Ador-Solid-Set: A coupled simulation model for commercial solid-set irrigated fields

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Abstract

The last five decades have seen strong developments in surface, drip and sprinkler irrigation modeling. However, most of these efforts have targeted irrigation units smaller than a field. In sprinkler irrigation, models have generally been applied to a few sprinklers in a regular arrangement, making them representative of a sector or a whole field. In this research, the Ador-Solid-Set model is presented for whole-field sprinkler irrigation in commercial fields. The model couples pipeline hydraulics, sprinkler ballistics and irrigation scheduling at execution time, permitting to simulate scenarios with minimum data management burden. Field experiments have been used to validate the model in an experimental solid-set. Observed and simulated irrigation depths and coefficients of uniformity showed statistically significant agreement. The model was applied to simulate irrigation events in two commercial solid-sets of 10.2 and 24.5 ha, producing maps of applied water in a sequential irrigation of their irrigation sectors lasting for 24 hours. The solid-set model produced whole-field irrigation performance estimates. The current adequacy thresholds for sprinkler irrigation uniformity need to be revised to apply them to complete solid-sets. The model highlighted the importance of finding suitable combinations of full- and partial-circle sprinklers to achieve optimal performance indicators. Finally, Ador-Solid-Set quantified the volume of drift outside the computational domain. This drift adds to the drift and evaporation losses obtained from empirical equations, in a process that requires further analysis. Research efforts are needed to enhance the current

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model capabilities to address the challenges related to water quantity and quality in sprinkler solid-sets.

Keywords: irrigation uniformity; irrigation scheduling; pipeline roughness; ballistics

1. Introduction

Computer modeling has been an area of growing interest in the past decades. Modeling has been applied to a wide variety of objects and processes. Interest in irrigation system models started in the 1970s, with the first modelling applications being to farm water management (Windsor and Chow, 1971). Models have proven very useful in irrigation practice, complementing and even partially replacing irrigation evaluations and experimentation. Computer models permit to quickly respond to a variety of "what if" questions. In the absence of computer models, answering these questions would require intense and expensive experimentation. A large number of models of different types have been developed for surface, drip and sprinkler systems.

The modeling of surface irrigation events has been an active area of research since the 1970s (Bassett, 1972). The complexity of surface irrigation hydraulics and the low number of parameters involved in the governing equations accelerated the adoption of modeling for surface irrigation design, analysis and parameter estimation. Most surface irrigation models focus on one irrigation unit (a border, basin or furrow). Only a few of these models focus on surface irrigated fields (composed of multiple irrigation units), concentrating on issues like the water distribution network (Pereira et al., 1998) or field-level efficiency (Zapata et al., 2000). Surface irrigation models have also been applied to simulate water flows in water users associations (Playán et al., 2000). These models are computationally intense, since they use numerical methods to solve the shallow-water equations. One-dimensional simulations were time-consuming in the 1980s. Developments in numerical techniques and personal computers have made WinSRFR (Bautista and Schlegel, 2020) - the current standard on 1D surface irrigation simulation – a fast model. However, two-dimensional models still represent an intense computational effort.

Simulation of drip irrigation also started in the 1970s, and developed in parallel with the consolidation of this irrigation method. Modeling focused on two different aspects: pipeline design considering emitter hydraulics and field layout (Wu and Gitlin, 1974), and the interaction between the emitted water and the soil profile, following a soil physics approach (Skaggs et al., 2004). The field approach has been more used in drip irrigation than in surface irrigation, responding to the need for whole-field design in conditions of almost continue water delivery along the emitter lines.

Sprinkler irrigation modeling started almost a decade later than surface and drip irrigation modeling. Fukui et al., (1980) presented a ballistic sprinkler irrigation model that laid down the basic structure of current models. A number of improvements to the original model were performed (Carrión et al., 2001; Montero et al., 2001; Seginer et al., 1991; Vories et al., 1987). As a result, by the beginning of the 21st century, sprinkler irrigation models were functional in field conditions and could be calibrated with experimental data. Ballistic models have been applied to solid-sets (Ador-Sprinkler) (Playán et al., 2006) and moving laterals (Ouazaa et al., 2015). While the models for moving laterals typically implement all the emitters in a sprinkler irrigated field, solid-set fields have been typically represented by a short number of full-circle sprinklers distributed in a given spacing and operating at the same pressure (Dechmi et al., 2003). When attempting to simulate the sectors in which a solid-set field is typically divided, a number of sprinklers have been used to reproduce each sector (Zapata et al., 2017). This approach has been used in Ador- simulation to model the performance of solid-sets, moving laterals and drip irrigated fields connected to a collective pressurized network (Zapata et al., 2023). These models have been connected to soil – water – yield models, such as Ador-Crop (Dechmi et al., 2004), to generate irrigation demand and to estimate crop yield and soil water content under different structural and water management scenarios.

Despite the success obtained when simulating solid-sets in large irrigated areas supplied by pressurized networks, the simplifications behind these models are relevant. In real life solid-sets, sprinklers are not always separated by the exact nominal spacing. This may be due to problems in construction (unlikely in these days, since GPS systems are used) or to the limitations imposed by the field dimensions or shape. Additionally, all sprinklers operate at different pressures. Moreover, two types of impact sprinklers are present in solid-sets: full-circle and partial-circle. Preparing for the future development of field-scale solid-set models, Ouazaa et al. (2016) performed experiments to characterize different types of sprinklers used at the field boundaries, and parametrized a ballistic model to reproduce their patterns of water application. In a further effort, Robles et al. (2019) developed a self-calibrated ballistic model for impact sprinklers, based on a database containing the results of the experiments required to calibrate a given combination of sprinkler model and nozzle diameter(s). These tests typically include the determination of the radial application pattern of an isolated sprinkler under no wind conditions and the determination of the water application pattern in a catch can network within a sprinkler spacing at different wind speeds. All these experiments are performed at a range of operating pressures, typically in the range of 200 - 400 kPa. In order to prevent poor overlap in the presence of high wind speeds, at least 16 sprinklers are used in these tests, with 25 catch cans being located in the central spacing (5 x 5 in a square arrangement). The combination of experiments with different sprinkler types (full-cycle and partial cycle) and pressures, in isolated sprinklers and in groups of sprinklers sets the scene for the development of solid-set models at the field scale.

In our experience, solid-sets often have a triangular 18 x 18 m sprinkler spacing and irrigate an area that usually extends from 1 ha to about 40 ha. Fields with shapes approximating a full circle or a partial circle and with areas in excess of 20 ha are often irrigated with center pivots. These machines have relevant advantages over solid-sets: cost-effectiveness, high uniformity with low wind effects and ease to mechanize farming operations. In many areas of the world, such large fields are not frequent and thus solid-sets are common. The simulation of water flows in a solid-set is characterized by the complexity of its layout.

De Andrade et al. (1999b, 1999a) and de Andrade and Allen (1999) presented the SPRINKMOD model, which simulates pressure along sprinkler irrigation distribution networks and flow through the sprinklers. The model did not simulate the distribution of water applied to the field surface, but solved flow in all pipelines.

With these features, SPRINKMOD focused on hydraulic uniformity and on attaining a minimum value of sprinkler pressure, but could not estimate irrigation uniformity or efficiency.

In the past decades, solid-set irrigation modeling has focused on water distribution in a sprinkler spacing using ballistics, although hydraulic pipeline modeling has been applied for decades now, and the combination of pipeline hydraulics and drop ballistics has already been simulated (Zapata et al., 2017). Solid-set irrigation models have been used to guide irrigation in small-scale (a sprinkler spacing) and large-scale applications (a collective pressurized network). However, the meso scale represented by a solid-set field is particularly useful to assess farmers' irrigation strategies and to establish relationships between water application, crop yield and diffuse pollution.

In a clear precedent to this work, Morcillo García et al. (2021) presented a model for solid-set irrigation at the field scale. Their model used EPANET (Rossman et al., 1994) to simulate flow in the solid-set pipelines and the SIRIAS ballistic model (Carrión et al., 2001) to simulate water distribution from the sprinkler to the soil surface. The experimental field was 2,82 ha in area, and was divided in two sectors. An EPANET layout of the field pipelines was created using the irrigation system design and a digital terrain model. EPANET was calibrated using pressure sensors at the sprinklers. Roughness was estimated for the main and submain pipelines, as well as for the risers. Radial curves were obtained for a full-circle and a partial-circle sprinkler at different wind speeds. These curves were used in SIRIAS to produce a database of sprinkler application simulations in the experimental plots under different pressure and meteorological conditions. These sprinkler application patterns were overlapped in the SORA software (Montero et al., 2001) to create a map of water application in the field for each irrigation event. Research was completed by using simulated water application as input to the AquaCrop model (Steduto et al., 2009) and comparing yield maps to maps of Normalized Difference Vegetation Index (NDVI).

Barberena et al. (2022) combined QGIS and EPANET to elaborate a model to assess sprinkler irrigation performance in greenhouses. The model was based on the overlap of individual sprinkler application in windless conditions. An irrigation design with a number of irrigation sectors was simulated at different pressures.

In recent years, the concept of digital twins (Jones et al., 2020) has received attention by researchers, particularly in the industrial domain. These authors described digital twins as “a physical entity, a virtual counterpart, and the connections between them”. This concept, allegedly coined in 2003, can be readily applied to solid-set fields, using models reproducing their characteristic features and exploring the connections between the field and the models… probably the most interesting part. Connections include processes such as irrigation scheduling, whole-field and whole-season uniformity as related to physical and meteorological parameters, the dependence on the conditions at the field inlet (commonly, pressure at the hydrant of a collective pressurized network), the generation of deep percolation and the diffuse pollution associated to it. The problems resulting from overfertilization in countries such as Spain, with escalating animal farming activities leading to abundance of organic fertilizers, require development of local strategies combining irrigation and fertilization. Digital twins and simulation models are close concepts. In the context of Agric. Water Manag, both can provide field-scale strategies alleviating quantitative and qualitative pressure on water resources.

The research group has produced the Ador family of irrigation simulation models (Dechmi et al., 2004; Playán et al., 2006; Zapata et al., 2023). This paper presents the development and initial results of a new family member: Ador-Solid-Set, a simulation model for solid-set sprinkler fields. The model has been conceived as a tool to identify best practices for agricultural production and the conservation of irrigation water quantity and quality.

The objectives of this research are: 1) to develop Ador-Solid-Set, a coupled model for whole-field solid-set sprinkler irrigation targeting commercial fields; pipelines, sprinkler ballistics and irrigation scheduling; 2) to validate the model in an experimental solid-set; and 3) to apply the model to perform irrigation events in two commercial solid-sets.

2. Materials and methods

2.1. Model concept

The main elements of Ador-Solid-Set are presented in Fig. 1. The model currently consists of a solid-set simulation C++ code coupled to: 1) a new Ador-Sprinkler release (a ballistic C++ solid-set irrigation model); 2) a C++ meteorological library; 3) a C++ irrigation scheduling library; and 4) EPANET. Previous developments in Ador-Sprinkler (Playán et al., 2006) have required a major upgrading to move from a regular, sixteen-sprinkler layout with uniform irrigation material, spacing and operating pressure to the real, irregular layout of commercial solid-set fields equipped with full- and partial-circle sprinklers operating at different times and with different pressures. Coupling Ador-Sprinkler and EPANET at run time has permitted to determine pressure and discharge conditions in each field sprinkler, considering the sectors in which the field is divided and the sequential operation resulting from typical irrigation schedules. Another advantage of this coupling is that ballistic simulations are performed in any point of the field and at any instant of simulated time, resulting in water distributions responding to the specific hydraulic conditions of each sprinkler and to the specific meteorology of each simulation time step.

Simulated water application is delivered to the cells of a square grid. Following the usual practice in Ador-Simulation, a sprinkler spacing contains about 25 cells of the square grid. This cell density permits to reveal the variability in water related properties (yield, uniformity, percolation) at the sprinkler spacing scale. In Ador-Solid-Set, this variability at the sprinkler spacing scale is combined with the variability at the field scale. The integration of these sources of variability represents a relevant step forward in the understanding of solid-set field performance.

Figure 1 presents in blue the current model developments, and in grey the elements required to complete the model concept. Research is in progress to integrate these elements and to render Ador-Solid-Set operative to reach its overall goals.

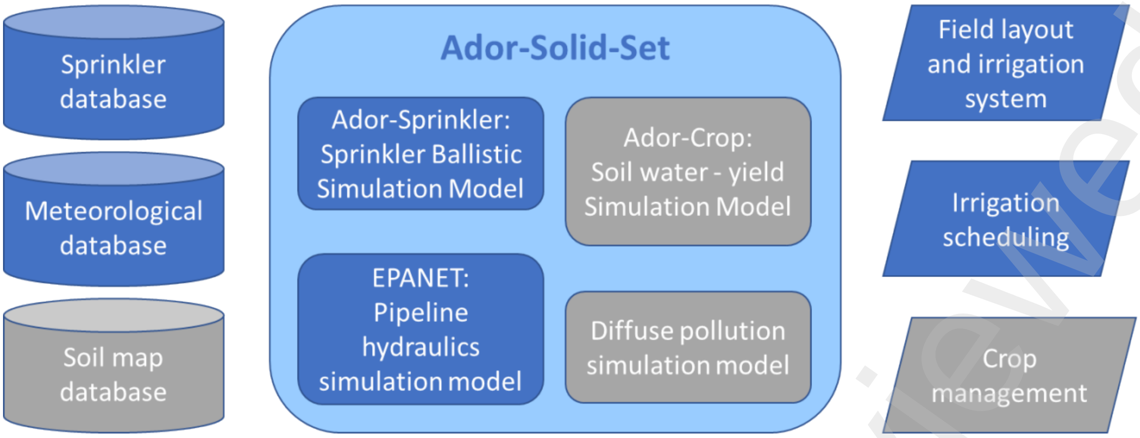


Figure 1. *Databases (left) submodels (center) and parametrization (right) of the Ador-Solid-Set model. The parts in grey represent ongoing model developments.*

The model can be run for a period of time, typically a natural year. The model time step for irrigation application is dictated by the semi hourly availability of meteorological data. Air temperature, relative humidity, wind speed, wind direction, and solar radiation are available at this time step. Additional variables are available at a daily time step: precipitation, maximum and minimum air temperature, solar radiation, average relative humidity, average wind speed and reference evapotranspiration. These data were obtained from agrometeorological stations of Spain via the Agroclimatic Information System for Irrigation (SiAR network, Ministry of Agriculture, Fisheries and Food in cooperation with the Autonomous Communities).

2.2. Modelling flow in solid-set pipelines

The EPANET software is used to represent the key elements of solid-set hydraulics:

- The hydrant. An elevated reservoir is used for this purpose, assuming that solid-set demand does not modify hydrant pressure.
- Buried pipelines. Represented by the x, y, z coordinates of their extremes, their length, diameter and roughness, as well as the pipelines connected in the extremes. PVC and Polyethylene are common plastic materials for these pipes.
- Vertical pipelines. These are the sprinkler risers, commonly built in galvanized iron and connected to a buried plastic pipeline and a sprinkler.

- Valves. These are used to open / close sectors. As a consequence, the sprinklers located downstream from a sector valve are associated to the sector.
- Emitters or sprinklers. These are represented by a reference, the sprinkler coordinates, the connection to a riser pipeline and the k coefficient (L s^{-1} $m^{-0.5}$), obtained by dividing the sprinkler discharge q (L s^{-1}) by the square root of nozzle pressure h (m of water column):

$$k = c\,(2g)^{\frac{1}{2}}\,\pi\,\frac{1}{4}\left(\frac{D}{1000}^{2} + \frac{d}{1000}^{2}\right) 1000 \qquad [1]$$

Where c is the sprinkler head loss coefficient (0.97 in this research), g is the acceleration of gravity (m s^{-2}), D is the main sprinkler nozzle diameter (mm) and d is the auxiliary sprinkler nozzle diameter (mm).

The EPANET programming library was included in the Ador-Solid-Set model to open and close valves dynamically, responding to an irrigation programming schedule. Irrigation simulation starts with a call to the EPANET simulation routine to determine - for a given combination of open sectors - the pressure and discharge of each operating sprinkler.

2.3. Modelling flow from the sprinkler nozzle to the soil surface

The Ador-Sprinkler library has evolved to simulate irrigation in a set of impact sprinklers installed within an irregular field perimeter. The parametrization of the solid-set field requires the following data:

- The field perimeter, in x, y, z coordinates.
- An additional set of x, y, z coordinates, used to estimate soil surface elevation inside the perimeter.
- The model and nozzle diameters of each type of sprinkler used in the solid-set. Additionally, the corresponding simulation parameters. As described by Li et al. (1994), the distribution of diameters of the drops emitted by a sprinkler can be represented by a mean drop diameter (D_{50}, mm) and a shape coefficient (n). Tarjuelo et al. (1994) developed the relation proposed by Seginer et al. (1991), proposing parameters K_1 and K_2, which determine the response of drop trajectories in the presence of wind.

- A list of the field sprinklers: reference (the same as the one used in EPANET), type (full or partial circle), x and y coordinates, sprinkler model, riser height and number of simulated drops in each irrigation event.
- Size of the square computational cells.

This information is used by the library to set up the sprinkler objects and to create a list of the computational cells. Cell properties include:

- Coordinates x, y, z of the cell center
- Field sector where this cell is located.
- Type of cell:
    - External. Completely out of the perimeter. Drops reaching these cells interrupt their trajectory. Their volume adds to the estimation of drift.
    - Internal. The cell center is inside the perimeter. When a drop flies over one of these cells, the calculation of trajectory continues. If the drop reaches the soil surface, its volume adds to precipitation in the cell.
    - Internal boundary. A small part of the cell is inside the perimeter, but the cell center is outside the perimeter. The trajectory is determined. If the drop reaches the soil surface, its volume adds to precipitation in the boundary cells (separated from internal cells).
    - External boundary. Located just outside the perimeter, adjacent to an internal boundary cell. The trajectory is determined. If the drop reaches the soil surface, its volume adds to the estimation of drift.

Robles et al., 2019 presented a detailed description of the determination of individual drop trajectories in Ador-Sprinkler. The method is based on the numerical solution of the ballistic governing equations using a third order Runge-Kutta scheme (Press et al., 1988). The irrigation simulations presented in this paper were based on the trajectory of 10,000 drops emitted from each sprinkler (full- or partial-circle). This large number of drops ensures that the volume of drops landing in each cell is representative of irrigation precipitation.

Ador-Sprinkler determines Wind Drift and Evaporation Losses (WDEL) using an empirical equation derived from all experiments in its data set (Robles et al., 2019). In this equation, WDEL depends on wind speed, air temperature, relative humidity, the operating pressure and the main and auxiliary diameter nozzles.

The drops landing on external boundary cells or flying above external cells directly contribute to drift outside the domain. These losses are denoted in the model as "additional drift", since WDEL empirical equations are obtained from experiments in which some drift losses are already included. In WDEL experiments the experimental sprinkler spacing is surrounded by buffer sprinkler spacings. As a consequence, in windy conditions, only small drops can be incorporated in the wind stream and drift away from the experimental area. Large drops drifting in and out of the experimental sprinkler spacing would compensate, since they can only drift for small distances. Additional drift can be relevant when the wind blows irrigation water from partial-circle sprinklers on a field boundary directly out of the field area.

2.4. Experimental sprinklers and their calibration

Four plastic sprinklers were used in this paper:

- VYR36 manufactured by VYRSA (Burgos, Spain). This is a full-circle impact sprinkler with brass nozzles, diameters 4.4 mm and 2.4 mm.
- VYR66 manufactured by VYRSA (Burgos, Spain). This is a partial-circle impact sprinkler with brass nozzles, diameters 4.0 mm and 2.4 mm.
- NDJ 5035 manufactured by NaanDanJain (Jalgaon, India). This is a full-circle impact sprinkler with plastic nozzles, diameters 4.5 and 2.5 mm.
- NDJ 5035SD manufactured by NaanDanJain (Jalgaon, India). This is a partial-circle impact sprinkler with a plastic nozzle, diameter 4.0 mm.

All sprinklers were parametrized using two types of experiments. Sprinkler NDJ 5035 was experimentally characterized by Paniagua (2016). The protocol used for the other three sprinklers is described in the following paragraphs.

The first type of experiments featured isolated sprinklers. The experiments for NDJ 5035 were performed under no-wind conditions at the outdoor facility of CITA-Aragón, while the experiments for the rest of sprinklers were performed at

CENTER, the Central Laboratory for Irrigation Equipment and Materials Testing, (San Fernando de Henares, Madrid, Ministry of Agriculture, Fisheries and Food, Government of Spain). Experiments were performed at 200, 300 and 400 kPa, measuring radial water application at 0.5 m spacing.

The second type of experiments, featuring overlapped sprinklers, was performed at the outdoor facility of EEAD-CSIC. In partial-circle sprinklers, two sprinklers irrigating 180° were arranged facing each other, separated by a distance of 18 m. Fifty catch cans were installed covering the area of 36 x 18 m between both sprinklers, with a spacing of 3.6 x 3.6 m. In full-circle experiments, a network of 16 sprinklers in a square 18 x 18 m arrangements was used. Twenty-five catch cans spaced 3.6 x 3.6 m were installed in the central spacing. Experiments were performed at 200, 300 and 400 kPa and variable wind speeds, with a minimum of 0.48 m s^{-1} and a maximum of 4.50 m s^{-1}.

Sprinkler parameters were determined from these experiments using the Multiple-Purpose Calibration and Optimization Tool (MPCOTool). This is a free calibration module that allows estimating the empirical parameters used in physical models once the objective function is defined (Burguete and Latorre, 2018). When applied to sprinkler parameter estimation, MPCOTool uses a combination of the Monte-Carlo, hill climbing and iterative method algorithms (Robles et al., 2019).

2.5. Experimental solid-set

An experimental solid-set was installed to validate model performance under controlled conditions. The solid-set had 24 sprinklers connected to a hydrant of the pressurized water distribution network of the EEAD-CSIC experimental farm. Full-circle sprinklers were VYR 36, while partial circle sprinklers were VYR 66. The field layout in the figure was prepared in EPANET. The figure shows the hydrant (represented as an elevated reservoir), the valve, the buried pipelines and the galvanized steel risers (depicted as short diagonal lines connecting the sprinklers to underground nodes). Four sprinkler spacings were used for experimentation, containing different types of sprinklers: full-circle and partial-circle (180° and 90°). Each experimental sprinkler spacing was equipped with a network of 5 x 5 catch-cans spaced 3.6 x 3.6 m. The main pipeline (horizontal in the Figure) had an azimuth of 129°. All sprinklers operated at 300 kPa.

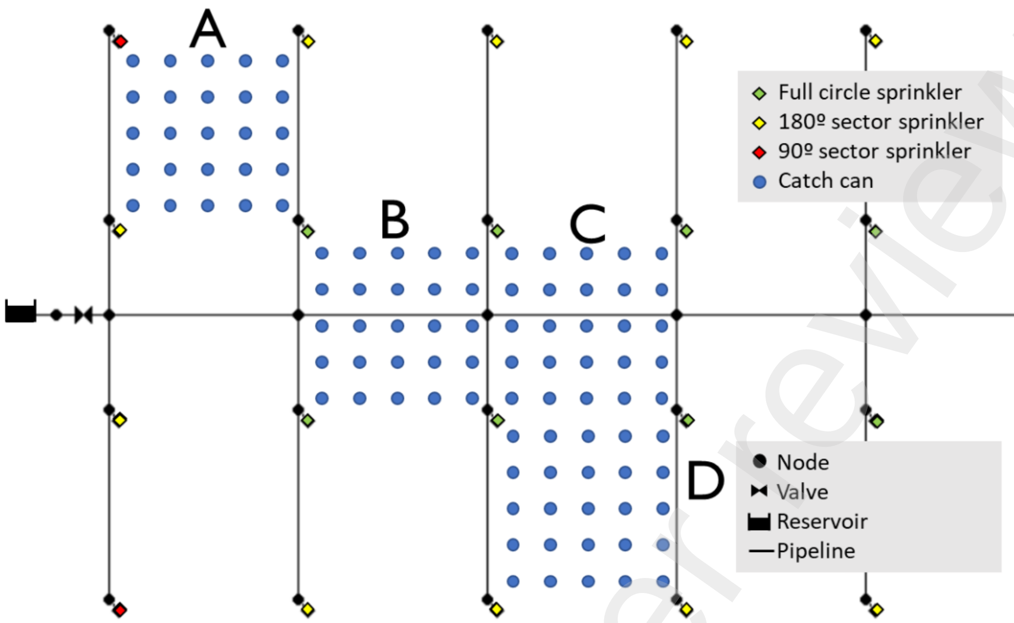


Figure 2. *Outline of the experimental solid-set. The sprinkler, pipeline, reservoir and valve layout reproduce the EPANET layout. The 25 catch-cans installed in sprinkler spacings A to D were located at the center of 3.6 x 3.6 m cells laid out between four sprinklers. Horizontal and vertical pipelines were buried 0.80 m deep. Short, diagonal pipelines represent the vertical sprinkler risers, running from 0.80 m below soil surface to 2.25 m above soil surface. The sprinkler spacing was square, 18 m in side.*

Three irrigation events were performed in the experimental solid-set (Table 1). Meteorological data were recorded at 30 min intervals and averaged for the Table. Vector averaging was used for wind speed/direction. Every irrigation event was reproduced as a succession of 30 min simulations, accumulating the precipitation received in each computational cell (coincident with each catch can). Observed and simulated precipitation in each catch-can and observed and simulated Coefficients of Uniformity (Christiansen, 1942) in each sprinkler spacing were compared to assess the predictive capacity of the model.

Table 1. *Duration and average meteorological variables of the three irrigation events in the experimental data set.*

Experiment	Duration (hours)	Air Temperature	Relative Humidity	Wind Speed	Wind Direction

		(°C)	(%)	$m\ s^{-1}$	(°)
VYR1	2.5	13.5	64.4	0.780	179
VYR2	3.0	18.4	45.5	0.253	176
VYR3	3.0	17.1	37.7	2.964	118

2.6. Commercial solid-set fields

Two commercial solid-sets were characterized to demonstrate the model capacities: the CA solid-set, located in Castejón del Puente (Huesca, Spain), and the ZA solid-set, located in Monzón (Huesca, Spain). As built construction plans were available for both solid-set fields, which were used to create the required EPANET files and the solid-set information used to run the model. This information was treated in QGIS (QGIS Development Team, 2023) to analyze information and to create thematic maps of the solid-sets. Figures 3 and 4 present the maps of the CA and ZA solid-sets, respectively, as outlined in EPANET.

CA is a 10.2 ha plot with an elevation difference of 25.5 m, irrigated from one hydrant located at the lowest part of the field. It is equipped with 315 full-circle VYR 36 sprinklers and 120 partial-circle VYR 66 sprinklers (28% of the sprinklers are partial-circle). The most common sprinkler spacing is triangular 18 x 18 m, although in the most elevated areas the spacing is triangular 15 x 18 (sprinklers separated 15 m within the line). The total number of sprinklers is 435, 43 sprinklers ha^{-1}. The field has 12 sectors (from sector 13 to sector 24). The number of pipelines is 999. The total length of the pipelines is 9.2 km, or 0,90 km ha^{-1}.

ZA is a 24.5 ha plot with an elevation difference of 17.1 m, irrigated from two hydrants (hydrant 1, 19,5 ha; hydrant 2, 5.0 ha) located at an intermediate elevation. It is equipped with 704 full-circle NDJ 5035 sprinklers and 195 partial-circle NDJ 5035SD sprinklers (22% of the sprinklers are partial-circle). The most common sprinkler spacing is triangular 18 x 18 m, although in the most elevated areas the spacing is triangular 18 x 15 (sprinkler lines separated 15 m). The total number of sprinklers is 899, 37 sprinklers ha^{-1}. The field has 26 sectors (sectors 1 to 6 irrigated from hydrant 2; sectors 7 to 26 irrigated from hydrant 1). The number of pipelines is 2,024. The total length of the pipelines is 20.2 km, or 0.82 km ha^{-1}.

Both solid-sets were built using a similar technique. The main pipes, extending from the hydrant to the valve of each sector, and the distribution pipelines within each sector were manufactured in PVC plastic using internal diameters from 59.2 to 188.2 mm. Sprinkler lines were generally manufactured in 1” Polyethylene, with an internal diameter of 28 mm. Sprinkler risers were manufactured in galvanized iron, with an internal diameter of 22 mm.

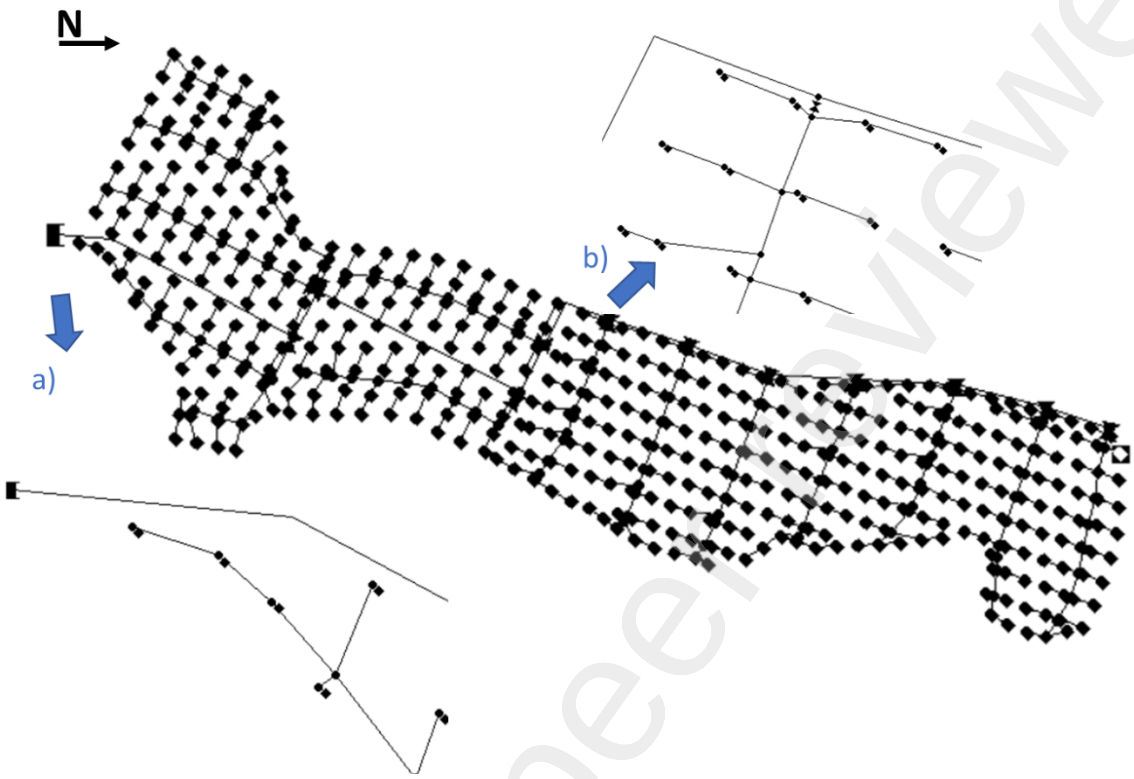


Figure 3. *EPANET layout of the CA solid-set field, with an irrigated area of 10.2 ha. A hydrant sequentially irrigates 12 sectors (one sector at a time). Two details are presented: a) the hydrant area; and b) the upstream part of sector 19 with its valve.*

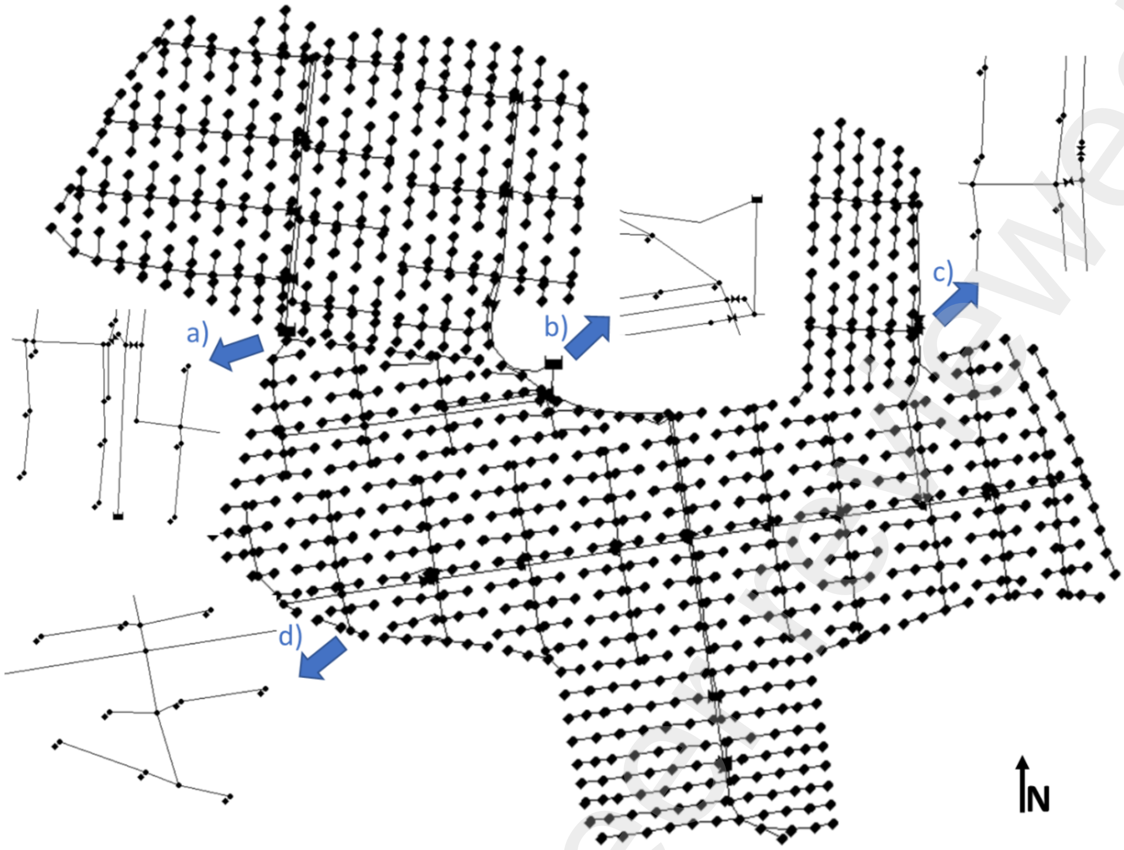


Figure 4. *EPANET layout of the ZA solid-set field, with an irrigated area of 24.5 ha. Two hydrants irrigate 5.0 and 19.5 ha. The first hydrant sequentially irrigates 6 sectors, while the second hydrant sequentially irrigates 10 pairs of sectors (26 sectors in total; up to three sectors at a time). Four details are presented: a) hydrant 2; b) hydrant 1; c) the valves of sectors 25 and 26; and d) pipelines connecting sprinklers in sector 12.*

Square computational cells with a size of 3.6 x 3.6 m were created in both solid-sets to accumulate irrigation water. A triangular 18 x 18 m sprinkler spacing fits 25 of these cells, the same number as catch cans in the experimental solid-sets. A total of 8,333 and 18,809 cells were created in CA and ZA, respectively. These cells are of types “internal” and “internal boundary”. The other two types of computational cells are automatically created by Ador-Sprinkler as needed.

2.7. Meteorological data

The commercial solid-sets are close to each other and to the nearest SiAR agrometeorological station: Selgua (Huesca). The data set for 2022 was used for simulation in CA and ZA, scheduling irrigation on August 1st (DOY 213). Figure 5 presents a plot of the key agrometeorological variables in that day: air temperature, relative humidity, wind speed and wind direction. August 1st was a hot and dry day with moderate winds during the day time and low winds during the night time. Moderate winds blew from the south, while low winds blew from the north.

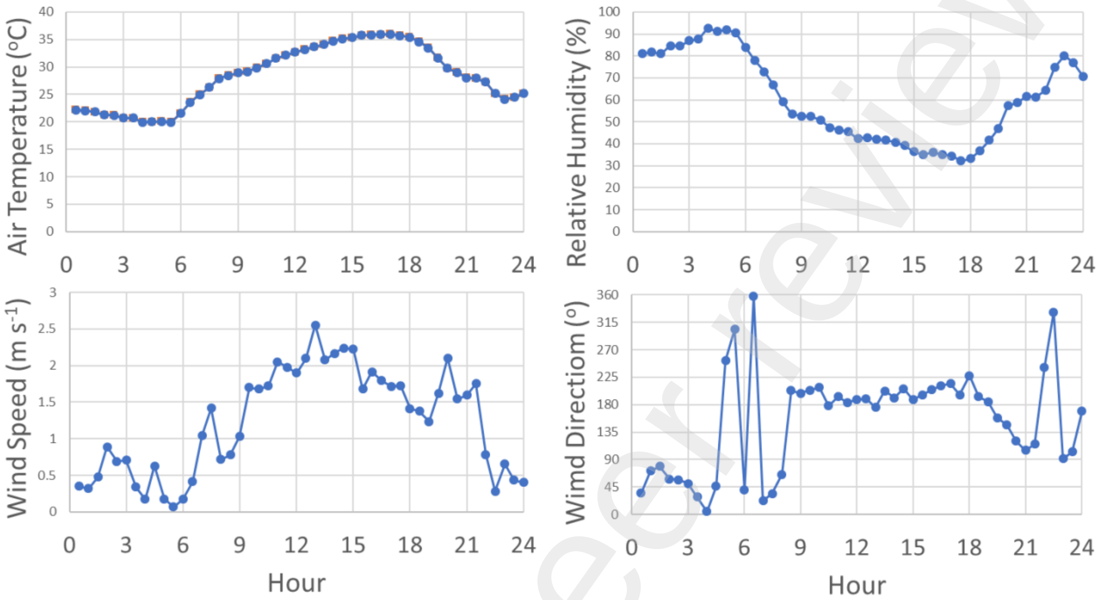


Figure 5. *Semi hourly evolution of air temperature (°C), relative humidity (%), wind speed (m s^{-1}) and wind direction (°) on August 1st 2022 (DOY 213) at the Selgua (Huesca, Spain) agro meteorological station.*

2.8. Scheduling irrigation

Irrigation can be scheduled in Ador-Solid-Set using a tool similar to commercial irrigation controllers. A number of irrigation programs can be created. Each program is characterized by a starting date and a final date, an interval (days) between program activations, the time of program start and a number of sequentially irrigated subprograms. Each subprogram can irrigate a number of field sectors for a number of minutes. When programs are intersected with the half-hour periods of meteorological information, subperiods can be created. Each subperiod has constant meteorological information and its duration is equal to or less than half hour. A given subprogram can be composed of a number of subperiods covering several half-hour intervals. Every subperiod is simulated with the ballistic routine. An irrigation event is created by the execution of an instance of a program. It involves one execution of all subperiods in each subprogram. The addition of the irrigation depth applied to every computational cell in all subperiods is the irrigation depth resulting from the irrigation event.

The August 1st irrigation event was scheduled in the following way:

- CA
  - Program 1
    - Starting at 0:00, ending at 24:00
    - Sequential irrigation of all sectors: from 13 to 24, 120 minutes each.
- ZA
  - Program 1
    - Starting at 0:00, ending at 12:00
    - Sequential irrigation of sectors 1 to 6. 120 minutes each
  - Program 2
    - Starting at 4:00, ending at 24:00
    - Sequential irrigation of sectors 9, 8, 7, 10, 11, 13, 12, 14, 15 and 16. 120 minutes each
  - Program 3
    - Starting at 4:00, ending at 24:00
    - Sequential irrigation of sectors 19, 26, 18, 25, 24, 23, 17, 22, 21 and 20. 120 minutes each

At the end of the day, all sectors have been irrigated for 120 min. The order of the sectors in programs 2 and 3 is dictated by the need to make the most of hydraulic energy. Program 2 irrigates sectors with high pressure (about 300 kPa), while program 3 irrigates sectors with low pressure (200-300 kPa). The coincidence in time of one sector from program 2 and another one from program 3 guarantees sufficient pressure in all cases. The order of the sectors also ensures that key pipelines are only used to irrigate one sector at a time, thus minimizing head losses.

2.9. Estimating roughness in the commercial solid-set fields

Gao (2017) presented a methodology for the estimation of roughness in hydraulic networks by using EPANET and minimizing the error in nodal pressure resulting from roughness estimates. A similar approach was used in this research, searching for the parameters that adequately parametrize EPANET to the characteristics of the CA and ZA solid-sets. The key parameter is the roughness of the different pipes. The Darcy-Weisbach roughness equation was selected, and experiments were performed to calibrate its parameter ε(mm).

Experiments were performed by simultaneously measuring pressure with calibrated manometers at two points of each pressurized network (1 network in CA, 2 networks in ZA): just downstream of the hydrant and at a sprinkler. All measurements were performed at maximum network pressure and 50 kPa below maximum pressure. A distal sprinkler of each sector (far downstream from the main pipes) was selected to characterize head losses when irrigating only this sector. Additionally, a proximal sprinkler (near the main pipelines) was selected to characterize head losses in the main pipelines. In CA, two sectors (13 and 14, located furthest from the hydrant) were open to characterize the main pipelines. In ZA, only sector 5 was open to characterize the main pipes of hydrant 2; two sectors were open to characterize the main pipes of hydrant 1 (12 / 13 and 23 / 24). As a result of these operations, 26 pairs of pressure observations were available for CA and 58 pairs of pressure observations were available for ZA.

A specific software (CaliNet) was written in C++ to determine the value of the objective function (O) in each solid-set field using EPANET simulations. The value depends on the tested value of the roughness parameter in each pipe (ε_i):

$$O(\varepsilon_{1,}\, \varepsilon_2 \ldots \varepsilon_{n,}) = \frac{\sum_{i=1}^{i=n} (P_M - P_S)^2}{n} \qquad [2]$$

Where n is the number of pipes and P is the pressure, which can be measured (M) or simulated (S) with EPANET using the hypothesis of the roughness parameters. The objective function is an error function. CaliNet was coupled to MPCOTool to obtain optimum values of ε for each pipeline. Seven hypotheses were explored regarding the values of ε:

- All pipelines in a network have the same roughness (1 parameter)
- There is a value for plastic pipes and another one for galvanized iron pipelines (2 parameters)
- There is a value for PVC pipes, another one for polyethylene pipes and another one for galvanized iron risers (3 parameters)

- There is a value for the main pipe, another one for all sectors and another one for galvanized iron risers (3 parameters)
- There is a value for the main pipe, another one each zone and another one for galvanized iron risers (5 parameters in CA, 7 parameters in ZA)
- There is a value for each pipeline diameter (10 parameters)
- There is a value for the main pipe, a value for each sector and a value for galvanized iron risers (14 parameters in CA, 28 parameters in ZA)

All hypotheses were tested in the search for the minimum value of the objective function in both solid-sets. In all cases, a minimum value of ε was set to 0.0015 mm, corresponding to plastic materials. This prevented unrealistic low values of roughness, even negative values.

2.10. Mapping water application and estimating irrigation performance

QGIS was used to map water application resulting from the simulated irrigation event in CA and ZA. The Coefficient of uniformity was used to characterize irrigation performance in each sector. The values of additional drift were analysed.

3. Results and discussions

3.1. Determination of ballistic sprinkler parameters

Tables 2 and 3 present the optimum irrigation parameters for each sprinkler model and operating pressure. Parameters K_1 and K_2 also depend on wind speed, starting from zero at zero wind speeds. Ador Sprinkler linearly interpolates all parameters for intermediate values of pressure and - if needed - wind speed (Playán et al., 2006).

Table 2. *Calibration parameters of the VYR sprinklers (full-circle and partial-circle models).*

Model	Pressure (kPa)	D_{50} (mm)	n -	Wind m s^{-1}	K_1 -	K_2 -
VYR36. Full-circle. 4.4 and 2.4 mm nozzles	200	2.74	1.11	0.00	0.000	0.000
				1.79	1.164	0.899
				2.29	0.180	0.982
				3.88	0.175	0.967
	300	1.72	1.61	0.00	0.000	0.000
				1.36	0.022	0.150
				3.55	0.027	0.875
	400	1.69	1.61	0.00	0.000	0.000
				0.48	0.157	0.130
				3.23	0.146	0.839
VYR66. Partial-circle. 4.0 and 2.4 mm nozzles	200	2.04	1.43	0.00	0.000	0.000
				1.28	0.233	0.070
				4.50	0.074	0.735
	300	1.58	1.73	0.00	0.000	0.000
				1.37	0.020	0.048
				3.61	0.233	0.342
	400	1.44	1.88	0.00	0.000	0.000
				1.15	0.161	0.137
				3.51	0.034	0.522

Table 3. *Calibration parameters of the NDJ sprinklers (full-circle and partial-circle models). Full-circle results were obtained by* Paniagua (2016).

Model	Pressure kPa	D_{50} mm	n -	Wind m s^{-1}	K_1	K_2
NDJ 5035. Full-circle. 4.5 and 2.5 mm nozzles	170	2.13	1.78	0.00	0.000	0.000
				0.74	0.076	0.117
				1.67	0.376	0.228
				2.67	0.209	0.139
	190	2.17	1.80	0.00	0.000	0.000
				0.88	0.644	0.132
				1.93	0.506	0.164
				2.75	0.179	0.242
				3.32	0.354	0.431
	210	1.98	1.89	0.00	0.000	0.000
				1.24	0.070	0.057
				1.91	0.351	0.096
				3.39	0.327	0.256
	300	1.79	2.03	0.00	0.000	0.000
				1.28	0.623	0.117
				1.97	0.829	0.144
				2.74	0.192	0.111
NDJ 5035SD. Partial-circle. 4.0 mm nozzle	200	2.10	1.95	0.00	0.000	0.000
				1.77	0.260	0.064
				4.08	0.061	0.263
	300	1.82	2.17	0.00	0.000	0.000
				1.38	0.239	0.130
				4.34	0.374	0.131
	400	1.62	2.30	0.00	0.000	0.000
				1.67	0.442	0.057
				2.93	0.527	0.048

3.2. Validation of the ballistic model in the experimental solid-set

Measured and simulated irrigation depth in the catch cans are presented in Figure 6 as a scatter plot. The regression line was y = 0.911 x + 2.01, with R^2 = 0.73***. The largest scatter was observed for experiment VYR3, the windiest of the series. In the local conditions, strong winds also showed high variability in speed and direction, which may not have been sufficiently revealed by the 30-minute averages. The large range in irrigation depth (roughly between 0 and 45 mm) is indicative of the existing variability. As a result, the values for CU were often low (Figure 7), particularly in the sprinkler spacings including partial-circle sprinklers. In experiments VYR1 and VYR2, with low and moderate winds, uniformity was close to 95%, while in VYR3 uniformity dropped to 65% in the sprinkler spacing with a 90° partial-circle sprinkler. The regression equation was y = 0.887 x + 6.55, with R^2 = 0.89***.

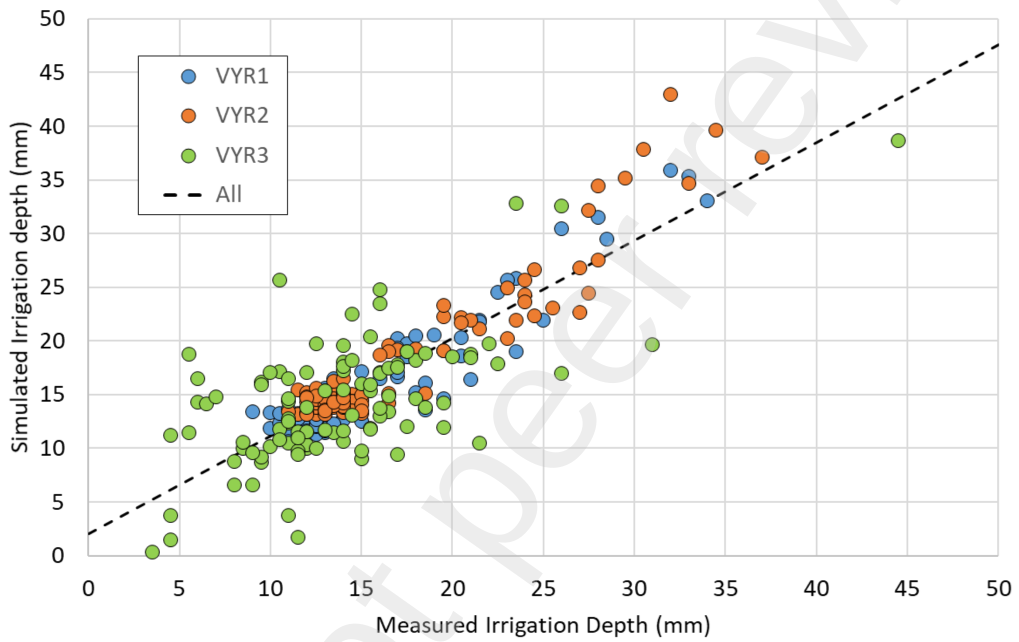


Figure 6. *Measured vs. simulated irrigation depth in the three solid-set experiments.*

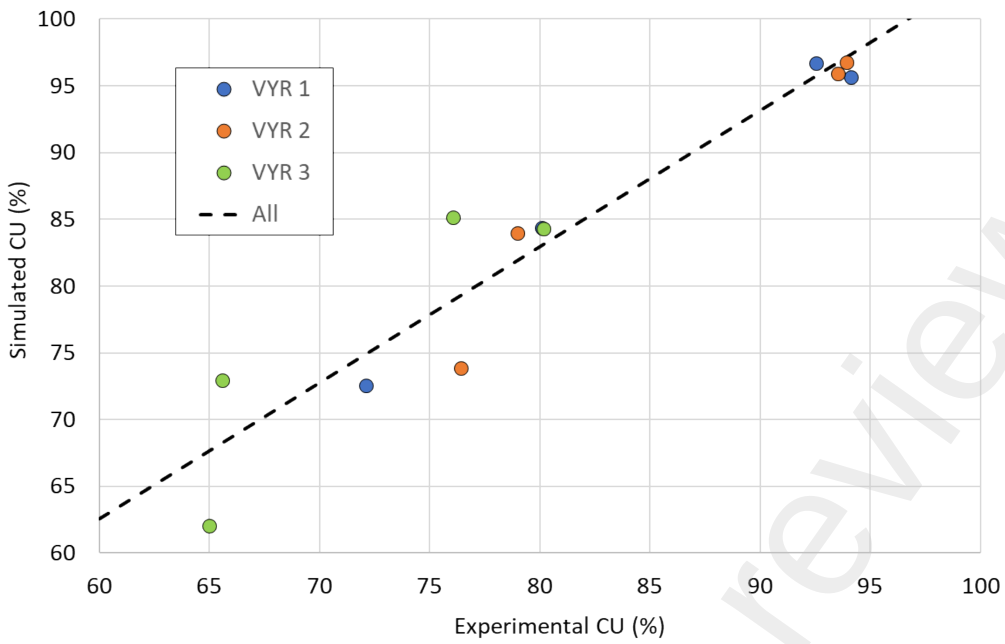


Figure 7. *Measured vs. simulated Coefficient of Uniformity in the four sprinkler spacings of the three solid-set experiments.*

3.3. Determination of pipeline roughness in the commercial solid-set fields

Results of the roughness optimization process are presented in Table 4. The first consideration is that the most complex model obtained the lowest values of error in both solid-sets. Consequently, a roughness parameter was used for the main pipes, another one for each sector and another for the sprinkler risers. This approach led to 14 parameters in CA and 28 in ZA. Optimizing these parameters required more than a million EPANET executions in each solid-set. The value of the error function was always higher in ZA than in CA, suggesting the ZA had more unexplained variability in observed pressure than CA. In fact, the collective pressurized network supplying water to ZA has a construction problem in the main pipeline (900 mm in diameter), and has had numerous fractures in the last years, resulting in mud and small gravel often flowing into the solid-set pipelines. The optimum value of the roughness parameters confirms that CA showed less roughness than ZA, with average ε values of 0.379 and 1.33 mm, respectively. Roughness was also less spatially variable in CA than in ZA, with standard deviations of 0.421 and 1.23 mm, respectively. From the optimization point of view, we did not expect that the most complex model would be selected. Such a complex model can adapt very well to the spatial variability in roughness, but we could not anticipate that the optimization tool would be able to identify such a large number of parameters, equal to half of the number of pairs of pressure observations.

Table 4. *Calibration of pipeline roughness in the commercial solid-set fields. Results of the seven calibration modes ordered by increasing error in both solid-set fields. The number of calibrated parameters (n) and the number of simulations are presented in all cases.*

CA Solid-Set Field				ZA Solid-Set Field			
Calibration mode	**n**	**Error (kPa)^2**	**Simulations**	**Calibration mode**	**n**	**Error (kPa)^2**	**Simulations**
Main / each sector / iron	14	34	1,081,344	Main / each sector / iron	28	202	1,048,576
Main / each zone / iron	5	88	74,240	Pipe diameters	10	357	524,288
Pipe diameters	10	114	734,600	Main / each zone / iron	7	419	296,960
Main / all sectors / Iron	3	143	19,096	PVC / PE / iron	3	523	19,096
Materials	2	149	4,704	Main / all sectors / iron	3	568	19,096
PVC / PE / Iron	3	149	19,096	Materials	2	619	4,704
All pipelines	1	192	712	All pipelines	1	619	712

Table 5. *Calibration of pipeline roughness in the commercial solid-set fields. Estimated value of Darcy-Weisbach ε (mm) for the main pipeline, each sector and the iron pipelines.*

CA Solid-Set Field		ZA Solid-Set Field			
Pipelines	**ε (mm)**	**Pipelines**	**ε (mm)**	**Pipelines**	**ε (mm)**
Main	0.0015	Main	1.233	Sector 14	0.043
Sector 13	0.363	Sector 1	0.987	Sector 15	1.130
Sector 14	1.072	Sector 2	0.353	Sector 16	2.117
Sector 15	0.834	Sector 3	0.102	Sector 17	1.904
Sector 16	1.027	Sector 4	0.422	Sector 18	3.957
Sector 17	0.946	Sector 5	0.094	Sector 19	2.839
Sector 18	0.138	Sector 6	2.498	Sector 20	0.553
Sector 19	0.565	Sector 7	0.317	Sector 21	0.276
Sector 20	0.209	Sector 8	0.186	Sector 22	0.654
Sector 21	0.0015	Sector 9	2.886	Sector 23	1.181
Sector 22	0.048	Sector 10	0.353	Sector 24	5.147
Sector 23	0.0015	Sector 11	0.415	Sector 25	2.308
Sector 24	0.042	Sector 12	0.236	Sector 26	3.988
Iron	0.060	Sector 13	0.002	Iron	1.136

3.4. Simulation of an irrigation event in the commercial sold-set fields

GIS processing of the information contained in the built solid-set projects permitted to prepare maps of soil surface elevation and irrigation sector for each computational cell. These maps are presented for CA and ZA in figures 8 and 9, respectively. The nearest sprinkler was attributed to each computational cell, creating a meandering effect on the sector boundaries.

EPANET files were prepared for each solid-set. This was a labor intense process, facilitated by importing nodal coordinates from the as built CAD solid-set map files. Pipelines were buried at 0.80 m, and risers set the sprinkler elevation at 2.20 m. Figures 3 and 4 present some details of the solid-set characterization in EPANET, including hydrants, valves and pipeline connections. Pressure downstream from the CA Hydrant was 438 kPa. In ZA, pressure downstream from Hydrant 1 was 305 kPa, while pressure downstream from Hydrant 2 was 311 kPa. These pressures are low, particularly considering the differences in elevation in both solid-sets. Sprinklers in the high spots of both fields often operated at pressures lower than 200 kPa.

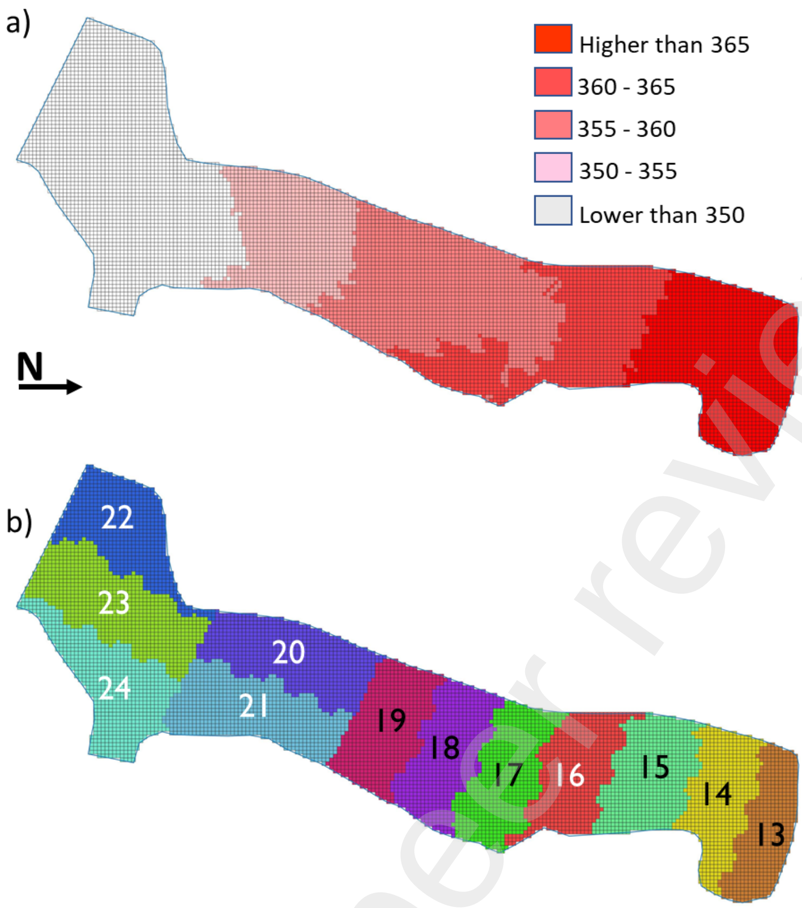


Figure 8. a) *Soil surface elevation above mean sea level (m); and b) irrigation sectors in the CA solid-set field. The plots represent these variables in the computational cells (3.6 x 3.6 m). The total difference in elevation is 25.5 m.*

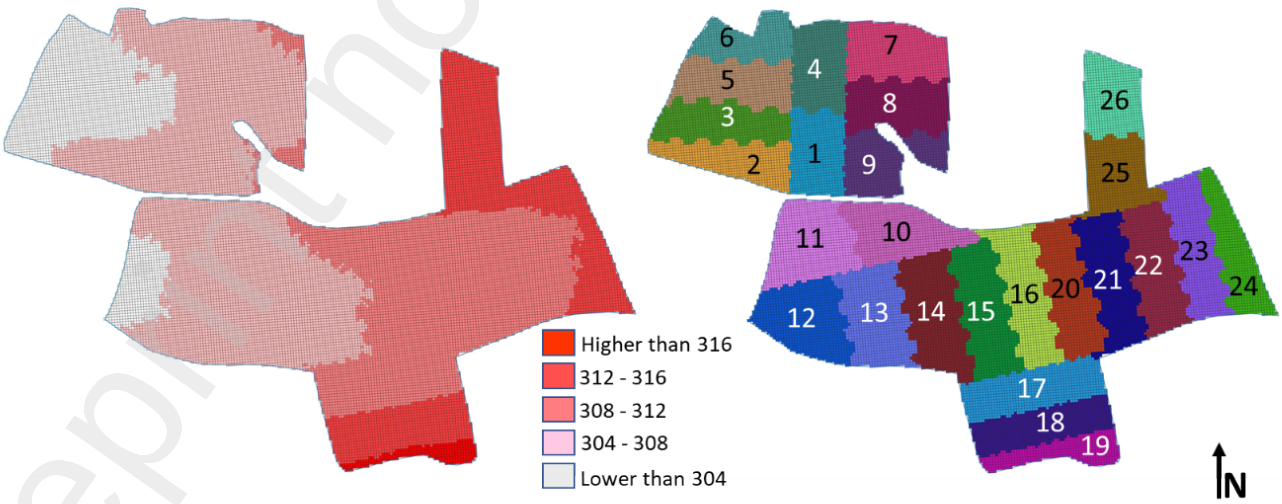


Figure 9. a) *Soil surface elevation above mean sea level (m); and b) irrigation sectors in the ZA solid-set field. The plots represent these variables in the computational cells (3.6 x 3.6 m). The total difference in elevation is 17.1 m.*

Figures 10 and 11 present the results of applying the irrigation schedule to the solid-set layout and the cell geometry for CA and ZA, respectively. Both figures show over irrigation at the boundaries, resulting from the large nozzle set of the partial-circle sprinklers when irrigating about 180° (the most common arrangement). When these sprinklers irrigate about 90° in corners, over irrigation is twice as intense.

Uniformity in CA was comparatively low in sectors 13 to 16 (Table 6, CU of 76-81%), where pressure is very low due to the high elevation and the long distance to the hydrant (although sprinkler spacing along the lines was reduced to 15 m in sectors 13 to 19). As irrigation progressed downhill, uniformity increased. In sectors 20 to 22, uniformity decreased due to the increased wind and to the accumulation of irrigation water in specific areas where sprinklers are too close. The evolution of WDEL along the day responded to the evolution of meteorological variables. Additional drift showed peak values in sectors 14 and 22. In both cases, the wind blew water out of the field: wind from the north blew water through the east side of sector 14, while wind from the south blew water through the west side of sector 22. The combination of local geometry and dominant winds determines the incidence of additional drift. Adding WDEL and additional drift, total WDEL reached a maximum value at sector 22 (24%). However, the CA average values were 13% for WDEL, 2.6% for additional drift and 16 for total WDEL. The whole-field CU was 81%, a value that is reasonable for field crops (Cuenca, 1989). However, this CU value corresponds to a complete solid-set, with wide pressure variations among sectors, meteorology variation along the day and different types of sprinklers. We do not believe that the threshold indicated by Cuenca (1989) can be readily applied to such a complex uniformity estimate.

The amount of water applied in ZA (Figure 11) followed the differences in soil surface elevation. The design of the highest sectors (18, 19, 25 and 26) reduced the distance between sprinkler lines, increasing water application. The amount of water applied by partial-circle sprinklers was not as different from that of full-circle sprinklers as it was in CA. In fact, nozzle diameters were smaller in ZA than in CA partial-circle sprinklers. Since there were up to three sectors irrigating at the same time, it is difficult to individualize the effect of meteorology on sector performance. Additional drift in ZA (Table 7) was maximum between 10 and 12 h (5.10%). The wind from the south blew water through the north side of sectors 6 and 10. Total WDEL reached its maximum value in this period (21.46%). The ZA average values were 12.06% for WDEL, 1.54% for additional drift and 13.61 for total WDEL. The whole-field CU was 81.01%

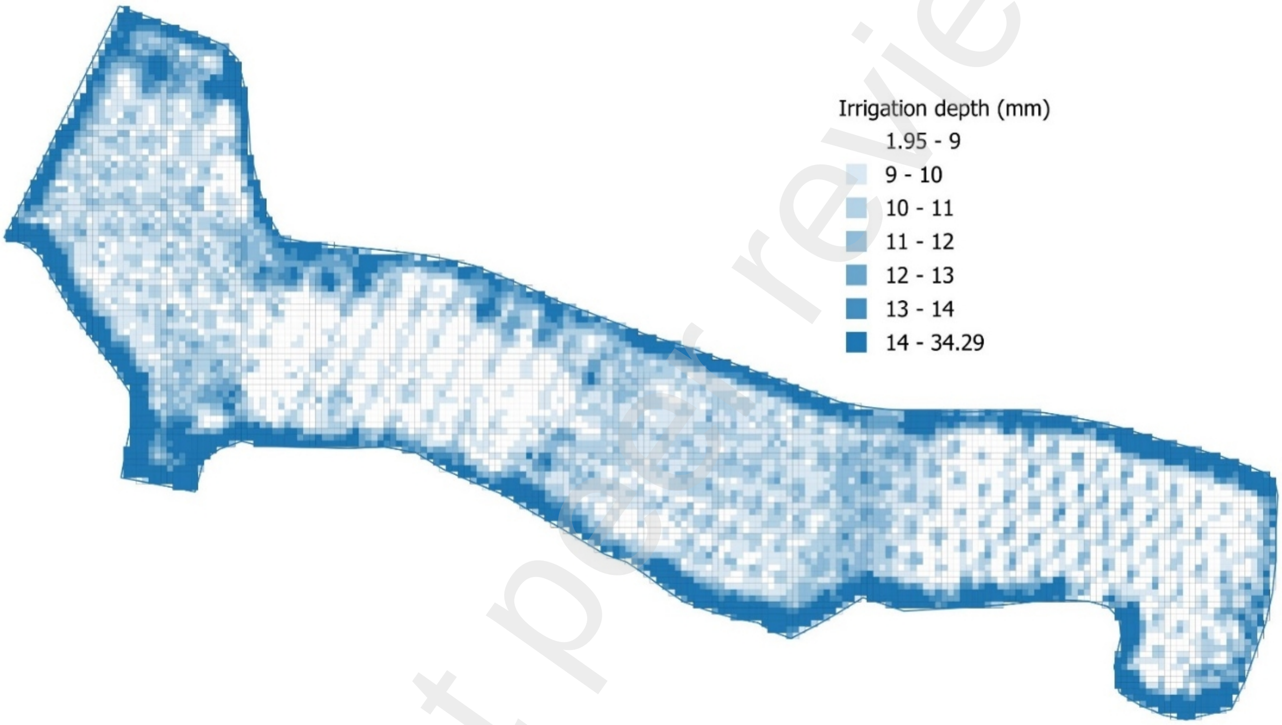
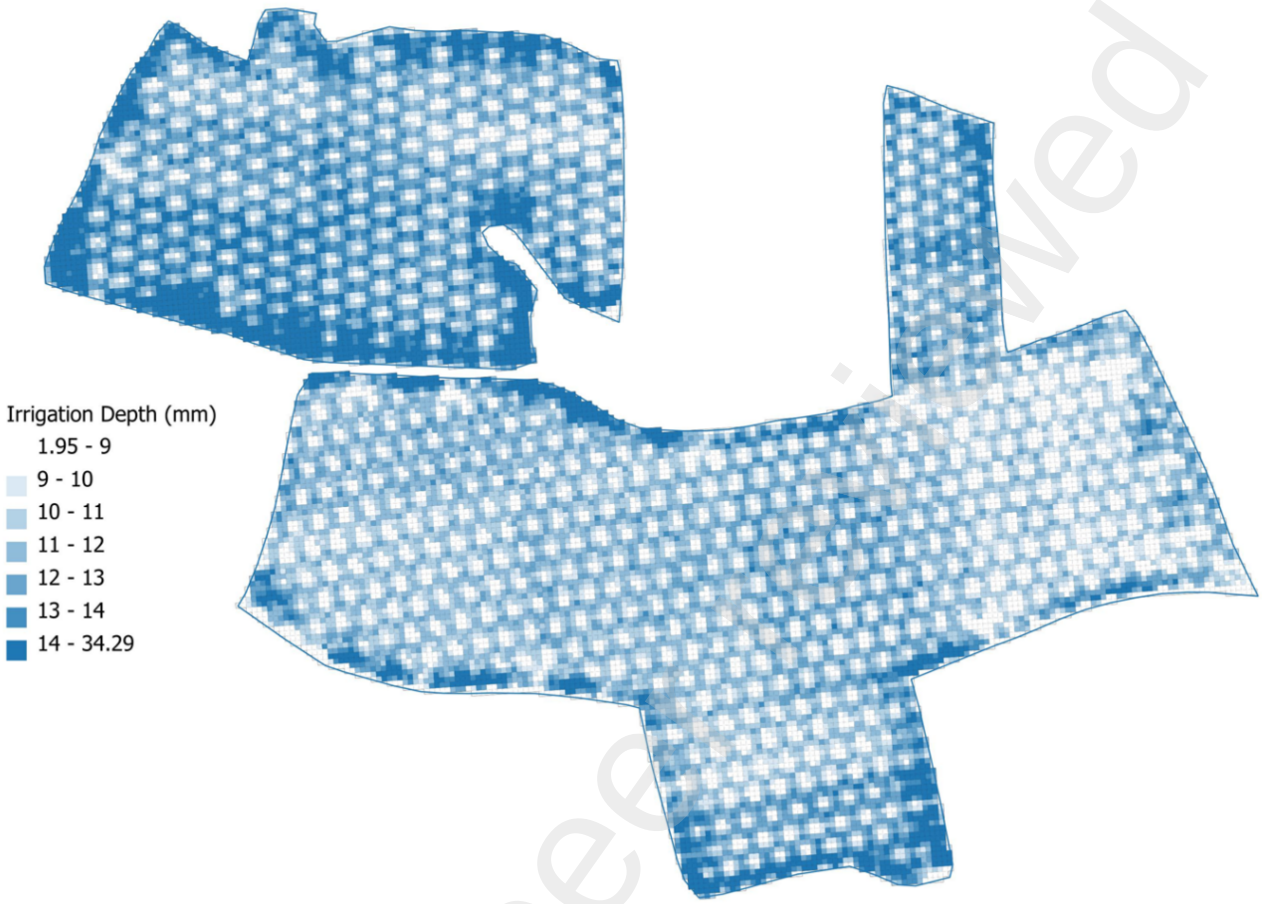


Figure 10. *Map of water application in the CA solid-set field.*



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660 **Figure 11**. *Map of water application in the ZA solid-set field.*

Table 6. *Irrigation performance indicators in CA. The following variables are presented for each 2-hour period: irrigating sector, CU, WDEL, additional drift and total WDEL.*

Hour	Sector irrigating	CU	WDEL	Additiona l Drift	Total WDEL
-	-	%	%	%	%
0-2	13	78.22	7.86	2.19	10.05
2-4	14	76.54	6.64	5.07	11.71
4-6	15	81.43	5.78	1.71	7.49
6-8	16	80.98	10.95	1.88	12.84
8-10	17	85.86	14.17	2.92	17.09
10-12	18	84.33	17.55	1.62	19.18
12-14	19	84.74	19.40	1.27	20.67
14-16	20	80.59	19.56	1.04	20.60
16-18	21	83.67	18.77	3.25	22.02
18-20	22	80.61	17.18	6.58	23.77
20-22	23	88.53	13.32	0.84	14.16
22-24	24	72.99	9.06	2.63	11.69

Table 7. *Irrigation performance indicators in ZA. The following variables are presented for each 2-hour period: irrigating sector, CU, WDEL, additional drift and total WDEL. Up to three sectors irrigate at the same time in this solid-set.*

Hour	Sector irrigating	CU	Sector irrigating	CU	Sector irrigatin g	CU	WDEL	Addition al Drift	Total WDEL
-	-	%	-	%	-	%	%	%	%
0-2	1	83.91					6.29	0.75	7.04
2-4	2	81.99					5.43	2.46	7.90
4-6	3	82.87	9	79.68	19	80.26	4.56	2.39	6.96
6-8	4	84.80	8	82.19	26	83.61	9.60	0.86	10.46
8-10	5	83.89	7	82.30	18	82.50	13.13	1.23	14.36
10-12	6	82.16	10	83.00	25	84.34	16.35	5.10	21.46
12-14			11	85.32	24	82.77	18.20	3.21	21.41
14-16			13	83.72	23	82.07	18.36	0.56	18.92
16-18			12	82.57	17	83.47	17.54	1.25	18.79
18-20			14	85.77	22	83.70	15.44	0.09	15.53
20-22			15	85.45	21	83.27	12.48	0.38	12.86
22-24			16	83.96	20	83.98	7.38	0.23	7.61

These simulations are exploratory in nature, and were designed to illustrate model capacities. Local farmers try to avoid irrigation from noon to 8 pm, increasing CU and decreasing WDEL. Additionally, scheduling irrigation by volume would reduce differences in irrigation depth among sectors.

Simulating irrigation in large solid-sets requires a large computational effort, particularly in the ballistic model. The Ador-Sprinkler library has been parallelized to take advantage of the large number of computational threads available in current personal computers. Running a seasonal simulation of ZA and CA will take a few minutes. The coupled nature of the model permits to perform unattended simulations once the solid-set and the sprinklers have been properly characterized. This is an important feature if the model is used to explore solutions or if it is run iteratively for optimization processes.

4. Conclusions

Solid-set models permit to progress from performance estimates based on a few sprinklers to field-scale performance. Irrigation uniformity indicators derived at this scale are conceptually different from those focusing on a few sprinklers. Uniformity thresholds in the literature need to be assessed for adequacy to the field-scale. This responds to the use of different types of sprinklers and to the presence of relevant spatial variability in pressure and relevant time variability in meteorology. The interaction between full- and partial-circle sprinklers can be evaluated using this type of models. The adequate choice of partial-circle models and their nozzle packages seems to be a key requirement for field-scale uniformity. In the analyzed commercial solid-sets, partial-circle sprinklers applied much more water than full circle sprinklers, lowering uniformity and leading to reduced efficiency. The proposed model has revealed a new, additional drift term. Field-scale models permit to assess the water blown away from the irrigation domain at the field boundaries. This has a relatively small quantitative effect, but can be relevant in specific sector geometries and winds, as well as during fertigation events. EPANET has permitted running complex hydraulic analyses with minimum effort *via* programming. Unfortunately, characterizing commercial solid-sets in EPANET remains a time-consuming process. The model needs to extend its capacities to address challenges related to water quantity and quality. Optimizing seasonal irrigation programming, estimating irrigation efficiency / crop yield and minimizing non-point agricultural pollution through adequate irrigation and fertilization are key issues for future developments. Farmers require directions to make their production processes clean, sustainable and profitable.

5. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

6. Acknowledgement

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