Preliminary water management assessment using the bucket mass balance approach in a 130-ha farm within the Baix Ter rice-growing area (Spain)

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Abstract

In Girona (North-East Spain), there is a rice-growing area of about 1,000 ha located on the Lower Ter (Baix Ter) valley, where irrigation water is taken from the Ter river and distributed by an open channel network. Despite being a small production area, its rice, labelled as "Arròs de Pals", is highly valued by consumers. Water use sustainability in the area is a major concern due to coexisting demands from agriculture as well as ecological and touristic services.

Water use in Baix Ter rice fields is highly variable depending on the specific farmer water-management, soil conditions and incidence of red swamp crayfish (*Procambarus clarkii)*. Although in some cases reported irrigation water requirements are of about 14,000 m^3 ha^{-1}, significantly higher values have also been measured. This variability and increasing limitations of water supply have fostered the testing of innovative rice irrigation techniques. The traditional wet seeding and continuous flooding irrigation (WFL) currently coexists with dry seeding with delayed flooding irrigation (DFL), which was already applied to about 40% of the rice-growing area in 2021.

Both WFL and DFL techniques have been tested in a 130-ha farm during 2020 and 2021, where irrigation water is distributed by an open channel network and obtained from three different sources. A preliminary model simulating water mass balances and circulation throughout the distribution network and paddy fields was developed in order to assess the impact of new water saving techniques at farm scale, and was successfully validated through daily-registered irrigation inputs. Scenario simulation showed that current irrigation management of the farm (DFL combined with zero runoff from the fields) resulted in an average irrigation water reduction of 36% compared to traditional management, increasing water use efficiency. Such model sets the approach to upscale the impact of on-field water saving techniques to the entire Baix Ter rice irrigation district.

Keywords: Rice; Irrigation network; Water balance model; Simulation; Water-saving

1. Introduction

Nowadays, rice is mainly produced in Asia and it is a staple food in many countries. In Spain, which is the second major rice producer of Europe (FAOSTAT, 2020), there is a rice-growing area of 1,000 ha located in the lower valley of the Ter River (Baix Ter valley, Girona, North-East Spain), producing a high-quality rice marketed under the label "Arròs de Pals". The Baix Ter is also a protected area standing out because of its ecological and touristic relevance. The Ter river supplies water not only to the agricultural activities, but also to industrial, touristic and domestic users.

Rice production uses from 34 to 43% of worldwide irrigation water (Bouman et al., 2007). Although the lowest reported irrigation water use in the Baix Ter rice fields is around 14,000 m^3 ha^{-1}, the majority of fields have highly variable irrigation inputs depending on its specific water-management, soil conditions and the presence of red swamp crayfish (*Procambarus clarkii*). Increasing concerns on water-scarcity in the Baix Ter area combined with the high water demands from rice paddies have led rice farmers to implement new irrigation techniques to reduce water consumption while maintaining yields. DFL water-saving technique currently coexists with traditional irrigation (WFL), being applied to nearly 40% of the rice area during 2021. The latter requires a drill sowing machine for rice sowing and delays 3 to 4 weeks the application of irrigation water to the field, when rice plants are at 3 – 4 leaves stage. To achieve higher water-savings, some farmers in the area apply the DFL irrigation combined with closure of the drainage valves of the fields (zero runoff).

Water balance is the basic principle for assessing alternative irrigation managements and therefore to support water management decisions. Most experiments and tests of irrigation practices use field-scale water balance. Water balance requires a precise delimitation of the system, whose complexity increases when upscaling from single field to groups of fields that share irrigation distribution and drainage networks. The bucket mass balance approach, combined with system-specific conceptualized water circulation (Mateos, 2008), simplifies this process, while accounting for the spatial variability of features such as soil properties. This approach was applied to a 130-ha farm located in Baix Ter rice irrigation district as part of MEDWATERICE project, to upscale the results obtained from on-field tests of water-saving irrigation techniques.

The objectives of the present work are (1) to develop a water balance and circulation model to simulate the fate of water in a 130-ha rice farm in the Baix Ter area; and (2) to compare the DFL and zero runoff irrigation practice in this farm with the traditional irrigation management in the area (WFL and water circulation allowing runoff).

2. Materials and methods

2.1. Description of the monitored farm and experimental measures

The study farm has 130-ha of rice fields (coordinates 42º00’57.8’’N 3º09’26.0’’E) located within the Baix Ter irrigation district (Girona, Spain). The area has a Mediterranean climate, with an average annual rainfall of about 650 mm, concentrated during spring and autumn. The soils in the farm are classified as *Aquic Xerofluvents* (Soil Survey Staff, 2014). Their texture within the first 30 cm presents a gradient from loam (in Northern fields, closer to Ter river) to silty-clay-loam (in Southern fields, further from Ter river). Water balance components in the study farm were monitored in 2020 and 2021 agricultural seasons.

The fields within the farm were sowed from mid-May to early-June and harvested from mid-October to mid-November. The irrigation practice was DFL except in a 2-ha experimental field where WFL was applied. Irrigation criteria was based on maintaining the fields flooded along the season, except when herbicide or fungicide treatments were applied and about 15 days previous to harvest to allow entrance of the harvesting machinery. Another water management practice specific at the study farm was to keep the field drainage valves closed during the whole irrigation period.

Farm irrigation inputs were continuously monitored using NivuFlow 750 (NIVUS, Eppingen, Germany) volumetric water meters, with an accuracy of ±1%. Those were located at water entrances 1 and 2 (Fig. 1). The independent hydrant water inputs were monitored using a tangential turbine meter, model CZ TJ125 (Contazara, Zaragoza, Spain), with an accuracy of ±2%. Irrigation inputs from water entrance 3, which accounted for 6.75 ha (6% of the total farm area), were not measured, but extrapolated from the other irrigation measurements within the farm. Precipitation was measured by the rain gauge Rain-O-Matic (Pronamic, Ringkøbing, Denmark) of a meteorological station located 1 km away from the monitored farm (accuracy of ±0.2 mm).

2.2. Water balance

2.2.1 Water balance model development

A daily water balance was computed during 2020 considering the entire 130 ha farm using the bucket mass balance approach (Mateos, 2008). The conceptualization of the system was based on topological diagrams where irrigation units are connected by the irrigation distribution and drainage networks. Fields supplied by an irrigation canal and draining to a drainage ditch were grouped into irrigation units. If those fields presented significantly different soil texture, then they were split into separate units. The result was that the 28 fields in the study farm were grouped into 15 irrigation units with similar soil and water management characteristics (Fig. 1).

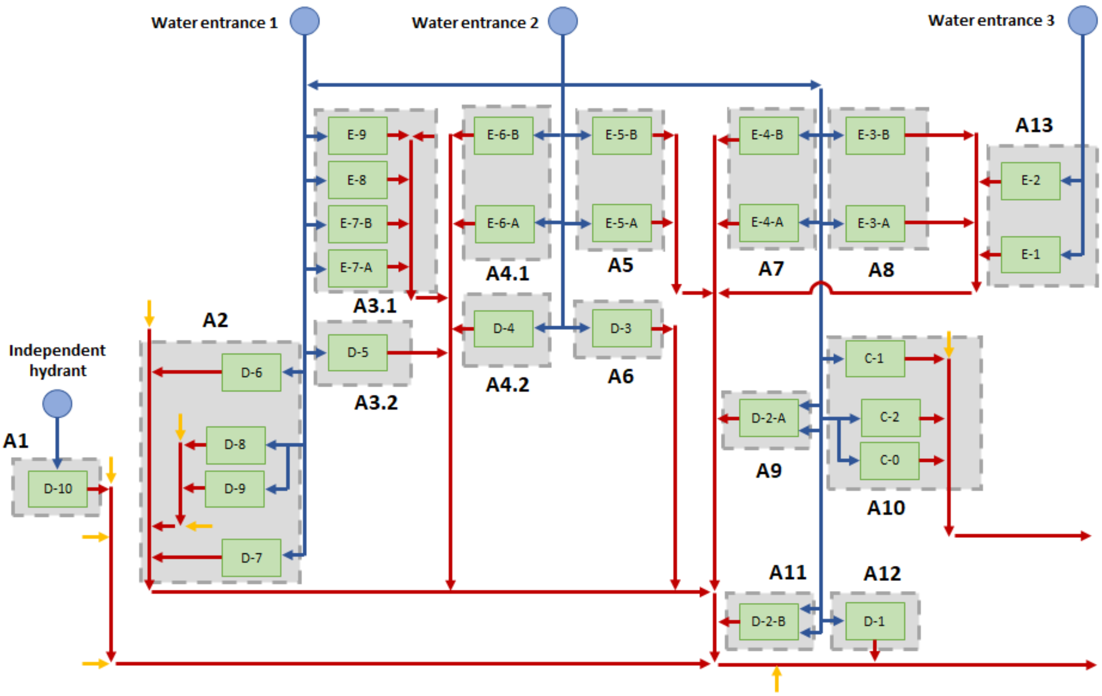

Fig. 1: Topological diagram conceptualizing irrigation units and their connections. Fields are represented in green and irrigation units in grey. Water fluxes are represented by arrows (irrigation water in blue; runoff water in red; external runoff water fluxes entering into the system in yellow).

The model first computed a daily water balance in each unit considering as boundaries the bottom of the soil root zone (assumed to be 60 cm below ground level) and the free water surface. The output was daily irrigation requirement from rice sowing to harvest (160 days after sowing, as usual in the area):

$$I = ETc + SP + R + \Delta\theta + \Delta h - P \qquad (1)$$

Where: I: irrigation water requirement (mm day^{-1}), P: precipitation (mm day^{-1}), Δθ: soil water content variation (mm day^{-1}), Δh: ponding water level difference variation (mm day^{-1}), ETc: crop evapotranspiration (mm day^{-1}), R: water runoff (mm day^{-1}) and SP: subsurface water fluxes (mm day^{-1}).

ETc was calculated using reference evapotranspiration (ETo) and crop coefficients (Kc) as suggested by Allen et al. (1998) for rice in the Mediterranean region. The selected initial Kc was 1.10, except for the non-flooded period in the DFL fields, when initial Kc was set on 0.30. The midseason Kc was 1.20.

Deep percolation plus lateral seepage (SP) was neglected when the soil was not saturated and assumed to increase linearly with the free water depth up to a maximum of 45 mm day^{-1} in loam soils and 63 mm day^{-1} in silty-clay-loam soils, starting from a minimum value at saturation estimated as 1/20 of the maximum value. These values were obtained from water balances computed for the 2020 irrigation season in two fields within the studied farm, where SP was the closure term of the balances.

Water runoff was calculated using equation (2):

$$\mathrm{R} = \mathrm{c} \cdot \mathrm{h}^{0.5} \cdot 8640 \cdot \mathrm{N} \cdot \mathrm{A} \tag{2}$$

Where: c: valve coefficient (0.05), h: ponding water level (m), N: number of drainage valves per hectare (valves ha^{-1}), and A: valve opening fraction (from 0, totally closed, to 1, totally opened).

Precipitation and ETo were computed from data recorded at the meteorological station located in the area.

Daily target ponding water levels were grouped into 11 periods based on crop development stages and irrigation water management criteria. The target levels ranged from 0.01 to 0.15 m based on observations in the farm.

2.2.2. Validation of the model

The model was validated using measured daily farm irrigation supply form 2020 and 2021. Since daily water supply was notably variable and the target water levels used in the simulation represented global management, 10-day moving averages of both measured and simulated results were used to validate the model.

The Nash-Sutcliffe efficiency (NSE), the percent bias (PBIAS, expressed in %) and the coefficient of determination (R^2), as well as graphical data visualization, were used to evaluate the goodness-of-fit of the model:

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \tag{3}$$

$$\mathrm{PBIAS} = \frac{\sum_{i=1}^{n}(O_i - P_i)}{\sum_{i=1}^{n} O_i} \cdot 100 \tag{4}$$

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \overline{O})(P_i - \overline{P})}{[\sum_{i=1}^{n}(O_i - \overline{O})^2]^{0.5}\,[\sum_{i=1}^{n}(P_i - \overline{P})^2]^{0.5}}\right]^2 \tag{5}$$

Where: Oi: observed or monitored values, Pi: simulated values, $\overline{O}$: mean of the observed values, and $\overline{P}$: mean of the predicted values.

The NSE, PBIAS and R^2 results interpretation was based on the guidelines of Legates and McCabe (1999) and Moriasi et al. (2007).

2.2.3. Scenario simulation

Two scenarios were simulated. Firstly, the 2020 and 2021 irrigation seasons were simulated to evaluate the model performance and assess current irrigation practices (scenario A). Then, another simulation for each monitored year was carried out to estimate the required irrigation if all the fields within the farm were WFL managed and drainage valves were opened to drain the fields before pesticide treatments, which is the traditional practice in the area (scenario B). Scenario B simulations were also used to assess current irrigation practices.

The same ponding water levels used in the validation of the model were used in both scenario simulations.

2.3. Irrigation performance indicators

Four indicators were used to assess irrigation performance on the farm: irrigation efficiency (IE), water efficiency (WE), runoff fraction (RF) and deep percolation fraction (DPF).

$$\mathrm{IE} = \frac{\mathrm{ETc} - \mathrm{P}}{\mathrm{I} - (\Delta\theta + \Delta\mathrm{h})} \tag{6}$$

$$\mathrm{WE} = \frac{\mathrm{ETc}}{\mathrm{I} + \mathrm{P} - (\Delta\theta + \Delta\mathrm{h})} \tag{7}$$

$$\mathrm{RF} = \frac{\mathrm{R}}{\mathrm{I}} \tag{8}$$

$$\mathrm{DPF} = \frac{\mathrm{SP}}{\mathrm{I}} \tag{9}$$

3. Results and discussion

3.1. Validation of the model

Measured farm irrigation supply was of 10,090 m^3 ha^{-1} and 10,406 m^3 ha^{-1} in 2020 and 2021, respectively, while the respective simulated irrigation requirements were 9,734 and 10,478 m^3 ha^{-1}.

Visual comparison of the simulated and observed 10-day averaged values (Fig. 2) showed a good model performance. The biggest discrepancy was in 2020, when the actual irrigation period started 10 – 15 days later and finalized 20 days earlier than the simulated one. NSE, PBIAS and R^2 indexes (Table 1) also showed a good model performance, with a satisfactory fitting of the observed values (NSE ≥ 0.75, and PBIAS < 10%). Positive PBIAS values indicated that the simulated results tended to be smaller than the experimental data. Acceptable R^2 values around 0.7 were obtained, indicating that 70% of the observed data variance was explained by the model.

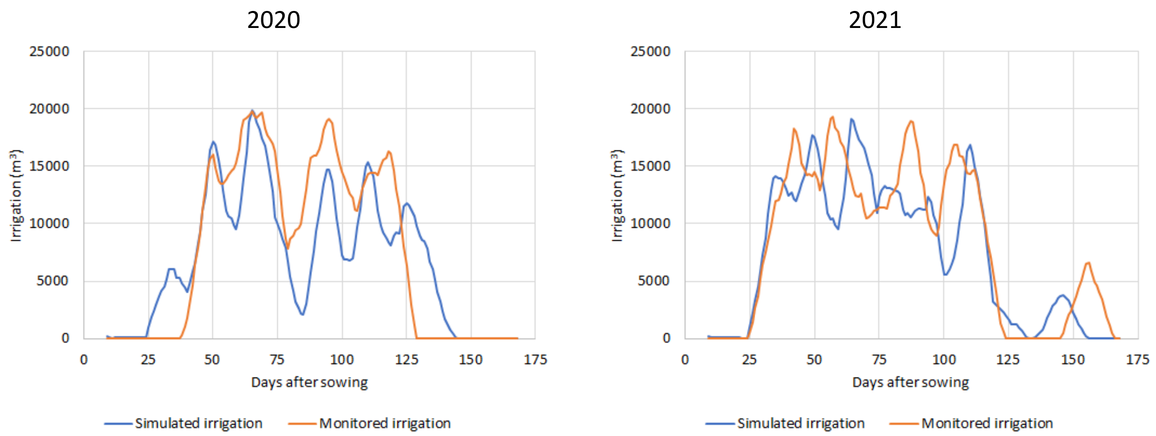

Fig. 2: Representation on a 10-days period moving averages of the simulated and monitored irrigation inputs for 2020 and 2021 campaigns.

Table 1: Model performance statistics for a 10-days period moving averages on 2020 and 2021 campaigns.

Statistic	2020 data	2021 data
NSE	0.84	0.88
PBIAS (%)	8.74	9.92
R^2	0.69	0.71

3.2. Irrigation assessment

3.2.1. Simulated results

The farm current water management (scenario A) and traditional water management (scenario B) were compared to assess whether the DFL and zero runoff practice led to any irrigation water savings.

As can be observed in Table 2, the modelled inputs exceeded the outputs, indicating that balance closure was not zero in any of the studied scenarios. Although those differences are not relevant in scenario A, they were significant in scenario B. Therefore, the model should be accurately revised to improve current results and obtain final conclusions.

Table 2 shows that current water management practices saved 5,261 m^3 ha^{-1} of irrigation water in 2020 and 4,707 m^3 ha^{-1} in 2021 compared to the traditional water management, representing an average irrigation water reduction of 36%. Results from other field experiments in MEDWATERICE project (Italian and Turkish case studies) as well as other studies in the Mediterranean basin such as Mayer et al. (2019) report DFL water savings ranging from 10 to 25%. The higher irrigation water reduction obtained using DFL in the present study could be explained because of DFL combination with zero-runoff from the fields, which was not implemented in the above mentioned studies.

The main water output in scenario A was ETc, followed by deep percolation plus lateral seepage, while runoff was zero (Table 2). Meanwhile, in scenario B the main water output was the combination of the SP and runoff terms, resulting in higher irrigation needs in the case of the traditional water management. Although subsurface flows and runoff water provide environmental services such as aquifer recharging, marine intrusion prevention and water provision to other inland aquatic systems, they should be minimized to improve paddies efficiency in an irrigation water-scarcity context.

Table 2: Water balance results (m^3 ha^{-1}) from the simulated scenarios in the studied farm.

Balance term	Scenario A		Scenario B	
	2020	2021	2020	2021
Irrigation	8,488	9,136	13,748	13,843
Precipitation	1,538	976	1,538	976
ETc	5,145	5,062	5,889	5,757
Runoff	0	0	2,627	2,320
Deep percolation plus lateral seepage	4,293	4,604	4,680	4,597
Soil water volume variation	549	440	546	440
Free water volume variation	12	0	11	0
Inputs – outputs difference	39 (0.4%)	7 (0.1%)	1,544 (10.1%)	1,705 (11.5%)

3.2.2. Irrigation performance indicators

Calculation of irrigation performance indicators showed higher irrigation and total water efficiencies under the farm water management (scenario A), with values ranging from 0.46 to 0.54, than under traditional management (scenario B), with values ranging from 0.33 to 0.40 (Table 3), respectively.

Several reports indicate that DPF is highly variable depending on field soil textures and specific water management. Studies in India reported DPF values ranging from 21% to 86% depending on irrigation criteria (Yadav et al., 2011; Hatiye et al., 2016), while others in the Mediterranean basin reported values from 40% to 68% in Egypt (Moursi and Abdelkhalek, 2015) and Italy (Mayer et al., 2019). DPF also varied depending on water management in the present study, and it was higher with the use of the zero-runoff method (scenario A) than when the drainage valves were opened before pesticide treatments (scenario B). Despite the lower DPF in scenario B, it must be noted that the water fraction that did not percolate outsourced the system through runoff, which did not contribute to increase irrigation efficiency.

Table 3: Irrigation performance indicators of the simulated scenarios on 2020 and 2021.

Index	Scenario A		Scenario B	
	2020	2021	2020	2021
Irrigation efficiency, IE	0.46	0.47	0.33	0.36
Water efficiency, WE	0.54	0.52	0.40	0.40
Runoff fraction, RF	0.00	0.00	0.19	0.17
Deep percolation fraction, DPF	0.51	0.50	0.34	0.33

4. Conclusions

A preliminary water mass balance model in a 130-ha farm in the Baix Ter rice irrigation area was successfully developed and validated throughout two irrigation seasons. Scenario simulations and irrigation performance indicators calculation were carried out to assess current irrigation practices (DFL irrigation and zero runoff) compared to the traditional water management (WFL irrigation and fields runoff before phytosanitary treatments are applied).

Simulated scenarios showed better irrigation performance under the current water management than under the traditional one, resulting in a 36% reduction of the irrigation inputs. The developed model can be used to assess the impact of other on-field water saving techniques such as DFL and others related to reduce the ponding water height at farm scale, becoming a first approach to upscale it to the whole Baix Ter rice irrigation district.

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