Rice irrigation in northern Italy: field and district scale evaluations

S. Cesari de Maria[a], A. Facchi[a], M. Rienzner[a], E.A. Chiaradia[a], E.F. Miniotti[b], M. Romani[b], C. Gandolfi[a]

[a] Department of Agricultural and Environmental Sciences (DiSAA), Universitá degli Studi di Milano, Milan, Italy
[b] Centro Ricerche sul Riso, Ente Nazionale Risi (ENR), Castello d'Agogna (PV), Italy

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ABSTRACT

The majority of rice produced in the European Union is grown in Italy, where the crop requires relevant amounts of irrigation water for the continuous flooding (CF) of rice fields. In this area some water saving technologies such as delayed flooding (DF) and flush irrigation (FI) are spreading. To improve the understanding of water management issues in rice systems, the paper presents the results of both field scale and district scale studies on water requirements of rice grown with water techniques.

At the field scale, we compared water balance terms and water performance indicators of CF, DF and FI rice over two growing seasons (2012 and 2013), whereas, at the district scale, we adopted a modelling approach to estimate the effects of a widespread conversion from CF to FI on the water requirements of the district.

Results obtained from field-scale experiments suggested that water inputs to rice can be reduced by 20% and 60% on average CF is replaced by DF and FI respectively, but at the expense of lower yields, especially in case of FI (-3% and -28% for DF and FI, respectively). Moreover, a great difference in irrigation requirements CF and DF between the two subsequent seasons was observed. Such inter-annual variability was attributed to the combined effects of environmental factors (e.g. groundwater depth, changes in soil structure, etc.).

With a focus on the district scale, the study highlighted the importance of carefully evaluating the effects of widespread changes in the water management of rice, since CF maintain a shallow water table which provides a direct water supply to other crops through the capillary rise. In fact, a complete conversion from CF to FI in the district resulted in a reduction of rice irrigation requirements by 60%, but it determined an increase of maize requirements by about 50% due to the decline of the groundwater depth.

Key words: water balance; water savings technologies; water use efficiency; water productivity; groundwater

1. Introduction

Italy is the leading rice producer of the European Union with around 220 thousands ha (FAOSTAT, 2014), mainly located in the Northern Po Valley (Piemonte and Lombardia regions). The traditional technique adopted in the area consists of broadcasting pre-germinated seeds over submerged levelled fields and then maintaining a ponded water depth from 5 to 20 cm from just prior to seeding to about three weeks before harvesting. Due to this water management, rice cultivation may require even more than 2,500 mm of irrigation depth over the whole growing season (INEA, 2013), nevertheless with significant variations depending on soil characteristics and groundwater depth. On the other hand, continuous flooding of rice fields is a key factor in recharging the phreatic aquifer, which is very shallow over most of the area and feeds many semi-natural springs, called “fontanili”, that form a longitudinal strip of groundwater-dependent ecosystems across the area. Moreover, the traditional rice cropping systems have created a very characteristic agro-environment, that has been included in the European ecological network NATURA 2000 and in the official list of the European Special Protected Areas (HABITAT Directive, 92/43/EEC).

Although water has never been scarce in most of the Po Valley, the claim to a more efficient use of water in agriculture enhanced the spreading of some water saving technologies for rice cultivation. The practice of dry seeding and delayed flooding has increased in the western part of the rice basin during the last decade, reaching in some areas 70% of the total rice surface in 2015. This expansion is also due to a number of agronomic reasons, including ease of crop rooting in sandy soils, ease of sowing in dry with respect to submerged soil, a lower development of aquatic weeds, as well as a less labour-intensive management of water in the first part of the season (Cesari de Maria et al., 2016a). In addition to delayed flooding, flush-irrigated rice has spread across some areas located in the Lombardy region, east of the Ticino River, especially close to residential areas or where some water scarcity may occur.

Changes in the irrigation management of rice may have relevant impacts on the water balance term at the filed scale as well as on water performance indicators such as the water use efficiency (evapotranspiration over water supply, mm mm^{-1}) and the water productivity (grain yield over total supply, kg m^3). Many authors investigated the effects of replacing traditional flooding with less water-demanding techniques (e.g. Tabbal et al., 2002), but almost all the studies were conducted in rice areas with very different conditions in terms of climate, soil type and agronomic practices compared to the Italian rice systems.

Moreover, few studies have been focusing on the large-scale and long-term effects caused by a widespread shift to alternative irrigation techniques. In fact, most research has been limited to individual field experiments where an increase of the water performance indicators is generally observed when moving from continuous flooding to different water regimes. However, authors observed that groundwater depths remained very shallow in various field experiments (e.g. Belder et al., 2005), while it can be expected that a large-scale change in the water management will lead to an increase in groundwater depth, due to reduced recharge. This will, in turn, increase the percolation and limit the root uptake from groundwater, thus reducing the ultimate water savings.

To improve the understanding of water management issues in rice systems, the paper presents the results of both field scale and district scale studies on water requirements of rice grown under different water techniques. With respect to the field scale, the paper presents the results of a two-year monitoring activity of water fluxes and crop productivity in rice fields comparing three water treatments: continuous flooding (CF), delayed flooding (DF) and flush irrigation (FI). Regarding the district level, the effects of a massive adoption of FI technique in a rice district where CF is currently practised were investigated. The paper presents the variations of water requirements from the present state (CF rice) to the scenario (FI rice), showing the results we obtained via a modelling approach specifically accounting for changes in groundwater levels.

2. Methods

2.1. Field scale analysis

2.1.1. Description of the site

The experiment was conducted during the growing seasons 2012 and 2013 at the Rice Research Centre of Ente Nazionale Risi (Castello d'Agogna, Pavia, Italy). In these agricultural seasons (June till September), average maximum and minimum temperature were 29.2 °C (±3.8°C) and 17.0 °C (±3.2°C) respectively; and average daily reference evapotranspirations in the months of June, July, August and September amounted, respectively, to 4.7, 4.6, 4.0 and 2.8 mm d^{-1}.

The surface horizon of the monitored plots is significantly homogenous in space due to the yearly agronomic practices; texture of the first layer is loam to silty loam (clay from 15 to 23%, bulk density 1.4-1.5 t m^{-3}). A greater spatial variability was found in the underlying horizons.

2.1.2. Description of the experiments

The experiments were laid out in six plots of about 20 m x 80 m with two replicates for each of the following water regimes: *i)* continuous flooding of water-seeded rice (CF), *ii)* continuous flooding from around the 3-leaf stage of drill-sown rice (DF), and *iii)* surface irrigation of drill-sown rice (FI). In the flooded plots the irrigation layout of the site required a flow-through irrigation, i.e. more water is continuously applied, discharging the excess through a spillway. The rice cultivar grown in all the plots was *Gladio cv.*, an early, semi-dwarf variety of tropical japonica type. Irrigation management is shown in Figure 1. Levels of nitrogen fertilizer, given as urea, were 160 kg ha^{-1} to all the treatments in both years.

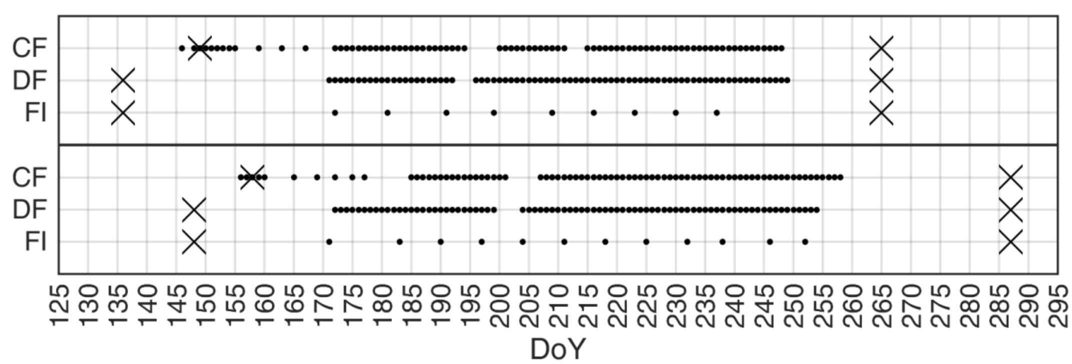

Figure 1. Irrigation events (dots) and sowing/harvesting dates (crosses)

2.1.3. Monitoring activities

One plot for each treatment was monitored throughout the growing seasons 2012 and 2013 by a prototype system described in detail in Chiaradia et al. (2015). Overall, 2 water level sensors, 12 piezometric wells, 6 devices for water inflows and outflows, 20 tensiometers, 4 soil moisture multi-level probes and an eddy-covariance station were installed. Data were automatically stored in data loggers, and downloaded and checked remotely.

2.1.4. Calculation of water balance

The water balance of each treatment was computed according to the following equation:

$$I + R = \Delta S + E_S + E_w + T - SP + D \qquad (1)$$

where: *I* irrigation input, *D* water output (discharge); *R* rainfall; E_s evaporation from the soil; E_w evaporation from the ponded water for CF and DF; *T* crop transpiration; *ΔS* change in the water storage in the root zone (between 0-40 cm depth) and, for CF and DF, in the ponded water depth; SP sum of seepage and net percolation. All terms are expressed in mm over the surface area of the individual plot, and the water balance was computed from dry seeding to harvest for DF and FI, and from the flooding before water seeding to harvest for CF.

I and D were measured, while R was obtained from the agrometeorological station located about 100 m far from the fields. ET was estimated through Penman-Monteith type models calibrated using the eddy-covariance data (Cesari de Maria et al., 2016a). ΔS values were derived from the available soil moisture measurements, considering also the ponded water depth in case of submergence. Finally, SP was obtained as the residual term of the water balance and will be referred to as 'Net Percolation' (NP) hereafter, since no seepage fluxes were observed.

Differences of net water supply (*WS*=I+R-D, Equation 1) were statistically analysed by applying multiple comparison analysis on paired data (Cesari de Maria et al. 2016a).

2.1.5. Calculation of water use indicators

Water Use Efficiency (*WUE*, %) and Water Productivity (*WP*, kg m^{-3}) were calculated referring to *WS* as:

$$WUE = 100 * \frac{ET}{WS} \qquad (2)$$

$$WP = \frac{Y}{WS} \qquad (3)$$

where *Y* is the grain yield in kg m^{-2}. A two-way ANOVA was performed on yield data, while a Monte Carlo approach was used for both *WUE* and *WP*.

2.2. District scale analysis

2.2.1.Study area

The study area is the San Giorgio East district, which comprises about 500 ha at the centre of the western Po Valley rice area (Northern Italy). The main soil type is Argic Udipsamments mixed mesic (USDA, 1975) with a percentage of sand higher than 60%. In spite of the coarse nature of the soil, favourable conditions to grow rice are created by the shallow groundwater depth, with summer minimums of less than one meter and winter maximums within two meters. Land use includes rice, maize and poplar (Table 1). Rice cultivation is currently performed under continuous flooding (CF), while border irrigation is used for maize and young poplar (up to the 4th year), on rotation of 15 days, with 150 and 200 mm per application, respectively.

Table 1. Surface occupied by each land use over the years 2010-2013

Year	Maize (ha)	Rice (ha)	Poplar (ha)	Bare (ha)
2010	86	240	148	24
2011	122	223	136	18
2012	177	163	133	26
2013	197	136	146	19

2.2.2. Analysis of the present state

For the study period 2010-2013, the agro-hydrological model SWAP (Kroes and van Dam, 2003) was used, in a semi-distributed way, for estimating water allocated to all the crops but CS rice, for which a monthly water balance was employed (details in Cesari de Maria et al., 2016b).

2.2.3.Relationship between percolation flux and groundwater depth

The monthly values of the total district percolation was then used to calibrate an empirical quadratic relationship relating recharge and groundwater depth to foresee the groundwater depths of the scenarios.

2.2.4. Conversion to FI rice

Two scenarios were considered: the 'No feedback' (NF) neglecting changes in the growndwater depth and the 'Feedback Accounting' (FA) specifically considering the effect of the change in growndwater recharge due to the different rice water management. Percolation fluxes from the different crop areas, including FI rice, were again simulated using the SWAP model, which was combined with the percolation-groundwater depth relationship to estimate the groundwater depths in FA scenario. Two cases of feedback accounting were examined: FA–15, keeping the 15 days water rotation on maize and FA–10 where the interval for maize was shortened to 10 days for overcoming the significant stress in July occurred under FA–15.

3. Results

3.1. Water balance and water performance indicators at the field scale

The amounts of irrigation applied to CF and DF were 9,970 and 8,600 mm respectively in 2012, while these decreased to 4,340 and 3,470 mm in 2013. On the other hand, irrigation water applied to FI increased in the second growing season compared to the first one, being 1,030 in 2012 and 1,400 in 2013. The water provided to CF and DF is considerably higher than what is reported in literature, especially during 2012. However, the values obtained depend strictly on the adopted flow-through irrigation, therefore, the actual irrigation water requirements of CF, DF and FI treatments are more reasonably given by the difference between I and D, which amounted, respectively, to 3,020, 2,240 and 620 mm in 2012; 1,520, 1,280 and 740 mm in 2013. Net water supply to DF was lower than CF by 24% in 2012 and 14% in 2013 although the reduction was not significant (5%). On the other hand, FI determined a reduction of the net water supply compared to CF between 47 and 75% depending on the year (significant at 5%). Net water supply to CF and DF decreased by 48 and 41% over the two seasons (significant at 5%), whereas FI increased by 10% (not significant at 5%). No relevant differences in the evapotranspiration were found between the treatments in either years, as the maximum difference assessed was of about 60 mm between CF and FI in 2012 (550 and 490 mm respectively). Values of *WUE* substantially reflected the variations in the irrigation water amounts among treatments and years, since no sensible differences were found with respect to evapotranspiration. WUE amounted to 17% (CF), 21% (DF) and 63% (FI) in 2012; and to 27% (CF), 31% (DF) and 49% (FI) in 2013. Rice yield was higher for CF with a production of 10.5 t ha^{-1} in 2012 and 9.3 t ha^{-1} in 2013, followed by DF with 10.3 (-2%) and 9.8 (-5%) t ha^{-1}, respectively; and by FI with 6.9 (-34%) and 7.8 (-20%) t ha^{-1}, respectively. The reduction of rice yield was significant only for the FI treatment. As a result, the best performance in terms of water productivity was achieved by FI, with WP values around 0.88 kg m^{-3} in both years, against 0.43 and 0.66 kg m^{-3} for DF in 2012 and 2013, respectively, and 0.33 and 0.59 kg m^{-3} for CF in 2012 and 2013, respectively.

Table 2. Main seasonal water balance terms, grain yield and water performance indicators

Year	Treat.	I (mm)	D (mm)	R (mm)	ET (mm)	NP (mm)	WS (mm)	Yield (t ha^{-1})	WUE (%)	WP (kg m^{-3})
2012	CF	9,970	6,950	130	550	2,570	$3,160^{a,a}$	10.5^{c}	$17^{a,a}$	$0.33^{a,a}$
	DF	8,600	6,360	170	510	1,820	$2,410^{a,a}$	10.3^{c}	$21^{a,a}$	$0.43^{a,a}$
	FI	1,030	410	170	490	300	$790^{a,b}$	6.9^{d}	$63^{a,b}$	$0.87^{a,b}$
2013	CF	4,340	2,810	130	450	1,200	$1,650^{b,a}$	9.8^{c}	$27^{a,a}$	$0.56^{b,a}$
	DF	3,470	2,190	130	440	970	$1,420^{b,o}$	9.3^{c}	$31^{a,o}$	$0.69^{b,o}$
	FI	1,400	660	130	430	440	$870^{a,b}$	7.8^{d}	$49^{a,a}$	$0.89^{a,b}$

a,b First letter refers to comparisons of the same treatment between years, the second to comparisons of different treatments within the same year. Different letters (a, b) are significantly different at alfa = 0.05

o As for a and b, but the letter indicates no significant difference either with a or with b at alfa = 0.05

c, d Different letters indicates significant differences at alfa = 0.05 (Tukey test after two-way ANOVA)

3.2. *Water use at the district scale*

Considering the present state, the average irrigation amount provided to maize over the period 2010 to 2013 was 675 mm (Table 3). Significant variations however occurred in 2010, when heavy rainfall during the irrigation period made the irrigation requirements drop to 450 mm. On the other hand, the average irrigation requirements for rice, under continuous submergence, were close to 3,900 mm. The irrigation requirements of young poplars amounted to 630 mm in the years 2011 to 2013 and 420 m in 2010. The average irrigation requirement for FI rice in case of no variations in the groundwater depth (NF scenario) was 825 mm, much smaller than for CS. The year-to-year variability was quite high, with similar irrigation requirements only in 2011 and 2012 (1,350 and 1,500 mm, respectively), while no irrigations were applied in 2010 and just 450 mm were required in 2013. With respect to the feedback accounting scenarios, irrigation requirements of maize increased from 750 mm per season (i.e. 5 irrigations) in FA-15 to 1,050 mm (i.e. 7 irrigations) per season in FA-10 (Table 3). The irrigation requirements for FI rice ranged between 1,350 mm in 2010 (9 irrigations) to 1,800 mm in 2013 (12 irrigations), provided approximately on a weekly basis. District water withdrawals under FA–10 scenario were estimated to be on average 41% less than the present state, while in the FA–15 and NF scenarios they were lower by 46% and 67% respectively.

Table 3. Average irrigation amounts and standard deviations for the different crops and the whole district obtained for the years 2010-2013.

Study case	Maize (mm)	CF rice (mm)	FI rice (mm)	Young Poplar (mm)	District ($10^6 m^3$)
Present state	675 (±150)	3,889 (±398)	-	577 (±105)	12.97 (±1.43)
NF	675 (±150)	-	825 (±719)	577 (±105)	4.31 (±2.55)
FA–15	750 (±0)	-	1,650 (±173)	630 (±0)	6.98 (±0.43)
FA–10	1,050 (±0)	-	1,650 (±173)	630 (±0)	7.63 (±0.23)

CF rice had the lowest water use efficiency (WUE = 0.15, Table 4) due to the need of continuously supplying water to maintain ponding water over a coarse soil. It follows that WUE of the district in the present state reflected that of CS rice (0.17 on average), due to the large area occupied by CS rice (up to 48% in 2010). The WUE of maize was about 0.50, due to the combination of the soil type, groundwater depth and the use of border irrigation with a fixed rotation scheme. Assuming a conversion from CS rice to FI rice and no changes in the groundwater depth from the present state (NF scenario), the WUE of rice increased to 0.47 and WUE referred to the whole district reached 0.38 (Table 4). When the feedback effects between irrigation and groundwater depth were accounted for (FA–15 and FA–10 scenarios), the WUE of FI rice decreased to an average of 0.20, being just 5% higher than CS rice. In contrast to the increase in WUE for FI rice, maize WUE decreased from an average of 0.49 in the present state to 0.36 in FA–10, due to the need of shortening the irrigation turn. Considering again the whole district, WUE under FA–10 scenario was 0.21 against 0.17 in the present state.

Table 4. Averages and standard deviations of the water use efficiency of the different crops and the whole district obtained for the years 2010-2013.

Study case	Maize (mm mm^{-1})	CF rice (mm mm^{-1})	FI rice (mm mm^{-1})	Young Poplar (mm mm^{-1})	District (mm mm^{-1})
Present state	0.49 (±0.05)	0.15 (±0.01)	-	0.31 (±0.08)	0.17 (±0.03)
NF	0.49 (±0.05)	-	0.47 (±0.29)	0.31 (±0.08)	0.38 (±0.15)
FA-15	0.43 (±0.06)	-	0.20 (±0.02)	0.25 (±0.01)	0.22 (±0.04)
FA-10	0.36 (±0.05)	-	0.20 (±0.02)	0.25 (±0.01)	0.21 (±0.03)

4. Discussion

4.1. Water requirements and water performance of different irrigation methods

The sensible variation of net water supply to CF and DF between the two subsequent seasons (-48% and -41% respectively) could be attributed to different causes that determined a relevant variation in the percolations. Most of the variation between the two years occurred during the period after the first submersion (data not shown, see Cesari de Maria et al. 2016a), whereas the average percolation rate in the remaining part of the agricultural season was much more constant over the two years. Focusing just on the first period, the groundwater level at the beginning of this phase was shallower in 2013 than in 2012 due to the heavy rainfall occurred in Spring 2013 (380 mm in the months from April to May). As a possible consequence, lower water requirements were observed in the same year likely due to smaller pressure gradients. Another reason for such different water requirements could be related to soil conditions. Although tillage operations were the same in both years, the pattern and intensity of rainfall events between ploughing and the first submersion were different, determining a different degree of soil compaction. In fact, although rainfall was higher in 2012 than in 2013 (180 mm against 113 mm), the events occurred in 2012 were distributed over a much longer period from ploughing to flooding. Conversely, in 2013 more intense rainfall events occurred shortly before the first flooding and this could have determined some degree of soil compaction even before the first flooding. In addition to that, tillage was performed on a wetter soil and this could have affected the soil structure with consequent effects on the soil structure. Another reason for the greater irrigation amounts required in 2012 could be the presence of macropores induced by earthworms, as we collected evidence of the presence of earthworms both in the experimental fields and in the surrounding.

With respect to FI treatment, the increase of net water supply from 2012 to 2013 was related to a greater number of irrigation events (9 and 12 in 2012 and 2013, respectively) due to: i) a growing season longer by 10 days, and ii) a less favourable rainfall pattern (in 2012, the repeated rainfall events occurred in the late part of the growing season likely replacing one or two irrigation events).

DF determined a reduction of total water use compared to CF amounting to 20% on average, while irrigation amounts applied to FI were on average 60% less than CF. On the other hand, CF determined the highest average yield (10.2 t ha^{-1}), whereas reductions by 3% and 28% were observed in case of DF and FI respectively. Values of water use efficiencies and water productivity were therefore in the order CF < DF < FI. The latter reached a water use efficiency of 0.56 mm mm^{-1} and a water productivity of 0.88 m^3 ha^{-1}. Considering the values of water use indicators, the best performance was achieved by flush irrigated rice. However, the yield reduction compared to the other treatments is very high (more than 20%) and it represents a significant limitation to the adoption of this technique by rice farmers in the area.

4.2. Effects of changing rice water management at the district scale

In the case of the S. Giorgio East district, the reduction in water withdrawals for rice declined from around 80% when no feedback between groundwater depth and recharge was considered to around 60% when feedbacks were accounted for. The relevant reductions in both scenarios are due to the fact that very high water requirements (3,900 mm on average) are needed in the present state to maintain ponding water over such a coarse soil. However, it can be observed that neglecting the feedback between percolation and groundwater depth led to an overestimation of the gains.

Moreover, even if changes in the irrigation method of rice determined a reduction of total water requirements of rice cultivation, the irrigation requirements of maize increased due to an increase of the groundwater depth. The current irrigation scheduling of maize, based on a 15-day rotation was found to be insufficient to satisfy crop water requirements in the scenario of FI rice, in which groundwater depths were greater. A reduction of the rotation to 10 days practically eliminated transpiration stress, but it increased the irrigation requirements of maize by about 50%. In addition, the time pattern of irrigation requirements of FI rice was more variable than that of continuously CS rice (data not shown, see Cesari de Maria et al., 2016b), with the peak value generally occurring in July, as is the case also for maize. Therefore, the reduction in simulated district irrigation deliveries in July was much smaller than reductions observed over the whole period (data not shown, see Cesari de Maria et al., 2016b). These results suggest that the reduction in irrigation deliveries to rice fields when changing from CS rice to FI rice might increase the irrigation requirement of other crops, due to the feedback effects of groundwater dynamics at larger scales, and amplify the variability of total irrigation requirements during the agricultural season.

Gains in water use efficiency at both the field and the district level are possible after a conversion to FI rice. In our study, the water use efficiency of the district was estimated to be about 5% greater than that of the present state, in contrast to an improvement of almost 20% when groundwater depths were assumed to remain unvaried after changes in the water management of rice.

Conclusions

This study, carried out in northern Italy, presented the water balance implications of different irrigation methods in rice farming with a focus on both the field and the district scale.

At the field scale, we observed that water inputs to rice can be reduced by 20% and 60% on average if continuous flooding is replaced by delayed flooding and flush irrigation respectively. However, yields of DF and FI were lower by 3% and 28% compared to CF and the yield reduction resulting from FI practice could represent a significant limitation to the adoption of this technique by rice farmers in the area. Moreover, a great difference in irrigation requirements of the flooded treatments (CF and DF) between the two subsequent seasons was observed, highlighting that the results obtained from just one season can significantly deviate from the average behaviour. Such deviation was determined by a variation in the percolation term, which is the one most affecting water requirements of flooded rice. The relevant inter-annual variability was attributed to the combined effects of the following factors: i) the groundwater level at the beginning of the rice season through its influence on the vertical hydraulic gradients; ii) the soil moisture during tillage operations affecting the soil structure; iii) the degree of soil compaction due to rainfall events of different intensity occurring between soil tillage and the first irrigation application; and iv) the possible occurrence of preferential macropore fluxes due the activity of earthworms, particularly in the early part of the agricultural season.

Focusing on the district scale, the study highlighted the importance of carefully evaluating the effects of widespread changes in the water management of rice. Under the present conditions of the S. Giorgio East District, a total irrigation depth greater than 3,000 mm per season is required to grow flooded rice, due to the coarse texture of the soils. At the same time, however, the regime of continuous submergence provides a significant recharge to the groundwater, which is maintained within one meter from the soil surface. These high groundwater levels provide a direct water supply to other crops of the district through the capillary rise. In fact, a complete conversion of the rice areas to flush irrigation resulted in a reduction of rice irrigation requirements by 60%, but it determined an increase of maize requirements by about 50% due to the decline of the groundwater depth. Taking into account these feedback effects in the simulation, the water use efficiency at the district scale in case of conversion of the water management in rice areas to flush irrigation was estimated to be only about 5% greater than that of the present state.

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