones.

Development of uniformity tables and a simulation software

Tables 3, 4, 5 and 6 present the results of simulated *CU* for the two sprinkler types, two nozzle diameters, eight sprinkler spacings and nine wind speeds (0 - 8 m s^{-1}). The tables were produced for management and design purposes.

At the management level, farmers must take quick irrigation decisions for a given sprinkler layout, operating pressure and wind speed. The latter two variables are often related in collective irrigation networks, since high wind spells reduce water demand, and may lead to an increase the operating pressure. As soon as the windy period is over, most farmers decide to turn their systems on, and the operating pressure can drop substantially due to a high simultaneity. The proposed tables can be used for *a priori* estimation of the *CU* resulting from irrigating under a particular pressure and wind speed.

In an experiment on sprinkler irrigated corn, Dechmi et al. (2003) found that the irrigation water applied when the wind speed was higher than 2.1 m s^{-1} (*CU* lower than 84 %) was significantly correlated with corn yield. Farmers could adopt *CU* management thresholds depending on the crop value and the on-farm irrigation equipment. An adequate selection of the proper irrigation timing (avoiding high winds) would lead to increased water conservation (reducing deep percolation losses and wind drift and evaporation losses) and increased crop yield (Dechmi et al., 2004b; Playán et al., 2005).

Additionally, these tables could be used as the basis of irrigation programmers capable of making advanced irrigation decisions. The user would preset a given irrigation depth, and the programmer would select the most appropriate irrigation timing to attain maximum *CU* and minimize *WDEL*. In order to make the right decisions the programmer should have access to variables such as wind speed, relative humidity (for *WDEL* estimation), and pressure at the hydrant.

At the irrigation system design phase, tabulated simulation results can be used to determine the adequate sprinkler model, nozzle diameter, operating pressure and spacing that can yield adequate performance under the wind pattern of a certain location. Table 7 has been prepared to illustrate such process. The Table presents the sprinkler producing higher uniformity under each parameter combination. When the absolute value of the difference in *CU* is smaller than or equal to the standard error of *CU* estimation in the validation (3.09 %), we can not conclude that one sprinkler performs better than the other. These cases are labelled as "indifference" in Table 7.

In general, the comparison between both sprinklers does not depend on the type of sprinkler spacing (rectangular *vs*. triangular). While for a principal nozzle diameter of 4.0 mm the RC-130H shows better performance than the VYR-70, for the 4.4 mm nozzle the situation is more balanced. At narrow sprinkler spacings RC-130H performs better than VYR-70, while at ample spacings the situation is somewhat reversed. For wind speeds in the range of 2 to 5 m s^{-1}, RC-130H performed better than VYR-70. The relative performance of both sprinklers at low or extreme winds very much depends on the particular case.

A simulation software (only available in Spanish) has been produced to further disseminate the results of this research. The software has been designed for irrigation professionals and advanced farmers. Simulation parameters have been implemented internally, and the user interaction has been limited to the common technical variables. Software output includes a water application map within the solid-set spacing, summary statistics on water application and wind drift and evaporation losses, and an irrigation recommendation. Research in underway to increase the choice of available sprinklers in the software. The simulation software can be freely downloaded from www.?.

Conclusions

The proposed methodology for the calibration and validation of the ballistic model has permitted to generate 1,440 discrete estimations of irrigation uniformity (involving a number of different solid set spacings) from just 12 isolated sprinkler evaluations and 43 solid set evaluations. The resulting model has proven to have a satisfactory predictive capacity (the calibration standard error for *CU* was 3.09 %), and permits to reduce the experimental work by 96 %. However, the required experimental effort is still important, and must be performed under strict quality control, since the model calibration procedure will amplify any experimental error.

Model simulation output tables have permitted to identify the conditions best suited for each sprinkler. As a consequence, technical criteria can be used for the selection of the adequate sprinkler and nozzle diameter for the prevailing operation and environmental conditions at a given location. *CU* tables can also be used in a given sprinkler layout to optimise irrigation management in response to the operating pressure and the wind speed. These tables could be implemented in advanced irrigation programmers, whose primary objective would be to guarantee a minimum irrigation uniformity in all irrigation events. In order to ensure the applicability of the model in an irrigated area, it will be important to estimate the calibration parameters for the most relevant sprinklers and nozzle diameters. Consequently, the required experimental effort may limit the benefits of the proposed methodology. On the other hand, in a context of growing concerns about water availability, it is very important that this information is made available to farmers and irrigation specialists.

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<u>List of Tables</u>

Table 1. *Characteristics of the field experiments for the RC-130H and VYR-70 sprinklers. Each experiment is characterized by the nozzle diameter (D, mm), the operating pressure (P, kPa), the wind speed (U, m s^{-1}) and the Coefficient of Uniformity (CU, %). The use of each experiment for either calibration (C) or validation (V) purposes is also reported in the table. The calibrated values of parameters K_1 and K_2, and the agreement indexes Root Mean Square Error (RMSE) and coefficient of correlation (r) are also presented.*

D	P	RC-130H							VYR-70						
(mm)	(kPa)	U (ms^{-1})	CU (%)	K1	K2	RMSE (mm h^{-1})	r	Use -	U (ms^{-1})	CU (%)	K1	K2	RMSE (mm h^{-1})	r	Use -
4.0	200	0.9	85.7	0.0	0.00	0.61	0.63	C	2.0	85.8	1.0	0.35	0.84	0.33	C
		3.8	81.7	1.2	0.25	0.57	0.84	C	2.5	82.9	-	-	-	-	V
		5.4	71.3	1.6	0.40	0.90	0.83	C	3.4	73.2	1.8	0.60	0.85	0.72	C
									6.9	69.1	1.2	0.65	0.95	0.72	C
	300	1.2	91.8	-	-	-	-	V	1.8	87.6	1.6	0.20	0.63	0.67	C
		1.8	84.9	2.2	0.20	0.75	0.62	C	2.9	73.1	2.4	0.50	1.08	0.73	C
		2.8	86.6	-	-	-	-	V	8.4	68.3	1.0	0.55	1.38	0.60	C
		3.0	84.9	1.6	0.25	0.67	0.73	C							
		3.2	83.4	1.6	0.15	0.69	0.70	C							
	400	1.7	91.1	0.0	0.00	0.75	0.33	C	0.4	92.9	0.2	0.05	0.72	0.29	C
		2.0	88.0	-	-	-	-	V	4.2	74.8	2.4	0.50	0.93	0.83	C
		2.4	91.0	1.2	0.10	2.06	0.61	C	9.3	60.3	2.6	1.00	1.29	0.80	C
		3.9	78.4	1.4	0.20	0.83	0.81	C							
4.4	200	1.3	86.5	0.6	0.00	0.69	0.55	C	1.2	87.6	-	-	-	-	V
		2.1	91.0	1.0	0.10	0.41	0.73	C	1.7	89.4	0.6	0.25	0.83	0.46	C
		7.6	71.6	1.8	0.15	1.20	0.84	C	4.0	74.4	0.8	0.65	0.97	0.73	C
									7.9	71.0	1.0	0.60	1.11	0.68	C
	300	1.1	90.2	0.4	0.00	0.56	0.73	C	1.4	93.6	0.4	0.10	0.51	0.29	C
		1.5	92.3	-	-	-	-	V	2.2	88.9	0.8	0.30	0.57	0.72	C
		3.6	83.8	1.4	0.15	0.69	0.80	C	6.8	71.0	1.0	0.55	1.13	0.66	C
		7.6	69.4	1.8	0.45	1.73	0.72	C							
	400	1.1	91.2	0.0	0.00	0.81	0.41	C	0.7	93.9	0.2	0.10	0.66	0.18	C
		4.3	75.7	2.4	0.05	1.28	0.74	C	4.0	80.8	1.8	0.40	0.84	0.83	C
		7.2	68.9	2.4	0.25	2.11	0.63	C	5.2	70.4	-	-	-	-	V
									7.0	62.6	2.8	0.95	1.87	0.81	C

Table 2. *Selection of model parameters D_{50} and n for each isolated sprinkler experiment. The root mean square error (RMSE) and coefficient of correlation (r) between observed and simulated data are presented for each case.*

Sprinkler	Nozzle Diameter (mm)	Nozzle Pressure (kPa)	D_{50} (m)	*n* (-)	*RMSE* (mm h^{-1})	*r* (-)
RC-130H	4.0	200	0.0019	2.0	1.23	0.80
		300	0.0017	2.0	1.82	0.70
		400	0.0015	2.2	3.64	0.50
	4.4	200	0.0021	1.9	1.71	0.66
		300	0.0017	2.1	1.92	0.68
		400	0.0017	2.0	2.12	0.63
VYR-70	4.0	200	0.0019	2.0	1.16	0.81
		300	0.0017	2.2	1.09	0.83
		400	0.0017	2.0	1.67	0.77
	4.4	200	0.0019	1.9	1.83	0.73
		300	0.0017	1.9	2.64	0.66
		400	0.0016	2.0	2.23	0.73

Table 3. *CU (%) resulting from different triangular sprinkler spacings, nozzle pressures and wind speeds for the RC-130H and VYR-70 sprinklers, using 4.0 and 2.4 mm nozzles.*

	P (kPa)	RC-130H									VYR-70								
		U ($m\ s^{-1}$)									U ($m\ s^{-1}$)								
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
T 15 x 12	**200**	90	89	88	88	86	84	84	83	83	90	89	87	83	82	79	77	77	74
	250	94	93	91	90	88	86	85	83	81	91	90	89	85	82	80	77	76	72
	300	96	95	93	91	90	86	87	84	81	91	91	90	86	82	79	78	74	72
	350	95	94	92	90	89	86	85	83	80	96	95	93	89	85	81	78	75	75
	400	93	92	90	89	86	86	83	82	79	99	98	95	92	87	83	77	77	75
T 18 x 15	**200**	81	81	84	90	90	82	76	72	68	81	82	83	80	77	76	74	74	72
	250	85	87	93	92	90	85	79	76	73	82	83	87	81	77	75	74	73	72
	300	88	91	92	90	89	85	80	77	75	82	85	91	78	77	74	74	72	71
	350	88	90	94	91	88	85	80	77	75	87	88	91	84	81	75	71	67	66
	400	88	87	91	91	87	84	79	77	75	92	92	93	89	83	76	68	65	66
T 18 x 18	**200**	84	84	89	90	79	67	59	56	54	84	86	85	75	67	67	62	63	61
	250	86	89	92	86	78	70	64	62	60	84	87	86	72	68	64	63	65	63
	300	89	93	83	81	75	69	66	64	63	84	89	85	68	65	60	61	62	63
	350	90	92	90	81	75	69	67	65	62	87	90	89	77	69	61	59	59	55
	400	91	90	94	80	73	68	66	64	60	90	92	91	84	72	63	59	54	50
T 21 x 18	**200**	90	90	93	87	73	60	49	48	43	90	90	84	72	63	60	57	59	56
	250	90	94	88	82	72	63	55	55	50	89	91	83	68	63	58	58	63	62
	300	93	94	77	75	69	62	58	57	52	89	93	81	61	59	55	58	61	62
	350	94	96	85	76	69	62	59	57	53	89	92	87	71	64	57	57	55	53
	400	97	96	93	75	67	60	59	56	53	91	92	90	79	67	59	58	51	48

Table 4. *CU (%) resulting from different triangular sprinkler spacings, nozzle pressures and wind speeds for the RC-130H and VYR-70 sprinklers, using 4.4 and 2.4 mm nozzles.*

	P (kPa)	**RC-130H U (m s^{-1})**									**VYR-70 U (m s^{-1})**								
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
T 15 x 12	**200**	95	93	91	89	86	84	84	85	84	93	92	90	86	84	81	78	78	76
	250	95	93	91	90	88	84	85	83	80	97	95	94	90	88	84	81	81	77
	300	93	92	90	90	89	85	83	80	78	98	97	95	93	90	87	83	82	79
	350	97	95	92	90	88	87	84	80	79	99	97	95	93	89	84	80	77	78
	400	99	97	94	90	85	86	84	81	80	99	95	92	91	88	83	76	76	74
T 18 x 15	**200**	82	82	86	89	92	92	88	80	75	84	84	83	78	74	75	75	77	78
	250	84	85	88	91	93	89	83	78	73	88	89	87	83	81	75	72	77	76
	300	85	86	90	93	90	85	78	73	69	92	91	91	88	86	83	81	78	76
	350	88	88	90	93	89	84	77	72	70	92	92	92	89	86	80	73	68	68
	400	92	91	92	92	86	80	75	72	70	92	91	94	92	85	76	67	63	63
T 18 x 18	**200**	81	82	89	92	88	80	73	65	60	87	87	85	78	73	72	71	68	66
	250	83	85	91	92	84	77	70	64	61	89	90	88	82	79	72	67	70	68
	300	87	88	93	87	78	70	64	61	56	92	92	90	86	83	79	73	70	69
	350	88	88	93	89	75	67	63	61	56	93	92	91	87	79	70	65	59	56
	400	90	89	93	88	73	64	62	61	55	92	91	94	85	71	63	58	50	47
T 21 x 18	**200**	83	85	92	94	85	76	64	56	50	92	90	86	78	71	71	69	66	63
	250	86	88	94	90	80	72	61	57	51	92	92	87	81	77	70	64	68	68
	300	91	93	95	84	72	63	56	54	47	94	95	88	84	81	77	72	70	70
	350	90	91	95	86	70	59	56	52	49	94	94	89	84	76	67	63	59	55
	400	91	90	94	86	67	57	56	51	51	94	94	93	81	66	60	58	48	45

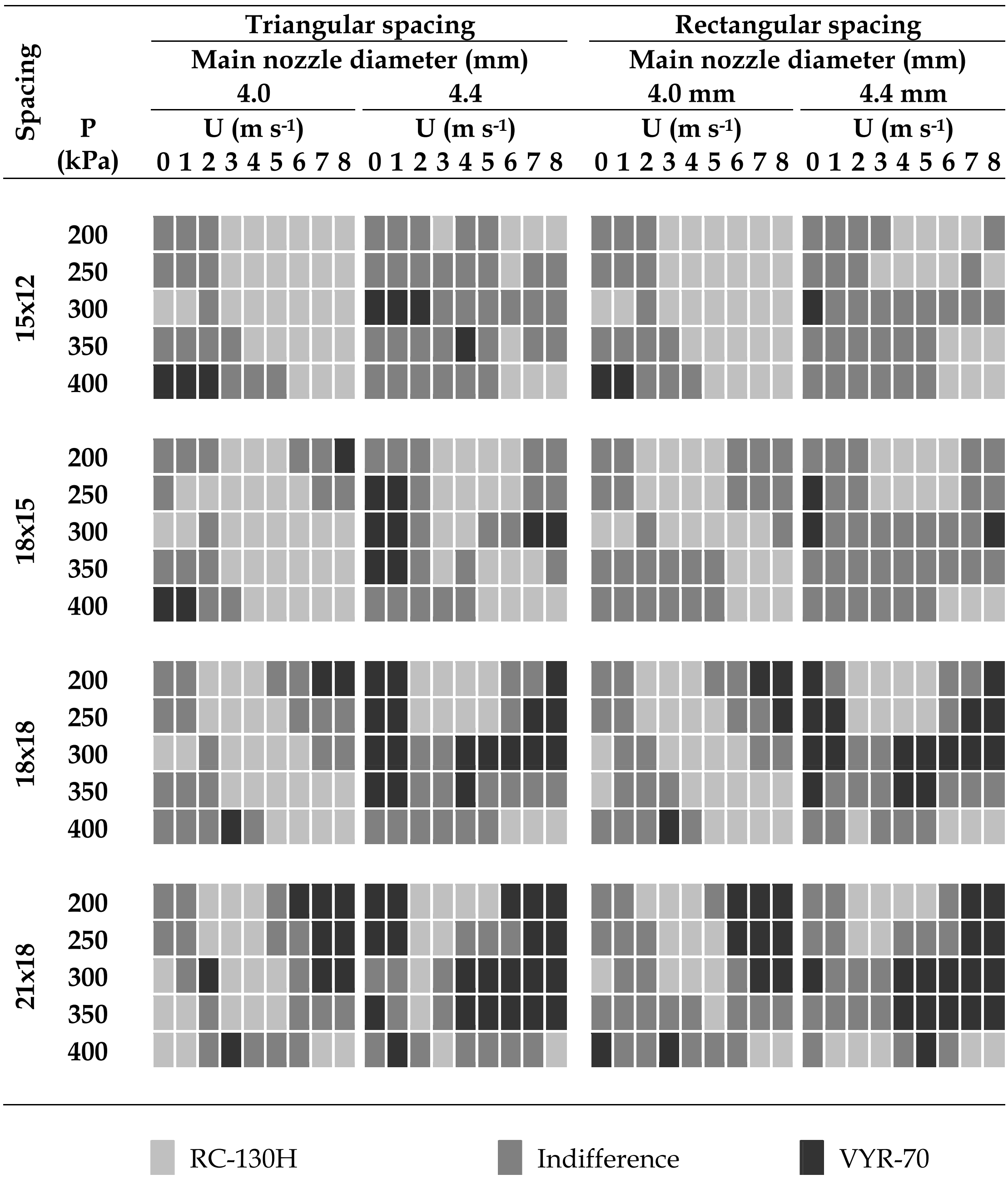
Table 5. *CU (%) resulting from different rectangular sprinkler spacings, nozzle pressures and wind speeds for the RC-130H and VYR-70 sprinklers, using 4.0 and 2.4 mm nozzles.*

	P (kPa)	RC-130H U (m s^{-1})									VYR-70 U (m s^{-1})								
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
R 15 x 12	**200**	88	88	89	90	88	85	83	80	81	88	88	87	83	80	78	76	76	74
	250	90	91	92	91	89	86	84	82	81	88	89	89	83	80	78	75	74	72
	300	93	94	91	90	89	85	84	82	79	89	90	90	83	81	77	76	73	72
	350	93	93	92	90	87	85	83	83	79	92	93	92	88	83	78	76	74	71
	400	92	91	91	90	85	85	81	82	78	96	95	94	91	85	80	76	74	70
R 18 x 15	**200**	88	88	88	89	84	77	73	71	68	88	87	84	77	75	73	72	72	71
	250	90	91	91	88	85	80	76	74	72	88	88	86	78	75	73	73	72	72
	300	93	93	86	85	83	80	78	76	74	88	89	87	77	74	74	73	72	71
	350	93	93	89	85	83	81	77	76	74	91	91	89	82	78	75	71	68	66
	400	93	92	92	85	81	80	76	76	73	93	93	91	87	81	77	69	65	67
R 18 x 18	**200**	89	87	89	85	78	67	60	56	54	89	87	83	74	68	66	63	62	61
	250	91	92	89	84	77	70	64	62	60	89	89	84	72	67	64	63	64	64
	300	94	93	82	81	75	70	66	65	62	90	90	83	69	64	61	61	62	64
	350	95	93	87	80	74	70	66	66	61	91	92	87	77	68	61	60	59	55
	400	94	92	91	79	72	69	66	65	60	93	93	90	84	72	62	60	53	50
R 21 x 18	**200**	86	85	84	79	69	58	50	47	43	86	83	77	69	62	59	58	58	56
	250	89	88	81	77	69	62	55	54	51	87	85	78	67	62	58	59	62	62
	300	92	87	73	72	66	61	57	56	54	87	86	75	62	57	55	58	60	63
	350	91	89	79	73	66	61	58	57	54	91	89	81	70	63	57	56	56	54
	400	90	89	84	71	64	60	58	56	54	95	92	86	77	67	59	56	51	48

Table 6. *CU (%) resulting from different rectangular sprinkler spacings, nozzle pressures and wind speeds for the RC-130H and VYR-70 sprinklers, using 4.4 and 2.4 mm nozzles.*

	P (kPa)	RC-130H U (m s^{-1})									VYR-70 U (m s^{-1})								
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
R 15 x 12	**200**	89	89	89	91	89	86	85	83	81	90	90	88	84	80	78	77	78	78
	250	90	90	90	92	89	86	85	81	80	93	92	90	87	85	80	77	79	76
	300	91	91	91	92	89	85	80	81	77	95	94	93	90	88	84	81	79	77
	350	93	92	92	92	87	84	82	80	78	95	94	93	90	87	81	78	74	73
	400	96	93	93	91	83	82	82	80	78	96	93	93	91	86	79	75	71	69
R 18 x 15	**200**	87	88	89	91	89	85	81	76	73	90	89	86	80	74	74	74	75	76
	250	88	90	90	90	88	83	79	76	72	93	92	89	83	80	74	69	77	75
	300	91	91	91	88	84	80	76	74	68	95	94	91	87	85	81	79	77	76
	350	92	92	92	88	83	80	76	73	70	95	93	91	87	83	79	73	70	68
	400	93	93	93	88	80	77	75	72	70	95	93	93	87	82	76	68	63	63
R 18 x 18	**200**	86	87	91	89	86	79	72	65	61	91	89	85	79	72	72	70	68	67
	250	88	89	92	88	83	77	70	64	61	93	93	88	83	78	72	67	71	69
	300	92	91	92	85	77	70	64	63	56	96	95	91	86	83	79	74	71	71
	350	92	92	94	87	75	67	63	62	56	96	94	91	86	79	71	64	61	57
	400	93	92	95	87	73	64	63	61	56	96	94	93	84	71	64	59	50	47
R 21 x 18	**200**	87	88	86	84	78	72	63	56	50	88	86	81	74	68	68	66	65	62
	250	89	89	87	82	75	69	61	56	51	91	89	83	78	74	69	63	68	68
	300	89	89	85	77	68	62	55	54	48	93	91	85	80	78	74	72	70	70
	350	92	92	88	79	67	59	55	53	49	94	91	85	80	75	67	63	60	55
	400	95	94	90	80	65	56	55	52	50	94	90	85	76	64	61	57	48	45

Table 7. *Sprinkler resulting in higher CU (%) for each combination of spacing, main nozzle diameter (mm), operating pressure (P, kPa) and wind speed (U, m s*$^{-1}$*).*



List of Figures

Figure 1. *Differences in the coefficient of uniformity (CU, %) measured using Small (S), Medium (M) and Large (L) catch cans as a function of wind speed (U, m s-1).*

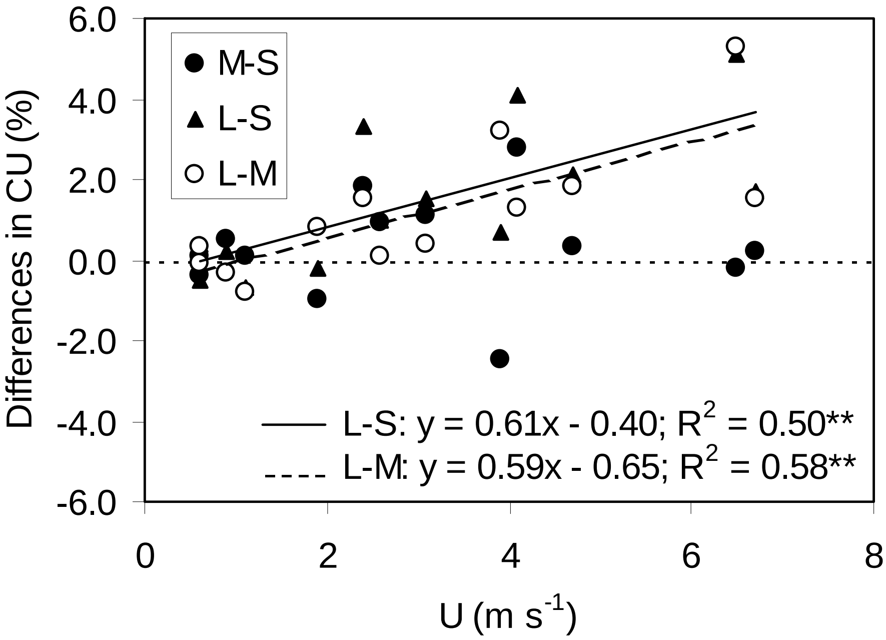


Figure 2. *a) Experimental vs. calibration coefficients of uniformity (CUe and CUc, respectively) for the RC-130H and VYR-70 sprinklers; and b) Experimental vs. validation coefficients of uniformity (CUe and CUv, respectively). The dashed line represents the 1:1 relationship.*

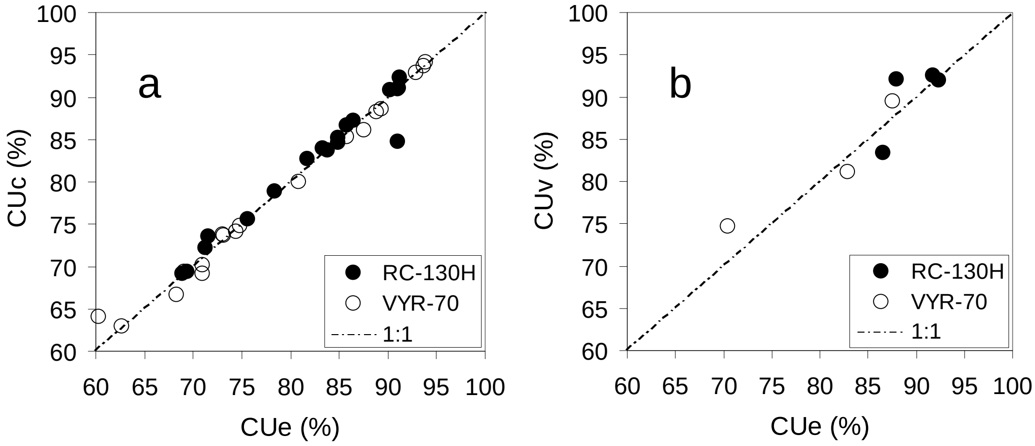
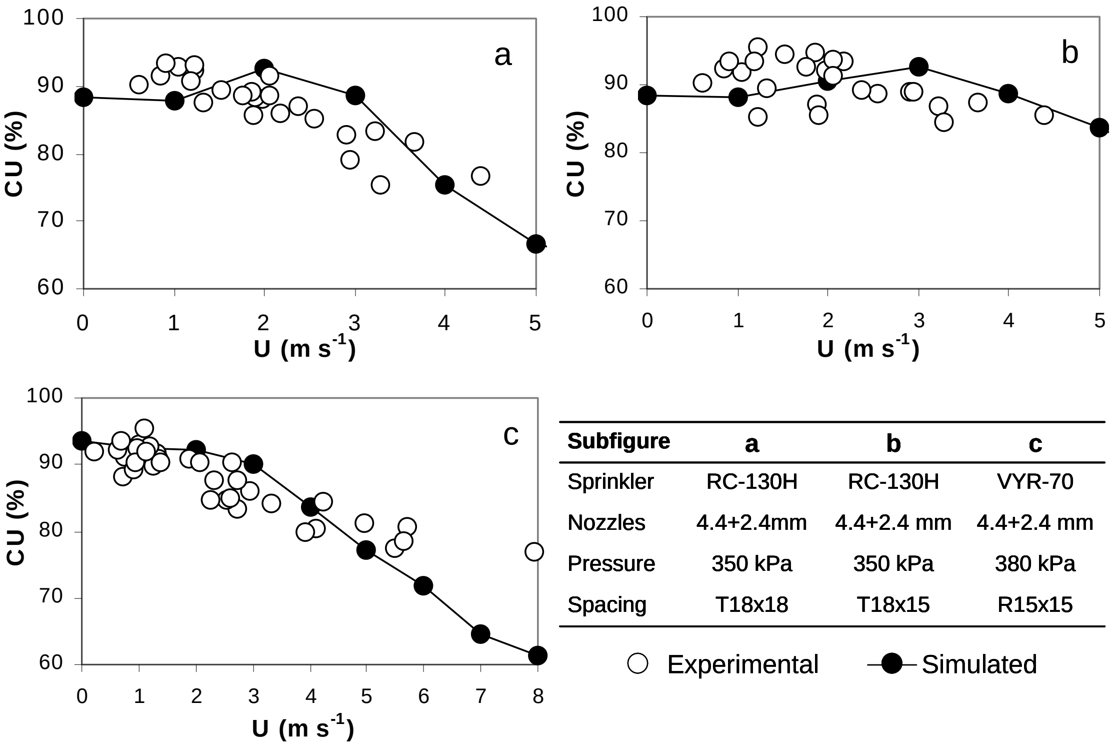


Figure 3. *Additional validation experiments performed using both sprinklers and different operating pressures and spacings. The nozzle diameters were 4.4 + 2.4 mm in all cases. The subfigures present experimental and simulated values of CU as a function of wind speed (U, m s*$^{-1}$*).*



Subfigure	a	b	c
Sprinkler	RC-130H	RC-130H	VYR-70
Nozzles	4.4+2.4mm	4.4+2.4 mm	4.4+2.4 mm
Pressure	350 kPa	350 kPa	380 kPa
Spacing	T18x18	T18x15	R15x15