Water-saving irrigation techniques for rice cultivation in Baix Ter irrigation district

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Abstract

Rice is the main staple food in many countries and, because of its particular irrigation water management, it provides complementary ecosystem services where it is cultivated. In the Mediterranean area, rice is traditionally cultivated under flooding conditions (WFL, water sowing and continuous flood irrigation), which are maintained with a variable ponding water level until 2 – 4 weeks before harvest. Because of the increasing fresh water scarcity, other irrigation methods are being tested to reduce water use while maintaining yield. Some of these techniques, such as dry seeding and delayed flood irrigation (DFL) and subsurface drip irrigation (SDI), have been studied as part of MEDWATERICE project to assess their viability in Baix Ter rice area (Girona, Spain).

Water balances to evaluate the effects of water-saving irrigation techniques and to support water-management decisions were carried out for 3 different irrigation management practices (WFL, DFL and SDI) as part of the tests performed in Baix Ter rice production area during 2020 and 2021. Three commercial rice fields of 1.16, 1.15 and 0.38 ha with silty-clay-loam, loam and silty-clay textured soils were selected for WFL, DFL and SDI testing, respectively. Irrigation water, soil water contents, ponding water level and meteorological variables were continuously monitored in all cases. No water runoff from the paddies was observed due to the irrigation management carried out by rice producers in the fields. Percolation plus lateral seepage (SP) was computed as water balance closure term.

No irrigation water reduction was registered in DFL when compared to WFL. In both cases, about 1,300 mm of irrigation water were applied during both agricultural seasons. SDI irrigation water application was 44% and 38% lower than in WFL during 2020 and 2021, respectively. The largest water output from DFL and WFL was SP, which averaged 77% of the irrigation input in both campaigns. When using SDI, SP accounted for 52% of the irrigation inputs, almost the same proportion as crop evapotranspiration, which accounted for 48% of irrigation. Yields were not significantly different when using different irrigation methods, and they were close to the average one in the area. DFL, however, showed slightly higher yields during both seasons due to agronomic reasons other than irrigation management.

Keywords: Rice; Irrigation; Water-saving; Aerobic rice; Water productivity

1. Introduction

Rice (*Oryza sativa L.*) is a staple food in many countries and is critical for global food security (Maclean et al., 2013). As stated in Food and Agriculture Organization of the United Nations (2021), almost 90% of rice is produced in Asia. In Europe, Spain is the second major producer after Italy, with a total surface of 102,060 ha in 2020.

In the Mediterranean area, paddy rice fields perform ecological and environmental functions on top of producing rice. Rice cultivation preserves wetlands and its surrounding areas, providing an agroecosystem of great ecological and environmental value. The Baix Ter rice cropping area, located in Girona (North-East Spain), covers nearly 1,000 ha irrigated by the Ter river water. Located about 100 km north from Barcelona, in Costa Brava, it also represents an important touristic area, so that water resources are disputed by touristic, industrial and recreational users. Limited water availability, competition of rice production with other water uses, inclusion of rice fields into a natural reserve protected area, aquifer vulnerability to nitrates, soil salinity problems and risk of marine intrusion are the main challenges that rice farmers in the Baix Ter area currently face, in addition to maintaining rice yields to sustain profitability.

Part of the rice produced in this area is included in the "Arròs de Pals" quality label, which is highly valued by consumers. Rice farmers from the Baix Ter area are interested in increasing rice production, but irrigation water availability limits the expansion of the rice cropping area. Therefore, there is a strong need to implement irrigation techniques that reduce irrigation demands while maintaining yields, which are currently around 6,000 – 6,500 kg ha^{-1}. In 2021, the traditional method (WFL) was used in 62% of the Baix Ter rice production area. DFL was introduced in 2017 as a water-saving irrigation technique, and in 2021 it was already used in 38% of the area. Previous field studies carried out in Lombardia (Italy) showed that DFL can reduce 20% of the irrigation requirements compared to WFL (Cesari de Maria et al., 2017).

Another irrigation technique that might expand rice cultivation area is SDI. This can be a plausible alternative for rice cultivation in fields that are currently not reached by the canal network, but can pump water from wells. There are very few studies using SDI worldwide. Among them, Rajwade et al. (2018) and Parthasarathi et al. (2015) concluded that under SDI yield was slightly reduced compared with conventional WFL, even though water productivity was increased. In previous tests within the MEDWATERICE project in the Baix Ter area, Arbat et al. (2020) showed that SDI allowed to cultivate rice using approximately half of the water with 17% yield reduction when compared to WFL.

The objectives of the present work are (1) to assess rice water management under three different irrigation practices (WFL, DFL and SDI) in the Baix Ter area; and (2) to identify the water outputs of paddy fields that should be minimized to improve irrigation efficiency while maintaining rice yields.

2. Material and methods

2.1. Description of the experimental fields

Tests were conducted during 2020 and 2021 agricultural seasons in three different fields located in the Baix Ter irrigation district (Girona, Spain). The study area has Mediterranean climate with a xeric humidity regime, a thermic soil temperature regime and average annual rainfall of about 650 mm, being maximum during the autumn and spring months. This entails a period of water deficit from March to September, when evapotranspiration is higher than rainfall.

Soils in the three fields were classified as *Aquic Xerofluvents* (Soil Survey Staff, 2014). Surface, geographical coordinates and the main physical soil characteristics of the 3 fields are summarized in Table 1. Irrigation water proceeded from the Ter river, showing an average electrical conductivity (EC) of 0.54±0.12 dS m^{-1} and a sodium adsorption ratio (SAR) of 0.65±0.11. As soils did not present either salinity or sodicity hazards, water was considered as adequate to irrigate all plots.

Table 1: Surface area and soil physical characteristics of the three fields from 0 to 30 cm depth.

Field	Geographical coordinates	Area (ha)	Sand (%)	Silt (%)	Clay (%)	Textural class (USDA)
WFL	42º0’37”N 3º9’5”E	1.16	5.6	65.1	29.3	Silty-clay-loam
DFL	42º1’23”N 3º9’6”E	1.15	35.1	46.6	18.3	Loam
SDI	42º0’12”N 3º8’46”E	0.38	6.5	53.4	40.1	Silty-clay

2.1.1. Water management and experimental setup in WFL and DFL fields

Irrigation water entrance in the fields was conditioned by water availability, since it was supplied by the irrigation community every 7 to 10 days, and by the phytosanitary treatments schedule, which required no ponding water level for a few days.

The farmers’ irrigation criteria in the flooded fields was to maintain a variable ponding water level and to avoid runoff during the irrigation period in order to reduce the water use. Thus, the drainage valves in the fields were closed during the entire irrigation campaign. The main difference in irrigation water management between the WFL and DFL fields took place during sowing period. Irrigation was not applied until the BBCH 14 crop stage (4 leaves) in the DFL field, while water was applied a few days before sowing in WFL.

Irrigation water entering into the WFL field was measured hourly with a tangential turbine meter, model CZ TJ125 (Contazara, Zaragoza, Spain) with an accuracy of ±2%. Soil water contents (SWC) were monitored hourly in the center of the field using a Drill & Drop probe (Sentek, Stepney, Australia), with integrated sensors at 5, 15, 25, 35, 45 and 55 cm depth, with an accuracy of 0.03% SWC. During the 2020 season, water height above ground surface was measured weekly in the center of the field using a measuring tape (accuracy ± 0.005 m). During 2021, water height above surface was measured every 10 minutes using the radar transmitter Siemens Sitrans LR100 (Munich, Germany), with an accuracy of ± 0.005 m.

The same parameters were monitored in DFL field, except for irrigation water, which was measured using an ultrasonic flowmeter, model CZ Octave US DN150 (Contazara, Zaragoza, Spain), with an accuracy of ±2%.

2.1.2. Water management and experimental setup in the SDI field

Irrigation system of the SDI field was divided in 4 sectors of equal surface. Two of them had a dripline spacing of 0.38 m, while in the others dripline spacing was 0.75 m. Driplines were installed at 0.15 m below soil surface. Pressure compensating and anti-draining integrated emitters of 1 L h^{-1} spaced 0.30 m within the dripline were used (Uniram CNL 16010, Netafim, Tel Aviv-Yafo, Israel).

Since rice has a shallow rooting system, irrigation criteria was set to maintain the first 15 cm of soil depth at matric potential between 0 and -10 kPa during the entire irrigation season, except for some days before every phytosanitary treatment and for two weeks previous to the harvest in order to dry the soil and reduce soil compaction by harvesting machine.

Irrigation water was applied on a daily basis, and was continuously measured using volumetric meters Woltman WP (Gaer, Barcelona, Spain), with an accuracy of ±5%. Soil water contents were measured at 0.05, 0.20 and 0.30 m depth at two horizontal positions. One was close to the emitter, at 0.08 m from the dripline, and the other was located at the middle between two driplines. Sensors (10HS, Meter Group, Pullman, United States) accuracy was of ± 3% vol.

2.2. Water balance and yield measurements

Daily water balance in each field and cropping season (2020 and 2021) was computed from rice sowing to harvest dates. The lower spatial boundary was the maximum rice rooting depth observed in the studied fields (30 cm below soil surface), and the upper boundary was defined by ponding water level. The following equation was used to compute the water balance:

$$\mathrm{I} + \mathrm{P} \pm \Delta\theta \pm \Delta \mathrm{l} = \mathrm{ET_c} + \mathrm{R} + \mathrm{SP} \tag{1}$$

Where: I: irrigation water (mm day^{-1}), P: precipitation (mm day^{-1}), Δθ: soil water content variation (mm day^{-1}), Δl: ponding water level variation (mm day^{-1}), ETc: potential evapotranspiration of the crop (mm day^{-1}), R: water runoff (mm day^{-1}) and SP: subsurface flows (mm day^{-1}).

Irrigation water was measured using volumetric meters. Precipitation was obtained from a meteorological station located in the rice area with ±0.2 mm accuracy. ETc was computed according to Allen et al. (1998). Initial Kc in the flooded fields was considered of 1.10, except for the non-flooded period of the DFL field, when it was set on 0.30. Middle Kc on those fields was set on 1.20. In the SDI field the selected initial and middle Kc were 0.30 and 1.15, respectively. Because of the fields water management, runoff was set to 0 mm in all fields. To compute the soil water contents variation, the probes located at 0 – 30 cm depth were used. Ponding water level change was computed from the experimental measurements. The balance closure term was percolation plus lateral seepage (SP).

Yield was quantified in all fields by 4 randomized rice samplings within a 0.0625 m^2 surface. An analysis of variance (ANOVA) was carried out to detect yield differences between the monitored fields ($p<0.05$).

2.3. Water use efficiency indexes

Relative water supply (RWS, dimensionless), deep percolation fraction (DPF, expressed in %) and irrigation water productivity (IWP, expressed in kg m^{-3}) indexes were computed to assess irrigation management considering the whole 2020 and 2021 campaigns:

$$\mathrm{RWS} = \frac{\mathrm{I} + \mathrm{P}}{\mathrm{ETc}} \tag{2}$$

$$\mathrm{DPF} = \frac{\mathrm{SP}}{\mathrm{I}} \cdot 100 \tag{3}$$

$$\mathrm{IWP} = \frac{\mathrm{Yield}}{\mathrm{I}} \tag{4}$$

Where ETc: crop evapotranspiration (m^3 ha^{-1}), I: irrigation water (m^3 ha^{-1}), P: precipitation (m^3 ha^{-1}), SP: percolation plus lateral seepage (m^3 ha^{-1}), and Yield: paddy rice yield standardized at 14% moisture content (kg ha^{-1}).

3. Results and discussion

3.1. Water balance results

A seasonal summary of the water balance is shown in Table 2 in each field during both agricultural seasons. Total irrigation in WFL, considering the first irrigation previous to sowing, was 1,411 mm in 2020 and 1,318 mm in 2021. Those values were low compared to irrigation requirements reported in other studies within the Mediterranean basin (Aguilar and Borjas, 2005; Cesari de Maria et al., 2017; Monaco et al., 2016) as well as in most of the MEDWATERICE case studies. Nevertheless, in the Portuguese and Egyptian case studies, values ranging from 1,250 to 1,600 mm were measured using WFL irrigation system, and Mayer et al. (2019) also registered similar irrigation inputs (1500 mm) in other studies in Italy.

Table 2: Water balance terms and paddy rice yield results for each studied irrigation system during 2020 and 2021. Initial flooding irrigation in the WFL field before sowing is presented separately.

Field	Year	WFL first irrig. (mm)	I (mm)	P (mm)	ETc (mm)	R (mm)	SP (mm)	Δθ (mm)	ΔI (mm)	Yield (t ha^{-1})
WFL	2020	73	1,337	150	547	0	919	32	-5	6.8 ± 2.0
	2021	80	1,238	123	567	0	1,070	-9	-57	6.7 ± 2.3
DFL	2020	-	1,270	162	545	0	864	20	0	8.0 ± 0.9
	2021	-	1,554	137	566	0	1,312	19	0	7.9 ± 2.5
SDI	2020	-	743	157	421	0	477	16	0	6.6 ± 1.3
	2021	-	763	103	425	0	446	6	0	5.9 ± 1.7

No relevant differences between WFL and DFL irrigation requirements (Table 2), ranging from 1,200 to 1,500 mm, were observed in both seasons. Although in 2020 the DFL field achieved a 10.5% total irrigation water saving compared to WFL, in 2021 the innovative irrigation system required more water than the traditional one. This higher water consumption during 2021 in the DFL field was partially due to the high ponding water levels achieved near flowering stages, being 15.5 cm and 23.5 cm in 2020 and 2021, respectively. Other studies in the Mediterranean basin (Cesari de Maria et al., 2017; Mayer et al., 2019) as well as the Italian and Turkish case studies from MEDWATERICE project have quantified DFL irrigation water savings from 10 to 25% when compared to WFL. In the Baix Ter tests, lower water savings registered in the DFL field were probably due to higher soil sand content compared to the WFL field, resulting in higher deep percolation rates and, consequentially, higher irrigation inputs requirement. No statistically significant differences in paddy rice yield were reported between DFL and WFL irrigation methods ($p>0.05$), which was consistent with the previously mentioned studies. Nevertheless, DFL field showed a tendency to achieve higher yields when compared to WFL (about an additional 1,250 kg ha^{-1}), probably because of better rice establishment uniformity and lower difficulties in weed control during initial development stages.

SDI irrigation system showed the highest irrigation water savings (Table 2), while rice yield was not statistically different to the one in flooded field. Irrigation water reductions of 47% and 42% compared to total irrigation in WFL were registered in 2020 and 2021, respectively. Reductions of 44% and 38% were measured when compared to irrigation after sowing in WFL in both seasons, respectively. Although the water balance was computed during the crop development period, the flooded fields required an extra 70 to 250 mm of irrigation water for puddling (values measured in 2019 and 2021), a labor that facilitates rice straw decomposition during winter. This implies that the SDI irrigation system would have a higher water-saving impact, using about 45 – 55% less water than WFL, if the whole year was considered.

Deep percolation and lateral seepage, grouped in SP term, were the main water outputs in all fields. Nevertheless, higher values were computed in the flooded fields (about 70% of the total water inputs, as mean of 2020 and 2021) than in the SDI field (about 52% of the total water inputs) due to the lower irrigation water use in the latter case. In this field the seepage term probably was small because of the non-flooded conditions, resulting in lower SP values. Daily water balance results of the flooded fields (data not shown) provided information about evolution of the water balance terms throughout the whole irrigation campaign, suggesting that higher ponding water levels (over 10 cm) resulted in higher SP values.

3.2. Irrigation performance indicators

RWS was calculated to relate irrigation water inputs to crop evapotranspiration demands. The highest RWS values were obtained for both flooded fields (Table 3), with a mean value of 2.43 during both seasons and both flooding irrigation alternatives. No differences were observed between WFL and DFL. Conversely, SDI showed lower values (mean RWS of 1.78 for both studied irrigation campaigns), indicating that water inputs exceeded crop evapotranspiration demands in about 80%. Even though it would be ideal to achieve RWS values closer to 1.00, especially in aerobic rice, some additional irrigation water from ETc demands must be supplied in order to achieve soil hydraulic potentials high enough to ensure proper plant development.

As in the case of RWS index, the highest DPF values were obtained in both flooded fields. From 68% to 86% of irrigation inputs throughout crop development period returned to the environment through deep and lateral percolation (SP term of the water balance). These values were consistent with the ones reported in the other MEDWATERICE case studies (with SP values ranging from 30% to 85%), and slightly higher than the 40% reported in Egypt (Moursi and Abdelkhalek, 2015) and the 68% reported in Italy (Mayer et al., 2019). As stated before, the SP term in SDI field presented lower values than in flooded fields, resulting in the highest water use efficiency irrigation technique amongst the tested ones.

As previously mentioned (Table 2), there were no statistically significant yield differences between the three studied irrigation techniques. Nevertheless, Table 3 depicts that SDI technique resulted in the highest IWP value (0.89 kg m^{-3}), while in the flooded fields IWP was 0.55 kg m^{-3} (mean of both WFL and DFL during both monitored seasons). The higher IWP in SDI field was due to its lower irrigation water use (irrigation in SDI was almost halve of the one in flooded fields).

Table 3: Irrigation performance indicators of each studied field on 2020 and 2021. RWS: relative water supply; DPR: deep percolation rate; IWP: irrigation water productivity.

Field	Year	RWS	DPF (%)	IWP (kg m^{-3})
WFL	2020	2.44	68.7	0.50
	2021	2.19	86.4	0.54
DFL	2020	2.33	68.0	0.63
	2021	2.75	84.4	0.51
SDI	2020	1.76	64.2	0.89
	2021	1.80	58.4	0.77

4. Conclusions

Overall, no differences in irrigation water inputs were registered between WFL and DFL fields, where about 1,300 mm were applied in each agricultural season, although literature quantifies the DFL water saving potential in a 10 – 25% compared to WFL. The different performance observed in the present study and the ones stated in literature was partially attributed to the different sand and silt contents of both fields. In contrast, SDI field showed a high irrigation water-saving potential, requiring only 55 – 60% of the irrigation water used in WFL.

The largest water output from the monitored flooded fields was the combination of deep percolation plus seepage, averaging 77% of the irrigation inputs (DPR index), and was consistent with results from previous studies. Therefore, water management that results in a SP term reduction should be identified and implemented in rice fields to reduce irrigation inputs.

Yield was not significantly different among all treatments, although DFL yields were slightly higher during both seasons due to better weed control and better crop establishment uniformity. DFL might be an interesting rice water management technique in the Mediterranean paddy areas because it preserves paddies ecological and environmental functions while maintaining or increasing yields; while SDI arises as an opportunity to spread rice cultivation into agricultural areas where flooding is not viable.

Funding: The present work was funded by the European Program for Research and Innovation Horizon 2020-PRIMA, grant number PCI2019-103738, “Towards a sustainable water use in Mediterranean rice-based agro-ecosystems” (MEDWATERICE).

Acknowledgments: The authors wish to thank the company Netafim for the technical support received during the field tests.

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