A COUPLED CROP AND SOLID SET SPRINKLER SIMULATION MODEL:

I. MODEL DEVELOPMENT

by

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CE DATABASE SUBJECT HEADINGS

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ABSTRACT

The development of a coupled crop model (Ador-Crop) and solid set sprinkler irrigation model (Ador-Sprinkler) is reported in this work. The crop model incorporates many of the features developed in the well-known CropWat model. Improvements include the use of thermal time and the input of daily ET_0 . The solid set sprinkler model applies ballistic theory to determine water distribution resulting from water droplets subjected to a wind vector. Regarding the validation of the coupled model (AdorSim), the plot of soil available water vs. measured and simulated yield reduction resulted in similar features. AdorSim explained 25 %** of the variability in measured yield reduction. Most of the unexplained variability is due to the effect of non water-related factors affecting crop yield. In a companion paper, AdorSim is used to investigate optimum water management options in the middle Ebro basin in NE of Spain.

Keywords: Solid set sprinkler irrigation model, Crop model, CropWat, ballistic theory

INTRODUCTION

High uniformity of irrigation water distribution and appropriate irrigation scheduling practices are required to optimize irrigation efficiency, crop yield and economic benefits. These practices may also lead to significant water conservation, reduced environmental impact and improved sustainability of irrigated agriculture (Smith et al., 1996). In sprinkler irrigation, the water distribution pattern is strongly affected by wind speed. Consequently, some areas of the field may not receive an adequate amount of irrigation water (Seginer et al., 1991; Faci and Bercero, 1991; Tarjuelo et al., 1994; Kincaid et al., 1996). Wind effects can be considered when designing a sprinkler irrigation system if the area is subjected to nearly constant wind speed and direction (Vories et al., 1987). While in some areas the wind direction shows a clear pattern, wind speed and direction are often subjected to a large variability within a given day and among days. This circumstance poses a serious limitation to the adequate design of sprinkler irrigation systems and makes water management a difficult task.

Field evaluations have been used to diagnose existing sprinkler irrigation systems and to determine optimum operating conditions (pressure, nozzle size and sprinkler spacing) (Tarjuelo et al., 1992). However, field evaluations may be impractical when it comes to testing a wide variety of irrigation variables under windy conditions because of 1) the cost and work involved; and 2) the difficulty to reproduce specific environmental conditions. Properly calibrated simulation models of sprinkler irrigation have emerged as useful tools to predict irrigation performance parameters such as the Christiansen Coefficient of Uniformity (*CU*) (Christiansen, 1942) for any combination of operating and meteorological conditions (Fukui et al., 1980; Vories et al., 1987; Seginer et al., 1991;

Tarjuelo et al., 1994; Carrión et al., 2001). However, *CU* does not provide information on the wind-induced areas of water deficit and surplus (Dechmi et al., 2003). This may be very important when sprinkler irrigation is analysed from the agronomic, economic and environmental points of view.

Several authors have proven that the spatial variability of crop available water may be responsible for most of the spatial variability in crop yield (Stern and Blesler, 1983; Warrick and Gardner, 1993; Or and Hanks, 1992). In irrigated fields, soil water availability at a given point depends on the spatial variability of soil water properties and on the uniformity of water application. The relationship between irrigation uniformity and the variability of crop yield has been analyzed using crop models and considering a constant irrigation water distribution pattern during all crop growth stages (Mantovani et al., 1995; de Juan et al., 1996; Li, 1998). However, in sprinkler systems irrigation uniformity varies with the meteorological conditions (particularly with the wind speed). This aspect is particularly important in order to adopt appropriate water management rules, although its modeling is complex.

The objective of this research is to develop a model capable to predict the effect of time and space variability of sprinkler irrigation water on crop yield. The model uses two related disciplines: irrigation engineering and agronomy. The sprinkler irrigation module simulates irrigation water application in a square grid within a given sprinkler spacing. The crop module simulates yield reduction at the same grid locations taking into account the simulated application depth and the soil proprieties at each point of the field. The model theoretical basis, description, calibration and validation are presented in this paper. In a companion paper, the model is applied to identify adequate sprinkler irrigation design and

management rules for the central Ebro basin (NE Spain), with particular reference to wind effects.

WATER STRESS IN CROP MODELS

Crop response to water supply may be summarized in a function relating yield to the seasonal amount of water made available to the crop. Solomon (1983) reviewed the literature on water-yield functions and presented typical functions for many agricultural crops. In the last decade, numerous models have been developed to simulate crop growth and water balance. These models help to identify factors controlling crop yield and evapotranspiration. Among the models that have been developed for this task, a distinction can be made between crop growth simulation models, simulating the main processes of crop growth (leaf area growth, biomass production and partition) (Jones and Kiniry, 1986; Stockle et al., 1994; Williams et al., 1984; Brisson and Mary, 1999), and those models that do not explicitly simulate crop growth (Smith, 1993). The first type of models takes account of dynamic processes and therefore requires more extensive input parameters than the second type.

Since it is difficult to assess soil hydraulic properties, models using simplified approaches to soil water flow and crop growth are often used. In fact, Cabelguenne (1996) found that at least 140 crop models had been developed based on the water production functions proposed by Stewart et al. (1977) and applied by Doorenbos and Kassam (1979). Following this approach, water stress affects crop yield through crop response factors:

$$1 - \frac{Y_a}{Y_{\max}} = K_y \left(1 - \frac{ET_a}{ET_{\max}} \right) \quad [1]$$

Where Y_a is the actual yield (kg ha^{-1}), $Y_{\max}$ is the maximum yield (kg ha^{-1}), ET_a is the seasonal crop evapotranspiration (mm), $ET_{\max}$ is the maximum seasonal crop evapotranspiration (mm) and K_y is an adimensional coefficient representing crop yield sensitivity to water deficit. K_y values are available for numerous crops (Doorenbos and Kassam, 1979).

NUMERICAL MODELS FOR SOLID SET SPRINKLER IRRIGATION

A number of sprinkler irrigation simulation models considering wind distortion have been developed in the last decades (Fukui et al., 1980; Vories et al., 1987; Seginer et al., 1991; Tarjuelo et al., 1994; Carrión et al., 2001). In these models, a sprinkler is considered as a device emitting drops of different diameters with a given initial velocity vector. A ballistic approach is used to model the drop trajectory until reaching the ground surface. The ballistic theory applied to water drops in the air considers that the movement of a drop is influenced by 1) its initial velocity vector; 2) gravity, acting in the vertical direction; 3) the wind vector ($\mathbf{W}$), acting in the horizontal plane; and 4) the resistance force applied in a direction opposite to the relative movement of the drop in the air (Vories et al., 1987; Seginer et al. 1991). Under no wind conditions, the drop velocity with respect to the ground ($\mathbf{U}$) is equal to the velocity of the drop in the air ($\mathbf{V}$), while under wind conditions $\mathbf{U}$ is equal to the sum of vectors $\mathbf{V}$ and $\mathbf{W}$.

A summation of forces acting on the drop leads to a differential equation describing the path of individual drops of water emitted by a sprinkler nozzle. The three directional components of the movement of each drop can be expressed as follows (Fukui et al., 1980):

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

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

$$A_z = \frac{d^2z}{dt^2} = -\frac{3}{4} \frac{\rho_a}{\rho_w} \frac{C}{D} VU_z - g \quad [4]$$

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, and C is a drag coefficient, which can be expressed as a function of the Reynolds number of a spherical drop (Fukui et al. 1980; Seginer et al. 1991):

$$\begin{aligned} Re &= V \frac{D}{\nu}; \\ C &= \frac{33.3}{Re} - 0.0033Re + 1.2 \quad \text{for } Re \leq 100 \\ C &= \frac{72.2}{Re} - 0.0000556 Re + 0.48 \quad \text{for } 100 \leq Re \leq 1000 \\ C &= 0.45 \quad \text{for } Re \geq 1000 \end{aligned} \quad [5]$$

Where Re is the Reynolds number of the drop, and ν is the kinematic viscosity of air (m^2s^{-1}).

Von Bernuth (1988) divided researchers developing ballistic simulation models in two groups. The first group assumed that the drag coefficient is a function of droplet size only (Von Bernuth and Gilley 1984; Hills and Gu 1989); while the second group assumed it to be a function of the velocity in the air and the droplet size (Fukui et al., 1980; Vories et al., 1987; Seginer et al., 1991; Kincaid, 1996).

Due to the complex sprinkler jet process, the following simplifications have been considered in these models: 1) the jet is disintegrated at the nozzle exit into individual drops with different diameters, moving independently in the air; 2) the drag coefficient is independent of the sprinkler height over the soil surface, the vertical jet angle, the wind velocity and the nozzle diameter; and 3) different-sized drops fall at different distances.

The ballistic approach requires a preliminary determination of drop size distribution for a given sprinkler and a set of operating conditions. Fukui et al. (1980) and von Bernuth and Gilley (1984) presented a simulation scheme based on obtaining drop size distributions from the sprinkler radial water curve for a given sprinkler-pressure combination under no-wind conditions. Li et al. (1994) proposed the following empirical model to fit the drop diameter distribution curve:

$$P_v = \left(1 - e^{-0.693 \left(\frac{D}{D_{50}} \right)^n} \right) 100 \quad [6]$$

Where: D is the drop diameter; P_v is the percent of total discharge in drops smaller than D ; D_{50} is the mean drop diameter, and n is a dimensionless exponent. The values of D_{50} and n can be estimated as:

$$D_{50} = a_d + b_d R \quad [7]$$

and

$$n = a_n + b_n R \quad [8]$$

Where a_d , b_d , a_n , b_n are empirical coefficients and R is the ratio of nozzle diameter to pressure (mm kPa^{-1}). Kincaid et al. (1996) presented experimental values of these parameters for a number of sprinkler types and nozzle diameters.

A considerable improvement in sprinkler irrigation simulation performance under windy conditions was obtained by introducing in the model empirical parameters to adjust the drag coefficient as proposed by Seginer et al. (1991) and Tarjuelo et al. (1994). This adjustment is expressed by the following equation:

$$C' = C(1 + K_1 \sin \beta - K_2 \cos \alpha) \quad [9]$$

Where: α is the angle formed by vectors V and W , β is the angle formed by the vectors V and U , and K_1 and K_2 are empirical parameters. The corrector coefficient K_1 narrows the water distribution pattern symmetrically in the direction perpendicular to the wind, while K_2 displaces the wetted area in the wind direction, shortening the distance from the centre

of the wetted area to the sprinkler (windward direction) and lengthening more behind (leeward direction). According to Montero et al. (2001), K_2 is much less relevant than K_1 .

DESCRIPTION OF THE COUPLED SIMULATION MODEL (*AdorSim*)

The AdorSim model was programmed using the C++ language. The model is composed of two principal modules: a crop simulation module and a solid set sprinkler irrigation simulation module (hereafter designated as Ador-Crop and Ador-Sprinkler, respectively). The fact that both modules interchange information during their execution required writing specific source code. Significant changes were introduced in both modules respect to previous models. Several additional Ador modules perform data input and output operations. Ador is a Spanish acronym for “Decision Support Tool on Irrigation Organization”.

***Ador-Crop* development**

The Ador-Crop module is similar to the Windows version of the well-known CropWat model (Smith, 1993, Clarke et al., 1998) in many aspects. We chose CropWat as a basis for Ador-Crop development because we found in a previous work (Cavero et al., 2000) that it adequately predicted the observed ET and yield reduction due to water stress in several maize field trials. Moreover, CropWat had a similar performance as the more input-demanding crop growth simulation model EPICphase (Cavero et al., 2000). The main differences between the Ador-Crop and CropWat models are: 1) CropWat uses monthly meteorological data and four interpolation models to convert monthly ET_0 values to daily values, whereas Ador-Crop uses daily meteorological data, including daily ET_0 ; 2)

CropWat computes the crop growth phases using the day as unit of time, while Ador-Crop uses degree-days; and 3) Ador-Crop simulates yield reduction at each cell i of a square grid defined within the sprinkler spacing. The irrigation module simulates the water applied at the center of each cell. In this way the spatial variability of irrigation water results in a spatial variability of soil water and therefore crop yield. The time step for calculations is one day.

The Ador-Crop model is based on the model proposed by Stewart et al. (1977) and applied by Doorenbos y Kassam (1979), where actual crop evapotranspiration and yield for subplot i (ET_{ai} , and Y_{ai} , respectively) are normalized according to their maximum values (ET_{max} , and Y_{max} , respectively) (Eq. 1). The model does not calculate real yield but reduction in yield when ET is reduced from the potential ET (ET_{max}). Crop phenological development is divided into the vegetative, flowering, and grain filling stages based on thermal time as defined by Gallagher (1979).

Just like in most functional models, all the soil water fluxes are considered one-dimensional (vertical). The soil is described as a single reservoir, characterized by its soil water content (SWC_{ij}), varying for each day (j) and cell (i) within the sprinkler spacing as follows:

$$SWC_{ij} = SWC_{ij-1} + P_j + ID_{ij} - ETa_{ij} - Dp_{ij} \quad [10]$$

Where SWC_{ij-1} is the soil water content of cell i on day $j-1$; P_j is the precipitation on day j , obtained from the meteorological data; ID_{ij} is the applied irrigation depth; ETa_{ij} is the actual crop evapotranspiration, and Dp_{ij} is the deep percolation, which occurs if SWC_{ij} is

greater than the Total Available Water of cell i (TAW_i) and is calculated as the difference between these variables. During crop growth TAW increases linearly with the rooting depth (from initial root depth to maximum root depth). Runoff and capillary rise were not considered in this model since, generally, sprinkler precipitation rates are designed to be lower than the soil infiltration rate, and shallow water tables are not frequent at sprinkler irrigated areas.

The procedures used for the calculation of crop evapotranspiration, crop water requirements and irrigation requirements are based on FAO methodologies (Allen et al., 1998; Clarke et al., 1998). Daily crop evapotranspiration (ETc_j) was estimated from daily values of reference evapotranspiration (ET_{0j}) calculated using the FAO Penman-Monteith equation, and from tabulated crop coefficients (K_c) following the FAO approach (Allen et al., 1998; Clarke et al., 1998). The actual crop evapotranspiration, ETa_{ij} is given by:

$$ETa_{ij} = ETc_j ; \quad \text{if } SWD_{ij-1} < AWD_{ij} \quad [11]$$

$$ETa_{ij} = ETc_j \left(\frac{TAW_{ij} - SWD_{ij-1}}{TAW_{ij} - AWD_{ij}} \right) ; \quad \text{if } SWD_{ij-1} > AWD_{ij} \quad [12]$$

Where SWD_{ij-1} is the soil water depletion of cell i and in day $j-1$; AWD is the allowable water depletion limit, which is calculated with p , the fraction of TAW that a crop can extract from the root zone without suffering water stress. The following equations were additionally used:

$$SWD_{ij-1} = TAW_{ij-1} - SWC_{ij-1} \quad [13]$$

$$AWD_{ij} = p * TAW_{ij} \quad [14]$$

Reduction in yield due to soil water stress is computed considering four crop development stages (f) and using a different crop response factor to water stress (K_y) for each stage. Cumulative yield reduction is determined using the following multiplicative formula (Stewart et al., 1977):

$$\frac{Y_{ai}}{Y_{max}} = \prod_{f=1}^4 \left[1 - k_{yf} \left(1 - \frac{ET_{ai}}{ET_{max}} \right)_f \right] \quad [15]$$

The default values of K_{yf} for maize in Cropwat (0.4, 0.4, 1.3 and 0.5, for phases 1 to 4, respectively) were used in Ador-Crop.

Ador-Sprinkler development

Ador-Sprinkler uses ballistic theory to predict the path of individual drops of water emitted by the sprinkler nozzles. The model calculations consist on 1) simulating a single sprinkler water distribution for a given wind condition; 2) overlapping a number of sprinklers at a given sprinkler spacing; and 3) determining water application depth in a user defined square grid of cells within a sprinkler spacing.

The drop size distribution corresponding to a given combination of sprinkler manufacturer, nozzle diameter and operating pressure was determined using the empirical

model proposed by Li et al. (1994) (Eq. 6, using D_{50} and n as calibration parameters). A fourth order Runge-Kutta numerical integration technique (Press et al., 1988) is used to solve the differential equations for drop movement and to determine the landing point for each drop. Finally, wind speed over an infinite plane varies logarithmically in the vertical direction (Vories et al., 1987). A total of 32,400 drops are used in each simulation, combining 180 different drop diameters (ranging from 0.2 to 7 mm), and 180 initial horizontal angles. At the end of this phase, the water application pattern of an isolated sprinkler was simulated.

The D_{50} and n model parameters need to be calibrated using no-wind experiments with an isolated sprinkler in order to reproduce the resulting water application pattern. To obtain the best combination of model parameters, two indexes are used for the comparison between measured and simulated water application: the Root Mean Square Error ($RMSE$) and the coefficient of correlation (r). The optimum values of D_{50} and n are those resulting in minimum $RMSE$ and maximum r .

Empirical equations are used in Ador-Sprinkler to estimate wind drift and evaporation losses ($WDEL$), following the findings of Dechmi et al. (2003):

$$WDEL = 5.29W + 7.48 \quad [16]$$

Where W is the wind speed in m s^{-1} .

The drop size distribution curve is corrected in each simulation run to account for $WDEL$. As a result, the value of P_v for the largest simulated drop diameter passes from

100% to $100 - \text{WDEL} \%$. For this correction, the option B of the procedure proposed in the *SIRIAS* model (Montero et al., 2001) is used. Drift losses are considered proportional to the volume of water collected in each point of the radial curve, while evaporation losses are considered inversely proportional to the drop size. In the model, both types of losses account for the same amount of water (Montero, 1999).

In order to simulate solid set sprinkler irrigation, 18 sprinklers are used in the model, and their water application is overlapped. The central sprinkler spacing is divided into a square grid, with the number of cells equal to the number of simulated catch cans. The irrigation depth at each cell is determined from the number of drops landing in the cell, their diameter, the drop size distribution curve and the sprinkler discharge (determined from the nozzle diameters and the operating pressure). Irrigation performance parameters such as the Christiansen Coefficient of Uniformity (CU) can be computed from the irrigation depth at the cells:

$$CU = \left(1 - \frac{\sum_{i=1}^{n_c} |ID_i - \overline{ID}|}{n_c \overline{ID}} \right) 100 \quad [17]$$

Where n_c is the number of catch cans, and $\overline{ID}$ is the average irrigation depth.

A new phase of model calibration is required at this point, since adequate values for K_l and K_2 must be identified. The comparison between measured and simulated irrigation depths is established in terms of the two above-mentioned indexes ($RMSE$ and r), and an additional index: the absolute difference between the measured and simulated CU

(DIF_{CU} , %). The optimum values of K_1 and K_2 result in minimum DIF_{CU} , minimum $RMSE$ and maximum r .

Model input and output

Figure 1 shows a functional diagram of AdorSim. The figure reflects the relationship between data types and between the two main simulation modules. Ador-Sprinkler input data include: 1) Characteristics of the irrigation system: vertical angle of the sprinkler jet ($^{\circ}$), diameter of the sprinkler nozzle(s) (mm), nozzle height (m), nozzle pressure (kPa), azimuth of the sprinkler line ($^{\circ}$), type of solid set (triangular vs. rectangular), sprinkler spacing (inside a line and between lines, m), number of cells (simulated catch cans), and calibration parameters (d_{50} , n , K_1 and K_2); 2) Meteorological data: wind sensor measurement height (m), 30-min averages of wind speed (m s^{-1}) and direction ($^{\circ}$), air temperature ($^{\circ}\text{C}$) and air relative humidity (%); and 3) Crop height (m), obtained from Ador-Crop.

Ador-Crop input data include: 1) Daily meteorological data: precipitation (mm), maximum and minimum air temperature ($^{\circ}\text{C}$), average air relative humidity (%), average wind speed (m s^{-1}), and ET_0 (mm); 2) Crop parameters: base temperature ($^{\circ}\text{C}$), temperature sum for each phenological stage, minimum and maximum rooting depth, allowable water depletion limit, crop coefficients for potential crop ET calculation, and crop response factors to water stress; 3) Soil characteristics: soil depth, TAW and initial soil water depletion at each simulated cell. These data represent the soil spatial variability within the sprinkler spacing area; and 4) Irrigation data: irrigation depth at each cell resulting from each irrigation event, obtained from Ador-Sprinkler.

The daily calculations of Ador-Crop start with an irrigation decision routine. Irrigation can be performed following an irrigation schedule or preset irrigation dates and times. In this work, the latter option will be used for calibration and validation purposes. In the companion paper, an irrigation scheduling routine will be applied to determine the irrigation dates, times, and durations. In that case, in a context of variable wind speed and direction, the irrigation criteria will try to avoid irrigating under unfavourable conditions.

Model output includes irrigation depth at each cell for each irrigation event, water balance and crop yield reduction at each cell, irrigation performance indexes (such as *CU* and *WDEL*), and field average yield reduction and deep percolation losses.

FIELD EXPERIMENTS

Two field experiments were performed in the summer of 2000 at the experimental farm of the Agricultural Research Service of the Government of Aragón in Zaragoza, Spain (41° 43'N, 0°48'W, 225 m of altitude) to calibrate and validate the coupled model. The first experiment consisted on a field irrigation evaluation of an isolated sprinkler under no-wind conditions and high air relative humidity. The sprinkler type was “VYR 70”, manufactured by VYRSA (Briviesca, Burgos, Spain), the nozzle diameters were 4.4 mm and 2.4 mm, and the nozzle operating pressure was 300 kPa. This experiment allowed characterizing the water application pattern for the sprinkler-nozzle-pressure combination used in the field experiment. Catch cans spaced 0.5 m were installed along four radii at 90° angles extending from the isolated sprinkler. This experiment was designed to calibrate the parameters of the drop size distribution curve.

The second experiment was performed on a solid set sprinkler irrigation system arranged in a triangular spacing of 18 m by 15 m. This solid set was used to irrigate a corn crop (*Zea mays* L. cv. Dracma). The sprinkler material and operating pressure were as described in the first experiment. The duration of the corn phases was derived from the measured phenological data. A detailed description and analysis of this second experiment can be found Dechmi et al. (2003). The objective of this second experiment was to provide experimental data for the calibration of the K_1 and K_2 parameters, and to validate the crop and solid set irrigation models.

Irrigation was scheduled to fulfil corn water requirements during all growth stages. A total of 24 irrigation events were applied. Irrigation evaluations were performed in 23 irrigation events using the methodology proposed by Merriam et al. (1980) in two sprinkler spacings identified as plots A and B (Figure 2). The first irrigation event of the season was not evaluated, although it was used for water budget in crop simulation. Corn yield was measured in 25 subplots of 1.5 m x 1.5 m, each of them with a catch can in the center. Data from the evaluated irrigation events was used to derive a predictive *WDEL* equation (Dechmi et al., 2003).

The meteorological data used for model input and for determining Penman-Monteith ET_0 were recorded during the crop season in an automated meteorological station (Campbell Scientific, Logan, Utah) installed on a 1.2 ha grass plot located at a distance of 200 m from the experimental plot. Wind speed (W) and direction (Wd) were recorded with a frequency of 2 minutes, while the rest of meteorological data were recorded with a frequency of 30 minutes. Since the field irrigation evaluations used for model calibration

were performed on corn and wind speed was recorded on grass, a correction was applied to the measured wind speed. For this purpose, the relationships between the wind speed measured at 2 m on grass and on corn (considering the different corn canopy heights) during the summer of 1997 in the same experimental farm were obtained by linear regression.

For model calibration and validation purposes, the irrigation depths (ID_c) measured after each irrigation event in catch cans located at the same position in plots A and B were averaged and assigned as the measured ID_c of the corresponding subplot. The experimental subplots correspond to the computational cells described in AdorSim. The measured yield reduction (YR) of each subplot of both plots was calculated as the difference between 100 and the percentage of grain yield (GY_i) to maximum (GY_{max}) (Dechmi et al., 2003).

The statistical significance levels considered in the regression analyses were: “ ns ” to indicate non significant ($P > 0.05$); “*” to indicate $0.05 \geq P > 0.01$; “**” to indicate $0.01 \geq P > 0.001$; and “***” to indicate $0.001 \leq P$.

CALIBRATION AND VALIDATION OF ADOR-SPRINKLER

Determination of the drop size distribution parameters D_{50} and n

The adjustment of the drop size distribution parameters was performed comparing the observed and simulated water distribution patterns for the combination of nozzle size and operating pressure used in the first experiment. The Ador-Sprinkler model was run for

272 combinations of D_{50} and n . In these model runs the value of D_{50} ranged from 0.8 mm to 1.55 mm, with an increment of 0.00005 m, while the value of n ranged from 2.0 to 2.8, with an increment of 0.05. The optimum parameter combination was $D_{50} = 1.30$ mm and $n = 2.50$ ($RMSE$ of 0.48 mm h^{-1} and r of 0.794). The application of the predictive drop size parameter equations proposed by Kincaid et al. (1996) (Eqs. 6, 7 and 8) to the experimental conditions yielded the following results: $D_{50} = 2.05$ mm, and $n = 1.82$. When these values were supplied to Ador-Sprinkler and the resulting water distribution pattern was compared to the experimental results, the similitude indexes worsened: $RMSE = 0.874 \text{ mm h}^{-1}$ and $r = 0.446$. This poor performance can be attributed to a number of facts: 1) the difference between the sprinkler and nozzle manufacturers used by Kincaid et al. (1996) and ourselves; 2) the fact that Kincaid et al. (1996) performed indoor experiments, while we did outdoor tests subjected to WDEL (8.6 % in the experimental conditions); and 3) possible model inaccuracies in areas such as the drag coefficient.

Selection of the optimum values of K_1 and K_2

In Ador-Sprinkler only one value of W and Wd is used for each simulation. In order to consider the variation of these meteorological variables during a given irrigation event, each event was subjectively divided in partial irrigations. The wind direction was divided in eight classes of 45° each, plus an additional class for calm conditions in which no corrections were required on the drag coefficient C . Each partial irrigation was characterized by its: 1) duration; 2) average wind speed; and 3) weighted average wind direction recorded in the dominant class.

Seven irrigation events, selected to reflect a wide range in wind speed, were used for the calibration process (Table 1). For each partial irrigation a total of 300 simulations

were performed, with the value of K_I ranging from 0.0 to 2.8 (with an increment of 0.2) and the value of K_2 ranging from 0.00 to 0.95 (with an increment of 0.05). The cell irrigation depth resulting from each simulated partial irrigation was accumulated to obtain the total cell irrigation depth for each irrigation event. Figure 3 presents DIF_{CU} , $RMSE$ and r obtained with each combination of K_I and K_2 for four of the calibration irrigation events, (17, 7, 8 and 22). The corresponding average wind speeds were 0.8, 2.6, 4.2, and 6.2 m s⁻¹, respectively.

Results show that for a wind speed of 0.8 m s⁻¹, the optimum value of r occurred in a different area than for DIF_{CU} and $RMSE$. For the other three wind conditions the optimum values of the three parameters are approximately coincident, and adequate values of K_I and K_2 could be selected that are close to satisfying all these similitude criteria. The optimum K_2 values increase linearly with wind speed. The optimum K_I values increase from 0.8 m s⁻¹ to a value between 2.6 m s⁻¹ and 4.2 m s⁻¹, to decrease again for a wind of 6.2 m s⁻¹. Tarjuelo et al. (1994) identified a different relationship between the magnitude of the correction parameters and the wind speed. Montero et al. (2001), in their calibration of the SIRIAS model, found no relationship between wind speed and the magnitude of the correction parameters.

According to these observations, the selection of the optimum K_I and K_2 values was performed as follows: 1) For each irrigation event with average wind speed above 2.1 m s⁻¹, a parameter combination satisfying $RMSE$ and r was selected; 2) DIF_{CU} was only considered if more than one optimum combination of K_I and K_2 could be identified (in this case, the set of parameters yielding the minimum value of $RMSE \times DIF_{CU}$ was selected); and 3) In irrigation events with $W < 2.1$ m s⁻¹, the parameter combination yielding

minimum $RMSE \times DIF_{CU}$ was selected. The points identified with a cross in Figure 3 represent the selected values of the parameters. Considering the selected parameters in all seven calibration irrigation events, the following relationship between K_2 and W was determined:

$$\begin{aligned} & \text{for } W \leq 1.1 \text{ ms}^{-1}; \quad K_2 = 0 \\ & \text{for } W > 1.1 \text{ ms}^{-1}; \quad K_2 = 0.0719W - 0.0814, \quad (R^2 = 0.985^{***}) \quad [18] \end{aligned}$$

Since the variation of K_l with W did not follow a linear trend, fixed values of K_l were considered for four wind speed ranges. The optimal values of K_l were 0.0, 1.0, 1.2 and 0.6 for wind speeds below 1.5 m s^{-1} , between 1.5 and 2.1 m s^{-1} , between 2.1 and 4.5 m s^{-1} and above 4.5 m s^{-1} , respectively. For wind speeds below 1.1 m s^{-1} , the correction of the aerodynamic drag coefficient C was not required.

Ador-Sprinkler validation

Two types of model validation were performed using the optimum values of K_l and K_2 obtained during the calibration process; partial and complete irrigations. The simulation input data for the complete irrigation events consisted of: 1) the average values of wind speed, air temperature and relative humidity recorded during the irrigation event; and 2) the weighed wind direction corresponding to the class in which the recorded wind direction was most frequent (Table 1). The seven irrigation events used for model calibration were not considered in the validation process. The experimental CU 's for each irrigation event were compared with the simulated values (partial and complete irrigation events) (Figure 4). Model validation was satisfactory in both cases, since the slopes and intercepts of the

regression lines were not significantly different from 1 and 0, respectively ($P = 0.95$), and both coefficients of determination were higher than 0.793***. The differences between partial and complete irrigation events are small, although complete irrigation events produced better validation results ($R^2 = 0.871$ ***).

Concerning water distribution, the *RMSE* for complete irrigation events varied from 0.48 mm h⁻¹ to 2.11 mm h⁻¹, with an average of 0.95 mm h⁻¹. When partial irrigation events were simulated, the *RMSE* varied from 0.44 mm h⁻¹ to 3.95 mm h⁻¹, with an average of 1.22 mm h⁻¹. Even if these *RMSE* values were somewhat higher than the *RMSE* between the measured water distributions in plots A and B (Table 1), a relevant part of the calibration error corresponded to experimental errors. It can be concluded that the model offered an appropriate prediction of water distribution under the experimental operating conditions. Since the simulation with complete irrigation events was slightly better and is simpler to implement, this was the procedure used in the rest of this work.

VALIDATION OF ADOR-CROP

Comparison with CropWat

In order to test the Ador-Crop simulation module, a comparison with the Windows version of CropWat (Clarke et al., 1998) was performed. In Ador-Crop, the crop coefficients were calculated from the FAO tabulated values (Allen et al., 1998), adjusted for the duration of the crop experimental growth phases obtained from observed phenological data. Both models were run using the measured soil characteristics (*TAW*,

initial soil moisture depletion and maximum soil depth) at each subplot of both plots, and the measured catch can irrigation depths (ID_c). A maximum soil depth of 0.9 m was considered because no soil water extraction was observed below that depth. CropWat YR 's were determined using the four proposed methods to derive daily values of ET_0 from monthly values (Clarke et al., 1998).

The regression of CropWat vs. Ador-Crop YR showed an adequate fit ($R^2 > 0.970^{***}$) for all four CropWat variants. The regression intercepts and slopes were not significantly different from 0 and 1, respectively, when the method to derive daily values of ET_0 was a linear distribution at the end of the month (Figure 5a) and when the method consisted in using the ET_0 monthly averages as daily values (Figure 5b).

Comparison with measured data

The measured and simulated YR 's corresponding to each subplot of both plots were plotted against the Seasonal Available Water (SAW), determined as the initial soil available water plus irrigation and precipitation (Figure 6a). Twelve subplots (out of the total of 50) were not considered in this analysis because of their low plant density or because of low infiltration and water logging. A linear response was found between the simulated YR and SAW up to the value of the maximum seasonal evapotranspiration. Beyond this value, no yield reduction was observed. The scatter plot for simulated vs. measured YR presents a large variability (Figure 6b). The resulting coefficient of determination was low but highly significant ($R^2 = 0.378^{***}$).

The large variability in the measured *YR* could be related to other non water-related factors, such as soil fertility or mild irrigation water and soil salinity (Dechmi et al., 2003). Figure 7 illustrates the effect of additional factors on *YR*. While the scatter plot of *SAW* between the same subplots in plots A and B shows a good agreement (Figure 7a), the scattering of the corresponding plot for measured *YR* is high (Figure 7b). If observed yield reduction would have been only due to *SAW*, Figures 7a and 7b would have shown similar behavior.

VALIDATION OF THE COUPLED MODEL ADORSIM

The first part of the validation consisted on reproducing Figure 6a, but using AdorSim instead of Ador-Crop. This implies using simulated *ID_c* instead of measured catch can data. The difference between the simulated and measured seasonal catch can irrigation depth (*ID_{CS}*) amounted to 13.1 mm, with respective standard deviations of 72.7 mm and 71.3 mm. Figure 8a presents a scatter plot of measured vs. simulated *ID_{CS}*. The correspondence between these two variables is very high, and therefore the scatter plot between *SAW* and AdorSim simulated *YR* (Figure 8b) is very similar to what could be observed in Figure 6a.

The validation of the coupled model AdorSim proceeded with the comparison of the *YR*'s 1) simulated with the coupled model, 2) simulated with Ador-Crop using the measured irrigation depth (*ID_C*) as water input, and 3) measured in the field experiment. A regression analysis performed between both simulated *YR*'s (Figure 9a) indicated that the regression slope and intercept were not significantly different from 1 and 0, respectively. AdorSim slightly over estimated *YR*, and explained 73 % of the variability in Ador-Crop

simulated *YR*. The difference between the average yield reductions simulated with both models was 2.92 % (corresponding to 292 kg ha⁻¹ in the present case). The standard deviation of the simulated and measured *YR*'s were 17.9 % and 15.4 %, respectively. Finally, Figure 9b presents a scatter plot between measured and AdorSim simulated *YR*. AdorSim could explain 25 %** of the variability in measured *YR*, while Ador-Crop could explain 38 %***. The simulation of sprinkler irrigation introduces additional error in the model, but most of the scatter in the validation plot is due to the relevance of non water-stress related factors on *YR*.

In a similar simulation study analyzing a surface irrigation experiment performed in the same farm, Cavero et al., (2001) used a surface irrigation simulation model and the crop growth model EPICphase. The combination of both simulation approaches explained between 26 and 56 % of the variability in measured crop yield. In the present work, the use of a more complete crop growth model could have resulted in a better simulation of the measured crop yield. This circumstance will be explored in future works.

SUMMARY AND CONCLUSIONS

The simulation of solid set sprinkler irrigation under windy conditions is a complicated task due to the frequent variation of wind speed and direction during an irrigation event. The calibration methodology applied in this paper allowed to introduce in the model wind effects in a satisfactory manner. The drop size distribution parameters identified from field experiments and model runs were $D_{50} = 1.30$ mm and $n = 2.50$. A relationship was found between the corrector parameters (K_1 and K_2) and the wind speed.

For wind speeds below 1.1 m s^{-1} , correction of the aerodynamic drag coefficient C was not required. The variation of K_2 with the wind speed was linear, while a step function was used to model the effect of wind speed on K_L .

After calibration, Ador-Sprinkler adequately predicted the spatial irrigation water distribution during the whole corn development season. The average *RMSE* between measured and simulated water application (0.95 mm h^{-1}) was comparable to the average *RMSE* between the measured water distributions in plots A and B (0.63 mm h^{-1}). Therefore, a relevant part of the simulation error could be attributed to experimental errors.

The Ador-Crop model was compared with CropWat. Both models produced similar yield reductions ($R^2 = 0.988^{***}$). The best fit was obtained when a linear distribution at the end of the months was used in CropWat to extrapolate monthly ET_0 . The plot of measured and Ador-Crop simulated yield reduction vs. soil available water resulted in similar features, but the scatter was much larger for the measured yield reduction than for the simulation results, indicating that in the real world factors other than water availability affect crop yield. AdorSim was validated comparing the measured and simulated values of *YR*. The coupled model explained 25 %** of the variability in measured *YR*. Although this percentage may seem modest, it is similar to previous findings in similar approaches used in surface irrigation.

The fact that the coupled model uses thermal time to simulate crop growth makes it very adequate to assess irrigation performance using time series, in which historical meteorological data could be used to analyze crop response to different irrigation strategies. AdorSim could be an adequate tool to: 1) Assess the effect of changes in solid-

set design on irrigation performance and crop yield; 2) Analyze the current irrigation management practices in windy areas where solid set sprinkler irrigation is relevant; 3) Characterize the relationship between wind speed and direction and irrigation uniformity and crop yield; and 4) Investigate irrigation scheduling scenarios based on the meteorological factors affecting irrigation water distribution, and soil, water, and irrigation system constraints. In a companion paper, AdorSim will be applied to address some of these questions in the context of a corn crop in the middle Ebro basin in NE of Spain.

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APPENDIX I: REFERENCES

- Allen, R.G., Pereira, L.S., Raes, D., and Smith, M. (1998). "Crop evapotranspiration: guidelines for computing crop water requirements". FAO irrigation and drainage paper 56, Rome, Italy.
- Brisson, N., and Mary, B. (1999). "STICS version 4.0. Modèle de simulation de culture, bilan hydrique et bilan azoté ". Notice concepts et formalismes.
- Cabelguenne, M. (1996). "Tactical irrigation management using real time EPIC-phase model and weather forecast: Experiment on maize". In "Irrigation Scheduling from Theory to Practice (Water Reports)", FAO, Rome. 185-193.
- Cavero, J., Farré, I., Debaeke, P., and Faci, J. M. (2000). "Simulation of maize yield under water stress with the EPICphase and CROPWAT models". *Agronomy Journal*, 92(4), 679-690.
- Cavero, J., Playán, E., Zapata, N., and Faci, J. M. (2001). "Simulation of maize grain yield variability within a surface-irrigated field". *Agronomy Journal*, 93(4), 773-782.
- Carrión, P., Tarjuelo, J. M., and Montero, J. (2001). "SIRIAS: a simulation model for sprinkler irrigation. I. Description of the model". *Irrig. Sci.* 20, 73-84.
- Christiansen, J. E. (1942). "Irrigation by Sprinkling". Univ. Of California. Agric. Exp. Sta. Bull. 670.

- Clarke, D., Smith, M., and El Askari, K. (1998). "CropWat for Windows: User Guide".
FAO, Rome.
- Dechmi, F., Playán, E., Caverro, J., Faci, J. M., and Martínez-Cob, A. (2003). "Wind effects on solid set sprinkler irrigation depth and corn yield". *Irrig. Sci.*, 22, 67-77.
- De Juan, J.A., Tarjuelo, J.M., Valiente, M., and García, P. (1996). "Model for optimal cropping patterns within the farm based on crop water production functions and irrigation uniformity. I: Development of a decision model". *Agric. Wat. Manag.*, 31, 115-143.
- Doorenbos, J., and Kassam, A. H. (1979). "Efectos del agua sobre el rendimiento de los cultivos". Food and Agriculture Organisation of the United Nations, Irrigation and drainage Paper 33, Rome, Italy.
- Faci, J., and Bercero, A. (1991). "Efecto del viento en la uniformidad y en las pérdidas por evaporación y arrastre en el riego por aspersión". *Inv. Agr.: Prod Prot. Veg.*, 6(2), 171-182.
- Fukui, Y., Nakanishi, K., and Okamura, S. (1980). "Computer evaluation of sprinkler irrigation uniformity". *Irrig. Sci.* 2, 23-32.
- Gallagher, J. N. (1979). "Field studies of cereal leaf growth". *J. Exp. Bot.*, 30(117), 625-636.

- Hills, D., and Gu, Y. (1989). "Sprinkler volume mean droplet diameter as a function of pressure". Trans. ASAE, 32, 471-476.
- Jones, C.A., and Kiniry, J. R. (1986). "CERES-maize: A simulation model of maize growth and development". Texas A&M Univ. Press, College Station.
- Kincaid, D.C., Solomon, K.H., and Oliphant, J.C. (1996). "Drop size distributions for irrigation sprinklers". Trans. ASAE, 39(3), 839-845.
- Li, J., Kawano, H., and Yu, K. (1994). "Droplet size distributions from different shaped sprinkler nozzles". Trans. ASAE, 37(6), 1871-1878.
- Li, J. (1998). "Modeling crop yield as affected by uniformity of sprinkler irrigation system". Agric. Wat. Manag., 38, 135-146.
- Mantovani, E.C., Villalobos, F.J., Orgaz, F., and Fereres, E. (1995). "Modeling the effects of sprinkler irrigation uniformity on crop yield". Agric. Wat. Manag. 27, 243-257.
- Merriam, J. L., Sheare, M.N., and Burt, C. M. (1980). "Evaluating irrigation systems and practices". In: Design and operation of farm irrigation systems. Ed M. E. Jensen. ASAE. Michigan. USA. 721-776.

- Montero, J. (1999). "Análisis de la distribución de agua en sistemas de riego por aspersión estacionario. Desarrollo del modelo de simulación de riego por aspersión (SIRIAS)," Doctoral Thesis, Universidad de Castilla-la Mancha, Albacete, Spain, 225 pp.
- Montero, J., Tarjuelo, J. M., and Carrión, P. (2001). "SIRIAS: a simulation model for sprinkler irrigation. II. Calibration and validation of the model". *Irrig. Sci.* 20, 85-98.
- Or, D., and Hanks, R.J. (1992). "Soil water and crop yield spatial variability induced by irrigation nonuniformity". *Soil Soc. Am. J.*, 56, 226-233.
- Press, W.H., Flannery, B. P., Teukolsky, S. A., and Vetterling, W. T. (1988). "Numerical recipes in C". Cambridge University Press, Cambridge, U.K.
- Seginer, I., Kantz, D., and Nir D. (1991). "The distortion by wind of the distribution patterns of single sprinklers". *Agric. Wat. Manag.* 19, 314-359.
- Smith, M. (1993). "CropWat. Programa de ordenador para planificar y manejar el riego". Estudio FAO riego y drenaje nº 46.
- Smith, M., Pereira, L. S., Beregena, J., Itier, B., Goussard, J., Ragab, R., Tollefson, L., and Van Hoffwegen, P. (1996). "Irrigation Scheduling: From Theory to Practice". FAO Water Report 8. ICID and FAO, Rome.
- Solomon, K. H. (1983). "Irrigation uniformity and yield theory". PhD thesis, Agricultural & Irrigation Engineering Department, Utah State University, Logan, UT.

- Stern, J., and Bresler, E. (1983). "Nonuniform sprinkler irrigation and crop yield". *Irrig. Sci.* 4, 17-29.
- Stewart, J. I., Hagan, R. M., Pruitt, W. O., Hanks, R. J., Riley, J. P., Danilson, R. E., Franklin, W. T., and Jackson, E. B. (1977). "Optimizing crop production through control of water and salinity levels". *Utah Water Res. Lab. PRWG*, 151-1, September.
- Stockle, C.O., Martín, S.A., and Campbell, G.S. (1994). "CropSyst, a cropping systems simulation model: water/nitrogen budgets and crop yield". *Agric. Syst.* 46, 335-359.
- Tarjuelo, J. M., Valiente, M., and Lozoya, J. (1992). "Working conditions of sprinkler to optimize application of water". *J. Irrig. Drain. Eng.* 118, 895-913.
- Tarjuelo, J. M., Carrión. P., and Valiente, M. (1994). "Simulación de la distribución del riego por aspersión en condiciones de viento". *Inv. Agr. Prod. Prot. Veg.* 9(2), 255-272.
- Von Bernuth, R. D., and Gilley, J. R. (1984). "Sprinkler droplet size distribution estimation from single leg data". *Trans., ASAE*, 27(5), 1435-1441.
- Von Bernuth, R. D. (1988). "Effect of trajectory angle on performance of sprinklers in wind". *J. Irrig. Drain. Eng.* 114, 579-587.

- Vories, E. D., Von Bernuth, R. D., and Mickelson, R. H. (1987). "Simulating sprinkler performance in wind". *J. Irrig. Drain. Eng.* 113(1), 119-130.
- Warrick, A.W., and Gardner, W. R. (1993). "Crop yield as affected by special variations of soil and irrigation". *Water Resour. Res.* 19, 181-186.
- Williams, J. R., Jones, C. A., and Dyke, P. T. (1984). "A modeling approach to determining the relationship between erosion and soil productivity". *Trans. ASAE* 27, 129-144.

APPENDIX II: NOTATION

The following symbols are used in this paper:

A = acceleration of the drop in the air (m s^{-2});

AWD = allowable water depletion limit (mm);

a_d, a_n = empirical coefficients;

b_d, b_n = empirical coefficients;

C = drag coefficient;

C' = adjusted drag coefficient;

CU = Christiansen's uniformity coefficient (%);

D = drop diameter (m);

D_{50} = volume mean drop diameter (mm);

DIF_{CU} = absolute difference between the measured and simulated CU (%);

Dp = deep percolation (mm);

D_r = root zone depletion (mm);

ET_0 = reference evapotranspiration (mm);

ETa = actual crop evapotranspiration (mm);

ETc = crop evapotranspiration (mm);

ET_{max} = maximum crop evapotranspiration (mm);

f = number of development stage;

GY = grain yield (kg ha^{-1});

GY_{max} = maximum grain yield (kg ha^{-1});

ID = irrigation depth (mm);

$\overline{ID}$ = average irrigation depth (mm);

- ID_c = catch can irrigation depth (mm);
- ID_{cs} = Seasonal irrigation depth (mm);
- IE = irrigation evaluation;
- IE_p = partial irrigation evaluation;
- i = subscript for cell or subplot;
- j = subscript for day;
- K_1, K_2 = empirical parameters;
- K_c = crop coefficients;
- K_y = crop yield sensitivity to water deficits;
- K_{yf} = crop yield sensitivity to water deficits in crop developmental phase f ;
- m = subscript indicating that the variable was measured;
- n = dimensionless exponent;
- n_c = number of catch cans;
- P = precipitation (mm);
- p = depletion factor (%);
- P_v = percent of total discharge in drops smaller than D (%);
- $RMSE$ = Root Mean Square Error;
- R = ratio of nozzle size to pressure head;
- r = coefficient of correlation;
- SAW = seasonal available water (mm);
- SWC = soil water content (mm);
- SWD = soil water depletion (mm);
- s = subscript indicating that the variable was simulated;
- t = time;
- TAW = total available water (mm);

U = drop velocity vector with respect to the ground (m s^{-1});

UD = uniformity of distribution (%);

V = drop velocity vector in the air (m s^{-1});

W = wind velocity vector (m s^{-1});

W = wind speed;

Wd = wind direction ($^{\circ}$);

$WDEL$ = wind drift and evaporation losses (%);

x, y, z = Cartesian coordinates referring to the ground (m);

Y_a = actual yield (kg ha^{-1});

Y_{max} = maximum yield (kg ha^{-1});

YR = yield reduction (%);

α = angle formed by vectors V and W ;

β = angle formed by the vectors V and U ;

ρ_a = density of the air (g m^{-3});

ρ_w = density of the water (g m^{-3});

APPENDIX III: TABLES

Table 1. *Characteristics of the 23 evaluated irrigation events used for calibration and validation of the Ador-Sprinkler model. The data include: duration of the irrigation event, catch can elevation above soil surface, average wind speed (W), dominant wind direction, percent of irrigation duration during which the dominant wind direction was recorded, number of wind direction classes, Root Mean Square Error between the irrigation depth collected in plots A and B for the same subplots (RMSE), and Average Christiansen Coefficient of Uniformity of plots A and B (CU). The character “c” indicates that the irrigation evaluation was used for model calibration.*

Irrigation Number	Irrigation Duration (h)	Catch Can Elevation (m)	W (m s^{-1})	Dominant Wd ($^{\circ}$)	Irrigation time with dominant Wd (%)	Number of wind direction classes	RMSE (mm h^{-1})	CU (%)
IE1	3.0	0.36	4.8	90-135	86	3	1.27	64.8
IE2	7.0	0.36	3.2	225-270	88	3	0.64	74.8
IE3	6.0	0.36	1.4	225-270 [‡]	23	8	0.40	93.9
IE4-c	2.0	0.36	2.7	180-225	51	3	0.92	81.5
IE5	5.0	0.36	1.1	135-180 [‡]	38	8	0.55	94.3
IE6-c	3.0	0.36	2.0	90-135 [‡]	46	8	0.62	87.6
IE7-c	2.0	0.75	2.6	135-180	44	4	0.52	81.3
IE8-c	5.0	0.75	4.2	315-360	58	4	0.75	75.0
IE9	4.1	1.50	5.3	315-360	64	2	1.13	54.7
IE10	4.0	1.50	1.2	135-180	47	6	0.39	91.6
IE11	6.0	1.50	2.4	180-225	51	5	0.44	73.7
IE12	3.9	1.50	0.6	0-45	35	6*	0.39	92.8
IE13	6.0	1.50	3.1	135-180	43	6	0.51	70.3
IE14	6.0	1.50	6.5	315-360	62	2	1.15	56.4
IE15-c	3.2	1.50	1.1	135-180	100	1	0.39	93.9
IE16	5.5	2.16	1.3	0-45	47	6*	0.50	87.1
IE17-c	4.2	2.16	0.8	0-45	63	3*	0.63	88.1
IE18	4.0	2.16	1.2	45-90	44	6*	0.40	86.1
IE19	3.0	2.16	0.6	45-90	42	7*	0.51	89.0
IE20	3.0	2.16	0.7	0-45	40	5*	0.45	90.1
IE21	5.0	2.16	1.0	0-45 [‡]	48	8*	0.63	88.0
IE22-c	5.0	2.16	6.2	270-315	53	3	0.79	54.3
IE23	4.0	2.16	1.8	225-270 [‡]	36	8	0.41	80.8
Average		-	2.4	-	-	-	0.63	80.5

[‡] A dominant wind direction was established, but wind blew from all directions during the irrigation event.

* Calm periods were recorded during the irrigation event.

APPENDIX IV: FIGURES

Figure 1. Schematic description of the AdorSim model.

Figure 2. Detail of field experiment describing the two experimental plots, the subplots, and the location of the sprinklers, catch cans and corn rows.

Figure 3. Absolute difference between the measured and simulated CU (DIF_{CU}), Root Mean Square Error (RMSE) and coefficient of correlation (r) obtained with each combination of K_1 and K_2 during the Ador-Sprinkler calibration process. Results are presented for four irrigation events characterized by different wind speeds (0.8 m s^{-1} , 2.6 m s^{-1} , 4.2 m s^{-1} and 6.2 m s^{-1}). Crosses indicated the selected combination of K_1 and K_2 for each case.

Figure 4. Relationship between measured (CU_m) and simulated (CU_s) CU considering partial irrigation events (CU_{sp}) and complete irrigation events (CU_{sc}). The dotted line represents the 1:1 relationship. The black dots and black regression line correspond to CU_{sp} , while the grey dots and grey regression line correspond to CU_{sc} .

Figure 5. Ador-Crop yield reduction (YR) vs. CropWat yield reduction (YR) using the ET_0 distribution model fitting: a) a linear distribution at the end of the months; and b) monthly averages as daily values. The dotted line represents the 1:1 relationship. The equation and the solid lines correspond to the regressions.

Figure 6. Ador-Crop validation: a) Relationship between the seasonal available water (SAW) for the crop and the yield reduction (YR) as measured and simulated with Ador-Crop; and b) Measured vs. Ador-Crop simulated yield reduction.

Figure 7. Relationship between: a) seasonal available water measured in plots A (SAW_A) and B (SAW_B), and b) yield reduction measured in plots A (YR_A) and B (YR_B). The dotted line represents the 1:1 relationship.

Figure 8. Relationship between: a) simulated and measured seasonal irrigation depth (IDcs); and b) between the simulated available water (SAW) for the crop and the yield reduction (YR) simulated with AdorSim. The dotted line represents the 1:1 relationship.

Figure 9. AdorSim validation: a) Yield reduction (YR) calculated with Ador-Crop model using catch can irrigation depths as water input and yield reduction calculated with the coupled model AdorSim using simulated irrigation depth; and b) Measured vs. AdorSim simulated yield reduction. The dotted line represents the 1:1 relationship.

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