Simulation of a collective solid-set sprinkler irrigation controller for optimum water productivity

by

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Abstract

The modernization of irrigation districts in Spain is based on the construction of collective pressurized networks equipped with remote control systems. In this paper, a simulation approach is used to explore the benefits of introducing a collective solid-set irrigation control software. The controller works in combination with a district management database, real time evapotranspiration and meteorology information and a remote control system. Controller decisions are based on the simulation of sprinkler irrigation performance and on crop water balance. The decision to irrigate a plot can be guided by the use of two simulation parameters: the estimated application efficiency of the irrigation event (heavily affected by wind speed) and a crop water stress index. Simulation experiments were performed in a district located at the Ebro basin of Spain. The collective controller resulted in water conservation (respect to the current situation) of 2,234 and 4,664 m³ ha⁻¹ for corn and alfalfa, respectively, and in an increase in water productivity of up to 91%. Although additional research is needed to produce a reliable collective controller, these preliminary results are encouraging.

Keywords: Irrigation Scheduling, Solid-Set Sprinkler, Ballistic Simulation, District, Automation.

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Introduction

The modernization of irrigated areas in Spain will reach about one fourth of the National irrigated area after a one-decade effort that started with the 21st century. A typical Spanish modernization project focuses on a whole irrigation district, and replaces surface irrigation structures with a collective pressurized network operating on demand. On-farm irrigation systems are oriented to either drip or sprinkler irrigation, depending on the productive orientation of the area. The vast majority of sprinkler modernization irrigation projects implement solid-sets. The social tradition of irrigation in Spain has resulted in a fragmented land tenure structure which is rarely adapted to pivot irrigation. Labor cost and scarcity prevent installation of hand-move sprinkler systems. While the public sector promotes modernization projects in order to conserve water quantity and quality, farmers see modernization as an opportunity to adapt to the new socioeconomic context.

Fifteen years ago, irrigation controllers were scarce in Spanish sprinkler irrigated districts (Dechmi et al., 2003). Irrigation was manually operated, frequently using long irrigation times (8-12 hours). At the time, farmers were satisfied because sprinkler irrigation labor requirements were lower than local surface irrigation requirements. By the turn of the century labor became a scarce resource in Spain, particularly in rural areas. Farmers then widely adopted irrigation controllers as the solution to the labor crisis and as a way to improve crop yield (through frequent, short irrigations). As the economic return from field crops decreased in the last years, farmers saw an opportunity in increasing the size of their farming operations leasing modernized sprinkler irrigated land. As a consequence, farmers had to program a number of controllers. In this circumstance, controllers became a problem more than a solution, and farmers often maintained their irrigation schedules even if the conditions changed. This has resulted particularly problematic in areas like the Ebro basin, where spells of strong winds require quick action on the part of the farmer to avoid poor irrigation performance (Dechmi et al., 2004b).

Modernization projects represent an opportunity to tackle these problems. Since these projects are promoted by the Government and include a long-term financing scheme, farmers have to accept a number of conditions. Among them is the need to install a remote control system that permits to open and close all network valves from the district office. The combination of remote control hardware and real-time meteorology

59 and crop water requirements information via a district-wide irrigation scheduling
60 software could result in an automation of the entire irrigation district operation. Such a
61 system could dramatically reduce the labor input and at the same time conserve water,
62 ensure high yields and optimize water productivity by timely providing crop water
63 requirements, avoiding unsuitable periods for irrigation (i.e., high winds), and
64 adjusting the irrigation level to the economic conditions of the crop.

65 The scientific literature does not show previous efforts in collective irrigation
66 controllers. Automatic irrigation controllers have been designed for individual water
67 users using ET broadcasting (Devitt et al. 2008) or soil water measurements (Blonquist
68 et al., 2006). Most of the commercial applications of such technologies focus on
69 residential water use, due to its high economic return. Irrigation scheduling
70 applications focusing on collective irrigation are not conceived as real-time controllers,
71 but as planning tools (Mateos et al., 2002; Fortes et al., 2005).

72 Developing a collective irrigation controller is a complicated research and development
73 task. In this paper we present a simulation exercise based on real data from the Ebro
74 basin in Spain which is aimed at providing insight on the possibilities of such
75 technology and on its benefits to agricultural water management. The specific
76 objectives of the paper are: 1) to characterize an irrigation district to be used as a
77 simulation training area; 2) to develop a model for district wide solid-set irrigation
78 scheduling ready for implementation in real-time controllers; and 3) to apply this
79 model to the simulation of seasonal operations in collective irrigation, to the calibration
80 of decision parameters and to the assessment of the possibilities for water conservation
81 and productivity enhancement.

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Characterization of the study areas

The Montesnegros Irrigation District (MID)

The MID includes part of the *La Almolza*, *Bujaraloz*, *Peñalba* and *Valfarta* municipalities (41°31' N, 0°10' W, center of Aragón region, central Ebro valley, Spain). The district, with an irrigated area of 3,493 ha, is almost completely solid-set sprinkler irrigated following a limited-rate on-demand schedule. The MID has a semi arid climate and suffers the strongest and most frequent winds in the central Ebro basin. According to Martinez-Cob et al. (1998), the area is characterized by an average reference evapotranspiration (ET_0) of 1,090 mm yr⁻¹, and an average precipitation of 416 mm yr⁻¹ (data obtained from a meteorological station located in Zaragoza). The district obtains its water supply from the *Riegos del Alto Aragón* project, through the *Monegros* canal. Pumping is required from the district headquarters to two regulating reservoirs. Water flows by gravity from the reservoirs to the fields. The MID has a well-developed collective irrigation network, with about 400 hydrants and more than 600 cadastral plots. In 2004 farmers had to pay to the MID 87 € per irrigated hectare and 0.047 € per cubic meter of water.

The Ador-management software for irrigation district management (Playán et al., 2007) is daily used at the MID office to store and process the crops planted in each plot, the water meter readings and the relationships between the farmers, the plots and the irrigation structures, among other variables.

Characterization of MID irrigation performance in 2004

Irrigation water use in the 2004 season was analyzed using the Annual Relative Irrigation Supply (ARIS) index proposed by Malano and Burton (2001). ARIS represents the ratio between the annual volume of irrigation water inflow and the gross crop irrigation demand, and has been successfully used to assess water use in Mediterranean conditions (Lorite et al., 2004). The annual volume of irrigation water inflow was obtained from the Ador-management data base of the MID. The crop irrigation demand was derived from crop water requirements and irrigation efficiency. Crop water requirements for 2004 were computed from ET_0 estimates and crop coefficients. ET_0 was estimated applying the FAO Penman-Monteith method (Allen et al., 1998) to the data obtained with a standard automatic weather station located at the MID (Campbell Scientific, Logan, Utah, USA). Semi hourly averages of wind speed (U , m s⁻¹), wind direction (WD, °Azimut), air temperature (T , °C), relative humidity

($RH, \%$), precipitation (P, mm) and global solar radiation ($R_s, \text{W m}^{-2}$) were recorded. Seasonal ET_0 at the MID in 2004 was 1,211 mm, while seasonal precipitation was 397 mm (Table 1). Crop coefficients were derived from relative cumulative degree-days (Martínez-Cob, 2008). An irrigation efficiency of 80% was used in this work, in agreement with efficiency surveys in the study area (Lecina et al., 2007) and the reported performance of the irrigation technology in place (Clemmens and Dedrick, 1994).

The major crops in the MID were corn and alfalfa (occupying 45% and 46% of the land, respectively). The rest of the MID area (9%) was planted to winter cereals and some horticultural crops. The analysis of crop water use focused on the two prevailing crops. In the case of alfalfa, the seasonal irrigation water inflow was $9,550 \text{ m}^3 \text{ ha}^{-1}$, while the net crop water requirements were $6,730 \text{ m}^3 \text{ ha}^{-1}$, with an average $ARIS$ of 1.27. In the case of corn, the seasonal irrigation water inflow was $9,300 \text{ m}^3 \text{ ha}^{-1}$ and the net crop water requirements were $6,310 \text{ m}^3 \text{ ha}^{-1}$, resulting in an average $ARIS$ of 1.00. These results suggest that on the average corn is adequately irrigated, while alfalfa is overirrigated.

Figure 1 presents a map of $ARIS$ in the MID computed for each plot, and a frequency table of $ARIS$ values. In the map, $ARIS$ is presented for all crops presented in the district, while the histogram is presented for alfalfa, corn and winter cereals. The Figure indicates that there is a large spatial variability in irrigation performance. 73% of the alfalfa area showed $ARIS$ values larger than 1.00. This percentage was reduced to 20.2% in the case of corn and to 44.0% in the case of winter cereals. The relatively high water cost seems to be responsible for a certain level of under irrigation in corn. In the case of corn the histogram resulted bimodal, with 1.4% of the area showing $ARIS > 1.50$. Lorite et al. (2004) identified similar values, dispersion and even bimodal traits in his detailed analysis of a district in southern Spain.

Gross and net margin and water productivity at the MID in 2004

Gross and net margin were computed for alfalfa and corn, taking into account income and variable costs (obtained from farmer interviews). Average yields and grain prices in 2004 were obtained from the *San Isidro* agricultural cooperative located in Bujaraloz. European Union subsidies resulting from the application of the Common Agricultural Policy were obtained from public databases. The Gross Margin resulting from this analysis is a function of the amount of water used by each farmer for each crop. When

the average 2004 water use was introduced in the analysis, the resulting values were 876 € ha⁻¹ for alfalfa and 1,029 € ha⁻¹ for corn.

Net Margin was determined by deducting the fixed costs from the Gross Margin. In the context of irrigated agriculture in the area, the yearly payback of irrigation structures (both collective and on-farm) is the dominant fixed cost. Zapata et al. (2007) presented an analysis of the investment cost and performance of different collective irrigation network capacities in the experimental conditions. Table 2 presents the results of this analysis: for each type of collective network, characterized by its hydrant capacity (L s⁻¹ ha⁻¹), there is an associated value of the time of hydrant operation (%) and a yearly investment payback (€ ha⁻¹ yr⁻¹). Since the irrigation network in the MID has a design capacity of 1.2 L s⁻¹ ha⁻¹, the average Net Margin could be estimated as 325 and 364 € ha⁻¹ for alfalfa and corn, respectively. A high-capacity network reduces the net margin due to its high payback. However, it can also increase it because the decrease in the time of hydrant operation permits to select moments of low wind for irrigation and therefore obtain more crop yield with less irrigation water. Taking advantage of the local relationship between these variables through collective centralized irrigation programming constitutes the core of this research.

Water productivity (*WP*) can be obtained by dividing the gross or net margin by the annual volume of irrigation water inflow (*WP_{GM}* and *WP_{NM}*, respectively), resulting in performance indicators in units of € m⁻³. In the local conditions, and using the spatially averaged values for 2004, *WP_{GM}* was 0.09 and 0.11 € m⁻³ for alfalfa and corn, respectively. In the case of *WP_{NM}* the resulting values were 0.034 and 0.039 € m⁻³ for alfalfa and corn, respectively. These productivity figures are low when compared with those of more intensive horticultural crops or orchards in Spain (Playán and Mateos, 2006).

Agrometeorological characterization of the MID and Tamarite in 2004

To analyze the effect of meteorological conditions on sprinkler irrigation scheduling the MID was not judged representative enough of the conditions of irrigated solid-set sprinkler irrigation in the central Ebro Valley. Following the path of previous studies in the same area (Dechmi et al., 2004b), a second study location, Tamarite, was introduced for comparison purposes. Tamarite, also in the central Ebro basin, is located in the north-east of the Aragón Department (41° 46'N, 0° 22'E) and is not a windy area.

According to Martinez-Cob et al. (1998), the area is characterized by an average ET_0 of 1,063 mm yr⁻¹, and an average precipitation of 459 mm yr⁻¹.

Table 1 presents an agrometeorological characterization of Tamarite in 2004, obtained from an automatic station similar to that used at the MID. Among the presented meteorological variables, differences between the MID and Tamarite are particularly high in wind speed, with yearly averages of 2.7 and 1.1 m s⁻¹ for the MID and Tamarite, respectively. While the wind speed was rather uniform in Tamarite during the year, winter and spring were particularly windy periods in the MID. Both yearly ET_0 and precipitation were higher in the MID than in Tamarite, with respective increments of 19 and 20%, respectively.

The simulation area in the MID

A representative portion of the MID (denoted as the simulation area) was selected for model development and application. The simulation area is located in the south-west quadrant of the MID, is characterized by a flat topography and has a total area of 113 ha (Figure 2). The area is divided into 28 cadastral plots owned by 21 farmers. A total of 15 hydrants provide water to the on-farm solid-set sprinkler systems. The average size of the plot is 4.35 ha, with a minimum size of 0.6 ha and a maximum of 25 ha. In 2004, the two main crops in the simulated area were corn and alfalfa, with 63% and 21% of the total area, respectively. The rest of the area (16%) was occupied by winter cereals. Seasonal water use in 2004 in the simulation area (9,387 m³ ha⁻¹) was similar to the MID average for corn, but in the case of alfalfa it was clearly higher (12,270 m³ ha⁻¹). The resulting *ARIS* values in the simulation area were 1.19 and 1.46 for corn and alfalfa, respectively.

A survey of the simulation area was performed to characterize soil physical parameters, the on-farm irrigation solid-set equipment and the collective network. A total of 26 auger holes were used to estimate soil depth and to obtain samples for laboratory analysis of bulk density and soil water at tensions of 0.33 and 1.5 MPa (characteristic of field capacity and wilting point, respectively). The average values of these variables were: soil depth of 1.0 m, bulk density of 1.31 Mg m⁻³, and volumetric soil water of 27.6% at field capacity and 16.4% at wilting point. As a consequence, the Total Available Water (Walker and Skogerboe, 1987) averaged 146 mm, and fluctuated in the range of 107-193 mm.

The solid-sets in the simulation area were mostly equipped with Vyrsa sprinklers (Burgos, Spain). The most common model was VYR35 (49% of the plots), followed by VYR60 and VYR70. These last two models were present in 35% of the plots. The average operating pressure was 350 kPa. The triangular 18 x 18 m sprinkler spacing was present in the vast majority of the plots. In 76% of the plots the sprinklers were equipped with 4.8 and 2.4 mm nozzles. The sprinkler height was 2.0 m in all cases.

Following the hierarchical scheme adopted in the Ador-management database, and extending it to the on-farm domain, the simulation area was organized in four scales.

- The smallest scale is the **irrigation block**, corresponding to the total area irrigated at the same time from a hydrant. The block area depends on hydrant capacity, on the design hydrant pressure and on the sprinkler (spacing and nozzle diameters).
- The second scale, called the **plot**, represents an agricultural water use. This is the area composed by one or more irrigation blocks, having a unique crop, owned by the same farmer and irrigated from the same hydrant.
- The third scale is the **farm**: composed by one or more plots, owned by the same farmer and irrigated from the same hydrant.
- The last and largest spatial unit is the total **area irrigated from a hydrant**. This land may be owned by one or more farmers. In the second case, the hydrant is shared, and farmers need to arrange their irrigation operations to avoid interferences.

Each plot in the simulation area was associated to its irrigation blocks, and farms were associated to their plots. Finally, hydrants were characterized by their capacity and the farms they supply. Out of the 15 hydrants of the simulation area, 9 were shared. The total number of farms was 18. Each farm had 1.6 plots on the average, with a total of 28 plots. The total number of irrigation blocks was 165, about 5.9 per plot.

Model development

A ballistic sprinkler irrigation model

Ador-sprinkler, a ballistic solid-set sprinkler irrigation simulation model (Dechmi et al., 2004a; Playán et al., 2006) was used in this research. In ballistic models, a sprinkler is simulated as a device emitting drops of different diameters. It is assumed that drops are formed at the sprinkler nozzle, and travel independently until reaching the soil surface (or the crop canopy). Ballistic theory is used to determine the trajectory of each drop diameter subjected to an initial velocity vector and a wind vector. The action of gravity (acting in the vertical direction) and the resistance force (opposite to the drop trajectory) complete the analysis of forces acting on the water drop. The movement equations are solved using a fourth-order Runge-Kutta method. General details about the construction and testing of ballistic models can be found in Fukui et al. (1980) and Carrión et al. (2001).

The model has proven to be robust, supplying accurate estimates of performance (Christiansen Coefficient of Uniformity, *CU*) and reproducing the spatial variability of soil water application under different experimental and meteorological conditions (mainly wind speed) (Playán et al., 2006). Two drawbacks make model use complicated for widespread application (Dechmi et al., 2004a). First, the model numerically solves the trajectory of a large number of drops, therefore requiring a large execution time. Second, the model needs to be calibrated and validated for each combination of sprinkler model, nozzle and operating pressure.

Optimization of the sprinkler simulation model computational time

The time required to run a typical Ador-sprinkler simulation in a 1.73 GHz Pentium® processor was about 50 s. We judged this simulation time excessive for real-time use in centralized scheduling applications, and decided to optimize the model for execution time. The adopter procedure was based on the optimization of the Runge-Kutta time step using two criteria: numerical stability and error control.

In order to ensure numerical stability, a coordinate system is proposed that moves with wind speed. In this case drag forces can slow down drop movement till it stops. However, the drop can not move backwards. This physical and mathematical principle can not be numerically violated, thus establishing a condition on the time step. In the proposed system of coordinates drop movement equations can be written as:

$$\dot{\mathbf{r}}_w = -\tau |\dot{\mathbf{r}}_w| \dot{\mathbf{r}}_w + \mathbf{g} \quad [1]$$

with $\mathbf{r}_w$ the drop position vector in a system of reference moving with the wind, τ a factor of aerodynamic drag and $\mathbf{g}$ the gravitational field. Solving Eq. 1 with a first order Runge-Kutta, and using a time step h :

$$\mathbf{r}_w(t+h) = \mathbf{r}_w(t) + h[-\tau(t)|\dot{\mathbf{r}}_w|(t)\dot{\mathbf{r}}_w(t) + \mathbf{g}] \quad [2]$$

Which in the horizontal coordinates results in:

$$\dot{x}_w(t+h) = \dot{x}_w(t) - h\tau(t)|\dot{\mathbf{r}}_w|(t)\dot{x}_w(t), \quad \dot{y}_w(t+h) = \dot{y}_w(t) - h\tau(t)|\dot{\mathbf{r}}_w|(t)\dot{y}_w(t) \quad [3]$$

The above mentioned condition (no backwards movement) can be formulated as:

$$0 \leq \frac{\dot{x}_w(t+h)}{\dot{x}_w(t)} = 1 - h\tau(t)|\dot{\mathbf{r}}_w|(t), \quad 0 \leq \frac{\dot{y}_w(t+h)}{\dot{y}_w(t)} = 1 - h\tau(t)|\dot{\mathbf{r}}_w|(t) \quad [4]$$

Which results in the following condition for the time step:

$$h \leq \frac{1}{\tau|\dot{\mathbf{r}}_w|} \quad [5]$$

Error control is a relevant issue in Runge-Kutta methods, since these methods do not estimate error at each time step. Error estimation is required in order to build an efficient solver respecting a certain tolerance (Hull et al., 1972). Runge-Kutta pairs (Butcher, 1987, and references therein) were designed to estimate error through the use of two different-order Runge-Kutta methods with similar time steps. Given a maximum tolerance (in absolute value) for the final solution, E_{max} , over the total time, t_f , the numerical error will be within the tolerance if in each time step h_i the local error e_i (also in absolute value) satisfies:

$$e_i \leq \frac{h_i E_{max}}{t_f} \quad [6]$$

If the condition is not satisfied, the time step will be reduced to one half.

If the Runge-Kutta pairs are used to estimate an error of order n :

$$e_i = \alpha(h_i)^n \quad [7]$$

with α constant and independent of h_i . The use of a time step h_j leads to:

$$e_j = \alpha(h_j)^n = e_i \left(\frac{h_j}{h_i} \right)^n \quad [8]$$

The number of time steps of size h_j , needed to complete the solution, is $\frac{t_f}{h_j}$. Therefore, in order to maintain the final error within the tolerance:

$$E_{\max} \geq \frac{t_f}{h_j} e_j = \frac{t_f}{h_j} e_i \left(\frac{h_j}{h_i} \right)^n \Rightarrow h_j \leq h_i \left(\frac{h_i E_{\max}}{e_i t_f} \right)^{\frac{1}{n-1}} \quad [9]$$

Eq. 9 can be used to estimate the next time step size:

$$h_{i+1} \leq \beta h_i \left(\frac{h_i E_{\max}}{e_i t_f} \right)^{\frac{1}{n-1}} \quad [10]$$

where a parameter $\beta \in (0,1]$ is introduced as a conservative criterion to ensure that Eq. 6 holds, thus avoiding additional computations. As an additional precaution, factor γ is introduced to have the next time step be similar to the previous one. Finally, the time step size is governed by:

$$h_{i+1} = \min \left[\gamma h_i, \beta h_i \left(\frac{h_i E_{\max}}{e_i t_f} \right)^{\frac{1}{n-1}}, \frac{1}{\tau |\dot{\mathbf{r}}_w|} \right] \quad [11]$$

A numerical case study was devised to estimate the value of the optimization parameters. The simplified, windless droplet dynamics equations presented by Lorenzini (2004), along with their analytical solution, were used for this purpose. A set of 20,000 drops with random diameters distributed in the range 0.2-7.0 mm were launched from an elevation of 2.3 m with an initial speed of 24 m s⁻¹, a vertical angle of 25°, and facing a wind with random speed in the interval 0-16 m s⁻¹ and random direction in the interval 0-360°. Figure 3 presents the Root Mean Square Error (RMSE) in drop landing distance (m) between numerical and analytical solutions *vs.* the number of function calls. Results are presented for different Runge-Kutta pairs, with the RK2-3 pair (orders 2 and 3) resulting the most efficient for virtually all the range in tolerance. A tolerance of 1 m resulted – after a bit more than a million function calls – in solutions with a maximum error of 0.2 m and a quadratic mean error of 0.05 m. Introducing this technique results in an increase in computational efficiency and

accuracy, but also in a control of the numerical error. Experimentation on the values of β and γ for the 2-3 Runge-Kutta pair revealed that values of 1.0 and 1.6, respectively, result in efficient and robust simulations.

When applied to a typical sprinkler irrigation simulation, the optimized model required a computation time of 5 s, resulting in a 90% reduction. This increase in computational time is very important for real-time model applications, such as a collective controller.

Sprinkler model calibration and validation

A series of experiments was performed using the most common irrigation equipment and operating conditions in the simulation area. Two types of experiments were used for model calibration and validation, following the two-step procedure outlined by Playán et al (2006). The first type of experiments involved an isolated sprinkler (VYR35, 4.8 and 2.4 mm nozzles, 350 kPa at the nozzle and 2.0 m elevation) surrounded by pluviometers arranged in seven radii at a 0.5 m spacing. Two experiments were performed in the absence of wind, with a duration of 2 h each. The purpose of these experiments was to calibrate the parameters D_{50} and n of the drop size distribution equation proposed by Li et al. (1994). D_{50} (m) is the mean drop diameter, and n is a dimensionless exponent. Optimization was performed by simulating water application with a range of values of both parameters. The combination of parameters showing a maximum ratio of coefficient of correlation (r) to $RMSE$ (observed vs. simulated) was identified as optimum. In this case, the optimum combination was $D_{50} = 0.0019$ m and $n = 2.3$, with $RMSE = 1.04$ and 1.02 mm h⁻¹ for the first and second experiment, respectively, and $r = 0.82$ for both experiments. Figure 4 presents the observed and simulated radial water application patterns. The oscillations in the simulated curve were described by Playán et al. (2006), and have little effect on the simulated irrigation performance.

A second type of experiments was performed using an experimental solid-set composed of 16 sprinklers. The sprinklers were as in the first experiment, and the spacing was triangular, 18 x 18 m. In the central sprinkler spacing a matrix of 5 x 5 pluviometers was installed. The purpose of these experiments was to calibrate the empirical parameters $K1$ and $K2$ of the equation adjusting drag as a function of the relative angles between the wind speed and the drop trajectory (relative to the soil and to the wind) (Tarjuelo et al., 1994). Table 3 presents the main characteristics of the ten

experiments performed in the solid-set. Seven of them were used for calibration, and three for validation. Experiment #1 ($U = 0.9 \text{ m s}^{-1}$) was simulated with $K1 = K2 = 0$, (values characteristic of windless operation). Parameter n was adjusted to a value of 1.8 to obtain a compromise between the optimization parameters and the difference between observed and simulated CU ($RMSE = 1.68 \text{ mm h}^{-1}$, $r = 0.77$ and simulated $CU = 92.1\%$). The next step was to optimize $K1$ and $K2$ for each of the seven calibration experiments. Optimization was performed by exploring a range of values of the parameters. Table 3 presents the optimum values for each experiment, along with the resulting values of the optimization parameters: the difference between simulated and experimental CU (ΔCU), and the $RMSE$ and r between the observed and simulated precipitation rate (mm h^{-1}) at the set of 25 pluviometers. The optimum values of $K1$ and $K2$ were plotted against wind speed, and stepwise relationships were derived as follows:

$$\begin{aligned}
 K1 &= 0 \quad (U \leq 0.7) \\
 K1 &= 9.6 * U - 6.4 \quad (0.7 < U \leq 0.9) \\
 K1 &= 2.5 \quad (0.9 < U \leq 5.3) \\
 K1 &= -0.32 * U + 4.3 \quad (5.3 < U \leq 6.6) \\
 K1 &= 2.2 \quad (6.6 < U)
 \end{aligned}
 \tag{12}$$

$$\begin{aligned}
 K2 &= 0 \quad (U \leq 0.9) \\
 K2 &= 0.32 * U - 0.29 \quad (0.9 < U \leq 2.7) \\
 K2 &= -0.19 * U + 1.1 \quad (2.7 < U \leq 4.3) \\
 K2 &= 0.25 \quad (4.3 < U \leq 5.3) \\
 K2 &= -0.079 * U + 0.67 \quad (5.3 < U \leq 6.6) \\
 K2 &= 0.15 \quad (6.6 > U)
 \end{aligned}
 \tag{13}$$

Eqs. 12 and 13 were used to simulate the validation experiments (#5, #6 and #8), producing the results presented in Table 3. Once calibrated and validated, the model was ready to simulate the most common local technical conditions in a broad range of meteorological situations. The model predictive capacity was characterized by errors in CU of about 1%, a $RMSE$ of about 1.7 mm h^{-1} and a correlation of 0.5-0.6.

Ador-Simulation: a version for a collective sprinkler irrigation controller

The Ador-Simulation software has been designed to simulate centralized irrigation control in a solid-set irrigated district. The model is composed of four modules that interchange input and output data to decide the irrigation timing of each plot and to

evaluate the effects of irrigation scheduling on crop yield. The four modules are: Ador-Sprinkler, Ador-Crop, Ador-Network and the Ador-Decision. The joint operation of the first two modules was presented by Dechmi et al. (2003), simulating the interaction between a solid-set irrigation system and a crop. Lecina and Playán (2006a; 2006b) presented a similar model for surface irrigation irrigated districts, including modules for the irrigation network (irrigation canals and reservoirs) and for irrigation decision making.

The long term objective of this research is to automatically make irrigation decisions during the season and to apply them to the irrigated plots via a remote control system. In the applications reported in this paper, the irrigation applications have been evaluated via the crop model. Therefore, simulation was not performed in real time but at the machine speed. Meteorology was introduced in the model through two sources of data: average daily data for crop modeling, and semihourly data for irrigation modeling and decision making. A review of the implementation of each module follows.

Ador-Sprinkler. Although the module was optimized for computational speed to enable real-time operation, 5 s of computational time was considered excessive for intensive application using a simulated crop. To address this problem, a database was created containing irrigation performance indexes and irrigation depths in the 25 points representative of a sprinkler spacing. Records were created via simulation for a combination of wind speeds (from 0 to 8 m s⁻¹ with a step of 0.5 m s⁻¹), wind directions (from 0° to 360° with 5° step) and relative humidity (from 30% to 90% with 10% step). Relative humidity was introduced because it is an independent variable in the determination of Wind Drift and Evaporation losses (*WDEL*) in the equation proposed by Playán et al (2005) for day and night irrigation.

Ador-Crop. The model was used as initially described (Dechmi et al., 2003). Simulation was run with a daily time step on a sprinkler spacing represented by the 25 points where water application is simulated with Ador-sprinkler. Water balances were kept for each of the 25 points. When 6 of the 25 simulation points were water stressed, an irrigation was requested for the crop.

Ador-Network. This module implements the previously discussed division of the irrigated district land into area irrigated from a hydrant, farm, plot and irrigation block. One of the main hypotheses of this model is that all the sprinklers of the

irrigation district operate at the same pressure at all times. This implies neglecting elevation differences and head losses within the irrigation blocks, assuming equal head losses between blocks, assuming a perfect functioning of pressure regulating devices at the hydrants and neglecting pressure drops due to simultaneous operation of hydrants. On the other hand, this hypothesis permits to simulate sprinkler irrigation in a block with just one sprinkler spacing. Therefore in each block irrigation is simulated with Ador-Sprinkler, while the crop water status and yield are simulated with Ador-Crop.

Ador-Decision. This module is the core of the proposed model, since this is where irrigation decisions are made taking into account the crop status, water availability (whether the hydrant is currently occupied or not) and the projected irrigation performance. Two indicators are used in this module to decide on irrigation: PAE_{lq} and ES . The first indicator, PAE_{lq} (%) is the Potential Application Efficiency of the Low Quarter, as defined (Merriam and Keller, 1978) and revised by (Burt et al., 1997). In this case $WDEL$ have been considered as a net water loss. PAE_{lq} applies to an irrigation event, is estimated with Ador-Sprinkler, and can be expressed as:

$$PAE_{lq} = \frac{\text{average depth of irrigation water contributing to target}}{\text{average depth of irrigation water applied such that } d_{lq} = \text{target}} \cdot 100 \quad [14]$$

PAE_{lq} greatly depends on wind speed. In the experimental conditions and with relative humidity of 50%, PAE_{lq} was estimated as 73, 64 and 42% for wind speeds of 0.0, 2.5 and 5.0 m s⁻¹, respectively.

The second indicator, ES , is the Equivalent Stress (days), applies to a plot divided in n blocks and cultivated to a given crop. ES can be expressed as:

$$ES = \frac{\sum_{j=1}^n \left(\frac{\sum_{i=1}^{25} \text{water deficit beyond the threshold reducing crop yield (mm)}}{25 * \text{daily crop ETc (mm day}^{-1}\text{)}} \right)}{n} \quad [15]$$

ES can be interpreted as the number of days the plot has been requiring an irrigation to alleviate its stress. ES can be determined every day using Ador-Crop water stress data.

In a model run the user establishes the thresholds for both indicators: a minimum PAE_{lq} and a maximum ES . If in a given plot ES is higher than the threshold, irrigation

can proceed even if PAE_{lq} is lower than the threshold. In the current version, thresholds are common to all crops. The establishment of crop specific threshold values appears as a need in order to optimize district water use.

Figure 5 illustrates the decision making process in a hypothetical case involving two hydrants, three farms (one hydrant is shared), four plots (cropped to alfalfa and corn), and a total of 21 irrigation blocks. The irrigation time is 2 h for corn and 4 h for alfalfa. Irrigation is required in the first two plots and begins by their first block at 12:00 (black vertical bands). Every half an hour PAE_{lq} is evaluated: if it is higher than the threshold, irrigation continues. Between 14:00 and 15:00, irrigation is not allowed (grey horizontal band) because PAE_{lq} is lower than the threshold due to an increase in wind speed or a decrease in relative humidity. At 15:00, PAE_{lq} is reevaluated and irrigation continues. In the case of corn, irrigation begins at this time at the second block. At 17:00, both plots change block. At the beginning of Julian day 163 Ador-Crop is updated, and so are the water balances in each irrigation block. In the case of Alfalfa, ES is higher than the threshold: water stress is very important and may seriously damage yield, therefore irrigation will be performed regardless of PAE_{lq} . In fact, irrigation in alfalfa begins at 00:30, while irrigation in corn must wait till 02:30, when meteorological conditions grant an acceptable value of PAE_{lq} . Irrigation in the last two plots can not start during the period presented in Figure 5 because only one block per hydrant can irrigate at the same time.

Ador-decision implements special rules for shared hydrants, following the local farmers' practices. The days of the week are distributed among each farm proportionally to their area. This permits farmers to schedule irrigation (in the allowed days of the week) without consulting the neighboring farmers, but results in inefficiencies due to the misuse of irrigation time.

Model Application

Generation of management strategies for Ador-Simulation

Three main management alternatives were designed for simulation purposes and implemented in Ador-simulation:

Manual (M). This alternative reproduces a situation in which farmers strictly follow the indications of an irrigation advisory service. They receive crop water requirements based on the previous week and program their plot irrigation controllers every week. Common irrigation scheduling practices in the study area are far from this ideal situation. Seasonal irrigation schedules are prepared for each plot and supplied to Ador-simulation.

Central (C). Irrigation starts in a given plot if 1) requested by more than 50% of its irrigation blocks; 2) the hydrant is idle; and 3) the day of the week is allowed for this farm (if the hydrant is shared). If condition 1 is met, conditions 2 and 3 will be re-evaluated every half an hour till irrigation can start.

Central optimum (CO). In this case, the conditions of the Central management alternative are necessary but not sufficient. Additionally, thresholds are imposed for PAE_{lq} and ES , as previously discussed. If a low value is selected for PAE_{lq} (such as 10%), the management strategy CO becomes equivalent to C, since irrigation will be accepted in all cases, regardless of the poor performance induced by inadequate environmental conditions.

Two additional management alternatives, **Csh** and **COsh**, were designed to overcome the limitations imposed by the present management of shared hydrants. If irrigation is centralized, there is no need to allocate days of the week to each farm. Instead, the central control will ensure that two blocks of the same hydrant are not irrigated at the same time.

In all management alternatives, irrigations lasted 2 h for corn and 4 h for alfalfa, following the local practices.

In the following sections these management alternatives are tested in two situations: 1) a study plot with an area of 25 ha, divided into 10 irrigation blocks, and the simulation area within the MID, as previously defined.

Calibration of the Central Optimum (CO) management strategy in the study plot

Simulations were performed in the study plot equipped with a 45 L s⁻¹ hydrant (hydrant capacity of 1.8 L s⁻¹ ha⁻¹, time of hydrant operation of 44%). The 2004 meteorological files for the MID and Tamarite were used to simulate corn and alfalfa. Simulations focused on the WP_{NM} resulting from combinations of PAE_{lq} (in the range of 50-70%) and ES (in the range of 0.75-1.25 days). The strategy based on $PAE_{lq} = 10\%$ and $ES = 1.00$ days (equivalent to strategy C) was also simulated and is presented for comparison purposes. Results show wide differences among the two analyzed crops (Fig. 6).

In the case of corn (characterized by high sensitivity to water stress), the windy conditions of the MID result in an optimum value of PAE_{lq} of 60% and an SE of 0.75 days. In the analyzed ranges the most important factor is PAE_{lq} . If irrigations are accepted with low PAE_{lq} , WP_{NM} is low due to the heterogeneity in crop yield and the high cost of water associated with low efficiency. If a high value of PAE_{lq} is requested, WP_{NM} is low due to a generalized crop water stress: irrigations are delayed till low-wind conditions appear. The optimum value of the decision parameters reflects an adequate tradeoff for the local conditions. The low-wind conditions of Tamarite result in a flat response to the decision parameters: small differences can be appreciated in the analyzed range. WP_{NM} is higher in Tamarite than at the MID due to a higher yield and lower water input (both are due to the lower wind speed).

In the case of Alfalfa, a drought resistant crop, the search for adequate irrigation timing (low-wind, high relative humidity) is rewarded with high water productivity. The best strategy is to request high PAE_{lq} (about 70%) and wait for as much as 1.25 days till conditions are met. The same trend can be observed in both the MID and Tamarite, although in this latter case the resulting WP_{NM} is higher.

Among the different locations, crops and values of the decision parameters, WP_{NM} fluctuates between 0.04 and 0.08 € m⁻³. These values can not be compared to those characteristic of more economically intensive crops. It is important to note, however, that the adequate choice of the decision parameters can result in WP_{NM} increases of up to 25% of the base case.

Evaluation of management strategies for different network capacities and locations in the study plot

Obtaining a high value of WP_{NM} requires an irrigation network whose capacity permits to concentrate water application in the periods of time resulting in adequate irrigation performance. The simulation experiment reported in Figure 7 explores the effect of the network capacity on seasonal water use and water productivity using the same 25 ha plot equipped with hydrant capacities ranging between 1.0 and 1.8 L s⁻¹ ha⁻¹ (discharges ranging between 25 and 45 L s⁻¹). Results are presented for the MID meteorology in subfigures a, b and c. Performance resulting from management alternatives M, C and CO is presented in each case. For management alternative CO the optimum values of the decision parameters were obtained in each case and are presented in Figure 7.

In the manual management strategy, seasonal water use increases with the network capacity. The same effect can be observed in the case of the C strategy. However, the water use for C is always smaller than for M, with an average reduction of 1,093 m³ ha⁻¹, representing 11% of the manual water use. The CO strategy shows little variation in seasonal water use with network capacity, and on the average demands 1,723 m³ ha⁻¹ less than the M strategy (a reduction of 17%). The differences in seasonal water use show little relation with simulated crop yield. The manual strategy results in low values of yield for the smallest network capacities, with 79 and 91% of maximum corn yield for capacities of 1.0 and 1.2 L s⁻¹ ha⁻¹, respectively (data not presented). In all other cases and management strategies, yields were in the range of 94-98%, with the lowest yields often associated to the lowest network capacities.

On the average, the most productive strategy was C (97%), followed by CO (94%) and M (91%). While strategy C focuses on the real-time satisfaction of crop water requirements, CO was optimized for WP_{NM} (affected by the crop productive income and the cost of irrigation water), and M responded to classical, *ex-post* irrigation scheduling. There is a clear parallelism between subfigures b and c, presenting results for WP_{GM} and WP_{NM} : in all cases the C strategy represents a clear advantage over M (35% for WP_{GM} ; 63% for WP_{NM}), while CO shows little improvements respect to C (6% for WP_{GM} ; 5% for WP_{NM}). The low productivities of the M strategy are particularly relevant for small network capacities. For instance, the MID network (equipped with 1.2 L s⁻¹ ha⁻¹ hydrants) could increase its WP_{NM} from 0.037 to 0.060 € m⁻³ by adopting the C strategy. In the manual strategy gross and net water productivities increase with network capacity, and find a plateau in the range of 1.4-1.6 L s⁻¹ ha⁻¹, coincident with

the current local design target for windy areas. Strategies C and CO see little variation in WP_{GM} with network capacity. In the case of WP_{NM} the trend is clear for strategies C and CO: both see a moderate decrease in WP_{NM} as the network capacity increases, with CO being close to a flat response. As a consequence, it can be concluded that irrigation strategies based on central management are not only much more productive than the best manual management for a given network capacity; they also take advantage of networks with low delivery capacity.

These findings are further supported by subfigure d, in which the results for WP_{NM} are presented for the low-wind conditions of Tamarite. The most significant difference between the analyzed locations is that the Tamarite conditions permit to complete the irrigation season with a water use not exceeding $6,750 \text{ m}^3 \text{ ha}^{-1}$ in all simulations. Since the water cost is reduced and yields are similar, WP_{MN} is higher in Tamarite than at the MID. Centrally operated strategies result in an average WP_{NM} increase of 45 and 51% respect to the manual strategy for C and CO respectively. For the manual strategy, productivity is high and constant in the range of $1.0\text{-}1.2 \text{ L s}^{-1} \text{ ha}^{-1}$, and shows a steady decrease for networks of larger capacity. Under low-wind conditions, manually and centrally operated networks are most productive in this low range of delivery capacity.

Analysis of management strategies in the simulation area

In the last numerical experiment of this research, simulation was extended to the simulation area in the MID. Figure 8 shows a comparison of the observed and simulated figures of seasonal water use for the extended set of management strategies (including the “sh” variants), and for the two prevailing crops in the simulation area. The central optimum strategies (CO and COsh) were jointly optimized, and the optimum values of the decision parameters were $PAE_{lq} = 30 \%$ and $ES = 1.0$ day for corn, and $PAE_{lq} = 65 \%$ and $ES = 1.0$ day for alfalfa. The Figure shows how strategy M results in a reduction of water use with respect to the observed values. The variability among plots (represented by the standard deviation bar) also decreases in the simulated case, in which variability is due to the differences in irrigation scheduling derived from differences in hydrant capacity and number of irrigation blocks. In all central strategies the variability among plots is due to the interaction between the irrigation scheduling module and the network capacity restrictions. All these strategies show much smaller than observed variability, although the variability is particularly low for the Csh and COsh, due to the central management of shared hydrants. In

addition to reducing the differences among plot water use, the central strategies present a very low water demand. For instance, the most evolved strategy, COsh resulted in reductions in seasonal water use of 23.8 and 38.0% for corn and alfalfa, respectively, when compared to the observed values for 2004. These results confirm the possibilities of conserving irrigation water in collective solid-set sprinkler irrigation networks by applying central irrigation scheduling techniques.

Water productivity results in Figure 9 illustrate the changes in WPNM for both crops respective to the normal strategy. When comparing strategies CO and M, these increments amount to 27.6% for corn and 91% for alfalfa. Improvements for corn are more limited than for alfalfa because 1) corn requires more network capacity to allow for an adequate selection of irrigation timing; and 2) because alfalfa seasonal water use at the simulation area was clearly higher than in the whole MID (with respective values of 12,270 and 9,550 m³ ha⁻¹). When the shared hydrants are centrally managed, corn water productivity experiments a sharp increase (31.5% from strategies CO to COsh), indicating that central scheduling is particularly rewarding in irrigated areas with small farms resulting in a large percentage of shared hydrants. The increment in WP is related to the increase in corn seasonal water use between C and Csh and between Co and COsh that can be observed in Fig. 8. Centralizing shared hydrants permit to exploit idle hydrant time and to apply water to corn following its requirements.

The central strategies result in deficit irrigation conditions at the simulation area. The COsh strategy results in *ARIS* values of 0.91 and 0.90 for corn and alfalfa, respectively. These values are compatible with average yields of 87.8 and 94.3% for the same crops (strategy COsh). The sharp reduction in irrigation water results in a potential water conservation of 2,234 and 4,664 m³ ha⁻¹, which is very relevant to alleviate the frequent water shortages of the MID.

617 Conclusions

618 The MID currently presents an adequate level of irrigation management, evidenced by
 619 *ARIS* of 1.27 for alfalfa and 1.00 for corn. Water productivity falls in the typical range
 620 for field crops, with WP_{GM} of 0.09 and 0.11 € m⁻³ for alfalfa and corn, respectively. The
 621 estimates for alfalfa and corn WP_{NM} are 0.034 and 0.39 € m⁻³, respectively.

622 A model was developed to schedule solid-set sprinkler irrigation at a district scale. The
 623 long-term objective is to use this model continuously during the season to control
 624 irrigation in the district, and to execute irrigation operations via a remote control
 625 system. In order to facilitate real-time operation, the numerical solution of the ballistic
 626 equations for sprinkler irrigation was accelerated using the Runge-Kutta pairs
 627 methods. Simulation time was reduced to 10% of the original. The most common local
 628 sprinkler hardware was calibrated and validated, with an expected error in *CU* of 1%
 629 and an *RMSE* of 1.7 mm h⁻¹.

630 Five irrigation management strategies were designed and tested. In a 25 ha test plot the
 631 centralized irrigation strategies permitted to achieve WP_{NM} of up to 0.08 € m⁻³. Relevant
 632 differences were found between corn and alfalfa, the major crops in the area, indicating
 633 that management strategies must be parameterized for each crop. This experiment
 634 revealed that in windy areas networks with low hydrant capacity can see important
 635 increases in their water productivity if central management is implemented. In fact,
 636 networks with hydrant capacities of 1.0-1.2 L s⁻¹ ha⁻¹ attained the best productivities
 637 under centralized management in all wind conditions and for both crops. Larger
 638 capacities – typical of many new designs – seem to be required to overcome the
 639 inefficiencies derived from manual operation. The application of the model to the
 640 simulation area identified great possibilities of water conservation (2,234 and
 641 4,664 m³ ha⁻¹ for corn and alfalfa, respectively), and announced increases in WP_{NM} of up
 642 to 91%.

643 This research has identified a niche for a centralized irrigation controller. The
 644 introduction of this technology will lead to relevant improvements for the farmers and
 645 for the society (increased productivity, low labor input, water conservation...).
 646 However a number of hurdles separate the proposed software from widespread
 647 application. First, the simulated results presented in this paper must be field verified;
 648 second, the reliability of remote control systems must be high enough to charge them

649 with irrigation operations; and third, farmers need to appreciate the convenience and
650 cost effectiveness of these techniques.

651

652 **Acknowledgements**

653 We appreciate the continuous support of the manager of the MID, Carmelo Lorente.
654 This research was funded by the *Plan Nacional de I+D+i* of the Government of Spain,
655 through grant AGL2004-06675-C03-03 and by the CONSI+D of the Government of
656 Aragón (Spain) through grant PIP090/2005. Ahmed Skhiri received a scholarship from
657 the Agronomic Mediterranean Institute of Zaragoza (CIHEAM).

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743

List of Tables

Table 1. Agrometeorological characterization of 2004 for the two climatic locations: the MID and Tamarite. Monthly values are provided for each location for reference evapotranspiration, crop evapotranspiration (corn and alfalfa), precipitation and wind speed.

Table 2. Determination of gross and net margin for Corn and Alfalfa in the study area in 2004. Net margin includes the yearly repayment of the irrigation structures. Six hypotheses of network capacity ranging from 1.0 to 1.8 L s⁻¹ ha⁻¹ resulting in different yearly repayments were analyzed, using data from Zapata et al., (2007).

Table 3. Experimental conditions and calibration parameters for the evaluations performed to calibrate (C) and validate (V) model parameters for the VYR35 sprinkler equipped with 4.8 and 2.4 mm nozzles.

Table 1. Agrometeorological characterization of 2004 for the two climatic locations: the MID and Tamarite. Monthly values are provided for each location for reference evapotranspiration, crop evapotranspiration (corn and alfalfa), precipitation and wind speed.

759

Month	MID					Tamarite				
	ET_0 (mm)	ET alfalfa (mm)	ET corn (mm)	P (mm)	U (m s ⁻¹)	ET_0 (mm)	ET alfalfa (mm)	ET corn (mm)	P (mm)	U (m s ⁻¹)
January	47.9	0.0	0.0	5.8	4.3	24.9	0.0	0.0	7.6	1.2
February	32.7	0.0	0.0	50.8	2.5	24.0	0.0	0.0	48.2	1.0
March	75.2	37.5	0.0	43.6	3.2	60.9	30.7	0.0	43.6	1.3
April	100.8	61.3	17.1	72.2	3.4	86.4	57.7	53.6	64	1.3
May	140.5	138.7	61.6	67.0	2.6	123.9	110.5	147.0	39.8	1.2
June	191.4	187.7	161.4	43.0	2.3	168.1	154.4	214.5	1.6	1.2
July	189.4	171.1	232.3	29.0	2.3	167.1	140.5	185.0	46.2	1.3
August	163.8	159.9	216.5	4.4	2.0	149.1	124.0	75.5	5.8	1.3
September	122.5	104.5	114.6	4.2	2.3	107.9	77.0	3.8	8.8	1.4
October	76.0	40.8	23.2	41.2	1.8	61.3	40.5	0.0	27.8	1.0
November	42.7	0.0	0.0	6.0	2.7	23.1	0.0	0.0	9.2	0.7
December	27.9	0.0	0.0	30.2	3.1	19.4	0.0	0.0	28	1.0
TOTAL	1210.8	901.5	826.7	397.4	2.7	1016.1	735.3	679.5	330.6	1.1

760

Table 2. Determination of gross and net margin for Corn and Alfalfa in the study area in 2004. Net margin includes the yearly repayment of the irrigation structures. Six hypotheses of network capacity ranging from 1.0 to 1.8 L s⁻¹ ha⁻¹ resulting in different yearly repayments were analyzed, using data from Zapata et al., (2007).

Hydrant capacity (L s ⁻¹ ha ⁻¹)	Time of hydrant operation (%)	Yearly Investment payback (€ ha ⁻¹ yr ⁻¹)
1.0	100	363
1.1	75	393
1.2	67	405
1.4	58	420
1.6	50	438
1.8	44	452

Table 3. Experimental conditions and calibration parameters for the evaluations performed to calibrate (C) and validate (V) model parameters for the VYR35 sprinkler equipped with 4.8 and 2.4 mm nozzles.

Evaluation #	Use	Experimental					Simulation				
		U (m s ⁻¹)	WD (°Azimut)	T (°C)	RH (%)	CU_{Exp} (%)	$K1$ (-)	$K2$ (-)	ΔCU (%)	$RMSE$ (mm h ⁻¹)	r (-)
1	C	0.9	112.5	8	81	89.1	2.4	0.00	1.7	1.0	0.4
2	C	2.7	270.0	10	61	78.3	2.6	0.55	1.7	1.1	0.7
3	C	3.2	292.5	9	55	74.0	2.6	0.50	0.5	1.5	0.7
4	C	3.3	292.5	8	62	76.0	2.4	0.55	2.7	1.5	0.7
5	V	3.5	292.5	14	63	74.0	2.5	0.43	0.1	1.8	0.5
6	V	3.9	292.5	15	60	73.5	2.5	0.35	1.0	1.6	0.6
7	C	4.3	292.5	14	65	71.5	2.4	0.25	1.0	1.8	0.6
8	V	5.1	315.0	13	60	71.7	2.5	0.25	1.3	1.7	0.6
9	C	5.4	315.0	14	57	70.5	2.6	0.25	0.3	1.8	0.6
10	C	6.7	315.0	13	52	71.8	2.2	0.15	1.6	2.0	0.5

List of Figures

Figure 1. Spatial representation of ARIS for 2004 in the MID, including an ARIS frequency table for corn, alfalfa and winter cereals.

Figure 2. Characterization of the simulation area: situation within the MID, layout and irrigation network.

Figure 3. Root Mean Square Error (RMSE) in drop landing distance(m) between numerical and analytical solutions vs. number of function calls for the case study involving different Runge-Kutta pairs, denoted by the order of each solution. The RK2-3 pair results the most efficient for virtually all the range in tolerance.

Figure 4. Observed vs. simulated radial water application from an isolated sprinkler using the optimum combination of drop diameter distribution parameters: $D_{50} = 0.0019$ m and $n = 2.3$. The observed values result from the two experiments. Each of them is the average of seven radii of pluviometers spaced 0.5 m.

Figure 5. Sample results for Ador-decision, detailing the processes involved in irrigation start, stop and resume. The example presents results for two hydrants, three farms, four plots and a total of 21 irrigation blocks. The irrigation procedure was semi hourly evaluated, covering part of Julian days 162 and 163. The black areas indicate that irrigation is in course. White areas indicate no irrigation. Grey areas indicate that irrigation is not allowed. Irrigations lasted for 2 h in corn and 4 h in alfalfa.

Figure 6. Water productivity based on net margin for a 25 ha plot, a network capacity of $1.8 \text{ L s}^{-1} \text{ ha}^{-1}$, different values of PAE_{iq} (%) and ES (days) for corn (a) and alfalfa (b). In both cases, results are presented for the meteorological conditions of MID and Tamarite.

Figure 7. Water use and water productivity for a corn crop grown in a 25 ha plot with a network capacity ranging from 1.0 to $1.8 \text{ L s}^{-1} \text{ ha}^{-1}$. Results are presented for the meteorological conditions of MID (a, b and c) and Tamarite (d). Subfigures present seasonal water use (a) and water productivity in terms of gross margin (b) and net margin (c and d).

Figure 8. Observed and simulated seasonal water use and inter plot standard deviations for corn and alfalfa in the simulation area and using the meteorological conditions of the MID in 2004. Simulations include the five management strategies described in the paper: M, C, Csh, CO and COsh.

Figure 9. Water productivity based on net margin for the simulation area and the meteorological conditions of the MID in 2004. Results are presented for corn and alfalfa, the

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Figure 2. *Characterization of the simulation area: situation within the MID, layout and irrigation network.*

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Figure 8. Observed and simulated seasonal water use and inter plot standard deviations for corn and alfalfa in the simulation area and using the meteorological conditions of the MID in 2004. Simulations include the five management strategies described in the paper: M, C, Csh, CO and COsh.

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