EFFECT OF INTRA-IRRIGATION METEOROLOGICAL VARIABILITY ON SEASONAL CENTER-PIVOT IRRIGATION PERFORMANCE AND CORN YIELD

Ouazaa, S.⁽¹⁾, Latorre, B.⁽²⁾, Burguete, J.⁽³⁾ and Zapata, N.^(4,*)

⁽¹⁾ Dept. Soil and Water. EEAD-CSIC. Avda. Montañana, 1005. 50059 Zaragoza. Spain.

sofiane.ouazaa@gmail.com

⁽²⁾ Dept. Soil and Water. EEAD-CSIC. Avda. Montañana, 1005. 50059 Zaragoza. Spain.

borja.latorre@csic.es

⁽³⁾ Dept. Soil and Water. EEAD-CSIC. Avda. Montañana, 1005. 50059 Zaragoza. Spain.

jburguete@eead.csic.es

^(4,*) Corresponding author. Dept. Soil and Water. EEAD-CSIC. Avda. Montañana, 1005.

50059 Zaragoza. Spain. v.zapata@csic.es

ABSTRACT

Water application depth of a center-pivot (CP) irrigation system is not uniformly distributed across a field due to emitter package design, tower dynamics and meteorological variability. The objective of this research was to measure and model the effect of the intra-irrigation meteorological variabilities on CP seasonal water distribution pattern and corn yield. The 2013 irrigation season of a commercial CP cropped with corn was analyzed. From sixty irrigation events applied to the corn, ten were evaluated using radial catch-cans. The mechanical movement of CP towers for the sixty irrigation events was characterized using Global Navigation Satellite System-Real Time Kinematic (GNSS-RTK) monitoring. Meteorological variables at one second frequency were measured with an automatic weather station installed in the farm. The ballistic model calibrated and validated for rotating spray plate sprinklers (RSPS) under different nozzle

sizes and wind conditions was mounted on the CP lateral, following the correspondent sprinkler package. The CP lateral was moved following the measured or simulated towers dynamic and the current or averaged meteorological conditions of each irrigation event applied to the corn. Crop yield was simulated by coupling the water distribution pattern simulated under the different cases with Ador-crop model. Differences on simulated seasonal water distribution pattern of the CP under homogenous wind conditions (averaged for each irrigation event) or under variable on time wind conditions (measures) were showed. Simulated yield considering discontinuous tower dynamics and intra-irrigation meteorological variability has the largest correlation coefficient with measured corn yield. Other factors not considered in the yield simulation as variability on nutrients availability, emergence problems, diseases and soil variability could explain the differences between simulated and measured corn yield. The intra-irrigation meteorological variability has an important effect on water distribution pattern of windy irrigation events of CP systems. Depending on the wind speed along the crop season the intra-irrigation variability will have a major or minor effect on seasonal water distribution pattern and on crop yield variability.

KEYWORDS

Center pivot irrigation; Simulation modeling; Water distribution patterns; Meteorological variability; Yield variability.

INTRODUCTION

Center-pivots (CP) are one of the most popular pressurized irrigation systems used worldwide. In an attempt to reduce the energy costs associated with their use, the actual trend is to use low-pressure systems, with spray sprinklers. This new generation sprinklers include rotating spray plate sprinklers (RSPS) or fixed spray plate sprinklers (FSPS). Center pivot irrigation is, however, energy intensive. The increasing unit cost of energy and possible shortages of energy in the future are intensifying efforts to develop acceptable design concepts and management strategies for reducing energy use which do not excessively lower the uniformity and/or efficiency of application (Moreno *et al.*, 2012). A system with reduced operating pressure but with excessive runoff and poor uniformity would be an unacceptable way of decreasing energy use. The development of simulation tools to analyze the effect of nozzle package, working pressure, towers dynamics and other variables affecting center-pivot irrigation can help to establish the adequate design and management strategies.

Water application uniformity is an important performance criterion for the design and evaluation of center-pivot sprinkler irrigation systems. Water application depths of a center-pivot system is not uniformly distributed, nor in space (across the field), nor in time (the whole irrigation season) and depends on the sprinkler package, the field topography, the tower dynamics and the meteorological conditions. Catch-can tests have been the method used to characterize the water distribution uniformity for center-pivot. Field evaluation of each design concept and management strategy on which a center pivot system might operate is a tedious and expensive process. Catch-can testing is very time-consuming and data can only be collected along a limited number of radial or circular lines. In fact, most tests involve only one set of catch-cans. If a center pivot system rotates at a constant speed, and the meteorological and technical (percentage timer setting, PTS (%)) conditions are constant, a spatial water application depth map may be constructed

based upon data only from one radial line. However, most center pivot systems operate on variable field conditions. Variations in meteorological and technical conditions can change the water application depth and irrigation uniformity at different lateral positions even with flow control nozzles or pressure regulators at each head. In such cases, using catch-can tests to determine the spatial distribution of water application depth and application uniformity is not practical. An alternative method is to use computer simulation models to generate water application depth data. A model that represents the performance of center pivot systems operating at different technical and meteorological conditions would greatly facilitate the evaluation process.

Crop water needs can vary due to within-field differences in soil texture, topography, and biotic stresses (O'Shaughnessy *et al.*, 2013). Knowledge of water spatial distribution in a field is essential for site-specific crop management, as such distribution maps can be used to adjust the input rates and target the critical areas in a field (known as precision farming). Once areas of either over-application or under-application are identified from the distribution maps, appropriate management practices can be taken to correct them. Current research on center pivot irrigation focus on precision farming by controlling site-specific variable rate irrigation (VRI) technologies (Kranz *et al.*, 2012; O'Shaughnessy *et al.*, 2013; Evans *et al.*, 2013; McCarthy *et al.*, 2014). To apply VRI, knowledge of irrigation water distribution patterns and crop water availability distribution for the whole center-pivot irrigated area is needed. Factors affecting irrigation water distribution patterns as sprinkler package, working pressure, tower dynamics and meteorological conditions should be considered in the analysis. Factors affecting soil water availability for crop are besides irrigation distribution depths, those related with soil water holding capacity.

The simulation of center-pivot water distribution patterns resulting from different sprinkler types has traditionally been conducted by mathematically overlapping experimentally measured isolated sprinkler patterns (Clark *et al.*, 2003). Molle and Le Gat (2000) proposed a model using

a mixture of beta probability. Recently, Sayyadi *et al.* (2012) proposed a new approach based on Artificial Neuronal Networks (ANN) to simulate the effects of wind on the distribution pattern of single sprinklers. A new approach based on droplet trajectory modeling was proposed by Ouazaa *et al.* (2015) to simulate water distribution patterns for FSPS. Also, the water distribution model was coupled with a simulation model of the pivot towers dynamics, incorporating most of the factor affecting irrigation water distribution pattern variability. Intra-irrigation variability of meteorological condition during a center-pivot irrigation event could also be important and affects the spatial variability of applied irrigation depth. O'Shaughnessy *et al.* (2013) using catch can trials reported that wind speed and direction did not appreciably modify uniformity of application, but affects the absolute application depth within the VRI management zone. Wind speed and direction should be considered when applying site-specific or precision irrigation management. In the literature the effect of wind speed has been analyzed from a partial point of view using radial or partial circle catch-can configurations (Dukes, 2006; O'Shaughnessy *et al.*, 2013). There are not works in the literature analyzing the effect of intra-irrigation variability of wind speed and direction on water distribution of the total center-pivot irrigated area. Also, the cumulative effect for the whole crop irrigation season was not reported in the literature.

The principal objective of this study was to advance in the development of a CP model. Ouazaa *et al.* (2015) proposes a model that includes the simulation of water distribution patterns for FSPS package and CP towers dynamic. In this research the simulation of water distribution patterns was extended for RSPS package, and the intra-irrigation meteorological variability during a CP irrigation event was included in the model. Furthermore, the new CP model was coupled with a crop model to simulate water distribution of the whole irrigation season and corn yield. Experimental determination of irrigation uniformity (for selected irrigation events) and spatial variability of corn yield were conducted to validate the model. The new model provides a valuable tool to analyze and quantify the effects of factors as intra-irrigation meteorological

variability and/or tower dynamics on CP water distribution patterns and crop yield variability. The effects were analyzed for individual irrigation events and for a whole corn irrigation season.

MATERIAL AND METHODS

1. The case study

The studied center-pivot cropped with corn was located in Marracos (Spain), at the north west of Zaragoza (Latitude: 42° 5' 27" N - Longitude: 0° 46' 35" W). The center-pivot, a Valley machine (manufactured by Valmont industries, Nebraska, USA), had four towers with 50 m spans and an overhang of 25 m. In the 2013 irrigation season the original sprinkler package of the machine (FSPS, Nelson D3000) was changed by rotating spray plate sprinklers (RSPS) with 6-streams red plates (R3000 Nelson Irrigation Corp. Walla Walla, Washington, USA), maintaining the pressure regulators of 138 kPa. The new sprinkler package had 40 nozzles of 21 different diameters ranging from 2.2 mm to 8.7 mm. The distance between nozzles was constant and equal to 5.56 m. The first nozzle was installed at 10.27 m from the pivot point and the last one at 224.54 m from the pivot point. Nozzles were located 2.0 m above the soil surface using a semi-rigid plastic drop pipe. More details of the center-pivot irrigation machine can be found in Ouazaa *et al.* (2015).

2. Simulating water distribution patterns for RSPS using the ballistic model

2.1. Drop velocity and trajectory characterization at the exit of the deflecting plate

Nine nozzle diameters of RSPS working at 138 kPa were selected for experimental characterization. Drop velocities and angles at the exit of the deflecting plate were measured using the photographic method proposed by Salvador *et al.* (2009). The aim of these experiments is to estimate drop energy losses due to jet impact with the sprinkler deflecting plate. A minimum of 40 drops per nozzle size were selected for measurements. The selection of the drops was performed based on image quality since the drop should be adequately focused (located near the vertical plane containing the reference ruler). Main difference between drop

velocity at the nozzle and after the impact was attributed to the energy losses at the plate (Ouazaa *et al.* 2014).

2.2. Experimental characterization of RSPS water distribution pattern under different technical and meteorological conditions

Six nozzle diameters of RSPS were selected (2.4 mm, 3.8 mm, 5.1 mm, 6.7 mm, 7.9 mm and 8.7 mm) for experimental water distribution pattern characterization. Experiments were carried out at 138 kPa working pressure (most common operating pressure of RSPS), maintained by pressure regulator installed just upstream the sprinklers. For each nozzle diameter, field tests were carried out at 3 different wind speeds (WS) levels, calm ($WS \leq 1 \text{ ms}^{-1}$), medium ($1 \text{ ms}^{-1} < WS \leq 3 \text{ ms}^{-1}$) and high ($WS > 3 \text{ ms}^{-1}$). The evaluation of the water distribution pattern for each nozzle diameter and wind velocity was performed individually following Faci *et al.* (2001).

2.3. Calibration of the ballistic model

The ballistic model approach was used in this study to simulate the water distribution pattern of the RSPS for different nozzle diameter and wind conditions. The calibration process of the model parameters (D_{50} , n , K_1 and K_2) is described in Ouazaa *et al.* (2014). D_{50} (mean drop diameter) and n (dimensionless exponent) are the parameters of the exponential model that characterize the drop diameter distribution (Li *et al.*, 1994). K_1 and K_2 are the parameters of the model that correct the aerodynamic drag coefficient in presence of wind (Seninger *et al.*, 1991). 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 center of the wetted area to the sprinkler (windward direction) and lengthening more behind (leeward direction). Two statistical indexes were used to compare measured and simulated water application patterns: the Root Mean Square Error (*RMSE*) and the coefficient of correlation (r). The ratio $RMSE/(1+r)$ was also used as the objective function for the optimization algorithm. The calibration of the

parameters K_1 and K_2 was performed once D_{50} and n model parameters were calibrated. For this purpose, field experiments under windy conditions were used. The wind speed (WS) and wind direction (WD) were characterized for each irrigation event in order to incorporate it to the model. The calibration of K_1 and K_2 were performed in two steps. The first step optimizes K_1 and K_2 values by comparing measured and simulated irrigation depths. The above-mentioned indexes (RMSE and r) were used for optimization purposes. The Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) coefficient and the percent bias (Gupta et al., 1999) were also provided to determine the model strength. A second step of the calibration process was performed to obtain K_1 and K_2 as a function of wind speed and nozzle size. The objective was to obtain K_1 and K_2 values for non-tested conditions in the range of the evaluated conditions.

3. Catch-can evaluation of irrigation performance for the commercial CP

The irrigation depth (ID, mm) and the uniformity of application along the CP lateral were measured during ten irrigation events using catch-cans arranged in a radial transect line with 2 m spacing. A total of 24 catch-cans were installed per pivot span and 14 catch-cans under the overhang. The evaluations were performed under different machine speed (PTS). A high precision GNSS-RTK (Global Navigation Satellite System-Real Time Kinematic, model GS15 receiver Leyca Geosystems AG, Heer-brugg, Switzerland) was installed at the top of each tower to record tower positions at 1 s frequency. An automatic meteorological station located adjacent to the center-pivot plot monitored wind velocity and direction, air temperature, relative humidity, precipitation and solar radiation at 1 s frequency. To characterize the meteorological conditions of the evaluated irrigation events, GNSS-RTK data of the center-pivot towers were analyzed and compared with catch-can location data to estimate the passing time period of the center-pivot lateral over the radial catch-can transect. The working pressure of the CP lateral was monitored with two pressure transducers tracking data each 15 minutes. The first pressure transducer was

installed at the pivot point, and the other at the beginning of the CP overhang. Another pressure transducer was installed at the pumping station.

4. Field harvest

Harvest of the center-pivot corn was performed with a commercial combine harvester equipped with a GNSS-RTK receiver. The system measures and records the amount of grain harvested and the position of each point of the field. An onboard computer installed in the harvester cab recorder the data. The combine header was 9 m wide and gathers in twelve corn lines at the same time. Yield data provided by the combine computer were refined since there are areas with higher catches due to the slower speed of the harvester, turns, machine's stop, etc. Once data were refined, a grid raster was set (whose parameter can be user-defined). Measured yield were compared with simulated irrigation depth and simulated corn yield.

5. Center pivot model formulation

For modeling purposes, the total area irrigated by the center-pivot system was divided into a static grid. A dynamic grid, composed of regular cells and representing the water application pattern of the sprinklers, passes over the static grid. The water depth collected in each static cell is the sum of the water received from the dynamic grid passing over during a time interval (one irrigation event, the irrigation season, etc). The dynamic grid moves with the towers dynamic, experimentally measured or simulated by the CP tower dynamic model. The applied water depth resulted from simulating the RSPS sprinkler package mounted on the CP lateral.

The time step selected for simulating CP tower dynamics was 1 s, which corresponds to the availability of GNSS-RTK tower location data and meteorological data. The spatial step of the square static and dynamic grid selected for simulation was evaluated. An optimization process for spatial step selection was performed to reduce computing time without affecting simulation adequacy for the dynamic grid (further details can be found at Ouazaa et al, 2015). The static grid

size was selected accounting with field measurement data (catch can trials and harvest measurements), for comparison purposes.

Model validation was performed comparing measured irrigation depths (radial catch-can data) with simulated irrigation depths at the catch can locations.

Simulations were performed with measured tower dynamic data, from one side and with simulated tower dynamics, from the other side. Comparison of the Heermann and Hein radial Uniformity Coefficient (CU_{HH} , %) between measured and simulated (under the two simulation cases) was also established.

Fig. 1 showed the flowchart of the data and simulation processes. Four simulation modules, CP tower dynamics, emitter water distribution, CP irrigation and crop yield were gradually coupled to provide a corn yield distribution pattern. The different modules were calibrated and validated with field data. Simulation results of tower dynamics and emitter water distribution patterns were provided to the CP irrigation module to obtain the water distribution pattern for the total CP irrigated area. The CP irrigation depths can be cumulated for different period of time, one irrigation event, several irrigation events or the irrigation season. The water distribution pattern simulated with the CP model was coupled with the Ador-Crop model (Dechmi *et al.*, 2004) to obtain the simulated corn yield distribution. The spatial grid selected to simulate corn yield was 9 x 9 m, because the measured corn yield integrates 9 m width of the harvester header.

6. Characterizing all the irrigations applied to the crop.

The farmer performed the irrigation schedule following crop water requirements provided by the regional advisory service (Oficina del Regante, <http://aplicaciones.aragon.es/oresa/>). The farmer programmed for each irrigation event the PTS (machine travel speed) and the total irrigation time. Data of pivot towers location (GNSS-RTK data) at the beginning and at the end of each irrigation event were determined to identify effective irrigated area. Measured tower dynamics

(Meas_Dyn) of each irrigation event with a 1 s frequency was obtained from GNSS-RTK data for simulation purposes. For each irrigation event the intra-irrigation variability of working pressure and meteorological conditions were analyzed. The developed model was used to simulate the water distribution pattern of each irrigation event at a square net of 3 m x 3 m. Since most of the applied irrigation did not perform complete CP rounds, the Christiansen Uniformity Coefficient (CUC, %, Eq. [1]) was determined referred to the effective irrigated area (CUC_{IA}) and to the CP area (CUC_{TCPA}). Irrigation dose was also established for the irrigated area (ID_{IA}) and for the CP area (ID_{TCPA}).

$$CUC = 100 \times \left[1 - \frac{\sum_{i=1}^{i=m} |d_i - \bar{d}|}{\bar{d} \times m} \right] \quad [1]$$

where d_i is the simulated (or collected) water depth in the i_{th} point, m is the number of points, and $\bar{d}$ is the average of simulated (or collected) water amounts. The performance indexes related to the total CP area of the irrigations that did not perform complete rounds resulted in CUC and average irrigation dose values lower than the indexes of the same irrigations referred only to the irrigated area.

7. Simulation of the seasonal water distribution pattern of the CP and the corn yield.

The experimentally measured mechanical movement of the CP towers for each applied irrigation event was prepared (Meas_Dyn). Also, the CP tower dynamic model presented in Ouazaa *et al.* (2015) was used to simulate the mechanical movement of the CP towers for each applied irrigation event (Sim_Dyn). Also, the CP tower dynamics of all irrigation events were simulated assuming an intermittent but completely aligned CP tower movement (Sim_Align).

The RSPS water distribution pattern for the different nozzle diameters of the center-pivot sprinkler package was simulated using the calibrated and validated ballistic model and the measured meteorological conditions of each irrigation event. The RSPS water distribution

patterns were simulated under two meteorological conditions: 1) a constant wind speed and direction (Avg_W) resulting from averaging the real meteorological conditions of the correspondent irrigation event and 2) a variable on time wind speed and direction (Var_W). Center pivot irrigation performance indexes (ID_{IA} , ID_{TCPA} , CUC_{IA} , CUC_{TCPA} and CU_{HH}) were calculated combining measured or simulated dynamics, and averaged or variable on time wind conditions for each irrigation event. The study cases were:

1. Measured tower dynamics and averaged wind speed and direction (Meas_Dyn & Avg_W).
2. Measured tower dynamics and variable on time wind speed and direction (Meas_Dyn & Var_W).
3. Simulated tower dynamics and averaged wind speed and direction (Sim_Dyn & Avg_W).
4. Simulated tower dynamics and variable on time wind speed and direction (Sim_Dyn & Var_W).
5. Simulated aligned tower dynamics and averaged wind speed and direction (Sim_Align & Avg_W).
6. Simulated aligned tower dynamics and variable on time wind speed and direction (Sim_Align & Var_W).

Seasonal spatial water distribution maps of the different study cases were built to analyze the effect of the different factors.

The simulated irrigation depth for each irrigation event along the irrigation season was coupled with Ador-Crop (Dechmi *et al.*, 2004) to simulate corn yield. Irrigation data (daily irrigation depth), daily meteorological data (rainfall, average air temperature and reference crop evapotranspiration, ET_0), crop parameters (sowing date and total cumulative degree days), and soil characteristics (soil depth, total soil available water- TAW- and initial water content) were

used as input data in Ador-crop model to simulate corn yield. Ador-crop was based on the water production functions proposed by Stewart *et al.* (1977) and applied by Doorenbos and Kassam (1979) and do not explicitly simulate crop growth. The crop only responds to water availability. Dechmi *et al.* (2004) calibrate the model for corn in a solid set sprinkler irrigation system. Crop yields were simulated only for Sim_Dyn & Avg_W, Sim_Dyn & Var_W, Sim_Align & Avg_W and Sim_Align & Var_W. Comparison between simulated and measured corn yield was performed.

RESULTS AND DISCUSSION

1. Ballistic model calibration for RSPS water distribution patterns

1.1 Kinetic energy losses in the RSPS

Measured drops velocities for the evaluated nozzle diameters are presented in Fig. 2a. The photographic method showed that the RSPS presents two exit jets with different vertical angle; an up-jet with an exit vertical angle of 16 degrees and a down-jet with an exit vertical angle of 7 degrees. The jet trajectory vertical angles exiting the plate were independent of the nozzle diameter and dependent of the deflecting plate shape. Approximately, up-jet discharges 67% of the total volume, while down-jet discharges 33% of the total water volume.

Regression models were adjusted to the measurement points to estimate drop velocity for non-measured nozzle diameters (Fig. 2a). Both models, the up-jet and the down-jet, were divided in two parts: for nozzle diameter ≤ 3.8 mm, the model follows a polynomial adjustment and for nozzle diameter larger than 3.8 mm the model remains constant (10.5 m s^{-1} and 10 m s^{-1} for down-jet and up-jet, respectively) (Fig. 2a). The impact with the deflecting plate produced large kinetic energy losses (and two different jet exit vertical angles) whose magnitude depends on nozzle diameter to a maximum diameter value (3.8 mm). As the nozzle diameter size increases,

impact kinetic energy losses decrease and eventually reach a stable minimum value (Fig. 2b). The shape of the impact area on the grooved plate changes with the jet thickness, explaining the experimental differences on kinetic energy losses between nozzle sizes. For nozzle diameters lower than 3.8 mm, the kinetic energy losses resulted similar between exit angles and reached about 85% of total for the smallest nozzle size (2 mm). Kinetic energy losses remain constant at 58% and 64% for nozzle diameters larger than 3.8 mm, for the down-jet and the up-jet, respectively (Fig. 2b). Ouazaa *et al.* (2014) characterized the kinetic energy losses in FSPS (Fixed Spray Plate Sprinkler) reporting similar trends. The smallest nozzle diameter evaluated of FSPS, 2 mm, resulted in kinetic energy losses of 80%. For FSPS nozzle diameter larger than 5.1 mm the kinetic energy losses remain constant at 45%. In general, RSPS presented slightly higher kinetic energy losses than FSPS.

The kinetic energy losses as a function of nozzle diameters have been incorporated in the ballistic model to simulate the RSPS water distribution pattern.

1.2 Measured and simulated RSPS water distribution pattern

Calibrated parameters D_{50} and n are shown in Figs. 2c and 2d, respectively. Regression models were developed to interpolate the parameters for unmeasured nozzle diameters within the measurement range. As the nozzle diameter increases, the parameter D_{50} increases. Similar trends but with slightly lower values for this parameters were presented by Ouazaa *et al.* 2014 for FSPS. The value of n decreases until a value of 1.63 as nozzle diameter increases until a diameter of 5.2 mm. For larger nozzle diameters the n value increases. The values of n were similar to those reported by Playán *et al.* (2006) for impact sprinklers. Ouazaa *et al.* (2014) presented opposite trends for this parameter for FSPS emitters. The values of n for the FSPS increase with nozzle diameter until a nozzle diameter of 6.7 mm, and decreases for larger nozzle diameters. The

difference could be attributed to the different water distribution pattern, since FSPS produces a circular crown, RSPS produces a triangular shape (similar to impact sprinklers).

Fig. 3 presents the differences between measured and simulated RSPS radial water application depths under no windy conditions. Differences between measured and simulated radial water distribution patterns were small for the three smallest nozzle diameters (Fig. 3a). Largest differences were obtained for the largest evaluated nozzle diameter (Fig. 3b). The correlation coefficient between measured and simulated radial water distribution in no windy conditions was very high with an average value of $r = 0.98$ at 138 kPa working pressure. *RMSEs* values ranged from 0.49 to 3.27 mm h⁻¹ (with an average value of 1.28 mm h⁻¹). The Nash-Sutcliffe efficiency coefficient ranged from 0.92 to 0.98, with an average of 0.97, indicating that the variance of the residuals has similar magnitude than the measured data variance and that the plot of observed versus simulated data fits the 1:1 line. Percent bias that measures the average tendency of the simulated data to be larger or smaller than their observed counterparts, ranged from 5.3% to 18.8% with an average of 8.7%, indicating moderate model underestimation bias. In general, the evaluation of all the statistics reveals a good performance of the simulation model.

Results of the calibration process for the correction parameters of the aerodynamic drag coefficient, K_1 and K_2 , for the evaluated RSPS were presented in Table 1. For each evaluated irrigation event, the meteorological conditions (wind speed and direction) the parameter values (K_1 and K_2) and their statistics for both steps of the calibration process were reported in the table. For the first step of the calibration process, the correlation coefficients ranged from 0.90 to 0.99, with an average value of 0.96. The RMSE ranged from 0.44 to 4.43 mm h⁻¹, with an average value of 1.61 mm h⁻¹.

No correlations were found between wind speed and the magnitude of the two correction parameters. A further research effort was needed to extrapolate the parameters to other non-evaluated windy conditions in the range of the evaluation. Several probability distribution

functions were evaluated to fit the variability of K_1 and K_2 parameter as a function of wind speed and nozzle diameter. The Rayleigh distribution function (Siddiqui, 1961) was finally selected due to its flexibility and because resulted in the best-fitting to the data. The Rayleigh model selected for the evaluated RSPS, Eq. [2], introduces as independent variables the nozzle diameter (Φ) and the wind velocity (W). a , b , and c are empirical parameters of the Rayleigh function.

$$K_i' = a \times (1 - e^{(-c \times \Phi)}) \times W \times (1 - b \times W) \quad [2]$$

Table 2 presents the values of the empirical parameters a , b , and c of the Rayleigh function resulted from the RSPS calibration process.

Values of K_1' and K_2' and their statistical indexes for the second step of the calibration process were also presented in Table 1. For this second step, the correlation coefficients slightly decrease compared with the first step. The r values ranged from 0.85 to 0.99, with an average value 0.92. The RMSE values increased moderately respect to those obtained in the first step, ranging from 0.49 mm h⁻¹ to 6.59 mm h⁻¹, with an average value of 2.46 mm h⁻¹. The new K_i' models presented an acceptable performance in simulating the water distribution pattern in windy conditions.

2. Results of the irrigation events evaluation

Table 3 summarizes the characteristic of the ten evaluated irrigation events. Irrigation events were named as the irrigation number during the season. The irrigation events presented variability on PTS and meteorological wind conditions. Irr 2* and 3* were performed at the same PTS (50%) but the collected average IDs resulted different (7.4 and 6.1 mm, respectively) due to important differences in wind conditions. Also CU_{HH} index was affected by wind speed and direction. The average wind speed and the dominant wind direction presented in Table 3 corresponded to the time that the CP lateral passed over the catch cans line. This time was obtained with tower location data provided by the GNSS-RTK and catch can location data. There

is not a clear pattern of wind speed on experimentally determined water uniformity coefficients. The wind direction respect to the radial catch can has a clear effect on uniformity results for similar intensities (Irr. 2* and Irr. 16*). In general, for the evaluated irrigation events as the wind speed increases from low to medium intensity the CU_{HH} increases, but for medium to higher wind speed the CU_{HH} decreases (Table 3).

3. Simulation of the evaluated irrigation event

The ten evaluated irrigation events were simulated considering the measured variable on time wind speed and direction. Two configurations of CP tower dynamics were considered, the measured (Meas_Dyn & Var_W) and the simulated (Sim_Dyn & Var_W). The simulated irrigation depths at the radial transect of the catch-can location were averaged and compared with the measured catch-can data of the ten evaluated irrigation events (Fig. 4a). The 1:1 line is presented in dashed line. The regression lines forced to the origin between measured and simulated irrigation depths resulted close to the 1:1 line with a slightly overestimation of the irrigation depths for both simulated cases. The differences could indicate an underestimation of wind drift and evaporation losses (WDEL) of the RSPS simulation model. For the RSPS simulation the experimental model for WDEL proposed by Playan et al. (2005) was used.. A further effort should be done to improve WDEL models for CP or linear move irrigation machines. Differences between both CP tower dynamics cases were negligible. Fig. 4b presents the comparison between measured and simulated CU_{HH} for the ten irrigation events. The model overestimates the CU_{HH} for both dynamics. The average differences between measured and simulated CU_{HH} are of 3 percentual points. Differences between measured and simulated decrease as wind speed increases. The pressure variability that was not considered in the simulation model could explain the differences. The model proved adequate accuracy in predicting both CU_{HH} and the average applied irrigation depth. The comparison showed that the

simulations results were within the acceptable range of the observed values. Since differences between both CP tower dynamics simulated cases were negligible, the model to simulate CP tower dynamics can be used to estimate CP water application pattern.

4. Characterizing all the irrigations applied to the crop

The farmer applied 60 irrigation events, 1456.5 hours of irrigation time, performing 63.4 complete CP rounds throughout the corn irrigation season. The events showed variable irrigation time and frequency, with an average irrigation time of 25 hours and an averaged interval between irrigation of 2 days. The first irrigation event of the season was applied on May 17th, and the last one on September 14th. CP tower location data at the beginning and at the end of each irrigation event showed that for an important number of irrigations (approximately 90%), the locations point of the outermost tower at the end and at the beginning of the irrigation event were not the same, indicating that these irrigations events performed incomplete circles. This fact will not be important if all the irrigations events were performed at the same machine speed or continued to perform complete rounds at the same PTS, but that was not the case (see Irr.22 and Irr 23 in Table 3). Changes in PTS were periodical and not adequately adjusted to ensure equal irrigation dose in the total CP area. The irrigation dose variability induced by the lack of control to perform complete circles was important and could mask the variability of the factors analyzed in this research.

Fig. 5 showed the water distribution applied in two consecutive irrigations events performed under 100% (Irr. 21) and 73% (Irr. 22) PTS, respectively. The double irrigated arc of Irr. 21 (Fig. 5a) was not compensated in the next irrigation event, Irr. 22 (Fig. 5b), since PTS was changed, and again, the irrigation event did not perform a complete circle.

The pressure at the pumping station averaged for the irrigation season was 239.5 kPa, with a standard deviation between irrigations of 18.5 kPa. The average pressure measured at the center-

pivot point was of 152 kPa, with a standard deviation between irrigations of 5.2 kPa. The average pressure measured at the CP overhang was of 144 kPa with a standard deviation between irrigations of 15.4 kPa (small topographic differences explain this higher value of standard deviation).. Pressure variability due to regulator mechanism was characterized by the intra-irrigation variability measured with the two pressure transducer installed at the CP lateral. For both measurement points, the average coefficients of variation of the intra-irrigation pressure variability for the sixty irrigation events applied to the corn were lower than 5%. To simplify the simulation the intra and inter-irrigation pressure variability was not considered and the working pressure for the simulation of all irrigation events and nozzle sizes was considered 138 kPa. The average experimental wind speed during the total irrigation season was 2.53 m s^{-1} , with a standard deviation of 0.56 m s^{-1} , ranging between 1.2 m s^{-1} and 7.8 m s^{-1} . The most common wind direction during the applied irrigations was from W and WNW (around 30% of the irrigation time) . The average wind speed and direction for each irrigation event and the coefficient of variance of the averages were also computed. 22% of the total irrigation time was performed under wind speeds lower than 2 m s^{-1} , around 52% of the irrigation time within the ranges of 2 and 3 m s^{-1} , 24% between 3 and 4 m s^{-1} and only 2% of the irrigation time was performed under wind speed larger than 4 m s^{-1} .

A further analysis of the intra-irrigation variability of wind speed and direction showed that irrigation performed under high average wind speed presented large intra-irrigation variability, larger standard deviation (SD). When the average wind speed is high and the intra-irrigation variability is also high the effect of this variability on CP water distribution pattern could be relevant. This effect was studied analyzing two irrigations Irr. 31 and Irr. 33. Irrigation 31 performed an trajectory of 740° since Irrigation 33 performed an trajectory of 374° . Figs. 6a and 6d presented a diagram of wind speed and direction variability along a complete circle of irrigation 31 and 33, respectively. The first 360° of Irr. 31 resulted in an average wind speed of

3.2 m s⁻¹, with a standard deviation of 0.8 m s⁻¹ and a NW predominant wind direction. The first 360° of Irr. 33 resulted in an average wind speed of 1.8 m s⁻¹ with a standard deviation of 0.6 m s⁻¹, and a NNE predominant wind direction. The water distribution pattern of both irrigation has been simulated under two meteorological conditions: first, considering a constant wind speed and direction equal to the averaged along the irrigation (Figs. 6b and 6e, for Irr 31 and 33, respectively) and second, considering variable on time wind speed and direction as measured (Figs. 6c and 6f, for Irr 31 and 33, respectively).

For Irr 31, differences between considering an average (Fig. 6b) or variable (Fig. 6c) wind speed and direction are graphically observed. The first irrigated semi-circle (180 ° from the start point following clock-wise direction) showed larger variability than the second semi-circle (Fig. 6c), following wind speed and direction variability and intensity (Fig. 6a). However differences in irrigation performance index CUC_{TCPA} are almost irrelevant, 93.3% (Fig. 6b) and 93.4% (Fig 6c). The same behavior was observed for Irr. 33, significant differences between considering an average wind speed and direction (Fig. 6e) or variable wind conditions (Fig. 6f) are graphically observed. However CUC_{TCPA} did not show the important observed variability since the values are quite similar, 94.3% (Fig. 6e) and 93.2% (Fig. 6f).

Comparison between considering homogeneous or variable wind conditions on Irr. 33 (Fig. 7) was also performed by selecting two radial transects; one irrigated under the highest wind speed (radial transect L1, Fig. 6f) and the other irrigated under the lowest wind speed (radial transect L2, Fig. 6f). Also, three circular paths (at 75 m, 125 m and 175 m from the pivot point) of water depth were selected from average (Fig. 6c) and variable wind conditions (Fig. 6f) for comparison. The radial transects L1 and L2 of Irr 33 for the homogeneous (averaged) wind condition case were similar (Fig. 7a). Differences between both transects were observed when variable meteorological conditions were simulated (Fig. 7c). Radial transect irrigated under the highest wind speed (L1), showed larger variability than transect irrigated under low wind conditions L2).

The circular paths of the average wind conditions simulated case (Fig. 7b) showed lower variability than the same circular paths under variable wind conditions (Fig. 7d). The graphically observed variability was quantified by the irrigation performance indexes CU_{HH} and CUC, for radial and circular paths, respectively. The values of CU_{HH} for the radial transects L1 and L2, resulted of 95.3 % and 95.8 %, respectively, for the average wind conditions and of 94.8% and 95.3 %, respectively, for the variable on time wind conditions. The CUC for the three circular transect resulted similar for the homogeneous wind, average 97%, small differences between circular transects were observed for the variable meteorology (95.4% at 75 m, 96.1% at 125 m and 96.4% at 175m), with an average value of 96.0 %. Again, irrigation performance indexes (CUC_{HH} and CUC) did not show relevant differences although graphical differences could be observed. Other statistics analyzing the differences as RMSE (0.6 mm for Irr 31), PBias (0.0024% for Irr 31) and NSE (0.99 for Irr 31) did not show either important differences.

The effect of variable on time wind speed and direction on water distribution pattern of an individual irrigation event has been showed. The cumulative effect of the intra-irrigation meteorological variability of the whole crop irrigation season and the inter irrigation meteorological variability will be analyzed in next section.

5. Simulating the whole irrigation season

The 60 irrigation events applied to the corn were simulated under the six configuration cases presented in material and methods section (Meas_Dyn & Avg_W, Meas_Dyn & Var_W, Sim_Dyn & Avg_W, Sim_Dyn & Var_W, Sim_Align & Avg_W and Sim_Align & Var_W)

The individual values of ID for each irrigation event were accumulated to obtain the seasonal water distribution pattern for each of the six cases studied. The average seasonal irrigation depth for the six simulated cases resulted analogous, between 647 and 648 mm, and similar to the

average value registered with the flow meter of the farm, 648.2 mm. Fig. 8 presents the spatial distribution of three intervals of seasonal irrigation depth (lower than the average, 650 mm, between 650 mm and 700 mm and higher than 700 mm) for the six cases: Meas_Dyn & Avg_W (Fig. 8a), Meas_Dyn & Var_W (Fig. 8b), Sim_Dyn & Avg_W (Fig. 8c), Sim_Dyn & Var_W (Fig. 8d), Sim_Align & Avg_W (Fig. 8e) and Sim_Align & Var_W (Fig. 8f). Figure 8 points out the differences in the selected intervals between the analyzed cases. Graphical differences on spatial distribution of seasonal irrigation depth for the three intervals between considering measured or simulated CP towers dynamics for the same meteorological case (Figs. 8a and 8c, or Figs. 8b and 8d) were negligible. The RMSE between both cases were also negligible. As reported before, CP towers dynamic models performs with a high accuracy. On the other hand, the effect of the discontinuous movement of the CP towers (measured or simulated) compared with totally aligned movement has a moderate effect on seasonal water distribution pattern for the three intervals of irrigation depth analyzed in Figure 8. This effect can be observed comparing the differences between the simulation considering the tower movement completely aligned (Fig. 8e) and the current tower dynamics (Figs. 8a and 8c) for the same meteorological case. Comparing the total irrigation depth data between case Sim_Dyn & Var_W and Sim_Align & Var_W, a RMSE of 15 mm, a PBias of 0.06 % and a NSE of 0.98 were obtained. Differences between the meteorological cases for the three intervals of irrigation depth analyzed were graphically more relevant. That can be observed comparing cases considering intra-irrigation variability of wind speed and direction (Figs. 8b, 8d and 8f) with cases considering an averaged wind speed and direction along each irrigation event (Figs. 8a, 8c and 8e). Analyzing the differences for the total irrigation data between the cases Meas_Dyn & Avg_W and Meas_Dyn & Var_W, the value of RMSE was of 1.6 mm, the PBias of -0.02% and the NSE of 0.99. The seasonal CUC_{TCPA} did not show the graphically observed differences. Meas_Dyn & Avg_W and Sim_Dyn & Avg_W as expected have the same CUC_{TCPA} (94.1%) and present any differences with the cases simulated

with variable wind conditions, Meas_Dyn & Var_W and Sim_Dyn & Var_W, CUC_{TCPA} of 94.2 %. The CUC_{TCPA} of Sim_Align & Avg_W and Sim_Align & Var_W cases resulted slightly higher with 94.9% and 94.5%, respectively.

Summarizing, the discontinuous movement of CP towers compared with a completely aligned movement of CP tower has a moderate effect on seasonal water distribution patterns, when considering the whole season the cumulative effect can intensify the differences. The intra-irrigation variability of wind speed and direction has a relevant effect on water distribution pattern of an irrigation event with intra-irrigation meteorological variability. Depending on the wind speed intensity and variability along the crop irrigation season the cumulative effect of the intra-irrigation variability will have a major or minor effect on seasonal water distribution pattern and on crop yield variability. A CP irrigation simulation model should consider both effects to accurately simulate spatial distribution of irrigation depth. Irrigation performance index CUC for the CP irrigated area did not showed enough precision to explain the observed variability and should be used carefully to compare the different cases.

6. Crop yield measured and simulated.

On November 19, 2013, the corn was harvested with a commercial combine with spatial yield and moisture monitoring and registering. The combine computer registered approximately one point of grain yield per m of advancement. The harvest data were processed to represent them in a 9 m x 9 m square grid for comparison with simulated yields. The measured yield was expressed at 14% of moisture. Fig. 9a shows the spatial variability of measured corn yield. The border of the CP irrigated area has the lowest corn yield. Also, the area surrounded the pivot point has low corn yield. The largest corn yield was obtained in the central area of the CP. The linear travel path of the harvester can be observed in the pixels of the measured yield data (Fig. 9a), probably

the 9 m width of the combine header masks the variability of water application pattern. Also, the linear yield path versus the circular water application path can introduce noise in the comparison. The crop yield was simulated coupling the simulated irrigation depth applied along the irrigation season at the static grid (3 m x 3 m) with a corn model (Ador-crop). The Ador-crop (Dechmi *et al.*, 2004) is based on CropWat (FAO, 1992) and simulates relative yield reduction as a function of evapotranspiration reduction. The total CP irrigated area, 15.9 ha, was divided in 17671 points to simulate corn yield. Daily meteorological data were used by the crop model to simulate crop evapotranspiration and available water from precipitation events. The total amount of rainfall for the growing season was 220 mm. General soil data, as initial soil moisture at seeding, soil depth and total available water of the soil were required for the crop model. The values of these general soil data were considered equal for all the simulated points and with values that represented the area. The irrigation depth applied at each grid point were obtained from simulated cases, Sim_Dyn & Avg_W, Sim_Dyn & Var_W, Sim_Align & Avg_W and Sim_Align & Var_W. Simulated corn yield distribution for the four cases are presented in Figs. 9b, 9c, 9d and 9e, respectively.

Simulated corn yield showed similar spatial distribution pattern than its correspondent simulated irrigation depth (Figs. 8c and 9b, Figs. 8d and 9c, Figs. 8e and 9d and Figs. 8f and 9e), because crop model responds only to water availability. Simulated corn yield for the different cases showed low values for the area surrounding the CP and the area surrounding the pivot point, as that of the measured. Although other factors as variability on fertilizer application, diseases and soil variability affects yield distribution the limitations of Ador-crop model did not permit to account for them in the simulations. The measured corn yield distribution integrates all factors affecting variability of crop development, explaining the difference between measured and simulated corn yield distribution patterns. Regression analysis between measured and simulated yield showed statistically significant correlation coefficients for the four simulated cases. The

correlations coefficients show appreciable differences between simulated cases, being those considering the intra-irrigation meteorological variability larger than those not considering the variability. Also the correlation is slightly larger for the cases considering the discontinuous movement of CP tower than those considering a complete alignment movement of CP towers. The CUC has been also computed for yield data, measured corn yield showed a CUC of 82% and the CUC for the simulated cases ranged from 87% for the Sim_Dyn & Var_W case to 91% for the Sim_Align & Avg_W case.

As reported in previous sections, the farmer management has largely affected the irrigation water distribution because of the link of incomplete circle irrigations at different CP travel speeds. The farmer was advised about the problems but the management of the CP irrigation was not easy and an update of the CP control system was needed. In 2014 the farmer installed at the end of the CP overhang a GPS connected to the control system that allows to program irrigation based on location and apply complete circle irrigations.

To analyze the new situation of major irrigation control, the 60 irrigations applied to the corn were adjusted to perform complete circles irrigations and maintaining approximately the same average irrigation depth (648 mm). Each irrigation event was simulated following the same irrigation schedule and maintaining the travel machine speed. This analysis tries to isolate the effect of towers dynamic movement and intra-irrigation variability of wind speed and direction on seasonal water and yield distribution patterns. A total of 63 irrigations performing 63 complete circles were simulated under the following conditions:

- a. Simulated tower dynamics and averaged wind speed and direction (Sim_Dyn & Avg_W)_{CC}.
- b. Simulated tower dynamics and measured variable on time wind speed and direction (Sim_Dyn & Var_W)_{CC}.

- c. Simulated aligned tower dynamics and variable on time wind speed and direction
(Sim_Align & Var_W)_{CC}.

Fig. 10 showed the spatial water distribution pattern simulated under case a (Fig. 10a), case b (Fig. 10b) and under case c (Fig. 10c). Differences in water distribution patterns were observed specially between considering an average wind speed (Fig. 10a) or considering intra-irrigation variability of meteorological conditions (Figs. 10b and 10c). Differences between considering the current tower dynamics (Fig. 10b) or a complete aligned tower movement (Fig. 10c) were lower. The values of CUC for the three cases were equal, 95.4%. The variability induced by the farmer schedule on seasonal water distribution pattern was relevant as showed the comparison between Figs. 10a and 8c, Figs. 10b and 8d, and Figs. 10c and 8e.

The corn yield was simulated with the three simulated water distribution patterns. Figs. 10d, 10e and 10f presented the correspondent simulated yield. Simulated corn yield distribution pattern resulted very close to the correspondent water distribution pattern. CUC of simulated yield resulted similar for the three cases ranging from 91.6% to 91.7%. Again CUC performance indexes did not catch the observed variability nor for irrigation water neither for corn yield.

CONCLUSIONS

The study aimed to improve the center-pivot simulation modeling including the effect of intra-irrigation variability of wind speed and direction on simulated water distribution pattern. Also the cumulative effect of individual irrigation applied along a crop irrigation season was analysed. The conclusions drawn from this study indicated that:

1. Farmer irrigation management, performing not complete circles irrigation at different PTS, introduces important variability on water distribution pattern when considering the whole irrigation season.

2. Uniformity coefficients as the Christiansen uniformity coefficient, Heermann and Hein uniformity coefficient or the standard deviation did not catch the observed variability of the simulated water distribution pattern for the whole CP irrigated area.
3. The intra-irrigation variability of wind speed and direction has a clear effect on water distribution patterns on CP irrigation systems. The cumulative effect of the intra and inter irrigation variability of wind speed and direction on seasonal water distribution patterns and on corn yield depends on the intensity and variability of the wind and on the frequency of the intra-irrigation variability along the season.
4. The center-pivot irrigation model proposed in this research accurately accounts for discontinuous movement of the CP tower, intra-irrigation variability of wind speed and direction, and designs of CP sprinkler packages (fixed or rotating spray plate sprinklers). The developed tool can be used to analyze the effect of these factors for different meteorological conditions and pivot designs.
5. The simulation model can be a valuable tool to analyze CP irrigation systems designs and management for the local meteorological conditions. Also, the tool can be applied to analyze the viability of Variable Rate Irrigation on a CP system under different designs, management alternatives and meteorological conditions.

ACKNOWLEDGE

This paper applied the “first-last-author-emphasis” approach for the sequence of authors. This research was funded by the Minister of Economy and Competitiveness of the Spanish Government through the grant AGL2010-21681-C03-01 and AGL2013-48728-C2-1-R. In memoriam of the farmer Oscar Salafranca for his generosity and relevant contribution to perform the field experiment of this research.

REFERENCES

- Clark, G. A., Srinivas K., Rogers D. H., Stratton R., Martin V. L., 2003. Measured and simulated uniformity of low drift nozzle sprinklers. Trans. ASAE 46 (2): 321-330.
- Dechmi, F., Playan, E., Cavero, J., Martinez-Cob, A., Faci, J.M., 2004 A coupled crop and solid set sprinkler simulation model: I. Model development. J Irrig Drain Eng, ASCE 130(6): 499-510.
- 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 (in Spanish).
- Dukes M. D. 2006. Effect of wind speed and pressure on linear move irrigation system uniformity. Appl. Eng. in Agric. ASABE 22(4): 541-548.
- Evans R. G., LaRue K., Stone K.C, King, B. A. 2013. Adoption of site-specific variable rate sprinkler irrigation systems. Irrig Sci. 31:871–887.
- Faci, J. M., Salvador, R., Playán, E., Sourell, H., 2001. A comparison of fixed and rotating spray plate sprinklers. J Irrig Drain Eng, ASCE, 127(4), 224-233.
- FAO. 1992. *CROPWAT, a computer program for irrigation planning and management* by M. Smith. FAO Irrigation and Drainage Paper No. 26. Rome.
- Gupta, H. V., S. Sorooshian, and P. O. Yapo. 1999. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. J. Hydrologic Eng. 4(2): 135-143.
- Kranz, W. L., Evans, R. G., Lamm R. G., O'Shaughnessy, S. A., Peters, R. T., 2012. A review of mechanical move sprinkler irrigation control and automation technologies. Appl. Eng. in Agric. ASABE 28(3): 389-397.
- Li J, Kawano H, Yu K, 1994. Droplet size distributions from different shaped sprinkler nozzles. Trans ASAE 37(6): 1871-1878.

- McCarthy, Alison C., Hancock, Nigel H., Raine, Steven R., 2014. Simulation of irrigation control strategies for cotton using model predictive control within the VARIwise simulation framework. *Computers and Electronic in Agric.* 101: 135-147.
- Molle, B., Le Gat, Y., 2000. Model of water application under pivot sprinkler: II. Calibration and results. *J Irrig Drain Eng* 126(6): 348-354.
- Moreno, M.A., Medina, D., Ortega, J.F., Tarjuelo, J.M., 2012. Optimal design of center pivot systems with water supplied from wells. *Agr. Water Manage.* 107: 112– 121.
- Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models: Part 1. A discussion of principles. *J. Hydrology* 10(3): 282-290.
- Oficina del Regante, <http://aplicaciones.aragon.es/oresa/>
- Ouazaa, S., Burguete, J., Paniagua, P., Salvador, R. and Zapata, N., 2014. Simulating water distribution patterns for fixed spray plate sprinkler using the ballistic theory. *Span J Agric Res* 12(3): 850-863.
- Ouazaa, S., Latorre, B., Burguete, J., Serreta, A., Playán, E., Salvador, R., Paniagua, P. and Zapata, N., 2015. Effect of the start–stop cycle of center-pivot towers on irrigation performance: Experiments and simulations. *Agr. Water Manage.* 147: 163–174.
- O’Shaughnessy, S.A., Urrego, Y.F., Evett, S.R., Colaizzi, P.D. and Howell, T.A., 2013. Assessing application uniformity of a variable rate irrigation system in a windy location. *Appl. Eng. in Agric.* ASABE 29 (4):497-510.
- Playán, E., Salvador, R., Faci, J.M., Zapata, N., Martínez-Cob, A., Sánchez, I., 2005. Day and night wind drift and evaporation losses in sprinkler solid-sets and moving laterals. *Agric. Water Manage.* 76 (3), 139–159.
- Salvador, R., Bautista-Capetillo, C., Burguete, J., Zapata, N., Playán, E., 2009. A photographic methodology for drop characterization in agricultural sprinklers. *Irrigation Sci* 27(4): 307-317.
- Sayyadi, H., Sadraddini, A.A., Farsadi Zadeh, D., Montero, J., 2012. Artificial neural networks for simulating wind effects on sprinkler distribution patterns. *Span J Agric Res* 10 (4), 1143–1154.

Seginer I, Kantz D, Nir D, 1991. The distortion by wind of the distribution patterns of single sprinklers. Agric Wat Manag 19: 314-359.

Siddiqui, M.M., 1961. Some problems connected with Rayleigh distributions. The Journal of Research of the National Bureau of Standards, Sec. D: Radio Propagation 66D(2): 169.

Stewart, J. I., Danielson, R.E., Hanks, R.J., Jackson, E.B., Hagan, R.M., Pruitt, W.O., Franklin, W.T. and Riley, J.P. (1977). "Optimizing crop production through control of water and salinity levels." Utah Water Research Laboratory PRWG 151-1.

LIST OF TABLES

Table 1. Optimum values of K_1 and K_2 for the 1st calibration process, and K_1' and K_2' for the 2nd calibration process for different nozzle diameters, wind speed (WS) and wind direction. The table also presents the values of the statistical index, root mean square error, RMSE, Pearson coefficient, r , obtained in the calibrations processes.

Table 2. Summarized results of the RSPS calibration parameters for the exponential models of K_1' and K_2' , correction parameters of the aerodynamic drag coefficient as a function of nozzle diameter and wind speed. a , b and c are the empirical parameters of the Rayleigh model.

Table 3. Characteristics of the evaluated irrigation event, trajectory ($^\circ$), center-pivot travel speed (PTS, %), average wind speed, predominant wind direction, average pressure at the span, average measured irrigation depth (ID, mm), standard deviation of the irrigation depth (SD ID, mm) and measured radial uniformities (CU_{HH} , %).

LIST OF FIGURES

Figure 1. Flowchart of data and simulation models processes.

Figure 2. (a) Measured drop velocity, (b) estimated kinetic energy losses, (c) parameter D_{50} , mean drop diameter and (c) parameter n (dimensionless exponent) as a function of nozzle diameter. Vertical bars represent $\pm$ the standard deviation of the average for the 40 measured drops.

Figure 3. Differences between measured and simulated radial water application pattern for (a) the three smallest and (b) the three largest nozzle diameters of the rotation spray plate sprinklers, RSPS, operating at 138 kPa.

Figure 4. Comparison between measured and simulated (with experimental and simulated mechanical movement) irrigation depth (ID, mm, Figure 7a) and Heermann and Hein Uniformity Coefficient (CU_{HH} , %, Figure 7b), for the evaluated irrigation events. Dashed lines in the figures represent the 1:1 line.

Figure 5. Simulated water distribution pattern of Irrigation.21 (a) performing a 388° round at a rotation speed of 100% percent time setting, PTS and Irrigation. 22 (b) performing a 400° round at 73% PTS.

Figure 6. Distribution maps of wind speed and direction (a and d) and simulated water distribution maps of the center-pivot traveling at current dynamic with homogeneous averaged wind conditions (figures b and e) and variable on time wind conditions (figures c and f). Upper and down figures represent the Irrigation. 31 and Irrigation. 33, respectively.

Figure 7. Simulated radial (a and c) and circular (b and d) water application depth of the center-pivot traveling at an averaged constant wind conditions (a and b) and variable on time wind conditions (c and d) for Irr. 33.

Figure 8. Spatial variability of the seasonal irrigation depth (mm) for five simulated cases: Measured center pivot towers dynamic and averaged wind speed, Meas_Dyn & Avg_W (Fig. 8a), Measured towers dynamic and variable wind speed, Meas_Dyn & Var_W (Figure 8b), Simulated towers dynamic and averaged wind speed, Sim_Dyn & Avg_W (Fig. 8c), Simulated towers dynamics and variable wind speed, Sim_Dyn & Var_W (Fig. 8d), Simulated towers dynamics travelling completely aligned and averaged wind speed, Sim_Align & Avg_W (Fig. 8e) and Simulated towers dynamics travelling completely aligned and variable wind speed, Sim_Align & Var_W (Fig. 8f).

Figure 9. Spatial variability of corn yield (kg ha^{-1}) experimentally measured (Fig. 9a), simulated with simulated towers dynamic and averaged wind speed, Sim_Dyn & Avg_W (Fig. 9b), simulated with

simulated towers dynamics and variable wind speed, Sim_Dyn & Var_W (Fig. 9c), simulated with simulated towers dynamics travelling completely aligned and averaged wind speed, Sim_Align & Avg_W (Fig. 9d) and simulated with simulated towers dynamics travelling completely aligned and variable wind speed, Sim_Align & Var_W (Fig. 9e).

Figure 10. Spatial variability of the seasonal irrigation depth and corn yield simulated under simulated towers dynamic and averaged wind speed (Sim_Dyn & Avg_W)_{CC} (Figs. 10a and 10d, respectively), simulated towers dynamics and variable wind speed (Sim_Dyn & Var_W)_{CC} (Figs. 10b and 10e, respectively), and simulated towers dynamics travelling completely aligned and variable wind speed (Sim_Align & Var_W)_{CC} (Figs. 10c and 10f, respectively).

Table 1. Optimum values of K_1 and K_2 for the 1st calibration process, and K_1' and K_2' for the 2nd calibration process for different nozzle diameters, wind speed (WS) and wind direction. The table also presents the values of the statistical index, root mean square error, RMSE, and Pearson coefficient, r , obtained in the calibrations processes.

Nozzle size (mm)	WS (m s ⁻¹)	Wind Direction	First calibration				Second calibration			
			RMSE (mm h ⁻¹)	r	K_1	K_2	RMSE (mm h ⁻¹)	r	K_1'	K_2'
2.4	0.16	W	0.55	0.99	0.00	0.00	0.55	0.99	0.005	0.005
	1.29	SSW	0.44	0.96	1.10	0.62	0.68	0.90	0.038	0.038
	5.76	WNW	0.45	0.90	1.95	0.50	0.73	0.89	0.17	0.168
3.8	0.15	W	0.49	0.99	0.00	0.00	0.49	0.99	0.006	0.006
	0.76	SSW	1.23	0.96	1.96	0.52	1.66	0.92	0.03	0.03
	6.45	WNW	0.66	0.95	1.72	0.84	1.20	0.89	0.253	0.249
5.2	0.03	NE	0.75	0.99	0.00	0.00	0.75	0.99	0.001	0.001
	1.46	N	1.42	0.94	1.78	0.78	2.01	0.86	0.068	0.067
	7.08	WNW	1.14	0.95	1.25	0.73	1.54	0.94	0.324	0.317
6.7	0.89	NE	1.13	0.98	0.00	0.00	1.13	0.98	0.046	0.045
	1.54	NNW	1.21	0.98	1.59	0.62	2.31	0.93	0.079	0.078
	7.27	WNW	2.23	0.93	1.94	0.62	3.34	0.90	0.366	0.358
7.9	0.67	NNE	1.47	0.98	0.00	0.00	3.99	0.85	0.036	0.036
	2.37	NW	2.37	0.96	0.98	0.71	3.95	0.90	0.127	0.125
	6.76	WNW	3.05	0.95	1.73	0.57	4.33	0.91	0.358	0.349
8.7	0.5	NNE	3.27	0.96	0.00	0.00	3.05	0.94	0.028	0.027
	1.98	NW	2.71	0.97	1.84	0.52	6.03	0.87	0.109	0.107
	6.71	WNW	4.43	0.95	1.89	0.63	6.59	0.89	0.364	0.355

Table 2. Summarized results of the RSPS calibration parameters for the exponential models of K_1' and K_2' correction parameters of the aerodynamic drag coefficient as a function of nozzle diameter and wind speed. a , b and c are the empirical parameters of the adjusted Rayleigh model.

	K_1'	K_2'
a	0.06	0.059
b	0.0024	0.0045
c	287.6	295.3

Table 3. Characteristics of the evaluated irrigation event, trajectory ($^{\circ}$), center-pivot travel speed (PTS, %), average wind speed, predominant wind direction, average pressure at the span, average measured irrigation depth (ID, mm), standard deviation of the irrigation depth (SD ID, mm) and measured radial uniformities (CU_{HH} , %).

Evaluated Irrigation event	Irrigation trajectory ($^{\circ}$)	PTS (%)	Av. WS ($m\ s^{-1}$)	Wind direction ($^{\circ}$)	Av. Pressure (kPa)	ID (mm)	SD ID (mm)	CU_{HH} (%)
Irr 2*	363	50	3.2	WSW	-	7.4	1.4	90.8
Irr 3*	371	50	5.1	WNW	-	6.1	1.2	86.5
Irr 4*	342	50	2.4	WNW	144 (8)	7.4	1.3	90.8
Irr 6*	314	50	1.7	E	142 (7)	7.5	1.6	88.8
Irr 10*	316	38	4.6	N	-	9.2	1.8	90.8
Irr 16*	348	49.5	3.5	WNW	-	6.2	1.4	86.6
Irr 18*	80	27	1.9	W	-	14	2.2	90.2
Irr 20*	162	25	1.7	N	149 (3)	13.4	2.6	90.8
Irr 22*	400	73	1	WSW	-	5.3	1	87.5
Irr 23*	602	25	2.7	W	-	14	3	86.5

Figure 1. Flowchart of data and simulation models processes.

Figure 2. (a) Measured drop velocity, (b) estimated kinetic energy losses, (c) parameter D_{50} (mean drop diameter) and (d) parameter n (dimensionless exponent) as a function of nozzle diameter. Vertical bars represent $\pm$ the standard deviation of the average for the 40 measured drops.

Figure 3. Differences between measured and simulated radial water application patterns for (a) the three smallest and (b) the three largest nozzle diameters of rotator spray plate sprinklers (RSPS) operating at 138 kPa.

Figure 4. Comparison between measured and simulated (with experimental and simulated mechanical movement) irrigation depth (ID, mm, Figure 7a) and Heermann and Hein Uniformity Coefficient (CU_{HH} , %, Figure 7b), for the evaluated irrigation events. Dashed lines in the figures represent the 1:1 line.

Figure 5. Simulated water distribution pattern of Irrigation21 (a) performing a 388° round at a rotation speed of 100% percent time setting (PTS) and Irrigation 22 (b) performing a 400° round at a rotation speed of 73% PTS.

Figure 6. Distribution maps of wind speed and direction (a and d) and simulated water distribution maps of the center-pivot traveling at current dynamic with homogeneous averaged wind conditions (figures b and e) and variable on time wind conditions (figures c and f). Upper and down figures represent the Irrigation 31 and Irrigation 33, respectively.

Figure 7. Simulated radial (a and c) and circular (b and d) water application depth of the center-pivot traveling at an averaged constant wind conditions (a and b) and variable on time wind conditions (c and d) for Irrigation 33. Radii L1 and L2 are located at Figure 6e. Circular water application depths were simulated at 75m, 125 m and 175 m from the pivot point.

Figure 8. Spatial variability of the seasonal irrigation depth (mm) for five simulated cases: Measured center pivot towers dynamic and averaged wind speed, Meas_Dyn & Avg_W (Fig. 8a), Measured towers dynamic and variable wind speed, Meas_Dyn & Var_W (Figure 8b), Simulated towers dynamic and averaged wind speed, Sim_Dyn & Avg_W (Fig. 8c), Simulated towers dynamics and variable wind speed, Sim_Dyn & Var_W (Fig. 8d), Simulated towers dynamics travelling completely aligned and averaged wind speed, Sim_Align & Avg_W (Fig. 8e) and Simulated towers dynamics travelling completely aligned and variable wind speed, Sim_Align & Var_W (Fig. 8f).

Figure 9. Spatial variability of corn yield (kg ha^{-1}) experimentally measured (Fig. 9a), simulated with simulated towers dynamic and averaged wind speed, Sim_Dyn & Avg_W (Fig. 9b), simulated with simulated towers dynamics and variable wind speed, Sim_Dyn & Var_W (Fig. 9c), simulated with simulated towers dynamics travelling completely aligned and averaged wind speed, Sim_Align & Avg_W (Fig. 9d) and simulated with simulated towers dynamics travelling completely aligned and variable wind speed, Sim_Align & Var_W (Fig. 9e).

Figure 10. Spatial variability of the seasonal irrigation depth and corn yield simulated under simulated towers dynamic and averaged wind speed (Sim_Dyn & Avg_W)_{CC} (Figs. 10a and 10d, respectively), simulated towers dynamics and variable wind speed (Sim_Dyn & Var_W)_{CC} (Figs. 10b and 10e, respectively), and simulated towers dynamics travelling completely aligned and variable wind speed (Sim_Align & Var_W)_{CC} (Figs. 10c and 10f, respectively).