EFFECT OF THE START-STOP CYCLE OF CENTER-PIVOT TOWERS ON IRRIGATION PERFORMANCE: EXPERIMENTS AND SIMULATIONS

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ABSTRACT

The simulation of center-pivot performance has been the subject of research efforts since the 1960s. Center-pivot models frequently use empirical equations relating pressure and sprinkler radial application pattern. Individual, stationary water application patterns are overlapped and the resulting water application is mapped in the field. Such models use constant tower angular velocity, neglecting the effect of tower alignment. In this work the discontinuous tower movement has been experimentally characterized and modelled, and a complete model has been developed by using a ballistic model of the center-pivot sprinklers considering nozzle diameter, operating pressure and wind speed. A detailed kinetic analysis of a four-tower commercial center-pivot was performed. Each tower was monitored using a high precision GPS, recording tower positions at high frequency. The experimental center-pivot was equipped with fixed spray plate sprinklers (FSPS). Five experimental center-pivot irrigation events were evaluated using catch-cans. The analysis of tower location data permitted to conclude that two key variables (linear speed and switching angle) showed normal distribution patterns. The center-pivot model was validated with catch-can data. Finally, the simulation tool was used to assess the effect of variable tower alignment quality, center-pivot travel speed and wind conditions on irrigation performance. Comparisons were performed in

terms of radial, circular and total irrigation uniformity. Results indicate that the observed tower dynamics had no measurable effect on irrigation uniformity. Tower alignment quality started to be relevant when the switching angle lag was equal to or larger than 5°. In the conditions of this analysis, wind speed showed a clear effect on uniformity. As wind speed increased, uniformity first decreased and then increased. Further research is required to generalize these results to other center-pivot sizes and designs (sprinkler packages).

I. INTRODUCTION

Self-propelled sprinkler irrigation machines have experienced worldwide success because of their advantages relative to other irrigation systems. Such advantages typically include: 1) high potential for uniform and efficient water application; 2) high degree of automation; and 3) ability to apply water and nutrients over a wide range of soil, crop and topographic conditions (Evans and King, 2012). For instance, self-propelled sprinkler irrigation machines irrigate 47% of the USA irrigated land, 20% of the Brazilian irrigated land and 8% of the Spanish irrigated land.

Center-pivots can be driven by hydraulic or electric systems. Hydraulic systems maintain all the towers in continuous motion, maintaining a perfect alignment. Electric motion systems are the most common, owing to their simplicity and low operating cost. In these systems the outermost tower is the master unit, driving the rest of towers in response to angular displacement of the pipe section adjacent thereto. The intermittent movement of each inner tower is dictated by the alignment between two adjacent spans. The movement of the outermost tower is governed by a percentage timer setting (PTS), which controls the ratio between the irrigation system move time and the cycle time. The PTS value also determines the irrigation depth resulting from a complete rotation, by controlling the machine angular speed. The operator selects the PTS (or center-pivot travel speed) in the central power control panel. At 100% PTS, the end tower moves continuously. At 50% PTS, the end tower moves during half of the cycle time. Consequently, at 50% PTS the applied irrigation depth doubles that

of 100% PTS. The most common cycle time of the end tower (considering different center-pivot manufacturers) is 60 s.

Center-pivot irrigation uniformity is commonly evaluated by installing a radial transect of catch cans extending outwards from the pivot point. This uniformity measurement characterizes the functional performance of the sprinkler package design and operation. Uniformity determined along the machine travel path is assumed to be high because a continuous movement of the machine integrates sprinkler pattern irregularities (Heermann and Kohl, 1980). However, tower alignment can be poor. Additionally, at some towers large time lapses may occur between moves (Hanson and Wallender, 1986). Since uniformity along the travel path theoretically depends on the particular start/stop sequence, its characterization will theoretically improve the simulation of the water distribution pattern. Hanson and Wallender (1986) presented an experimental study to analyse the effect of start/stop sequence on irrigation uniformity. They concluded that non-uniformity along the travel path of a ten-tower center-pivot appears in part related to the start/stop sequences of the towers. However, a firm association was difficult to establish. Yan et al. (2010) presented another experimental study analysing the effects of two center-pivot travel speeds and two cycle times on irrigation performance, concluding that cycle time has a slight effect on radial uniformity but no effect on circular uniformity.

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). Le Gat and Molle (2000) proposed a model using a mixture of beta probability distributions in which parameters were first estimated using water application

data measured in no-wind conditions. Data measured in wind conditions were then used to assess wind effects on the water application patterns. 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. The study presented the characterization of a unique nozzle type and size, working at 140 kPa under different wind conditions. The experimental effort necessary to train and validate the ANN model to simulate a center-pivot package, with different nozzle sizes and working pressures, is time and labour consuming.

An alternative approach to simulate the center-pivot water distribution pattern is based on droplet trajectory modelling. The pressure head at the nozzle, the nozzle diameter and the sprinkler design determine droplet size and velocity. In kinetic energy analyses of sprinkler irrigation, droplet trajectory and velocity are commonly simulated using an estimation of initial velocity and ballistic simulation models (Kincaid, 1986). Ouazaa et al. (2013) presented the characterization of initial velocity after the jet impact for FSPS equipped with a 36-grooved blue plate in an ample range of nozzle sizes and working at two pressures (103 and 138 kPa, equivalent to 15 and 20 psi). The authors presented the first application of the ballistic theory to the simulation of FSPS water distribution pattern. Calibration and validation of the ballistic model parameters were also presented for different nozzle sizes, wind conditions and two working pressures.

The simulation of center-pivot performance has been addressed since the 1960s. Most of the developed models simplify irrigation machine dynamics assuming continuous movement and circular sprinkler trajectory (Bittinger and

130 Logenbaugh, 1962; Heermann and Hein, 1968; Heermann and Stalk, 2004).
131 Omary and Sumner (2001) presented a model that only accounted for the
132 intermittent movement of the outermost tower, assuming perfect alignment
133 between all towers (hydraulic drive machine). Delirhasannia et al. (2010)
134 modified the model presented by Omary and Sumner (2001) to include the
135 effect of wind speed and direction on sprinkler water distribution patterns,
136 overlapping the experimental application patterns of isolated sprinklers.

137 The general objective of this paper is to develop a center-pivot simulation model
138 aiming at improving irrigation uniformity and at reducing water losses induced
139 by machine dynamics and wind speed. Specific objectives include:

- 140 1. To characterize and model the intermittent movement of center-pivot towers;
- 141 2. To couple the tower movement dynamics model with the ballistic simulation
142 of FSPS water distribution patterns;
- 143 3. To validate the coupled model with catch-can data; and
- 144 4. To analyse the effect of different tower movement dynamics, wind speeds
145 and center-pivot travel speeds on center-pivot irrigation system performance.

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II. MATERIAL AND METHODS

Two field experiments were carried out to fulfil the specific objectives of this research. In the first experiment, tower dynamics were characterized using a commercial center-pivot. In the second experiment, five irrigation events of the commercial center-pivot were evaluated with a catch-can radial transect. The working pressure of the sprinkler package was also monitorized by installing ten pressure transducers along the center-pivot lateral and another one at the pumping station.

A scheme describing the interaction of the experimental work, the data analysis and the model development is presented in Figure 1.

II.1 Characterization of the center-pivot mechanical movement

The first field experiment was conducted in a 16 ha commercial plot irrigated with a center-pivot in Marracos (Huesca, Spain) during the 2012 irrigation season. 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. The machine was equipped with Nelson D3000 (Nelson Irrigation Corp. Walla Walla, Washington, USA) FSPS with 36-grooved blue plates and 138 kPa (20 psi) pressure regulators. The center-pivot 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.

The location of the four towers was tracked using high precision GPS receivers (model GS15 receiver Leyca Geosystems AG, Heerbrugg, Switzerland) installed on top of each tower (Figure 1a). Post processing of the recorded data was performed to ensure positioning errors lower than 0.10 m. At the beginning of the 2012 irrigation season the GPS receivers were programmed to log data every 5 s. After five irrigation events, receivers were reprogrammed to log data every second. The initial log frequency provided insufficient accuracy to characterize tower movement. GPS data were used to characterize the movement / stop cycle times in each tower and irrigation event. The time evolution of the tower travel speed during the movement phase of each cycle was obtained for each irrigation event. Fisher's Least Significant Difference method (LSD) was used to compare tower travel speeds.

The on and off switching angle was determined for each tower and movement cycle using the coordinates of the neighbouring towers. Tower acceleration and deceleration times were also determined from experimental data. Acceleration time (AT) was determined for each cycle as the time it takes for a tower to reach its average travel speed. Deceleration time (DT) was determined as the time it takes for a tower to stop from its average travel speed. Comparisons were established for each center-pivot tower between AT and DT using paired-sample t-test analyses. Statistical differences between towers were assessed using the LSD test. The high number of movement / stop cycles within an irrigation event evidenced inter- and intra-irrigation variability in tower travel speed, switching angles, AT and DT.

Variability in tower travel speed and switching angles was explored in each irrigation event using “interval method” frequency analysis. This method consists on counting of the number of occurrences in previously defined intervals. The number of movement / stop cycles per tower and irrigation event was computed. Three irrigation events performed at 50%, 40% and 25% PTS were selected to calibrate AT and DT via optimization. Five irrigation events performed at 100%, 75%, 50%, 40% and 31% PTS were selected to validate the center-pivot tower movement dynamic model (Figure 1e). This model simulates center-pivots with tower motors similar to the experimental ones. The outermost tower movement is driven by the percentage timer setting of the correspondent center-pivot cycle time.

II.2 Individual and stationary water distribution pattern of FSPS

The parameters of the ballistic model applied to the simulation of FSPS were obtained from Ouazza et al. (2013). These authors calibrated and validated model parameters for 36-grooved, blue plate Nelson D3000 FSPS for a range of nozzle diameters from 2.4 to 8.7 mm, working at pressures in the range of 103 to 138 kPa (15 to 20 psi) and under different wind conditions (from 0 to 8m s⁻¹). The resulting ballistic model was used to simulate the water application pattern corresponding to the different nozzle sizes of the commercial center-pivot package, operating at the design pressure and at the meteorological conditions of the evaluated irrigation events.

II.3 Catch-can evaluation

Five irrigation events were evaluated with catch-cans arranged in a radial transect line with a 2 m spacing (Fig. 1 b). A total of 24 catch-cans were installed per pivot span, except for the first span, which was not monitored. Only 13 catch-cans were installed at the center-pivot overhang. Catch cans were conical in its lower part (200 mm height) and cylindrical in its upper part (100 mm height); the diameter of the upper part was 160 mm. The catch cans were marked in millimetres for direct readout up to 45 mm. They were placed over mowed corn at approximately 1.0 m above the ground.

An automatic meteorological station located adjacent to the center-pivot plot (Fig. 1b) monitored wind velocity and direction, air temperature and relative humidity with a frequency of 1 s. A 3-cup rotor anemometer Series A-100 and a wind direction sensor model 024-L (Campbell Scientific Ltd., Shepshed, UK) were used to measure wind speed and direction, respectively. A model CS-215 probe (Campbell Scientific Ltd., Shepshed, UK) was used to measure temperature and relative humidity. Meteorological variables were recorded in a model CR1000 data-logger (Campbell Scientific Ltd, Shepshed, UK).

To characterize the meteorological conditions of the evaluated irrigation events, GPS data of the center-pivot towers were analysed to estimate the passing time period of the center-pivot lateral over the radial catch-can transect. The vector average of wind velocity and direction, the average temperature and the average relative humidity of the selected irrigation period were considered representative of the evaluated irrigation. Eleven pressure transducers-loggers (Dixon, model PR150) were installed, one at the pumping station and the others along the center-pivot lateral (Figure 1b). Pressure transducers provided measurements with a 5 min time interval. The first measurement point at the

irrigation lateral was located at the pivot point (maximum elevation). The other nine pressure transducers were installed at the drop pipes, between the pressure regulator (138 kPa) and the sprinkler nozzle. Two pressure transducers per span were installed: one at the first nozzle and the other at the nozzle located in the middle of the span. The last transducer was installed at the beginning of the overhang. The average of the two pressure transducer measurements of a given span at the passing time of the center-pivot lateral over the radial catch can transect was used as representative of the span nozzle pressure.

II.4 Validation and application of the simulation model coupling tower dynamics and sprinkler water distribution patterns

The water distribution patterns for the different nozzle diameters of the center-pivot sprinkler package were simulated following Ouazaa et al. (2013). Simulations were performed under the different wind conditions and at the measured working pressure of the evaluated irrigation events. Each simulation involved mounting the water distribution patterns under the four spans and the overhang, and intermittently moving them with the pivot towers following the current measured dynamics (Fig. 1f). Model validation involved comparing simulated and measured (catch can evaluation data) irrigation depths and irrigation uniformities. Model application permitted to assess the effect of the PTS on the irrigation uniformity for different wind speed conditions and under different alignment qualities. Three PTS (30%, 50% and 100%), three wind conditions (three of the evaluated irrigation events) and four alignment qualities

were simulated. The analysed alignment qualities addressed the effect of the towers' start/stop sequences on irrigation performance. Comparisons were established between a center-pivot traveling under complete alignment (Complete), a center-pivot incorporating the current tower dynamics (CD), a center-pivot with a difference between on and off switching angles of 1° (A 1°) and a center-pivot with a difference between on and off switching angles of 2° (A 2°).

Each simulated irrigation event considered constant wind speed, wind direction, and pressure during the irrigation time. Comparisons between simulated cases were established in terms of radial, circular and total uniformity. Eight radial transects starting from the East (R-0°), separated 45° and following a counter clockwise direction were selected to estimate radial uniformity (along the lateral). Nine circular paths, corresponding to distances of 20, 40, 70, 90, 120, 140, 170, 190 and 220 m from the pivot point, were selected to estimate circular uniformity (along the machine travel path). Additionally, a total uniformity coefficient corresponding to the entire irrigated field was determined. The Heermann and Hein uniformity coefficient (CU_{HH} , %) (Equation [2]) was used for irrigation performance characterization of measured and simulated radial application data (Heermann and Hein, 1968).

$$CU_{HH} = 100 * \left[1 - \frac{\sum_{i=1}^m |d_i - \overline{d_w}| * S_i}{\sum_{i=1}^m d_i * S_i} \right] \quad [2]$$

where S_i is the distance from the pivot point to the i_{th} collector, d_i is the collected water depth in the i_{th} collector, m is the number of collectors, and $\overline{d_w}$ is the weighted average of collected water amounts (Equation [3]):

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$$\bar{d}_w = \frac{\sum_{i=1}^{i=m} d_i * S_i}{\sum_{i=1}^{i=m} S_i} \quad [3]$$

294 The Christiansen Uniformity Coefficient (CUC, %) (Equation [4]) was used for
295 the simulated circular paths and for the total irrigated area:

296

$$CUC = 100 * \left[1 - \frac{\sum_{i=1}^{i=m} |d_i - \bar{d}|}{\bar{d} * m} \right] \quad [4]$$

297

298 **III. RESULTS AND DISCUSSION**

299

300 **III.1 Characterizing and modelling center-pivot dynamics**

301

302 The experimental center-pivot applied 59 irrigation events, completing 70.4
303 rounds in 1,472.4 hours throughout the 2012 irrigation season. A total of 50 of
304 these irrigations had sufficient data quality to be used to characterize center-
305 pivot movement. The selected irrigations completed 50.2 rounds in 1,182.8
306 hours. These irrigation events used a variety of PTS, with 35% and 50% being
307 the most frequent (80% of the irrigation events and 64.5% of the irrigated
308 hours). The average cycle time for the outermost tower was 71.6 s, with an
309 inter-irrigation standard deviation of 0.4 s. This cycle time slightly differs from
310 the most commonly used by center-pivot manufacturers.

311 The farmer uses the water application chart provided by the manufacturer to
312 operate the center-pivot. This chart specifies that at 100% PTS the revolution
313 time is 9.5 hours and the theoretical irrigation depth is 4.1 mm. At different PTS
314 the revolution time and the irrigation depth can be obtained by dividing values

above by the value of PTS. Figure 2 presents the comparison between the measured and manufacturer-provided relationships between PTS and irrigation time. A regression analysis between measured and manufacturer-provided irrigation time showed that the correlation coefficient was not statistically different from 1. These results indicate that the experimental center-pivot movement is as originally manufactured.

Table 1 summarizes the results for the main tower dynamics variables. Some of these variables were used for simulation parameterization purposes. Measured average and inter-irrigation standard deviation tower travel speed were obtained from 45 analysed irrigation events (Table 1). Fisher's Least Significant Difference (LSD) method indicated that T4 speed was significantly different from the inner tower (T1, T2 and T3) speeds (95% confidence level). The test also indicated that T1, T2 and T3 speeds were statistically similar. The motors of the four towers had the same characteristics. Consequently, differences in speed can only be attributed to differences in load and/or to differences in tensions from the adjacent towers. The travel speed of the three inner towers was 80% of the speed of the outermost tower. The average inter-irrigation standard deviation of tower travel speed resulted very low (Table 1).

Comparison between AT and DT for each tower (t-test) showed significant differences except for T1. However, the differences in T2, T3 and T4 (average of 0.12 s) were lower than the measurement interval (1 s). Comparisons between towers (LSD test) indicated that the ATs of T2, T3 and T4 were not statistically different. However, they were found to be statistically different from the DT of T2, T3 and T4. Again the magnitude of the differences was lower than the measurement interval.

The intra-irrigation variability of towers' travel speed was evaluated using a frequency analysis. These travel speed analyses were performed only for the movement part of the cycles. Four irrigation events performed at different PTS (75%, 50%, 40% and 25%) were selected (Figure 3). For a given irrigation event the tower travel speed presented a clear distribution pattern, which was similar for irrigations performed at different PTS. For each tower, the intra-irrigation variability (amplitude of the histogram) was larger than the inter-irrigation variability (difference between histograms). Intra-irrigation variability increased from the inner tower (T1) to the outermost tower (T4). Figure 3 also shows relevant similarities between the inner towers' (T1, T2 and T3) travel speed patterns, and the difference with the outermost tower travel speed pattern (T4).

Figure 4 presents the frequency analysis of the on and off switching angles controlling the movement / stop cycles of towers T1, T2 and T3 for four irrigation events performed at 75 %, 50 %, 40 % and 25 % PTS. The T1 on and off switching angles computed with the locations of the pivot point (T0), T1 and T2 did not show a clear variability pattern. Their behaviour was very different from T2 and T3, and the error was attributed to the determination of T0 co-ordinates. Since T0 was a fixed point a GPS receiver was not permanently installed at this point. T0 location was measured once after the season, and the satellite positioning correction was applied at that moment. On the other hand, the GPS records from T1, T2, T3 and T4 were continuously corrected through satellite positioning. Differences in the measurement and correction times resulted in relevant errors affecting T1 angles.

The distribution pattern for the T2 and T3 switching angles was similar for irrigations performed at different PTS. The average measured on switch angles for T2 and T3 were 179.7° and 179.5° , respectively. An average value of nearly 180.0° was found for the off switch angle corresponding to T2 and T3 (Table 1). Again, the intra-irrigation variability (the amplitude of the histograms) was larger than the inter-irrigation variability (differences between histograms). An intra-irrigation standard deviation of 0.0655° was found for all the measured switching angles.

A simulation model of tower movement was proposed based on the analysis of the experimental data. The model simulates a center-pivot with similar individual motors powering the wheels of each tower. The outside tower advances following the pre-set PTS. Inner tower dynamics are driven by the on and off switching angles, for which a restricted random variability was built, reproducing the experimental variability.

Linear speeds and control angles were obtained for each tower from Table 1 to simulate the current center-pivot dynamics. The switching angles were considered equal for all inner towers (Table 1). To simulate the intra-irrigation variability of the switching angles, a random value between 0 and the observed variability (0.0655°) was added to the average values.

Instead of using the average values of the experimentally determined AT and DT, the Monte Carlo simulation method (Fishman, 1995) was used to optimize their values. The goal was to analyse the effect of the AT and DT on the simulation of the center-pivot tower dynamics. The objective function for the Monte Carlo method was based on the minimization of two errors: 1) the total movement and stop times for each tower; and 2) the distribution frequency of

the movement and stop times for each of the towers. Three irrigation events performed under different PTS (50%, 40% and 25%) were used for optimization purposes. The Monte Carlo process provided an optimized value of 2.45 s for both, AT and DT. Table 1 presents the input data for the simulation model.

Model validation used the same cycle time as measured (71.6 s). Five part-circle (180°) irrigation events performed at different PTS (100%, 75%, 50%, 40% and 31%) were selected for validation purposes. For these irrigation events a detailed analysis of the experimental data was performed, and observations were compared to simulation results. Table 2 presents the comparison for total movement time and total stop time for each tower and irrigation event. In general, simulated times were slightly larger than measured times. However, differences were always lower than 4.2% of the measured times.

In addition, the model should also adequately simulate the movement and stop cycle times for each tower. Figures 5 and 6 present measured and simulated frequency analyses of the on-times (left side figures) and off-times (right side figures) for each tower and for the validation irrigation events performed at 40% and 75% PTS, respectively. The measured variability of the movement and stop cycle times was in general well reproduced by the model. It has to be noted that the frequency analysis used a 5 s time step. An important difference in the specific duration will not be so important if it is compensated by the immediately previous or subsequent cycle time. For example, this is the case for the movement cycle time of tower 4 for the irrigation performed at 40% PTS (bottom left Figure 5). Measured movement cycle durations ranged between 25-30 s and between 30-35 s, with respective frequencies of 452 and 110 events. The

simulated cycle durations of 25-30 s had a frequency of 574 events. Although the difference appears graphically important, its effect on machine movement is not relevant.

III.2 Irrigation evaluation results

Table 3 summarizes the results of the evaluated irrigation events. Results are presented for each evaluated center-pivot span. For the first and second irrigation events all the center-pivot length was measured (Fig. 1b). After the second evaluated irrigation event it was necessary to uninstall the catch-can radial transect for agronomical operations. It was decided to reinstall catch-cans only under the fourth span, and occasionally under the overhang. Consequently, for the third irrigation event only the catch cans of the fourth span and the overhang were measured; for the fourth and fifth irrigation events only the fourth span was measured.

The average pressure at the pumping station (all the evaluated irrigation events) was 218 kPa, with a standard deviation between irrigations of 4.5 kPa. The average pressure measured at the center-pivot point was of 140 kPa, with a standard deviation between irrigations of 5.0 kPa. Although all the nozzles were equipped with a pressure regulator of 138 kPa, slight differences in working pressure were measured along the center-pivot lateral (Table 3). From the first span to the middle of the fourth span, the operating pressure could be considered similar to the regulator setting. Pressure at the beginning of the overhang measurement point was lower than the regulator setting in all evaluated irrigation events. A pressure of 138 kPa was used to simulate the nozzles located at the first, second, third and fourth span. A pressure of 130kPa was used at the nozzles located at the overhang.

The measured CU_{HH} was affected by wind speed and the sprinkler package (Table 3). Comparing the CU_{HH} of the fourth span in different irrigation events, a decrease in uniformity was observed from low (1.1 m s^{-1}) to medium (2.8 m s^{-1}) wind speeds. Uniformity increased in this span from medium (3.1 m s^{-1}) to high wind speeds (4.7 and 4.9 m s^{-1}). Irrigation events 2 and 3 were performed under similar average wind conditions, but CU_{HH} at the fourth span resulted different. Uniformity can be dictated not only by the average wind conditions, but also by the short-term wind variability in intensity and direction. Additionally, Faci et al. (2001) and Ouazaa et al. (2013) underlined the difficulty of experimentally characterizing water distribution patterns of FSPS using catch-cans.

III.3 A model coupling tower dynamics and water application patterns: validation and application

The spatial water application to the irrigated area was computed using a static grid whose parameters can be user-defined. The static grid is irrigated by moving grids representing the water distribution pattern of the sprinklers along the center-pivot lateral. The grids representing the sprinklers were computed using ballistic theory as reported in Ouazza et al. (2013). Other authors have used experimentally determined water distribution grids (Delirhasannia et al, 2010) or statistically defined water distribution patterns (Gat and Molle, 2000). The advantage of the method used in this paper is that model parameters can be extrapolated to non-evaluated nozzle diameters (within the experimental range), wind speeds (from 0 to 8 m s^{-1}) and working pressures (from 15 to 20 psi).

The effect of grid size on center-pivot irrigation performance was analysed. Five square grid sizes (from 0.5 m to 0.03125 m in side) defining the nozzle water distribution pattern of each sprinkler were simulated with the ballistic model presented in Ouazaa et al (2013). Relevant differences in distribution uniformity were observed between the simulated results with the coarse grid (0.5 m) and the fine grid (0.03125 m). Since differences between the two fine grids (0.0625 m and 0.03125 m) were negligible, the 0.0625 m grid was selected to represent the sprinkler water application pattern.

The five evaluated irrigation events were simulated to validate the model. The simulated nozzle patterns (under variable diameter, pressure and wind) were mounted at their corresponding locations. Center-pivot movement was simulated using the experimental parameters (PTS of 45% for irrigation events 1 and 5, and PTS of 50% for irrigation events 2, 3 and 4). Irrigation depths were simulated at the location of the experimental catch-cans.

Figure 7a presents the relationship between measured and simulated irrigation depth of the evaluated events (as presented in Table 3). The 1:1 line is presented in dashed line. The comparison regression line forced to the origin between measured and simulated irrigation depths has a slope of 1.0007 and is not statistically different from 1. The ballistic model presented in Ouazaa et al. (2013) included the experimental wind drift and evaporation losses (WDEL) function presented in Playan et al. (2005). These authors reported experimental WDEL in sprinkler irrigation machines of around 10% for daytime irrigation events. Figure 7b presents the comparison between measured and simulated CU_{HH} . The regression line forced to the origin has a slope of 1.005. This line is not statistically different from the 1:1 line (dashed line in Fig. 7b). The coupled

simulation model adequately reproduces irrigation depth and irrigation performance (CU_{HH}).

Different center-pivot sprinkler package designs (nozzle location and sizing), dynamics (PTS and alignments) and meteorological conditions (wind speed and direction) can be simulated with the developed model. In this study four scenarios of the experimental center-pivot tower dynamics (Complete, CD, A 1° and A 2°) were explored using the experimental sprinkler package. These alternative dynamics were simulated for three PTS (100%, 50% and 30%) and three wind speed conditions (1.1 m s^{-1} , 3.1 m s^{-1} and 4.7 m s^{-1}). Results were compared in terms of radial (R-), circular (C-) and total uniformity.

Average radial, circular and total irrigation depths (ID, mm) and uniformities (CU_{HH} and CUC, %) for the three PTS, the four alignment scenarios and the three wind speed conditions are summarized in Table 4. As expected, simulated average irrigation depth increases with PTS (from 4.1 for 100% to 13.5 for 30%). These values are similar to those provided by the manufacturer in the experimental center-pivot application chart. A comparison between simulated and manufacturer-provided ID is presented in Figure 2.

The effect of center-pivot travel speed (PTS, %) on CU (radial, circular or total) was in general irrelevant, except for the cases of the largest misalignment (A 2°), in which for the slowest PTS (30%) radial CU_{HH} increased respect to the fastest PTS (100%) (from 0.8 to 1.8 percent points). The effect of PTS was lowest for the circular and total uniformity coefficients.

In the experimental center-pivot and environmental conditions, the effect of the studied range of tower alignment qualities on irrigation uniformity can be classified as light. Radial, circular and total uniformity slightly decrease as

misalignment increases. This issue will require further analysis for different pivot lengths and sprinkler characteristics.

Wind speed effect on irrigation uniformity shows the same pattern for the radial, circular and total uniformity. However, the effect is clearer for circular uniformity than for the rest of parameters. From low to average wind speed (from 1.1 to 3.1 m s⁻¹), the average decrease in uniformity is 5.3%, 0.5% and 0.4% for circular, radial and total uniformity, respectively. On the other hand, from medium to strong wind speeds (from 3.1 to 4.7 m s⁻¹) the average increase in uniformity is 7.3%, 3% and 3.1%, for circular, radial and total uniformity, respectively. It has to be noted that real center-pivot irrigation event last for several hours, and meteorological conditions (such as wind speed and direction) may show relevant changes. This important effect has not been analysed in this study. The small effect of alignment quality and PTS on uniformity increases with wind speed.

The center-pivot dynamic model permits to explore the maximum misalignment between adjacent towers that a defined center-pivot can allow before collapse. Center-pivot tower travel speed and reach length determine the maximum allowed misalignment. For the studied commercial center-pivot, the maximum misalignment between towers was 15°. Larger values could not be managed by the current towers' speeds and the security system of the center-pivot would stop movement.

A further analysis of tower alignment quality on center-pivot irrigation performance is presented in Figure 8. The Figure includes radial, circular and total uniformities and their variability (standard deviation of the eight radial transects and nine circular paths) for the center-pivot traveling under five

alignment scenarios: Complete, CD, A 5°, A 10° and A 15°. Simulations were performed for 100% PTS under three wind speed conditions (1.1 m s⁻¹, 3.1 m s⁻¹ and 4.7 m s⁻¹, subfigures a, b and c, respectively). For low and strong winds (1.1 and 4.7 m s⁻¹) circular uniformities were considerably larger than radial and total uniformities. Differences between extreme misalignment qualities on circular uniformity were larger (from 6.7 to 9%) than radial (from 2.8 to 4.8%) and total (2.8 to 5.3%) uniformities. Also, the variability in circular uniformity was significantly larger than in radial uniformity. The variability in radial uniformity increased with misalignment and with wind speed. The variability in circular uniformities increased from low to average wind speed and then decreased for strong wind speeds. In general, radial uniformity provides a better approximation to total uniformity than circular uniformity. Center-pivot evaluation standards (UNE-EN ISO 11545:2002 and ANSI/ASAE S436.1) are only based on radial uniformity characterization. For average wind speeds the radial, circular and total uniformities were found to be quite similar (Figure 8b). Generalizing, tower misalignment reduces irrigation performance (radial, circular and total). The reduction starts to be relevant for misalignment larger than A 5°. Figure 9 provides a visual representation of simulated water distributions resulting from three alignment qualities: Complete (Figure 9a), A 5° (Figure 9b) and A 15° (Figure 9c). Simulations were performed under 3.1 m s⁻¹ wind speed at 100% PTS. The towers stop and start cycles result in different amounts of local water application, the effect is stronger for the largest misalignment analysed and for the area irrigated by the inner towers. Differences in radial, circular and total uniformity between the Complete and A 5° alignment qualities were 1.1%, 1.2% and 1.2%, respectively. Differences in

radial, circular and total uniformity between the two extreme alignment qualities (Complete and A 15°) were 4.8%, 7.0% and 5.3%, respectively.

CONCLUSIONS

1. The experimental characterization of the mechanical movement of center-pivot towers using a high precision GPS receiver provided valuable information to develop a comprehensive center-pivot irrigation simulation model. A position sampling interval of 1 s was required to guarantee sufficient accuracy in the characterization of tower movement. An important intra-irrigation variability of the variables controlling tower start / stop cycles was observed. This variability was modelled by introducing random variability in the switching angles. The proposed model successfully simulated the mechanical movement of the center-pivot towers.
2. The simulation model coupling center-pivot tower dynamics and the FSPS water distribution pattern satisfactorily reproduced the measured center-pivot irrigation depth and radial uniformity.
3. The coupled model was used to analyse the effect of different tower alignment qualities and wind speeds on the radial (along lateral), circular (along machine travel path) and total water uniformity. Simulation results indicate that in the experimental conditions (four span pivot, FSPS, wind speed) the experimentally measured tower alignment quality (around 0.5°) did not have a relevant effect on uniformity compared to a complete

alignment. The poorest analysed tower alignment quality ($A\ 15^\circ$) had more effect on circular uniformity than on radial or total uniformity.

4. In the experimental conditions and in the simulated range of the control variables, tower alignment quality showed a relevant effect on center-pivot irrigation performance for misalignment qualities larger than 5° . Pivot travel speed showed a mild effect on center-pivot irrigation performance. The sprinkler package design of the center-pivot had a strong effect on irrigation performance.

5. Wind speed showed a clear effect on irrigation uniformity. As wind speed increased, uniformity first decreased and then increased. The wind speed effect is clearer for circular uniformity than for radial or total uniformity.

6. Further research is needed to assess the effect of alignment, travel speed and wind conditions on other center-pivot lengths, sprinklers and operational conditions. The simulation of the intra-irrigation variability of wind speed seems to be important to understand center-pivot irrigation efficiency.

7. The model shows potential to become a valuable tool to manage center-pivot irrigation under different technical and meteorological conditions. Further research on sprinklers and designs will contribute to validate the practical potential of this coupled model.

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ACKNOWLEDGEMENTS

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612 This paper applied the “first-last-author-emphasis” approach for the sequence of
613 authors. This research was funded by the Ministry of Economy and
614 Competitiveness of the Government of Spain through grant AGL2010-21681-
615 C03-01. The authors would like to thank farmer managers Oscar Salafranca
616 (father and son), for their continuous support and contribution to gather field
617 data.

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620 **GLOSSARY OF ABBREVIATIONS**

621 A 1° = Center-pivot dynamics with a difference between on and of switching

622 angles of 1° ;

623 A 2° = Center-pivot dynamics with a difference between on and of switching

624 angles of 2° ;

625 A 5° = Center-pivot dynamics with a difference between on and of switching

626 angles of 5° ;

627 A 10° = Center-pivot dynamics with a difference between on and of switching

628 angles of 10° ;

629 A 15° = Center-pivot dynamics with a difference between on and of switching

630 angles of 15° ;

631 Complete = Center-pivot dynamics complete aligned;

632 AT = Acceleration time (s);

633 C = Circular;

634 CD = Center-pivot movement with the current experimental dynamics;

635 CUC = Christiansen Uniformity Coefficient (%);

636 CU_{HH} = Herman and Hein Uniformity Coefficient (%);

637 d = Average collected water depth (mm);

638 d_i = Water depth collected in the i_{th} collector (mm);

639 DT = Deceleration time (s);

640 d_w = Weighted average of collected water depths (mm);

641 FSPS = Fixed Spray Plate Sprinkler;

642 GPS = Global Position System;

643 ID = Irrigation depth (mm);

644 LSD = Fisher's least significant difference test;
645 m = Number of collector;
646 PTS = Percent Timer Setting (%);
647 R = Radial;
648 S_i = Distance from the center-pivot point to the i_{th} collector (m);
649 T1= Inner tower of the experimental center-pivot;
650 T2= Second center-pivot tower from the pivot point;
651 T3= Third center-pivot tower from the pivot point;
652 T4= Outermost tower of the experimental centre-pivot;
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Figure 9. Simulated water distribution pattern (mm) of the center-pivot travelling complete aligned (Complete, figure a), at a misalignment of 5° (A 5° , figure b) and at its maximum tower misalignment (A 15° , figure c) at 100% PTS and at a wind speed of 3.3 m s^{-1} .

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	Tower	Tower speed (m s ⁻¹)	AT/DT (s)	On switch angle (°)	Off switch angle (°)	SD Switching angles (°)
Measured	T1	0.0302 (0.003)	2.8/2.8	-	-	-
	T2	0.0302 (0.004)	2.7/2.8	179.7	180.0	0.0655
	T3	0.0303 (0.003)	2.7/3.0	179.5	180.0	0.0655
	T4	0.0377 (0.003)	2.7/2.9	-	-	-
Simulated experimental dynamics	T1	0.0302	2.45	179.6	180.0	0.0655
	T2	0.0302	2.45	179.6	180.0	0.0655
	T3	0.0302	2.45	179.6	180.0	0.0655
	T4	0.0377	2.45	-	-	-

Table 2. Measured and simulated total movement and stop time for the four pivot towers and for five irrigation events performed at different PTS (31%, 40%, 50%, 75% and 100%). Differences between measured and simulated times are presented.

Timer Setting	Tower	Measured		Simulated		Δ (Measured-Simulated)	
		Movement Time (s)	Stop Time (s)	Movement Time (s)	Stop Time (s)	Movement Time (s)	Stop Time (s)
100%	T1	5080	11329	5204	11500	-124	-171
	T2	10198	6216	10407	6296	-209	-80
	T3	15260	1127	15607	1096	-347	31
	T4	16423	0	16703	0	-280	0
75%	T1	5124	17214	5202	16989	-78	225
	T2	10277	12056	10404	11787	-127	269
	T3	15451	6868	15613	6578	-162	290
	T4	16794	5514	16704	5487	90	27
50%	T1	5118	27608	5198	27942	-80	-334
	T2	10238	22546	10403	22737	-165	-191
	T3	15482	17286	15606	17534	-124	-248
	T4	16496	16263	16704	16437	-208	-174
40%	T1	5168	35622	5199	35800	-31	-178
	T2	10292	30496	10396	30603	-104	-107
	T3	15451	25342	15595	25404	-144	-62
	T4	16620	24204	16703	24295	-83	-91
31%	T1	5118	47964	5191	48315	-73	-351
	T2	10230	42853	10389	43116	-159	-263
	T3	15446	37681	15593	37912	-147	-231
	T4	16554	36566	16703	36803	-149	-237

Table 3. Characteristics of the evaluated irrigation event, center-pivot travel speed (PTS, %), average wind speed, predominant wind direction, catch can location, 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} , %).

Irrigation event	PTS (%)	Av. Wind Speed ($m s^{-1}$)	Av. Wind Direction ($^{\circ}$)	Catch can Location*	Av. Pressure (kPa)**	Measured		
						ID (mm)	SD ID (mm)	CU_{HH} (%)
Event 1	45	3.1	278	Span 2 (24)	142 (3)	7.8	1.6	83.5
Event 1	45	3.1	278	Span 3 (24)	138 (3)	8.5	2.2	77.4
Event 1	45	3.1	278	Span 4 (24)	136 (5)	8.5	2.0	80.9
Event 1	45	3.1	278	Overhang (13)	130 (9)	8.3	2.6	74.4
Event 2	50	4.7	273	Span 2 (24)	142 (3)	7.0	1.2	87.0
Event 2	50	4.7	273	Span 3 (24)	139 (4)	7.5	1.0	86.3
Event 2	50	4.7	273	Span 4 (24)	135 (4)	7.0	1.3	86.8
Event 2	50	4.7	273	Overhang (13)	130 (6)	6.4	1.6	77.9
Event 3	50	4.9	275	Span 4 (24)	136 (5)	6.4	1.3	83.3
Event 3	50	4.9	275	Overhang (13)	130 (5)	7.0	2.0	78.5
Event 4	50	2.8	271	Span 4 (24)	136 (5)	7.8	1.9	79.0
Event 5	45	1.1	250	Span 4 (24)	136 (5)	8.5	1.8	82.5

*Number of catch-cans between brackets

**Standard deviation between brackets

827 Table 4. Simulated radial, circular and total, average irrigation depth (Av. ID, mm) and uniformity coefficient (CU, %) for four
828 analysed tower alignment scenarios: Complete aligned, current dynamics, and alternative dynamics allowing angle lags of 1° (A
829 1°) and 2° (A 2°) and for the three wind speeds (1.1 m s⁻¹, 3.3 m s⁻¹ and 4.7 m s⁻¹). Results are presented for three PTS (100%,
830 50% and 30%).

Wind Speed	Measurement Location	Align. Quality	Complete Aligned			Current Dynamics			A 1°			A 2°		
		PTS (%)	100	50	30	100	50	30	100	50	30	100	50	30
1.1 m s ⁻¹	Radial	Av ID (mm)	4.1	8.0	13.1	4.1	8.1	13.5	4.1	8.1	13.5	4.2	8.1	13.5
		CU _{HH} (%)	81.6	81.6	81.5	81.7	81.6	81.6	81.3	81.4	81.5	80.8	81.6	81.6
	Circular	Av ID (mm)	3.8	7.4	12.1	3.7	7.4	12.4	3.7	7.4	12.4	3.7	7.4	12.4
		CUC (%)	86.2	86.1	86.1	86.1	86.1	86.1	85.9	86.0	86.0	85.5	85.2	86.1
	TOTAL	Av ID (mm)	4.1	8.0	13.1	4.0	8.1	13.5	4.1	8.1	13.5	4.0	8.1	13.5
		CUC (%)	82.1	82.1	82.1	82.1	82.1	82.1	82.0	82.0	82.0	81.7	81.7	81.8
3.1 m s ⁻¹	Radial	Av ID (mm)	4.1	8.0	13.0	4.1	8.1	13.6	4.1	8.1	13.6	4.2	8.0	13.6
		CU _{HH} (%)	81.2	81.2	81.3	81.0	81.3	81.0	80.6	81.0	81.3	80.0	80.3	81.8
	Circular	Av ID (mm)	4.0	8.0	13.0	4.0	8.0	13.4	4.0	8.1	13.4	4.0	8.1	13.4
		CUC (%)	80.8	80.8	80.8	80.8	80.7	80.7	80.7	80.8	80.7	80.1	80.3	80.3
	TOTAL	Av ID (mm)	4.1	8.0	13.1	4.1	8.1	13.5	4.1	8.1	13.5	4.1	8.1	13.5
		CUC (%)	81.7	81.7	81.7	81.7	81.7	81.7	81.6	81.7	81.7	81.3	81.3	81.4
4.7 m s ⁻¹	Radial	Av ID (mm)	4.1	8.0	13.1	4.1	8.1	13.5	4.1	8.1	13.6	4.2	8.0	11.6
		CU _{HH} (%)	84.3	84.3	84.2	84.1	84.2	84.1	83.7	84.1	84.3	82.9	83.0	84.8
	Circular	Av ID (mm)	4.1	8.1	13.2	4.1	8.2	13.6	4.1	8.2	13.6	4.1	8.2	13.6
		CUC (%)	88.1	88.1	88.1	88.1	88.1	88.1	88.0	88.1	88.0	87.0	87.3	87.7
	TOTAL	Av ID (mm)	4.1	8.0	13.1	4.1	8.1	13.5	4.1	8.1	13.5	4.1	8.1	13.5
		CUC (%)	84.8	84.8	84.8	84.8	84.8	84.8	84.7	84.8	84.8	84.2	84.3	84.5

832 Figure 1

Figure 2. Measured and manufacturer provided relationships between percent timer setting (PTS, %) and irrigation time (hours). Simulated and manufacturer provided relationships between PTS and applied irrigation depth (ID, mm).

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923 m s-1.
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