Agricultural Water Management 284 (2023) 108337

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

A simulation tool to optimize the management of modernized infrastructures in collective and on-farm irrigation systems

N. Zapata [a,*], S. Bahddou [b], B. Latorre [c], E. Playán [d]

[a] Dept. Soil and Water. EEAD-CSIC, Avda. Montañana, 1005, 50059 Zaragoza, Spain
[b] School of Water, Energy and Environment, Cranfield University, Building 52A, Wharley End, Bedford MK43 0AL, United Kingdom
[c] Dept. Soil and Water, EEAD-CSIC, Avda. Montañana, 1005, 50059 Zaragoza, Spain
[d] Dept. Soil and Water, EEAD-CSIC, Avda. Montañana, 1005, 50059 Zaragoza, Spain

ARTICLE INFO

Keywords:
On-farm irrigation methods
Irrigation modernization
Collective irrigation networks
Water use efficiency
Energy use efficiency
Low-pressure sprinkler
Simulation models

ABSTRACT

Irrigated areas face new, pressing challenges due to escalating energy costs for pumping, increasing cost of seeds, fertilizers and agrochemicals, volatility of agricultural commodities, pressure of environmental regulations, water scarcity and mounting cost of irrigation infrastructure investments. At the same time, from the technical standpoint, farmers can chose from a wide array of irrigation design and operation alternatives for collective and on-farm systems, with variable effects on crop yield and profitability. These factors are often subjected to quick changes, complicating decision making. Simulation models have proven useful to support decision making in irrigation infrastructure, water / energy use, crop agronomy and soil management. In this research, new capacities of the Ador-Simulation software are reported, targeting comprehensive analyses of irrigation modernization. The model implements additional on-farm irrigation methods (low-pressure solid-set, center-pivot and drip irrigation); crop intensification (double cropping in the same season); and crop response to different on-farm irrigation management options (timing and frequency). Model performance was verified using a set of theoretical case studies. Finally, the model was applied to the optimization of irrigation design and management (water and energy) in the Bardenas XI project of northeastern Spain. Water application in center-pivot and drip irrigation were simulated using a normal distribution characterized by a user-defined Distribution Uniformity. In center-pivot, the application depth was randomized in every irrigation event, reproducing the random nature of wind disturbances. In drip irrigation, the application depth followed the same random distribution in all irrigation events, reproducing the deterministic effect of manufacturing and hydraulic variability. According to the literature, the effect of irrigation timing was treated differently for two key sprinkler irrigated crops: corn and alfalfa. Differences in water application and crop yield between on-farm methods resulted in different gross and net income. In the Bardenas XI project, irrigation performance indicators showed different patterns of inter-annual variability. Deep percolation was strongly affected by the amount of seasonal precipitation and by Distribution Uniformity. Indicators at the plot level were strongly determined by the on-farm irrigation method, the soil type, and the crop. In the conditions of Bardenas XI, the design option without pumping station was the most adequate. Natural pressure proved sufficient for a combination of low-pressure sprinkler irrigation, pivot and drip irrigation methods, distributed throughout the irrigated area. Escalating energy costs emphasize the need for careful assessment of pumping requirements at the design phase of irrigation projects.

1. Introduction

Climate change is expected to continue modifying water supply and demand over the world. For instance, the United States has increased water demand in the last years, particularly in the western States. This has raised uncertainty about the sustainability of irrigated agriculture in the West (Schaible et al., 2010). In 2007, the Australian government launched the National Plan for Water Security package (almost $6 billion over ten years). The plan set out to modernize irrigation infrastructure both on- and off-farm, targeting water conservation. Khan et al. (2010) reported that this Plan would lead to more efficient, productive and profitable water use, with a view to maintaining the value of

* Corresponding author.
E-mail address: v.zapata@csic.es (N. Zapata).

https://doi.org/10.1016/j.agwat.2023.108337
Received 13 January 2023; Received in revised form 24 April 2023; Accepted 27 April 2023
Available online 2 May 2023

irrigated production in the face of declining water availability.

In Europe, the problem of water scarcity is particularly relevant in Mediterranean countries, such as Spain, Italy or Greece. In these countries, as is commonly the case in semiarid regions, agriculture is the sector obtaining the largest share of water use. Uncertainty in water supplies will further constrain already over-allocated water resources and will increase competition among agricultural, municipal, industrial and ecological uses (Smith et al., 2007). Increasing competition underlines the importance of efficient use of irrigation water, developing capacities to apply irrigation water at the time, in the amount and in the way needed to meet consumptive-use requirements for each crop and at each growth stage.

In the XXI century, National Irrigation Modernization Plans (MAPAMA, and MAPAMA, 2002, 2010) were launched by the Spanish Government to address irrigation project deficiencies, water scarcity problems, water EU directives and changes in social structure. These plans took advantage of new information and communication technologies (Playán et al., 2018). In addition, most Spanish Regional Governments designed and applied their own irrigation modernization plans, also addressing European regulations. A new Plan to improve the efficiency and sustainability of irrigated areas has been deployed in the framework of the post-COVID Recovery and Resilience plan of the European Union (BOE, 2021).

Both obsolete and recently modernized irrigated areas face new, pressing challenges. Among them, the escalating costs of energy and other agricultural inputs (such as seeds and fertilizers), the price volatility of agricultural commodities, the pressure of environmental regulations and the mounting interests rates (that increase the payback cost of investments in irrigation modernization). These challenges are currently threatening the economic viability of many irrigated areas. The wide array of irrigation design and operation alternatives for collective and on-farm systems, their effect on crop yield and their water and energy requirements complicated decision making. All these concerns stress the need for adequate management at all irrigation levels in order to obtain full benefit from public and private investments in irrigation modernization. Simulation models have proven useful to support decision making in irrigation infrastructure, water / energy use, crop agronomy and soil management.

When planning future crops, farmers also need to decide between on-farm irrigation methods, and need to install designs optimized for their local conditions. Irrigation management requires frequent tactical decision making. Simulation models and sensing platforms using a variety of information sources are increasingly used to support these decisions in each irrigation method.

Zapata et al. (2009) presented an early version of Ador-Simulation, a software combining capacities for the simulation of solid-set sprinkler irrigation, crop water requirements and yield in irrigation districts. Zapata et al. (2013) presented the experimental application of a version of this software applied to real-time irrigation control in a solid-set sprinkler irrigated maize farm. The model was based on available daily local reference evapotranspiration (ET_0) data (obtained via internet), local sensors (pressure and discharge at the farm inlet, temperature and wind speed), and simulation of irrigation application variability and the soil/crop water balance. The main contribution of this research was the explicit consideration of both space and time variability (hydraulic, hydrological, meteorological and agronomical) for irrigation decision-making, leading to optimum crop yield and water use efficiency.

Miranda et al. (2005), also working on solid-sets and using sensor-based irrigation decision making, proposed to install a controller at each irrigation management unit. Each controller would be programmed to process the information received from three soil water potential (SWP) sensors. When two of the sensors indicated that the SWP reached a user-defined threshold (the management allowable depletion), the irrigation controller would open the valve, triggering irrigation of the management unit. Irrigation would continue until two of the three soil sensors would indicate that the SWP exceeds the threshold. This development was based on the hypothesis that three soil sensors adequately characterize soil water spatial variability, mainly resulting from random wind speed and direction. A key limiting factor of this solution is the investment and maintenance costs of the programmer, the sensors and the wireless communication network. In solid-set sprinkler irrigated areas, an irrigation management unit is a sector within a plot. For instance, in the Ebro valley of Spain the average number of sectors per plot is around 8, ranging from 1 to 12 (Stambouli et al., 2014). As a consequence, 24 SWP sensors, 8 programmers and a communication network would be required to control irrigation in an average local solid-set farm.

The analysis of different sources of variability of water application in center-pivot and linear-move sprinkler irrigation machines has led to the implementation of site-specific water application devices (Sadler et al., 2005; Peters and Evett, 2008; Chávez et al., 2010a, b). Variable rate application was obtained by adjusting the machine travel speed multiple times during an irrigation event and/or implementing on-off cycles and/or variable flow at the sprinklers (King and Kincaid, 2004). The long-term maintenance requirements of such systems remains a challenge. However, as in solid-sets, the cost of the required software/hardware - ranging from $2000 for a system monitor to over $20,000 for the control of individual sprinklers (Zhu et al., 2018) - can limit its adoption.

For on-farm drip irrigation, sensing networks with wireless communications governed by an algorithm have been the most researched option for irrigation decision-making (Fernández et al., 2008; Casadesús et al., 2012; Domínguez-Niño et al., 2020). These systems are usually associated to cash crops (fruits and vegetables). The control equipment necessary to manage the variability of water application in small, homogeneous management zones is now commercially available. Such systems could become complex when controlling large commercial farms with heterogeneous soils and significant variability in pressure and irrigation equipment. The investment and maintenance costs of the distributed sensors required to measure soil water, crop status and irrigation performance could limit the widespread adoption of this technology. Finally, the algorithms integrating sensor data for decision making face relevant challenges for the site-specific application of water, nutrients and pesticides (Zhu et al., 2018).

The irrigated land of the Ebro Valley in Aragon is mainly devoted to field crops (around 86% of the total), followed by horticultural crops (14%), particularly fruit orchards (Zapata et al., 2020). One of the effects of irrigation modernization in the 21st century has been the increase in the acreage of double cropping, in some areas reaching 35% of the area (Zapata et al., 2020). Field crops are strongly associated to solid-set and center-pivot irrigation. Corn (with wettable crop leaves) and alfalfa (with non-wettable crop leaves) respond differently to the irrigation time within the day, being the wettability of leaves a critical trait for interception water losses and determining yield. In solid-set irrigation system, the wind is the key factor affecting wind drift and evaporation losses (WDEL) (Playán et al., 2005; Ortiz et al., 2009) and irrigation uniformity (Tarjuelo et al., 1999; Dechmi et al., 2003). In many windy areas of the world and in the Ebro valley in particular, the wind is higher during the daytime than during nighttime (Martínez-Cob et al., 2010). Therefore, daytime irrigation results in higher WDEL and lower uniformity than nighttime irrigation (Playán et al., 2005; Cavero et al., 2008). Microclimatic changes last for up to 2–3 h after a sprinkler irrigation event (Robinson, 1970; Tolk et al., 1995; Playán et al., 2005; Martínez-Cob et al., 2008). These changes cause a decrease in crop transpiration and canopy temperature (Martínez-Cob et al., 2008; Cavero et al., 2009), which is greater in daytime irrigation than in nighttime irrigation (Cavero et al., 2009). Solid-set sprinkler daytime irrigation of maize in a Mediterranean climate has been reported to decrease grain yield by 5–13%, as compared to nighttime irrigation (Urrego-Pereira, a et al., 2013 and b). According to these authors, the decrease in grain yield is due to the lower uniformity of irrigation and the lower photosynthetic activity during daytime irrigation. The reduction in photosynthetic activity is related to the high wettability of the maize leaf, which reduces CO_2 exchange and to the decrease in air and vegetation temperature below the optimal for maize photosynthetic activity (Urrego-Pereira et al., 2013b). In the case of alfalfa, daytime sprinkler irrigation does not reduce photosynthesis (Urrego-Pereira et al., 2013b) because the maximum temperature to reduce transpiration is not reached and the alfalfa leaf is not-wettable. The water intercepted by leaves during irrigation quickly slips and falls to the ground without affecting CO_2 exchange. Cavero et al. (2016) concluded that in alfalfa there are no forage yield or quality differences between daytime and nighttime sprinkler irrigation.

When integrated in a collective irrigation network, on-farm irrigation decision-making should take into account the constraints imposed by the shared infrastructure (pipeline network and, in some cases, pumping station). Recent research efforts to combine hydrologic and economic optimization are based on models for water and energy allocation accounting for crops, soils, meteorology and infrastructure management (Mannocchi and Todisco, 2006; Alizadeh and Mousavi, 2013; Banihabib and Shabestari, 2017; Zapata et al., 2017). These days, investing in digital infrastructure and forecasting / management tools may be more productive than investing in additional physical infrastructure (Ilich et al., 2020).

Loureiro et al. (2023) addressed the importance of optimizing energy consumption for collective network sustainability in Portuguese irrigation districts. Different approaches to reduce the energy dependence of irrigation systems have been presented in the literature. The optimization of irrigation facilities, such as pumping stations and collective pressurized networks (Rodríguez Díaz et al., 2009; Moreno et al., 2010; Fernández García et al., 2013; Belaud et al., 2020) and recently the use of renewable energies (photovoltaics and wind) in irrigated projects (Campana et al., 2015; Narvarte et al., 2019; Naval and Yusta, 2022) have proven useful and cost-effective. Additional solutions, such as the reduction of energy requirements at the farm level by reducing the working pressure at the sprinkler nozzles, have been experimentally demonstrated (Robles et al., 2017; Zapata et al., 2018). These authors performed a field experiment in a maize crop comparing two working pressures at the sprinkler nozzle, 300 kPa (standard) and 200 kPa (low-pressure). They did not find statistical differences in maize yield between the pressure treatments when irrigating with the same amount of water and at the same time.

Recent model developments in Ador-Simulation (Zapata et al., 2017) coupled network hydraulics to a comprehensive analysis of water use, crop yield and economic profitability in solid-set sprinkler irrigated areas for advanced design and management. The general objective of this research is to progress in the expansion of model capacities to simulate modernization in real areas. The specific objectives of this paper are:

1. To simulate additional on-farm irrigation methods (center-pivot and drip irrigation);
2. To simulate crop intensification, with the possibility of double cropping in the same plot and season;
3. To simulate the crop response to different management options: irrigation time within the day, irrigation duration and standard vs. low-pressure sprinkler irrigation;
4. To verify and illustrate model performance using a variety of theoretical case studies; and
5. To apply the expanded simulation tool to a real irrigation project, optimizing irrigation design and the management of water and energy.

2. Materials and methods

2.1. The Ador-Simulation software of irrigated areas: description and improvements

2.1.1. The Ador-Simulation tool

This simulation tool started with the development of Ador-Sprinkler (Dechmi et al., 2004a; Playán et al., 2006), for the on-farm solid-set sprinkler irrigation method. Dechmi et al. (2004a and b) presented the coupling between on-farm solid-set irrigation and maize crop growth (Ador-Crop). Zapata et al. (2009) presented a new development of the tool that simulates seasonal irrigation in irrigation districts equipped with solid-sets. This version did not explicitly consider pipeline hydraulics in the connection between the on-farm irrigation systems and the collective network. The model was used to develop an automatic controller for sprinkler irrigation (Zapata et al., 2013), which was validated in the conditions of the Ebro Valley (North Eastern Spain). Zapata et al. (2017) presented progress in the Ador tool for the simulation of solid-set sprinkler irrigated areas using collective pressurized networks hydraulics for water supply to farms. Fig. 1 presents the different modules of the simulation software. A short description of the Ador-Simulation modules follows:

1. The EPANET module (Rossman, 2000) simulates the collective pressurized network. This module is coupled to the rest of Ador modules (Fig. 1a) for bidirectional communication. EPANET receives information on open/closed network hydrants and determines the pressure and discharge at each open network hydrant. A semi hourly time step is used for this process. The hydraulic design of the collective network in EPANET is required.
2. The on-farm irrigation module Ador-Sprinkler simulates solid-set sprinkler irrigation. A variety of sprinkler configurations can be simulated by selecting the sprinkler type, the nozzle size (principal and auxiliary nozzles), the working pressure at the nozzle(s), the meteorology and the sprinkler layout (sprinkler spacing along the sprinkler lines and between lines; rectangular on triangular arrangement). The spatial distribution of irrigation water within a sprinkler spacing and a number of irrigation performance indicators are retrieved from a database containing results from a previously calibrated and validated on-farm simulation model (Robles et al., 2019). A farm is typically divided into sequentially-irrigated sectors following a pre-established order, as presented in Fig. 1b. A sprinkler spacing is used to simulate water distribution in each sector using the Ador-Sprinkler module (Fig. 1c). Ballistic theory is applied to simulate drop dynamics and to determine irrigation depth at 25 simulation points uniformly distributed within the sprinkler spacing (Fig. 1d). Simulations are performed at a semi hourly time step (even if an irrigation event lasts for hours) to use the current meteorological variables conditioning uniformity and wind drift and evaporation losses (WDEL).
3. Ador-Crop. A soil water balance is performed at each of the 25 points in the sprinkler spacing representing each sector to simulate soil water and crop yield reduction from its maximum value (Fig. 1d). A variety of crops have been implemented in Ador-Crop (Zapata et al., 2017), but only one crop can be simulated at a plot in an irrigation season. Soil depth and its water holding capacity (WHC) are required to perform soil water balance. Irrigation requirements are determined from crop water status at the sector and plot level using a daily time step.
4. The Ador-Decision module performs irrigation decision making in all plots of the study area. Ador-Decision selects the plots to be irrigated taking into account their water stress (Zapata et al., 2017) and a series of user-defined limitations (such as crop water status, network hydraulics, electricity restrictions for pumping, and environmental or irrigation performance requirements). Ador-Decision is run at a semi hourly time step to fulfill both crop water requirements and the

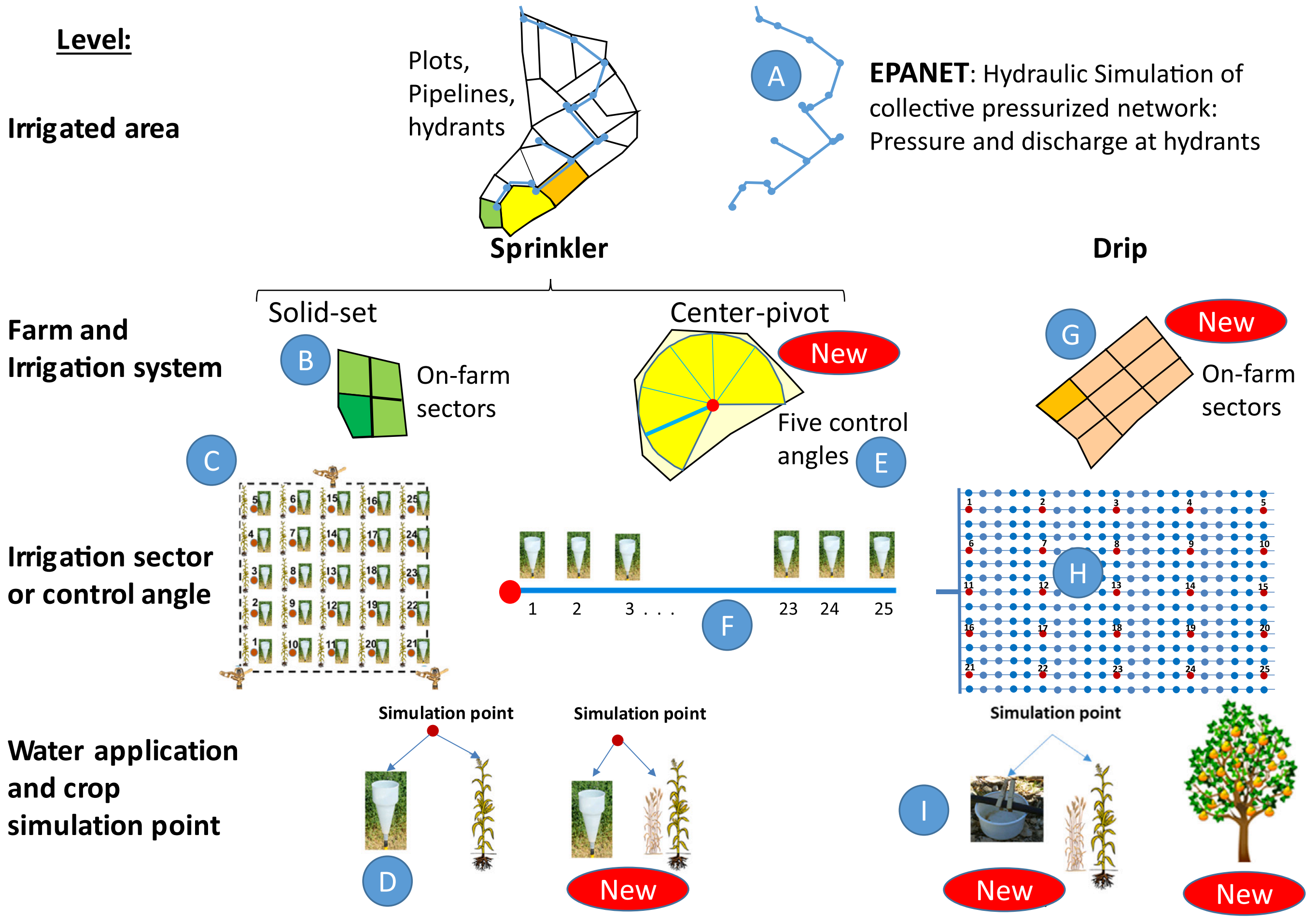


Fig. 1. Scheme of the Ador-Simulation tool, indicating its capacities at different levels, as well as the developments presented in this paper. A) EPANET hydraulic simulation of network. B) Solid-set on-farm. C) Solid-set simulation unit. D) Ador-Crop schemes for sprinkler irrigation (single and new double cropping). E) Center-pivot irrigation module (New). F) Center-Pivot simulation unit. G) Drip irrigation module (New). H) Drip irrigation unit. I) Ador-Crop schemes for drip irrigation (single and double cropping, and orchards).

user-defined limitations in a context of time-variable meteorology, network occupation and electricity costs.

Fig. 1 presents the new developments of the Ador-Simulation software, which are presented in this paper. These include improvements in Ador-Sprinkler, new on-farm irrigation methods (the Ador-Pivot and Ador-Drip modules), extended simulation capacities in Ador-Crop (two consecutive crops in the same plot and season) and improved on-farm irrigation management practices (the effect of irrigation frequency and timing on crop development and irrigation water losses).

2.1.2. Ador-Sprinkler: enlarging the sprinkler simulation results database

The sprinkler simulation module has been improved by extending the database of sprinkler irrigation simulation cases. Impact sprinklers working at low pressure (200 kPa) have been made available for additional sprinkler manufacturers and nozzle sizes (5.2 mm main nozzle and 2.5 mm auxiliary nozzle). The combination of low pressure (200 kPa), these nozzle diameters and usual sprinkler spacings (18 $\times$18 m) results in an adequate pluviometry for solid-set irrigation systems (about 5.2 mm/h) and permits to moderate pumping costs.

2.1.3. Ador-Pivot: new module

The implementation of center-pivot sprinkler irrigation started with a classification based on the angle covered by the machine: Full-circle (Pivot-FC) or partial circle (Pivot-PC). The following variables have been implemented in Ador-Pivot to characterize the hardware and the operation of the machine:

1. Angle covered by the irrigation machine: 360º for a Pivot-FC and between 0 and 360º for the Pivot-PC.
2. Gross Irrigation Depth (GID, in mm h^{-1}): The irrigation depth emitted by the pivot machine when operated at 100% speed (i.e., when the outermost pivot tower does not stop).
3. Irrigation period: The time it takes for the pivot to cover its angle when operating at 100% speed, expressed in h $round^{-1}$.
4. Irrigated area: the effective area irrigated by the pivot, expressed in hectares.
5. Experimental Distribution Uniformity of the low quarter (DUlq, %). This variable is user-defined and can be obtained from ad-hoc experimentation or from the literature (Evans et al., 1995).
6. Pressure at the nozzle: The designed working pressure of the center pivot sprinkler package, expressed in kPa, and established by the pressure regulators installed just upstream from each spray sprinkler.
7. Direction of rotation: FC pivots have one direction of rotation (clockwise), while PC pivots sequentially irrigate clockwise and counterclockwise.
8. Current angle: the location (angle) of the pivot span at a given time, expressed in degrees. It always starts at 0º and increases to reach the total irrigated angle. At that time it starts again if the pivot is FC and it changes the direction of rotation (decreasing the angle) if the pivot is PC.

9. Control angle: The total irrigated area of a pivot is represented by five control radii (Fig. 1e), dividing the area in five homogeneous portions and locating a control radius at the middle of each section. A control angles is the angle where each control radius is located. Each control radius has twenty-five simulation points (Fig. 1f) homogenously distributed along the radius length. At each point, irrigation depth and crop development are simulated.

When the pivot passes over one of the control angles, irrigation is simulated in its 25 simulation points. The net irrigation depth (NID, mm h^{-1}) at each point is determined using the pivot GID (variable 2 in this list) and two irrigation performance indexes: Wind Drift and Evaporation Losses (WDEL, %) and Distribution Uniformity (DUlq, %). WDEL are estimated using the empirical equation presented in Eq. (1) (Playán et al., 2005). WDEL are used in Eq. (2) to determine the average net irrigation depth ($\overline{NID}$, mm h^{-1}) at every simulation point.

$$WDEL = -2,1 + 1,91 * u + 0,231 * T \quad (1)$$

$$\overline{NID} = \frac{GID(100 - WDEL)}{100} \quad (2)$$

With u the wind speed, in m s^{-1}, and T the temperature, in Celsius degrees.

To assign the net irrigation depth at each simulation point, a normal distribution with a known average ($\overline{NID}$) and Standard Deviation (SD) is applied (Eqs. (3) and (4)). The SD is determined from $\overline{NID}$ and DU_{lq} through the coefficient of variation (CV), assuming a random distribution of pivot water application. The variability in net irrigation depth is randomly assigned in every irrigation event to the twenty-five simulation points. This procedure permits the integration of the random wind disturbance into the distribution of irrigation water in pivot irrigation machines.

$$CV = 100 * \frac{1 - \frac{DU_{lq}}{100}}{1} - 1.27 \quad (3)$$

$$SD = \overline{NID} * \frac{CV}{100} \quad (4)$$

Wind speed has been recognized as the meteorological variable with the largest effect on WDEL and DU_{lq} in solid-set sprinkler irrigation. However, the effect of wind speed on DU_{lq} in center-pivot irrigation systems is much lower than in solid-sets (Playán et al., 2005; Ouazaa et al., 2016). The key hypothesis in this module is that the DU_{lq} of a pivot-irrigated plot does not change with meteorology, while WDEL varies with wind speed and air temperature. The value of NID resulting from a constant DU_{lq} and a variable WDEL is randomized in every irrigation event. We assume that this variability is randomly generated by the wind, given the small distance separating spray sprinklers (typically, about 3 m), much smaller than their irrigated radius. Therefore, the NID (mm h^{-1}) of a certain point in a pivot-irrigated plot will be different in every irrigation event. These assumptions are supported by the findings of Ouazaa et al. (2016), who pointed out differences between 0.5% and 3% on radial Heermann and Hein uniformity coefficient for irrigation events performed by a center pivot under wind speed from 1.0 to 4.7 m s^{-1}.

2.1.4. Ador-Drip: new module

This module (Fig. 1 g, h and i) uses the following variables to represent a drip-irrigated field:

1. The distance between the lateral lines (m);
2. The distance between the drippers in the laterals (m);
3. The nominal flow (discharge) of the drippers (L h^{-1});
4. The nominal working pressure of the dripper (kPa); and
5. The experimental DU_{lq}. This variable is user-defined and can be obtained from ad-hoc experimentation or from the literature (Burt, 2004).

Twenty-five simulation points are considered in each drip-irrigated field. As in the case of center-pivot irrigation, the variability in net irrigation depth is obtained by applying a normal distribution model with known average ($\overline{NID}$) and standard deviation (SD, Eqs. (3) and (4)). In the drip irrigation case, the spatial distribution of NID is random, but it is the same in all irrigation events (making an important difference with the Center-Pivot case), since the only sources of variability considered in this case are the design of the irrigation system and the variability in the fabrication of the emitters. Therefore, the NID (mm h^{-1}) of a certain simulation point in a drip-irrigated plot will be the same in all irrigation events.

2.1.5. Ador-Crop: extension to two consecutive crops per season

The Ador-Crop module was updated to simulate two consecutive crops in the same season (double cropping). Four such schemes have been considered in this research: barley + maize, barley + sunflower, peas + maize and peas + sunflower. The selection of these cropping schemes responds to their current representativeness in the Ebro River Basin irrigated area. The frequency of double cropping has increased in some modernized irrigation areas due to the possibilities of the new automated irrigation systems and to the necessity of increasing net income to payback the investment in irrigation equipment and, in some cases, the energy costs.

To simulate a double cropping scheme, the seeding date of the second crop is not user-controlled, but determined by the harvest date of the first crop. In turn, the harvest date of the first crop is controlled by the completion of the thermal time target (Eq. (5)).

$$Thermal \quad time = \sum_{k=seed}^{senescence} (Tk - Tb), Tk \geq Tc \quad (5)$$

With Tb the basal temperature (ºC) and Tk the daily average air temperature (ºC).

The soil water content at the beginning of the second crop is inherited from the first crop (the soil water content at harvest of the first crop). Ador-Crop provides a number of agronomic, hydrologic and economic parameters individually determined for each crop and for both successive crops when adequate. Irrigation efficiency was seasonally determined as the ratio between net irrigation depth and gross irrigation depth.

2.1.6. Sprinkler irrigation management: Irrigation frequency and timing

In solid-set and center-pivot sprinkler systems, irrigation frequency affects the wetting-drying events of the leaves, and consequently interception water losses. Previous research works (Martínez-Cob et al., 2008; Cavero et al., 2009; Urrego-Pereira, a et al., 2013 and b) reported that interception losses depend on crop architecture, being leaf wettability a critical trait. Corn (with wettable crop leaves) and alfalfa (with non-wettable crop leaves) respond differently to the intercepted water. The Ador-Simulation release presented by Zapata et al. (2017) considers WDEL, but does not consider interception losses. In the current model release, interception losses have been incorporated.

Martínez-Cob et al. (2008) conducted a detailed study in maize using weighing lysimeters. These authors concluded that net interception losses (i.e., consumptive losses due to interception), amounted to 0.5 mm in daytime irrigation and between 0.1 and 0.3 mm in nighttime irrigation. Stambouli et al. (2013), following the same methodology as Martínez-Cob et al. (2008) but in an alfalfa crop, proposed similar values (0.5 mm for daytime irrigation and between 0.1 and 0.28 mm for nighttime irrigation). These developments have made it possible to integrate interception losses into Ador-Crop.

The irrigation timing (daytime vs. nighttime irrigation) can also affect crop transpiration. Microclimatic changes originate during sprinkler irrigation and can last for up to 2–3 h, causing a decrease in transpiration and vegetation cover temperature (Martínez-Cob et al., 2008; Cavero et al., 2009), which are more significant in daytime than in nighttime irrigation (Cavero et al., 2009). In daytime irrigation, there are differences in photosynthetic activity and yield between wettable and non-wettable leaves. The high wettability of the maize leaf reduces CO_2 exchange and, at the same time, the microclimatic changes reduce the air and vegetation cover temperature below the optimum for the photosynthetic activity of maize (Urrego-Pereira et al., 2013b). During nighttime irrigation - since transpiration is practically null - there are no differences between wettable or non-wettable leaves. For alfalfa, with non-wettable leaves, stomata are not plugged by the sheet of irrigation water and the temperature is not below optimum. Therefore, this crop follows its normal transpiration processes during daytime irrigation (Cavero et al., 2016).

The effect of irrigation timing has been treated differently in the model for corn and alfalfa. The reduction of the photosynthetic activity during maize daytime irrigation has been indirectly incorporated in Ador-Crop, since this simplified model does not simulate photosynthetic processes. Following the results of Martínez-Cob et al. (2008), Cavero et al. (2009) and Cavero et al. (2016), when maize is daytime irrigated, a reduction in the thermal time governing crop development is introduced. This reduction is proportional to the duration of the irrigation event. The thermal time of alfalfa was not modified. For the rest of simulated crops in Ador-Crop, the differential response between daytime and nighttime irrigation was not implemented either, in this case due to the absence of experimental data in the literature. Incorporating this effect is very important in the Ebro valley, due to the prevalence of maize in most crop rotations.

2.2. *Application of the updated Ador-Simulation model to a theoretical problem*

2.2.1. *General characteristics of the study area*

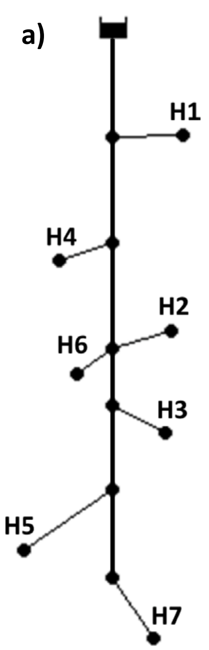
Fig. 2 presents the layout of the collective pressurized irrigation network of the theoretical problem, as defined in EPANET. The network has seven hydrants (from H1 to H7), all with the same nominal flow rate (48 L s^{-1}). Each hydrant irrigates a 30 ha farm. The considered on-farm irrigation systems include:

- Pivot-FC machines. A theoretical DU_{lq} of 85% has been selected to simulate irrigation water distribution. This value represents modern center-pivots with high design standards, equipped with suitable sprinkler nozzle packages and pressure regulators (Dukes et al., 2006; Ouazaa et al., 2016), adequately operated and maintained.
- Pivot-PC machines. The theoretical DU_{lq} was 85%, equal to Pivot-FC machines.
- Solid-set sprinkler irrigation. The sprinkler layout is triangular, with 18 m between lines and 18 m between sprinklers. Impact sprinklers have main and auxiliary nozzles with diameters of 4.4 and 2.4 mm, respectively.
- Surface drip irrigation for fruit orchards (Drip-O). The drip layout has larger spacing than that for field crops. The spacing is user-selected and adapted to the layout of the trees in the orchard. A theoretical DU_{lq} of 90% has been selected for this problem. The value corresponds to adequately designed and maintained systems (Burt, 2004; Styles et al., 2008)
- Subsurface drip irrigation for field crops (Drip-SS). The drip layout has spacings of 0.75 m between drip lines and 0.5 m between drippers. A theoretical DU_{lq} of 90% was selected, as in the previous drip system.

The agrometeorological data of the Grañén SIAR Network station for the 2014 irrigation season was used in this problem. The soils of the plots were considered homogenous, with an average depth of 1.00 m and a moderate soil water holding capacity (SWHC) of 107 mm m^{-1}.

Four case studies were simulated (from CS1 to CS4). Fig. 2b summarizes the characteristics and the objective of each variant:

- CS1. Simulates the irrigation of four plots with maize crops with different on-farm methods: Pivot-FC (H1), Pivot-PC of 180º (H3), Solid-Set (H4) and Drip-SS (H6). The case study evaluates the new model developments related with on-farm irrigation (Fig. 1E and G).
- CS2. Similar to CS1 but using double cropping (barley followed by short-cycle maize) in all plots. The case study evaluates the new model developments related with double-cropping (Fig. 1D and I).
- CS3. Simulates that all hydrants of the collective network are cropped with maize. This case compares two solid-set sprinkler design and management cases: standard pressure (300 kPa) versus low pressure (200 kPa). Network operation requires pressures at the



b)

Case Study	Operative hydrants	On-farm irrigation method	Crops	Objective
CS1	H1, H3, H4, H6	Solid-Set (H4), Pivot-FC (H1), Pivot-PC (H3), Drip-SS (H6)	Maize	To compare on-farm irrigation method to irrrigate a maize crop
CS2	H1, H3, H4, H6	Solid-Set (H4), Pivot-FC (H1), Pivot-PC (H3), Drip-SS (H6)	Barley + Maize	To compare on-farm irrigation methods to irrrigate a barley + maize double cropping scheme
CS3	H1, H2, H3, H4, H5, H6, H7	Solid-Set	Maize	To compare on-farm Solid-Set at two working pressures: standard (300 kPa) and low (200 kPa)
CS4	H1, H2, H3, H4, H5, H6, H7	Solid-Set	Maize	To compare irrigation timing (nighttime *vs.* any time) and duration.

Fig. 2. The irrigation network of the theoretical problem: a) layout as represented in EPANET; and b) key characteristics of the four case studies (CS).

pumping station of 40 m and 30 m to irrigate at 300 and 200 kPa, respectively. The only difference required in the on-farm irrigation design is the nozzle diameters. The standard pressure implements sprinklers equipped with 4.4 mm and 2.4 mm nozzles, while the low-pressure implements sprinklers equipped with 5.2 mm and 2.5 mm nozzles.

- CS4. The seven plots are equipped with solid-set irrigation systems and cultivate maize. The effects of irrigation management (duration and timing) on yield, gross irrigation depth, interception losses and net income were analyzed. Simulations were performed for two soil types: the original one (as described above) and a second one with higher depth and water holding capacity, 1.40 m and 180 mm, respectively.

In all cases, hydrologic (seasonal gross irrigation, irrigation efficiency, seasonal distribution uniformity, seasonal water losses), agronomic (crop yield) and economic (gross and net income) indicators were determined and compared.

2.3. Application of the updated Ador-Simulation model to a real problem

2.3.1. General characteristics of the study area

This problem involves a recently formed Water Users Association (WUA) on a previously dry-farmed area of 931 ha, which is being transformed to pressurized irrigation (with sprinkler and drip irrigation methods). This WUA, named "Bardenas XI", belongs to the Bardenas project in the Aragón Autonomous Community and the Zaragoza province of Spain (Fig. 3a and b). Crop water requirements were determined using data from the "Ejea de los Caballeros" station of the SIAR agro-meteorological network, located 7 km west of the study area. The analyzed data set covers the period 2004–2018: 15 years of daily and semi-hourly meteorological data.

A soil sampling campaign was performed in January 2019 to determine soil physics properties of interest for irrigation. The 1/50.000 geologic map of Spain (IGME, 2015) was overlapped with the map of the study area to determine the sampling locations. The points selected for soil sampling resulted from the litho-stratigraphic distribution of the study area. A total of 13 points were sampled (from P3 to P15 in Fig. 3c). An auger was used to obtain 0.30 m samples to a maximum depth of 1.20 m. Soil samples were analyzed at the laboratory following the methodology proposed by the Soil Survey Field and Laboratory Methods Manual (2014) for stoniness (as a percentage). Soil water content at field capacity (FC) and at permanent wilting point (PWP) were determined using pressure plates set at 33 and 1500 kPa, respectively. The soil bulk density was obtained from a study performed nearby (Lecina et al., 2004), assigning values of 1.40 and 1.52 Mg m^{-3}, for lower river valley and upper platform soils, respectively. The SWHC (mm m^{-1}) was obtained for each sample from stoniness, FC, PWP and bulk density (Porta et al., 2003). Table 1 presents the classification ranges for this variable. Soil depth was classified in four classes: lower than 0.60 m, 0.60–0.90 m, 0.90–1.20 m and higher than 1.20 m. These classes will be referred to as shallow, moderate, deep and very depth, respectively. The combination of SWHC and soil depth was used to define the soil types of the study area.

The network design used in the construction project aimed to supply irrigation water to a predefined cropping pattern: 25% alfalfa, 10% fruit orchards (peach trees), 18% sunflower, 32% maize, 5% vineyard and 10% wheat. The key design question at this WUA is whether to pump irrigation water.

2.3.2. Collective network design without pumping station

The designed network starts at an elevated reservoir providing natural pressure to the 52 network hydrants supplying water to the irrigated plots. This option results in different pressures at the hydrants (from higher than 400 kPa to lower than 250 kPa). These differences are mainly due to differences in hydrant elevation within the irrigated land (the difference between the highest and the lowest hydrant was 68 m).

On-farm irrigation systems were assigned as a function of the available pressure at the hydrant. Plots with pressure at the hydrant larger than 400 kPa were equipped with solid-set sprinkler using standard pressure at the sprinkler nozzles (300 kPa). Plots with pressure at

Table 1
Soil classification used in the study area by Soil Water Holding Capacity (*SWHC, mm m*$^{-1}$).

SWHC (mm m^{-1})	Classification
< 43	Very Low
43–85	Low
85–127	Moderate
127–167	High
> 167	Very High

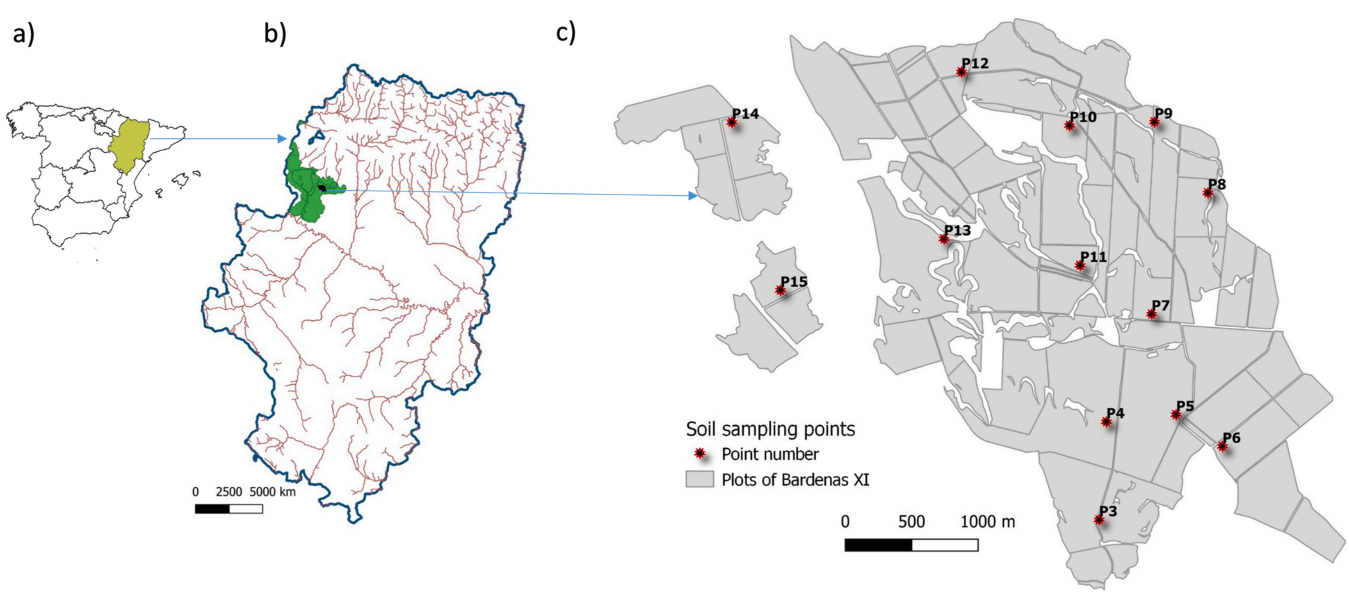


Fig. 3. Location of the real problem: a) Spain and its Autonomous Communities, with Aragón in green; b) Aragón and the Bardenas Irrigation project; and c) Water Users Association "Bardenas XI", indicating its plots and the soil sampling points.

the hydrant between 400 and 300 kPa were equipped with solid-set sprinkler using low-pressure at the sprinkler nozzles (200 kPa). Plots with pressure at the hydrant between 300 and 200 kPa were equipped with center-pivots. Finally, plots with pressure at the hydrant equal to or lower than 200 kPa were equipped with drip irrigation.

A relationship between the crop and the on-farm irrigation method was established: horticultural crops and orchards used drip irrigation, while field crops used any sprinkler irrigation system (solid-set or center-pivot).

2.3.3. Collective network design with pumping station

A pumping station was designed to ensure a minimum pressure of 400 kPa at all hydrants. The pumping station added a supplementary pressure of 180 kPa to natural pressure. A total power of 350 kW was required at the pumping station. In 2019, the electricity tariff adequate for this pumping station was the "3.1″ tariff, with three periods for both power and energy costs. The three periods, off-peak, base and peak, were associated to cheap, medium and expensive electricity, respectively. The timing and the power price of the different periods were regulated by the Spanish law (BOE, 2018). The energy price of the different periods was not regulated, and was obtained from neighboring WUAs (Zapata et al., 2017). The description of each tariff period considered in this study was as follows:

1. The off-peak period runs from 0:00–8:00 on working days and from 0:00–18:00 on weekends and national holidays. The power cost is 8.368 € kW^{-1} $year^{-1}$ and the energy price is 0.078 € kWh^{-1}.
2. The base period runs from 8:00–10:00 and from 16:00–24:00 on working days and from 18:00–24:00 on weekends and national holidays, from April to October both included. The power cost is 36.491 € kW^{-1} $year^{-1}$ and the energy cost is 0.097 € kWh^{-1}.
3. The peak period runs from 10:00–16:00 from April to October, both included. The power cost is 59.173 € kW^{-1} $year^{-1}$ and the energy cost is 0.106 € kWh^{-1}.

The payback of the investment cost and the maintenance of the pumping station should also be included when computing net income for this design option. The annual payback was estimated at 50 € ha^{-1} and year, in agreement with observations of similar systems in the Ebro valley.

2.3.4. Analyses performed at the studied WUA

In a first step, Ador-Simulation was applied to the Bardenas XI pressurized network and the abovementioned cropping pattern for the multiannual meteorological data set. Hydrologic, agronomic and economic performance indicators were obtained.

In a second step, comparisons were established between network designs with and without the pumping station. Originally, the collective network was designed without pumping station. The only difference with the previous simulation in the WUA was the cropping pattern. A new crop distribution was introduced, only including field crops: 25% maize, 25% alfalfa, 10% wheat and 40% double cropping of peas and maize.

Differences in annual irrigation and crop performance indicators induced by differences in on-farm irrigation methods, soils and crops were assessed using mean comparisons. The interaction between explicative variables can be relevant and is not always intuitive. For instance, vineyards and fruit orchards are only irrigated by drip irrigation, while field crops are irrigated by different on-farm methods. Box plots were used to facilitate this analysis.

3. Results and discussion

3.1. Application of Ador-Simulation to a theoretical problem

The Ador-Simulation tool was applied to the five case studies described in Fig. 2 with the aim of illustrating the capacity of the software to contribute to the design and management of collective pressurized WUAs.

3.1.1. Maize and pressurized irrigation systems, CS1

The simulated irrigation depth, irrigation performance indexes, maize yield and gross and net income are presented in Fig. 4 for each on-farm irrigation method. The seasonal irrigation depth of the irrigation methods, presented in decreasing order, was: Solid-Set, Pivot-FC, Pivot-PC and Drip-SS (Fig. 4a). Deep percolation losses, WDEL and total losses are presented in Fig. 4b. The most significant losses were observed in the Solid-Set method. Center-pivot irrigation obtained the lowest deep percolation losses and the highest seasonal distribution uniformity (98%) due to the complete random spatial distribution of irrigation water. Drip irrigation had zero WDEL since in this method water is directly applied to the soil. Regarding total water losses, the irrigation methods can be decreasingly ordered as: Solid-Set, Pivot-FC, Pivot-PC and Drip-SS (Fig. 4b). Differences between pivot methods, full circle and partial circle, were very low and could be considered similar in this CS. The large total losses of the Solid-Set method explain its large seasonal irrigation depth (Fig. 4a), in comparison with the other on-farm methods. Surface drip has some evaporative losses from the wet bare soil surface, and even subsurface drip does because some water moves to the surface by capillary action. However, these processes have not been considered in this research because there are not sufficient experimental data in the literature and because the magnitude of losses is expected to be low.

Fig. 4c shows how on-demand irrigation adequately irrigated maize in all irrigation methods, obtaining relative yields of 96–98%. The design of this case study ensures that differences in irrigation depth, irrigation losses and economic income are almost completely due to the on-farm method. Seasonal actual evapotranspiration (ET_{actual}) presented minor differences between on-farm methods (Fig. 4c), mostly due to small differences in maize seeding date between plots. Differences in gross and net income between on-farm methods were also minor, since the operation of the collective network operation does not require energy for pumping (Fig. 4d). Differences in income only accounted for differences in yield and the cost of irrigation water.

3.1.2. On-farm irrigation systems and crop intensification validation and comparison, CS2

The only difference between CS1 and CS2 is that in this case the four plots are double-cropped with barley followed by short cycle maize. Irrigation depth, losses, ET and income were larger for CS2 than for CS1 in all irrigation methods, since CS2 is more intensive than CS1 (Fig. 5). Comparisons between on-farm methods are quite similar to CS1, with small differences. In CS2 the lowest seasonal irrigation depth was obtained for Pivot-PC (Fig. 5a), due to its high seasonal irrigation uniformity (99%) and its moderate total losses (Fig. 5b). As in CS1, the lowest deep percolation losses were found in Pivot systems (Pivot-PC and Pivot-FC). This is related to their high seasonal DU_{lq} (99% and 98%, respectively). The largest deep percolation losses were obtained for Drip-SS (25 mm), followed by Solid-Set (24 mm). These losses resulted from seasonal DU_{lq} of 90% and 91%, respectively. The effect of seasonal DU_{lq} on deep percolation is remarkable. Solid-Set systems showed the largest WDEL and total irrigation losses, since Drip-SS has null WDEL and the lowest total losses (Fig. 5b).

CS2 presented high crop yields and similar values of ET_{actual} (Fig. 5c) for all the studied methods. Differences in crop yield between on-farm methods amounted to 3% and 4%, for barley and maize, respectively. In all on-farm methods, the yield of the second crop was reduced from 7% to 11% from maximum, for Pivot-FC and Drip-SS, respectively. The parameters describing the thermal time for maize as a second crop were calibrated in a different meteorological area within the Ebro Valley. A shorter cycle maize variety would probably have obtained a lower yield reduction.

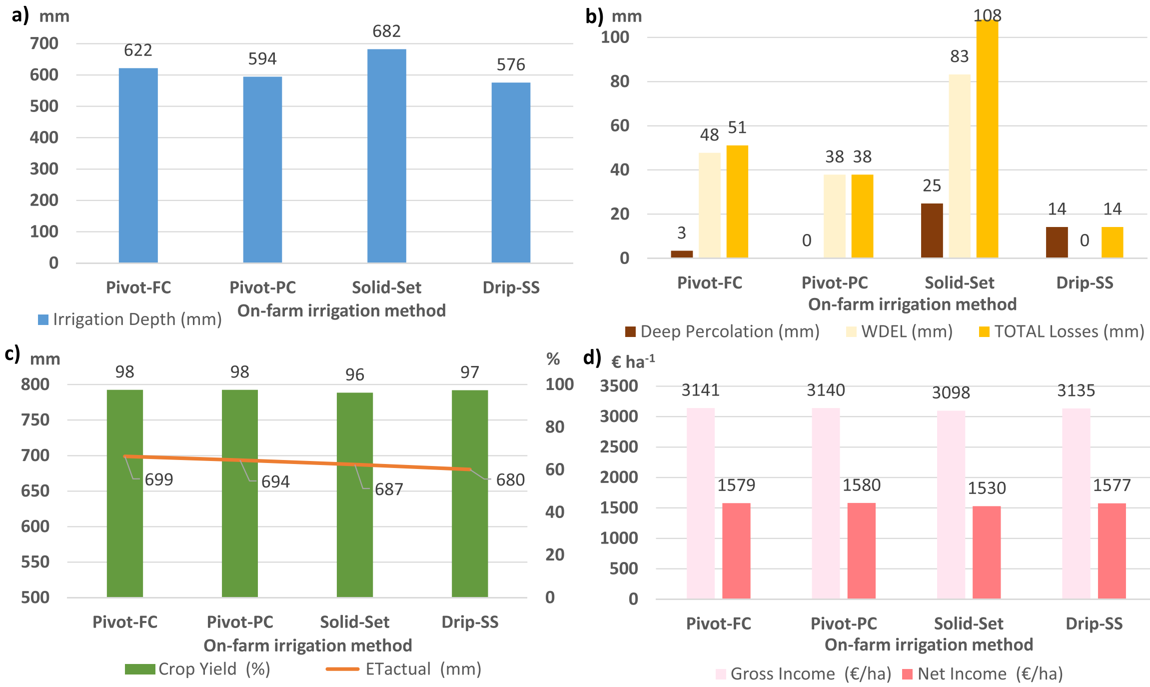


Fig. 4. Results of Case Study 1, maize irrigated with four irrigation methods: a) seasonal irrigation depth; b) irrigation losses; c) crop yield; and d) gross and net income.

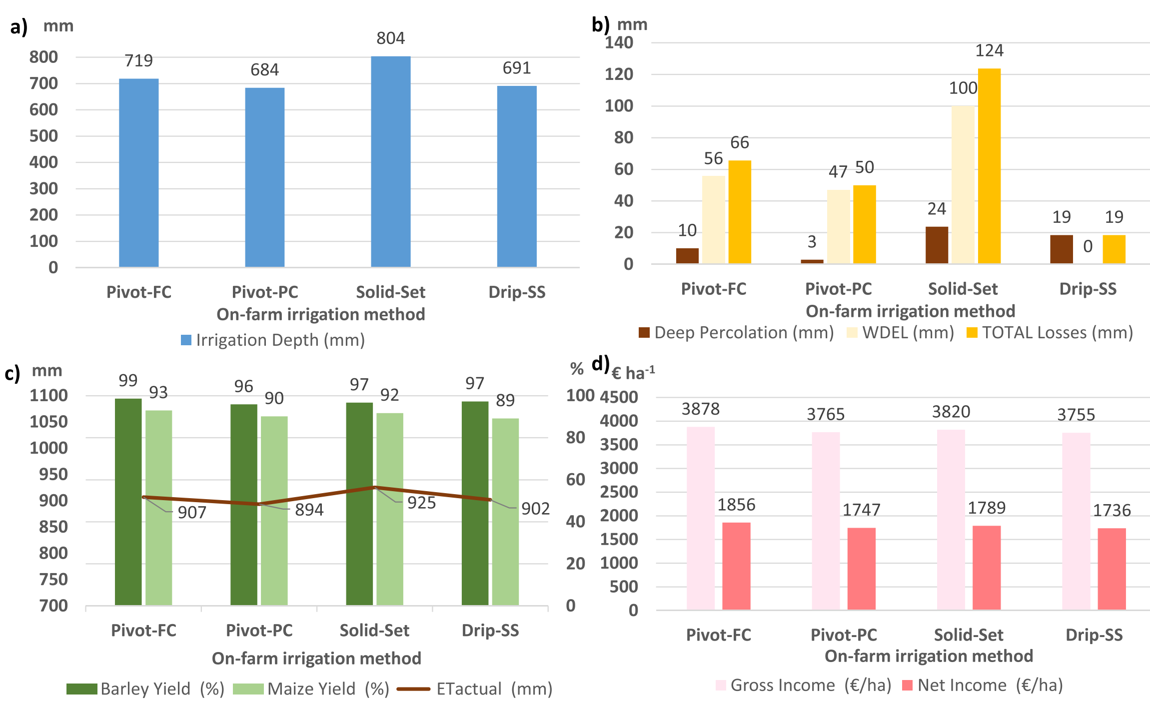


Fig. 5. Results of Case Study 2, double cropping (maize and barley) irrigated with four irrigation methods: a) seasonal irrigation depth; b) irrigation losses; c) crop yield; and d) gross and net income.

Differences in gross and net income between on-farm methods account for differences in gross irrigation and yield (Fig. 5d). Pivot-FC showed slightly larger gross and net income for this intensive cropping pattern than the other irrigation methods. Minor differences were found between the other irrigation methods. Results highlight the important effect of a small yield decrease on net income (in this case a slightly larger yield reduction was observed for the second crop with Drip-SS). The effect of differences in water use between irrigation methods on net income was small because no energy (and no cost) was required for water application in CS2.

CS2 results validate the use of different on-farm irrigation methods under double cropping. Further efforts are required to adjust the thermal time parameters of short cycle maize to different meteorological areas in the Ebro valley. If water application requires energy for pumping, the electric cost will primarily affect net income for the different irrigation methods.

3.1.3. Standard vs low-pressure in solid-set irrigation, CS3

Case Study 3 compares standard and low-pressure sprinkler solid-set irrigation with different nozzle configurations leading to a similar sprinkler discharge (about 1650 L h^{-1}) and irrigation application rate (about 5.2 mm/h) when operated at 300 and 200 kPa. The difference in nozzle pressures induces a difference in pressure requirements at the collective network inlet, which is 100 kPa higher for standard pressure than for low pressure.

Table 2 presents a set of irrigation and yield performance variables for both working pressures. Average values for the total irrigated area and differences between working pressures are presented. Simulated results reveal that differences in almost all analyzed variables are very low (lower than 3% for all variables except for the deep percolation, which reached 6%). Differences are quite similar to those reported by Robles et al. (2017) and Zapata et al. (2018), who presented experimental comparisons of maize under both working pressures. Robles et al. (2017) reported differences of 10% in seasonal Christiansen Uniformity Coefficient and no differences in yield. Zapata et al. (2018) explained that maize canopy partitioning reduces the differences in irrigation performance indexes between the pressure treatments, explaining why differences in grain yield between pressures were not found. These authors indicated that caution should be used when measuring sprinkler irrigation performance above tall canopies, since the elevation of the catch-cans and the crop canopy partitioning affect performance estimations. The corrections proposed by these authors were included in the crop simulation model, which produced adequate yield estimates.

3.1.4. Effect of irrigation frequency and timing on simulation results, CS4

Different solid-set irrigation duration and timing (daytime or nighttime) were evaluated in Case Study 4 under two soil types, as described above. The model generates an irrigation schedule based on soil water balance, but the user can control the irrigation duration per irrigation event. Different durations were tested: from 1 to 4 h, with a time step of 1 h. The shorter the irrigation event, the higher the irrigation frequency. Additionally, different irrigation timing arrangements were simulated for maize: on-demand (daytime or nighttime) and only nighttime irrigation.

Fig. 6 presents the average seasonal irrigation depth, interception losses and yield for the different subcases. As the irrigation duration increased (and frequency decreased), the seasonal irrigation depth increased for the soil with moderate water holding capacity (Fig. 6a). For the soil with high water holding capacity (Fig. 6d), the seasonal irrigation depth remained constant for irrigation durations equal to or larger than 2 h $event^{-1}$. These differences are mainly related to deep percolation losses, which drastically increased with long irrigations (4 h $event^{-1}$) in soils with moderate water holding capacity. On-demand irrigation of maize resulted in slightly larger seasonal irrigation depth than nighttime irrigation for soils with moderate water holding capacity (Fig. 6a). In the soil with high water holding capacity, the irrigation duration had less impact on irrigation depth (Fig. 6d).

Table 2
Hydrologic, agronomic and economic performance indicators for the solid-set irrigation systems of Case Study 3 working at two nozzle pressures: standard (300 kPa) and low (200 kPa). Average values and differences are presented.

Performance Indicator	Working pressure at the sprinkler nozzle (kPa)		Difference respect to 300 kPa (%)
	300	200	
Seasonal WDEL (mm)	94.7	96.5	1.9
Seasonal Deep Percolation (mm)	54.3	57.7	6.3
Seasonal DU_{lq} (%)	87.3	84.9	-2.7
Irrigation Efficiency (%)	84.0	83.8	-0.2
Yield (%)	97.3	97.4	0.1
Seasonal irrigation depth (mm)	668	675	1.0
Gross Income (€ ha^{-1})	3134	3136	0.1
Net Income (€ ha^{-1})	1634	1636	0.1

Interception losses drastically decreased with the increase in irrigation duration (Fig. 6b and e). The number of wetting-drying events decreased as the duration of irrigation events increased. Therefore, interception losses were severely reduced. Soil characteristics and irrigation timing (daytime or nighttime) showed no effect on interception losses.

Irrigation durations exceeding 2 h $event^{-1}$ showed a slight effect on maize yield, particularly for the soil with high water holding capacity (Fig. 6f). Irrigation timing had a moderate effect on yield for the soil with moderate water holding capacity (Fig. 7c), and practically no effect for the soil with high water holding capacity (Fig. 6f). In soils with moderate water holding capacity, an optimum irrigation duration $2-3$ h $event^{-1}$ could be identified (Fig. 6c).

These results also suggest that there is not a general irrigation strategy regarding these variables, and that specific analyses are required for each physical environment (soils, meteorology) and irrigation structures (collective irrigation networks and pumping stations).

3.2. Application of Ador-Simulation to a real problem: the Bardenas XI WUA

The average annual precipitation of the time series was 405 mm, with an inter-annual coefficient of variation (CV) of 25%. The highest annual precipitation was 636 mm in 2018 (wettest year) and the lowest precipitation was 238 mm in 2005 (driest year). Monthly precipitation showed a large variability during the study years. April was the wettest month (average precipitation of 56 mm), while August was the driest one (average precipitation of 16 mm). August presented the highest inter-annual precipitation variability (with a CV of 126%), while October was the month with the lowest variability of precipitation.

The average annual reference evapotranspiration (ET_0) was 1271 mm, with a low inter-annual coefficient of variation (4.6%). The highest annual ET_0 was 1365 mm in 2012, while the lowest was 1167 mm in 2008.

The irrigated area can be classified as moderately windy (Martínez-Cob et al., 2008). The average annual wind speed was 2.9 m s^{-1}, with an inter-annual CV of 7%. February was the windiest month on record, with an average wind speed of 3.4 m s^{-1}. September was the least windy month, with an average of 2.5 m s^{-1}. The average monthly wind speed was equal to or larger than 2.5 m s^{-1} in the twelve months of the year. The windiest year was 2010, with an annual average of 3.3 m s^{-1}, while the least windy year was 2008, with an annual average of 2.5 m s^{-1}. Like in other windy areas of the Ebro river basin, the windiest hours were the central hours of the day, from 12 to 16 GMT, and the least windy period was the nighttime, from 20 to 6 GMT.

The thirteen soil samples (Fig. 3c) were processed at the laboratory to determine SWHC. The average SWHC was 152 mm m^{-1}, with 83 mm m^{-1} being the lowest value (P5, Fig. 3c) and 236 mm m^{-1} being the highest (P6, Fig. 3c). In general, low SWHC values were found in soils with the lowest depth.

The spatial distribution of the eight soil types is presented in Fig. 7a. Plots with a soil sample were assigned their measured value. Plots without a soil sample were assigned the same value than their geological class. As previously reported, the geological map was used to determine the number and location of soil samples to characterize the different geological classes. In Fig. 7a, intense red color presents soils with moderate depth and SWHC, while intense green presents soils with high depth and SWHC. The combination of SWHC and soil depth and its percentage of representativeness in the area is presented in Table 3. Eight soil types are represented in the study area. Deep soils with moderate, high and very high SWHC are the most common, with 20.6%, 15.7% and 21% of the total area, respectively. The soil types with lowest

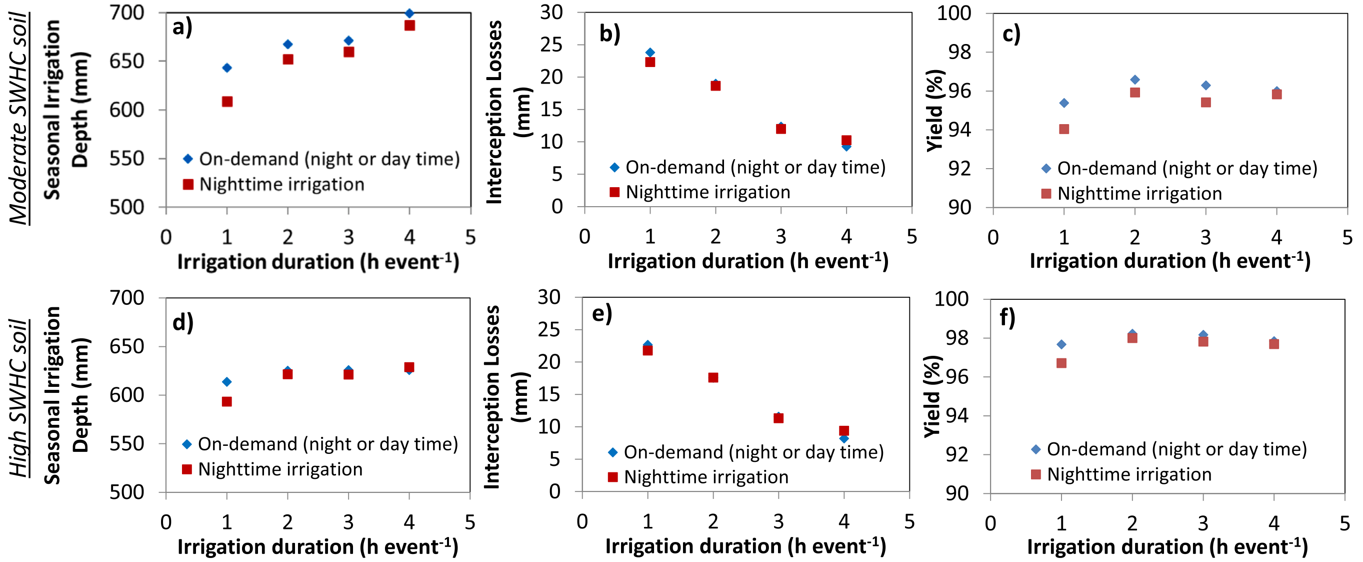


Fig. 6. Results of Case Study 4. Seasonal irrigation depth (a and d), interception losses (b and e) and net income (c and f) as a function of irrigation duration under two management options: irrigation on-demand or only during the nighttime. Subfigures a, b and c correspond to a soil with moderate depth and water holding capacity (1.00 m and 107 mm, respectively), while subfigures d, e and f correspond to a deep soil with high water holding capacity (1.40 mm 180 mm, respectively).

representativeness are deep soils with low SWHC, with 5.6% of the area, followed by soils with moderate depth and high SWHC, with 6.2% of the area.

Crop spatial distribution was randomly attributed, respecting the crop pattern percentages accounted for during the design of the collective network. Only vineyard plots were manually assigned, since vineyards were cultivated before the irrigation project. After crop attribution, the percentage of the different crops was 24% alfalfa, 11% fruit orchards (peach trees), 16% sunflower, 34% maize, 6% vineyards and 9% wheat. Fig. 7b presents the simulated crop distribution. Small differences between the simulated crop distribution and the cropping pattern considered in the project design are due to the area of the individual plots.

The collective network of the Bardenas XI WUA irrigates 931 ha supplied by 50 hydrants (Fig. 7c). The average area irrigated per hydrant is 17.9 ha, with a maximum of 56.6 ha for hydrant 140, and a minimum of 0.8 ha, for hydrant 113. The total number of irrigation sectors is 510. Each plot has an average of 10.2 sectors, being 11 sectors per plot the largest and most common arrangement (41 hydrants have 11 sectors). The largest hydrant discharge is 84.9 L s^{-1}, while the lowest is 15 L s^{-1}. The pipes of the collective network have a total length of 17,684 m, with diameters ranging from 115 to 1000 mm. The reservoir is located at the south of the irrigated area, at an elevation of 421 m.a.s.l., 27 m above the highest hydrant (#222) and 85 m above the lowest hydrant (#112).

As reported in the previous section, the on-farm irrigation method was assigned as a function of the available pressure. The most common on-farm irrigation methods (Fig. 4c) were solid-set sprinkler irrigation at standard pressure (Solid-Set 300) with 281 ha (30% of the total area) and solid-set at low-pressure (Solid-Set 200) with 275 ha (30%). Drip irrigation for fruit orchards (Drip-O) irrigates 158 ha (17%) and drip irrigation for field crops (Drip-SS) covers 52 ha (6%). Pivot full circle (Pivot-FC) irrigated 116 ha (12%), while pivot partial circle (Pivot-PC) irrigated 49 ha (5%).

3.2.1. Simulating the meteorological data series for the current design

The meteorological variability of the analyzed data series induced a slight effect on total ETc, with an average value of 789 mm and an inter-annual CV of 3.6% (Table 4). The average precipitation was 404 mm, with an inter-annual CV of 25%. The average precipitation during the cropping season was 226 mm, with a CV of 35% (Table 4). The simulated gross irrigation depth showed an inter-annual average of 710 mm and a CV of 13%.

The irrigation performance indicators showed different degrees of inter-annual variability. Seasonal DU_{lq} showed the smallest inter-annual differences, with an average value of 89.1% and a CV of 0.9%. The Irrigation Efficiency (IE, %) showed an average value of 86.6% and a CV of 1.2%. Seasonal WDEL and deep percolation losses showed annual averages of 79.9 mm and 54.2 mm, both with moderate and strong inter-annual variability, 16.4% and 56%, respectively. The inter-annual variability of these variables was due to the meteorological variability. The moderate inter-annual variability of WDEL was mainly attributed to wind speed differences during irrigation. Yearly deep percolation was strongly affected by precipitation (with a Pearson correlation coefficient, PCC, of 0.53 and a high significance, p-value < 0.0001). The largest values of deep percolation were found in 2004 and 2018 (with average values of 125 and 121 mm, respectively). However, in these years the values of IE were above the annual average (86.8% and 87.5%, respectively). Both years had the highest precipitation (annual and during the crop season). Moreover, both years showed intense precipitation events at the beginning of the crop season (90 and 144 mm, respectively, lasting for 6–7 days). These intense precipitation events during periods of low crop water requirements can explain the high values of deep percolation and the moderate effect on IE. In these years, deep percolation was largely due to excess of precipitation, instead of over irrigation.

The on-farm irrigation method had a determinant effect on irrigation performance indicators. It had an important effect on DU_{lq}. Although the variability between irrigation methods was moderate (with a CV of 6.2%), the comparison of means indicates that DU_{lq} are statistically different. The largest values of DU_{lq} were obtained for center pivots, while the lowest values were obtained for solid-set 200. The variability of IE between irrigation methods was also moderate (CV of 8.5%), but the comparison of means again confirmed the statistical differences (p-value $< 2.2 * 10^{-6}$). Differences in WDEL and deep percolation between irrigation methods were very high, with CVs of 62% and 44%, respectively. The largest values of WDEL and deep percolation losses were obtained for solid-sets. Solid-set 300 showed the largest WDEL (113 mm), while solid-set 200 showed the largest deep percolation (75 mm). Drip irrigation showed average deep percolation losses (49 and 52 mm for Drip and Drip-SS, respectively) and null WDEL. Pivots showed moderate WDEL (64 and 53 mm for Pivot-FC and Pivot-PC, respectively) and low deep percolation losses (16 and 13 mm,

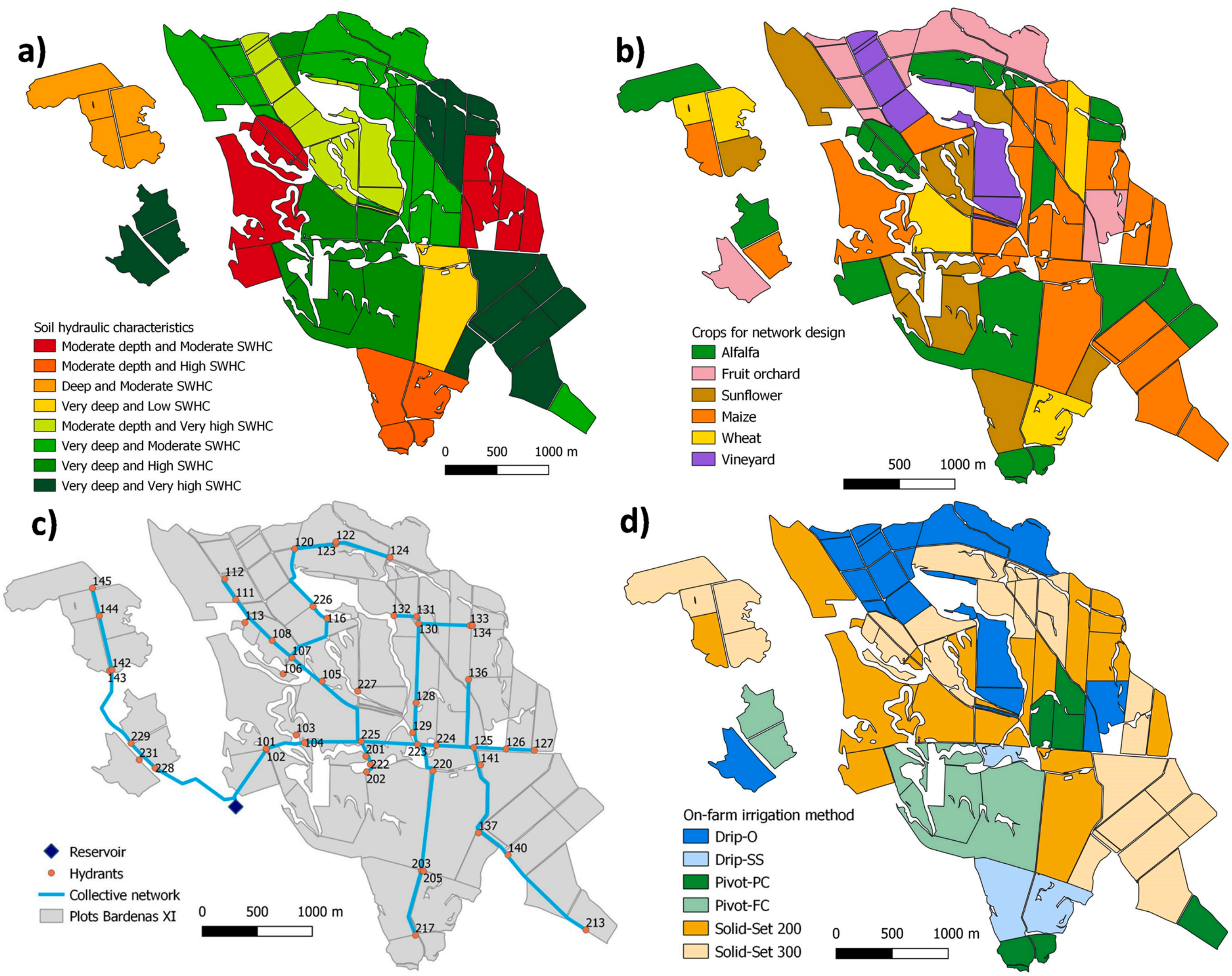


Fig. 7. Simulation input data for the Bardenas XI WUA: a) Soil hydraulic characteristics, combining soil depth and soil water holding capacity, as introduced in Table 1; b) cropping pattern considered for the design of the collective network; c) collective network layout and hydrant locations; and d) on-farm irrigation methods.

Table 3
Area distribution (%) of each soil type, classified according to soil depth and soil water holding capacity. The abbreviation of each soil type is included in brackets.

Soil depth (m)	SWHC (mm m^{-1})				
	Very Low < 43	Low 43–85	Moderate 85–127	High 127–167	Very High > 167
Shallow (0.00 – 0.60 m)	-	-	-	-	-
Moderate (0.60 – 0.90 m)	-	-	14.6 (S2)	6.2 (S5)	9.3 (S7)
Deep (0.90 – 1.20 m)	-	-	7.0 (S3)	-	-
Very deep (> 1.20 m)	-	5.6 (S1)	20.6 (S4)	15.7 (S6)	21.0 (S8)

respectively).

Soil physics had an important effect on deep percolation losses, particularly when combined with on-farm irrigation methods such as solid-set and drip. The largest values of deep percolation losses were obtained for soils with moderate depth and SWHC (S2, 93.3 mm), and for deep soils with a low SWHC (S1, 70.6 mm). The first soil type had a moderate representativeness (14.6% of the total area, Table 3), and was only present in plots equipped with solid-set or drip irrigation methods. The second type had a low representativeness (5.6% of the total area, Table 3) and was only drip-irrigated. Since deep percolation is a key component of IE, soil type also affected IE and contributed to explain its variability.

Crops also induced effects on irrigation indicators, because of their association with on-farm methods and because irrigation depth depends on crop evapotranspiration. The coefficient of variation between crops was low for DU_{lq} (1.3%), moderate for IE (8.6%) and high for deep percolation and WDEL (45.6% and 61.2%, respectively). These coefficients of variation are quite similar to those found for the on-farm irrigation methods.

Annual irrigation performance at plot level was related to three categorical variables: soil type, irrigation method and crop. A box plot (Fig. 8) was used to analyze these interactions. Alfalfa and maize plots present the largest number of combinations of irrigation methods and soil types, 10 and 12, respectively. DU_{lq} and IE showed a moderate data spread and low skewness. The irrigation method had the most significant effect on both indicators, with crops and soils showing moderate (IE) or low effects (DU_{lq}). WDEL showed a larger spread (due to the effect of wind speed) and low skewness. Again, the irrigation method

Table 4
Average annual irrigation depth, crop evapotranspiration, precipitation during the crop season, and irrigation performance indicators (DUlq, IE, Deep percolation and WDEL) for the time data series (2004–2018). Inter-annual average, standard deviation (SD) and coefficient of variation (CV, %).

Year	Hydrologic Indicator						
	Irrigation depth (mm)	ETc (mm)	Precipitation in crop season (mm)	DU_{lq} (%)	IE (%)	Deep Percolation (mm)	WDEL (mm)
2004	620.2	759.7	365.0	88.9	86.8	125.4	66.9
2005	854.3	816.3	106.2	89.0	85.7	38.6	97.1
2006	678.9	780.4	234.7	88.8	87.0	40.2	76.1
2007	712.5	806.2	262.9	89.1	86.0	79.1	84.6
2008	626.3	761.4	240.9	89.9	88.3	32.1	65.8
2009	796.1	798.5	133.3	89.8	86.6	35.0	87.1
2010	821.7	812.2	132.9	87.6	84.9	38.6	95.9
2011	784.9	807.3	162.2	89.1	85.8	43.9	86.9
2012	843.5	832.0	138.1	90.6	85.8	38.8	101.3
2013	619.3	756.8	266.3	89.0	87.4	50.3	66.7
2014	671.6	809.6	257.4	88.4	86.9	35.9	76.5
2015	686.1	803.9	248.5	90.0	86.6	45.1	80.6
2016	763.9	806.5	197.9	88.3	85.4	54.7	88.6
2017	584.0	755.7	295.2	89.8	88.2	34.3	64.8
2018	587.4	739.1	347.1	88.5	87.5	121.2	59.9
Average	**710.0**	**789.7**	**225.9**	**89.1**	**86.6**	**54.2**	**79.9**
SD	**94.2**	**28.2**	**79.2**	**0.8**	**1.0**	**30.4**	**13.1**
CV (%)	**13.3**	**3.6**	**35.0**	**0.9**	**1.2**	**56.0**	**16.4**

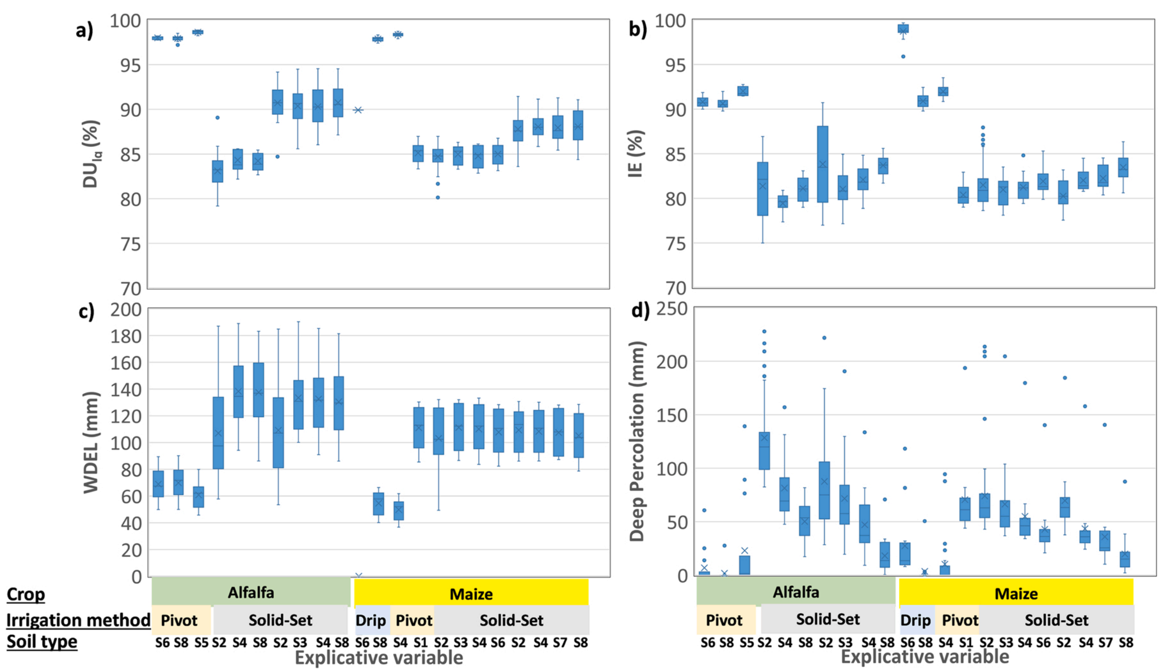


Fig. 8. Box plot of annual irrigation performance indicators in Bardenas XI: a) DU_{lq}, b) IE, c) WDEL and d) Deep percolation, for alfalfa and maize plots irrigated with different on-farm methods and under different soil types.

had more effect than the crop (moderate to low effect) and the soil type (very low effect). Deep percolation showed the largest spread, skewness and number of outliers, underlining the abovementioned effect of precipitation variability. The irrigation method and the soil type showed important effects on deep percolation.

Fig. 9 maps the inter-annual average of plot deep percolation, IE, WDEL and DU_{lq}. The CV of these average indicators was moderate for DU_{lq} (5.3%) and IE (8.1%) and high for WDEL (59.7%) and deep percolation (61.8%). The comparison of Fig. 9a with Fig. 7a permits to relate the plots with low deep percolation losses with the soils with adequate hydraulic characteristics. Plots with very high IE were with drip irrigated (Fig. 7d), while plots with low IE and high WDEL were solid-set irrigated.

When analyzing the spatial variability of DU_{lq} (Fig. 9d), the irrigation method is the key variable. All considered methods can attain high uniformities, although some of them are sensitive to meteorology and to irrigation management practices. This is the case of solid-sets, whose uniformity is strongly affected by wind speed. The highest uniformity was attained by pivot irrigation machines, followed by drip irrigation. This is due to the random and systematic treatment of irrigation depth used for the simulation of pivot and drip irrigation, respectively. In pivot irrigation machines, the random effect of the wind resulted in a seasonal DU_{lq} higher than the input provided to the model. However, in the case of drip irrigation, the seasonal DU_{lq} was equal to the input provided to the model.

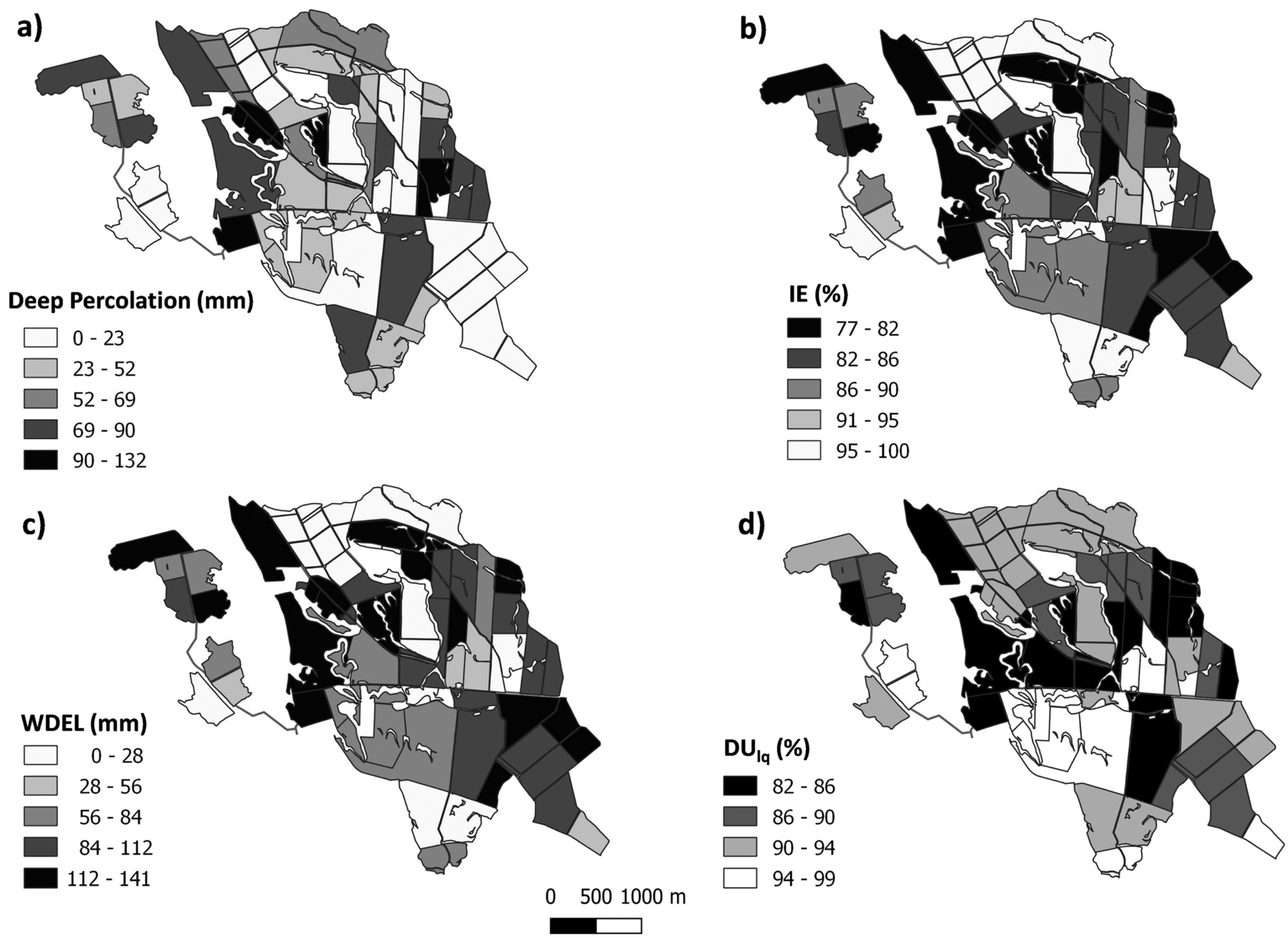


Fig. 9. Average annual irrigation performance indicators for the time data series (2004–2018) of the irrigated area: a) Deep percolation, b) Irrigation Efficiency (IE), c) Wind Drift and Evaporation Losses (WDEL) and d) Distribution Uniformity of the low quarter (DU_{lq}) are presented.

3.2.2. *Comparison between network designs with and without pumping station*

The introduction of the pumping station introduces relevant differences in irrigation performance, energy costs and investment costs, thus affecting the income produced by irrigated agriculture at the Bardenas XI WUA. Differences in irrigation performance indicators between design options and crops are presented in Fig. 10. IE and WDEL were almost equal for both design options, with average differences of 0.4% and 0.5 mm, respectively. DU_{lq} and deep percolation showed larger average differences of 3.7% and 6 mm, respectively. The average difference in gross irrigation depth was quite moderate, 1.1%, larger for the option without pumping station. These results are in agreement with those published by Robles et al. (2017) and Zapata et al. (2018). These authors compared irrigation and crop performance indicators on an experimental irrigated maize plot under standard and low pressure (300 and 200 kPa, respectively). They concluded that the differences in uniformity had no effect on gross irrigation requirements and grain yield.

Electricity costs were null for the design option without pumping station, and amounted to an average cost of 84 € ha^{-1} yr^{-1} for the design with pumping station. The maximum annual electricity cost occurred in 2005, with 137 € ha^{-1} yr^{-1}, while the minimum occurred in 2018 and amounted to 41 € ha^{-1} yr^{-1}. Inter-annual differences were related to crop water requirements, being 2005 a dry year and 2018 a wet year. Fig. 11 presents the annual average net income for both design options. The average difference is 134 € ha^{-1} yr^{-1}, with a maximum of 187 and a minimum of 91 € ha^{-1} yr^{-1}, again for 2005 and 2018, respectively.

The design option without pumping station is the most adequate in the Bardenas XI WUA. Natural pressure has proven sufficient for low-pressure sprinkler irrigation, pivot and drip irrigation methods. The escalating energy costs emphasize the need for careful assessment of pumping requirements at the design phase of irrigation projects. Low-pressure solid-set sprinkler irrigation was completely independent of energy costs, without hurting the irrigation performance indicators.

4. Conclusions

1. Center-pivot sprinkler irrigation was introduced in the model using the angle covered by the machine and a normal distribution of irrigation depth derived from a user-defined DU_{lq}. The random water application depth in each irrigation event adequately represented the variability induced by the wind. Drip irrigation was also introduced in the model using random water application, but using the same water application pattern in all irrigation events. The selected approaches satisfactorily simulated the irrigation methods.
2. Double-cropping simulation adequately reproduced the development of both crops. However, this crop scheme will require further research efforts to adjust the thermal time parameters of short cycle maize to different meteorological areas in the Ebro valley
3. The effect of irrigation timing was successfully implemented in the model. It has been treated differently in the model for corn and alfalfa. Interception losses and the adjustment of thermal time were implemented for wettable leaf crops (maize), while only interception losses were implemented for non-wettable leaf crops (alfalfa).

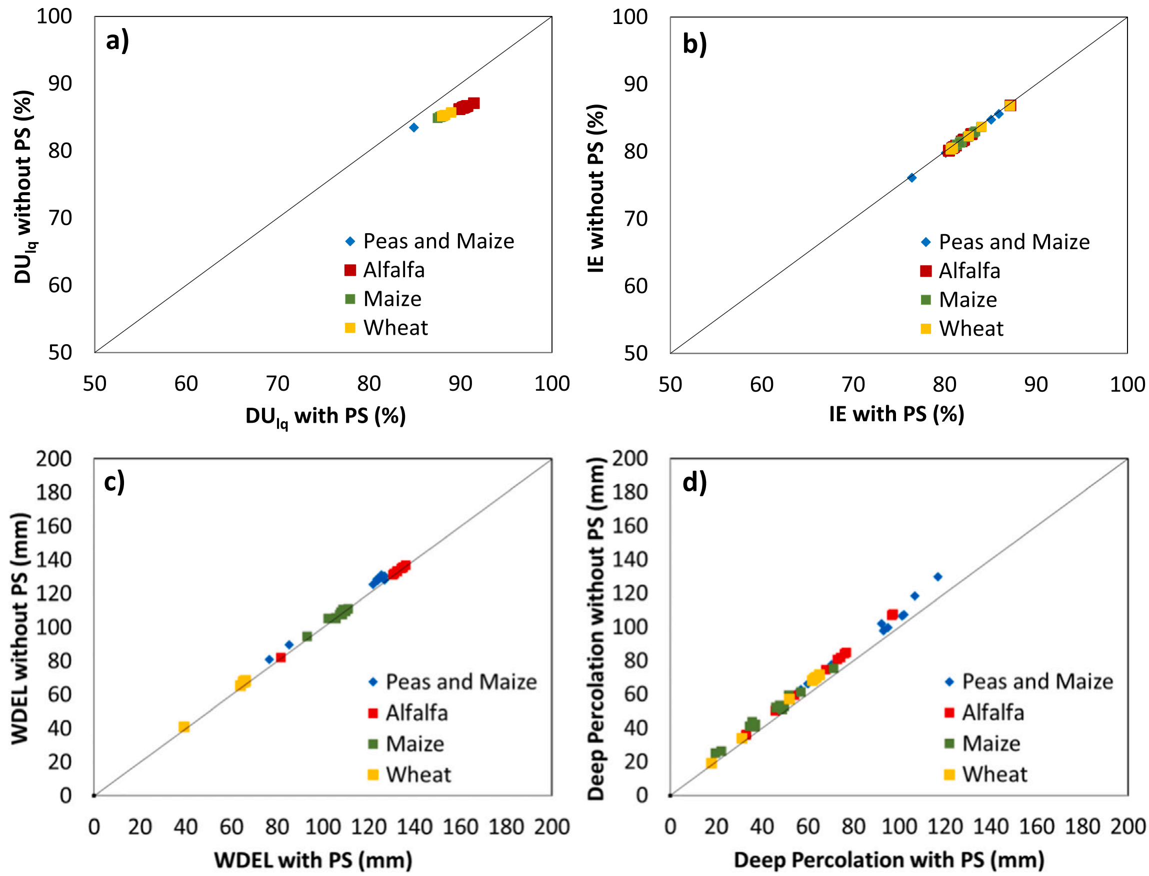


Fig. 10. Comparison of average seasonal irrigation performance indicators (DUlq, IE, WDEL and deep percolation in subfigures a, b, c and d, respectively) between network designs with and without pumping station (PS) at the Bardenas XI WUA. Crops are represented in different colors.

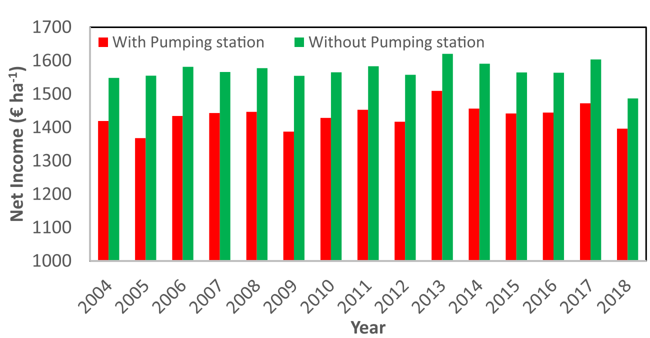


Fig. 11. Comparison of annual average net income (€ ha^{-1}) at the Bardenas XI WUA for the two design options: with and without pumping station. Electricity costs and pumping station investment payback were considered for the design option with pumping station.

4. A general irrigation strategy was not found for irrigation timing and duration. Specific analyses are required for each physical environment (soils, meteorology) and irrigation structures (collective irrigation networks and pumping stations).
5. The simulated irrigation performance indicators at the Bardenas XI WUA showed different degrees of inter-annual variability. Deep percolation was strongly affected by the amount of seasonal precipitation and DU_{lq}.
6. Irrigation performance indicators at the plot level were strongly dependent on the on-farm irrigation method, the crop and the soil type.
7. The design option without pumping station was the most adequate at the Bardenas XI WUA. Natural pressure has proven sufficient for low-pressure sprinkler irrigation, pivot and drip irrigation methods. The escalating energy costs emphasize the need for careful assessment of pumping requirements at the design phase of irrigation projects.

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.

Acknowledgements

This paper applies the “first-last-author-emphasis” approach for the sequence of authors. Thanks are due to the engineering consulting CINGRAL S.L. for providing the original network design of the Bardenas XI WUA. Funding: This work was supported by the State Research Agency of the Government of Spain (Agencia Estatal de Investigación, Gobierno de España) through grants AGL2017–89407-R and PID2021–124095OB-I00. The International Center for Advanced Mediterranean Agronomic Studies of Zaragoza (CIHEAM-Zaragoza) provided a M. Sc. scholarship to Ms. Sophia Bahddou.

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