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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 irrigation modeling. In solid-set sprinkler irrigation, models have generally been applied to a few sprinklers in a regular arrangement, making them representative of a sector or a field. In this research, the Ador-Solid-Set model for whole-field solid-set sprinkler irrigation is presented, validated and applied to simulate an irrigation event in two fields: CA (10.2 ha) and ZA (24.5 ha), equipped with 12 and 26 sectors, respectively. The model couples pipeline hydraulics (EPANET), sprinkler ballistics and irrigation scheduling at execution time. Field experiments were used to validate the ballistic model in a solid-set combining full- and partial-circle sprinklers. Observed and simulated irrigation depths and coefficients of uniformity showed determination coefficients of 0.73*** and 0.89***, respectively. Optimization was used to estimate pipeline roughness based on pairs of pressure measurements (at the inlet and specific sprinklers): 26 pairs in CA and 58 pairs in ZA. Roughness parameters were estimated for the main pipeline, each sector and the sprinkler risers: 14 parameters in CA and 28 in ZA. More than a million hydraulic simulations were required to estimate roughness in each field. Maps were produced for applied water in CA and ZA following a sequential irrigation of their sectors lasting for 24 hours. The model produced whole-field coefficients of uniformity of 80.2 in CA and 80.9 in ZA. Finally, Ador-Solid-Set quantified the volume of drift outside the field (2.4 and 1.5% of the applied water in CA and ZA, respectively). This additional drift can be added to the wind drift and evaporation losses obtained from empirical equations, in a process that requires further analysis. Research efforts are also needed to enhance the current model capabilities and address the challenges related to water quantity and quality in sprinkler solid-sets.

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 1970 s, with the first applications for 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 1970 s (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 1980 s, but developments in numerical techniques and personal computers have made WinSRFR

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(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 1970 s, 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.

On-farm 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 under 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 full-circle 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 and moving laterals connected to a collective pressurized network (Zapata et al., 2023). These models have been coupled to soil – water – yield models, such as Ador-Crop (Dechmi et al., 2004a), to generate irrigation water 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 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 (5×5 in a square arrangement). The combination of experiments with different sprinkler types (full-cycle and partial cycle) and pressures, using 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 18×18 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.

de Andrade et al., (1999a), de Andrade et al., (1999b)) 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. 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 agricultural water management, 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., 2004a; 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 the elements of the WEFE Nexus (Water, Energy, Food and the Environment) (Udias et al., 2018) at the field scale. The proposed model can explore the relation between irrigation scheduling and crop yield, considering issues like the time variation of meteorology during the irrigation of a solid-set. The field irrigation time, which is often close to 24 hours, can be subjected to a large variation in wind speed and direction, temperature, humidity and solar radiation. These variables have been reported to affect irrigation performance and crop yield in solid-sets using approximations to the field scale (Tarjuelo et al., 1999; Dechmi et al., 2004b). Simulating low-pressure solid-set irrigation (Robles et al., 2017) at the field scale will lead to the identification of trade-offs between energy for pumping and the rest of WEFE variables.

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) an updated version of Ador-Sprinkler (a C++ ballistic sprinkler 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 their sequential operation. 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 meteorological conditions 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. Ador-Solid-Set, introduces field scale variability. The integration of these sources of variability represents a relevant step forward in the understanding of solid-set field performance.

Fig. 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.

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 air temperature, relative humidity, wind speed, wind direction, and solar radiation. 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 EPANET network physical component of the type reservoir is used to simulate a hydrant. A reservoir represents an infinite external source of water (Rossman et al., 1994). The reservoir hydraulic head is equal to the water source elevation. Pressure Head at the Reservoir (PHR, m) can be determined by subtracting the elevation of the reservoir base from the hydraulic head. When representing a hydrant, PHR is the hydraulic head at the hydrant, equal to the sum of the hydrant pressure and velocity heads. The pressure head at an irrigation hydrant is often between 98% and 99% of PHR. The water demand of the solid-set cannot modify PHR, which constitutes a boundary condition to the problem.
- Buried pipelines. Represented by the x, y, z coordinates of their extremes, their length, diameter and roughness, as well as the pipelines connected to their 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

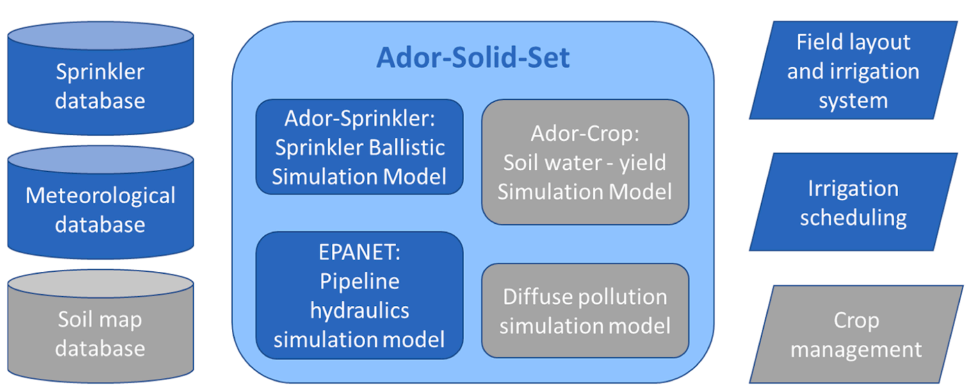

Fig. 1. Databases (left) submodels (center) and parametrization (right) of the Ador-Solid-Set model. The parts in grey represent ongoing model developments.

discharge (L s^{-1}) by the square root of the sprinkler pressure head (m):

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

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 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 sprinklers: reference (the same as the one used in EPANET), type (full or partial circle), coordinates, sprinkler model and nozzle diameters, 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 cell properties:

- Coordinates x, y, z of the cell center
- Field sector where the cell is located.
- Type of cell:
  - o External. Completely out of the perimeter. Drops reaching these cells interrupt their trajectory. Their volume adds to the estimation of drift.
  - o 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.
  - o 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).
  - o External boundary. Located just outside the perimeter, adjacent to an internal boundary cell. The drop trajectory is determined.

Robles et al. (2019) presented the determination of individual drop trajectories in Ador-Sprinkler, solving the governing equations with a third order Runge-Kutta scheme (Press et al., 1988). The irrigation simulations presented in this paper are 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 depth.

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.

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, 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. In the simulations we have added WDEL and additional drift to create a new variable, Total WDEL (%).

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 5035 SD 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 180º were arranged facing each other, separated by a distance of 18 m. Fifty catch cans were installed covering the area of 36 ×18 m between both sprinklers, with a spacing of 3.6 ×3.6 m. In full-circle experiments, a network of 16 sprinklers in a square 18 ×18 m arrangements was used. Twenty-five catch cans spaced 3.6 ×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), which estimates 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 Fig. 2 was prepared in EPANET. The figure shows the hydrant (represented in EPANET as a reservoir), the valve, the buried pipelines and the galvanized steel risers (depicted as short diagonal lines connecting the sprinklers to underground pipeline junctions). Four sprinkler spacings were used for experimentation, containing different types of sprinklers: full-circle and partial-circle (180º and 90º). Each experimental sprinkler spacing was equipped with a network of 5×5 catch-cans spaced 3.6 ×3.6 m. The main pipeline (horizontal in Fig. 2) had an azimuth of 129º. All sprinklers operated at 300 kPa.

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. Observed and simulated precipitation in each catch-can and observed and simulated Coefficients of Uniformity (Christiansen, 1942) in each sprinkler spacing were compared.

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). Figs. 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 18×18 m, although in the most elevated areas the spacing is triangular 15×18 (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 5035 SD sprinklers (22% of the sprinklers are partial-circle). The most common sprinkler spacing is triangular 18×18 m, although in the most elevated areas the spacing is triangular 18×15 (sprinkler lines separated 15 m). The total number of sprinklers is 899, 37 sprinklers ha^{-1}. The field has 26 sectors (sectors 1–6 irrigated from hydrant 2; sectors 7–26 irrigated from hydrant 1). The number of pipelines is 2024. 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 pipe, with an internal diameter of 28 mm. Sprinkler risers were manufactured in galvanized iron, with an internal diameter of 22 mm. Pipelines were buried at 0.80 m and risers set the sprinkler elevation at 2.20 m above the soil surface.

The typical hydrant pressure was reproduced for the simulation of the commercial solid-sets using the PHR (Reservoir Pressure Head) concept. PHR at the CA Hydrant was 44.7 m. In ZA, PHR at Hydrant 1 was 31.1 m, while PHR at Hydrant 2 was 31.7 m. These values of pressure plus velocity head downstream from the hydrants are low, particularly considering the uphill differences in elevation in both solid-sets. When EPANET was solved for these conditions, some sprinklers at the high spots of both fields often operated at pressures lower than 200 kPa.

Square computational cells with a size of 3.6 ×3.6 m were created in both solid-sets to accumulate irrigation water. A triangular 18×18 m sprinkler spacing fits 25 of these cells, the same number as catch cans in the experimental solid-sets. A total of 7865 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.

Maps of computational cells with different soil surface elevation and irrigation sector are presented for CA and ZA (Figs. 5 and 6, respectively). The nearest sprinkler was attributed to each computational cell, creating a meandering effect on the sector boundaries.

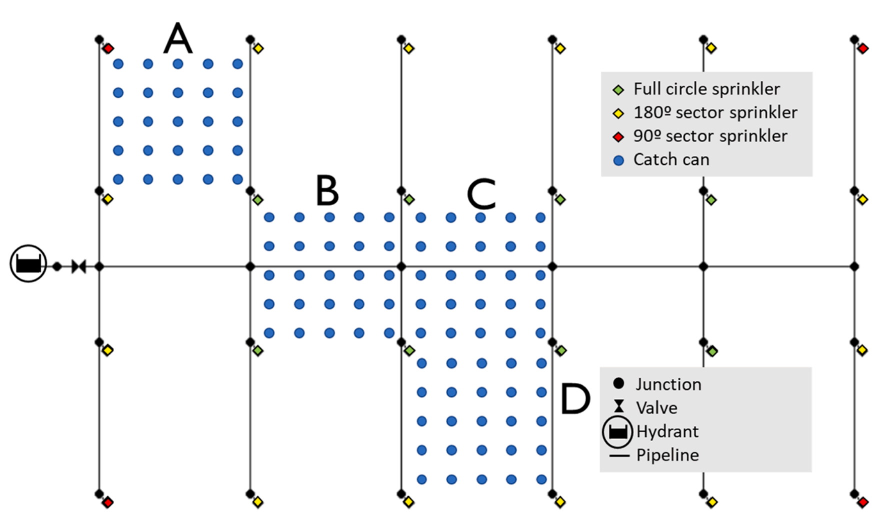

Fig. 2. Outline of the experimental solid-set. The sprinklers, pipelines, hydrant and valve layout reproduce the EPANET layout. The 25 catch-cans installed in sprinkler spacings A to D were located at the center of 3.6 ×3.6 m cells laid out between four sprinklers. Pipelines represented as horizontal and vertical lines 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.

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

Experiment	Duration (hours)	Air Temperature (°C)	Relative Humidity (%)	Wind Speed m s^{-1}	Wind Direction (°)
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

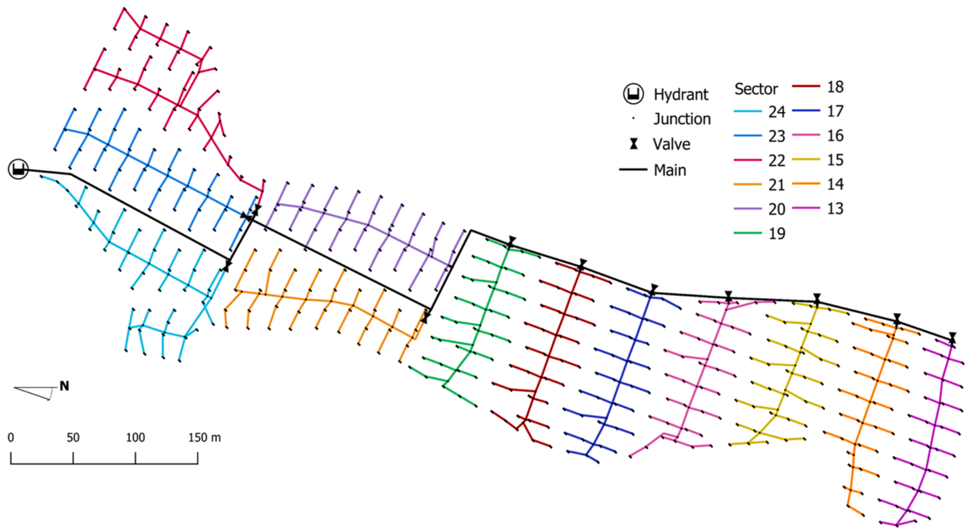

Fig. 3. EPANET layout of the CA solid-set field, with an irrigated area of 10.2 ha. A hydrant sequentially irrigates 12 sectors (numbers 13–24, one sector at a time). The main pipeline is presented in black. Sector pipelines are presented in different colors. A hydrant located on the south supplies water to the system. Each sector is connected to the main through a hydraulic valve. Junctions connect different pipelines and pipelines to sprinklers (through vertical riser pipelines).

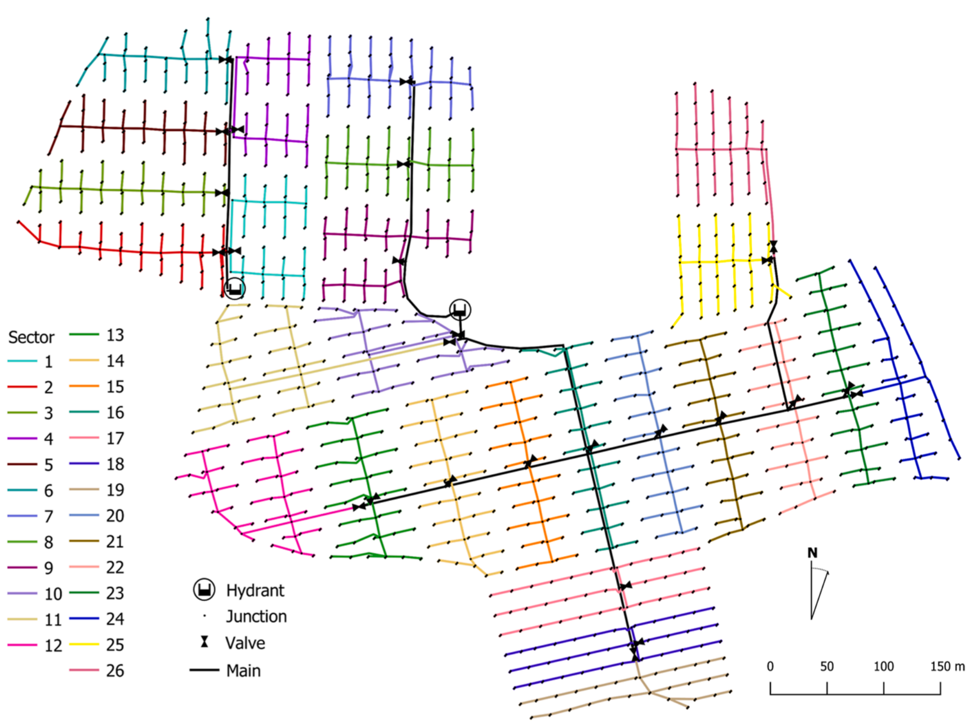

Fig. 4. EPANET layout of the ZA solid-set field, with an irrigated area of 24.5 ha. The field is divided in 26 sectors. Hydrants 2 and 1 irrigate different areas (5.0 ha divided in sectors 1–6 and 19.5 ha divided in sectors 7–26, respectively). Hydrant 2 sequentially irrigates its sectors, while hydrant 1 sequentially irrigates 10 pairs of sectors. As a consequence, up to three sectors can be irrigated at a time. The main pipelines are presented in black. Sector pipelines are presented in different colors. Each sector is connected to its main through a hydraulic valve. Junctions connect different pipelines and pipelines to sprinklers (through vertical riser pipelines).

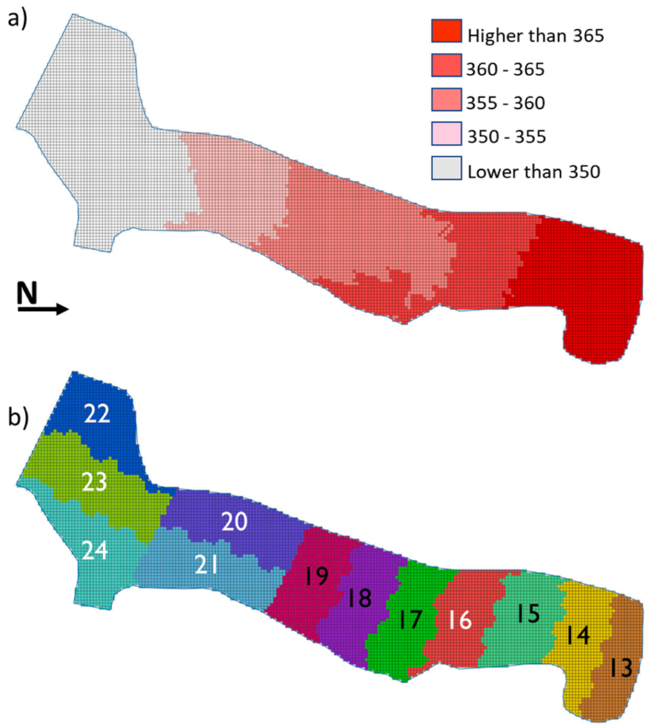

Fig. 5. a) Soil surface elevation above mean sea level (m); and b) irrigation sectors in the CA solid-set field. The plots represent these variables in the computational cells (3.6 ×3.6 m). The total difference in elevation is 25.5 m. Elevation at the hydrant is 345.31 m.

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). Fig. 7 presents a plot of the key agrometeorological variables in that day. 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.

2.8. Scheduling irrigation

Irrigation can be scheduled in Ador-Solid-Set using a tool similar to commercial irrigation controllers. Each program is characterized by a starting date and a final date, an interval (days) between program activations, the start 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 subprograms are intersected with the half-hour periods of meteorological information, subperiods can be created with a duration equal to or less than half hour. A given subprogram can be composed of a number of subperiods. Irrigation is simulated in subperiods using 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
  - o Program 1
    - ▪ Starting at 0:00, ending at 24:00
    - ▪ Sequential irrigation of all sectors: from 13 to 24, 120 minutes each.
- ZA
  - o Program 1
    - ▪ Starting at 0:00, ending at 12:00
    - ▪ Sequential irrigation of sectors 1–6. 120 minutes each
  - o 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
  - o 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 ZA programs 2 and 3 is dictated by the need to make the best use 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.

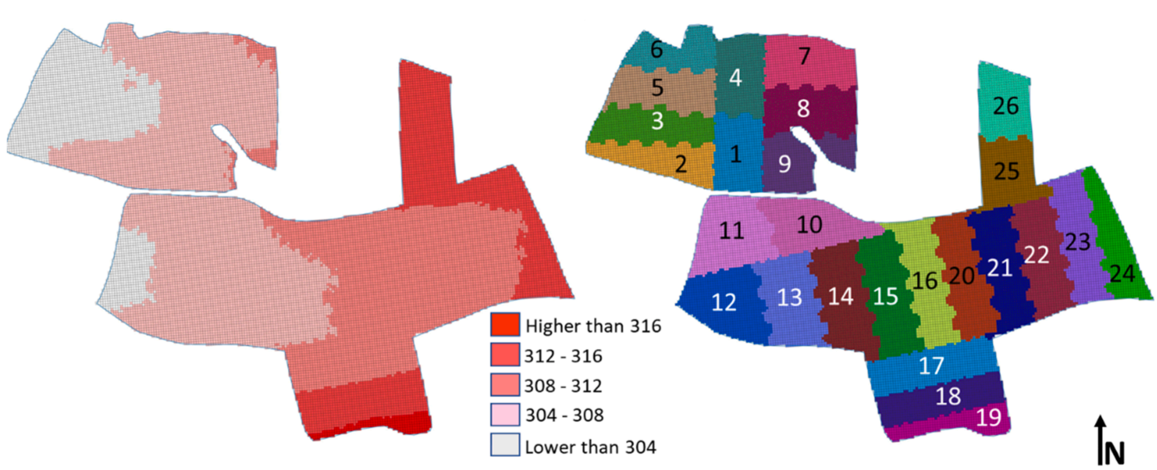

Fig. 6. a) Soil surface elevation above mean sea level (m); and b) irrigation sectors in the ZA solid-set field. The plots represent these variables in the computational cells (3.6 ×3.6 m). The total difference in elevation is 17.1 m. Elevation at hydrant 1 is 309.91 m and elevation at hydrant 2 is 310.30 m.

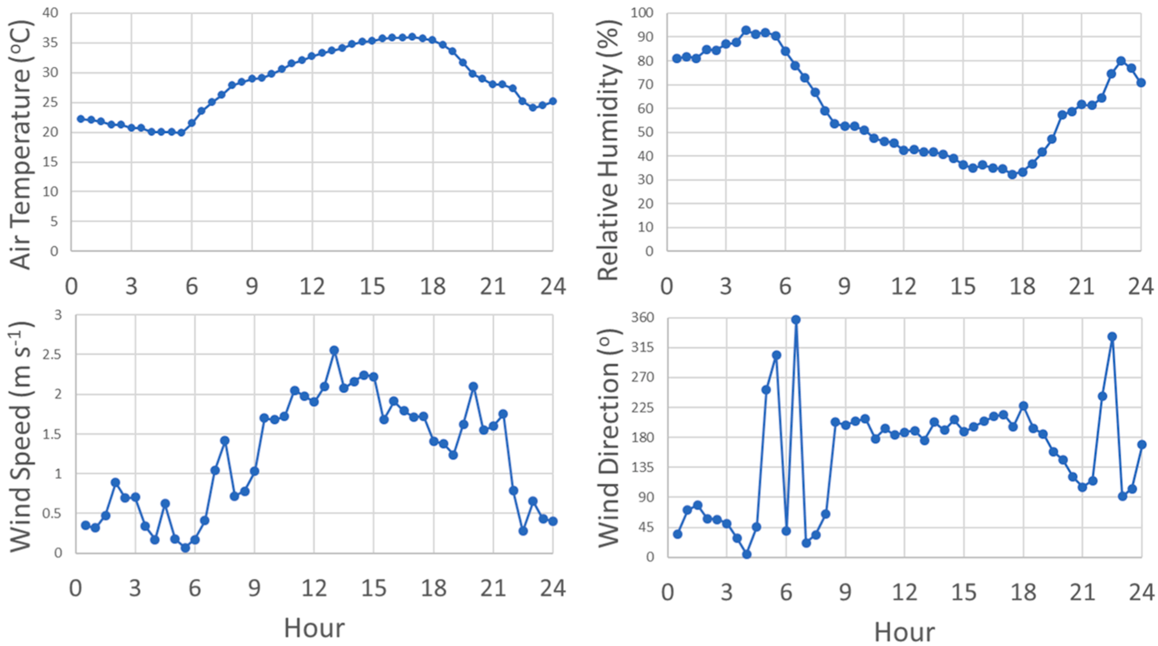

Fig. 7. Semi hourly evolution of air temperature (ºC), relative humidity (%), wind speed (m s^{-1}) and wind direction (º) on August 1st 2022 (DOY 213) at the Selgua (Huesca, Spain) agro meteorological station of the SIAR network.

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 in CA and ZA. 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 at each network (one network in CA, two networks in ZA) by opening one of the sectors and simultaneously measuring pressure with calibrated manometers at two points: just downstream the hydrant and at an irrigating sprinkler. All measurements were performed at maximum pressure at the hydrant and 50 kPa below maximum pressure. A distal sprinkler of each sector (far downstream from the main pipes) was selected to characterize head losses in each 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, two sectors were open to characterize the main pipes of hydrant 1 (12 / 13 and 23 / 24); only sector 5 was open to characterize the main pipes of hydrant 2. 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:

- CA Solid-Set:
  - o Sector pipelines characterization: 12 pairs of pressure observations at maximum pressure and 12 pairs at low pressure.
  - o Main pipelines characterization: 1 pair at maximum pressure and 1 pair at low pressure.
- ZA Solid-set:
  - o Sector pipelines characterization: 26 pairs of pressure observations at maximum pressure and 26 pairs at low pressure.
  - o Main pipelines characterization: Hydrant 1, 2 pairs of pressure observations at maximum pressure and 2 pairs at low pressure. Hydrant 2, 1 pair of pressure observations at maximum pressure and 1 pair at low pressure.

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 of O depends on the tested value of the roughness parameter in each pipe (ε_i):

$$O(\varepsilon_1, \varepsilon_2 \ldots \varepsilon_{n,}) = \frac{\sum_{i=1}^{i=n} (P_M - P_S)^2}{n} \quad [2]$$

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. CaliNet was coupled to MPCOTool to obtain optimum values of ε for each pipeline. Seven Calibration Modes were explored regarding the values of ε:

- CM1. All pipelines in a network have the same roughness (1 parameter)
- CM2. There is a value for plastic pipes and another one for galvanized iron pipelines (2 parameters)
  CM3. There is a value for PVC pipes, another one for polyethylene pipes and another one for galvanized iron risers (3 parameters)
- CM4. There is a value for the main pipe, another one for all sectors and another one for galvanized iron risers (3 parameters)
- CM5. 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)
- CM6. There is a value for each pipeline diameter (10 parameters)
- CM7. 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, even negative values of roughness.

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 5035 SD. 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. Results

3.1. Determination of sprinkler parameters

The emitter coefficient k (Eq. 1) was determined for sprinkler models VYR36, VYR66, NDJ 5035 and NDJ 5035 SD. The respective values were 0.0848, 0.0734, 0.0894 and 0.0540 L s^{-1} $m^{-0.5}$. Tables 2 and 3 present the optimum ballistic parameters for each sprinkler model and operating pressure (D_{50}, n, K_1 and K_2). 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).

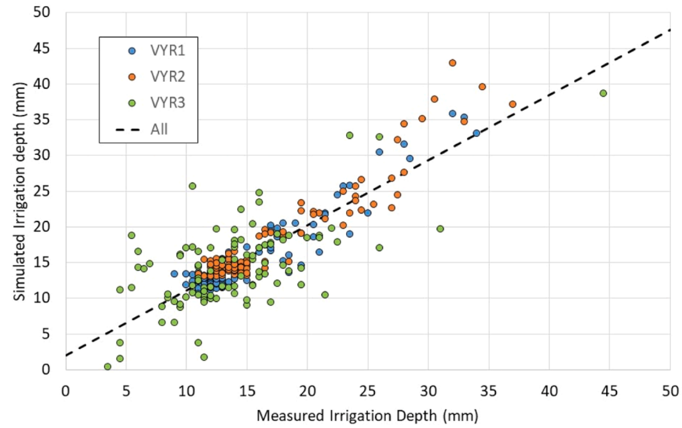

Fig. 8. Measured vs. simulated irrigation depth in the three solid-set experiments ($R^2 = 0.73$***).

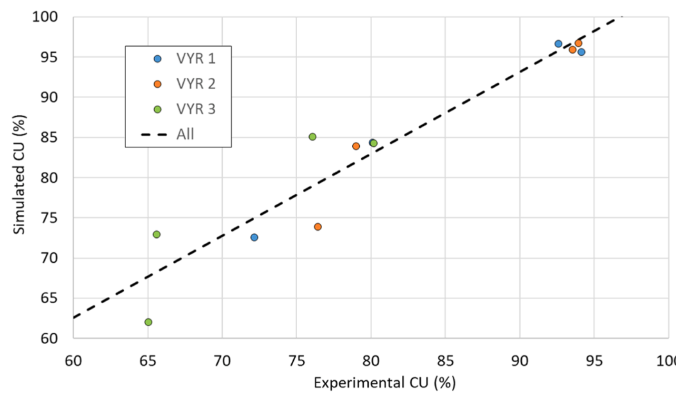

Fig. 9. Measured vs. simulated Coefficient of Uniformity in the four sprinkler spacings of the three solid-set experiments ($R^2 = 0.89$***).

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

Measured and simulated irrigation depth in the catch cans are presented in Fig. 8 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 (Fig. 9), 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 90º partial-circle sprinkler. The regression equation was y = 0.887 x + 6.55, with $R^2 = 0.89$***.

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

Results of the roughness optimization process are presented in Table 4. 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,

Table 4
Calibration of pipeline roughness in the solid-set fields. Results are presented for the seven calibration modes ordered by increasing error in both solid-set fields. The number of calibrated parameters (n) and the number of hydraulic 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
CM7 (Main / each sector / iron)	14	34	1081,344	CM7 (Main / each sector / iron)	28	202	1048,576
CM5 (Main / each zone / iron)	5	88	74,240	CM6 (Pipe diameters)	10	357	524,288
CM6 (Pipe diameters)	10	114	734,600	CM5 (Main / each zone / iron)	7	419	296,960
CM4 (Main / all sectors / iron)	3	143	19,096	CM3 (PVC / PE / iron)	3	523	19,096
CM2 (Plastic / iron)	2	149	4704	CM4 (Main / all sectors / iron)	3	568	19,096
CM3 (PVC / PE / iron)	3	149	19,096	CM2 (Plastic / iron)	2	619	4704
CM1 (All pipelines)	1	192	712	CM1 (All pipelines)	1	619	712

resulting in mud and small gravel often flowing into the solid-set pipelines. The optimum value of the roughness parameters (Table 5) 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.

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

Figs. 10 and 11 present the results of applying the hydrant conditions and irrigation schedule to the solid-set layout and the cell geometry for CA and ZA, respectively. Both figures show areas of large irrigation depths. This is particularly true at the field boundaries, resulting from the large nozzle set diameters of the partial-circle sprinklers when irrigating about 180º (the most common arrangement). When these sprinklers irrigate about 90º in corners, irrigation is twice as intense. Areas of relatively large and small irrigation depths are also appreciated near each sprinkler. The extension and intensity of these areas are modulated by wind speed and direction, as well as by sprinkler pressure. The average irrigation depth was 13.1 mm for CA and 10.7 mm for ZA (Table 6), with relevant variability between sectors in both fields.

Uniformity in CA was comparatively low in sectors 13–16 (Table 6, CU of 76.8–80.9%), 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 13–19). As irrigation progressed downhill, uniformity increased. In sectors 20–22, 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 (Table 7). 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. Total WDEL reached a maximum value at sector 22 (23.2%). However, the CA average values were 13.4% for WDEL, 2.4% for additional drift and 15.7% for Total WDEL. The whole-field CU was 80.2%, a value below the 84% threshold recommended for high-value crops (Keller and Bliesner, 1990).

Table 5
Calibration of pipeline roughness in the commercial solid-set fields. Estimated value of Darcy-Weisbachε(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

The amount of water applied in ZA (Fig. 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 (Table 6). 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, partial-circle sprinkler nozzle diameters were smaller in ZA than in CA. 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 8) was maximum between 10 and 12 h (5.1%). 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 (21.5%). The ZA average values were 12.1% for WDEL, 1.5% for additional drift and 13.6% for Total WDEL. The whole-field CU was 80.9%.

4. Discussion

The procedure used for the estimation of roughness was different than the one used by Morcillo et al. (2021). These authors used four pressure transducers located at different points of each sector, and compared pressure measurements and simulations for each of the two sectors. They used a pre-defined calibration model with three roughness parameters (main pipeline, secondary pipelines and sprinkler riser pipeline). In this paper, the optimization routine explored seven calibration models. The most complex model was selected in both fields, revealing a strong variability in roughness in both cases. Morcillo et al. (2021) calibrated two sectors with four sensors and a large number of measurements in one operating pressure. The solid-set fields used in this paper had a large number of sectors. We used a measurement point per sector, obtaining just two measurements per point, operating at two different pressures. The high number of potential roughness estimates required an optimization engine. The experimental conditions of both works are different, but the complexity of the roughness models suggests that roughness estimation is an important step in the hydraulic modeling of sprinkler irrigation solid sets. The convergence of the optimization problem supports the effectiveness of the method, as reported by Gao (2017).

Table 6 reveals a large variability in sector average irrigation depth, with coefficients of variation of 8.0% in CA and 11.7% in ZA. Sources of inter-sector variability include sprinkler density, the ratio between partial- and full-circle sprinklers and sprinkler operating pressure (largely due to differences in elevation). The fields used in this research had important internal elevation differences, which are partially

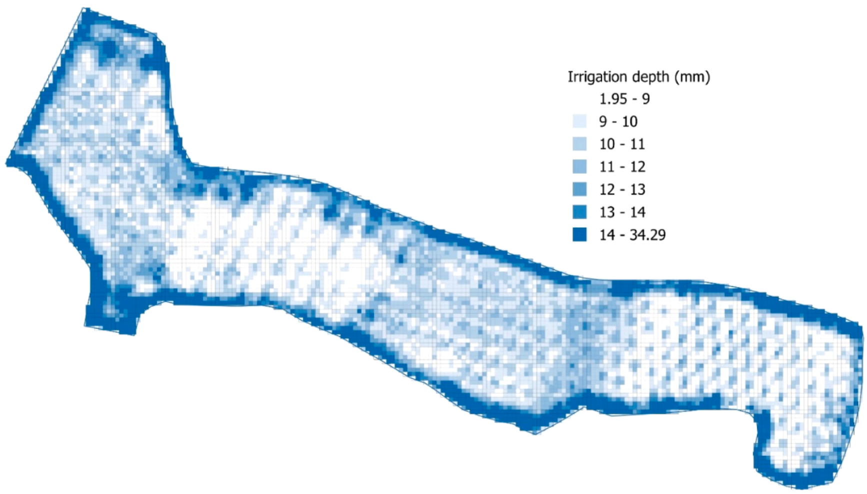

Fig. 10. Map of water application in the CA solid-set field. The average irrigation depth was 13.1 mm.

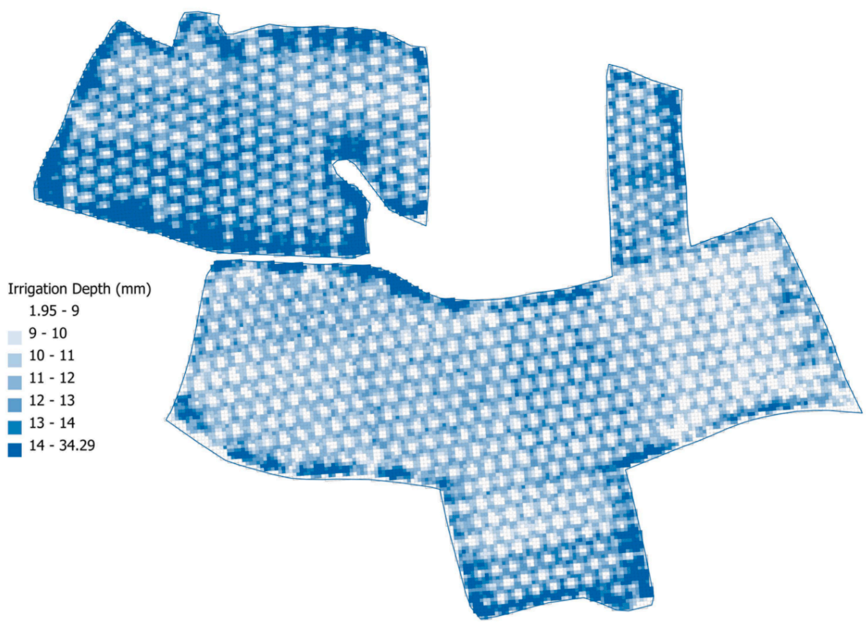

Fig. 11. Map of water application in the ZA solid-set field. The average irrigation depth was 10.7 mm.

Table 6
Selected irrigation performance indicators in CA and ZA. Irrigation depth (mm) and CU (Christiansen Coefficient of Uniformity, %).

CA			ZA					
Sector	Irrigation depth	CU	Sector	Irrigation depth	CU	Sector	Irrigation depth	CU
-	mm	%	-	mm	%	-	mm	%
13	13.2	78.1	1	12.2	84.0	14	10.1	84.8
14	12.8	76.8	2	13.8	82.2	15	9.8	85.3
15	12.4	80.6	3	12.4	82.8	16	10.4	83.7
16	13.5	80.9	4	11.3	84.2	17	9.7	82.8
17	13.2	85.9	5	11.2	83.8	18	11.2	82.1
18	12.9	84.4	6	11.4	81.9	19	13.0	79.0
19	13.2	85.1	7	10.8	82.0	20	10.6	84.2
20	12.1	80.6	8	10.9	82.4	21	9.8	83.2
21	11.8	83.4	9	12.7	78.8	22	8.7	82.6
22	14.0	80.2	10	11.2	82.3	23	8.9	81.2
23	12.4	88.6	11	10.2	84.7	24	9.5	80.2
24	15.8	72.7	12	9.7	80.8	25	10.6	83.3
-	-	-	13	9.7	82.3	26	11.3	82.2
Field	13.1	80.2	Feld Irrigation depth: 10.7 mm; Field CU: 80.9%					

Table 7
Irrigation performance indicators in CA. The following variables are presented for each 2-hour period: irrigating sector, WDEL, additional drift and total WDEL.

Hour	Sector irrigating	WDEL	Additional Drift	Total WDEL
-	Program 1	%	%	%
0–2	13	7.9	2.1	9.9
2–4	14	6.6	4.9	11.6
4–6	15	5.8	1.2	6.9
6–8	16	11.0	1.7	12.7
8–10	17	14.2	2.8	17.0
10–12	18	17.6	1.3	18.9
12–14	19	19.4	1.0	20.4
14–16	20	19.6	0.9	20.5
16–18	21	18.8	3.0	21.8
18–20	22	17.2	6.0	23.2
20–22	23	13.3	0.7	14.0
22–24	24	9.1	2.7	11.6
Average	-	13.4	2.6	15.9

responsible for the differences in irrigation depth. However, the sprinkler spacing was reduced at the highest sectors during the construction of both solid-sets to reduce inter-sector differences in irrigation depth and ensure adequate performance at low pressures. The duration of irrigation at each sector could be adjusted to reduce the observed differences. This would increase whole-field irrigation uniformity and efficiency. In CA and ZA, Irrigation scheduling by fixed volume would be more adequate than scheduling by fixed time.

The simulated value for whole-field uniformity in CA was 80.2. This value corresponds to the sequential irrigation of 12 sectors during 24 hours. The experiments reported in Table 1 (VYR1, VYR2 and VYR3) used the same sprinkler models as in the CA solid-set. Wind speed, the critical environmental variable affecting the uniformity of sprinkler solid-sets (Tarjuelo et al., 1999), was similar in both cases. The average wind speed during the experiments was 1.33 m s ^{1}, while the average wind speed during the simulated irrigation of CA was 1.23 m s^{-1}. As a consequence, the experimental uniformity can be used as approximation to the uniformity of the CA solid-set. The average experimental uniformity in full-circle sprinkler spacings (B and C in Fig. 2) was 88.4%, much higher than the simulation. When the uniformity of all four experimental sprinkler spacings was considered (including 31% of partial-circle sprinklers, when CA has 28% of partial-circle sprinklers), uniformity dropped to 80.7%, very similar to the simulated value. This confirms the importance of considering the relevant sources of variability in irrigation depth in solid-set fields, as Ador-Solid-Set model does. On the other hand, simulated CU corresponds to a complete solid-set, with wide pressure variations among sectors, meteorology variation along the day and different types of sprinklers. We believe that recommended uniformity thresholds, such as the one indicated by Keller and Bliesner (1990), may not be of application to the solid-sets analyzed in this paper, since solid-set irrigation evaluations have traditionally been applied to simplifications of commercial fields (for instance, avoiding partial-circle sprinklers). As a consequence, whole field uniformity thresholds could be reassessed with a wider consideration of the sources of variability of irrigation depth. This responds to the use of different types of sprinklers and to the presence of relevant spatial variability in pressure and time variability in meteorology. The adequate choice of partial-circle models and their nozzle packages in commercial solid-sets seems to be a key requirement for field-scale uniformity. In CA and ZA, partial-circle sprinklers applied much more irrigation depth than full circle sprinklers, lowering field-scale uniformity.

The proposed model permitted to gain a different perspective on WDEL. The current empirical models explain up to 81% of data sets composed by experiments performed by different research groups (Aminpour et al., 2023). However, WDEL experiments are typically performed in fully overlapped sprinkler spacings, where all water eventually reaching the soil surface is accounted for as irrigation depth. This is not the situation when a sprinkler is located at or near the field boundary, since a fraction of the water reaching the soil surface will not be inside the field. This water landing outside the field – additional drift – adds to Total WDEL. The proposed model has exposed this process and has led to its quantification. The combination of local geometry and dominant winds determines the incidence of additional drift. The average of CA and ZA additional drift, 2.0%, is a relevant amount of water. This is particularly important from the point of view of hydrology, since WDEL losses are highly consumptive (Martínez-Cob et al., 2008).

The simulations above are exploratory in nature, and were designed to illustrate the capacities of Ador-Solid-Set. Simulating irrigation in large solid-sets requires a large computational effort, particularly in the ballistic model. The proposed model executes this model in real time, while the model by Morcillo et al. (2021) extracts the required solution from a collection of previous simulations stored in a database. The proposed model is much more computationally intense, although its solutions are more adapted to each situation in field geometry (i.e., irrigation angle of partial-circle sprinklers), hydraulics and meteorology. The Ador-Sprinkler library has been parallelized to accelerate computations taking 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. Optimization is a clear destination of the model, in order to address the WEFE questions leading to sustainable and productive solid-set irrigation.

Table 8
Irrigation performance indicators in ZA. The following variables are presented for each 2-hour period: irrigating sector(s), WDEL, additional drift and total WDEL. Up to three sectors irrigate at the same time in this solid-set.

Hour	Sector irrigating	Sector irrigating	Sector irrigating	WDEL	Additional Drift	Total WDEL
-	Program 1	Program 2	Program 3	%	%	%
0–2	1			6.3	0.8	7.0
2–4	2			5.4	2.5	7.9
4–6	3	9	19	4.6	2.4	7.0
6–8	4	8	26	9.6	0.9	10.5
8–10	5	7	18	13.1	1.2	14.4
10–12	6	10	25	16.4	5.1	21.5
12–14		11	24	18.2	3.2	21.4
14–16		13	23	18.4	0.6	18.9
16–18		12	17	17.5	1.3	18.8
18–20		14	22	15.4	0.1	15.5
20–22		15	21	12.5	0.4	12.9
22–24		16	20	7.4	0.2	7.6
Average	-	-	-	12.1	1.5	13.6

5. 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 (usually full-circle) sprinklers. Uniformity thresholds in the literature need to be assessed for applicability to the field-scale. 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.

CRediT authorship contribution statement

Javier Burguete: Writing – review & editing, Writing – original draft, Investigation, Data curation, Conceptualization. **María Angeles Lorenzo:** Software, Methodology, Investigation. **Enrique Playán:** Writing – original draft, Software, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Nery Zapata:** Writing – review & editing, Methodology, Funding acquisition, Formal analysis. **Piluca Paniagua:** Investigation. **Eva T. Medina:** Investigation. **Borja Latorre:** Writing – review & editing, Software, Conceptualization. **José Cavero:** Writing – review & editing, Investigation.

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.

Data Availability

Data will be made available on request.

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