SELF-CALIBRATED BALLISTIC MODEL FOR SPRINKLER IRRIGATION WITH A FIELD EXPERIMENTS DATA BASE

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Abstract

Simulation models of sprinkler irrigation are a valuable tool to improve the irrigation water management at plot scale. Ballistic theory has been commonly used to simulate drop dynamics in sprinkler irrigation models. A number of experiments on sprinkler irrigation performed in previous studies in the Ebro Valley Spain were analyzed and integrated in a data base. The evaluations were performed on six sprinkler types with different nozzle sizes, operating pressures under different meteorological conditions and spacings. The data base includes 40 isolated and 167 solid-set experiments that were processed with a self-calibrated model to calibrate and validate the ballistic parameters. The ballistic model used in this research was improved with respect to a previous model, moreover some novelties were added. These modifications were done in the phases of: the numerical solution, a wind drift and evaporation losses model, simulations considering slope in the terrain, drop generation (using regular and random methods), the size of the terrain cells where the drops are simulated and considering two drop size distributions, upper limit lognormal and Weibull. The results indicated larger and significant differences of Christiansen's Uniformity Coefficient measured and simulated when considering a constant wind velocity (9%) and no differences when the wind velocity is defined for intervals equal to or less than 30 minutes (6%). Regarding the effect of the slope in the terrain, differences between both uniformity coefficients are relevant (11%) when the wind velocity is larger than 4 m s⁻¹. Both drop size distributions were similar in accuracy however, the upper limit lognormal was more suitable to simulate a

sprinkler especially designed to operate under low pressure. The predictive ability of the model once calibrated and validated was satisfactory (99% and 75%, respectively). The new model improves the accuracy with respect to previous research and minimizes the computing time for the calibration and validation processes using the cluster Trueno-CSIC.

Keywords

Self-calibrated model, ballistic model improved, experimental database, sprinkler irrigation.

1. Introduction

Simulation models of sprinkler irrigation are a valuable tool to improve the irrigation water management at plot scale. The simulation of the water distribution patterns of impact sprinkler has been performed through the study of the drop dynamics.

Ballistic theory has been commonly used to describe and simulate drop movements in sprinkler irrigation models. To simulate the dynamics of the droplets, a standard model for sprinkler irrigation considers: a) where the drops are formed and its initial velocity; b) a module to predict the volumetric drop size distribution, diameter ranges and model parameters (Li et al. 1994; Kincaid et al. 1996); c) the simulation of the trajectories of the individual droplets, accounting for the major forces acting on the droplet (including drag coefficient and wind distortion pattern), with a physically based droplet dynamics model (Fukui et al. 1980; von Bernuth and Gilley 1984; Vories et al. 1987; Seginer et al. 1991; Carrión et al. 2001; Playán et al. 2006); d) determination of irrigation precipitation patterns as a function of computed landing coordinates of the individual drops and the corresponding volumetric application rates (Vories and von Bernuth, 1986; von Bernuth, 1988; Seginer et al. 1991; Carrión et al. 2001); and including e) water losses due to wind drift and evaporation, separating evaporation from drift (Yazar, 1984; Edling et al. 1985; Thompson et al. 1993) or consider it as unique losses (Dechmi et al. 2004; Playán et al. 2005).

The models have evolved along the time, improving the definition of the involved processes. A number of research works simulate drop dynamics assuming that all drops were formed at the nozzles (Fukui et al. 1980; Carrión et al. 2001; Playán et al. 2006; Zerihun et al. 2016). Vories et al. (1987) divided the main jet in two parts, the disturbed by the arm stream that is assumed to form individual drops immediately after the main nozzle and the undisturbed stream that assumes to travel one meter along the initial velocity vector before breaking into individual drops (von Bernuth and Gilley 1984). In this research it is assumed that the jet of the main nozzle travels one meter without been affected by any drag force and then breaks into individual drops, while the drops formation of the secondary nozzle occurs at its exit.

A number of experimental techniques have been reported in the literature to measure drop sizes resulting from precipitation, sprinkler irrigation and atomization of liquids. The first intrusive methodologies (stain method, flour method, oil immersion method, momentum method) were replaced by non-intrusive optical methods (used in sprays or sprinkler irrigation) such as laser method (Montero et al. 2003; King et al. 2010), disdrometer method (Burguete et al. 2007), photographic method (Salvador et al. 2009) and particle tracking velocimetry (Bautista-Capetillo et al. 2014).

From the experimental data of the intrusive and non-intrusive methodologies, a number of volumetric drop size distributions have been proposed, some of them applied to sprays or impact sprinkler. Solomon et al. (1985) established the parameters of the Upper Limit Lognormal distribution (ULLN, Equation 1) presented by Mugele and Evans (1951) to adjust the volumetric drop size distribution of a spray sprinkler with different pressures and nozzle sizes. An exponential model based on Weibull distribution was later adapted to impact sprinklers by Li et al. (1994). The authors compared the ULLN and Weibull distributions using two impact sprinklers, concluding that both distributions are quite similar but Weibull (2 parameters) is much simpler than the ULLN distribution (3 parameters). Kincaid et al. (1996) used a modified distribution from Weibull (Equation 2) establishing as a constant one of the variables of the equation, lightening the calibration process. Different types of sprinklers were tested: impact sprinklers and spray sprinklers. The authors conclude that the exponential distribution has a good fit except for drops smaller than 1 mm.

$$f(d) = \frac{\alpha \exp \left[-\frac{1}{2} \left(\frac{\beta - \mu}{\sigma} \right)^2 \right]}{\sigma d (\alpha - d) \sqrt{2\pi}} \quad (1)$$

with $\beta(d) = \ln [d/(\alpha-d)]$

$$f(d) = 0.693 n \frac{d^{n-1}}{d_{50}^n} \exp \left[-0.693 \left(\frac{d}{d_{50}} \right)^n \right] \quad (2)$$

where $f(d)$ is the volumetric probability density function of the total discharge from

the sprinkler, d is the drop diameter, μ and σ are the mean and the standard deviation of β , respectively, and d_{50} is the volume mean drop diameter. The ULLN distribution has three regression parameters α , μ and σ . The Weibull distribution has two regression parameters, d_{50} and n .

The expected value (EV), acting as the mean drop diameter for both volumetric drop size distributions, can be numerically approximated by:

$$EV = \frac{\sum_i f(d_i) \cdot d_i}{\sum_i f(d_i)} \quad (3)$$

where d_i are the numerical drop diameters tested from 0 mm to 7 mm with 0.1 mm intervals.

Recently, a new impact sprinkler has been commercialized specially designed to operate at low pressure (200 kPa) following the procedures of Kincaid (1991). The sprinkler has a deflecting plate attached to the arm. The plate diffuses the jet filling the intermediate irrigated portion achieving a nearly triangular application pattern. Decreasing the pressure becomes the water application in an annular or toroidal shape. The previous suggest that a different drop size distribution has to be adapted to this pattern compared with standard pressures. The ULLN is a more flexible distribution that could allow adapting to these patterns.

The most common equation applied to sprinkler droplet dynamics is Newton's second law of motion (Fukui et al. 1980; von Bernuth and Gilley 1984; Vories et al. 1987; Seginer et al. 1991; Carrión et al. 2001; Playán et al. 2006). They involve a set of differential equations that can be solved by numerical methods to determine the landing point of a drop. Between the major aerodynamic forces acting on the droplet, the drag coefficient has been profusely studied. According to the literature, the drag coefficient could be established as a function of Reynolds number (Fukui et al. 1980) or as a function of the drops diameter (von Bernuth and Gilley, 1984; Hills and Gu, 1989) or as a function of pressure and diameter (Li and Kawano, 1995). Another advance in the definition of the drag coefficient has been proposed by

Seginer et al. (1991) modified later by Tarjuelo et al. (1994). The authors introduced two factors, K_1 and K_2 , describing the effect of the wind velocity and the direction of the drop movement:

$$C' = C(1 + K_1 \sin \theta - K_2 \cos \delta) \quad (4)$$

where C' is the drag coefficient of a drop in wind conditions, C is the Fukui et al. (1980) drag coefficient for a spherical drop in function of Reynolds number, θ is the angle formed by the drop velocity vector with respect to the air ($\mathbf{V}$) and drop velocity respect to the ground ($\mathbf{U}$), and δ is the angle formed by the vectors $\mathbf{V}$ and the wind velocity ($\mathbf{W}$), with $\mathbf{V}=\mathbf{U}-\mathbf{W}$.

Among the numerical methods to solve droplet dynamics, the fourth order Runge-Kutta is the most used (Fukui et al. 1980; Vories et al. 1987, Carrión et al. 2001, Dechmi et al. 2003, Playán et al. 2006). Zapata et al. (2009) compared the fourth order Runge-Kutta with a second-third order Runge-Kutta pair concluding that the latter is more efficient, reducing the computational time on 90% from the original. Zerihun et al. (2016) used a fourth-fifth order Runge-Kutta pair in order to precise the drop dynamics but increasing the computational time.

The objective of sprinkler droplet dynamics modeling is limited to compute the landing coordinates of the droplets on the field surface and does not include the determination of their volumetric application rates (Zerihun et al. 2016). Volumetric application rates and associated parameters are estimated using semi-empirical procedures (Fukui et al. 1980; von Bernuth and Gilley 1984; Vories et al. 1987; Seginer et al. 1991; Montero et al. 2001; Playán et al. 2006; Zerihun and Sanchez 2014). In order to overcome the empiricism that limits the predictive ability of the model, field experiments are required to calibrate and validate the model parameters. Authors such as Fukui et al. (1980); Vories et al. (1987); Seginer et al. (1991), presented the parameter calibration for one type of sprinkler by single test under the same technical and meteorological conditions. Montero et al. (2001) reported the calibration of the parameters using SIRIAS model for different combinations of sprinkler types, riser heights, nozzle diameters, pressure head and

wind velocities and directions. Playán et al. (2006) presented the Ador-Sprinkler simulation model including a database for two sprinkler types commonly used in the Ebro Valley irrigation systems. The model parameters are presented as a function of sprinkler type, nozzle size (two combinations), nozzle pressure head (from 200 kPa to 400 kPa) and wind velocity (from 0 to 8 m s⁻¹).

During the irrigation, a significant part of the water discharged by the sprinkler does not reach the soil surface due to evaporation and drift of the drops. These losses are known as Wind Drift and Evaporation Losses (*WDEL*) and depend mostly on meteorological conditions. Analytical approaches to describe the evaporation of the sprinkler droplets under no windy conditions have been presented in the literature (Kincaid and Longley, 1989; Thompson et al., 1993; Lorenzini, 2002; Lorenzini, 2004; Lorenzini, 2006; De Wrenchien, 2006; Li et al. 2015). But in presence of small, medium or high wind speeds (common in our environment and in our data base of field experiments) few approaches have been developed due the complexity of the process. Yazar (1984) measured the evaporation of impact sprinklers in an open field by using catch-funnels to measure electric conductivity (evaporating range losses between 1.5% and 16.8%) and also measured drift with plates covered by magnesium oxide (drift measured up to 15%). King et al. (2012) proposed a methodology for measuring *WDEL* from center pivot sprinklers using a combination of applied water collectors, bromide tracer and air samplers. These experimental methods allow measuring separately evaporation from drift. Depending on the experimental conditions, some research works reports minimum percentage of losses due the evaporation (lower than 5%) compared with drift (Seginer, 1971; Heerman and Kohl 1980; Edling, 1985; Thompson et al. 1993). A well-defined coupled heat and mass transfer approach is needed to completely match evaporation and drift losses of the sprinkler droplets. Also specific experiments are needed to effectively calibrate and validate the separate model.

Experimentally, the evaporation and drift losses on impact or spray sprinklers have been measured in the literature as the difference of percentage of the total water discharged by the sprinklers and the water collected by catch-cans (Tarjuelo et al.

2000; Dechmi et al. 2004; Playán et al. 2005) following international standards as ISO-15866-3 and Merriam and Keller (1978). The sprinkler simulation models take these losses into account by: a) correcting the water distribution radial curve, b) subtracting it from the pluviometry accumulated in every cell of the simulated grid or c) by adjusting the volumetric drop size distribution curve (Carrión et al. 2001; Playán et al. 2006). SIRIAS (Carrión et al. 2001) implemented an experimentally based *WDEL* model on the findings of Montero et al. 1999, where the vapor pressure deficit of the air and the wind velocity are the main factors in the equation.

Summarizing, the previous research works on sprinkler irrigation simulation (Fukui et al. 1980; Vories et al. 1987; Carrión et al. 2001; Montero et al. 2001; Dechmi et al. 2003; Dechmi et al. 2004; Playán et al. 2006; Zapata et al. 2009) consider a variety of equations to predict the *WDEL*, different methodologies to solve the drops trajectory and drop size distributions, likewise their calibration process resulted time-consuming. This research presents a new simulation model based on that reported in Playán et al. (2006) (Ador-Sprinkler) that includes improvements on the drops size distributions, drops generation, the ballistic model definition and on the calibration and validation processes.

The new model incorporates a database of field experiments, 40 performed under isolated sprinkler and 167 under solid-set configuration (from which, 60 were done under low operating pressures). The experiments include a wide variety of sprinkler types (including those with the modification of Kincaid et al. 1991), nozzle sizes, pressure heads, sprinkler layouts and meteorological conditions (wind velocity and direction), that covers the features found in the sprinkler irrigated area of the Ebro Valley (Spain). In addition, a self-calibration module was developed to optimize model parameters based on the experimental database. The objective is to develop a simulation tool for sprinkler irrigation that adjusts the model parameters to the current experimental database or to an extended database including new experiments provided by the users. The specific objectives of this research are: 1) to compile a database of field-experiments considering a variety of sprinkler types, nozzle sizes, working pressures, solid-set configurations and meteorological

conditions commonly used in the irrigation systems of the Ebro Valley; 2) to improve the ballistic simulation model; 3) to develop a self-calibration module to optimize the parameters of the model to reproduce adequately the field-experiment database and 4) to develop an on-farm sprinkler simulation model coupling the field-experiment database, the self-calibration module and the on-farm sprinkler simulation module.

2. Materials and methods

2.1 The ballistic model

2.1.1 Numerical solution

Considering weight, buoyancy and drag forces, the ballistic dynamics of a spherical drop is given by:

$$\mathbf{A} = (1 - \rho_a/\rho_w) \mathbf{g} - \frac{3 \rho_a C' |\mathbf{U} - \mathbf{W}|}{4 \rho_w d} (\mathbf{U} - \mathbf{W}) \quad (5)$$

where $\mathbf{A}$ is the drop acceleration vector, $\mathbf{g}$ is the gravity vector, ρ_a is the air density, ρ_w is the water density, $\mathbf{U}$ is the drop velocity vector with respect to the ground and $\mathbf{W}$ is the wind velocity vector.

The drops trajectory was solved by using the following third order Runge-Kutta (RK3):

$$\mathbf{R}_0 = \mathbf{R}(t), \quad \mathbf{U}_0 = \mathbf{U}(t), \quad \mathbf{A}_0 = \mathbf{A}(\mathbf{U}_0)$$

$$\mathbf{R}_1 = \mathbf{R}_0 + \mathbf{U}_0 \Delta t, \quad \mathbf{U}_1 = \mathbf{U}_0 + \mathbf{A}_0 \Delta t, \quad \mathbf{A}_1 = \mathbf{A}(\mathbf{U}_1)$$

$$\mathbf{R}_2 = \mathbf{R}_0 + \frac{\Delta t}{4} (\mathbf{U}_0 + \mathbf{U}_1), \quad \mathbf{U}_2 = \mathbf{U}_0 + \frac{\Delta t}{4} (\mathbf{A}_0 + \mathbf{A}_1), \quad \mathbf{A}_2 = \mathbf{A}(\mathbf{U}_2)$$

$$\mathbf{R}(t + \Delta t) = \mathbf{R}_0 + \frac{\Delta t}{6} (\mathbf{U}_0 + \mathbf{U}_1 + 4\mathbf{U}_2), \quad \mathbf{U}(t + \Delta t) = \mathbf{U}_0 + \frac{\Delta t}{6} (\mathbf{A}_0 + \mathbf{A}_1 + 4\mathbf{A}_2) \quad (6)$$

where $\mathbf{R}$ is the position vector of the drop, Δt is the time (t) increase and the numbers 0, 1 and 2 are the step numbers.

A variable temporal increase has been used following Equation 7. The maximum error allowed for the drops trajectory was 10 cm.

$$\Delta t = k_t \left(\frac{4 \rho_w d}{3 \rho_a C' |\mathbf{U} - \mathbf{W}|} \right) \quad (7)$$

where k_t is a dimensionless factor between 0 and 1.

An analysis of maximum efficiency has been performed between Runge-Kutta methods from first to fourth order and with different k_t (0.1, 0.2, 0.3 and 0.4). Comparisons were made based on the maximum error and computing time of the numerical solutions.

2.1.2 Meteorological simulation conditions

The simulation of a sprinkler irrigation event typically uses a mean of the meteorological variables during the total irrigation time. In this new approach, the measured variability of the meteorological data during the experiment was considered. The meteorological conditions of the experiments presented in Table 1 were obtained from an ad-hoc meteorological station that measured data every 5 or 10 seconds and recorded averages every 5 minutes. The meteorological variables were: air temperature, relative humidity, wind velocity, resultant of wind velocity and wind direction.

The experimental irrigation events lasted for two hours. The simulation of the irrigation events was performed in four different ways: considering only one average of the wind velocity data (120 min frequency), average of four wind velocity data (30 min frequency), with twelve wind velocity data (10 min frequency) and the average of twenty-four wind velocity data (5 min frequency). Differences on simulated Christiansen's Uniformity Coefficient (*CUC* – Christiansen, 1942) and the Root Mean Square Error (*RMSE*) between the four frequencies of wind data were analyzed. A common practice in sprinkler simulation modeling is to consider a constant wind velocity during the irrigation time that corresponds to the average value obtained from agrometeorological stations (the Spanish SIAR agrometeorological network provides data every 30 minutes). Field experiments

presented in Table 1 have different availability of wind velocity data. Only some of them installed an *ad-hoc* meteorological station to record wind velocity data with a 5 minute frequency. The experiments with high frequency wind velocity data were selected for this analysis.

2.1.3 Wind drift and evaporation losses model

Due to the limitation of the data-base field experiments on wind drift and evaporation losses measurement conditions, *WDEL* could not be separated on evaporation and drift losses with a minimum scientific rigor. A compromise between data availability and modeling approach has resulted in the selection of an empirical based *WDEL* model.

An equation for computing *WDEL* was obtained from a statistical analysis considering the whole solid-set experiments (167). The model was integrated in a multiple linear regression with the *WDEL* (dependent variable) obtained from each experiment for each sprinkler of Table 1 and with five explicative variables (independent variables), three of them meteorological conditions (wind velocity, air temperature and relative humidity) and two more from sprinkler configuration and operation (nozzle diameter and operating pressure). The *WDEL* and meteorological variables measured were obtained from each of the 167 solid-set experiments.

2.1.4 Throwing and landing point of the drops

The irrigated area was partitioned in square or rectangular cells to simulate its irrigation depth. In previous research works (Dechmi et al. 2004; Playán et al. 2006) the simulated area was considered flat and all the cells have the same elevation. In this research the topography of the terrain was incorporated in the model by introducing the elevation of several location points. The elevation of each cell was interpolated from three closest elevation points and its relative location. At each cell, two rainfalls were accumulated, the one that falls to the crop or the one that falls to the pluviometer at its corresponding height (if the cell as a pluviometer). The volume of a drop is associated to a pluviometer if the cell has a pluviometer and if the drop falls downwards to the plane of the pluviometer. The trajectory of a simulated drop

ends when the drop passes under the crop height.

The effect of the terrain topography (slope) on irrigation uniformity was studied. The whole sprinkler irrigation solid-set experiments of Table 1 were used for the analysis. Although all the field experiments of the database were performed under a flat terrain, slopes of 5% were also simulated. This is roughly the maximum slope in sprinkler irrigation that is observed in our study region. The simulated layouts had 16 sprinklers with different elevation describing the slope. The slope was rotated in the axis between the sprinkler lines from 0 to 360° with 45° intervals. Maximum and minimum differences on simulated CUC between considering a flat layout (CUC_{flat}) or a sloped layout (CUC_{slope}) were presented.

2.2 Generation of simulated drops

Ballistic models require the generation of a number of virtual drops to simulate their dynamics that matches the behavior of the real drops. The number of simulated drops does not need to be coincident with the number of real drops generated by the sprinkler. The large number of drops with similar characteristics landing in the area close to the sprinkler could be simulated by a low number of simulated drops with similar volume. The technique is especially important for the irrigated area far away from the sprinkler, where the number of landing drops is small. In this area, to simulate an adequate pluviometry, a large number of simulated drops is needed. The sampling error is the error due to the lack of representativeness of the virtual drops. In Monte-Carlo and regular sampling methods, this error is known to be inversely proportional to the root of the number of samples. Then, the sampling error in the simulated pluviometry is also inversely proportional to the root of the number of simulated drops landing on the terrain cell. Therefore, to minimize the sampling error and to maximize computing efficiency, the most convenient procedure is to have a uniform spatial density of drops at the irrigated area. Also, a minimum number of drops are required at each cell of the terrain to control the sampling error. It has to be noted that the number of drops landing in an area is not always proportional to the pluviometry because it depends on the drop associated volume.

In order to maintain the sampling error at low values ($\approx 2\%$) around 2,000 drops were required to fall in each cell of the terrain, resulting in 7,200,000 total drops in isolated sprinklers and 800,000 for solid-set configuration.

2.2.1 Regular systematic sampling method (RSS)

In previous sprinkler simulation models (Fukui et al. 1980; Vories et al. 1987; Carrión et al. 2001; Dechmi et al. 2003; Playán et al. 2006), a set of regular horizontal angles from 0° to 360° and a set of regular drop diameters from 0.2 mm to 7 mm were generated using a constant interval. The drop diameters and throw angles were generated following:

$$d_i = 0.2 \text{ mm} + (7 \text{ mm} - 0.2 \text{ mm}) \frac{D_i}{N_D}, \quad \varphi_i = 360^\circ \frac{\psi_i}{N_\varphi} \quad (8)$$

where $D_i = 0, 1, \dots, N_D$ and $\psi_i = 0, 1, \dots, N_\psi$

and with d_i and φ_i the drop diameter (mm) and the horizontal throw angle of the i -th drop, respectively, D_i and ψ_i the sampled number of diameter and of throw angle, respectively, and N_D and N_φ the total sampled number of drop diameter and of throw angle, respectively. The total number of virtual drops is given by: $(N_D + 1) \cdot (N_\varphi + 1)$.

In the RSS method, the number of virtual drops increases exponentially with the number of sampled variables. Therefore, the computational cost of this method can be too high sampling three or more variables.

The density function of this sampling method is constant and can be defined by:

$$p(d, \varphi) = 1 \quad (9)$$

2.2.2 Uniform Monte-Carlo sampling method (UMCS)

In this research the meteorological conditions were also sampled in the virtual drops. This additional variable increases the number of virtual drops of the RSS method.

Random based methods, as UMCS, have proven more efficient than regular systematic methods when sampling multiple variables (Bergstra and Bengio 2012).

1 The UMCS method generates the drops according to:

$$2 \quad d_i = 0.2 \text{ mm} + (7 \text{ mm} - 0.2 \text{ mm}) r_1, \quad \varphi_i = 360^\circ r_2, \quad t_i = T r_3 \quad (10)$$

3 with t_i the meteorological conditions sampling time, T total time simulated and r_1 ,
 4 r_2 , and r_3 random numbers between 0 and 1. The total number of virtual drops is
 5 fixed, not depending on the number of sampled variables. Therefore, UMCS method
 6 is usually more efficient sampling three or more variables.

7 The sampling density function is constant and can be defined as:

$$8 \quad p(d, \varphi, t) = 1 \quad (11)$$

9 2.2.3 Bimodal Monte-Carlo sampling method (BMCS)

10 In order to improve the computational efficiency and the sampling errors with respect
 11 to the UMCS method, a new Monte-Carlo method (BMCS) with a variable density
 12 function was analyzed. The BMCS method has a sampling density function
 13 depending on the drop diameter in a bimodal way:

$$14 \quad p(d, \varphi, t) = d^{a-1} \exp(-b d^a) \quad (12)$$

15 with a and b two parameters to calibrate. This method generates t_i and φ_i in the
 16 same way as the UMCS method but the drop diameter as:

$$17 \quad d_i = \left[0.2^a - \frac{1}{b} \ln(1 - \{1 - \exp[-b (7^a - 0.2^a)]\} r_1) \right]^{1/a}, \quad \varphi_i = 360^\circ r_2,$$

$$18 \quad t_i = T r_3 \quad (13)$$

19 The coefficient of variation (CV) was assessed for the tree sampling methods (RSS,
 20 UMCS and BMCS) defined as the ratio of the standard deviation to the mean of the
 21 number of virtual drops per terrain cell.

22 2.2.4 Volume assigned to the simulated drops

23 As an alternative to obtain drop sizes, such as the intrusive or not intrusive
 24 techniques listed in the Introduction section, in this work the ballistic model was used

to estimate drop size distribution. The landing distance of different drop diameters resulting from a given sprinkler model, nozzle elevation and operating pressure in the absence of wind has been simulated with the ballistic model. The percentage of the irrigation water collected at each landing distance measured from isolated sprinklers in the absence of wind was used to estimate the percentage of the irrigation water emitted in drops of a given diameter. The model and its parameters d_{50} and n from Weibull (Equation 1) or α , μ and σ from ULLN (Equation 2) that resulted in the best agreement with the experimental radial water application pattern were selected for each combination of sprinkler model, nozzle size, nozzle elevation and operating pressure in the absence of wind.

The performance of both distributions (ULLN and Weibull) was analyzed for each sprinkler type and operation condition.

Summarizing, the falling point of each simulated drop was obtained with the ballistic theory, its associated volume was given by the volumetric drop size distribution and finally the volume of water was accumulated in its respective ground cell.

The associated volume of a drop entering a cell was accumulated following:

$$V_i = (1 - WDEL_j) Q_j T \frac{f(d_i)/p(d_i, \varphi_i, t_i)}{\sum_i f(d_i)/p(d_i, \varphi_i, t_i)} \quad (14)$$

where V_i and d_i are the associated volume and diameter, respectively, of the i -th drop, Q_j and $WDEL_j$ are the sprinkler application rate and the wind drift and evaporation losses, respectively, of the j -th nozzle, T is the irrigation time of the experiment, $f(d_i)$ is the volumetric drop size distribution (Equations 1 and 2) and $p(d_i, \varphi_i, t_i)$ is the sampling density function (Equations 9, 11 and 12).

Note that the associated volume to the simulated drops V_i (Equation 14) has no relationship with the real volume of a spherical drop.

2.3 Database of field experiments

Table 1 summarizes the field experiments that were considered for calibration and validation of the proposed model. All these experiments were performed following

international standards (Merriam and Keller, 1978) and were accomplished by the RAMA research group (RAMA, 2018). Six types of impact sprinklers equipped with different nozzle sizes and operating at different pressures were available in the database.

Two types of field experiments were reported in the database for each sprinkler type: isolated sprinkler and solid-set layouts.

The isolated sprinkler experiments were performed in a wind protected plot and the radial pluviometry was determined under no wind conditions. A set of catch-cans were located around the sprinkler in four radii at 90° each (oriented to the cardinal points); the catch cans were spaced every 0.5 m. The height of the sprinkler was 2 m and the irrigations lasted 2 h for all the experiments. The water application pattern of the isolated sprinklers was used to calibrate the parameters of the volumetric drop size distribution functions (Equations 1 and 2).

The experiments on solid-set covers different sprinkler layouts as rectangular and square with distances of 18 m and 15 m between sprinkler lines and 18 m and 15 m between sprinklers. All the solid-set experiments lasted 2 h. The solid-set layout was composed of 16 sprinklers. A 25 catch-can network was homogeneously distributed between the four central sprinklers of the solid-set layouts. Catch-can network allowed measuring the irrigation depth and determine the irrigation performance indexes as the *CUC* and the *WDEL*. Each sprinkler type arranged in a solid-set configuration was evaluated under different working pressures from 200 kPa to 400 kPa and under different wind velocities ranging from a minimum of 0.4 m s⁻¹ to a maximum of 9.3 m s⁻¹. The meteorological conditions of each experiment were measured every 5 or 10 seconds and monitored every 5 min with an automatic meteorological station located in the experimental plot. The solid-set experiments provide data to calibrate the parameters of the model describing the drag coefficient, K_1 and K_2 (Equation 4). The experiments were also used to validate the solid-set irrigation model.

The plastic catch-cans used for both field experiment types (isolated and solid-set)

were 0.40 m high and were conical in shape with a circular opening of 0.16 m. The pluviometers were marked for direct readout with 1 mm intervals of precipitation. The cans were placed at 0.40 m from the soil using plastic sticks to place them vertically. Further information about the cans set-up used for each sprinkler can be found in the works cited in Table 1 (Playán et al. 2006; Sánchez et al. 2011; Stambouli et al. 2014; Paniagua 2015; Robles et al. 2017).

A new set of field experiments were performed in this research (RC130p) to include in the database (Table 1). Using the same impact sprinkler Riegos Costa 130 H from Playán et al. (2006) and Stambouli et al. (2014), different nozzles made of plastic and threaded to the sprinkler were tested. The nozzles used in Playán et al. (2006) were made of brass threaded to the sprinkler, while those of Stambouli et al. (2011) were of bayonet coupled and made of plastic. Further details of the experiments features can be found in their respective reference in Table 1.

For the RC130p sprinkler, the principal nozzle size was 5.2 mm and the auxiliary nozzle was 2.4 mm. The experiments of RC130p sprinkler were performed under low pressure, 200 kPa. The objective of this set of experiments was to include in the database an alternative configuration to operate at low pressure (200 kPa) but maintaining the discharge of the sprinklers working at the standard pressure (300 kPa) (Robles et al. 2017). Four experiments were performed on isolated sprinkler configuration under no wind conditions and with an average air temperature of 17°C (ranged between 11°C and 26°C). Eleven experiments were performed on a rectangular 18 m by 18 m solid-set configuration, with wind velocities ranging from 0.6 to 5.0 m s⁻¹ and an average air temperature of 24°C (ranged between 11°C and 33°C). The features of both experiment types were in accordance to the procedures of the other field experiments included in the database.

Totalizing, the database was integrated by 40 experiments on isolated sprinkler configurations and 167 experiments on solid-set layouts.

2.4 Calibration process

2.4.1 Terrain cell size

The dimension of the cells (where the drops are accumulated) for calibrating the parameters of the Equations 1 and 2 were fixed in 0.5 m x 0.5 m in accordance with the spacing of the pluviometers in isolated sprinkler.

An analysis to define the optimal cell size was performed for the calibration parameters of the Equation 4 (K_1 and K_2). Different cell sizes were analyzed (0.5 m, 1.2 m and 3.6 m) considering the *CUC* correlation and the corresponding computational time. It is necessary to take into account that reducing the cell size increases the number of simulated drops in order to control the sampling error.

2.4.2 Objective function

An adequate sprinkler irrigation model should provide a good estimation of the averaged applied irrigation depth and also a good approximation of its spatial variability. The most common index to describe the variability of the irrigation performance in sprinkler irrigation is the *CUC*. The objective function of the proposed model included both variables by minimizing the error between measured and simulated values (Equation 15). The error norm usually includes parameters as the *RMSE*, the coefficient of determination (r^2) or correlation (r) and a combination between *RMSE* and the other two coefficients (r^2 or r). This error norm has been established as the objective function in previous irrigation simulation models (Dechmi et al. 2004; Playán et al. 2006). In this research, the objective function to minimize was:

$$RMSE + \Omega (CUC_{mea} - CUC_{sim})^2 \quad (15)$$

where $\Omega = 0.05 \text{ mm hr}^{-1}$ is a weight coefficient, and CUC_{mea} and CUC_{sim} are the *CUC* measured and the *CUC* simulated, respectively.

2.4.3 Optimization algorithms

The Multiple-Purposes Calibration and Optimization Tool (MPCOTool) has been used to compute the optimal parameters of the ballistic simulation model in sprinkler irrigation. MPCOTool is a free calibration module that allows computing the input empirical parameters used in physical models once the objective function is defined

(Burguete, J. and Latorre, B. 2018).

The module implements different optimization algorithms such as: regular systematic sampling-RSS, Monte-Carlo, hill climbing and genetic algorithms (Burguete et al. 201Xa). The search interval of the brute force methods (Monte-Carlo and RSS) can be progressively decreased using an iterative method to improve the convergence.

A combination of three algorithms (Monte-Carlo, hill climbing and iterative method) has been used to optimize the parameters of Equations 1, 2 and 4. The best result by Monte-Carlo algorithm is refined using the hill climbing search method. An iterative method was applied to the combination between Monte-Carlo and hill climbing algorithms selecting a given number of simulations (10 in this research) with the lowest values of the objective function. These candidates define the extreme values of the next iteration where Monte-Carlo and high climbing algorithms are again performed to improve the convergence. This process will be repeated as many times as iterations are established. An exhaustive description of these methods can be consulted in the user manual of the MPCOTool.

For the calibration of the 2 parameters of the Weibull distribution (Equation 2) and the C' distribution (Equation 4), a total of 348 simulations were performed: 100 Monte-Carlo simulations plus 16 simulations for hill climbing search were repeated 3 times with the iterative method. For the calibration of the 3 parameters of the ULLN distribution (Equation 1), the number of simulations and iterations, 896, increased because one additional dimension has to be explored. In this case 200 Monte-Carlo simulations plus 24 simulations for hill climbing search were repeated 4 times with the iterative method. A schematic description of the convergence of the algorithms was represented for the Weibull distribution, C' and ULLN distribution using one sprinkler as an example.

Optimal parameters and the simulated pluviometry were obtained for all irrigation events. Moreover, for solid-set experiments the CUC of the simulated pluviometry was computed and a set of equations for the empirical parameters of C' model was

established for the whole database.

2.5 Validation process

Cross-validation was used to assess the predictive performance of the model. This approach splits the available data into two parts, a training set and a validation set. The first set was used to fit the regression model and the test set provides an error estimate. We focused on a particular form of cross-validation, called leave-one-out cross-validation (LOOCV). In this case, only one point was selected as the test set. The regression model was built on the remaining data, evaluating its error on the single-point held out. A global error estimate was obtained by repeating this procedure for each of the training points available. Although the LOOCV increases the computational costs, since a number of iterations were performed, the error was minimized and estimated for all data points. Comparisons of pluviometry and *CUC* of simulated and measured values were performed for the experiments. From the 167 experiments, 40 of them were not considered for validation because predictions with high wind velocities ($>5 \text{ m s}^{-1}$ up to 9.3 m s^{-1}) produce important errors. The predictive ability of the model was assessed in terms of *CUC* and *RMSE*. Both Weibull and ULLN distributions were validated independently and the results were compared.

3. Results and discussions

3.1 Analysis of computational efficiency

Numerical comparisons between Runge-Kutta methods were presented (Figure 1) to select the optimal numerical method, including variable and constant time step. The filled symbols in Figure 1 represent the first to four order Runge-Kutta methods with a constant time step (Δt), while the empty symbols represent the same Runge-Kutta methods but with variable time step, with k_t between 0 and 1 (Equation 7). The computational efficiency, inversely proportional to the steps number, depends on the required accuracy, being the low order methods more efficient for low accuracy. In all cases, it is noticeable that considering a variable Δt reduces the number of steps with respect to any constant Δt . In this research, a maximum error of 10 cm was

allowed in the numerical drop trajectories. The method of third order Runge-Kutta with $k_t = 0.3$ was the most efficient to solve the drops dynamics within the required accuracy. Fourth order Runge-Kutta method (RK4), commonly used to solve the drops dynamics, with variable time step is the most efficient technique for errors less than 5 cm. Nevertheless, for the desired accuracy, the calculation time of RK4 increases in 8.5% with respect to the RK3.

3.2 Wind measurement interval

Figure 2a shows the analysis of the CUC_{mea} and the CUC simulated (CUC_{Wvfreq}) considering different wind measurement intervals (5 min, 10 min, 30 min and 120 min). The simulations of these analyses have been performed using both ULLN (Equation 1) and Weibull (Equation 2) drop size distributions. The results indicate an increase in the CUC differences with the wind measurement frequency. These differences reached maximum values when the wind is considered as a constant value in the simulations (frequency of 120 min) and reached minimum values for the 5 min measurement interval. The CUC differences generally increased with the wind velocity. The average of CUC differences for all measurement intervals was less than 4% particularly for calm wind conditions ($< 2 \text{ m s}^{-1}$). Analyzing all data, the differences between CUC_{mea} and CUC_{Wvfreq} for measurement intervals of 5 min, 10 min, 30 min and 120 min reached average values of 5.5%, 5.6%, 6.0% and 9.0%, respectively.

The $RMSE$ of the pluviometry simulated with the four measurement intervals ($RMSE_{Wvfreq}$) was obtained and summarized in Figure 2b. Maximum, minimum and average values are shown for each interval. Statistically, there is a significant difference at 95% confidence level (Fisher's LSD test) of the means of $RMSE$ for the interval of 120 min with respect the other three. Larger values of $RMSE_{Wvfreq}$ for 120 min were observed, particularly for the average and the maximum value.

From the analysis of the differences in CUC and $RMSE$ of pluviometry for the four wind measurement intervals, there is no significant difference of considering the wind velocity frequency at intervals lower than 30 min for all the simulations. Considering

a constant average (120 min), as commonly used in the previous works, significantly increases the errors on the estimated pluviometry.

3.3 Wind Drift and Evaporation Losses

The 167 solid-set experiments (Table 1) were analyzed to compute the *WDEL* as a percentage of the water collected in the pluviometers and the water emitted by the sprinklers. The application rate of the sprinklers was considered using the flow-pressure curves reported by the authors or obtained from the manufacturers catalog. Maximum losses of 45% and minimum of 0.14% were obtained. It is important to mention that these losses are subjected to the uncertainty of the experimental measurements.

The *WDEL* for the 167 experiments on solid-set configuration were obtained by using a multiple linear regression considering a number of factors:

$$WDEL = 35.4 + 3.13 W + 0.262 T - 0.0827 Rh - 7.45 \cdot 10^3 Ed + 3.65 \cdot 10^{-6} P \quad (16)$$

with $Ed = (d_m^3 + d_a^3) / (d_m^2 + d_a^2)$

where *WDEL* is expressed in %, *W* is the wind velocity (m s^{-1}), *T* is the air temperature ($^{\circ}\text{C}$), *Rh* is the relative humidity (%), *Ed* is the diameter equivalent of the sprinkler nozzles (mm), *P* is the operating pressure (Pa), *d_m* and *d_a* are the main and auxiliary diameter nozzles (mm), respectively.

The performed statistical analysis as a linear regression by using only the wind velocity as explicative variable of the 167 solid-set experiments, suggests that wind velocity explains 35% (coefficient of correlation, r^2) of the *WDEL*. In previous research works, wind velocity is reported as the most important factor in *WDEL* (Yazar, 1984; Tarjuelo, 1999; Dechmi et al. 2003; Playán et al. 2005). In contrast, using a linear regression for the solid-set experiments with only the operating pressure, this was the lowest significant factor, contributing only to 1% (r^2) of the *WDEL* variability.

The coefficients of the equation 16 represents the physics of *WDEL*, which increases with the wind velocity, temperature and pressure, and decreases with relative humidity and nozzle diameter. The uncertainty of the individual measurements is reduced by the model since a high number of experimental tests are considered. The Equation 16, as a multiple linear regression by using the wind velocity, the air temperature, relative humidity, diameter equivalent of the sprinkler nozzles and the operating pressure as explicative variables of the *WDEL* for the 167 solid-set experiments, explains 60% (r^2) for the measured *WDEL* of the 167 solid-set experiments.

3.4 Effect of slope on irrigation performance

The effect of the slope on *CUC* is presented in Figure 3 for different wind velocities. The maximum and minimum *CUC* differences of the eight simulated slopes directions (every 45°) in each experiment were represented with a different line. The consideration of the slope in the terrain increases or decreases the *CUC*, to a greater or less extent, depending on the wind velocity, the wind direction and the slope direction. In general, there is a tendency in *CUC* differences to overpass 5% when the wind velocity is higher than 4 m s^{-1} . On the contrary, at wind velocities lower than 4 m s^{-1} the *CUC* differences barely reach 5%. The largest *CUC* differences of 11% were found for maximum and minimum values. The differences are more noticeable when the slope is in the same direction of the predominant wind direction of the experiment because drops trajectory is lengthened or cut depending on the slope sense and the water application pattern is modified. On the other hand, this effect is less important when the slope is perpendicular to the wind direction.

3.5 Drop generation

The spatial distribution of the simulated drops falling points for an isolated sprinkler is shown in Figure 4a, 4b and 4c for the three sampling methods. The number of simulated drops falling in a terrain cell with respect to the distance between the cell center and the sprinkler is presented in Figure 4d, 4e and 4f for its respective sampling method.

Figure 4a and 4d shows the drops generated with the RSS method by Playán et al. (2006) using 180 horizontal angles (radially distributed) and 180 drop diameters. It is observed a high concentration of simulated drops in the center of the sprinkler that decreases with the distance of the sprinkler. The average number of drops generated in the simulated cells is around 10, with a coefficient of variation (CV) of 37%.

The same behavior has been observed in the UMCS method (Figure 4b and 4e) but the number of simulated drops increases to an average of 2071 with a CV of 25%.

The parameters a and b (Equations 12 and 13) of the BMCS method have been calibrated to minimize the CV, resulting in optimal values $a=0.39$ and $b=1.30$. Using these values, the BMCS method simulates the drops more homogeneously (Figure 4c and 4f), the CV is reduced to 10% and the average number of drops is increased to 2120.

3.6 Model calibration

3.6.1 Size of simulation cells

Figure 5 shows the relationships between CUC_{mea} and CUC_{sim} for the three terrain cell sizes analyzed. The relationships shown in the Figure 5 were performed for the Weibull distribution since statistically no significant differences were observed with respect to the ULLN distribution at 95% confidence level after a t-test. The coefficient of determination (r^2) was 0.75 approximately for the three cell sizes analyzed. The slope of the regression line for the 3.6 m cell size was the most different from the 1:1 line (Figure 5c), and therefore a large variability of the CUC_{sim} was observed. Simulating with a cell size of 3.6 m slightly overestimate the CUC compared with the other cell sizes, particularly for the high wind velocity events (lower values of CUC). As expected, the computing time increases as the cell size decreases. At smaller cell size, a larger number of drops per nozzle size should be simulated in order to maintain the sampling error. Decreasing the cell size from 3.6 m to 1.2 m increases the computing time by 9 times with respect to the 3.6 m cell size; whereas, for the 0.5 m cell size the computing time increases by 49 times with respect to the 3.6 m

cell size. In order to achieve the best fit of *CUC*, avoiding a time consuming process, the 1.2 m cell size has been selected for calibration and validation.

3.6.2 Optimization algorithms

The convergence of the algorithms for each model (Weibull, *C'* and ULLN) is reflected in Figure 6. The models with two parameters to calibrate (Weibull and *C'*) simulate 116 times for iteration Figure 6a (Weibull) and Figure 6b (*C'*), while the ULLN distribution (Figure 6c) simulates 224 times for iteration. The optimum values of each model are those combinations of the parameters of the models that produce the minimum value of the objective function.

The boundary values for Weibull distribution (Weibull Figure 6a) are: 0.2-7.0 mm (d_{50}) and 0-5 (n). The drag coefficient thresholds (*C'* Figure 6b) are: 0-4 (K_1) and 0-1 (K_2). Finally, ULLN distribution (Figure 6c) is bounded by: 0.5-7.0 mm (α), -3 to 1 (μ) and 0.3-1.4 (σ). The optimal parameters could exceed these values since a tolerance of 10% has been established for each iteration. Further details of algorithms and tolerances could be found in the MPCOTool manuals (Burguete, J. and Latorre, B. 2018).

3.6.3 ULLN and Weibull distributions in isolated sprinklers

The 40 experiments performed on isolated sprinkler (Table 1) were used to calibrate the volumetric drop size distribution using the Equation 1 (ULLN) and Equation 2 (Weibull). The results of calibrations with both distributions are shown in Table 2. The experiments were performed with wind velocities ranging from 0.39 m s⁻¹ to 2.8 m s⁻¹ with a minimum pressure of 173 kPa to a maximum of 420 kPa. The flow measured in each experiment is also reported in the Table 2 for every sprinkler and pressure.

According to Table 2, there is no significant difference of *RMSE* between Weibull and ULLN distributions. The average *RMSE* was 0.7 mm hr⁻¹ for both distributions. The minimum and maximum values of *RMSE* were similar for both distributions with an average of 0.37 mm hr⁻¹ and 1.3 mm hr⁻¹, respectively. The correlation

coefficients were also similar ranging of 0.75 to 0.97. In 90% from the 40 cases analyzed, the *RMSE* is below 1 mm hr⁻¹ for the Weibull as much for ULLN distribution. The *RMSE* average of the other 10% reaches 1.12 mm hr⁻¹ for the two distributions. In Table 2, the maximum values of *RMSE* for both Weibull and ULLN distributions (1.29 mm hr⁻¹ and 1.33 mm hr⁻¹, respectively) were found for the same sprinkler type, nozzle size and operating pressure: sprinkler RC130BY, main nozzle size of 5.16 mm and an operating pressure of 385 kPa. Despite low values of *RMSE*, ULLN distribution requires a large calibration time. For further research to calibrate new irrigation material the recommendation is to establish a target *RMSE* and/or *r* values to choose the most adequate volumetric drop size distribution.

In this research work, the metrics *RMSE* and *r* were improved using different values of d_{50} and n than those by Playán et al. (2006) with the same distribution (Weibull–Equation 2) for the sprinklers RC130 and VYR70. The *RMSE* decreases with the new version of the model from an average value of 2.1 mm h⁻¹ to 0.68 mm h⁻¹ for the RC130 sprinkler and from an average value of 1.77 mm h⁻¹ to 0.55 mm h⁻¹ for the VYR70 sprinkler. Also the values of the correlation coefficient were improved from 0.66 to 0.90 for the RC130 sprinkler, and from 0.75 to 0.95 for the VYR70 sprinkler. In agreement with the findings of Playán et al. (2006), our d_{50} optimum parameters (acting as the volume median diameter) show a moderately strong relationship ($r^2=52\%$) with respect to the operating pressure and nozzle diameters but the optimum values of n shows a weak relationship ($r^2 < 1\%$) with respect to the pressure.

The optimization methods used in both research works could explain the differences, since Playán et al. (2006) used a supervised method to select the optimum values of the parameters. The new model uses automatic algorithms (MPCOTool) to select the optimum values.

The drop diameter (d_{50}) reduces as the operating pressure increases (at higher pressure smaller drop sizes) and as the nozzle size decreases. This effect was clear for the RC130, RC130BY, SOM30C and VYR70 sprinklers, but was not for the NAAN and RC130p sprinkler for pressures lower than 200 kPa and 220 kPa, respectively. These two sprinklers maintain similar d_{50} values for 200 kPa. It has to be noted that

only these two sprinklers have been operated at pressures lower than 200 kPa, so it was not possible to compare this behavior with other sprinklers. There is no explanation for this behavior except that the model is not able to catch the differences on d_{50} for pressures lower than 200 kPa or that the pressure decrease is not enough for the model to catch the difference. Intrusive or not intrusive drop size measurement techniques could be useful to understand the simulated values.

The EV (shown in Table 2) that acts as the mean drop diameter indicates a moderately strong relationship with respect to the operating pressure for both volumetric drop sizes distributions ($r=0.56$). Nevertheless, the EV using ULLN and Weibull distributions are statistically different at 95% confidence level after a t-test since the ULLN distribution is more susceptible identifying drop small diameters compared with Weibull distribution.

In the research work of Zapata et al. (2018), the authors measured the drop size distribution using an optical disdrometer of three different impact sprinklers at different distances in isolated configuration. The sprinklers analyzed, also included in our research work (Table 1), were: RC130 (nozzles 4.4 + 2.4 mm, pressure 300 kPa), RC130p (pressure of 200 kPa) and NAAN (pressure of 200 kPa). They found smaller drops in the experiments with the sprinkler RC130 (300 kPa) and in the sprinkler NAAN (200 kPa) compared with the sprinkler RC130p (200 kPa). Also, they found the larger $WDEL$ for the sprinkler NAAN (200 kPa) and lowest losses for RC130p (200 kPa). Our semi-empirical results of Weibull distribution confirm their results since the EV and d_{50} values (Table 2) indicated larger drop sizes for the sprinkler RC130p (200 kPa) compared with the other two sprinklers. The ULLN distribution also indicates the larger drops for RC130p (200 kPa) and also for NAAN (200 kPa).

3.6.4 Calibration of drag coefficient

The optimum parameters of C' (K_1 and K_2) obtained from the solid-set experiments of the database (a total of 167) are shown in Appendix A. The presented values are divided into two groups: optimized values for the Weibull distribution and optimized

values for the ULLN distribution. Appendix A shows K_1 and K_2 and the reference wind velocity average value of each experiment. Depending on the wind velocity, the uniformity values ranged from 60% to 97%. With respect to the parameters of the drag coefficient C' , minimum values of 0.0 and maximum of 4.89 were found for K_1 using the Weibull distribution and values from 0.0 to 4.0 for the ULLN distribution. The values of K_2 remain between 0.0 and 1.2 for Weibull distribution and between 0.0 and 1.0 for ULLN distribution. There is a statistically significant relationship between wind velocity and the K parameters of the two distributions. The relationship is weak for K_1 , wind speed explains <10% of the K_1 variability for both distributions, while for K_2 parameter there is a moderately strong relationship with respect to wind velocity (wind velocity explains an average of 33% of the K_2 variability for both distributions). Montero et al. (2001) and Playán et al. (2006) showed similar results. The optimum parameters of K_1 and K_2 for both Weibull and ULLN distributions were used to simulate the pluviometry and uniformity of each irrigation event. The $RMSE$, the correlation coefficient r and the CUC from the calibrations (CUC_{cal}) of both distributions were obtained. The optimum values of K_1 and K_2 of the ULLN and Weibull distribution resulted in the same average value of $RMSE$ with 1.0 mm hr⁻¹, respectively. In both distributions the standard deviation of $RMSE$ was similar with an average of 0.43 mm hr⁻¹. The correlation coefficients ranged from 0.0 to 0.91 for Weibull distribution while for ULLN ranged from 0.0 to 0.90. In general, low values of the correlation coefficient correspond to high values of irrigation uniformity (CUC > 84%) reached under low wind velocity conditions.

For the NAAN, RC130p and VYR70 sprinkler types, the ULLN distribution showed lower values of $RMSE$ than the Weibull distribution with an average of 4% for the three sprinklers. Weibull distribution showed lower $RMSE$ values than ULLN with an average of 0.8% for the sprinklers RC130, RC130BY and SOM30C. Statistically, there is no significant difference between the mean of $RMSE$ for both distributions at 95% confidence level. Statistically, three outlier values of $RMSE$ were found for the RC130BY sprinkler equipped with a 5.16 mm main nozzle operating at a pressure of 400 kPa under calm wind conditions and had a possible experimental uncertainty.

Analyzing low pressure, just as observed by Li et al. (1994), ULLN and Weibull distributions were quite similar for the sprinklers RC130, VYR70 and SOM30C independent of the working pressure and the nozzle size. Nevertheless, ULLN distribution reduced the *RMSE* compared Weibull distribution for the NAAN sprinkler using low pressure. Even when the *RMSE* differences are small (0.13 mm hr^{-1}), it represents an important amount of the total sprinkler discharge (13%). The modification of the sprinkler suggested by Kincaid (1991) changes the water application profile making it necessary to adjust the curve by a more robust distribution as ULLN.

The predictive ability of the proposed ballistic model was also assessed comparing the CUC_{mea} with the calibrated CUC_{cal} (Figure 7). The ballistic model explains 99% of the variability of the CUC_{mea} for both Weibull (Figure 7a) and ULLN (Figure 7b) distributions. Summarizing, the new ballistic simulation model, independent of the volumetric drop size distribution selected, showed a good capacity to reproduce the irrigation uniformity.

The K_1 and K_2 values shown in Appendix A were formulated in equations for both distributions of Weibull (Table 3) and ULLN (Table 4). The equations were integrated as a function of the operating Pressure (kPa) using linear and quadratic regressions as a function of the Wind velocity (m s^{-1}). The dependent variables c and b of Tables 3 and 4 were computed through the expression: $x + y (\text{Pressure}-z)$; once c and b are computed, the K_1 and K_2 values are given by the expression: $c * \text{Wind velocity}^2 + b * \text{Wind velocity}$, for each sprinkler type. The maximum operating pressure analyzed was 300 kPa for the sprinklers NAAN and RC130p, 420 kPa for the sprinkler SOM30C and 400 kPa for the rest of sprinkler types.

3.7 Model validation

The predictive ability of the model was assessed comparing measured CUC with simulated CUC using LOOCV for both drop size distributions, Weibull (Figure 8a) and ULLN (Figure 8b). The Weibull and ULLN distributions provide a similar coefficient of determination ($r^2=0.75$). Differences between CUC_{mea} and CUC

validated (CUC_{val}) averaged 2.9% and 2.7%, for the Weibull and ULLN distributions, respectively. Again as in the calibration process, the largest differences between CUC_{mea} and CUC_{val} occurred for the high values of CUC_{mea} (low spatial variability of the irrigation pluviometry). Attending to the $RMSE$, the same differences were found for both distributions just as in the calibration process (averages of 1 mm hr^{-1}). In a particular analysis of $RMSE$ per sprinkler type, ULLN distribution minimized the $RMSE$ for the NAAN and RC130p sprinklers with respect to the Weibull distribution (6.5% and 7.2%, respectively). No differences were observed in $RMSE$ for the rest of sprinklers between using one or another distribution.

3.8 Computational efficiency

Another feature of the proposed model is that the calibrator MPCOTool enables to perform in parallel all the simulations from the calibrations and validation processes by using a computer cluster. With this parallelization, it was possible to perform the calibrations in 11 h using the Weibull distributions while 36 h were required for ULLN distribution using the cluster Trueno (CSIC– Ministry of Economy, Industry and Competitiveness). The calibration and simulations of the drag coefficient of the 167 solid-set experiments consumed 11 h and 13 h for the Weibull and ULLN distributions, respectively. The previous processes cost around 4 months in a conventional computer.

4. Conclusions

An improved ballistic sprinkler simulation model with a self-calibration tool and a database of field experiments was presented. The database covers a wide range of experimental conditions with different sprinkler types and layouts, nozzle sizes, operating pressures and meteorological conditions that were used for calibration and validation of the model parameters.

The third order Runge-Kutta method has been the most efficient computationally compared with the commonly used fourth order Runge-Kutta method establishing a maximum error of 10 cm in the drops trajectory calculations.

A wind velocity measurement interval of 30 minutes (just as the information provided by the agrometeorological services in Spain, SIAR network) was enough to reproduce adequately the water distribution pattern of an irrigation event, when it is not possible to measure at lower intervals.

The effect of considering the plot with slope was not very important in terms of the uniformity, particularly for wind velocities lower than 4 m s^{-1} ($CUC < 5\%$). This effect was more relevant when the slope is in the direction of the wind velocity and at winds higher than 4 m s^{-1} .

The numerical efforts made in drop generation suggested that bimodal Monte-Carlo sampling method simulated the drops more homogenously minimizing the sampling error and increasing the accuracy with respect to regular systematic sampling and uniform Monte-Carlo sampling methods. The cell size of the terrain where the drops fall, has been defined in 1.2 m reaching an agreement between accuracy and calculation time.

The upper limit lognormal was the most efficient model to reproduce the drop size distribution of the sprinklers especially designed to operate at low pressure. No differences were found for the rest of the sprinklers using the Weibull or the upper limit lognormal distributions. The predictive ability of the model in terms of Christiansen's uniformity coefficient in calibration and validation stages was satisfactory (99% and 75%, respectively).

The parallelization of the MPCOTool with the Trueno cluster allowed speeding up the calibrations and simulations processes, minimizing the computing time with respect to a conventional computer (40 times faster).

The auto-calibration procedure incorporated in the model provides a valuable tool for the actualization of the model parameters under new field experiments or under changes in the mathematical definition of the model.

The information provided in tables could be useful in the management irrigation arena at a farm level and irrigation scheduling.

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Highlights

- A sprinkler irrigation ballistic model was modified and automated
- A database with 207 field experiments was integrated in the simulation model
- Wind data intervals should not exceed 30 min for a better sprinkler simulation
- Terrain slope can be relevant for sprinkler simulation specially at high wind speed
- The new model improves accuracy and computing time of calibrations and simulations

Table 1. Summary of field experiments analyzed. The features of each sprinkler are shown for nozzle size and operating pressure for both experiment types. The reference of the research works where each sprinkler type was used is also reported.

Reference	Sprinkler - abbreviation	Nozzles size (mm)	Pressure (kPa)	Experiment type			
				Isolated sprinkler	Solid-set configuration		
				Number of experiments	Spacing (m)	Wind velocity rank (m s ⁻¹)	Number of experiments
Playán et al. 2006	Riegos Costa 130H -RC130	4.0 + 2.4 4.4 + 2.4	200 300 400	6	18 x 15	1.0 – 7.6	20
	Vyrsa 70 - VYR70	4.0 + 2.4 4.4 + 2.4	200 300 400	6	18 x 15	0.4 – 9.3	21
Sánchez et al. 2011	Somlo 30C - SOM30C	4.0 + 2.4 4.4 + 2.4 4.8 + 2.4	240 320 420	10	15 x 15	0.4 – 8.0	55
Stambouli et al. 2014	Riegos Costa 130 H - RC130BY	4.0 + 2.5 4.5 + 2.5 5.16 + 2.5	200 300 400	10	18 x 18	0.4 – 7.5	49
Paniagua, 2015	Naandanjain 5035 - NAAN	5.16 + 2.5	200 300	4	18 x 18	0.8 – 7.1	11
Robles et al. 2017	Riegos Costa 130H - RC130p	5.16 + 2.4	200 300	4	18 x 18	0.6 – 5.0	11

Table 2. Calibrations of the Weibull and ULLN parameters for drop size distribution in isolated sprinklers.

Sprinkler	Main Nozzle size (mm)	Pressure (kPa)	Flow (L hr ⁻¹)	Wind Velocity (m s ⁻¹)	Weibull					ULLN					
					d ₅₀ (m)	n	RMSE (mm hr ⁻¹)	r	EV (mm)	α (m)	μ	σ	RMSE (mm hr ⁻¹)	r	EV (mm)
NAAN	5.16	173	1521	1.30	0.0018	1.61	0.65	0.91	0.0022	0.0070	-1.02	1.02	0.66	0.90	0.0020
		191	1552	0.79	0.0018	1.54	0.61	0.91	0.0022	0.0068	-0.96	1.10	0.62	0.90	0.0022
		200	1683	1.13	0.0017	1.66	0.49	0.95	0.0020	0.0068	-1.08	0.98	0.43	0.97	0.0019
		303	2007	1.38	0.0017	1.74	0.76	0.93	0.0019	0.0067	-1.09	0.94	0.71	0.93	0.0019
RC130	4.0	200	1082	0.97	0.0017	1.86	0.54	0.88	0.0019	0.0042	-0.40	1.03	0.62	0.85	0.0018
		300	1335	1.17	0.0015	1.82	0.91	0.85	0.0017	0.0051	-0.89	0.93	0.91	0.85	0.0016
		401	1757	0.78	0.0014	1.72	0.67	0.93	0.0016	0.0028	0.07	1.35	0.57	0.95	0.0014
	4.4	200	1264	2.40	0.0017	1.76	0.59	0.92	0.0019	0.0067	-1.10	0.89	0.59	0.92	0.0019
		300	1507	2.80	0.0016	1.75	0.73	0.90	0.0018	0.0061	-1.03	0.90	0.72	0.91	0.0018
		400	1718	1.07	0.0015	2.10	0.65	0.91	0.0016	0.0033	-0.24	1.01	0.68	0.90	0.0015
RC130p	5.16	180	1460	0.61	0.0018	1.64	0.89	0.77	0.0021	0.0038	-0.04	1.33	0.86	0.79	0.0018
		200	1594	0.99	0.0018	1.68	0.57	0.91	0.0021	0.0040	-0.16	1.24	0.57	0.91	0.0019
		220	1655	0.57	0.0018	1.64	0.95	0.78	0.0021	0.0037	-0.02	1.33	0.92	0.79	0.0018
		308	2152	1.20	0.0015	1.65	0.64	0.94	0.0018	0.0036	-0.30	1.17	0.62	0.94	0.0016
RC130BY	4.0	200	1140	1.08	0.0021	1.96	0.37	0.86	0.0023	0.0045	-0.19	1.06	0.38	0.87	0.0021
		285	1388	0.60	0.0016	2.15	0.49	0.90	0.0018	0.0038	-0.29	0.96	0.51	0.90	0.0017
		382	1678	1.12	0.0014	2.28	0.54	0.93	0.0015	0.0040	-0.62	0.81	0.53	0.94	0.0015
	4.5	183	1500	1.18	0.0019	2.09	0.41	0.91	0.0021	0.0049	-0.46	0.94	0.41	0.91	0.0020
		291	1677	1.08	0.0016	2.17	0.44	0.93	0.0018	0.0058	-0.94	0.80	0.42	0.93	0.0018
		400	1850	1.08	0.0016	2.07	0.76	0.84	0.0018	0.0057	-0.90	0.85	0.78	0.83	0.0018
	5.16	201	1633	0.96	0.0018	2.16	0.56	0.93	0.0035	0.0042	-0.27	0.97	0.62	0.92	0.0018
		215	1980	0.62	0.0019	1.75	0.98	0.79	0.0021	0.0042	-0.21	1.19	0.96	0.80	0.0019
		299	2064	1.02	0.0017	1.79	0.93	0.85	0.0019	0.0043	-0.43	1.07	0.94	0.85	0.0018
		385	2378	1.57	0.0017	1.60	1.29	0.76	0.0020	0.0062	-0.95	1.05	1.33	0.75	0.0020
SOM30C	4.0	240	1200	0.63	0.0015	1.33	0.60	0.94	0.0019	0.0040	-0.48	1.34	0.61	0.94	0.0017
		320	1366	0.77	0.0016	1.40	0.55	0.94	0.0020	0.0039	-0.39	1.31	0.53	0.95	0.0017
		420	1490	1.23	0.0014	1.53	0.58	0.95	0.0017	0.0046	-0.80	1.11	0.61	0.94	0.0016
	4.4	240	1470	0.97	0.0017	1.42	0.82	0.90	0.0021	0.0044	-0.50	1.25	0.83	0.90	0.0018
		340	1667	0.44	0.0015	1.46	0.76	0.93	0.0019	0.0039	-0.41	1.28	0.80	0.92	0.0016
		420	1879	0.62	0.0014	1.49	1.01	0.90	0.0017	0.0031	-0.12	1.36	1.00	0.90	0.0015
	4.8	240	1673	0.41	0.0017	1.41	1.14	0.81	0.0021	0.0038	-0.15	1.44	1.07	0.83	0.0018
		330	1981	0.79	0.0016	1.44	0.97	0.88	0.0019	0.0033	-0.11	1.43	0.86	0.90	0.0016
		384	2148	0.69	0.0014	1.27	1.12	0.92	0.0018	0.0033	-0.22	1.54	1.01	0.93	0.0015
VYR70	4.0	420	1658	0.94	0.0017	1.44	0.65	0.93	0.0021	0.0054	-0.69	1.22	0.69	0.92	0.0020
		200	1170	1.95	0.0016	1.50	0.53	0.93	0.0019	0.0053	-0.81	1.11	0.51	0.94	0.0018
		300	1546	1.68	0.0013	1.89	0.52	0.96	0.0015	0.0032	-0.33	1.07	0.53	0.96	0.0014
	4.4	400	1701	0.39	0.0014	1.68	0.67	0.93	0.0017	0.0038	-0.47	1.13	0.67	0.93	0.0016
		200	1459	1.57	0.0016	1.63	0.49	0.95	0.0019	0.0048	-0.65	1.09	0.49	0.95	0.0018
		300	1722	1.06	0.0015	1.71	0.43	0.97	0.0018	0.0056	-0.96	0.99	0.41	0.97	0.0017
		400	1973	1.30	0.0014	1.79	0.68	0.95	0.0016	0.0040	-0.61	1.02	0.66	0.95	0.0015

Table 3. Coefficients to predict K_1 and K_2 for the solid-set sprinklers analyzed using Weibull distribution.

Sprinkler	Nozzle size (mm)	K_1											
		Pressure ≤ 300						Pressure > 300					
		c			b			c			b		
		x	y	z	x	y	z	x	y	z	x	y	z
NAAN	5.16 + 2.5	-0.0085			0.1068	0.0002							
RC130	4.0 + 2.4	-0.0232	-0.0017		0.4787	0.0059		-0.1975	-0.0008		1.0657	0.0069	
	4.4 + 2.4	-0.0679	-0.0005		0.7402	0.0042		-0.1138	0.0001		1.1597	-0.0010	
RC130	5.16 + 2.4	0.0435	-0.0019		0.2971	0.0051							
RC130BY	4.0 + 2.4	-0.0818	-0.0014		0.6922	0.0082		-0.2178	0.0011		1.5115	-0.0072	
	4.5 + 2.4	-0.0031	-0.0014	200	0.3275	0.0071	200	-0.1369		300	0.9968	0.0019	300
SOM30C	5.16 + 2.5	-0.0162	0.0004		0.2347	-0.0005		0.0282	-0.0080		0.1827	0.0442	
	4.0 + 2.4	0.0150	-0.0010		0.3541	0.0034		-0.0640	0.0001		0.6225	0.0012	
	4.4 + 2.4	-0.0042	-0.0001		0.4826	-0.0033		-0.0109	-0.0008		0.2292	0.0074	
VYR70	4.8 + 2.4	-0.2264	0.0004		1.5171	0.0024		-0.1965	0.0010		1.7063	-0.0062	
	4.0 + 2.4	-0.0576	0.0001		0.5511	-0.0015		-0.0428	0.0005		0.4008	-0.0013	
	4.4 + 2.4	-0.0160	0.0003		0.1660	-0.0011		0.0117	0.0004		0.0598	0.0007	

Sprinkler	Nozzle size (mm)	K_2											
		Pressure ≤ 300						Pressure > 300					
		c			b			c			b		
		x	y	z	x	y	z	x	y	z	x	y	z
NAAN	5.16 + 2.5	-0.0382	0.0003		0.3873	-0.0025							
RC130	4.0 + 2.4	-0.0393	-0.0001		0.2690	-0.0002		-0.0531	0.0004		0.2442	-0.0016	
	4.4 + 2.4	0.0172			0.0027	0.0003		0.0142			0.0281	-0.0003	
RC130	5.16 + 2.4	-0.0829	0.0009		0.5150	-0.0030							
RC130BY	4.0 + 2.4	-0.0113	0.0001		0.2249	-0.0008		-0.0013	-0.0002		0.1405	0.0009	
	4.5 + 2.4	-0.0918	0.0010	200	0.4471	-0.0037	200	0.0006		300	0.0925	0.0004	300
SOM30C	5.16 + 2.5	0.0096	-0.0004		0.0444	0.0019		-0.0285	-0.0025		0.2383	0.0146	
	4.0 + 2.4	-0.0378	0.0002		0.3164	-0.0007		-0.0212	0.0002		0.2627	-0.0012	
	4.4 + 2.4	-0.0471	0.0005		0.3846	-0.0028		-0.0103	-0.0002		0.1740	0.0007	
VYR70	4.8 + 2.4	-0.0334	-0.0001		0.3517	0.0004		-0.0439			0.3803	-0.0001	
	4.0 + 2.4	-0.0240	0.0001		0.2952	-0.0011		-0.0116	-0.0001		0.1884	0.0011	
	4.4 + 2.4	-0.0251	0.0001		0.3083	-0.0011		-0.0108	0.0002		0.1943	-0.0009	

$$c/b = x + y \text{ (Pressure - z)}$$

$$ki = c * \text{Wind velocity}^2 + b * \text{Wind velocity}$$

Table 4. Coefficients to predict K_1 and K_2 for the solid-set sprinklers analyzed using ULLN distribution.

Sprinkler	Nozzle size (mm)	K_1											
		Pressure ≤ 300						Pressure > 300					
		c			b			c			b		
		x	y	z	x	y	z	x	y	z	x	y	z
NAAN	5.16 + 2.5	-0.0247	0.0002		0.2210	-0.0005							
RC130	4.0 + 2.4	-0.0550	-0.0009		0.6066	0.0026		-0.1439	-0.0029		0.8651	0.0139	
	4.4 + 2.4	-0.0666			0.7188	0.0018		-0.0715	-0.0004		0.9012	0.0026	
RC130	5.16 + 2.4	-0.0051	-0.0015		0.4000	0.0059							
RC130BY	4.0 + 2.4	-0.1502	-0.0008		1.0756	0.0043		-0.2252	0.0013		1.5064	-0.0082	
	4.5 + 2.4	-0.0118	-0.0012	200	0.3897	0.0057	200	-0.1293	-0.0001	300	0.9333	0.0034	300
SOM30C	5.16 + 2.5	-0.0469	-0.0004		0.4172	0.0037		-0.0863	-0.0058		0.7830	0.0341	
	4.0 + 2.4	-0.0268	-0.0019		0.4802	0.0102		-0.1825	-0.0006		1.2997	0.0053	
	4.4 + 2.4	-0.0303	-0.0013		0.5152	0.0059		-0.1271	-0.0008		0.9658	0.0036	
VYR70	4.8 + 2.4	-0.1656	0.0007		1.1364	-0.0034		-0.1085	-0.0012		0.8659	0.0082	
	4.0 + 2.4	-0.0388			0.3954	0.0004		-0.0435	0.0003		0.4350	0.0004	
	4.4 + 2.4	-0.0075	0.0002		0.0985	-0.0004		0.0118	0.0001		0.0547	0.0021	

Sprinkler	Nozzle size (mm)	K_2											
		Pressure ≤ 300						Pressure > 300					
		c			b			c			b		
		x	y	z	x	y	z	x	y	z	x	y	z
NAAN	5.16 + 2.5	-0.0281	0.0002		0.3079	-0.0016							
RC130	4.0 + 2.4	-0.0197			0.1783			-0.0241	0.0007		0.1738	-0.0017	
	4.4 + 2.4	0.0066	0.0001		0.0844	-0.0005		0.0116			0.0378	-0.0004	
RC130	5.16 + 2.4	-0.0654	0.0006		0.4333	-0.0021							
RC130BY	4.0 + 2.4	0.0084	-0.0001		0.1019	0.0003		-0.0007	-0.0003		0.1368	0.0010	
	4.5 + 2.4	-0.0781	0.0008	200	0.4120	-0.0029	200	-0.0043	-0.0001	300	0.1371	0.0008	300
SOM30C	5.16 + 2.5	0.0061	-0.0003		0.0609	0.0013		-0.0214	-0.0028		0.1891	0.0159	
	4.0 + 2.4	-0.0151	-0.0002		0.2182	0.0007		-0.0275	0.0001		0.2746	-0.0003	
	4.4 + 2.4	-0.0398	0.0004		0.3128	-0.0019		-0.0107	-0.0002		0.1655	0.0006	
VYR70	4.8 + 2.4	-0.0222	-0.0002		0.2573	0.0006		-0.0360			0.3064	0.0008	
	4.0 + 2.4	-0.0300	0.0002		0.3368	-0.0014		-0.0130	0.0001		0.1975	-0.0003	
	4.4 + 2.4	-0.0223	0.0002		0.2857	-0.0013		-0.0031	0.0001		0.1581	-0.0003	

$$c/b = x + y \text{ (Pressure - z)}$$

$$ki = c * \text{Wind velocity}^2 + b * \text{Wind velocity}$$

Appendix A. Optimum parameters of drag coefficient for the solid-set field experiments with Weibull and ULLN drop size distributions.

Sprinkler	Main nozzle size (mm)	Pressure (kPa)	Wind velocity (m s ⁻¹)	CUC _{mea} (%)	Weibull					ULLN						
					K ₁	K ₂	CUC _{cal} (%)	RMSE (mm hr ⁻¹)	r	K ₁	K ₂	CUC _{cal} (%)	RMSE (mm hr ⁻¹)	r		
NAAN	5.16	200	1.04	89	0.414	0.373	89	0.88	0.07	0.005	0.000	91	0.52	0.74		
			2.10	85	0.253	0.446	85	0.75	0.65	0.760	0.433	85	0.72	0.66		
			3.59	69	0.055	1.017	69	1.23	0.67	0.217	0.922	69	1.19	0.71		
			7.07	67	0.374	0.838	67	1.32	0.71	0.385	0.748	67	1.22	0.74		
		300	0.78	93	0.279	0.000	93	0.88	0.13	0.763	0.000	93	0.81	0.07		
			1.28	94	0.129	0.017	94	0.57	0.39	0.053	0.016	93	0.59	0.49		
			1.84	89	0.098	0.208	90	0.60	0.72	0.056	0.244	89	0.64	0.70		
			2.24	86	0.069	0.326	86	0.74	0.72	0.189	0.305	86	0.76	0.71		
			4.36	76	0.365	0.579	77	1.05	0.78	0.768	0.494	76	1.05	0.80		
			5.00	73	0.686	0.552	73	0.89	0.88	0.803	0.562	73	0.92	0.86		
			6.18	74	0.342	0.586	74	1.20	0.82	0.787	0.428	74	1.23	0.79		
			RC130	4.0	200	3.75	82	1.409	0.460	82	0.45	0.79	1.461	0.385	82	0.44
5.35	75	1.858				0.339	75	0.50	0.86	1.665	0.395	75	0.49	0.87		
300	1.23	92			0.776	0.216	92	0.63	0.13	0.701	0.154	92	0.63	0.10		
	1.81	85			1.777	0.218	85	0.82	0.51	1.424	0.206	85	0.88	0.40		
	2.76	89			0.600	0.345	89	0.49	0.78	0.648	0.355	89	0.45	0.80		
	3.23	85			1.894	0.205	85	0.61	0.69	1.677	0.268	85	0.51	0.79		
400	1.65	91			2.706	0.002	92	0.54	0.55	3.982	0.163	92	0.73	0.18		
	2.04	88			2.382	0.116	88	0.40	0.85	2.752	0.093	88	0.42	0.81		
	2.42	91			1.812	0.197	91	1.53	0.66	1.338	0.260	91	1.51	0.70		
	3.83	79			2.826	0.075	79	0.92	0.73	2.773	0.684	79	0.97	0.70		
	4.4	200			1.26	86	2.616	0.013	87	0.96	0.02	2.448	0.000	87	0.94	0.02
					2.14	91	0.036	0.087	92	0.46	0.54	0.091	0.270	92	0.54	0.32
7.56			72	1.821	0.954	72	0.74	0.81	1.728	0.977	72	0.73	0.82			
1.07			90	1.975	0.041	91	0.93	0.02	0.211	0.340	90	0.94	0.04			
300		1.47	92	1.621	0.117	92	0.63	0.32	1.454	0.027	93	0.62	0.36			
		3.57	84	2.039	0.225	84	0.75	0.72	2.242	0.165	84	0.68	0.77			
		7.63	69	2.433	1.000	70	1.07	0.76	2.740	0.941	69	1.08	0.75			
		1.06	91	1.707	0.001	91	0.77	0.45	1.889	0.000	92	0.63	0.59			
400	4.26	76	2.291	0.031	75	1.35	0.67	2.411	0.055	76	1.35	0.67				
	7.19	69	2.632	0.798	69	1.55	0.66	2.658	0.729	69	1.62	0.63				
	RC130p	5.16	200	0.87	86	0.134	0.492	86	1.16	0.00	0.042	0.460	86	1.20	0.01	
				1.99	82	1.086	0.563	82	1.19	0.29	1.252	0.461	82	1.15	0.28	
3.19				72	1.046	0.857	73	1.06	0.72	0.823	0.766	72	0.98	0.78		
4.56				68	2.258	0.646	68	1.15	0.74	1.773	0.631	68	1.14	0.77		
300			0.57	90	0.308	0.165	91	1.18	0.22	0.227	0.194	91	1.05	0.13		
			0.77	86	2.090	0.266	87	1.39	0.03	1.137	0.401	86	1.38	0.12		
			1.99	81	1.429	0.555	82	1.33	0.47	1.494	0.494	81	1.26	0.49		
			2.28	86	0.700	0.352	86	0.89	0.62	1.745	0.270	86	0.85	0.66		
			2.34	84	0.335	0.444	84	1.12	0.42	0.880	0.382	85	0.96	0.54		
			5.00	63	0.497	1.096	63	1.42	0.79	0.545	0.988	63	1.37	0.83		
			5.02	64	0.776	1.200	64	1.33	0.77	1.822	0.759	64	1.34	0.80		
			RC130BY	4.0	200	1.47	85	0.458	0.385	85	0.56	0.56	2.438	0.000	85	0.48
3.06	80	1.767				0.497	80	0.46	0.82	1.475	0.440	80	0.42	0.86		
3.72	71	1.356				0.709	71	0.68	0.79	1.417	0.578	71	0.67	0.80		
5.46	65	1.164				0.888	65	0.68	0.86	1.352	0.809	65	0.70	0.85		
300	5.86	67			1.349	0.939	67	0.54	0.90	1.423	0.848	67	0.55	0.90		
	1.42	90			1.710	0.055	90	0.49	0.79	1.903	0.021	90	0.52	0.78		
	1.69	87			2.000	0.321	88	0.49	0.77	2.135	0.234	87	0.46	0.81		
	2.53	75			2.363	0.377	74	1.03	0.73	2.006	0.464	74	1.03	0.71		
	5.64	61			1.718	0.824	61	1.12	0.79	1.344	0.824	61	1.08	0.81		
	5.71	66			1.421	0.683	66	0.85	0.83	1.287	0.672	66	0.79	0.86		
	1.02	90			0.892	0.028	90	0.50	0.69	0.356	0.031	91	0.43	0.79		
	4.59	66			1.487	0.518	66	0.75	0.91	1.616	0.532	66	0.77	0.90		
5.63	64	0.861	0.572	64	1.18	0.83	0.702	0.571	64	1.14	0.83					

4.5	200	7.50	75	0.087	0.206	75	1.93	0.55	0.114	0.218	75	1.89	0.59
		0.48	82	0.829	0.993	82	1.85	0.35	0.342	0.995	82	1.86	0.35
		1.14	81	0.121	0.582	82	1.21	0.17	0.000	0.548	82	1.19	0.21
		2.89	79	0.559	0.415	80	0.68	0.72	1.199	0.493	80	0.79	0.64
		3.23	72	1.237	0.577	73	0.78	0.82	0.950	0.590	72	0.85	0.79
		3.61	74	0.698	0.537	74	0.84	0.76	1.134	0.547	74	0.90	0.74
		4.01	73	1.695	0.427	73	1.20	0.55	1.534	0.534	73	1.21	0.55
		2.29	87	1.096	0.126	87	0.62	0.60	1.276	0.102	87	0.69	0.49
		3.25	79	0.837	0.326	80	0.60	0.81	0.924	0.346	80	0.69	0.76
		1.05	87	0.096	0.112	88	0.81	0.67	0.133	0.321	87	1.08	0.31
		1.68	90	1.488	0.100	90	0.74	0.34	1.182	0.121	90	0.74	0.25
		2.29	87	1.096	0.126	87	0.62	0.60	1.276	0.102	87	0.69	0.49
	300	2.43	79	1.911	0.406	79	1.07	0.57	1.262	0.491	79	1.13	0.53
		2.97	79	2.154	0.194	80	0.77	0.79	2.163	0.349	80	0.94	0.70
		5.77	67	1.111	0.560	67	1.05	0.88	1.011	0.653	67	1.11	0.86
		1.33	93	1.188	0.176	93	0.37	0.85	1.466	0.168	93	0.42	0.70
		0.59	91	1.006	0.012	92	0.87	0.65	0.000	0.019	92	0.87	0.65
		2.19	81	0.989	0.456	81	1.72	0.16	2.042	0.452	82	1.72	0.19
5.16	400	2.35	80	2.730	0.155	81	1.54	0.40	2.570	0.357	81	1.47	0.43
		4.09	77	2.478	0.516	77	0.85	0.82	2.727	0.546	77	0.81	0.82
	200	0.94	84	0.064	0.016	85	1.11	0.59	0.053	0.020	84	1.08	0.58
		1.04	84	0.051	0.044	85	1.26	0.54	0.000	0.000	84	1.24	0.56
		1.13	84	0.246	0.142	84	1.15	0.54	0.002	0.174	83	1.08	0.60
		1.19	83	0.348	0.112	84	0.80	0.75	0.641	0.102	83	0.79	0.76
		1.35	84	0.487	0.024	83	0.91	0.71	1.262	0.137	84	1.15	0.47
		4.27	76	0.665	0.332	76	0.86	0.83	0.829	0.286	76	0.81	0.85
	300	5.07	72	0.797	0.493	73	0.90	0.87	0.959	0.521	73	0.89	0.90
		1.32	91	0.077	0.236	90	0.94	0.48	0.093	0.232	91	0.99	0.45
		1.78	91	0.073	0.002	93	0.73	0.40	0.000	0.005	93	0.67	0.53
		2.21	83	0.150	0.450	83	1.41	0.51	2.035	0.399	83	1.56	0.33
		2.90	76	1.654	0.723	76	1.55	0.66	2.490	0.514	76	1.57	0.65
		5.03	75	1.473	0.419	75	0.78	0.90	1.495	0.376	75	0.81	0.89
	400	0.40	79	2.423	1.000	80	2.81	0.03	3.761	1.000	81	2.89	0.07
		0.53	81	4.775	0.853	81	2.41	0.35	4.000	0.949	81	2.56	0.30
		0.80	80	0.993	0.951	81	3.23	0.16	0.344	0.985	81	3.27	0.08
		5.22	61	2.950	1.179	61	1.51	0.86	3.746	0.986	61	1.85	0.78
SOM30C	4.0	0.39	87	0.120	0.066	87	1.16	0.26	3.700	0.086	88	0.95	0.49
		1.06	91	0.073	0.000	90	0.84	0.40	0.224	0.025	91	0.79	0.60
		1.19	92	0.111	0.005	92	0.63	0.28	0.902	0.002	92	0.65	0.24
		1.47	92	1.226	0.185	93	0.65	0.18	0.269	0.088	92	0.60	0.38
		2.89	90	1.625	0.689	90	0.58	0.57	1.484	0.632	90	0.56	0.71
		4.31	84	1.254	0.988	84	0.72	0.80	0.773	0.857	84	0.79	0.71
		8.01	78	3.881	0.023	79	1.26	0.22	2.315	0.722	78	1.19	0.23
	320	0.52	92	0.516	0.018	92	0.83	0.22	3.743	0.009	92	0.59	0.58
		0.83	91	0.061	0.268	92	0.80	0.34	0.372	0.134	91	0.67	0.55
		0.99	97	0.107	0.017	93	0.53	0.26	1.686	0.168	95	0.47	0.26
		3.49	85	2.314	0.790	85	0.75	0.80	2.557	0.638	85	0.73	0.84
		5.18	90	0.565	0.738	90	0.97	0.48	0.013	0.798	90	0.98	0.51
		6.50	86	1.704	0.814	86	0.72	0.77	1.797	0.549	86	0.82	0.68
	420	0.77	94	0.003	0.002	93	0.78	0.21	3.934	0.232	91	0.87	0.00
		0.82	97	0.013	0.000	94	0.70	0.21	3.724	0.015	94	0.66	0.24
		3.10	89	1.684	0.552	89	1.47	0.61	1.501	0.619	89	1.49	0.63
		5.83	84	2.193	0.771	84	0.82	0.74	2.920	0.725	84	0.85	0.75
		3.47	89	2.437	0.423	90	0.78	0.53	2.875	0.599	89	0.69	0.65
		0.82	90	0.869	0.337	91	0.92	0.44	0.674	0.005	90	0.63	0.79
4.4	240	1.84	87	2.379	0.918	87	1.10	0.33	3.455	0.776	88	1.03	0.38
		3.44	86	0.398	0.946	86	0.67	0.72	1.148	0.837	86	0.72	0.68
		3.69	84	2.658	0.026	84	1.40	0.12	0.659	0.017	85	1.17	0.45
		3.74	89	1.104	0.779	89	0.86	0.41	0.212	0.721	89	0.86	0.42
		4.90	84	1.110	1.064	84	0.73	0.76	1.551	0.673	84	0.51	0.88
		5.87	81	3.576	0.625	81	1.15	0.37	2.808	0.486	82	1.20	0.32
	300	1.00	92	0.096	0.306	93	0.74	0.34	2.605	0.239	93	0.77	0.27
		6.39	86	0.512	0.677	86	0.86	0.61	0.663	0.574	85	1.12	0.43
		0.86	94	1.453	0.076	92	0.76	0.18	2.497	0.093	94	0.57	0.44
		2.75	93	0.229	0.361	94	0.63	0.50	0.196	0.363	94	0.79	0.24

4.8	400	7.14	85	1.520	0.731	84	0.60	0.85	0.837	0.671	83	0.85	0.68			
		2.50	93	1.983	0.454	94	0.85	0.72	3.652	0.272	93	0.98	0.26			
		6.79	89	1.793	0.455	88	1.05	0.33	0.072	0.253	86	1.80	0.52			
		0.97	95	1.074	0.125	93	0.90	0.00	1.149	0.221	95	0.62	0.43			
	1.50	92	0.436	0.419	92	0.92	0.31	0.047	0.343	92	0.90	0.35				
	3.65	89	1.566	0.671	89	0.93	0.64	2.550	0.407	88	1.10	0.53				
	5.09	86	3.479	0.117	86	1.28	0.53	0.007	0.553	87	1.26	0.37				
	1.14	91	2.264	0.223	92	0.88	0.20	1.119	0.094	91	0.61	0.65				
	1.74	89	2.286	0.877	89	1.25	0.11	1.760	0.207	89	1.13	0.28				
	4.37	84	0.054	1.012	86	1.37	0.28	0.026	0.808	85	1.40	0.31				
	4.88	88	3.687	0.532	88	1.20	0.13	3.341	0.892	87	1.22	0.18				
	6.69	85	0.034	0.997	85	1.42	0.07	0.000	0.608	84	1.59	0.00				
	1.26	93	0.115	0.230	93	1.06	0.06	0.501	0.162	93	1.00	0.22				
	1.67	92	2.998	0.247	92	0.91	0.35	2.677	0.296	93	0.85	0.40				
	3.62	89	3.481	0.761	89	0.96	0.49	0.362	0.682	89	1.20	0.21				
	3.73	86	4.180	1.156	86	1.17	0.54	2.290	0.747	86	1.66	0.12				
	7.45	86	2.235	0.125	86	1.56	0.20	0.032	0.499	86	1.75	0.16				
	7.65	85	1.059	0.543	87	1.69	0.00	0.756	0.012	86	1.52	0.19				
	0.80	96	4.891	0.525	95	0.95	0.02	3.577	0.591	96	0.90	0.30				
	0.85	96	3.075	0.013	95	0.90	0.18	3.928	0.566	94	0.97	0.13				
	1.94	95	0.556	0.355	95	0.90	0.05	0.038	0.548	95	0.82	0.15				
	3.60	92	2.022	0.531	92	0.73	0.62	2.930	0.658	91	0.71	0.69				
	4.62	86	2.115	0.988	86	1.42	0.46	2.921	1.000	87	1.60	0.31				
	5.03	86	2.459	1.006	86	1.49	0.41	2.544	0.893	86	1.52	0.39				
	6.55	88	2.628	0.522	88	1.45	0.12	1.104	0.819	88	1.54	0.05				
	6.79	86	3.880	0.341	86	1.75	0.16	1.168	0.832	87	1.78	0.06				
	VYR70	4.0	200	2.03	86	0.859	0.304	86	0.71	0.50	0.264	0.433	86	0.73	0.49	
				2.49	83	0.399	0.612	83	0.88	0.43	0.785	0.565	83	0.87	0.45	
				3.37	73	1.755	0.838	74	0.99	0.61	1.142	0.954	74	0.98	0.65	
				6.86	69	1.048	0.884	69	0.75	0.79	0.870	0.887	69	0.69	0.82	
		300	1.81	88	0.286	0.143	87	0.72	0.52	0.556	0.168	87	0.74	0.47		
			2.92	73	0.997	0.550	73	1.39	0.59	0.933	0.555	73	1.29	0.63		
			8.42	68	0.384	0.758	69	0.76	0.84	0.625	0.741	68	0.87	0.80		
			0.38	93	0.589	0.029	93	0.72	0.11	0.425	0.056	93	0.74	0.18		
		400	4.17	75	1.132	0.901	75	1.10	0.74	1.663	0.570	75	1.13	0.73		
			9.30	60	3.054	1.075	61	1.49	0.72	3.154	1.000	61	1.57	0.70		
			4.4	200	1.19	88	0.931	0.267	88	0.98	0.07	0.401	0.242	88	0.90	0.19
					1.72	89	0.066	0.237	89	0.63	0.52	0.111	0.225	89	0.64	0.49
		3.96			74	0.135	0.979	75	1.00	0.68	0.141	0.922	75	0.95	0.70	
		7.88			71	0.383	0.856	71	0.73	0.85	0.339	0.847	71	0.61	0.89	
300		1.39	94	0.058	0.188	94	0.68	0.23	0.053	0.001	94	0.54	0.55			
		2.23	89	0.214	0.406	89	0.92	0.40	0.202	0.475	89	0.83	0.49			
		6.77	73	0.913	0.813	73	1.04	0.76	0.881	0.905	74	1.03	0.75			
		0.70	94	0.753	0.025	95	0.95	0.14	0.262	0.006	95	0.85	0.38			
400		3.99	81	1.082	0.530	80	1.23	0.63	1.275	0.535	81	1.20	0.67			
		5.15	70	2.004	0.694	71	1.66	0.70	2.190	0.730	71	1.56	0.75			
	6.98	63	3.420	1.002	63	1.62	0.75	2.999	0.966	63	1.53	0.78

Figure 1. Computational efficiency analysis for different Runge-Kutta methods with constant and variable time steps. The number of steps is showed in logarithmic scale. The dotted line represents the maximum error established of 10 cm in drops trajectory.

a **b**

Figure 2. *CUC* differences and *RMSE* for different wind velocity frequencies. Absolute differences of *CUC* measured (CUC_{mea}) and *CUC* simulated (CUC_{sim}) with respect the wind velocity frequencies (Figure 2a). *RMSE* of the simulations for every wind velocity frequency is shown in Figure 2b. Each line in Figure 2a corresponds to the simulation of a solid-set experiment with a different average of the wind velocity ($m s^{-1}$). In Figure 2b, the numbers followed by a different letters are significantly different after ANOVA according to a Fisher's Protected LSD test at 95% confidence level.

Figure 3. Differences in CUC simulated considering different slopes (CUC_{slope}) and without slope (CUC_{flat}) as function of wind velocity. Each line with a symbol represents maximum and minimum CUC differences for all solid-set experiments.

Figure 4. Schemes and histograms of drops generation in an isolated sprinkler under calm wind conditions based on RSS method (Figure 4a and 4d), UMCS method (Figure 4b and 4e) and BMCS method (Figure 4c and 4f).

Figure 5. Relationships of CUC simulated (CUC_{sim}) with respect CUC measured (CUC_{mea}) for 0.5 m, 1.2 m and 3.6 m cell size. Each relationship is shown with different lines.

Figure 6. Convergence of the optimized parameters of the models. a) Weibull, b) C' and c) ULLN. Application case to NAAN sprinkler at 200 kPa. Every point in the subfigures represents a simulation and every delimitation line represents the number of iterations depending on the model.

Figure 7. Relationship between CUC measured (CUC_{mea}) and CUC calibrated (CUC_{cal}) for the whole 167 solid-set experiments database for ULLN (Figure 7a) and Weibull model (Figure 7b). The dotted line represents the 1:1 relationship.

Figure 8. Relationship between CUC measured (CUC_{mea}) and CUC validated (CUC_{val}) for the whole 167 solid-set experiments database for ULLN (Figure 8a) and Weibull model (Figure 8b). The dotted line represents the 1:1 relationship.