Dynamic Model for Water Application using Centre Pivot Irrigation

by

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ABSTRACT

The application pattern for single, stationary spray sprinklers exposed to the wind was modelled to simulate water application in a centre pivot irrigated field. In the model, a dynamic square grid of cells for water application and a static square grid of cells for water collection were defined. The dynamic grid contained the information on the water application pattern of an isolated spray sprinkler, and this followed the motion of the centre pivot lateral. The static grid represented the entire the field, and received water from the dynamic grid at fixed time intervals. Model outputs included the applied water distribution pattern and measures of irrigation uniformity (radial, travelling path and global). A series of experiments using pivoted and single spray sprinklers were conducted simultaneously. The results from the model compared well with field observations. The resulting root mean square errors for the Heermann and Hein uniformity coefficient and the average applied water depth were 0.02 % and 0.08 mm, respectively. Model simulations were carried out to illustrate the effect of wind on irrigation uniformity.

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- 22 ***Key words:*** centre pivot, dynamic grid, model, static grid, uniformity coefficient,
23 application depth.

24 **NOMENCLATURE**

- 25 CU_c Christiansen uniformity coefficient, %;
- 26 CU_H Heermann and Hein uniformity coefficient, %;
- 27 d collected water depth, mm;
- 28 d_i collected water depth at the i^{th} collector, mm;
- 29 $\bar{d}$ arithmetic average of the collected water depth, mm;
- 30 $\bar{d}_w$ weighted average of the collected water depth, mm;
- 31 i average water application intensity, mm s^{-1} ;
- 32 I applied water depth, mm;
- 33 n number of collectors;
- 34 R^2 coefficient of determination, %;
- 35 S_i distance from the pivot point to the i^{th} collector, m;
- 36 T duration of the experiment(s), s;
- 37 t_s time of dynamic cell passage, s;
- 38 WDEL wind drift and evaporation losses, %;
- 39 X row of collectors;
- 40 Y row of collectors;
- 41 W row of collectors; and
- 42 Z row of collectors.

1. INTRODUCTION

Water is the main yield-determining factor in the majority of agricultural systems. Irrigation systems help growers manage weather related risks by effectively supplementing rainfall (Perry et al. 2002). To sustain agricultural production in the coming years, it is important to optimise irrigation systems, adjusting water application to crop water requirements. This will help protect both the quantitative and qualitative aspects of water conservation. Centre pivots are an interesting technological option for irrigation, since their performance can be very high (Clemmens and Dedrick, 1994).

Centre pivots are commonly used in modern irrigation developments all over the world (Faci et al. 2001, Evans et al. 1993). Consequently, it is important to characterise the relevance of several design and management factors affecting the efficiency and uniformity of these machines (Montero et al. 2003). Quality control for centre pivot irrigation involves measuring the levels of irrigation precipitation under the machine (Bremond and Molle, 1995). Centre pivot simulation models have been used to improve the design of new systems and to modify existing systems with the view of improving irrigation performance.

The simulation of centre pivot performance has been the subject of a series of research efforts since the 1960s. Bittinger and Logenbaugh (1962) simulated precipitation under centre pivots with the objective of defining the optimal sprinkler spacing in order to obtain uniform water distribution. They developed an analytical model of precipitation under a sprinkler assuming that its water application pattern was either triangular or elliptical. The model was based on the additional hypotheses of continuous movement and linear or circular sprinkler trajectory. They estimated the irrigation depth by moving the water application pattern at the same velocity of sprinkler movement on the pivot lateral. Heermann and Hein (1968) continued this line of research by taking into account the overlapping effect of neighbouring sprinklers, and introduced the uniformity coefficient that bears their name. This led to the introduction of the CPED (centre pivot evaluation and design) software package (Heermann and Stahl, 2004). CPED input data included sprinkler positions on the lateral, discharge, radial application pattern and time of system revolution. Triangular, elliptical and toroidal application patterns were assumed for single nozzle, dual nozzle

75 impact sprinklers and spray sprinklers, respectively. Model output included the
76 applied water depth as a function of radial distance from the pivot point, application
77 intensity under the lateral and a uniformity coefficient. Wind effects were not
78 considered in the model. Evans et al. (1993) developed the CPIM (centre pivot
79 irrigation model) software for water and/or water-nitrate distribution analyses from
80 centre pivots. Their model used an empirical equation relating the water application
81 pattern in the absence of wind to supply pressure. The CPIM software overlapped
82 individual water application patterns and represented water application over the
83 irrigated field. Bremond and Molle (1995) developed a model for the simulation of
84 water application under centre pivots, focusing on irrigation uniformity. The basic
85 model input was the sprinkler application pattern, obtained from field experiments.
86 The overlap between sprinklers and the estimated water application as a function of
87 machine speed were determined numerically.

88 The above-mentioned models used one-dimensional, geometrical water application
89 profiles for simulation purposes. This can lead to significant errors since water
90 application patterns are not always adequately reproduced by a simple geometrical
91 shape, and even light winds can produce asymmetric water application patterns.
92 Consequently, models were required where water application related to more than just
93 distance from the sprinkler.

94 In a direct precedent to the present work, Omary and Sumner (2001) developed a
95 model to simulate water application and irrigation uniformity resulting from
96 overlapping spray nozzles mounted on a centre pivot. Building on a previous effort
97 (Omary et al. 1997), their objective was to simulate water application resulting from a
98 moving spray sprinkler using the stationary water application pattern as the main
99 input data. The area under a single spray sprinkler during its movement on a centre
100 pivot was discretized using two regular grids. One grid represented water application
101 (the sprinkler application pattern), whilst the other represented water collection (the
102 soil surface). The grid representing the single spray sprinkler moved along the pivot
103 trajectory, whilst the grid representing the soil was stationary. Taking into account
104 precipitation intensity in each cell of the moving grid, and its time to pass over the
105 fixed grid, water application distribution in the fixed grid was determined. Following
106 the simulation of water application from all spray nozzles, a uniformity coefficient
107 was calculated (Omary and Sumner, 2001). The authors used a moving grid that

108 included experimentally determined application intensities, rather than simple
109 geometric water application patterns. However, the model included simplifications,
110 such as assuming a linear movement of the spray sprinklers (as if the pivot lateral was
111 a linear-moving machine). This assumption can lead to significant errors, particularly
112 near the pivot point. On the other hand, it simplified model design, since each cell of
113 the moving grid applied water over only one line of cells in the fixed grid.

114 Considering a fixed water application pattern for the whole system operation time
115 may also result in poor model performance since wind speed and direction may
116 significantly vary during pivot irrigation varying the pattern. Thus, the use of wind
117 dependent, variable, two-dimensional sprinkler application patterns appear to be
118 required in order to produce accurate simulation models.

119 The main objective of this research was to develop an improved model of water
120 application by centre pivot spray sprinklers. The model was designed to improve on
121 previous efforts by; 1) taking into account wind effects; 2) considering the real
122 circular path of the spray nozzles in their rotation around the pivot point; 3)
123 characterising the water application pattern as a grid of observed irrigation depths, and
124 rotating this application pattern during pivot rotation; and 4) changing the water
125 application pattern with wind speed and direction. In this paper, the model is
126 formulated, validated and applied to the simulation of a case study.

2. MODEL DEVELOPMENT

2.1 Building and moving grids for spray sprinkler application pattern

In the model, the water application pattern of a stationary, isolated spray sprinkler is used to calculate the water depth applied when mounted on a centre pivot. For modelling purposes, the entire field covered by the centre pivot system is divided into square cells to produce a static grid.

A second dynamic grid, composed of regular cells, represents the water application pattern resulting from a single spray sprinkler. In this grid, the water application rate can be determined in each cell as:

$$i = \frac{I}{T} \quad [1]$$

Where i is the average water application intensity (mm s^{-1}), I is the applied water depth (mm); and T is the duration of the experiment (s). This grid moves reproducing the movement of the spray sprinkler on the centre pivot lateral. In the model, the dimensions of the square static and dynamic grids must be equal in size. As the dynamic grid passes over the static grid, the water applied by each dynamic cell is transferred into to some of the static cells. The water depth collected in each static cell is the sum of the water received from all the dynamic components passing over during a time interval. If the time of passage (i.e. water application opportunity) is t_s (s), the water depth received in a specific static cell from each dynamic cell is:

$$d = t_s i \quad [2]$$

where d (mm) is the received water depth.

Water application opportunity is not uniform for all static cells because during the passage of a dynamic cell over a static cell, non-complete overlapping can occur. Under these circumstances, each dynamic cell applies water to more than one static cell at the same time.

The dynamic grid of each spray nozzle is fixed with respect to the spray sprinkler; it does not rotate. Even if nozzle pressure and elevation are kept constant during pivot irrigation, the water application pattern is affected by the temporal changes in wind velocity and direction that occur during the irrigation event. The spatial variability of wind velocity and direction were neglected in the model because they were

considered to have little relevance over the complete domain of an irrigated field. Consequently, the sprinkler water application pattern was considered independent of the azimuth of the pivot machine (Fig. 1).

In order to prevent the rotation of the dynamic grid during the evolution of the model, the circular path of each dynamic cell must be kept separate. Particular attention must be paid to this point, since during rotation the relative position of the cells with respect to the pivot point changes. However, the dynamic grid remains fixed in relation to the spray sprinkler. This feature is schematically presented for the paths of three cells in Fig. 1. For a given sprinkler the radius of all circular paths of the dynamic components is the same, but the trajectories cross at particular points. At these points, the model accumulates water from all passing cells.

2.2 Dividing water application into static cells

Assuming that one axis of both grids is orientated to the North, and that the starting point for the movement of the grid system is at 0° (i.e., North). Under these conditions, dynamic and static grid cells will be full overlapped at 0, 90, 180 and 270° . This means that each dynamic cell completely covers one static cell. However, because the movement is circular, full overlap will not occur at any other angle, and the dynamic cells will find their applied water divided among four static cells. In this model, the division among static cells was based on the area covered in each static cell by the moving cell during each time step (Fig. 2).

The time step in the model was kept constant at 1 s. During this time, the water application of each dynamic cell was divided into the covered static cells. Since the pivot travelling speed and the position of the dynamic cells was known, the dynamic grid was shifted to its new position corresponding to 1 s displacement, and water application was divided and assigned to the static cells. Newly received water depths were accumulated to previous water depths. This process was repeated until the pivot returned to its original position. Once the process was completed, the dynamic grid of a given spray sprinkler described a complete circular trajectory over the whole field area.

2.3 Variability in time of the water application pattern

Even if the operating pressure and sprinkler elevation are kept constant, the water application patterns change in time responding to changes in wind velocity and

direction. Using one application pattern for each spray sprinkler during the time of pivot operation may cause errors in the simulated water application pattern. This is particularly important since the time required for a pivot to perform a complete rotation is about one day. During this time, wind conditions may be subjected to relevant changes. In the model, the water application time of each spray sprinkler can be varied in time.

2.4 Overlapping the pattern of each spray sprinkler

The revolution of a single water application pattern produced by a sprinkler creates a circular distribution pattern of water application over the static grid. Once this process is completed, it is repeated for the next spray sprinkler along the pivot lateral. Considering the typical wetted diameter of a single spray sprinkler, and the typical sprinkler spacing along the centre pivot lateral, overlapping is quite important, since most static cells receive water from two or more spray sprinklers.

2.5 Estimating radial, travelling path and global irrigation uniformities

Because of the radial geometry of pivot irrigation, evaluation processes have often relied on radial measurements of water application, which has led to the development of area-weighted radial uniformity coefficients (Merriam and Keller, 1978). According to ASAE S436.1 (Anon. 1996), the modified Heermann and Hein (1986) weighted equation is often used for this purpose:

$$CU_H = 100 \left[1 - \frac{\sum_{i=1}^n |d_i - \bar{d}_w| S_i}{\sum_{i=1}^n d_i S_i} \right] \quad [3]$$

where CU_H is the Heermann and Hein uniformity coefficient, 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, n is the number of collectors, and $\bar{d}_w$ is the weighted average of collected water amounts, calculated by:

$$\bar{d}_w = \frac{\sum_{i=1}^n d_i S_i}{\sum_{i=1}^n S_i} \quad [4]$$

The circular movement of the pivot lateral permits to define an additional uniformity coefficient; the travelling path uniformity, which evaluates irrigation uniformity along the circular path of a given radial distance from the pivot point. Rigorous implementation of this concept in the proposed model was carried out by 1) moving the dynamic grid over the static grid; 2) changing the dynamic grid direction with respect to the pivot of the lateral; and 3) crossing of the dynamic cell paths during their revolution. In order to illustrate these features, for a given travelling path the contribution of different dynamic grid cells to water collected in collectors m and p is shown in Fig. 3. While collector m receives water from cells a , b and c , collector p receives water from cells d , b and e . This may produce differences in uniformity under windy conditions. Since all static grid cells have the same area, the Christiansen uniformity coefficient (Keller and Bliesner, 1990) can be used for determining travelling path uniformity:

$$CU_c = 100 \times \left[1 - \left(\frac{\sum_{i=1}^n |d_i - \bar{d}|}{n\bar{d}} \right) \right] \quad [5]$$

Where CU_c is the Christiansen uniformity coefficient and $\bar{d}$ is the arithmetic average of the water collected. The set of n cells consists of all static cells located in the circular path of a pivot lateral point.

Radial and travelling path uniformities represent different phenomena. Radial uniformity results from all spray sprinklers mounted on the lateral. Travelling path uniformity comes from a limited number of spray nozzles overlapping at a certain point along the lateral. The most complete approximation to pivot irrigation uniformity derives from the analysis of the whole set of irrigated static cells (i.e., global uniformity). In this model, the proposed formulation relies on a cartesian coordinate system, where water application is estimated in a number of cells having the same area. Consequently, non-weighted uniformity coefficient equations can be used. The model uses the Christiansen uniformity coefficient for this purpose, applied to all non-zero water depth values in the static grid.

2.6 Wind drift and evaporation losses

Wind drift and evaporation losses (WDEL) constitute major water sinks in sprinkler irrigation. The proposed model uses experimental isolated spray sprinkler patterns to simulate pivot irrigation over a field. Water losses are properly taken into account if the isolated spray sprinkler experiment is used to simulate a pivot irrigation event carried out under the same wind conditions as in the field experiment.

2.7 Computer programming

The software code was developed using the MATLAB software (The Mathworks Inc, MA, USA). MATLAB has capabilities for matrix calculations, therefore the static and dynamic grids were defined as square matrixes whose elements corresponded to water depth in the grid cells. The initial condition for the static grid was zero depth in all elements. The elements of the dynamic matrix store non-zero values, except for the corner areas. During model execution, static matrix elements changed to non-zero numbers, except for the corner areas.

Model input data included:

- the irrigation lateral length;
- the grids dimensions and spacing;
- the duration of the experiment;
- the distribution of spray sprinklers along the pivot lateral; nozzle diameters and distances from the pivot point;
- the timer percentage (time for one complete revolution);
- the time of change in water application patterns (following changes in wind speed and direction), along with the identification of each successive pattern; and
- the experimental water application patterns, selected from a database including different models of spay sprinklers, nozzle diameters, operating pressures, sprinkler elevations and wind speeds.

Model outputs include collected water depth in all static cells and the global uniformity coefficient. Radial and travelling path uniformities could also be specified by the user.

3. FIELD EXPERIMENTS

A series of experiments were performed to determine the water application pattern of single sprinklers under different wind conditions. The same sprinklers were installed on a centre pivot lateral. Experiments were performed on both configurations at the same time, recording water application using different collector arrangements. The experiments were carried out at the experimental irrigation farm of the University of Tabriz, Iran. A centre pivot and an adjacent area were used for the experiments. Two spray sprinklers, Nelson R3000 and Senninger LDN were selected for the experiments. These sprinklers used a rotating red plate (R3000) and a fixed black plate (LDN). Nozzle diameters were 4.76 mm for the Nelson R3000, and 8.73 mm for the Senninger LDN. The arrangement of collectors followed the ASAE S436.1 standard, as described in the following paragraphs.

In the pivot experiments, four rows of 30 collectors were located at 1.25 m spacing along the pivot radius (covering a total length of 38.75 m each) and used to determine applied water depth. Collectors were cylindrical in shape, and 0.12 m in height and diameter. In order to evaluate the model predictive capacity, two pairs of collector rows were set up; one in the eastern part of the field and the other in the southern part of the field. The layout of the collectors in the pivot irrigated area is shown in Fig. 4. Each pair of collector sets was installed in a different pivot span. The X-Y and W-Z collector rows were installed under the second and third spans, respectively. The use of two different spans made the experiment more representative. In each experiment, 10 spray sprinklers were installed on the centre pivot second or third spans, and the pivot was stopped at a suitable distance from the collector rows. The nozzle size of all sprinklers was same. The experiments were conducted for model validation and calibration, and were not intended to reproduce performance of a real irrigation machine. Different nozzle sizes are typically used along laterals of commercial centre pivots.

In order to characterise the isolated spray sprinklers, a 50 x 50 m² field adjacent to a centre pivot was used. A regular, square array of 21 x 21 collectors, with a spacing of 1.25 m was established (Fig. 5a). An isolated sprinkler nozzle was mounted on a metal frame in the centre of the collector array (Fig. 5b).

The ASAE S330.1 standard (Anon 1996) was considered in the design of single spray sprinkler experiments. A portable weather station was installed at the experimental site, and wind velocity and direction were recorded in 10 min intervals. Pressure regulators are a common solution to avoid variations in operating pressure. Perry and Pocknee (2001) and Faci et al. (2001) reported using pressure regulators for sprinklers. Two types of pressure regulators were used in this research; 138 kPa and 103 kPa. At these pressures, the discharge of the experimental nozzles was: 1) for the Nelson R3000 (4.76 mm in diameter) 0.28 and 0.24 l s⁻¹, respectively; and 2) for the Senninger LDN (8.73 mm in diameter) 0.90 and 0.77 l s⁻¹, respectively. Nozzle heights of 1.80 and 2.25 m above the soil surface were used.

In each experiment, the centre pivot was started and, as soon as the first droplets reached the collectors, the pump feeding the single spray sprinkler was started. The pump to the single sprinkler was stopped as soon as the pivot ceased applying water to the collectors. This procedure ensured that the same wind conditions applied to both systems. The collectors located near the pivot point received water before the collectors located on the other side of the row. Therefore, the collectors located at the middle of the row constituted the reference for the pump to start and stop. As soon as the experiments ended, the collected water volumes were measured.

Spans not included in the experiments used different types of sprinklers. In order to remove the effect of neighbouring spans on the experiments, some of the outlets located in adjacent pivot spans were plugged. Therefore, a decline in water application was observed at both sides of the experimental span. Experimental and simulated water depths in collectors installed in the first and last 3 m sections of the pivot span were not used in the uniformity calculations.

4. MODEL VALIDATION

The experiments reported in this paper concerned two spray sprinkler models, two pressures, two nozzle elevations and two pivot spans. Therefore, there were 16 different experimental conditions. Also, experiments were repeated in order to obtain data under different wind conditions, giving a total of 34 experiments. The experimental data on water application patterns was introduced into the model, and the pivot experiments were computer simulated. As previously explained, the model did not require the use of an area weighed uniformity equation. However, the observed water application data are distributed along the pivot radius. Consequently, the modified Heermann and Hein radial uniformity coefficient was used for comparison purposes.

Observed and simulated uniformity and water application are compared in Table 1, where results are presented for each sprinkler, operating pressure, pivot span and nozzle elevation, and for the average of the experimental wind conditions. The average experimental wind speed was 2.93 m s^{-1} , ranging between 0.55 and 5.43 m s^{-1} . The model proved accurate in predicting both CU_H and the average applied water depth, with mean absolute errors of 1.38 % and 1.13 mm, and root mean square errors of 0.02 % and 0.08 mm. A regression analysis was performed between the 34 observed and simulated values of irrigation uniformity. The regression model was:

$$CU_{H \text{ Simulated}} = 1.013 CU_{H \text{ Observed}} - 0.436; \quad R^2 = 0.908 \quad [6]$$

Where R^2 is the coefficient of determination. The regression model resulted significant at a probability level of 95%. The regression coefficients could not be distinguished from those corresponding to a 1:1 regression line.

It can be concluded from Table 1 that increasing pressure or nozzle elevation often results in increased uniformity. Additionally, the rotating plate Nelson R3000 spray sprinkler produced more uniform water distribution than the fixed plate Senninger LDN spray nozzle. Although different nozzle diameters were used, similar results were reported by Faci et al. (2001) using standard conditions. Because of the larger nozzle diameter and higher discharge, under the same experimental conditions the

358 applied water depths from the Senninger LDN sprinklers were higher than those
359 resulting from Nelson R3000 sprinklers.

360 As a further illustration of model validation, Fig. 6 presents experimental observations
361 and model simulated results for water application corresponding to the Nelson R3000
362 sprinkler, at an operating pressure of 138 kPa, an elevation of 1.80 m, a wind speed of
363 1.8 m s^{-1} and a wind direction of 146° . Experimental data were obtained at the Z row,
364 under the 3rd pivot span. Fig. 6 shows close agreement in applied water along the
365 pivot span. The decline in water application depth at both ends of the experimental
366 pivot span is shown in the figure.

5. MODEL APPLICATION

A case study was devised to demonstrate the model capacity to simulate uniformity using experimental data. Three water application patterns obtained for Senninger LDN spray sprinklers operating at 103 kPa and installed at a nozzle elevation of 2.25 m were used for input. These experiments were performed under the following wind speeds and directions: a) 3.3 m s⁻¹ and 311°; b) 4.9 m s⁻¹ and 342°; and c) 4.1 m s⁻¹ and 59°.

The model was run counter clockwise from a starting angle of 90°, completing a full revolution in 21.3 h. In the first three runs, the wind patterns corresponded to cases a, b and c, respectively. The simulation was performed for the 2nd pivot span (from 37.8 to 71.6 m from the pivot point). Only one nozzle diameter was used in the span length. Fig. 7, subfigures a, b and c present the simulated water application (mm) corresponding to the travelling path of a point located a distance of 52.5 m from the pivot point. The total length of the travelling path at that radius was 329.9 m. The subfigures show large variability in water application with travelling path resulting from the overlapping of individual sprinklers. In the reported simulations, variability was amplified by wind speed, with uniformity decreasing as wind speed increased. Travelling path CU_c ranged from 85.5 to 87.2 %, while global CU_c ranged from 77.6 to 81.3 % (Table 2).

Finally, the model was run for a time of 7.1 h (120°) in each wind condition (a, b or c), to complete a full revolution in the same total time. This simulation represents the case of wind varying in speed and direction during the irrigation time. A travelling path length of 110.0 m corresponded to each of the water application patterns. The simulated travelling path water application (mm) is presented in Fig. 7, subfigure labelled a+b+c. The radial uniformity resulting from the irrigation event was computed at angles 30, 270 and 150°, with respective values of 74.9, 72.2 and 73.6 %. These results show the effect of changing wind speed and pivot overlapping in the case study. The travelling path uniformity amounted to 87.9, 85.1 and 86.4 %, for sectors a, b and c, respectively. The overall travelling path uniformity was 85.4 %. Finally, the global uniformity of the circular pattern irrigated by the simulated pivot span was 79.1 % (Table 2). The uniformity resulting from this simulation case was similar to the average values of cases a, b and c. However, using time varying wind

399 speed, more realistic predictions of water application in different parts of the pivot-
400 irrigated area are produced.

6. SUMMARY AND CONCLUSIONS

A new model of pivot irrigation has been developed. The model is based on the displacement of a moving grid representing each spray sprinkler moving over a static grid. Grid displacement produces circular paths for each of the grid cells. The analysis of the intersecting paths of the dynamic cells during their rotation around the pivot point led to a new concept in pivot irrigation modelling. It was shown that that uniform water application along a centre pivot lateral does not fully guarantee the uniformity of water distribution at the field level. The model was formulated in a software package that is capable of estimating the uniformity resulting from a full pivot revolution.

Comparisons between experimental observations and model simulations revealed that the model can accurately predict radial irrigation uniformity and water application along the centre pivot. The model simulation accuracy was high for both types of spray sprinkler (rotating and fixed plate). Differences in model accuracy owing to different sprinklers were not significant. Nozzle elevation, operating pressure, machine position respect to the dominant winds, and centre pivot span did not appear to influence model accuracy either. The model can therefore be further developed to provide a useful tool for centre pivot design and management. Model application provided insight into the importance of considering temporal variability of wind during irrigation. Although the model was developed and validated for centre pivots, it could be readily used for linear moving systems, which constitute a simplification of the simulation approach adopted. The most innovative aspect of the proposed model is that water application can be determined at any point of the irrigated field (via the static matrix).

Commercial pivot irrigation laterals use a wide variety of sprinkler nozzle sizes in order to produce uniform water application. The model needs additional work in order to be able to simulate pivot irrigation in full detail. A particular research line will be devoted to optimising the distribution of nozzle sizes in order to maximize global uniformity. The research reported here constitutes the introduction and validation of a new modelling approach. Experimental work is underway to obtain the water application patterns characteristic of a centre pivot under varying conditions of nozzle size, wind speed, operating pressure and nozzle elevation. Such data is required to

perform complete centre pivot irrigation simulations. Extending the recent efforts in ballistic simulation of impact sprinklers (Carrión et al. 2001; Montero et al. 2001; Playán et al. 2006) to centre pivot spray sprinklers will surely extend the prediction of water application patterns in the presence of wind to untested values of some of the major governing variables.

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Please note that mention of a commercial product does not imply endorsement.

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494 ballistic simulation model." *Agricultural Water Management*, 84(1-2), 89-100

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 520 application is presented for three different wind conditions (a , b and c), and for the
 521 combination of them ($a+b+c$).

522 **Table 1.**

523

524

Spray sprinkler	Pressure regulator (kPa)	Span number	Nozzle elevation (m)	Wind		Average applied water depth (mm)*		Uniformity Coefficient CU_H (%)	
				speed (m s ⁻¹)	direction (°)	observed	simulated	observed	simulated
Nelson R3000	138	3	1.80	1.13	146	11.49	10.48	85.3	86.1
Nelson R3000	138	3	1.80	3.37	161	10.13	9.78	81.4	82.8
Nelson R3000	138	3	1.80	5.43	210	8.23	8.06	78.2	77.7
Nelson R3000	138	3	2.25	0.65	150	6.70	9.23	87.7	88.3
Nelson R3000	138	3	2.25	2.82	124	8.94	7.67	80.5	82.9
Nelson R3000	138	2	1.80	0.55	154	14.91	15.09	86.8	84.2
Nelson R3000	138	2	1.80	4.35	330	12.84	11.98	74.4	76.1
Nelson R3000	138	2	1.80	1.77	345	10.56	11.75	82.7	81.2
Nelson R3000	138	2	2.25	2.97	175	10.39	9.70	84.5	85.0
Nelson R3000	138	2	2.25	4.80	191	6.51	5.96	81.9	82.2
Nelson R3000	103	3	1.80	1.78	94	9.69	9.88	79.7	82.7
Nelson R3000	103	3	2.25	3.18	11	8.36	6.86	85.4	87.3
Nelson R3000	103	3	2.25	5.08	101	6.22	4.48	79.0	82.1
Nelson R3000	103	2	1.80	0.90	45	10.41	12.06	81.3	82.5
Nelson R3000	103	2	1.80	2.65	127	12.65	14.42	75.9	73.9
Nelson R3000	103	2	2.25	4.60	56	6.97	8.73	80.4	80.9
Nelson R3000	103	2	2.25	3.20	139	9.19	10.89	81.8	84.3
Average	-	-	-	-	-	9.65	9.83	81.5	82.4
Senninger LDN	138	3	1.80	1.72	26	27.22	29.38	79.4	78.8
Senninger LDN	138	3	1.80	3.80	34	24.98	25.20	75.2	74.6
Senninger LDN	138	3	2.25	2.20	157	20.66	18.97	82.9	83.4
Senninger LDN	138	3	2.25	3.34	166	21.87	20.09	78.7	78.5
Senninger LDN	138	3	2.25	4.55	198	22.90	21.33	76.6	76.9
Senninger LDN	138	2	1.80	1.10	124	18.94	17.56	78.3	78.6
Senninger LDN	138	2	1.80	4.41	38	21.18	21.74	74.5	76.2
Senninger LDN	138	2	2.25	3.30	22	27.88	28.17	76.2	78.2
Senninger LDN	138	2	2.25	2.28	56	23.66	24.59	79.6	82.2
Senninger LDN	103	3	1.80	0.74	60	26.76	25.39	74.8	73.2
Senninger LDN	103	3	1.80	3.53	127	22.55	23.14	68.1	70.9
Senninger LDN	103	3	1.80	3.66	157	21.82	20.26	68.6	69.2
Senninger LDN	103	3	2.25	2.38	210	20.24	22.46	73.9	74.3
Senninger LDN	103	2	1.80	5.17	101	16.98	17.21	71.0	68.7
Senninger LDN	103	2	1.80	2.02	26	21.72	23.39	75.6	74.9
Senninger LDN	103	2	2.25	4.62	30	24.66	24.45	71.4	70.5
Senninger LDN	103	2	2.25	1.43	175	29.24	30.03	76.8	79.3
Average	-	-	-	-	-	23.00	23.15	75.3	75.8
Total average	-	-	-	-	-	16.30	16.50	78.4	79.1
MAE ¹	-	-	-	-	-	1.13		1.38	
RMSE ²	-	-	-	-	-	0.08		0.02	

* Average applied water depth in each experiment (two rows of collectors in each experiment)

1. Mean Absolute Error

2. Root Mean Square Error

525 **Table 2.**

526

527

Simulation case	<i>a</i>	<i>b</i>	<i>c</i>	<i>a+b+c</i>
Wind speed (m s^{-1})	3.3	4.9	4.1	all
Wind direction ($^{\circ}$)	311	342	59	all
Traveling path <i>CUC</i> (%)	87.2	84.7	85.5	85.4
Global <i>CUC</i> (%)	81.3	77.6	79.2	79.1

Figure 1.

532
533

Figure 2.

534

Figure 3.

Figure 4.

Figure 5.

b)

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543

544

Figure 6.

547

Figure 7.