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Strategies to increase water productivity in irrigated rice systems:
is reducing water inputs the key?

PhD Thesis:
Sandra CESARI DE MARIA
Student ID: R10155

Supervisor: **Prof. Claudio GANDOLFI**
Coordinator: **Prof. Roberto PRETOLANI**

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Abstract

In a context of increasing food demand and increasing risk of water scarcity, irrigated rice systems are receiving a specific attention because of the role of rice in food nutrition and because of the relevant share of water withdrawals required by rice farming. More than 75% of the global rice supply is in fact produced in lowland irrigated areas, which in turn require around 40% of the global water used for irrigation.

Given this background (Chapter 1), the Thesis investigates the role of water management in irrigated rice system, in response to the compelling pressures on farmers to maximise crop production while reducing the amount of water used for irrigation purposes. Three interlinked focus areas have been evaluated: (i) the role of monitoring techniques in improving knowledge on processes driving water use in rice systems, (ii) field-scale evaluation of the performance of different water regimes, (iii) effects induced by a large adoption of water saving technologies on the irrigation requirements at the district scale.

First, a prototype of an innovative integrated multi-sensor system was developed in order to monitor water dynamics in paddy fields under different water regimes. Several monitoring devices were effectively used in an combined way, enabling to measure different processes with a high temporal resolution (Chapter 2). In addition to on-ground devices, the opportunity offered by the use of remote sensed data to capture the spatio-temporal evolution of crop growth and study crop-related processes was investigated (Chapter 3).

Focussing on the field scale (Chapter 4), water balances and water use indices of three rice water managements were compared: water seeding-continuous flooding ("traditional" practice) and two alternative regimes being dry seeding-delayed flooding and dry seeding-intermittent irrigation. If delayed flooding determined average yield reductions by 3% against a decrease of water applications by 20%, the 65% reduction of water applications in intermittent irrigated rice was counterbalanced by yield losses close to 30%. Therefore, in spite of intermittent irrigation achieving the highest water productivity, the economic practicality of the method could be questioned. Moreover, the irrigation requirements of the flooded treatments were found to vary significantly between years, with variations by 40% to 50% (mostly occurred in the first part of the season). Taking as a reference the traditional flooding regime, irrigation requirements halved from 3,000 mm in the first season to 1,500 mm in the subsequent one. Variations were statically validated and they were attributed to a combination of abiotic and biotic factors including groundwater levels at the beginning of the season and soil-related aspects.

Then, the extent of reductions in irrigation requirements when replacing traditional flooding with intermittent irrigation was investigated at the scale of an irrigation district (Chapter 5). Water requirements of the different crops (flooded rice, irrigated maize and irrigated poplars) were investigated over a 4-year period by the application of a distributed modelling approach (use of the SWAP model) and water balance equations. An empirical relationship between groundwater recharge (provided by percolation from irrigated fields) and the groundwater levels was thus identified. For the scenario of intermittent irrigated rice, a particular attention was paid to the role of the feedback between groundwater levels and irrigation applications. The importance of feedback effects was highlighted by developing a case study where groundwater is assumed invariant from the present state (no feedback) and a case study where the estimated irrigation requirements are congruent with the “new” equilibrium state between groundwater levels and groundwater recharge. According to the estimates of the scenarios, irrigation withdrawals of the district decreased by around 65% when the feedback mechanism was neglected, while a reduction by 45% was observed when the feedback was accounted for. However, maintaining a 15-days turn for maize irrigation, like in the present state, was found to be inadequate for the full satisfaction of maize water requirements due to the decrease in the groundwater levels. Shortening the irrigation turn of maize to 10 days instead of 15 further decreased the estimate of the savings achievable with flush irrigated rice (reduction of irrigation requirements equal to 40%).

In addition to implications on water balance terms, a specific attention was paid on the dynamics of dissolved organic carbon in relation to the water regime. Results of the study highlighted a strong link between the cycling of dissolved organic carbon and the reducing soil conditions resulting from field flooding (Chapter 6).

Finally, the role of shallow groundwater table on the reduction of the irrigation requirements of lowland crops under intermittent irrigation was quantified via modelling simulations. Results showed a contribution of capillary rise up to 50% of the amount of water evapotranspirated by the crop (Chapter 7).

In spite of the tendency to seek for general and global solutions, the research activities presented in the Thesis highlighted the difficulty to provide a univocal response to the question as to whether reductions of water consumptions in rice paddies should really represent the target to be reached regardless the specific context (Chapter 8).

Keywords: Paddy; Water saving technologies; Monitoring; Water balances; Groundwater; SWAP model

Sommario

La crescita della domanda mondiale di cibo e l'aumentata incidenza di situazioni di carenza idrica ha notevolmente accentuato l'attenzione sulla risicoltura, data la sua importanza per la nutrizione umana e il suo contributo ai prelievi idrici per fini irrigui. Più del 75% della produzione mondiale di riso ha infatti luogo in risaie irrigate che utilizzano circa il 40% dell'acqua destinata al settore agricolo.

Alla luce di questo contesto (descritto nel Capitolo 1), la Tesi si pone l'obiettivo di valutare diverse tecniche di gestione dell'acqua in risaia come risposta alle crescenti pressioni sugli agricoltori che sono chiamati a massimizzare le produzioni, riducendo al contempo i volumi irrigui apportati. Il lavoro è articolato su tre principali aree di indagine tra loro interconnesse: (i) ruolo delle tecniche di monitoraggio nel favorire l'analisi dei fattori che determinano l'efficienza d'uso dell'acqua; (ii) valutazione di diverse strategie irrigue alla scala di risaia; (iii) studio delle variazioni dei fabbisogni irrigui distrettuali laddove la sommersione tradizionale fosse sostituita da tecniche di risparmio idrico su larga scala.

Per quanto concerne il primo punto, l'attività di Tesi ha contribuito allo sviluppo del prototipo di un innovativo sistema per il monitoraggio delle dinamiche dell'acqua in camere di risaia soggette a diverse tecniche irrigue. Svariati sensori sono stati utilizzati in maniera integrata permettendo la misura di diversi processi con alta risoluzione temporale (Capitolo 2). In aggiunta alle tecniche di monitoraggio a terra, è stata valutata la possibilità di impiego di dati da satellite per la valutazione dello sviluppo della vegetazione nel tempo e nello spazio, informazione necessaria per lo studio di processi legati allo sviluppo vegetativo (Capitolo 3).

Alla scala di campo sono stati valutati i bilanci idrici e gli indici di uso dell'acqua di tre diverse tecniche di gestione: semina in acqua e sommersione continua (pratica tradizionale), e due tecniche alternative che consistono nella semina interrata e sommersione ritardata e semina interrata e irrigazione intermittente. Se, da un alto, la sommersione ritardata ha determinato riduzioni del raccolto del 3% a fronte di risparmi idrici del 20%, l'irrigazione intermittente ha visto riduzioni del raccolto pari a circa il 30% come contraltare a risparmi idrici dell'ordine del 65%. I valori più alti per quanto riguarda l'indice di produttività dell'acqua sono stati ottenuti con riso irrigato ad intermittenza, tuttavia la sua sostenibilità economica sarebbe da valutare attentamente, date le significative perdite di raccolto osservate. Inoltre, è stata riscontrata una significativa variabilità nei fabbisogni irrigui dei trattamenti in sommersione, i quali hanno subito variazioni comprese tra il 40% e il 50% da un anno al successivo (variazione concentrate soprattutto all'inizio della stagione). Prendendo come riferimento la sommersione tradizionale, si è riscontrato un dimezzamento dei volumi irrigui necessari che sono passati da circa 3000 mm a 1500 mm. Tali variazioni sono state avvalorate da un'analisi statistica e sono state attribuite alla combinazione di diversi fattori quali la profondità di falda all'inizio della stagione e modificazioni a livello delle proprietà e della struttura del suolo.

Successivamente, il potenziale risparmio idrico conseguente ad un abbandono della tecnica di sommersione è stato valutato alla scala di distretto irriguo (Capitolo 5). I fabbisogni irrigui delle diverse colture del distretto (riso sommerso, mais irriguo e pioppo irriguo) sono stati stimati lungo un periodo di 4 anni grazie all'applicazione, in maniera distribuita, del modello idrologico SWAP e all'uso di equazioni di bilancio di massa. Successivamente, è stata individuata una relazione empirica che lega la soggiacenza alla ricarica di falda (data dall'acqua di percolazione dei campi irrigati). Per lo scenario di conversione a riso irrigato, si è prestata particolare attenzione al meccanismo di feedback che lega il livello di falda ai volumi irrigui necessari. L'importanza di questo legame è stata messa in luce attraverso lo sviluppo di due casi di studio. Nel primo caso, il feedback è stato trascurato e la stima dei fabbisogni irrigui è fatta sulla base degli attuali livelli di falda. Nel secondo caso invece, la stima devi volumi irrigui necessari è fatta in funzione dall'equilibrio soggiacenza-ricarica che verrebbe ad instaurarsi a seguito di una consistente variazione delle pratiche irrigue. Nello scenario senza feedback sono state stimate riduzioni dei fabbisogni irrigui dopo una conversione delle tecniche irrigue pari al 65%. Tali riduzioni sono state invece del 45% quando il meccanismo di feedback è stato considerato nell'analisi. Tuttavia il mantenimento di un turno irriguo per il mais di 15 giorni si è rivelato non sufficiente per il soddisfacimento dei fabbisogni idrici della coltura a causa dell'aumentata soggiacenza. Accorciare il turno irriguo del mais a 10 giorni ha determinato un'ulteriore riduzione dei risparmi ottenibili con una completa conversione a riso irrigato ad intermittenza (riduzione dei fabbisogni irrigui distrettuali pari al 40%).

Oltre ad aspetti strettamente legati ai volumi idrici, sono state inoltre investigate le dinamiche del carbonio organico disciolto in funzione delle diverse tecniche di gestione dell'acqua (Capitolo 6). Lo studio ha evidenziato un legame molto forte tra il ciclo del carbonio organico disciolto e le condizioni riducenti indotte dalla continua saturazione del suolo.

Infine è stato sviluppato un caso di studio per quantificare il ruolo della falda nella riduzione dei fabbisogni irrigui di colture irrigate ad intermittenza come il mais. I risultati hanno evidenziato un contributo della risalita capillare pari a circa il 50% del volume evapotraspirato dalla coltura in aree con bassa soggicanza di falda (Capitolo 7).

In conclusione, nonostante la tendenza a voler proporre soluzioni di carattere generale al problema dell'efficienza d'uso dell'acqua in agricoltura, le attività di ricerca proposte nella seguente Tesi hanno messo in luce come sia difficile stabilire se il risparmio idrico sia effettivamente un obiettivo da perseguire in qualsiasi contesto produttivo (Capitolo 8).

Parole chiave: Risaia; Tecniche di risparmio idrico; Monitoraggio; Bilanci idrici; Profondità di falda; modello idrologico SWAP

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CHAPTER 1

General introduction

The Thesis investigates the role of water management in irrigated rice systems, in response to the compelling pressures on farmers to maximise crop production while reducing the amount of water used for irrigation purposes. Indeed, in a context of increasing food demand and increasing risk of water scarcity, the call appears certainly legitimate and unquestionable. In this framework, rice is probably the most targeted crop for several reasons relating to both its importance as a food crop and to its share of water withdrawals.

Rice is cultivated on surface of 165 million ha that feeds almost half of humanity, with a global production of unmilled rice of around 750 million tonnes (FAOSTAT, 2013). According to some scenarios (e.g. Timmer et al., 2010), a general decline in rice demand may occur by 2050, especially in Asia and the Middle East; while an increase is expected in the African countries. There is, however, a high degree of uncertainty relating to these projections, since future rice consumption will depend on different factors such as the population growth, the income growth and its distribution, and the urbanization of the population (Timmer et al., 2010). In spite of these scenarios, many studies stress the importance of increasing rice productions in order to provide sufficient and affordable food for a growing population and to alleviate rural and urban poverty (Bouman et al., 2007c). However, even maintaining the existing levels of rice productivity in light of the increasing incidence of local water scarcity could become a challenge.

The other reason driving the specific focus on rice systems is related to its peculiar link with water resources. Cultivated rice evolved from a semiaquatic perennial ancestor and, due to this origins, the crop presents morphological and physiological characteristics that differ from those of the other cereals (Lafitte and Bennett 2002). Consequently, rice is grown under flooding conditions in many rice-growing countries because most of varieties maintain a better growth and produce higher grain yields when grown in a flooded soil compared to non-flooded soil (De Datta, 1981). Indeed, lowland irrigated rice provides more than 75% of the global rice supply (Maclean et al., 2002), but such productions are achieved “at the expense” of water withdrawals amounting to 40% of the global water used for irrigation (Bouman et al., 2007c). In light of these statistics, improving water use efficiency and water productivity of rice systems has become an imperative, which is even more compelling considering the fact that the irrigated rice areas that will be suffering some degree of water scarcity are estimated to increase significantly by 2025 (Tuong and Bouman, 2003).

Many authors have advocated improvements in water use efficiency and water productivity to such an extent that these two concepts are now widely used in most of the literature concerning water management in agriculture. In general terms, these concepts refer to ratios between a productive output such as evapotranspiration, grain yield or crop value, over a selected amount of water that is consumed or applied for the growing process. A univocal and more precise definition is hindered by the use of these indicators in different research fields, going from crop physiology to irrigation science and water management. Regardless specific uses, some authors agree that talking about either water use efficiency or water productivity can be reductive or lead to erroneous conclusions when the original domain of analysis is extended or a wider perspective is adopted (e.g. Perry 2007, van Halsema and Vincent, 2012, Heydary, 2014, Zoeble, 2006). In fact, these indices are generally not robust to changes in the spatial or temporal domain of analysis, with the consequence that any extension of results to different scales may bring to biased conclusions. Moreover, even though these indices seem to facilitate the comparison between different realities, they actually convey little information on the overall efficiency of the productive system with respect to all the productive factors. An interesting reflection on the matter is found in Zoeble et al. (2006), who reports the following questions: “What is the value of a high yield per unit water use in a region or season where rain or irrigation water is not scarce? Is it advisable or wise to increase this water productivity in situations where a higher productivity of one category of desired outputs (crop yields) goes at the expense of another one (water table)”? In our opinion, the quote wisely highlights the need for evaluating the performance of agricultural systems with a wider perspective, going beyond a mere ratio between crop production and water inputs applied to achieve such production.

This kind of approach is even more important when the focus is on rice systems, since the continuous presence of ponded water for most of the crop cycle performs relevant functions that cannot be valued if the attention is just on a balance between mass of grain yield per unit volume of applied water. In fact, continuous submergence of rice fields has relevant impacts on the hydrology of an area, on the environment, as well as on biodiversity, landscape and culture. Impacts can be either positive or negative. Positive functions are related to the recharge of groundwater systems by percolation from flooded rice fields; to the removal of nitrogen and phosphorus from paddy water; to the reduction of soil erosion, to the removal of salts from soils with a good drainage; to the mitigation of air temperature; to the sustainment of biodiversity; and to the maintenance of a unique and characteristic landscape (Bouman et al., 2007c, Bouman et al., 2007b, Kim et al., 2006). On the other hand, rice cultivation is an important source of atmospheric methane and of nitrous oxide. Moreover, biocides or their residues may be directly transferred to open water bodies through drainage water, with consequent negative impacts on the environment (Bouman et al., 2007c; Bouman et al, 2007b; Kim et al 2006).

Concluding, the need to investigate the sustainability of flooded rice systems is compelling for many reasons relating to the complex interactions between this agro-ecosystem and factors such as nutrition, economy, water resources, and the environment. In spite of the tendency to seek for simple and generalized solutions based on water use indicators, the Thesis addresses the matter with a wider perspective that encompasses field experiments and scenario analysis, local and district scales, monitoring techniques and modelling tools.

1.1 Research objectives

Specific objectives of the Thesis are

I. Develop and apply monitoring setups to investigate water dynamics and water productivity of rice systems. Use of in-field measurements and remote-sensed data depending on the domain under investigation.

II. Compare water balances, water use efficiencies and water productivities of rice under different water regimes including traditional flooding and less water-demanding practices (i.e. delayed flooding and intermittent irrigation). Highlight the effects of environmental factors on seasonal water requirements and on water use indices of rice considering the field as spatial domain.

III. Investigate the changes on water withdrawals at the district scale if traditional flooding of rice is replaced by a less water-demanding regime like intermittent irrigation. A specific attention is paid to the link between the irrigation supplies and the groundwater levels and to the feedbacks between the two.

IV. Study the cycling of organic carbon at the field scale in response to different water regimes, including traditional flooding, delayed flooding and intermittent irrigation.

Another sub-objective the Thesis aims to pursue that is related to the objective number III. is:

V. Analyse, through modelling and simulation, the role of shallow groundwater table on the reduction of the irrigation requirements of lowland crops under intermittent irrigation.

1.2 Thesis outline

The Thesis consists of a general introduction (Chapter 1) four research papers (Chapter 2, 4, 5 and 6), two contributions in the form of either a technical note (Chapter 3) or a conference paper (Chapter 7) and a general discussion with conclusive remarks (Chapter 8). Each chapter focuses on a specific objective presented in the previous section, apart from Chapter 2 and 3, both focussing on objective I.

Chapter 2 (Environ Monit Assess 2015, 187:586) presents the prototype of an integrated, multi-sensor system for the continuous monitoring of water dynamics in rice fields under different irrigation regimes. The system was successfully applied over a two-year period in three experimental rice fields in Northern Italy where different water regimes were compared. Information relating to the different instruments selected, their inter-connections, and their integration in a common remote control scheme are presented, along with considerations on material and labour costs of the installation.

Chapter 3 (Technical note, in preparation) describes the first season of a rice project investigating drivers of yield variability in Australian rice farming. The potentialities of integrating on-ground monitoring with remote sensing are underlined by showing preliminary results concerning spatial variation of water temperature (measured by in-field sensors), crop development in terms of evolution of Normalized Difference Vegetation Index (from remote sensed data) and final grain yield (from monitoring devices on the harvester).

Chapter 4 (Irrigation Sci, submitted) details results of the monitoring activity described in Chapter 2. It focuses on water use aspects with the aim to compare water balance terms, water use efficiencies and water productivities of the different regimes and to discuss inter-annual variations of paddy irrigation requirements due to environmental factors. A statistical analysis of percolation fluxes of flooded treatments was conducted in order to validate results of the water balance and to provide insights into the subsurface water dynamics.

Chapter 5 (Agr Water Manage, under review) describes a scenario analysis investigating the impacts on irrigation requirements induced by a shift from continuous flooding to flush irrigation in a rice-growing district of Northern Italy characterised by a shallow water table. A three-stage procedure was applied comprising the following steps: i) analysis of water use in the present state by using the SWAP (Soil, Water, Atmosphere, Plant) model to simulate irrigation applications, soil waster dynamics and percolation fluxes; ii) calibration of an empirical relationship between estimated percolation fluxes and measured groundwater levels; iii) prediction of the district irrigation requirements in the scenario of flush irrigated rice by applying the SWAP model and the relationship previously calibrated to identify the new equilibrium between percolation and groundwater levels.

Chapter 6 (Plant Soil, accepted) evaluates the trends in dissolved organic carbon (DOC) concentrations, composition and fluxes in paddy soil solution, water supply and drainage canals during rice cropping season. It identifies the main mechanisms and drivers that link soil solution DOC cycling to the input of organic carbon to subsoils, export to surface waters and methane emissions as a function of different water management practices.

Chapter 7 (Journal of Agricultural Engineering, 2013) provides an estimate of the capillary fluxes in an experimental case characterized by a shallow groundwater table, in order to quantify their contribution to the satisfaction of the water requirements of a lowland crop (maize) under intermittent irrigation. For this purpose, the hydrological SWAP model was implemented using detailed monitoring data collected in field. The calibration of the effective saturated hydraulic conductivities along the soil profile was achieved by coupling the SWAP model with an optimization algorithm, named SCEM-UA that is extremely effective in identifying the optimal parameter values of non-linear systems.

Finally, in *Chapter 8* (Summary and conclusions) the main findings of the research are summarized and discussed with a focus on future developments as well.

CHAPTER 2

An integrated, multisensor system for the continuous monitoring of water dynamics in rice fields under different irrigation regimes[1]

E.A. Chiaradia[a], A. Facchi[a], D. Masseroni[a], D. Ferrari[a], G.B. Bischetti[a], O. Gharsallah[a], S. Cesari de Maria[a], M. Rienzner[a], E. Naldi[a], M. Romani[b], C. Gandolfi[a]

[a] Department of Agricultural and Environmental Sciences (DiSAA), Universitá degli Studi di Milano, 20133 Milan, Italy

[b] Centro Ricerche sul Riso, Ente Nazionale Risi (ENR), 27030 Castello d'Agogna (PV), Italy

Abstract

The cultivation of rice, one of the most important staple crops worldwide, has very high water requirements. A variety of irrigation practices are applied, whose pros and cons, both in terms of water productivity and of their effects on the environment, are not completely understood yet. The continuous monitoring of irrigation and rainfall inputs, as well as of soil water dynamics, is a very important factor in the analysis of these practices. At the same time, however, it represents a challenging and costly task because of the complexity of the processes involved, of the difference in nature and magnitude of the driving variables and of the high variety of field conditions.

In this paper we present the prototype of an integrated, multi-sensor system for the continuous monitoring of water dynamics in rice fields under different irrigation regimes. The system consists of: 1) flow measurement devices for the monitoring of irrigation supply and tailwater drainage, 2) piezometers for groundwater level monitoring, 3) level gauges for monitoring the flooding depth, 4) multi-level tensiometers and moisture sensors clusters to monitor soil water status and 5) eddy covariance station for the estimation of evapotranspiration fluxes, 6) wireless transmission devices and software interface for data transfer, storage and control from remote computer.

The system is modular and it is replicable in different field conditions. It was successfully applied over a two year period in three experimental plots in Northern Italy each one with a different water management strategy. In the paper, we present information concerning the different instruments selected, their inter-connections, and their integration in a common remote control scheme. We also provide considerations and figures on the material and labour costs of the installation and management of the system.

Keywords Water fluxes; Rice; Monitoring; Water balance; Instrumentation

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[1] Environ Monit Assess (2015) 187:586

1 INTRODUCTION

The cultivation of rice, one of the most important staple crops worldwide, is undeniably characterized by high water requirements. In many areas of the world, rice is traditionally grown in bounded fields that are kept flooded from crop establishment to close to harvest by maintaining a ponded water depth of about 5-10 cm (Bouman et al., 2007b). Owing to this particularly demanding water management and to the large harvested area, it is estimated that irrigated rice receives about 40% of the total water globally used for irrigation purposes (Bouman et al., 2007b), and that the total seasonal water input to irrigated rice (rainfall plus irrigation) can be up to 2-3 times more than for other cereals, like wheat or maize (Tuong et al., 2005). Seepage and percolation are the main responsible for the low water use efficiency of flooded rice since they are estimated to account altogether for about 25-50% of all water inputs in heavy soils with a groundwater table within 50 cm from the soil surface (Cabangon et al., 2004; Dong et al., 2004), but they can reach a percentage of 80% in coarse-textured soils with a groundwater table of 1.5 m or more (Sharma et al., 2002; Singh et al., 2002). As a consequence, new approaches known as “Water Saving Technologies” are being investigated in order to exploit the opportunity of reducing the water amounts required by traditional rice cropping systems (e.g. Tabbal et al., 2002; Belder et al., 2007; Bouman et al., 2007a; Govindarajan et al., 2008; Dunn and Gaydon, 2011; Sudhir-Yadav et al., 2011). However, few studies have been carried out in Europe, where soil types, climate conditions and, mostly, rice cultivation practices are different from those adopted in Asian countries (e.g., no soil puddling to reduce water percolation is usually conducted). Obtaining reliable site-specific data on water efficiencies at the field scale under different irrigation treatments is crucial to address the planning and management of irrigation in rice areas.

Besides the assessment of water consumptions, the monitoring of water fluxes in rice fields is crucial also for the analysis and the solution of a variety of different problems related to water pollution (e.g. Vu et al., 2005; Jang et al., 2012), crop productivity (e.g. Cabangon et al., 2002; Bouman et al., 2005; Xiaoguang et al., 2005), gas emissions (e.g. Yagi et al., 1996; Alberto et al., 2014) and ecosystems conservation (e.g. Natuhara, 2013 for a general review).

In order to compute the water use efficiency, the different terms of the water balance must be measured or estimated. Generally, researchers use different approaches and methods for monitoring water fluxes, according to research objectives, specific field characteristics and water management strategy, and resources availability. In some cases, the monitoring activity concerns only some of the water fluxes (Alberto et al., 2014; Bethune et al., 2001; Chen and Liu, 2002; de Silva and Rushton, 2008; Thakur et al., 2014) and/or is carried out for a limited interval of time during the agricultural season (Chen and Liu, 2002). In the literature, therefore, no unique way for water fluxes monitoring can be found and it is recognised that this is still a difficult task (Feng et al., 2007).

Designing, implementing and managing a system for the continuous monitoring of water fluxes in rice fields under different water management strategies over the entire crop season is therefore a challenge and the present paper aims at contributing to fill this gap. In the paper we present an innovative prototypal system for water fluxes monitoring, specifically designed for rice fields under flooded and non-flooded conditions. In particular, we use the experience gained in a pilot study implementation of the system to provide information concerning the different sensors and devices selected, their connection, their field installation and their use in an integrated, remotely controlled system. Considerations on the material and labour costs of the entire installation are also included.

2 WATER FLUXES IN IRRIGATED RICE FIELDS

Water fluxes in irrigated rice fields depend on the type of water management strategy that is adopted. Three of the strategies that are currently most widely used worldwide are:

i) Water seeding, continuous FLooding (WFL): the rice field is submerged immediately after tillage operations; seeding is made directly in water, which is maintained for the whole crop cycle except for brief periods to allow treatments with herbicides or fertilizers;

ii) Dry seeding and delayed FLooding (DFL): seeding is made before flooding, which takes place approximately when rice is around the 3-leaf stage; water management is then similar to WFL; iii) Dry seeding and intermittent IRrigation (DIR): no flooding takes place; the field is irrigated intermittently, either by border or sprinkler irrigation; this strategy is known as “aerobic rice” cultivation. Figure 1 provides a schematic representation of water fluxes in rice fields under flooded and non-flooded conditions. Overall, the main fluxes are: irrigation supply and tailwater drainage, direct precipitation and evapotranspiration, percolation and capillary rise. Seepage through bunds may be also relevant for WFL and DFL when a hydraulic difference exists between the water levels in adjacent fields. Only few of these fluxes can be measured directly - namely precipitation, irrigation supply and tailwater drainage – and even these few not without difficulties. The direct measurement of evapotranspiration and percolation is practically unfeasible, due to the spatially distributed nature of these fluxes and to the high variability of factors that determine their intensity. An estimate of evapotranspiration can be obtained indirectly, by measuring other related variables and applying suitable modelling tools to derive the unknown evapotranspiration value. Typically, Penman-Monteith type models (e.g. Bouman et al., 2005) or eddy-covariance approaches (e.g. Alberto et al., 2011) are applied. In the first case, the variables that need to be measured refer to meteorological conditions (solar radiation, air temperature and humidity) and to the soil-crop system (soil heat flux and crop development stage). Eddy covariance approaches have been developed in the last decade, since high frequency sonic anemometers and gas-analysers became available for field applications. Evapotranspiration fluxes are derived from the direct measurement of 3D wind velocity components and of air humidity at frequencies of approximately 50 Hz, using simplified equations of eddy dynamics over the canopy (e.g. Alberto et al., 2011).

Similar to evapotranspiration, estimates of the local percolation fluxes can be obtained by applying suitable mathematical models, usually based on Richards' equation, to derive the percolation beneath the root zone. The application of these models requires the direct measurement of the upper boundary conditions (irrigation and precipitation inputs for DIR and water level for WFL and DFL) and of the lower ones (depth to the groundwater), along with an hydraulic characterization of the soil. This last is generally achieved through either a combination of direct measurements and indirect estimates, or inverse modelling, starting from the measurement of soil hydraulic variables as soil water content and potential. Given the high spatial variability of soil characteristics, several soil profiles generally need to be instrumented and monitored in order to capture the differences in soil water dynamics across the field, the number of profiles increasing with the degree of soil variability and with the size of the field. In summary, therefore, a system for the detailed monitoring of the water dynamics in rice fields needs to include a variety of different instruments, distributed over the entire extension of the monitored field, with very different sampling intervals (from intervals of the order of 10^{-1} s for the eddy covariance variables, to ones of the order of 10^{3} s for saturated soil depth), and with a very high requirement of periodic inspections.

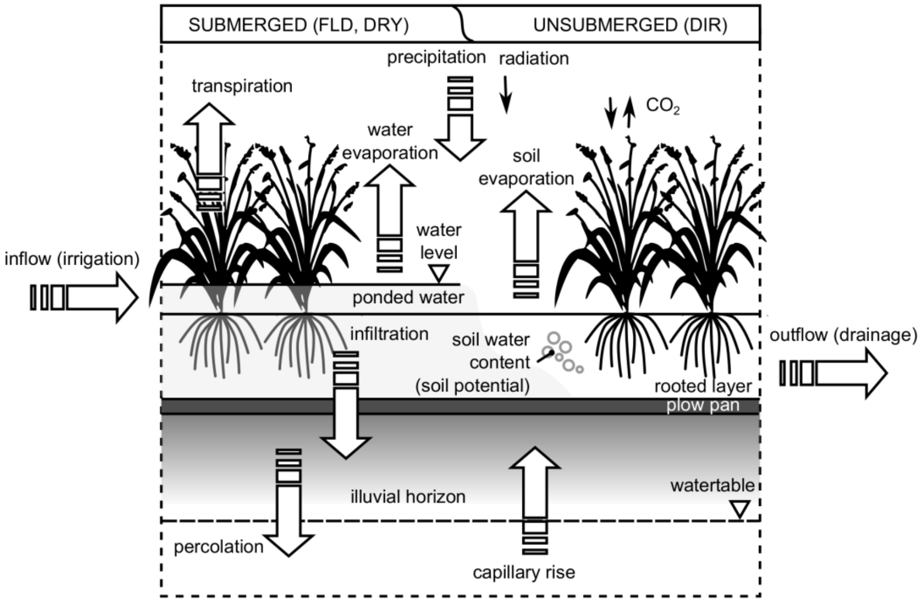

Figure1: Water fluxes and storages in flooded (on the left) and aerobic (on the right) rice fields

3 SUMMARY OF THE PILOT SITE CHARACTERISTICS

We realized a prototype version of integrated system for monitoring water fluxes in irrigated rice fields at the experimental station of the Italian rice research centre (Ente Nazionale Risi, ENR), located in Northern Italy (Castello d’Agogna, 45° 14’ 56.6’’ N, 8° 41’ 59.9’’ E, 108 m a.s.l., see Figure 2). The system was designed for measuring all the relevant flux variables in three out of six experimental fields, where the three water regimes mentioned in Section 2, namely WFL, DFL and DIR, were adopted. The system was fully operational over the agricultural seasons 2012 and 2013.

The experimental station is at the heart of the largest rice production district in Europe. The local climate is a humid subtropical climate (Cfa) according to the Köppen climate classification (Köppen et al. 1936). Meteorological data have been regularly collected since the early nineties from the agrometeorological station placed at the ENR site, about 100 m from the experimental fields. Historical measurements show that, during the agricultural season (April to September), the average temperature at the experimental site is about 20°C, while rainfall is around 360 mm, rather variable throughout the years (data for years 1993-2013). Air humidity is generally high and implies the presence of foggy conditions during the winter and hot and muggy days in summer (Masseroni et al., 2014). Average wind velocity is 2.1 m s^{-1}.

Six laser-levelled fields were selected for the experiments. Each of them was approximately 20 x 80 m^2 in size and was delimited by earth bunds. Each water regime was applied in replicate to two adjacent fields. Irrigation supply was delivered by a concrete canal running along the East side of the fields, while outflows were collected by an earth canal at the opposite side. Figure 3 shows the layout of the pilot site and the location of the various instruments, which will be described in detail in the next section.

Available soil maps show that soils at the station are predominantly Ultic Hapludalfs coarse loamy over sandy, mixed, mesic (ERSAL, 1996), but a dedicated soil survey was carried out in March 2012 to assess the specific soil properties of the experimental fields. Six trenches were opened just outside of the experimental fields (to avoid disturbances within the fields) to allow the identification and description of the sequence of horizons. In addition, soil variability in the fields was evaluated by collecting a significant number of samples across the six fields with a Dutch auger. A total number of 112 points were investigated by collecting samples at three fixed depths from the auger bore in each point, so that each sample was taken from a different genetic horizon along the profile.

Standard physical and chemical analysis were performed on soil profiles samples (Violante, 2000), whereas only textural analysis was determined on auger samples. Results of the soil survey showed that all the experimental fields have a surface horizon (Apg) that is largely similar since the agronomic practices (e.g. yearly irrigations, fertilizations and laser levelling) significantly reduced the spatial variation of soil characteristics.

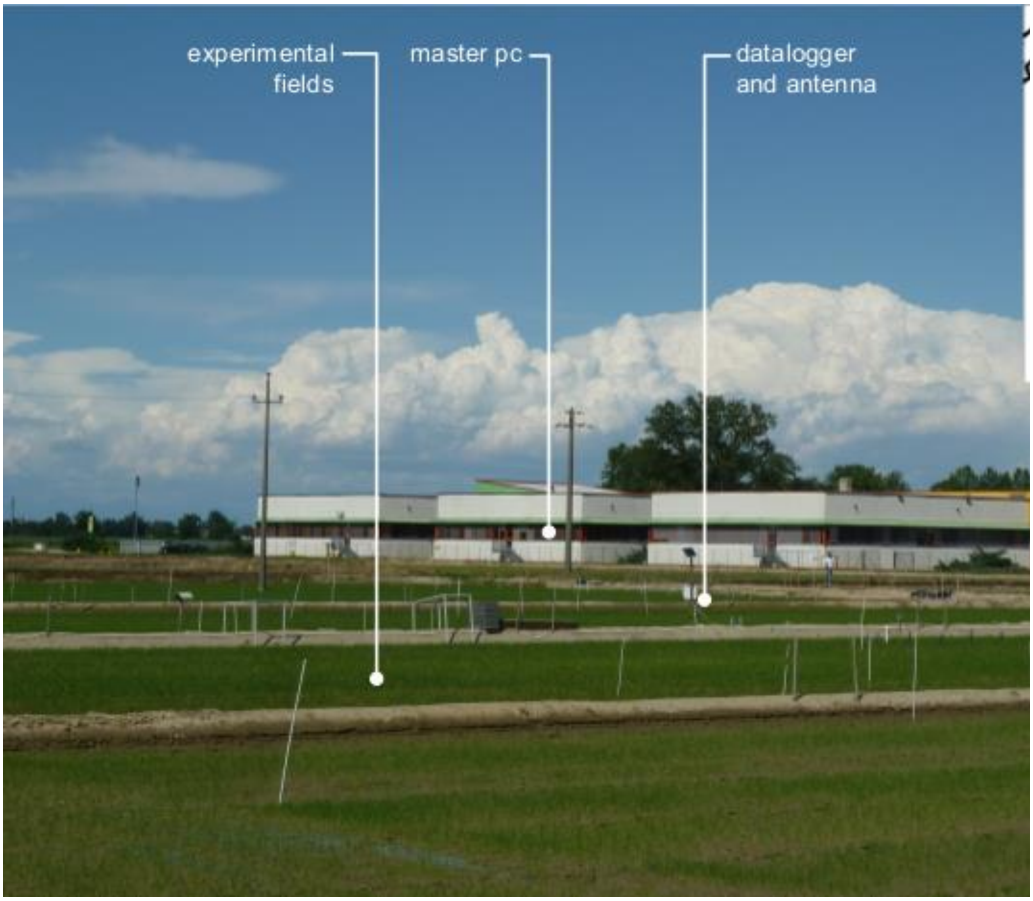

Figure 2: Picture of the experimental area, located west of Milan. In the foreground the experimental fields, in the background the ENR offices were the remote control is placed

This horizon is characterized by a loam to silty loam texture, with a clay content ranging from 15 to 23% (coarse to fine silty granulometric classes), by a complete lack of coarse fragments, by a soil bulk density of about 1.4-1.5 kg m^{-3}; an average value of $pH_{(H2O)}$ of 6.3, organic C of 9 g kg^{-1}; N of 1 g kg^{-1}; and CEC of 10 $cmol^{(+)}$ kg^{-1}. Differently, sub-surface horizons show wider differences, mainly from a granulometric point of view, but also with respect to the organic carbon content and the genetic horizons sequence. Details about the soil texture classification are reported in Table 1, while Figure 3 shows a map of the distribution of the soil textures, mainly based on the characteristics of the deeper layer.

During the two experimental years, the seeding date was staggered for the different irrigation treatments, to ensure that the crop maturity was reached, as far as possible, at the same time. The agricultural operations were carefully managed in order to keep them as similar as possible to the ordinary ones, but avoiding disturbance to the measurements or damages to the installed hardware.

Table 1 - Average particle size distribution of each explored soil layer. Three soil units were found: S (Sand), SCL (Silty Clay Loam) and SL (Silty Loam). The most superficial soil layer was homogeneous as expressed by the standard deviation, SD, while differences existed between deeper layers.

	Layer 0-35 cm			**Layer 45-70 cm**			**Layer 90-120 cm**		
Soil Unit	Sand %	Silt %	Clay %	Sand %	Silt %	Clay %	Sand %	Silt %	Clay %
S	35.8	46.9	17.3	65.4	28.1	6.6	89.2	7.5	3.4
SCL	28.7	50.8	20.5	21.1	52.9	26.0	19.6	54.2	26.2
SL	29.9	50.7	19.4	24.6	54.5	20.9	27.5	58.0	14.5
Average	31.5	49.5	19.1	37.0	45.2	17.8	45.4	39.9	14.7
SD	3.8	2.2	1.6	24.6	14.8	10.1	38.1	28.1	11.4

4 CHARACTERISTICS OF THE PROTOTYPE MONITORING SYSTEM

The integrated, multi-sensor system that was installed at the experimental site of Castello d’Agogna for the continuous monitoring of water dynamics in three rice fields under different irrigation regimes includes a variety of instruments and devices from various manufactures and with different hardware specifications. A total of 12 piezometric wells for groundwater depth measurements, 2 stilling wells for the measurement of the flooding depth, 6 devices for discharge measurements, 20 tensiometers, 4 soil moisture multi-level probes, 1 thermo-hygrometer, 1 four-components net radiometer, 1 pyrgeometer, 1 pyranometer, 3 soil heat flux plates, 6 soil thermistors, and an eddy-covariance station were installed (see Table 2 for a complete list of the sensors and of their characteristics).

Before entering into more details for the group of sensors that we selected for the monitoring of the different fluxes, it is worth underlining that digital devices, when available, should be preferred to analogical ones, because signal acquisition is less affected by local noises and, therefore, the length of cable connections is less limiting. In addition, digital devices support many hardware standards and communication protocols, which simplifies the connection of several of them to a single data logger.

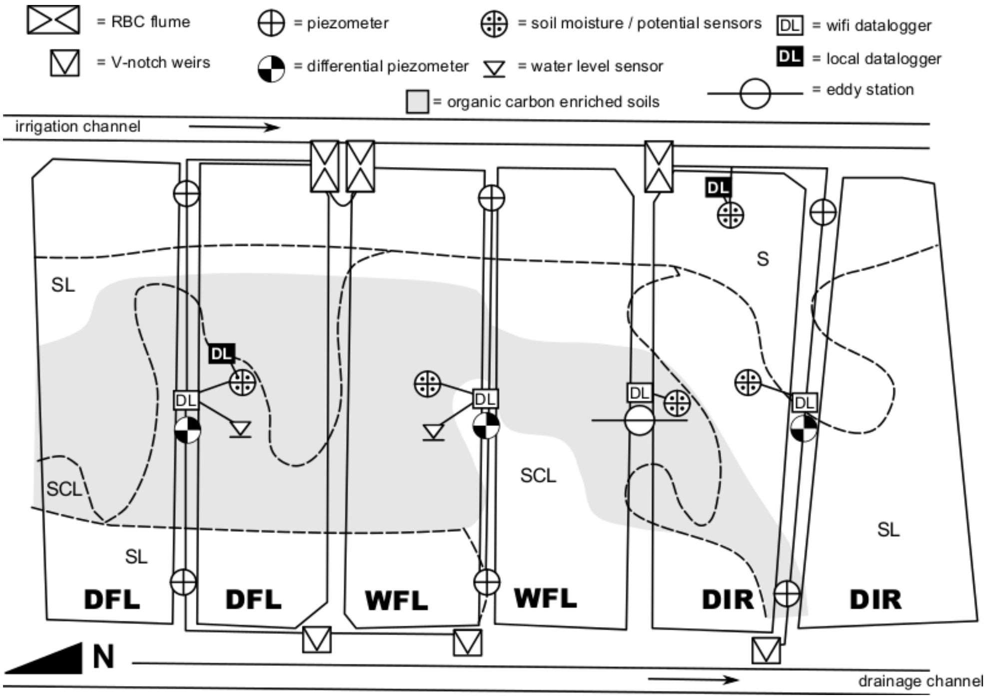

Figure 3: Scheme of the experimental installation, showing the position of the instruments and the soil type distribution. WFL, DFL and DIR are the three different irrigation treatments. Symbols: S = sand soils, SL = silty-loam soils, SCL = silty-clay loam.

Table 2 - List of installed sensors (detailes can be found on web sites of manufacturers)

Type of variables	Sensor	Producer	Communication specifics	Quantity
Water levels and temperatures (stilling weirs for flow measurements, piezometric tube and water levels)	Capacitive pressure transmitter Series 41 X	Keller	Digital, Modbus RS485	20
Soil moisture	Enviroscan probe	Sentek instruments	Digital, SDI12	5
Soil water potential	Irrometer Tensiometers	Irrometer	Mixed (Analogical/digital/manual)	20
Soil temperature	Thermistors	Campbell scientific	Analogical	6
Soil heat fluxes	HFP01	Campbell scientific	Analogical	3
CO2/H2O fluxes	Li-7500	Licor	Digital, SDM	1
3D Wind velocity	Ultrasonic anemometer 81000	R.M. Young Company	Analogical	1
Air temperature and moisture	HMP155 termoigrometer	Vaisala	Analogical	1
Net radiation	CNR 1 Net Radiometer	Kipp & Zonen	Analogical	1
Far Infrared radiation	CGR 3 pyrgeometer	Kipp & Zonen	Analogical	1
Solar radiation	CMP 3 pyranometer	Kipp & Zonen	Analogical	1

4.1 Surface water fluxes

Irrigation distribution to rice fields generally takes place through free-surface canals, but pressurized pipes are sometimes used as well. In this latter case, irrigation inflow to the field can be measured by industrial flow meters (Belder et al., 2004; Xiaoguang et al., 2005; Hirozumi Watanabe et al., 2007; Jang et al., 2012) or estimated considering the time spent for pumping, when pumping occurs (Xiaoguang et al., 2005). If irrigation is supplied by free-surface canals, generally V-notch weirs or flumes are used (see e.g. Bouman et al., 2005). For WFL and DFL treatments, under specific conditions (namely when infiltration is negligible), the irrigation input can be derived from the variation of the flooding level (see e.g. Watanabe and Takagi, 2000).

V-notches weirs and flumes are also used for measuring the tailwater drainage (Bouman et al., 2005; Watanabe et al., 2007; Antonopoulos, 2010; Jang et al., 2012). In particular, Bouman et al. (2005) used a single Parshall flume installed at the end of the main drainage channel (measuring in this way the total discharge outflowing from several plots), and Jung et al. (2012) used flow rates from each outlet and related them to the measured water levels inside the chambers, in order to control the surface water fluxes in a large rice district.

Our choice was to measure the irrigation supply to each plot by portable RBC long throated flumes equipped with a level gauge. The advantages in using this kind of device are: 1) a good performance also with small upstream head values, that is one of the more severe constrains in plane territories, 2) the possibility to predict the hydraulic performance of flumes by a well-known theoretical approach, allowing an accurate design and sizing, 3) a low level of uncertainty (less than 2%) for a relatively wide range of discharges, 4) little problems with sedimentation (Clemmens et al., 2001) and algae growth, that may severely reduce the performance of the flumes, 5) the possibility to install and remove easily the devices, in order to allow the annual agricultural works.

A first problem in the design of RBC flumes is determining the range of discharges that needs to be measured, which is generally unknown a priori. In the case study of the experimental fields at Castello d'Agogna we considered that, according to the consortium that manages irrigation in the area, the average continuous water request for flooded rice paddies is of about to 5 l/s ha, while the irrigation depth of an application of flush irrigation is of between 100 and 150 mm. Consequently, the reference mean inflow to both the WFL and DFL fields for the RBC flumes design was set to 1 l/s. In the case of the DIR field, we calculated the design flow rate assuming that an irrigation depth of 100 mm must be applied in one hour time, which leads to a value of 30 l/s. The same design flow rate was considered suitable also for the outflows from the WFL and DFL fields, in order to ensure a rapid drainage of the fields when necessary to carry out specific farming operations (e.g. pest control, harvesting).

The RBC flumes were built using a 1.26 m long metal sheet, trapezoidal-shaped in section according to Clemmens et al. (2001) guidelines. In our case, channel base was 0.09 m large and walls inclined of 63.4°. The throat was obtained by a trapezoidal element placed at the bottom of the flume. A stilling well was connected by a PVC tube to the upstream section and two metal walls were placed to increase the handcraft stiffness. Discharge scale was calculated using the WinFlume software version num. 1.06.0004 (www.usbr.gov/pmts/hydraulics_lab/winflume) and verified by volumetric sampling tests. In paddy fields, where the terrain is nearly horizontal, a particular attention must be given in positioning the base of the flumes with respect to the seedbed, to avoid backwater when fields are flooded.

To measure tailwater discharge from the WFL and DFL fields, thin plate weirs were initially adopted. Weirs were installed on a metal box of 1.2 m length, 1.0 m width and 0.4 m height, equipped along the internal side with a woody gate to allow the regulation of the flooding depth in the paddy fields. A stilling well was placed in the middle of a lateral wall of the box. One of the problems in the weir design is the great variability of possible discharge values, from the small ordinary outflows required to maintain the desired water level in the fields, to the much greater outflows involved when the rapid drying of the field is needed (e.g. for agricultural operations). We solved this problem by customizing a standard rectangular weir with a moveable V-shaped plate. The plate was kept in place for measuring the ordinary low discharges; when field drying occurred the plate was removed, allowing much larger discharges (up to 30 l/s) through the rectangular weir. For both the triangular and the rectangular weir, a specific stage-discharge relationship was developed and calibrated by volumetric tests. As RBC flumes worked very well and, on the contrary, weirs required a continuous maintenance due to algae formation and presented small practical problems in removing the V-shaped plate, in the second year we installed RBC flumes also at the plot discharge points.

Both flumes and weirs were equipped with pressure transmitters for industrial applications (41X, Keller, USA; www.keller-druck.com) to measure the water level within the stilling wells. The sensors have a full scale (FS) of 30 mbar (relative pressure), i.e. 30.6 cm of water, and an error of 0.1-0.2 % FS (i.e. <1 mm). Measures were recorded every 10 minutes and stored in a datalogger connected by cables. Sensors were initially installed vertically and then they were turned in a horizontal position, in order to avoid air bubbles formation when the stilling well dried.

4.2 Soil water fluxes

The monitoring of soil water fluxes was indirectly achieved through a combination of sensors for the measurement of the soil water content and potential at multiple depths in a number of profiles, of the water table depth in several field locations, and of the flooding depth in the paddy fields.

Water table depth was monitored through piezometers made by windowed plastic tubes (see, e.g., Watanabe and Takagi, 2000; Cabangon et al., 2002; Xiaoguang et al., 2005; Bouman et al., 2005; Antonopoulos, 2010) installed at different depths. The piezometers were positioned along the bunds dividing the paired plots with the same treatment (Figure 3). One issue when designing groundwater depth monitoring is that the range of fluctuations of the variable is often unknown, or very loosely known. In the case of the Castello d'Agogna experiment we carried out a preliminary survey in the year before the experiment started, by installing three piezometric tubes instrumented with pressure transducers in order to explore the water table depth variability. The observations that were collected showed that water table depth reached a minimum of about 0.5 m during the irrigation period and then dropped to approximately 2 m at the end of the winter season. This information was crucial to designing the characteristics of the piezometers that were installed during the seasons 2012 and 2013. Six piezometers were installed at the upstream side and six more at the downstream side of the plots; these piezometers were 3 m long and windowed for 1.5 m of their length from the bottom. Moreover, at the midpoint of each bund, two piezometer with lengths of 3 and 1.5 m respectively and a 0.10 m windowed segment at the bottom of each tube were installed very close to each other. These piezometers were designed to measure the vertical hydraulic head difference in the saturated zone, in order to derive the vertical component of the groundwater flow. The piezometers were constructed by carefully inserting 1”1/5 plastic tubes into suitable holes drilled using a manual auger. Each piezometer was equipped with a pressure transmitters (PR-46X, Keller, USA) with 100 mbar FS (1.02 m) and error less than 0.1% FS (1.02 mm), connected to dataloggers by cables.

Water level in paddy fields is generally measured at a single point, by sensors inserted in windowed tubes (Watanabe and Takagi, 2000; Watanabe et al., 2007) or sloping gauges (Khepar et al., 2000). We used two pressure transmitters (41X, Keller, USA) with FS equal to 30 mbar, placed in a vertical windowed tube (similar to those used for the piezometer), firmly fixed into the ground in a position near to the datalogger. Groundwater and flooding depths were recorded hourly.

Soil water content and potential are the two relevant variables when rice cultivation is in aerobic conditions. For soil water content monitoring, we used multiple sensor capacitance probes, capable of continuous measurements of soil moisture at different depths. These sensors exploit a technique known as FDR (Frequency Domain Reflectometry) by measuring the change in frequency response of the soil's capacitance, which depends on the soil water content. We used EnviroSCAN multilevel probes (Sentek Pty. Ltd., South Australia), that were placed at four depths: 10, 30, 50, 70 cm. At the same depths, we placed 4 tensiometers, as close as possible to the FDR sensors, in order to measure the combined values of soil water content and potential (see Figure 3).

Five soil water content and tensiometers groups were installed, as shown in Figure 3: three groups in the DIR plot to monitor each of the three main soil typologies, one in each of WFL and DFL plots to monitor the most widespread soil type in the parcel. Data were recorded every 10 minutes.

4.3 Atmospheric water fluxes

Evapotranspiration fluxes are generally estimated by the application of the Penman Monteith equation (Allen et al., 1998) from meteorological data (Jang et al., 2012) or by the installation of controlled volume box (i.e. lysimeters) of small dimensions (30-50 cm, Khepar et al., 2000; Watanabe and Takagi, 2000; Vu et al., 2005; Watanabe et al., 2007). Daily weather data, including rainfall, are commonly collected from local agro-meteorological weather stations (Bouman et al., 2005; Xiaoguang et al., 2005). Advanced micro meteorological stations (i.e. eddy covariance stations) have been recently introduced in field monitoring activities (Alberto et al., 2014).

The instruments for agrometeorological monitoring are well known and widespread and we refer to standard hydrology textbooks for details. In our case, we obtained the timeseries of the values of the agrometeorological variables from the monitoring station of the Regional Environmental

Protection Agency (ARPA Lombardia), which has been operating right at the ENR site since the early nineties. The station includes a rain gauge, which provided the data for deriving the direct precipitation inputs to the three experimental plots.

The eddy covariance tower was equipped with 1) a 3D sonic anemometer, 2) an infrared gas analyser, 3) a four component net radiometer, 4) two heat flux plates, 5) four thermistors, 6) a thermohygrometer, 7) a pyrgeometer and a pyranometer.

The 3D sonic anemometer (Young RM-81000, Campbell Scientific, USA) and the infrared gas analyser (LI-COR 7500, LICOR, USA) for the measurement of energy and gas (H2O, CO2) were held at one meter over the canopy along the whole monitoring time, by moving the device according to the vegetation growth. The sonic anemometer was mounted on the top of an adjustable pole thrust into the soil, while the gas analyser was fixed on an aluminium arm at the same height of the anemometer, but with a horizontal separation of about 30 cm and a tilt of about 30 degrees with respect to the vertical direction.

The four-component net radiometer (CNR1, Kipp & Zonen, USA) was installed in the case of non-paddy cultivation, while a pyrgeometer and a pyranometer (CGR3 and CMP3, Kipp & Zonen, USA), mounted on an arm and oriented towards the ground, were installed for flooded fields. Downward solar radiation and longwave components, in fact, could be considered equal for paddy and non-paddy fields and the cost of instrumentation was slightly reduced. Also radiometers were kept at the height of one meter from the canopy by mobile devices.

The heat flux plates (HFP01, Hukseflux, USA) were installed as a couple in the non-paddy fields, while a single plate was used in the paddy field, since a lower spatial variability of the flux was expected for this treatment. The heat flux plates were installed at 8 cm below the soil surface.

To calculate the ground heat flux at the soil surface, two thermistors (107L, Campbell Scientific, USA) were respectively installed at 2 and 6 cm near each soil heat plate.

The thermohygrometer (HMP155A, Vaisala, USA) was installed at the height of 2 m from the ground, opportunely shielded to avoid direct solar radiation.

Eddy covariance data (gas analyser and 3D sonic anemometers) were acquired at high frequency (10 Hz), all the other data with a time step of 30 min.

The acquisition spots were installed on the levees (Figure 5) which are about 300 meters distant from the web connected PC, which was placed in the ENR building (Figure 2).

A special attention was devoted to the positioning of the eddy covariance tower. As shown in Table 3, the cost of the station is very high and budget constraints may often restrict the possibility of installing multiple stations. One option is using a mobile tower, which, however, has some limitations due to the delicacy of the operation, the restrictions in the access to the fields and the labour requirements. Another option, which we investigated in our experiment, is to install the tower on the levee between two different fields. If the regime of winds does not show a largely predominant direction, this solution may provide a reasonable amount of well-characterized data for each of the two fields, without the need of moving the tower (see Masseroni et al., 2014). In our case, the tower was installed on the levee between the WFL and DFL treatments, as shown in Figure 3.

4.4 Data acquisition and storage and power supply

The monitoring system must be able to collect and store the data coming from all the sensors. This poses a number of technical problems in order to guarantee the accuracy of data transmission and the reliability of energy supply

The layout of the cable connections of sensors to dataloggers, for example, must take into account the requirements of agricultural operations (that in the case of paddy field are peculiar because of the use of tractors with iron gears that can damage the cables) and power supply must be guaranteed without interruption in any conditions.

The number of dataloggers (which significantly affects the total cost of the system) depends primarily on the total number of installed sensors and on their position, but also on other factors. Such factors are the maximum allowed cable length to limit noise and voltage losses, the distribution of computational work required for data recording (in order to make these resources equally distributed between each device), the installation costs (dataloggers and cables are among the more expensive materials).

In our system CR1000 Campbell Scientifics dataloggers, DL, were used as data acquisition and storage spots for different sensors. Each CR1000 DL, in fact, can manage up to 16 single-ended analog input channels, 2 pulse input and 8 digital ports. Moreover, among the supported protocols, there are Modbus, SDI-12 and SDM, which fit with those of the sensors.

Figure 4 shows a typical configuration of the monitoring scheme where the CR1000 DL spot collects data from inflow and outflow devices, from three piezometers, from one soil water content and soil potential measuring group, and from the surface water level in the paddy field.

Analogical sensors (see Table 2) were connected directly to DL ports in order to make distances as short as possible (less than 5 meters) to limit signal noise.

As the CR1000 DL can manage RS232 standard connection only, a standard RS485 to RS232 converter was use to link the LAN enslaved to the transmitters to the datalogger digital ports. Soil moisture sensors (Sentek) were instead connected through a second local network directly to one digital port of the CR1000 DL by a common screened 3 x 0.25 conductors cable (C3025, Tasker) of maximum length of 54 meters.

Each CR1000 DL was powered by a 12 V/ 12 Ah rechargeable sealed lead-acid battery automatically recharged by a standard solar panel (CanadianSolar Mo. Type CS5F-14M) with a nominal maximum power of

14W through a 12 V charge controller (Steca Solsum 8.8F). All groups were protected by an industrial control panel enclosure (Stahlin).

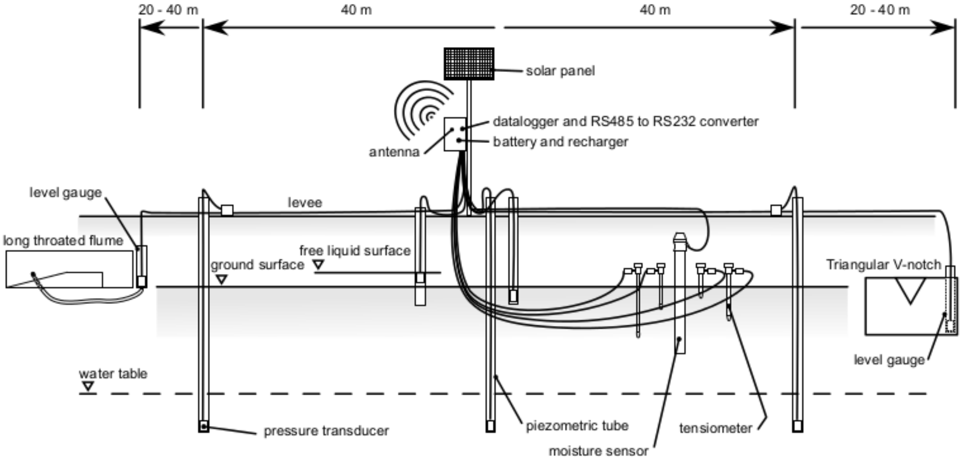

Figure 4: General scheme of sensors and devices connected to the CR1000 dataloggers.

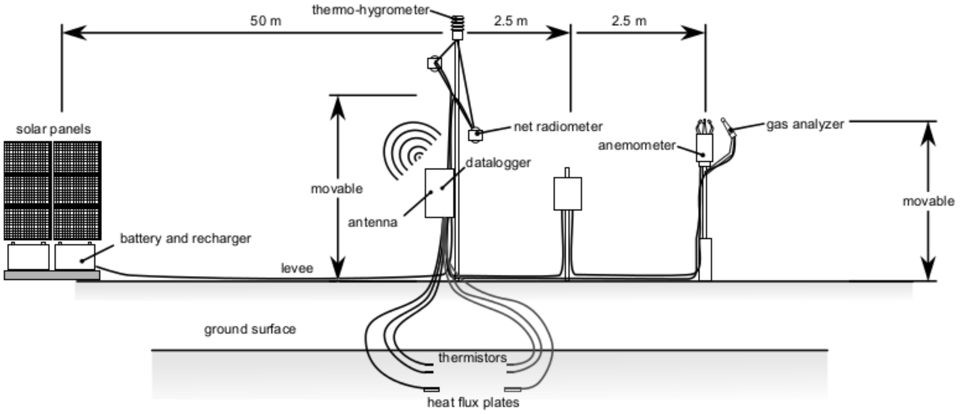

Figure 5: General scheme of sensors and devices connected to the CR5000 datalogger

In the case of the eddy covariance station, all sensors were linked to a CR5000 Campbell Scientific datalogger (Figure 5). Power was supplied by two 12 V/ 98 Ah lead batteries, recharged by a couple of solar panels (nominal power 100 W and 50W). Since, in our case the distance between the eddy station and the batteries was quite long (50 meters), a FG7 3 x 6 mm conductors cable was used to transfer the required power.

One group of sensors for soil water content and soil potential measure was installed in a standalone mode and sensors were connected to two dataloggers Watchdog 2000 series (Spectrum, 2009).

4.5 Remote control and data analysis

The possibility of remote control of the system and the availability of tools for the real time analysis of monitoring data are crucial to the success of the monitoring activity and to the reduction of the costs.

The system control can be obtained in many different ways, from radio or mobile phone networks to satellites. Our choice was to establish a connection between the data collecting spots and a web access point. To avoid the problems associated to long cables (cost, signal quality, etc.), each datalogger (except for the two manually controlled, of course) was wirelessly connected through a RF416 radio (Campbell, 2011), to a RF432 radio (Campbell, 2011) installed on a local PC with access to the web. The radio is coupled with a 0 dBd, ¼ wave whip antenna (model num. 15730).

Figure 6 shows the steps followed by the acquisition system and all the preliminary checks applied to the dataseries in order to prevent loss of that and rapidly take actions to resolve malfunctioning.

The data storage process was programmed by the software LoggerNet 4.3.1 (Campbell Scientific, Inc 2012) and the connection was automatically scheduled every day for data download. After any download, moreover, an automatic procedure produced a compressed backup file of the data that was sent via FTP to a remote storage device by a standard web network. From a local PC, a routine verified that the compressed file was correctly created and uploaded. Possibilities of error could be due to blackouts, hardware breakages or operating system error.

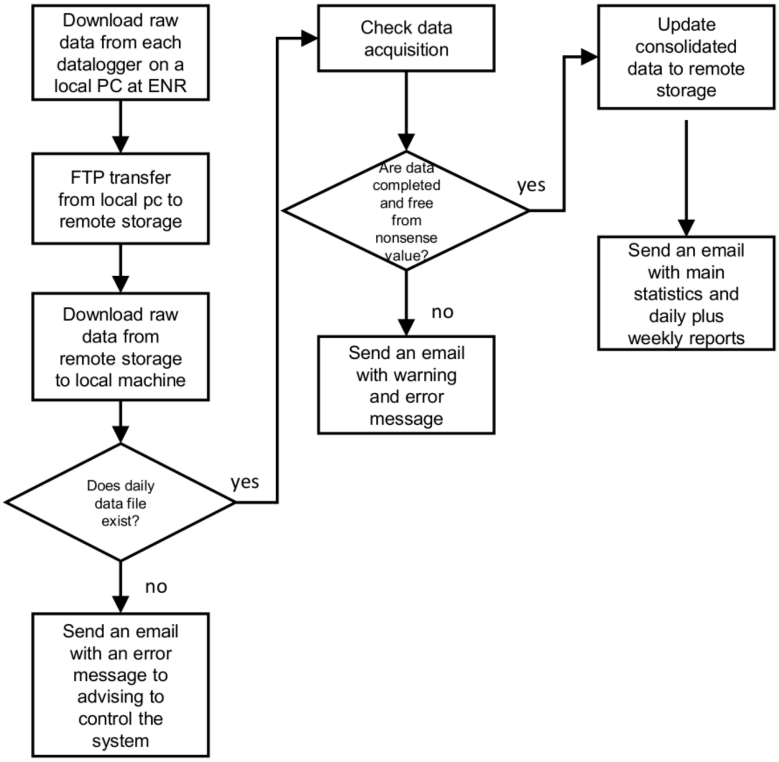

Figure 6: Flowchart of the process of data acquisition, storage and checking from dataloggers to the central storage. The system performed a download of the data every days at 8.00 a.m.. Afterwards, the system uploaded raw data to the remote storage system. A chain of functions verified if the connection to the datalogger was successful and if error in the timeseries existed. In the negative case, the maintainer automatically received an email with warnings and error messages, otherwise a report was sent to a group of selected users to inform about the state of the monitored variables.

In case of failures, the system sent an error message to the maintainer. Otherwise, the process checked the state of the new timeseries. Checks were about: 1) the state of the batteries to prevent energy supplies drawbacks at each datalogger; 2) the lack of data in the timeserie (e.g. due to a probable error of communication between the local PC and dataloggers, or their malfunction) and 3) the presence of meaningless values due to communication errors between sensors and dataloggers or malfunctions of the sensors (e.g. exceeding of the full scale).

In case the control process finished successfully, the system sent an email with a report of the download data to the maintainer and a restricted group of users. In this way the operational status of the entire monitoring system was controlled every day with little effort and field trips to the experimental area were limited to what strictly necessary and, more important, the loss of data was reduced at minimum.

Finally, to manage the huge quantity of data produced in the monitoring activity, a custom graphical software written in Java language and supported by SQLite database, was developed to provide a complete framework for database query and graphical visualization of timeseries, for post-acquisition data corrections and export in text file format.

5 IMPLEMENTATION AND MANAGEMENT COSTS OF THE MONITORING SYSTEM

In Table 3 the costs of instruments, devices and other materials required for installing the system are reported. More than 40% of the total cost (which amounts to approximately 70,000 euros) is ascribed to the gas fluxes monitoring devices (eddy covariance station), approximately 25% to the soil water status probes (soil water content and potential), 16% to data loggers and 12% to surface water fluxes and groundwater measurements. Data transmission, power supply and consumables required only few percentage points of the total investment. As it can be noted, gas flux monitoring represented a great part of the budget, but, in many cases, estimating evapotranspiration with a great accuracy may not be so relevant and the Pennman-Monteith equation applied by a standard meteorological station can be an adequate tool (Facchi et al., 2013a). On the other hand, power supply, which has negligible costs, represents a key point and money used to guarantee a robust power supply is really well spent.

In terms of human effort, it was not easy carrying out an accurate estimate of the time devoted to the installation and management of the system, also because of the number and the variety of skills of the people involved in the different activities (7 persons in both the agricultural seasons). In particular, it was impossible to trace exactly the time spent in the design phase of choosing the appropriate combination of instruments, and in the laboratory for programming the sensor and data loggers during the winter 2011-2012. A rough (possibly underestimated) evaluation of the field activities in 2012 is 67 man-days: 29 for the system installation, 24 days for the management during the crop season, 14 days for removing the system to allow the field operations for the new agricultural season. In 2013, the time required for the installation was drastically reduced, approximately to half, because all the elements were available near to the fields and ready to be installed (e.g. cables were already available in corrugated tubes and with the right length).

Table 3: Cost of instrument (in 2011 in Italy) and devices installed during the research activity. Entries in italics indicate that instruments and sensor were already available for the research.

Material	**Individual Cost (€)**	**Number**	**Total Cost (€)**
Surface flow			
Keller pressure sensor 41X	310.00	8	2,480.00
Material for RBC flumes and V-noch weirs			1,138.51
Total			3,618.51
Soil water			
Keller pressure sensor PR-46X	300.00	12	3,600.00
Piezometer wells			531.19
USB-driver for Interface converter K-104	80.00	1	80.00
Additional cables			228.00
Groundwater			4,439.19
EnviroSCAN	*2,400.00*	*5*	*12,000.00*
Tensiometers Irrometer with manometer (manual recording)	*150.00*	*20*	*3,000.00*
Pressure transducers for tensiometers	*350.00*	*2*	*700.00*

Table 3: (Continued)

Material	**Individual Cost (€)**	**Number**	**Total Cost (€)**
Pressure transducers for tensiometers	392.00	4	1,568.00
Total			17,268.00
Eddy station			
3D sonic anemometer	*7,500.00*	*1*	*7,500.00*
infrared gas analyser	*18,120.00*	*1*	*18,120.00*
CGR 3 pyrgeometer	1,300.00	1	1,300.00
CMP 3 pyranometer	760.00	1	760.00
Heat flux plate HFP01	512.00	3	1,536.00
Thermistors	53.00	6	318.00
Total			29,534.00
Data Logger			
CR1000	1,438.00	3	4,314.00
CR5000	*3,500.00*	*1*	*3,500.00*
Case	270.00	3	810.00
Mast Mount bracket	79.00	3	237.00
SDI-12 interface for EnviroSmart devices	438.00	3	1,314.00
I/O device with 1 serial channel, RS232 protocol, 485 e 422 (NO CR5000)	210.00	3	630.00
Total			10,805.00
Power supply			
12 V/ 12 Ah rechargeable sealed lead-acid battery	65.00	3	195.00
14 W solar panel	27.30	6	163.80
Charge controller 8.8A Solsum	31.20	3	93.60
Total			452.40

Table 3: (Continued)

Material	Individual Cost (€)	Number	Total Cost (€)
Cables, etc.			
RF416 radio	466.00	3	1,398.00
RF432 radio	486.00	1	486.00
Whip antenna	35.00	4	140.00
Remote transmission			2,024.00
Cables,			708.29
Connectors and other material			597.00
Total			1,305.29
Grand Total			69,446.39

6 PRELIMINARY RESULTS

Figure 7 shows the main balance terms in the hydrological system like paddy field. Compared to the incoming superficial flow, superficial outflow represented the 63-74% in case of WFL and DFL and 40-47% in case of DIR. These relatively high percentages were due to the water management adopted that consist in applying more water than the amount needed and then draining the excess (so called “flow through irrigation”, Hasegawa 1992). The contribution of precipitation during the growing season was very low (1-4%) in case of both flooded conditions, while it was slightly greater in case of DIR (10-16%). Evapotranspiration share was from 6 to 13% in case of WFL and DFL while it was significantly greater in case of DIR (31-48%). The net percolation rate obtained as the residual term of the balance and including the percolation (outcome) and the capillary rise (income), had a close range of variability (21-31%) but the greater percentages were obtained in case of intermittent irrigation (DIR).

Reported data highlight the importance of the contribution of the superficial fluxes compared to all the other terms of the water balance.

Evapotranspiration and precipitation had a minimum effect on the water balance in case of WFL and DFL, but not in case of DIR treatment where both rain and ET had the same magnitude of the superficial drainage. This highlights the importance of using a micro weather station (i.e. eddy covariance station) to predict actual water losses by evapotranspiration processes. At the same time, the data obtained from the eddy station combined with those obtained from the Sentek sensor (i.e. Soil Water Content) permitted to analyse in detail the energy fluxes in the soil-plant-air continuum (Masseroni et al., 2014).

Anyway, cumulative seasonal evaluation hides the complexity of the distribution of the water fluxes in rice paddy. Figure 8, for example, shows a sample from the monitored period for the DIR plot.

In particular, input and output discharges, water table depth under the average seeding bed elevation and soil water content, SWC, at 10 and 70 cm in depth are shown from the 27th of July 2013 to the 15th of August 2013. The implemented monitoring system enabled to control and follow the trends of all the main hydrological variables: in Figure 8 – A, the irrigation events are well described by the peaks, that are different for inflows with respect to outflows both in time (the first are obviously before the latter) and magnitude (maximum inflow peak is 32.69 l/s while outflow peak was 35.37 l/s). After each irrigation event, a rise of the water table occurs with an increase from -1.28 m below the soil surface to - 0.80 m. SWC at 10 cm is naturally affected by the irrigation event, moving from 18.08 % (before irrigation) to 34.10 % (immediately after). At the same time, SWC at 70 cm, near to the water table, is almost constant at 35.0 % (standard deviation: 0.06 %).

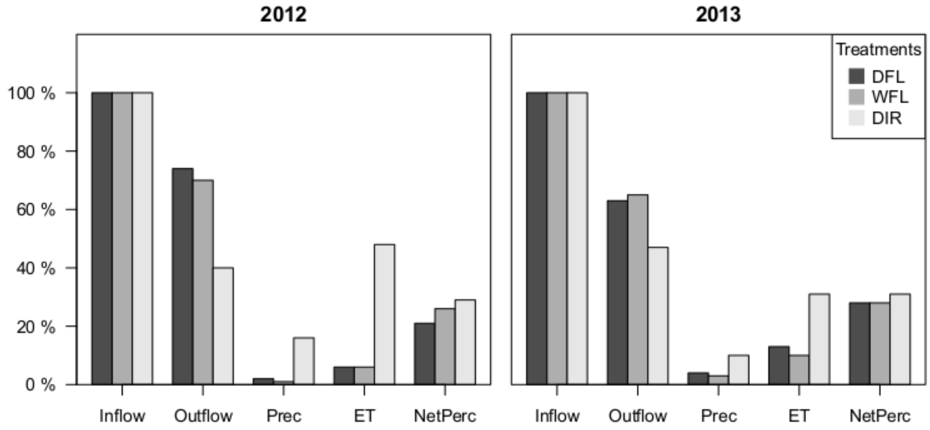

Figure 7: Cumulative water balance volumes distinguished by each terms and years: superficial inflow and outflow, precipitation (Prec), evapotranspiration (ET) and the difference between the percolation and the capillary rise, i.e. the residual term of the balance, net percolation (NetPerc).

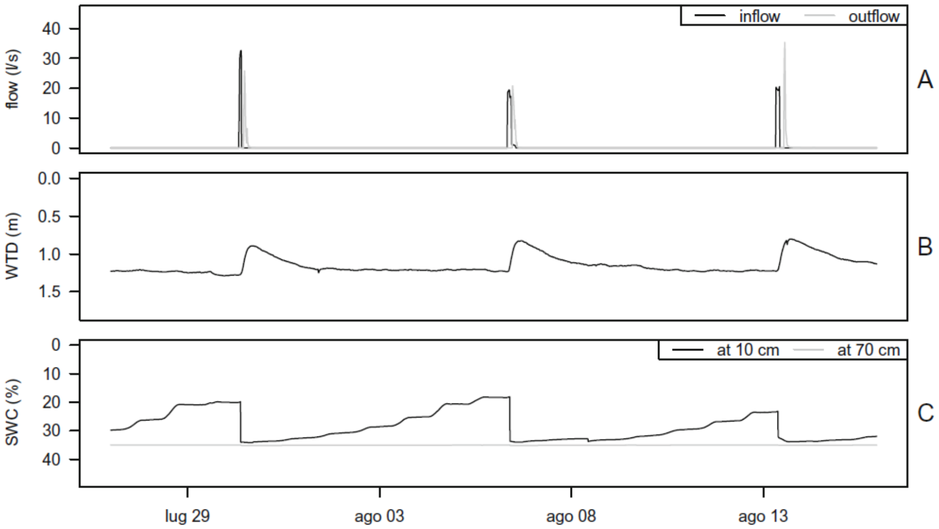

Figure 8: Temporal pattern of some monitored variables in DIR experimental field: discharge (inflow and outflow, A), water table depth (WTD, B) respect the field bed and soil water content (SWC, C) for a selected time period in 2013. Continuous monitoring activity permits to control all the irrigation practice (3 picks in the chart A), the following depletion of the paddy (light gray line in A), the effect of irrigation on the water table (B) and on the soil moisture (C). In the last case, differences between the upper layer and the deeper is well shown by the SWC trend at 10 cm and 70 cm.

The absence of steps (i.e. marked discontinuity) along the lines suggests that the frequency of acquisition was high enough with respect to the speed of variability of the phenomena. Such accurate monitoring activity will be the base for further researches related to the issue of water fluxes in paddy fields. Furthermore, the availability of a rich network of sensors and a recording step higher than those required to describe the process can help the researcher to check the rationality of the measurements and exclude spurious data.

7 CONCLUSIVE REMARKS

This paper presents an experimental setup for a complete and integrated monitoring activity of the water fluxes and water storage quantities in three rice plots characterized by different types of irrigation management in order to provide useful information to researchers that are going to deal with a similar issue. If, on one hand, the use of single sensors and probes, or groups of them, does not represent a novelty, on the other their use in a such massive and synergic way was a challenge in practice and, especially, for the rice crops. The information herein provided in great detail could therefore be very useful to those researchers involved in monitoring water fluxes, with particular reference to rice cultivation. The “in-house” character of our system allowed a relevant saving of economic resources, mainly by buying many sensors and elements directly from factories. The price of this saving was a great effort and time spent in choosing the right combination of instruments in order to guarantee the proper connection and communication between sensors and dataloggers over a local net and using different protocols. In fact, most sensors came from different manufacturers and it was important to evaluate the compatibility of communication protocols.

Another point we deem is worth highlighting is the possibility to remotely check if all the instruments are working correctly, which represents a crucial point in managing a so complex in-field monitoring system subjected to environmental adversities (high temperature and humidity). This, in fact, limited the loss of data, reduced the research costs and more important made the work of researcher and technicians more efficient.

The use of open standard should be a milestone of a monitoring system but that it is not always possible for technical needs and constraints caused by the market of scientific instruments. In our case, we struggled to use industrial standards and to link different communication protocols in order give to the reader useful information out from what the vendors are used to suggest. In other cases, that was not possible due to the limits induced by “close” solutions. The development of a complete open standard architecture was out of the objective of the project (the main objective was to provide information about water fluxes to other research teams), but the use of low cost sensors and “open” acquisition systems in order to reduce costs and increase the monitoring performances, represents the future development of our research activity.

Acknowledgments

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CHAPTER 3

Tools for measuring and managing spatial variability of rice yields

S. Cesari de Maria[a], J. Hornbuckle[b], M. Collins[c], R. Zandona[d]

[a] Department of Agricultural and Environmental Sciences (DiSAA), Universitá degli Studi di Milano, 20133 Milan, Italy

[b] Centre for Regional and Rural Futures (CeRRF), Deakin University, Griffith NSW 2680, Australia

[c] Gatton Campus, University of Queensland, Gatton QLD 4343 Australia

[d] CSIRO, Griffith NSW 2680, Australia

Abstract

Spatial variations of rice yields within and between fields is a relevant issue in Australian rice farming. In-field variability may be ascribed to different factors including soil physical and chemical properties, cut/fill operations and the effects of water depth, wind and temperature. The latter has a strong impact on yield because of spikelet sterility induced by low temperatures during night-time.

This contribution describes the monitoring activity conducted in three rice bays located in the Murray Valley (NSW, Australia) over the cropping season 2014-2015 as part of a project entitled “Developing and testing tools for measuring and managing variability in rice”. The first season of the project focussed on the spatial monitoring of water temperatures in relation to crop density and water depth with the purpose of (i) collecting data for the development of a water temperature model based on NDVI values for the effects of crop shading and (ii) investigating the spatial component of water temperature, crop development and grain yield.

Spatial differences of grain yield within the same bay were higher than 3 t ha^{-1} according to the raw values recorded by the yield monitor on the harvester. The monitoring of water temperature showed spatial variations across the field that could be attributed to a different degree of canopy cover as shown by the different values of NDVI (up to 4°C difference in the daily maximum temperatures). Canopy thickness should be included in models simulating water temperature of rice paddies. The Normalized Difference Vegetation Index (NDVI) computed from Landsat 8 images represents a useful tool for evaluating crop development during the growing season and identify areas with a stunted growth that can be specifically managed. This spatially distributed information could be effectively used for real–time yield forecast.

Keywords: Rice, paddy, water temperature, NDVI, yield, spatial variability

1 GENERAL INTRODUCTION

Australia is the country with the highest average rice production per hectare, which amounts to 10.2 t ha^{-1} (FAOSTAT, 2013). However, the cropped surface has been subject to relevant changes in the last fifty years, fluctuating from more than 170,000 ha in 2001 to less than 10,000 ha in 2008 and 2009 because of severe drought conditions (FAOSTAT, 2013). Rice surface is mainly located in the temperate zones of the Riverina region, in southern New South Wales. The region comprises four main growing areas: the Murrumbidgee Irrigation Area (MIA), the Eastern Murray Valley (EMV), the Western Murray Valley (WMV) and the Coleambally Irrigation Area (CIA). Rice target yields are variable across the region, depending on both the area and the variety grown (DPI, 2012). As reported in the Ricecheck recommendations 2012 (DPI, 2012), the higher target yield of the region can be achieved in the MIA, where higher minimum temperatures allow to reach a target yield up to 11 t ha^{-1}. On the other hand, the WMV has a lower potential yield than the EMV, likely due to a greater incidence of turbidity that lowers the water temperature in the seed zone, while no climate differences are found between the two zones (Humphreys and Barrs, 1999).

Moreover, a significant spatial variability of crop yield may occur also within the same field as reported by many farmers of the region. According to the Rural Industries Research and Development Corporation (RIRDC, 2013), the in-field variability may be ascribed to different factors including soil salinity and sodicity, soil physical and chemical properties, landforming cut/fill operations and the effects of water depth, wind and temperature. Results from their field experiments conducted in Coleambally (CIA) and Willbriggie (MIA) indicate that nutrient deficiencies are the main cause of in-field yield variability in case of exposed subsoils resulting from cut/fill operations (RIRDC, 2013). However, further research is needed to understand the interactions between the different factors driving on-farm spatial variability and to provide farmers with prescription tools to manage it (RIRDC, 2011).

Authors report that water temperature can directly influence rice yield through impacts on growth (Roel et al., 2005) and nitrogen uptake (Shimono et al., 2012). The occurrence of low temperatures during nighttime is considered the main factor responsible for yield losses in Australian rice systems (e.g. Heenan, 1981; Godwin et al., 1994, Subasinghe and Bechaz, 2005). Farrell et al. (2001) estimated the cost of yield reduction due to low temperatures to be on average $20 million a year in the Riverina Region. Microspore stage is the more susceptible to cold injuries. Whithworth and Dunn (2012) suggested that minimum temperatures between 17°C and 15°C during the microspore stage may result in cold damages known as cold-induced sterility or flatheads. Similarly, Boerema (1974) reported a high proportion of spikelet sterility due to minimum temperatures lower than 15°C during the reproductive stage, according to an experiment conducted in the MIA. An effective tool to protect the developing panicle from cold injuries is to raise the water depth to 20-25 cm (DPI, 2012), since deep water can provide an increase over the air temperature up to 9°C (Whithworth and Dunn, 2012). Deep water during microspore development becomes even more important when high nitrogen applications are applied, as the effect of low temperatures is further accentuated by high levels of nitrogen (e.g. Boerema, 1974; Williams et al., 1994). The best practices suggest maintaining the target water from around 7-10 days after the panicle initiation to around mid-flowering (Department of Primary Industries, 2012; Whithworth and Dunn, 2012). Heenan (1981) reported no differences in yield between a shallow and a deep water treatment (5 and 22 cm respectively) during panicle development in Yanco (MIA), nevertheless the author asserted that low temperatures were neither prolonged enough nor during the more critical stage. In light of these issues, the knowledge of water temperature of flooded fields is considered a key factor in modelling yield of flooded rice systems (e.g. Godwin et al., 1994, Confalonieri et al., 2005, Shimono et al., 2005, Shimono et al., 2007a,b).

Temperature dynamics in paddy water show a different behaviour if compared to non-vegetated shallow waters, due to the shading effect of crops, which not only reduce the amount of solar radiation reaching the water surface, but also alter the spectral energy distribution of the solar radiation itself (Uchijima, 1961; Ohta and Kimura, 2009; Hanayama et al., 2006). For instance, Ohta and Kimura (2009) found that the difference between the temperature of paddy water and that of open shallow waters was quite uncorrelated to the solar radiation, while it depended on the stage of crop development, which influenced the proportion between the emission and the interception of radiation by the canopy.

A few models are found in literature to predict the water temperature in rice paddies. These models are essentially based on either simplified empirical relationships (Godwin et al., 1994; Confalonieri et al., 2005, Gombos, 2008; Anastácio et al., 1999) or mechanistic approaches (Kuwagata et al., 2008; Confalonieri et al., 2005; Maruyama et al., 2010; Ohta and Kimura, 2007; Ohta and Kimura, 2009). Empirical models generally adopt simple or multilinear regression to estimate water temperature as function of air temperature only (Anastácio et al., 1999; Gombos, 2008), or as a function of air temperature plus either other meteorological variables (Gombos, 2008) or water depth (Godwin et al., 1994). However, these models do not consider the important effect of canopy on water temperature. A different empirical model is presented by Confalonieri et al. (2005) who used a Gaussian filter to simulate the smoothing effect of flooded water on temperatures and developed four different equations for the maximum water temperature so as to account also for the effect of crop development. On the other hand, mechanistic models adopt surface energy balance equations, estimating the water temperature as the residual term of the budget. An example is provided by Kuwagata et al. (2008) who applied heat balance equations to estimate first the daily mean water temperature of a water surface without vegetation coverage, given meteorological data as input. Then, they obtained the daily mean water temperature of a rice paddy by adding an empirical correction term that is function of LAI, solar radiation and wind speed. To estimate the hourly water temperature of paddy water, Confalonieri et al. (2005) developed a model based on the surface energy balance that requires just minimum and maximum air temperature as input and applies empirical relationship to account for the effect of canopy development. A slightly different approach is proposed by Maruyama et al. (2010) who coupled a crop growth model and a land surface model based on an empirical relationship between stomatal conductance and rice phenology. Although these mechanistic models showed to reproduce fairly well the water temperature in rice fields, their potential application to different regions and different varieties needs to be assessed, especially with respect to the effects of crop development on water temperature dynamics.

Moreover, spatial variability of water temperature within the same field is generally not considered, therefore water temperature models provide just of a representative value. Such approach may hold in small fields as shown by Kuwagata et al. (2008) who found little horizontal differences of water temperature in small test fields (14 x 18 m). However, the effect of water temperature on in-field variability at larger scales seems to be poorly understood and controversial results are found in the literature. In this respect, Roel et al. (2004, 2005) report that the effect of cold water on yield across a 10-ha field of California was not uniform and it was estimated to account for 84% of the yield variation. Conversely, Simmonds et al. (2013) did not observe any effect of water temperature on in-field yield variability, which was instead attributed to soil electrical conductivity and plant available phosphorus.

Considering the need to better understand and manage factors driving yield variability, a monitoring activity was conducted in the agricultural season 2014-2015 in three rice fields located in the Murray valley as part of a project entitled “Developing and testing tools for measuring and managing variability in rice”. The first season of the project focussed on the spatial monitoring of water temperatures in relation to crop density and water depth in order to: (i) collect data for the development of a water temperature model based on NDVI values for the effects of crop shading, (ii) investigate the spatial component of water temperature, crop development and grain yield, (iii) evaluate the possibility of improving the existing rice growth model maNage rice, developed by Williams and Angus (1997), by including remote sensed data for modelling crop-related processes (evolution of Leaf Area Index, water temperature variations and, ultimately, crop nitrogen status). As a first step towards the fulfilment of these aims, the contribution describes the monitoring activity that was conducted and illustrates the data collected, providing also insights on the future developments.

2 MATERIAL AND METHODS

2.1 Site description

The rice experiment was conducted at the Rice Research Australia Pty Ltd, located at Coree (35°18.2’S 145°32.3’E, Deniliquin, NSW, Australia) during the agricultural season 2014-2015.

The area is classified as a zone with a hot dry summer, cold winter and uniform rainfall (yearly values between 400 and 600 mm) (Bureau of Meteorology, 2015). Figure 1 shows the pattern of monthly averages of reference evapotranspiration, rainfall, and minimum and maximum temperature recorded at the Finley weather station (around 35 km South of the site) in the years 2010-2015.

Two main soil types are found in the area and they are classified as Non Self-Mulching Clays (NSMC) and Transitional Red-Brown Earths (TRBE) (Rengasamy et al., 2010). NSMC are characterised by a shallow topsoil (usually less than 5 cm in depth) with a texture ranging from a clay loam to a light clay, whereas the underlying subsoil is a dense heavy clay. Due to the texture and the propensity to disperse, both infiltration and permeability are poor (Rengasamy et al., 2010). TRBEs are a specific subgroup of red-brown earths characterised by finer sediments than the red-brown earths. These soils have a shallow clay loam topsoil of 5-10 cm depth, overlying a clay subsoil (Rengasamy et al., 2010).

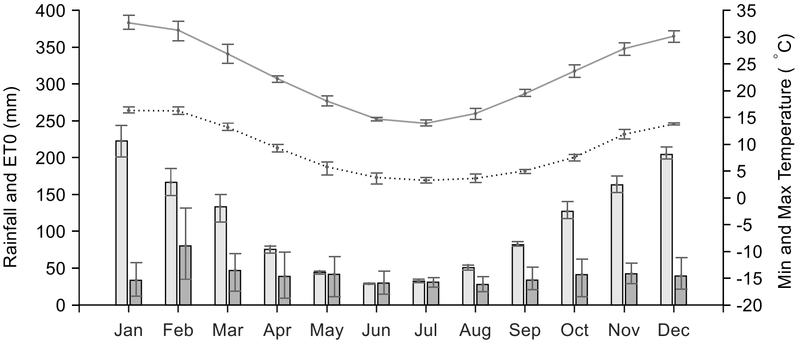

Figure 1 – Pattern of monthly meteorological variables recorded at the Finley weather Station over the period 01/05/2010-30/04/2015. Reference evapotranspiration (ET0, light grey bar, left y-axis) and rainfall (dark grey bar, left y-axis) are cumulated monthly values; Minimum Temperature (dotted line, right y-axis) and Maximum Temperature (thick line, right y-axis) are monthly averages. Error bars show 25th and 75th percentile.

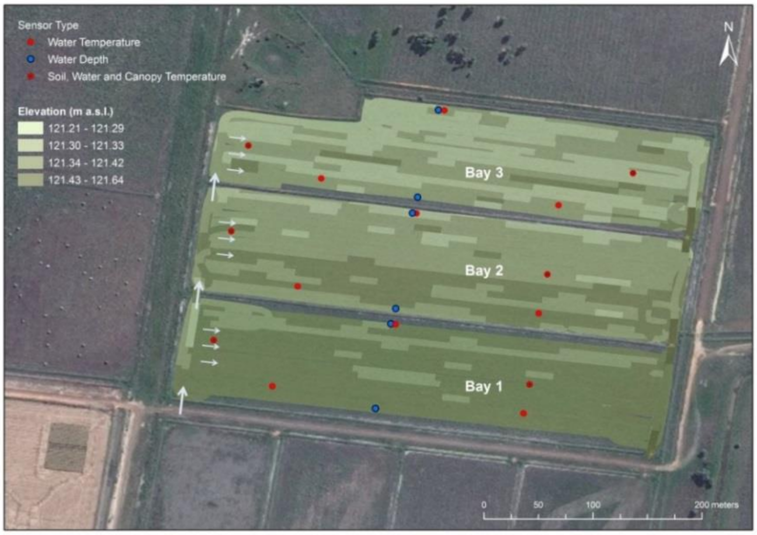

Figure 2 – Location of the sensors in the bays and elevation (m.a.s.l). White arrows represent water supply

2.2 Data collection

Monitoring activities involved three adjacent fields approximately 380 m long and 100 m wide with actual areas of 3.65 ha (Bay 1), 3.45 ha (Bay 2) and 3.21 ha (Bay 3). The variety Koshihikari, a short-grain rice variety better known as "Koshi", was drill-seeded on Sep 28th with seed rates of 150 kg ha^{-1} except for around half surface of Bay 3 where seeding rates were equal to 75 kg ha^{-1} (west side of Bay 3, see Figure 2). Rice was harvested at the end of March.

Fields were arranged according to a bankless channel layout, with a longitudinal slope going from bay 1 to bay 3 of about 0.06% (see Figure 2 showing the field elevation as recorded by the sensor mounted on the tractor). Five flush irrigations were applied on days Sep 29th, Oct 11th, Oct 29th, Nov 6th and Nov 14th until the establishment of permanent water on Nov 29th. A water depth of around 10-15 cm was maintained until the draining occurred on Mar 16th, except for about ten to fifteen days in the second half of January when water depth was increased to 25-30 cm (progressive increase of water levels started after panicle initiation, which occurred on Dec 28th, to ensure that target water depths for microspore were achieved within the following 14 days). Topdress nitrogen fertiliser was applied in rates of 80 kg ha^{-1} on Jan 9th, around 12 days after panicle initiation.

A total of 21 sensors, each equipped with its own logger, were installed in the field and they included 9 sensors for water temperature, 6 multilevel sensors measuring soil, water and canopy temperature and 6 water depth sensors. The location of the instruments is shown in Figure 2. Along with automatic measurements, three campaigns were conducted to manually measure soil, water, canopy and air temperature with a higher spatial resolution and in different moments of the days. Measurements were taken every 10-15 meters along transects running in the North-South direction.

At harvesting, mass yields were measured by the yield monitor on the header (two rows of measurements per bay). Data have been filtered with a moving average once removed some outliers likely caused by occasional malfunctioning of the sensor (yield values dropping down to zero followed by increases to up to 20 t ha^{-1}). Point yield values were then aggregated to obtain average values over a cell size of 10*10 m (Figure 4). Finally, the evolution of the normalized difference vegetation index (NDVI) was investigated over the cropping season (Figure 3). NDVI was computed from Standard Landsat 8 data products provided by the USGS (USGS, 2015a) after applying the atmospheric corrections suggested by USGS (2015b).

3 PRELIMINARY RESULTS

Figure 3 shows variations of the NDVI index in the three bays monitored during the agricultural season. In the first part of the season (images related to Dec 16th and Jan 1st), low values were obtained in the East side of the top Bay (Bay 3) due to the lower seeding rates and consequently to the poor coverage of the ponded water. However, in spite of the lower crop density, NDVI values were consistent with values in other sections of the field later in the season (see Feb 25th and Mar 13th).

Yield data are shown in Figure 4. Average yield was 9.9 t ha^{-1}, but relevant variations were observed across the three bays. For instance, in the East side of the top bay (Bay 3) yield was consistently higher reaching values of 12 t ha^{-1}.

Figure 5 presents water temperature patterns recorded in Bay 3-West side (low density area) and in Bay 3-East side (regular seeding rates). In general terms, fluctuations of water temperature were higher in the first part of the season when the crop coverage was still quite low and the water depth was around 10 cm. As the season progressed and the water depth increased, the range of variation became smaller due to both the effect of crop shading and to the higher heat storage of the ponded water. Differences in water temperature between West and East side of Bay reached up to 4°C because of the effect of the canopy cover on the proportion of radiation reaching the soil surface, whereas differences were smaller at night-time.

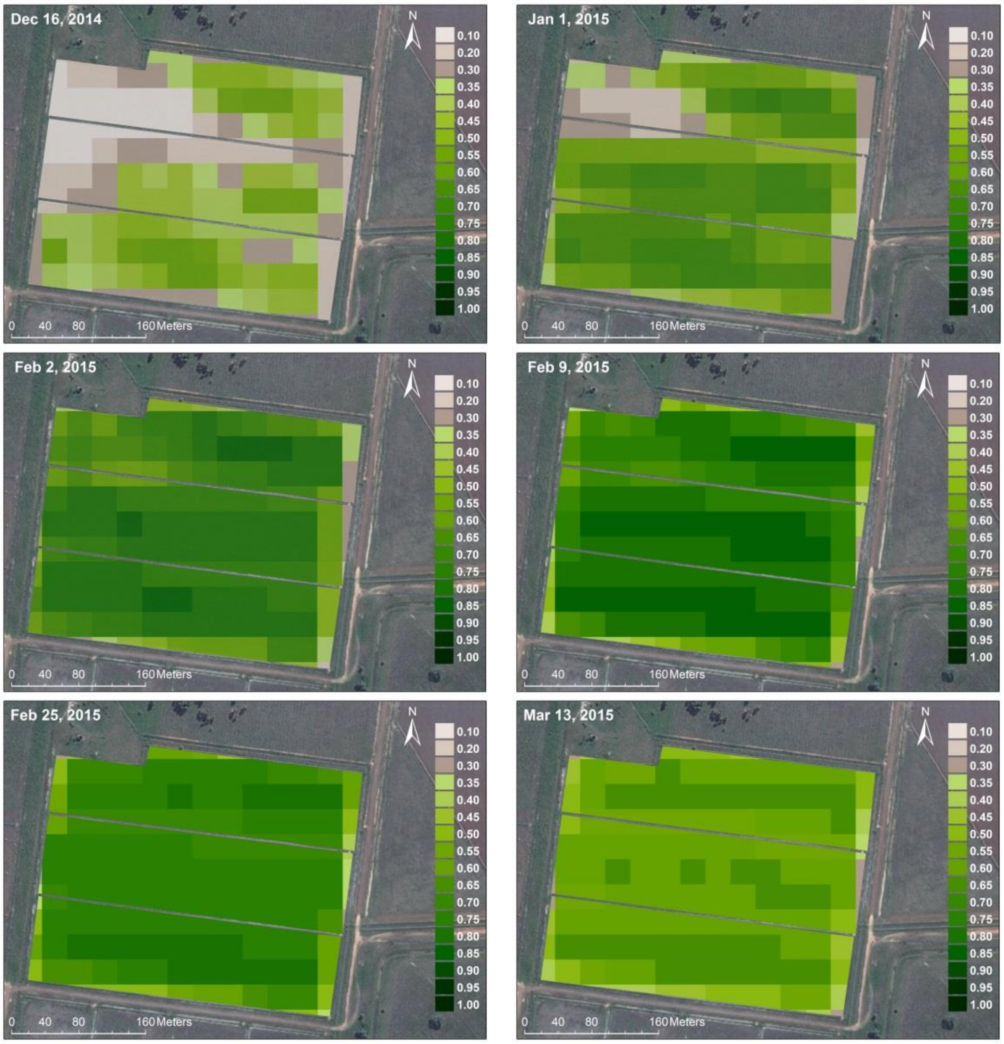

Figure 3 – Evolution of NDVI values over the cropping season (resolution 30x30m) for the three bays monitored (Bay 1 to 3 from South no North)

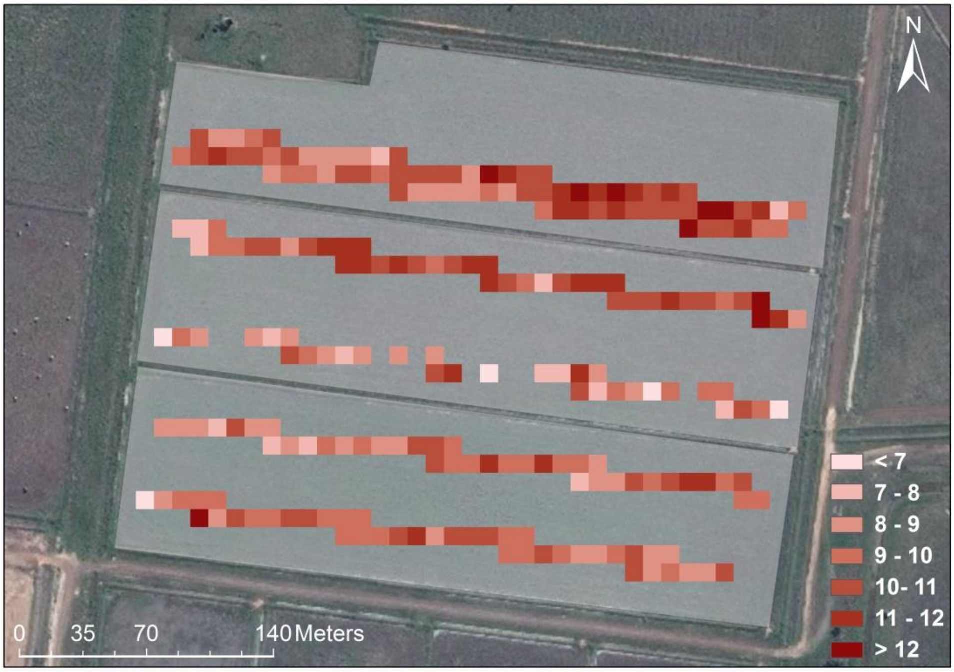

Figure 4 – Average mass yield (t ha^{-1}) (cell size 10x10m)

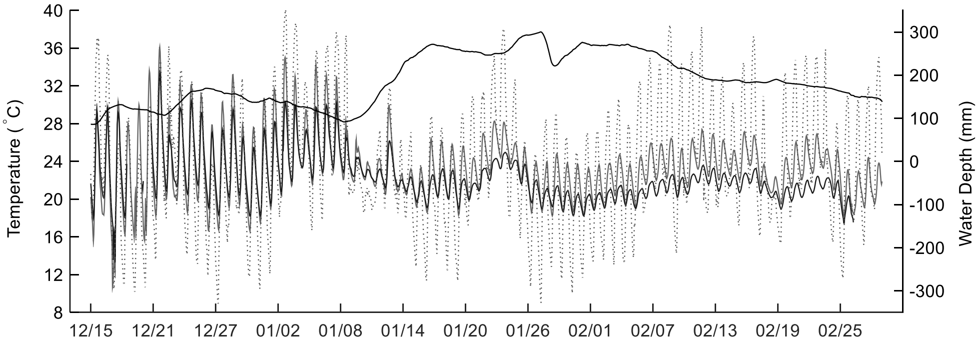

Figure 5 – Water temperature pattern recorded in a zone with a lower NDVI (dark grey line) and in a zone with a higher NDVI (light grey line) and air temperature (dotted grey line) on the left y-axis; water depth (black line) on the right y-axis. Data show West and East side of Bay 1.

4 CONCLUSIVE REMARKS

From the activities conducted in the agricultural season 2014-2015, the following considerations can be made:

- Variations in rice yields are a relevant issue in Australian rice farming and differences of more than 3 t ha^{-1} were observed within the same field as shown by values recorded by the yield monitor on the header. Causes of these variations have still to be understood since factors such as soil properties should be considered in addition to the effects of water temperature.
- The monitoring of water temperature showed spatial variations across the field that could be attributed to a different degree of canopy cover as shown by the different values of NDVI. Daily fluctuations of water temperature are in fact higher in zones with lower values of NDVI, with daily maximums that could differ of up to 4°C compared to zones with a less dense canopy cover. It would be therefore very useful to include the effect of canopy shading in models simulating water temperature in rice paddies as relationship solely based on air temperature cannot simulate variations between canopies of different thickness.
- A vegetation index computed from remote sensed data such as the Normalized Difference Vegetation Index (NDVI) represents a useful tool for evaluating crop development during the growing season and identify areas with a stunted growth that can be specifically managed. NDVI maps with a 30 m resolution can be effectively obtained from Landsat 8 that images the Earth every 8-16 days. Dramatic improvements in both the temporal and spatial resolution of land surface images could be obtained thanks to recent Satellite Platform Sentinel 2 that capture images with a 10 m pixel resolution and 5 day revisiting time. Moreover, remote sensed data could be useful input data to models simulating the soil-crop-atmosphere system. In fact, they provide spatially distributed

information that can be used for real–time simulations such as yield forecast.

CHAPTER 4

The role of water management and environmental factors on field irrigation requirements and water productivity of rice[2]

S. Cesari de Maria[a], G.B. Bischetti[a], E.A. Chiaradia[a], A. Facchi[a], E.F. Miniotti[b,c] , M. Rienzner[a], M. Romani[b], D. Tenni[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
[c] Soil Biogeochemistry (DiSAFA) University of Turin, Turin, Italy.

Abstract

Rice cultivation requires a significant share of irrigation water, mostly because of the practice of continuous flooding; therefore, interest for alternative water managements is increasing. The paper presents results of a 2-year experiment in Northern Italy comparing three rice water managements: Water seeding-continuous FLooding (WFL), Dry seeding-delayed FLooding (DFL), Dry seeding-intermittent IRrrigation (DIR). The main objective was to assess the effects of water regimes on the agro-ecosystem as a whole (from water use and yield components to nutrient dynamics etc.). This paper is focussed on water use aspects with the aim of: i) comparing and discussing water balance terms, water use efficiencies and water productivities; ii) conducting a statistical analysis of percolation fluxes of flooded treatments (WFL and DFL) in order to validate results of the water balance; iii) discussing inter-annual variations of paddy irrigation requirements due to environmental factors. Net irrigation requirements of WFL ranged between 1,500 and 3,000 mm in the two seasons, while DFL and DIR determined average reductions by 20% and 65%. On the other hand, WFL provided an average yield of 10.2 t ha-1, which decreased by 3% and 28% in DFL and DIR respectively. Percolations of flooded treatments showed a strong correlation with groundwater levels, especially during the first part of the season (R^2 0.90 and 0.95 respectively). Data analysis highlighted complex subsurface water dynamics dependent on groundwater levels and influenced by soil characteristics. Between-years variability could be attributed to environmental factors including groundwater levels and soil responses to abiotic and biotic factors.

Keywords: paddy; rice; water balance; water savings; groundwater; temporal variability

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[2] Submitted to Irrigation Science

1 INTRODUCTION

Worldwide, rice is one of the most important crops representing the staple food for over half of the world's population, with a global production of more than 700 million tons per year (FAOSTAT, data for 2013) and an harvested area reaching 165 million ha (FAOSTAT, data for 2013). More than the 75% of the global rice supply is provided by lowland irrigated rice (Maclean et al., 2002), where rice has been traditionally grown under the continuous presence of a water depth ranging between 5 to 10 cm (Bouman et al., 2007b). Because of the large rice surface and the particularly water-demanding regime, it is estimated that irrigated rice receives around 40% of the water globally used for irrigation purposes (Bouman et al., 2007b). According to some scenarios, improvements in the effectiveness of rice irrigation are becoming more and more urgent since 15–20 million ha of irrigated rice could suffer from some degree of water scarcity by 2025 due to an increasing water competition among users (Tuong and Bouman, 2003). In this framework, Bouman and Tuong (2001) identified three major challenges rice producers will have to face: i) to save water, ii) to increase water productivity (i.e. grain yield over water input) and iii) to "produce more rice with less water".

The irrigation amount provided to rice fields depends on several factors with strong cross-interactions such as the irrigation management (e.g. Belder et al., 2007, Tabbal et al., 2002), the land preparation method (e.g. Singh et al., 2001; Kukal and Aggarwal, 2001), the layout of the fields (e.g. Neumann et al., 2009), the soil characteristics (e.g. Watanabe, 1992; Garg et al., 2009; Janssen and Lennartz, 2007) and the groundwater depth (e.g. Belder et al., 2007), in addition to the meteorological conditions that directly affect the contribution of rainfall and evaporation to the field water balance.

Seepage and percolation are considered the main responsible for the low water use efficiency of paddy rice at the field scale. They are often evaluated together, as it is not easy to separate those fluxes in either seepage or percolation. In flooded fields they are estimated to account altogether for about 25-50% of all water inputs in heavy soils with a groundwater table within 50 cm from the soil surface (Cabangon et al., 2004; Dong et al., 2004), but they can reach some 50-85% in coarse-textured soils with a deeper groundwater table (say 1.5 m or more) (Sharma et al., 2002; Singh et al., 2002). The two processes are driven by hydraulic conditions (e.g. depth to the groundwater, water level in drainage canals, ponded water depth) and by the soil characteristics, including porosity and presence of cracks (Watanabe, 1992). However, seepage is considered relevant either in case unpuddled spots are present within a puddled field (as for instance unpuddled soil underneath the bunds) (Kukal and Aggarwal, 2002; Tuong and Bhuiyan, 1999; Neumann et al., 2009), or in small fields with a high perimeter-to-area ratio that are surrounded by dry-lands (Chen et al., 2002; Neumann et al., 2009). Percolation is governed by a variety of soil related factors, such as structure, texture, bulk density, mineralogy, organic content (Wickham and Singh, 1978). Moreover, percolation is affected by the water regime in and around the field through its influence on the groundwater depth (Bouman et al., 2007b; Tabbal et al., 2002). Quantifying the influence of groundwater on the irrigation water requirements is however difficult under experimental conditions, therefore simulation models are generally adopted to study the effect of different groundwater levels (e.g. Belder et al., 2007)

New approaches known as Water Saving Technologies (WSTs) provide an opportunity to lower the significant water use associated with traditional rice farming, especially because of their potential to reduce seepage and percolation losses associated with the regime of continuous submergence. WSTs involve a series of practices that include the land preparation method, the crop establishment technique and, mostly, the water management during the crop growth. With respect to WSTs, wet land preparation is giving way to dry tillage, which enables to save the water used before the actual crop growth (Tabbal et al., 2002). Moreover, other establishment techniques are replacing the transplanting of the seedlings performed after wet land preparation. Such techniques consist in either direct wet seeding (i.e. broadcast of pre-germinated seeds) or direct dry seeding (i.e. drill-seeding). As regards water management during crop growth, the more common regimes considered as WSTs are: *i)* saturated soil culture (e.g. Tabbal et al., 2002; Borrell et al., 1997); *ii)* delayed flooding (e.g. Dunn and Gaydon, 2011; Borrell et al., 1997); *iii)* alternate wetting and drying (e.g. Singh et al., 2001; Belder et al., 2007; Feng et al., 2007; Bouman et al., 2007a; Belder et al., 2004; Yadav et al., 2011; Borrell et al., 1997; Tan et al., 2014); and *iv)* flush irrigation (e.g. Belder et al., 2007; Xue et al.,, 2008; Feng et al., 2007; Bouman et al., 2007a; Tabbal et al., 2002; Govindarajan et al., 2008; Bouman et al., 2005).

Evaluating the performance of different water regimes requires the adoption of monitoring systems that enable to quantify the contribution of each component to the paddy water balance (e.g. Kukal and Aggarwal. 2002; Belder et al., 2004; Yadav et al., 2011; Bouman et al., 2005; Borrell et al., 1997). As a further step, simulation models can be adopted in order to gain a deeper understanding of water dynamics and explore also the effects of different scenarios (e.g. Singh et al., 2001; Belder et al., 2007; Xue et al., 2008; Feng et al., 2007; Bouman et al., 2007a; Govindarajan et al., 2008; Chen et al., 2002). Understandably, monitoring is generally limited to some of the variables of interest, therefore the water balance terms that are not directly measured have to be estimated from related measures when a modelling approach is not adopted. For instance, Singh et al. (2001) derived the amount of irrigation applied to flooded rice from the difference between the water depths measured immediately before and after the irrigation event, while Tabbal et al. (2002) calculated the evapotranspiration from the measured pan evaporation using equations developed by other authors for lowland rice. Additionally, some water budget terms that cannot be easily measured (e.g. percolation) are usually computed as the residual term of the mass balance equation (e.g. Zhao et al., 2015).

However, values obtained in this way are likely to be affected by any error made on the measurements/estimations of all the other components.

Moreover, regardless the specific regime of flooding, quite a significant inter-annual variation of paddy water requirements is found in the literature reporting experiments carried out in the same fields and lasting at least two seasons. For instance, Zhao et al. (2015) observed that the total water use of continuously flooded rice in some plots varied up to more than two fold as much between seasons and, in general terms, they attributed this difference to different meteorological occurrences and soil behaviour. Belder et al. (2007) reported more than a two-fold variation in water requirements of alternately submerged–nonsubmerged rice when a deep drain was excavated in order to increase internal drainage and lower the groundwater table. Increase in water use by 30% to 50% are reported also by Kukal et al. (2005), Sudir-Yadav et al. (2011), Bhushan et al. (2007) in rice experiments under different regimes of flooding, but no specific reasons are mentioned. Despite their relevance, such variations are often moved to the background since authors generally focus their discussion more on the comparison between different irrigation strategies speaking about water uses averaged over two seasons; or, else, they deal with the issue of temporal variability, but mostly with respect to variations of processes within the same season. However, besides comparisons of different water regimes, it is very important to investigate also the role of environmental factors, especially because they can determine variations in irrigation requirements that are even greater than those induced by changes in water regimes themselves.

In this framework, the paper presents the results of an intensive monitoring activity (years 2012 and 2013) performed at the Rice Research Centre located in Catello d’Agogna (Northern Italy) where the performance of three different water regimes of rice have been investigated and compared. The water management practices under evaluation are: Water seeding and continuous FLooding (WFL), Dry seeding and delayed FLooding imposed at around the 3-leaf stage (DFL), and Dry seeding and intermittent flush

IRrrigation (DIR). The specific objectives of the paper are: *i)* to compare the effects of the different irrigation regimes on the water balances and the water use indicators over two agricultural seasons; *ii)* to provide a validation of the results through the application of a multiple linear regression analysis examining the relationship between percolation and groundwater levels, *iii)* to critically discuss the effect of environmental factors on the inter-annual variability of rice irrigation requirements.

2 MATERIAL AND METHODS

2.1 Field experiments

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 (CRR-ENR) located in Castello d'Agogna, Pavia province, Italy (45° 14' 56.616'' N, 8° 41' 59.924'' E, 108 m.a.s.l.). The centre is located in the main Italian rice growing area (around 90% of the total national surface; ENR 2013) where rice fields have generally a size ranging between 2 and 3 ha (INEA 2013). The traditional technique consists of broadcasting pre-germinated seeds over submerged levelled fields and then maintaining a ponded water depth from 5 to 20 cm for almost the whole growing season (INEA 2013). However, the practice of dry seeding and delayed flooding has increased in the Western Po Valley during the last decade, reaching a maximum of 30% of the total Italian rice area in 2011 (ENR 2013). In addition, flush irrigated rice has spread across some areas located in the Lombardy region, east of the Ticino River and it is gaining some interest due to the potential of reducing the irrigation requirements.

The local climate of the area is humid subtropical (Cfa) according to the Köppen climate classification (Köppen, 1936), with average temperatures in the months from April till September of 20°C and rainfalls of about 360 mm, rather variable throughout the years (data for the period 1993-2013). During the agricultural seasons 2012-2013 (June till September), average maximum and minimum temperature were 29.2 °C (±3.8°C) and 17 °C (±3.2°C) respectively; and average daily evapotranspirations of the months June, July, August and September amounted, respectively, to 4.7 mm d^{-1}, 4.6 mm d^{-1}, 4.0 mm d^{-1} and 2.8 mm d^{-1}.

In 2012, flooded paddies surrounded the experimental fields apart from a soybean field located on the West side (see Figure 1), while in 2013 only flooded paddies were adjacent to the experiments.

Soil characteristics of the site were assessed thanks to a detailed soil survey carried out in March 2012. Specific results of the soil survey are presented in Chiaradia et al. (2015), therefore just a brief summary is reported here. The fields involved in the experiment are characterized by a surface horizon (corresponding to the Apg horizon) that is significantly homogenous in space due to the agronomic practices performed on a yearly basis. The texture of the first layer is loam to silty loam, with a clay content ranging from 15 to 23% and a bulk density of about 1.4-1.5 Kg m^{-3}. A greater spatial variability in terms of granulometry, organic carbon content and genetic horizons sequence was found in the underlying layers explored (corresponding to B horizons and to BC or C horizons). Sub-surface horizons are characterized by a texture going from sand to silty clay loam and some of the samples collected below 1 m depth revealed the presence of clay contents higher than 27% and an enrichment in organic carbon showed by the very dark colour of the soil sampled (see Figure 1 for the spatial distribution of soil characteristics in the deeper layers).

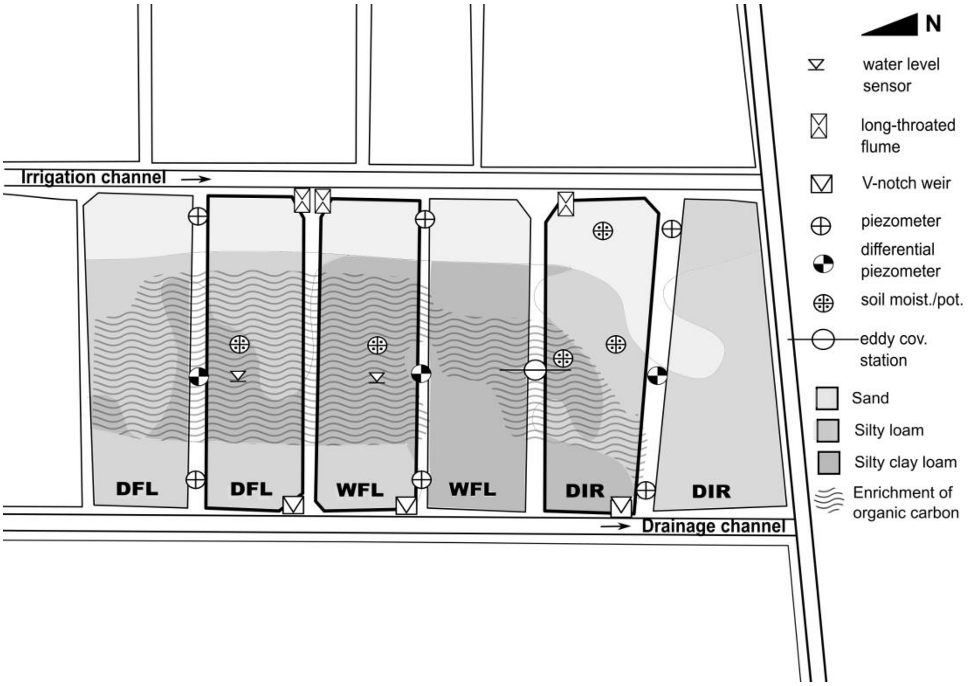

Figure 1 **-** *Soil characteristics of the deeper layers (below 1 m depth) and locations of the instruments*

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 (WFL), *ii)* continuous flooding from around the 3-leaf stage of drill-sown rice (DFL), and *iii)* surface irrigation of drill-sown rice (DIR).

Thanks to the irrigation layout of the site, the method of flow-through irrigation is applied in the flooded plots (WFL and DFL), i.e. more water than the amount needed is applied to the plots and any excess is then drained to the drainage channel. Provided there is a stable water supply, the flow-through irrigation is generally adopted to cool the field, save water management labour and exert a control over the ponded water depth (Watanabe, 1992).

The rice cultivar grown in all the plots was *Gladio cv.*, an early, semi-dwarf variety of tropical japonica type. Before crop establishment, the fields were dry-ploughed, laser-levelled and delimited by earthen bunds 40 cm high. Seedbed preparation involved one run of rotary harrow for water-seeded rice (WFL) and two runs for drill-sown rice (DFL and DIR). In 2013, the land preparation and the sowing dates were postponed compared to 2012 due to adverse weather conditions (i.e. heavy rainfall for several days). Seed rates in case of both water seeding and dry seeding were 160 kg ha^{-1}. Table 1 presents sowing and harvesting dates of each treatment in the two seasons. A 25 cm-deep furrow was dug on both sides of each bund, so that possible lateral infiltration could be easily drained in case any seepage occurred between adjacent fields under different water regimes. Negligible water in the furrows suggested that seepage losses throughout the bunds were not relevant.

The WFL treatment was flooded a couple of days before water seeding and then repeatedly dried out and flooded (pinpoint irrigation, LSU AgCenter, 2014) during the early stages of seedlings in order to enhance the rooting phase, avoid soil hardening and keep algae under control. Two more drying periods of few days were imposed to apply herbicides or fertilizers, before the final drying occurred 17 and 29 days before harvest in 2012 and 2013 respectively. Ponded water depth during submerged periods was maintained between 10 and 20 cm.

The DFL was dry seeded and submerged at around the 3-leaf stage occurred 35 and 24 days after sowing in 2012 and 2013 respectively. A ponded water depth again between 10 and 20 was maintained until the final drying, except for a short drying period imposed to apply fertilizers. The water amounts given to WFL and DFL treatments were managed by a daily control on the outflow discharges in order to maintain the desired ponded water depth within the plot (flow-through irrigation). Therefore, the net irrigation amount provided to the plots is given by the difference between the water inflows and the water outflows.

The DIR treatment was drill-sown and irrigated on average every 7-10 days from around 35 days after sowing onwards. The number of irrigation events of DIR treatment were 9 in 2012 and 12 in 2013, when the crop cycle was 10 days longer than in 2012 and less rainfall events occurred in the second half of the irrigation season.

Levels of nitrogen fertilizer, given as urea, were 160 kg ha^{-1} to all the treatments in both years, but the split applications were different depending on the water regime as shown in Table 1. Phosphorus and potassium were applied before sowing through a compound fertilizer with a rate of 18 kg P ha^{-1} and 70 kg K ha^{-1}. Pesticide treatments were diversified depending on the year and on the seeding technique and enabled an optimal control of diseases, pests and weeds in both years.

Table 1 Details of the field experiments

Year	**Treatment** [a]	**Sowing**	**Harvest**	**Growing Season (days)**	**Nitrogen applications (kg N ha^{-1})**
2012	**WFL**	28 May	21 Sep	117	Pre-sowing: 60; Tillering: 60; Panicle initiation: 40;
	DFL	15 May	21 Sep	130	Pre-sowing: 40; Tillering: 70; Panicle initiation: 50
	DIR	15 May	21 Sep	130	Pre- sowing: 50; Tillering: 40; Panicle initiation: 40; Booting: 30
2013	**WFL**	07 Jun	14 Oct	130	Pre-sowing: 60; Tillering: 60; Panicle initiation: 40;
	DFL	28 May	14 Oct	140	Pre-sowing: 40; Tillering: 70; Panicle initiation: 50
	DIR	28 May	14 Oct	140	Pre- sowing: 50; Tillering: 40; Panicle initiation: 40; Booting: 30

[a] WFL: Water seeding-continuous FLooding; DFL: Dry seeding-delayed FLooding; DIR: Dry seeding-intermittent Irrigation

2.2 Monitoring activities

2.2.1 Overview of the monitoring system

One plot of each water treatment (WFL, DFL and DIR) was monitored throughout the growing seasons 2012 and 2013 by a non-standard and innovative prototypal system specifically developed for case studies on paddies' water fluxes. Details about the monitoring systems are provided by Chiaradia et al. (2015), therefore just a brief summary is given in the following Sections.

Overall, 2 water level sensors, 12 piezometric wells for groundwater measurements, 6 devices for discharge measurements, 20 tensiometers, 4 soil moisture multi-level probes and, finally, an eddy-covariance station were installed (Figure 1). Data were automatically collected and checked remotely.

2.2.2 Measurements of surface water fluxes and soil water status

In 2012, inflow discharges in each plot were measured by a RBC long throated flume, while outflow discharges were measured by V-notch weir. Both weirs were associated to a specific stage-discharge relationship. In 2013 instead, both inflow and outflow discharges were measured by RBC long throated flumes since they were found to perform better in terms of algae formation (Chiaradia et al. 2015). Data were recorded every 10 minutes.

Groundwater levels were monitored in 12 piezometric wells positioned along the bunds dividing the two replicates of the same water treatment (Figure 1). In more detail, two identical slotted wells were installed at the upstream and downstream section of each bund (length of the pipe: 3.00 m, length of the well screen: 1.50 m), while a pair of slotted wells used as differential piezometer were installed in the midpoint of each bund (length of the pipes: 3.10 m and 1.6 m, length of the well screen: 0.10 m). Readings were recorded at hourly time-steps. In both the flooded plots (WFL and DFL), the water depth was recorded by a pressure transducer inserted in a slotted tube installed in the field and connected to the datalogger that recorded hourly measures.

Soil water contents were measured by 4 soil moisture multi-level probes (depths: 10, 30, 50 and 70 cm) calibrated by volumetric measures on undisturbed soil samples collected at the end of the season. Three out of the four probes were installed in DIR in order to monitor the three soil units characterizing the plot, while the fourth one was placed in DFL during periods of non-submergence. Data were recorded every 10 minutes. Nearby the probes, a set of four tensiometers was installed at the same depths as moisture sensors and one more set of tensiometers was placed also in WFL (Figure 1).

2.2.3 Eddy covariance measurements

On the bund dividing WFL and DIR an eddy-covariance station was installed in order to measure energy and gas exchanges of both the treatments. In fact, the lack of a dominant wind direction enabled a single station placed between the two treatments to register fluxes coming from the two cropped areas in different semi-hourly time steps (Facchi et al., 2013a; Masseroni et al., 2015). Devices comprised: a 3D sonic anemometer, an infrared gas analyser, a four-component net radiometer, a pyrgeometer and a pyranometer, three heat flux plates (placed at 8 cm below the soil surface), three pairs of two thermistors (placed at 2 and 6 cm below the soil surface) and a traditional thermohygrometer,. Moreover, water temperature was measured together with water level in WFL in order to estimate also the water heat storage in the flooded treatment.

2.2.4 Crop measurements

Periodic campaigns were conducted in both 2012 and 2013 (11 and 14 campaigns, respectively) to measure Leaf Area Index (LAI, $m^2\ m^{-2}$) by a LP-80 AccuPAR Ceptometer, crop height (m) and rooting depth (m) of rice under the three different water regimes. Values of LAI and crop height of each plot were obtained as the average of a set of four measures taken in six different points of the field so that the final data are an average of 24 measurements. As regards rooting depth, fewer measurements both in space and in time were performed to limit the number of uprooted plants. The number of culms per square meter was assessed at tillering and before harvesting by averaging the number of culms quantified over a surface of 0.25 m^2 in three replicates. Moreover, a sample of 20 panicles was collected in order to quantify the number of sterile spikelets over the total number of spikelets. Eventually, harvesting was performed by an Iseki type harvester with grains at 21% moisture. Immediately after harvesting, grains were dried and, after a period of 30 days needed to reach an equilibrium in the moisture content, rice yield was measured and expressed at 14% moisture content (t ha^{-1}).

2.3 Calculation of the water balance

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

$$I + R = \Delta S_s + \Delta S_w + E_s + E_w + T + SP + D \tag{1}$$

where *I* is the amount of irrigation supplied, *D* is the tail water drainage flowing out of the plot, *R* is the rainfall, E_s is the evaporation from the soil, E_w is the evaporation from the ponded water for WFL and DFL, *T* is the transpiration from the canopy (the sum of E_s, E_w and *T* thus define the crop evapotranspiration *ET*), ΔS_s is the change in the soil water storage (where the soil water storage includes the soil water content of the root zone, between 0-40 cm depth), ΔS_w is the difference in the ponded water depth for WFL and DFL (the sum of ΔS_s and ΔS_w defining the difference in the field water storage, ΔS), and *SP* is the sum of seepage and net percolation (i.e. the difference between percolation and seepage minus the capillary rise, if any). All terms are expressed in mm over the surface area of the individual plot and the water balance was computed on a daily time step from dry seeding to harvest in case of DFL and DIR, and from the flooding before water seeding to harvest in case of WFL.

I and *D* were directly measured for each treatment, while *R* was assumed to be the same for all treatments and it was obtained from the registrations of the agrometeorological station of the regional meteorological service (ARPA), located at the ENR centre, about 100 m far from the experimental fields.

ET was estimated by the application of Penman-Monteith type models that were calibrated using the discontinuous *ET* data series obtained by processing the eddy-covariance measurements. In more detail, a careful footprint analysis was first performed to determine the size and the position of the footprint area at half-hourly time steps, thus deriving two discontinuous datasets of *ET* values related to either WFL or DIR. Thanks to these datasets of eddy data adjusted by Bowen ratio, and to data collected during three monitoring campaigns with microlysimeters, it was possible to calibrate the “double-layer” Shuttleworth and Wallace model (1985) for deriving *T* and E_S, while the Penman equation as modified by Jensen (1987) for the estimation of E_w. For further details on the *ET* computation, the reader should refer to Facchi et al. (2013a) and to BioGesteca (2014).

The ΔS values were derived from the available soil moisture measurements, considering also the ponded water depth in case of submergence. Regarding the DIR treatment, the soil water contents measured by each of the three probes were weighted according to the surface area of the main soil types within the plot.

Finally, the term *SP* was obtained as the residual term of the water balance and will be referred to as ‘Net Percolation’ (*NP*) hereafter, since seepage is not supposed to be the most relevant component of *SP* due to the following reasons: i) ploughing involved the planted region of the fields as well as soil beneath the bunds, therefore no great differences in the hydraulic conductivities of under-bund soil were expected (Neumann et al., 2009) ii) bunds were created at the beginning of the agricultural season, after ploughing, and well maintained during the whole season (Bouman et al., 2007b), iii) the experimental plots are not excessively small (Zhao et al., 2015); and iv) any lateral seepage occurring between plots with different water regimes was canalized in the furrows dug alongside the bunds.

2.4 Calculation of water use indicators

For each treatment, the Water Use Efficiency (*WUE*, %) was calculated as proposed by Bouman et al. (2005):

$$WUE = 100 * \frac{ET}{I + R} \tag{2}$$

WUE computed according to (2) represents the share of water effectively used by the crop over the total water inputs. However, the value computed according to (2) strongly depends on the particular water management adopted (i.e. flow through irrigation), since more water is deliberately applied and then the excess is drained to maintain the desired ponded water depth. Therefore, a modified index (*WUE**, %) accounting only for the field water losses was computed as suggested by Dunn and Gaydon (2011) :

$$WUE^* = 100 * \frac{ET}{I + R - D} \tag{3}$$

Similarly, the Water Productivity referred to water inputs (WP_{IR}, kg m^{-3}) defined as weight of grains over cumulative weight of water inputs by irrigation (Bouman et al. 2007b) was computed both including (WP_{IR}) and subtracting (WP_{IR}^*) the term D according to eq. (4) (Bouman et al., 2005) and (5) (Dunn and Gaydon 2011) respectively:

$$WP_{IR} = \frac{Y}{I_{in} + R} \tag{4}$$

$$WP_{IR}* = \frac{Y}{I + R - D} \qquad (5)$$

where Y is the grain yield in kg m^{-2}, and I, D and R are expressed in m^3 m^{-2}.

2.5 Statistical analysis

Water balance of flooded treatments is always highly dependent on the amount of water percolating due to the almost continuous presence of ponded water. In order to check the accuracy of the percolation term *NP* that was estimated by solving Equation (1), we decided to carry out a statistical analysis for WFL and DFL data, investigating the relationship between *NP* and measured groundwater levels. As a matter of fact, groundwater level data were not used in the estimation of *NP*, thus a good accordance between the two datasets would confirm the *NP* data. Moreover, considering that *NP* was obtained as the residual term in the water balance and that water balances of flooded treatments are always highly dependent on the amount of water percolating, the confirmation of the reliability of *NP* term would indirectly confirm also the reliability of the measurements/estimations for the others terms of Equation (1).

To this purpose, the relationship between *NP* and measured groundwater levels was investigated through a multiple linear regression with input of daily values. *NPs* of WFL and DFL in both years were first filtered by using a symmetric (centred) moving average with a window size of 5 in order to filter out the daily fluctuations while preserving the trend. The focus of the analysis was on the periods of submergence, therefore data related to days with no ponded water on the field have been excluded, since the relationship between percolation and groundwater dynamics is expected to hold only with significant downward water fluxes. Moreover, we kept out from the analysis data related to either two days after flooding or two days prior to drainage in order to remove the border effect caused by the filter.

Data have been firstly grouped into two samples depending only on the plot (either WFL or DFL). For each plot we decided to consider the two years as a unique sample, based on the assumption that the same relationship between *NP* and groundwater levels should hold in both years and thus should not be influenced by year-dependent factors involving the aquifer. Instead, plots were considered separately the one from the other since, in this case, subsurface water dynamics could be different between the two plots. A different form of the model may be therefore required. Finally, we further split each sample into two different datasets that were identified based on groundwater levels and of percolation trends, considering drainage events as benchmarks. Two phases were thus distinguished: phase *I* and phase *II*. Phase *I* is the phase characterised by transitional processes with increasing groundwater levels and percolation fluxes decreasing over time. Such occurrences were identified during the first flooding event of DFL (both years) and WFL-2013, while they involved the first two floodings of WFL-2012 (see Figure 3, panel a). For the data analysis, however, just values of the second flooding of WFL-2012 were used since groundwater measurements were not available for the first flooding because of a delay in the automatic acquisition of pressure heads. The rationale behind the distinction in two phases is explained in the following. First of all, flooding tends to decrease the porosity and the hydraulic conductivity of the soil because of compaction and clogging of the pores in the top layer and this phenomenon is more pronounced for the first flooding events (Kukal and Aggarwal, 2002; Sacco et al., 2012). Secondary, an effect of the increased percolation following the first submersion is generally the rise of the groundwater levels, which, in turn, may alter the local, field scale, subsurface water dynamics, particularly if the saturated surface is very shallow.

Eventually, four multiple linear regressions *NP* vs. groundwater levels were applied to the samples WFL-*I*, WFL-*II*, DFL-*I*, DFL-*II*. Pressure heads in the subsoil were provided by the piezometers located at the upstream and downstream sections of WFL, DFL and DIR (see Figure 1). The final models were identified taking into consideration the relationship between the regressors, the adjusted R-squared, the significance of the regressors, and an evaluation of the meaning of the parameters signs.

3 RESULTS AND DISCUSSION

3.1 Seasonal water balance and water use indicators

Results of the water balance analysis of the three treatments WFL, DFL and DIR over the agricultural seasons 2012 and 2013 are presented in Table 2, along with crop yields and indices accounting for the performance of each irrigation treatment. The amounts of irrigation applied to WFL and DFL were 9,970 and 8,600 mm respectively in 2012, while they decreased to 4,340 and 3,470 in 2013. On the other hand, irrigation water applied to DIR increased in the second growing season if compared to the first one, being 1,030 in 2012 and 1,400 in 2013. The water provided to WFL and DFL is considerably higher than what is reported in literature, especially during season 2012. However, the values obtained depend strictly on the water management adopted that consist in applying more water than the amount needed and then draining the excess as reported by Watanabe (1992). Therefore, the actual irrigation water requirements of WFL, DFL and DIR treatments are more reasonably given by the difference between *I* and *D*, which amounted, respectively, to 3,020 mm, 2,240 mm and 620 mm in 2012; 1,520 mm, 1,280 mm and 740 mm in 2013 (Figure 2). Rainfall was lower than 200 mm in both the two season. The values of net water inputs (i.e. net irrigation plus rainfall) applied to traditional flooding (WFL) are in reasonable agreement with some data found in literature reporting water consumptions ranging from 1,500 to 3,000 mm (see for instance Singh et al., 2001, Tabbal et al., 2002, Zhao et al., 2015).

Total water use of DFL was lower than WFL by 24% in 2012 and 14% in 2013. On the other hand, DIR determined a reduction of the total water use compared to WFL between 47 and 75% depending on the year. Results for

2013 are within the range of 27-60% found by other authors (Tabbal et al. 2002, Bouman et al., 2005, Borrell et al., 1997). Slightly higher water savings were obtained in 2012 mainly because of the greater water amounts required by WFL.

Total water use of WFL and DFL decreased by 48 and 41% over the two seasons, whereas DIR increased by 10%. The sensible variation occurred to WFL and DFL could be attributed to different causes that determined a relevant variation in the percolations, which will be discussed in detail in Section 3.3. In fact, values of percolations obtained for WFL and DFL amounted, respectively, to 2,570 and 1,820 mm in 2012; and 1,200 and 970 mm in 2013. On the other hand, the increase of total water use in the DIR treatment from 2012 to 2013 is 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; ii) a less favourable rainfall pattern (in 2012, the repeated rainfall events occurred in the late part of the growing season likely replaced one or two irrigation events). In this respect, while rainfall events during periods of submergence were not such that they determined variations in the water application to the flooded treatments (WFL and DFL), they did influence the number of irrigations events required by the flush-irrigated treatment (DIR). In fact, when the different length of the agricultural seasons and the different number of applications are taken into account, it turns out that the average amount of net irrigation per event in the DIR treatment was slightly higher in 2012 than 2013 (respectively around 70 and 60 mm per irrigation event), which is quite consistent with the behaviour observed for WFL and DFL treatments.

No significant differences in the evapotranspiration were found between the treatments in either years, as the maximum difference assessed was of about 60 mm between WFL and DIR in 2012 (550 and 490 mm respectively) (see Figure 2). Other authors indeed agree on evapotranspiration being the water balance term less affected by changes in the water management (e.g. Yadav et al., 2011).

Values of water use efficiencies, either *WUE* (referred to the total water inputs) or *WUE** (referred to the net water inputs), substantially reflect the variations in the irrigation water amounts among treatments and years, since no sensible differences were found with respect to evapotranspiration. *WUE* is relatively low (i.e. minimum 5% for WFL in 2012 and maximum 12% for DFL in2013) due to the *D* term that is not deducted from the water inputs. These values are due to the practice of flow through irrigation as mentioned before, therefore *WUE** should be considered a more representative value of the actual water use efficiency of each treatment. In the experiment, *WUE** amounted to 17% (WFL), 21% (DFL) and 63% (DIR) in 2012; and to 27% (WFL), 31% (DFL) and 49% (DIR) in 2013. In literature, a wide range going from 20% to more than 60% is reported for the irrigation efficiency of flooded rice (e.g. Tuong and Bhuiyan 1999, Singh et al., 2001). In this respect, comparisons between experiments may be somehow tricky due to site-specific conditions highly affecting the value of *WUE** through their influence on seepage and percolation and, consequently, on the irrigation amounts needed to compensate for these losses.

Rice yield was higher for WFL with a production of 10.5 t ha^{-1} in 2012 and 9.3 t ha^{-1} in 2013, followed by DFL with 10.3 (-2%) and 9.8 (-5%) t ha^{-1} respectively; and by DIR with 6.9 (-34%) and 7.8 (-20%) t ha^{-1} respectively. As a result, the best performance in terms of water productivity (i.e. m^3 of water required to produce 1 kg of rice) was achieved with DIR in both years with *WP** values around 0.88 kg m^3 in both years against 0.43 and 0.66 kg m^3 for DFL in 2012 and 2013 respectively. Values of *WP** for WFL were 0.33 kg m^3 in 2012 and 0.59 kg m^3 in 2013 in agreements with findings of other authors (e.g Tuong and Bhuiyan, 1999).

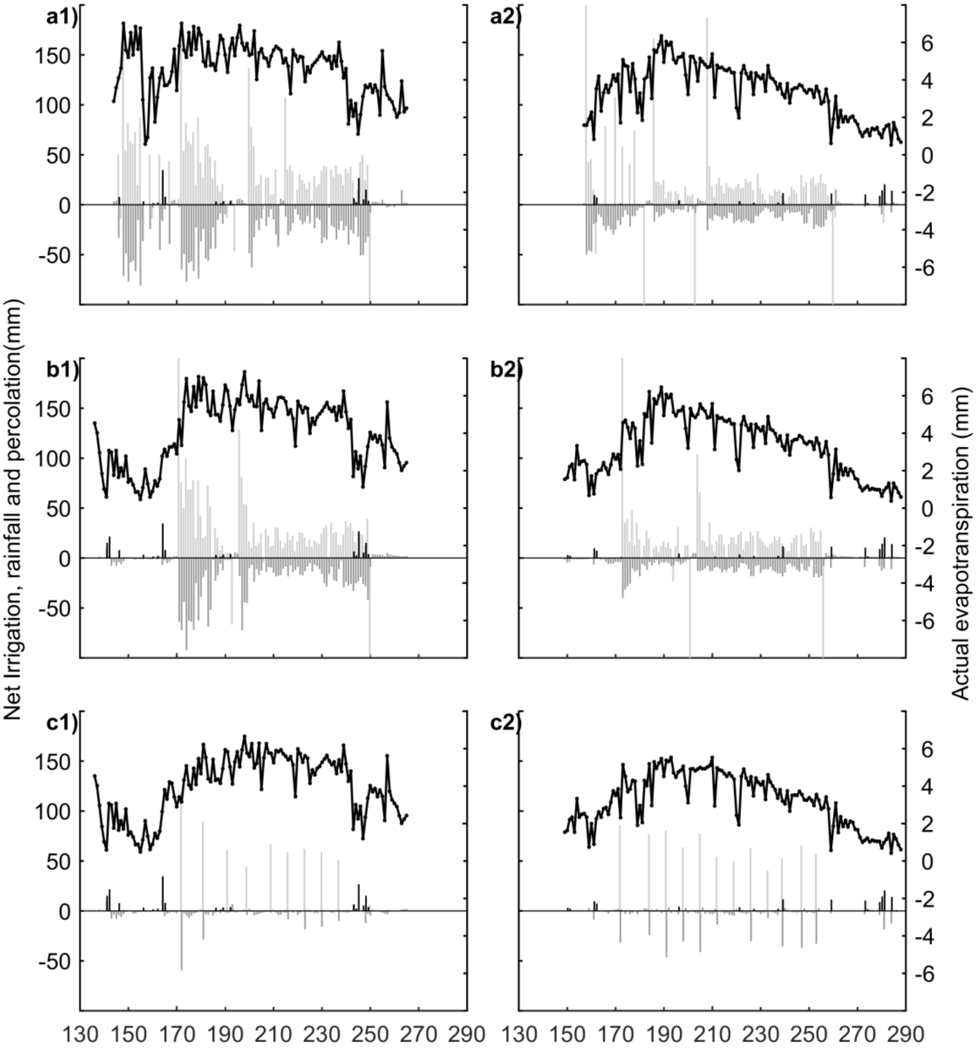

Figure - 2 Daily patterns of net Irrigation (light grey bars), Percolation (dark grey bars) and Rainfall (black bars) on the left y-axis; and actual evapotranspiration (thick black line) on the right y-axis. Day of the Year (DoY) is shown on the x-axis. Panels a), b) and c) show, respectively, WFL, DFL and DIR during 2012 (panels 1, left hand side) and during 2013 (panels 2, right hand side)

Table 2 - Seasonal water balance terms (mm), grain yield (t ha^{-1}) and values of water Application Efficiency (-) and Water Productivity (kg m^{-3}) referred to the total water use (WUE and WP) and to the net water input (WUE and WP*) for the years 2012 and 2013. Irrigation (I), Drainage (D), Rainfall (R), Evapotranspiration (ET), Difference in the water storage including the soil storage in the root zone and the ponded water (DS), Net Percolation (NP) and total Water Use (I+R-D). Positive values indicates water inflows, while negative values water outflows.*

Year	Treat.[a]	No.Days[b]	I	D	R	ET	DS	NP	Water use	Yield	WUE	WUE*	WP	WP*
			mm	mm	mm	mm	mm	mm	mm	t ha^{-1}	(-)	(-)	kg m^{-3}	kg m^{-3}
2012	**WFL**	120	9,970	-6,950	130	-550	30	-2,570	3,160	10.5	0.05	0.17	0.10	0.33
	DFL	130	8,600	-6,360	170	-510	75	-1,820	2,410	10.3	0.06	0.21	0.12	0.43
	DIR	130	1,030	-410	170	-490	-5	-300	790	6.9	0.41	0.63	0.57	0.87
2013	**WFL**	132	4,340	-2,810	130	-450	-1	-1,200	1,650	9.8	0.10	0.27	0.21	0.56
	DFL	140	3,470	-2,190	130	-440	10	-970	1,420	9.3	0.12	0.31	0.27	0.69
	DIR	140	1,400	-660	130	-430	10	-440	870	7.8	0.28	0.49	0.51	0.89

[a] WFL: Water seeding-continuous FLooding; DFL: Dry seeding-delayed FLooding; DIR: Dry seeding-intermittent IRrigation

[b] Water balance computed either from the first day flooding in case of WFL (25 May 2012 and 6 Jun 2013 respectively) or from seeding in case of drill-sown rice (DFL and DIR) till harvest.

3.2 Analysis of percolation fluxes

As highlighted in Section 3.1 and Table 2, net percolation of the flooded treatments WFL and DFL decreased significantly from year 2012 to year 2013. Table 3 reports a more detailed description of these variations focussing only on days when fields were actually flooded and thus when significant downward water fluxes are expected to occur. Data have been divided into two sub-datasets referred to as phase *I* and phase *II*. In addition to percolation fluxes, also statistics related to groundwater levels are reported.

Most of the reduction in percolations from 2012 to 2013 occurred in phase *I* for both WFL and DFL, with a decrease amounting to 69% and 65% respectively. On the other hand, reductions in Phase *II* were 30% and 40% for WFL and DFL respectively. Disregarding the number of days of flooding that depend on the specific weather conditions of the year, also the average percolation rate of the two phases decreased significantly between 2012 and 2013 for both WFL and DFL. Average daily percolations in phase *I* were 43 mm for WFL-2012 and 39 mm for DFL-2012, while they decreased to 18 mm for WFL-2013 and to 10 mm for DFL-2013. Reductions were still higher than 50% in both the treatments, reaching 70% for DFL. In phase *II,* average daily percolations were 23 mm for WFL-2012, 18 mm for DFL-2012, 11 mm for WFL-2013 and 12 mm for DFL-2013. The coefficient of variation tends to be higher in phase *I* that in phase *II*, likely due to the effect of soil compaction and clogging on the daily percolation. Such effect, as expected, reduced the daily percolation over phase *I* to a higher extent than what occurred in phase *II.*

Groundwater levels on the other hand, increased from season 2012 to season 2013, especially at the downstream section of the plots and mostly during phase *I.* Groundwater levels of the first part of phase *I* in WFL are missing because of a delay in the automatic acquisition; however they are expected to be fairly below the values observed in 2013 as it can be deducted observing Figure 3 panel a).

Table 3 - Descriptive Statistics of Percolation fluxes (negative as outflows from the domain considered) and groundwater levels below the soil surface

Water regime[a]	**WFI**				**DFI**			
Year	2012		2013		2012		2013	
Phase of the season	*I*	*II*	*I*	*II*	*I*	*II*	*I*	*II*
N of days (d)	31	47	23	69	21	54	28	52
Total percolation (mm)	-1,340	-1,100	-420	-770	-810	-1,000	-290	-600
Average daily percolation (mm)	-40	-20	-20	-10	-40	-20	-10	-10
Standard deviation of percolation (mm)	20	10	10	6	30	10	10	4
Minimum upstream groundwater level (m)	-0.43[b]	-0.34	-0.84	-0.33	-0.27	-0.31	-0.29	-0.32
Maximum upstream groundwater level (m)	-0.28[b]	-0.16	-0.31	-0.11	-0.09	-0.09	-0.13	-0.14
Minimum downstream groundwater level (m)	-1.24[b]	-0.74	-1.04	-0.70	-1.14	-0.76	-1.03	-0.62
Maximum downstream groundwater level (m)	-0.74[b]	-0.50	-0.89	-0.33	-0.75	-0.54	-0.40	-0.31

[a] WFL: Water seeding-continuous FLooding; DFL: Dry seeding-delayed FLooding; DIR: Dry seeding-intermittent IRrigation

[b] Groundwater levels at the beginning of WFL season in 2012 are missing, so values reported here are not to be considered as absolute minimum/maximum

Such a variation can be partly attributed to the heavy rainfall events occurred in Spring 2013, and partly to the change the water regime of the field on the West side (see Figure 1) that was cropped with soybean in 2012 and with rice under delayed flooding in 2013.

To verify the accuracy of the percolations fluxes, which suggest significant variations between two consecutive growing seasons, we performed a statistical analysis that led to the identification of four multiple linear regression models for the treatments DFL and WFL during phase *I* and phase *II*. Net percolations obtained from the water balance (*NP,* considered here as positive quantities*)*, were analysed in the relation to pressure heads (*h*) measured by the pressure transducers in the upstream and downstream piezometers of each treatment (see Figure 1 for the piezometers location). Figure 3 compares the trends of *NP* and the estimated percolations according to the models for WFL and DFL over the crop seasons 2012-2013.

Overall, the fitting between *NP* and pressure heads was very satisfactory during phase *I,* as shown by the high coefficient of determination (R^2) amounting to 0.95 for DFL and 0.79 for WFL, and less satisfactory during phase *II*, mostly in case of DFL (0.40 for DFL against 0.71 obtained for WFL in the same phase). The lower performance of DFL-*II* compared to WFL-*II* was somehow expected, since groundwater levels at the North border of DFL were not available (see Figure 1), while for WFL both the conditions at the North and South borders were monitored. The coefficient of determination is higher in phase *I* than in phase *II* for both the plots, revealing that *NP* dynamics during the first flooding event were in very good agreement with the pressure heads we measured. On the other hand, the variability of *NP* in the subsequent flooding was not entirely explained by the pressure heads of the measurements points we monitored.

As suggested by the models we identified, the relationship between *NP* and groundwater levels can be expressed as a linear relationship between the groundwater recharge (i.e. *NP*) and both the average pressure head in the subsoil (mean between upstream and downstream) and the hydraulic gradients between two measurements points (namely the difference between pressure heads of two points divided by their distance).

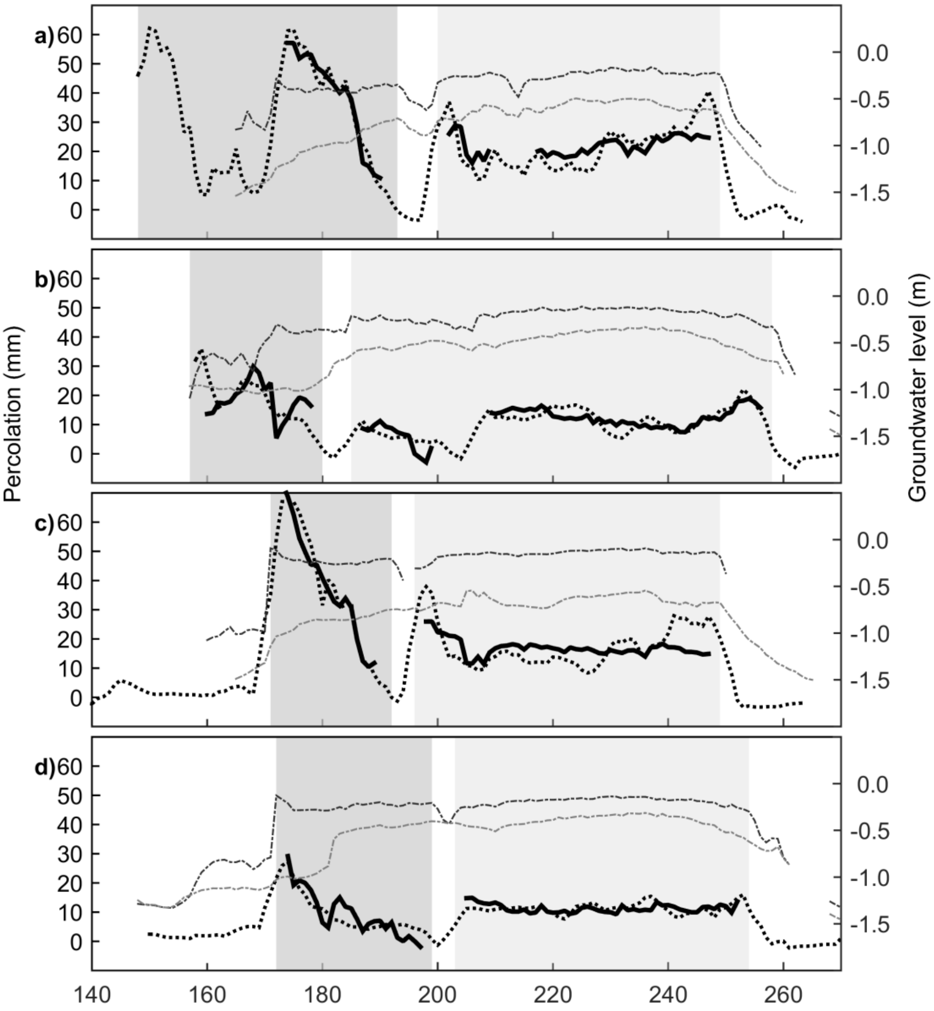

Figure 3 - Patterns of percolations and groundwater levels of the treatments Dry seeding-FLooding (DFL) and Water seeding-FLooding (WFL) during the agricultural seasons 2012 and 2013. Filtered net percolations obtained from the water balance (dotted black line) and estimated via linear regression (thick black line) are on the left y-axis. Upstream groundwater levels (dashed dark grey line) and downstream groundwater levels (dashed light grey line) are on the right y-axis. Phase I is shaded with dark grey background; phase II with light grey. Day of the Year (DoY) is shown on the x-axis. Panel a) WFL-2012, b) WFL-2013, c) DFL-2012, d) DFL-2013

With respect to the physical interpretation of the model, the following considerations can be made, on account of the soil characteristics described in Section 2.1. Net percolations were very well correlated with the average pressure heads of the same plot or in the adjacent plot (e.g. see model WFL-*I*) and with the hydraulic gradients occurring in both the East-West direction and the North-South direction (p-values < 0.05 in all cases, see Table 4). It follows that a unique predominant direction of subsurface water flow cannot be assumed, but rather a more complex circulation can be expected. Moreover, the identified models suggest that different flow dynamics occurred depending on the specific phase (either *I* or *II*). In fact, the signs of the regression coefficients are opposite in the two phases, yet equal among the plots. With respect to phase *I,* the higher the average pressure head in DFL, the lower the percolation of both DFL and WFL. That is to say, when the groundwater table is relatively deep (groundwater levels below 0.5 m), the percolation appears to be higher. In addition to that, the higher the hydraulic gradient between the upstream and downstream section of DFL plot, the higher the percolation occurring in both DFL and WFL. Finally, also an increase in the hydraulic gradient at the downstream section of the plots is related to higher percolations. For the above considerations, water fluxes in DFL-*I* (i.e. when the groundwater is still quite low) seem to be mainly in the East-West direction, but a relevant water flow towards South (i.e. where the DIR plot is located) appears to have occurred.

Conversely, higher average pressure heads are related to higher percolations in phase *II.* One possible explanation is that the shallow groundwater depth triggers a lateral flux towards the drainage channel. Moreover, the significant water flux from North to South at the downstream section is no longer evident in phase *II,* since the coefficients are positive (see Table 4). Finally, also the upstream hydraulic gradient between WFL and DIR is significant in phase *II*, suggesting some subsurface water movement from the WFL plot to the DIR plot.

Such complex water dynamics derive their justification from the soil characteristics of the experimental fields. The soil survey identified an enrichment in organic carbon and high clay contents in some of the deep layers in both the WFL and DFL plots. Because of that, the field can be likely characterised by the presence of strata with different permeability, with a consequent significant anisotropy of the soil. Consequently, different water dynamics may occur depending on whether the groundwater level is still relatively low (phase *I*) or the soil is saturated (high groundwater table, phase *II*).

Table 4 - Multiple linear regression models relating net percolations versus average pressure heads ($\dot{h}$) and hydraulic gradients (i) obtained from piezometer measurements located in the upstream (us) and downstream (ds) sections of the plots. WFL and DFL stand for Water seeding-continuous FLooding and Dry seeding-delayed FLooding. Symbols I and II refer, respectively to the first part of the season (phase I) and second one (phase II).

Sample	R-squared	Regressors	Coefficients	p-values
WFL-*I*	0.90	*Intercept*	92	< 0.01
		$\dot{h}_{DFL}$	-16,788	< 0.01
		$i\ (DFL_{us}, DFL_{ds})$	8,345	< 0.01
		$i\ (DFL_{ds}, WFL_{ds})$	8,749	< 0.01
WFL-*II*	0.71	*Intercept*	-69	< 0.01
		$\dot{h}_{WFL}$	1,593	0.05
		$i\ (WFL_{us}, WFL_{ds})$	-1,198	0.03
		$i\ (DFL_{ds}, WFL_{ds})$	-50	< 0.01
		$i\ (WFL_{ds}, DIR_{ds})$	-870	0.04
		$i\ (WFL_{us}, DIR_{us})$	535	0.03
DFL-*I*	0.95	*Intercept*	-163	< 0.01
		$\dot{h}_{DFL}$	-14,585	< 0.01
		$i\ (DFL_{us}, DFL_{ds})$	7,459	< 0.01
		$i\ (DFL_{ds}, WFL_{ds})$	7,523	< 0.01
DFL-*II*	0.40	*Intercept*	112	< 0.01
		$\dot{h}_{DFL}$	4,313	< 0.01
		$i\ (DFL_{us}, DFL_{ds})$	-2,208	< 0.01
		$i\ (DFL_{ds}, DIR_{ds})$	-2,249	< 0.01

In summary, the analysis we conducted provided a validation of the percolation fluxes we obtained from the water balance computation in both the years and confirm the relevant variations we assessed between the two seasons. In fact, high values of the coefficient of determination were obtained especially in phase *I,* when most of the variation among years occurred. Furthermore, the models we identified highlighted the presence of flow dynamics that are phase-specific and quite complex because of the soil heterogeneity in the subsurface layers.

3.3 General remarks on fluctuations of rice irrigation requirements

Results of water balances presented in Section 3.1 highlighted that irrigation water requirements of flooded rice nearly double between two consequent crop seasons. In our case, such variation was mainly attributed to a significant variation in the percolation term, since crop evapotranspiration did not vary more than 20% between the two seasons, whereas variations in the percolation term reached 70% in DFL and 90% in WFL. This variability between the seasons is indeed supported by the analysis on groundwater dynamics we presented in Section 3.2.

To our understanding, several factors can be responsible for the significant variations of the water use in the same field over two different cropping seasons. These factors are briefly discussed in the following. It was not possible, in our case, to clearly identify which one of factors was decisive nor to quantify the relative contribution of each one, however their combination could have played a relevant role.

Most of the variation between the two years occurred during the period after the first submersion (see Section 3.2, phase *I*), whereas the average percolation rate in the remaining part of the agricultural season (phase *II*) was much more constant over the two years. Focussing just on phase *I*, the groundwater level at the beginning of the phase was shallower in 2013 than in 2012 and in this year lower water requirements were observed. The higher groundwater level was likely due to the heavy rainfall occurred in Spring 2013 that amounted to 380 mm in the months from April to May.

According to the statistical analysis presented in Section 3.2, the relatively deep groundwater level at the beginning of the irrigation season (say water table deeper than 0.5 m) was negatively correlated with the percolation fluxes, i.e. the lower the groundwater levels, the higher the percolation.

A preliminary consideration on the sign of the coefficient may suggest that the strong negative correlation between the two trends could be due to a random similarity in the trends that should not be explained in terms of causal relationship. That is to say, the groundwater raised because of the recharge from flooded fields in the area, and the percolation decreased because of soil clogging, but none of the two occurrences was related to the other. However, the Richards equation (Richards, 1931) clearly demonstrates that the water flow between two points is a function of the pressure gradient between the points and of the hydraulic conductivity, therefore the water table depth does play a fundamental role in determining vertical water fluxes in the unsaturated zone. This does not mean that soil clogging did not have an impact on the amount of water percolating, but, rather, that a causal relationship between groundwater levels and percolation can be assumed in phase *I* in addition to the effects induced by changes in the soil structure.

On the other hand, a different phenomenon occurred during phase *II* when the relationship between percolations and groundwater levels became positive, i.e. the higher the percolations, the higher the groundwater levels. During phase *II*, when the depth to the groundwater is less than 0.5 m, the cascading model appears to be more meaningful, i.e. downward water fluxes maintained a saturation of the soil profile by continuously providing a recharge to the phreatic aquifer (see the conceptual functioning of a tank model). Moreover, the shallow groundwater may trigger a lateral flux towards the drainage channel that further explain the positive correlation between the two variables. Therefore, subsurface water dynamics could have had a not negligible effects on the irrigation amounts we estimated.

Another issue involves the soil conditions. Although tillage operations were the same in both years, the pattern and intensity of rainfall events between ploughing and the first submersion was different. In this respect, intense rainfall events occurring between tillage operations and the first irrigation can lead to a greater soil compaction (Sacco et al., 2012) thus reducing the significant percolation that is generally observed in correspondence with the first flooding (see Figure 3). In our case, rainfall was higher in 2012 than in 2013 (180 mm against 113 mm), but in 2012 they were distributed over a much longer period occurred between ploughing and flooding. In 2013, soil tillage was delayed by around one month due to adverse meteorological conditions and more intense rainfall events occurred shortly before the first flooding. This could have determined some degree of soil compaction even before the effect induced by the first flooding. In addition to that, Bhagat et al. (1996) suggest that the effect of soil tillage on the soil structure is highly dependent on the soil moisture antecedent to tillage. Due to the heavy rainfall occurred in Spring 2013, tillage was performed on a wetter soil, with consequent effects on the soil structure.

Another reason for the greater irrigation amounts required in 2012 could be the presence of macrospores induced by earthworms, as suggested by some authors like Garg et al. (2009) who report on profuse earthworm casts in paddy plots especially early in the season. Although a systematic analysis on earthworm population in both years was not performed, we collected evidence of the presence of earthworms both in the experimental fields and in the surrounding (e.g. during a deep excavation 1 m deep we identified a specimen compatible with the *Criodrilus lacuum* - Hoffmeister 1845).

On the contrary, we excluded possible effects on the hydraulic conductivity of variations of the water viscosity triggered by fluctuations of the water temperature, as reported by Yukawa (1992). In our case no significant changes in water temperature were detected in the series of values recorded by all the sensors.

In light of the different explanations listed above, the irrigation requirements of rice are clearly not only determined by the water regime that is adopted (either traditional flooding or less water-demanding methods) nor only by the mere granulometry of the soil where rice is grown. Even when the very same regime is applied to the very same field, a significant inter-annual variability my occur in response to variations of environmental factors including groundwater levels, changes in the soil structure, meteorological conditions also prior to crop establishment and biotic factors.

4 CONCLUSIONS

A 2-year rice experiment was carried out in a rice growing area on Northern Italy where three different water regimes were compared, namely continuous flooding of water seeded rice (WFL), delayed flooding of dry seeded rice (DFL) and intermittent irrigation of dry seeded rice (DIR). Net irrigation water requirements of conventional flooded rice (WFL) ranged between 1,500 and 3,000 mm with a marked variability between two consequent seasons (3,020 mm in 2012 against 1,520 in 2013). DFL determined a reduction total water use compared to WFL amounting to 20% on average, while irrigation amounts applied to DIR were on average 60% less than WFL. On the other hand, WFL determined the highest average yield (10.2 t ha^{-1}), whereas reductions by 3% and 28% were observed in case of WFL and DFL respectively. Values of water use efficiencies (evapotranspiration over net water input) and water productivity (grain yield over net water input) were therefore in the order WFL < DFL < DIR. 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 intermittent 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. Moreover, an overall balance of different water regimes in rice paddies should consider various aspects not addressed in this paper e.g. the actual water availability and its cost, a balance between the cost of yield losses versus the profit for the water amount that is saved, the effects of water saving regimes on the hydrology of the area and the consequent feedbacks at both the field and the regional scale, the effects the different agronomic practises required by aerobic rice on pollutant loads in surface and subsurface water, on gas emissions, on quality of grain yields etc.

The great difference in irrigation requirements of WFL and DFL between the two seasons can be mainly attributed in variations of the percolation term, since the difference in crop evapotranspiration was within 20% against a percolation that halved from 2012 to 2013. The percolations we obtained as the residue of the water balance were investigated in relation to measurements of groundwater levels collected in six different piezometers installed across the experimental fields. Data were divided into four samples, based on the type of treatment (WFL or DFL) and on the phase of the agricultural season (distinguishing between the period of the first submersion and the remaining part of the season). Data of the years were instead treated as a unique sample. Satisfactory R-squared were obtained especially during the first period (0.90 for WFL and 0.95 for DFL), when most of the variations between the two years occurred, revealing a very good agreement between percolation fluxes and groundwater levels. The relationship between the variables is however different depending on the groundwater level, as revealed by the signs of the coefficients of regressions that are different between the two phases, yet equal between the plots. The models we obtained suggest that quite complex water movements may occur in case of the presence of layers with different permeability like the case under examination, and that the flow intensity and directions may change significantly with varying the groundwater level itself, which is lower at the beginning of the agricultural season and rises after the first flooding.

An attempt to provide explanations for the relevant changes in percolation between consequent seasons is also presented. Such differences, can be 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 hydraulic gradients; *ii)* the soil moisture antecedent to the tillage operations affecting the soil structure; *iii)* the rainfall intensity occurred between soil tillage and the first irrigation event producing an effect of soil compaction; and *iv)* the possible occurrence of preferential macropore fluxes due the activity of earthworms, particularly in the early part of the agricultural season. In conclusion, a proper comparison of different water regimes in rice fields require the adoption of integrated monitoring systems able to investigate not only punctual phenomena, but also their dynamics across space. Moreover, results obtained from just one experimental season can significantly deviate from the average behaviour due to the significant effect of year-specific occurrences on paddy irrigation requirements.

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CHAPTER 5

Water balance implications of switching from continuous submergence to flush irrigation in a rice-growing area[3]

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

[a] Department of Agricultural and Environmental Sciences (DiSAA), Universitá degli Studi di Milano, 20133 Milan, Italy
[b] Centro Ricerche sul Riso, Ente Nazionale Risi (ENR), Castello d'Agogna (PV), Italy

Abstract

Studies conducted at the field scale report significant reductions in water requirements of rice when continuous submergence (CS) is replaced by less water-demanding regimes like flush-irrigation (FI, i.e. intermittent irrigations of rice growing in aerobic conditions). The effects of their extensive application in paddy areas with shallow groundwater is however much less investigated.

The paper presents a scenario analysis investigating the impacts on irrigation requirements induced by a shift from CS to FI in an irrigation district of Northern Italy where rice is the main crop, followed by maize and poplar. The area is characterised by a shallow water table fluctuating between two meters (wintertime) and few tens of centimetres (summertime). We applied a three-stage procedure, where we first analysed present state conditions using the SWAP (Soil, Water, Atmosphere, Plant) model to simulate irrigation deliveries and percolation fluxes. Then, we calibrated an empirical relationship between estimated percolation fluxes and measured groundwater levels. Finally, we applied this relationship, in combination with the SWAP model, to predict the variation of district irrigation requirements due to a widespread shift from CS to FI.

Results show that neglecting the feedbacks between irrigation and groundwater depth led to overestimating the reduction of irrigation requirements, which decreased from around 65% when no feedback is considered to around 40% when accounting for feedbacks between groundwater levels and groundwater recharge. Moreover, changes in the irrigation method of rice could determine higher irrigation requirements of maize because of decreased groundwater levels. The study underlines the importance of specifically addressing the role of field irrigation management on hydrological processes at larger scales.

Keywords: Paddy; Water saving techniques; Shallow groundwater; Irrigation district; SWAP model; Scenario analysis

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[3] Agricultural Water Management (under review)

1 INTRODUCTION

Water saving technologies in rice production have received more and more attention in the last couple of decades because of their potential to reduce the high water requirements of rice farming, which are estimated to be around 40% of the total irrigation water (Bouman et al., 2007b). Although water saving technologies usually represent a way to cope with water scarcity rather than a deliberate choice of farmers to save water (Bouman et al., 2007b), an increased interest towards these methods is assessed even in some rice-growing areas where water shortages is not an issue of major concern. Among water saving techniques, flush irrigation, i.e. rice irrigated just like an upland crop such as wheat or maize, has been tested in different environments (e.g. Belder et al., 2007; Bouman et al., 2005; Bouman et al., 2007; Feng et al., 2007; Govindarajan et al., 2008; Kato et al., 2009; Tabbal et al., 2002; Xue et al., 2008). Various authors report that flush irrigation (FI) of aerobic rice may determine a reduction of water inputs by up to 60% compared to continuous submergence (CS), with a yield loss of 10-30% (Borrell et al., 1997; Bouman et al., 2005; Tabbal et al., 2002). However, most research on alternative irrigation techniques so far has been limited to individual field experiments and there is still the need to assess and quantify the nature of the savings when replacing continuous flooding with less water-demanding irrigation regimes, especially with respect to large-scale and long- term effects (see, e.g., Guerra et al., 1998; Humphreys et al., 2005). One issue, in particular, refers to the role of the feedback effects on rice irrigation requirement due to the likely increase of groundwater depth when a large-scale shift from CS to FI takes place. Indeed, Belder et al. (2005) and Cabangon et al. (2004) observed that groundwater table depths remained very shallow in various field experiments, while it can be expected that the large-scale adoption of FI or of similar techniques will lead to an increase of the groundwater table depth due to reduced recharge (Belder et al., 2004; Mishra et al., 1990). This, in turn, will increase percolation and limit the root uptake from the groundwater, affecting the actual magnitude of the water savings (Belder et al., 2007; Tabbal et al., 2002).

Italy is the leading rice producer of the European Union with around 235,000 ha amounting to 52% of the rice areas located in Europe (ENR, 2013). Around 92% of this surface is found in the Western Po Valley (ENR, 2013), where rice has been traditionally grown in bunded fields, that are kept flooded from April to September. The traditional agricultural practice consists of broadcasting pre-germinated seeds over submerged levelled fields and then maintaining a ponded water depth of about ten centimetres for almost the whole growing season. Currently, the seasonal irrigation depth averages approximately 3,000 mm (INEA, 2013), but it is quite variable in the area depending on soil characteristics and groundwater depth. The long-term persistence of a traditional rice cropping system in the vast majority of the area has 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). Moreover, the continuous submergence practice is a key factor in the recharge of the phreatic aquifer, which is very shallow over most of the area and feeds a huge number of semi-natural springs, called “fontanili”, that form a longitudinal strip of groundwater dependent ecosystems across the area. The increasing competition among water users is pushing towards the adoption of water saving techniques also in this area. The practice of dry-seeding and delayed flooding has been increasing during the last decade, and, more recently, the interest for the FI technique has grown significantly in view of its potential to reduce rice irrigation requirements and, ultimately, to diminish the pressure due to agricultural water diversions on the riverine environments, in order to achieve the objectives of the EU Water Framework Directive (2000/60/EC).

In this paper, we present a pilot study on the impacts of the shift from CS to FI technique for rice irrigation in an agricultural district with shallow groundwater table, accounting for the feedbacks between water amounts applied for irrigation and fluctuations of groundwater depth. The district has mixed land use (rice in combination with maize and poplar) and is located in Northern Italy, within the largest traditional rice growing area in the European Union. We applied a three-stage procedure based on a simplified representation of the complex, distributed interactions between the water dynamics in the unsaturated zone and in the groundwater. We first used the SWAP model (Kroes and van Dam, 2003) to simulate the different soil-crop systems, deriving an estimate of the average percolation fluxes per unit area (Stage 1). Then, we calibrated an empirical relationship between the estimated percolation fluxes and the corresponding observations of groundwater depth (Stage 2). Finally, we used this relationship in combination with the SWAP model for a scenario analysis to study the effects of the shift from CS to FI on the district irrigation requirements of rice and of the other crops (Stage 3). We compared the results obtained with both a static groundwater level (i.e. invariant with respect to the present state) and with a dynamic one (i.e. groundwater level changes according to smaller recharge occurring under the scenario land use)

2 MATERIAL AND METHODS

2.1 Pilot study area

The study area is the San Giorgio East district, which is located at the centre of a large rice area about 45 km southwest of the city of Milan, Northern Italy (see Figure 1).

The study area is bounded to the West and East by two small streams, Arbogna and Terdoppio, respectively (see Figure 1) and is characterised by nearly homogeneous soils and an average slope around 1‰. The main soil type is Argic Udipsamments mixed mesic (ERSAL, 1996; USDA, 1975), with a high percentage of sand (see Table 2). According to the ROSETTA pedo-transfer functions (Schaap et al., 2001), the saturated hydraulic conductivities of this soil range from 170 cm d-1 in the Apg horizon, to 550 cm d-1 in the deeper horizon. It is a highly draining soil for CS rice cultivation; however, favourable conditions are created by the shallow groundwater depth, with summer minimums of less than one meter and winter maximums within two meters.

The local climate is humid subtropical (Cfa) according to the Köppen climate classification (Köppen 1936), with average temperature of 20°C and cumulated rainfall depth of about 360 mm during the agricultural season (April-September, average over the period 1993-2013).

Land use includes rice, maize and poplar (see Table 1). Rice surface has been steadily decreasing in the last years, from 50% of the total district surface in 2010 to less than 30% in 2013, mostly due to an increase of maize that was enhanced by the construction of a biogas plant nearby.

Irrigation supply is provided by two canals, the S.Giorgio and Daglio canals, which are managed by the Associazione Irrigazione Est Sesia (AIES), one of the most important irrigation associations in the EU, distributing 260 m3s-1 for irrigation over an area of more than 200,000 ha. Both the irrigation canals are fed by surface water diversions. CS is adopted for rice irrigation, while border irrigation is used for maize, with water deliveries on rotation of 15 days. The same method and rotation interval are used also for poplars, which, however, are irrigated only during the first four years after plantation, while they are rainfed for the subsequent six years of the average production cycle.

Monitoring data were obtained from AIES and from ARPA Lombardia (the Regional Environmental Protection Agency). AIES provided daily values of the water flow in the two irrigation canals and bi-weekly values of the groundwater level below the soil surface at two piezometers, one located in Ottobiano, close to the southern border of the district and the other at Cascina Stella, N-E from the district (see Figure 1).

The hourly values of the agro-meteorological variables (temperature, precipitation, wind speed, solar radiation and relative humidity) were acquired from the closest ARPA station, located in Castello d'Agogna, less than 10 km N-W from district centre.

Site-specific information on crop biometrical variables (including the typical evolution of crop height, root depth, Leaf Area Index), crop coefficients, and stomatal resistance were derived from a collateral activity that we carried out on experimental rice plots during the years 2012 and 2013 (Chiaradia et al., 2015; Facchi et al., 2013a; BioGesteca, 2014).

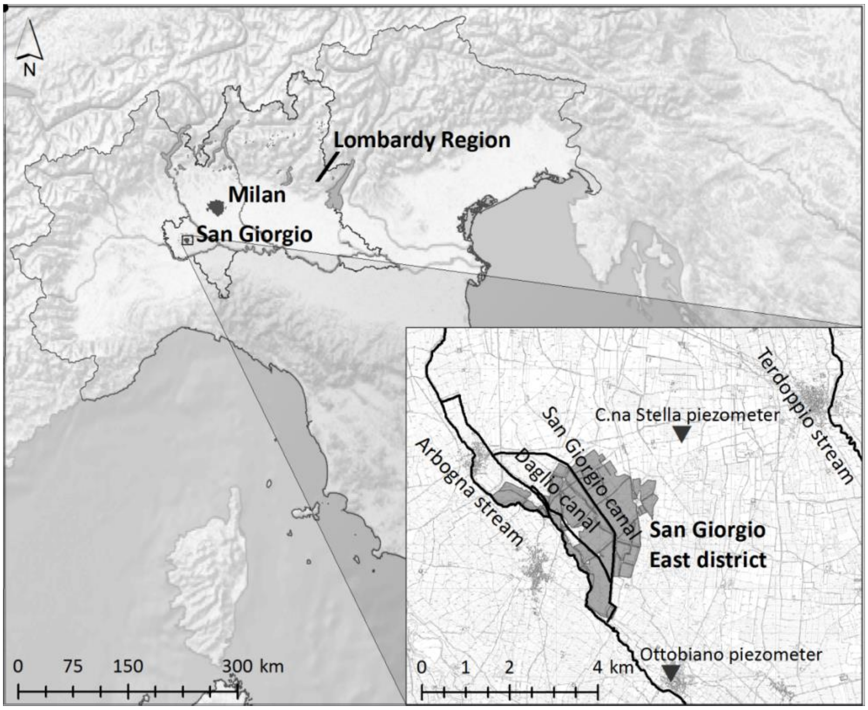

Figure 1 – Pilot study area of the San Giorgio East district (Italy) with location of the main streams and piezometers

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 Methodological framework

In order to assess the effects of the shift from CS to FI on the district irrigation requirements of the S.Giorgio-E district, we implemented a multi-stage approach making use of either physically-based or empirical models and water balance equations.

Stage 1 (Section 2.3) involved a preliminary phase of data collection and, later, the analysis of the water use in the district. To this purpose, we collected continuous measurements of total irrigation supply to the district, of agrometeorological variables, and of groundwater table depths over four years (2010-2013). Thanks to these data, we applied the SWAP model (Kroes and van Dam, 2003), in order to simulate the water dynamics in the maize, poplar and bare areas and to estimate the amount of irrigation water provided to the irrigated crops (Section 2.3.1). Results of the simulations have been aggregated to derive the total percolation from these areas and estimate the share of the total district irrigation that is needed to satisfy maize and poplars water requirements. It was then possible to obtain the irrigation supply to CS rice, as the residual of the district irrigation (given by the measurements) minus the irrigation provided to maize and poplar (obtained through SWAP). As last step of Stage 1, we applied the field water balance equation for the CS rice, in combination with a Penmann-Monteith type model of evapotranspiration fluxes, to estimate the amount of water percolating from flooded fields and thus the contribution of rice area to the district percolation (Section 2.3.2).

In Stage 2 (Section 2.4), we computed the total value of the district net percolation flux (percolation minus the upward water flux 1 m below the soil surface) on a monthly basis over the four year 2010-2013; we derived the average monthly values of groundwater levels from bi-weekly measurements at the Ottobiano piezometer; and then we calibrated an empirical relationship between the estimated net percolation fluxes (PF) and the groundwater level (GWL). In the following, we will refer to this empirical model as PF-GWL relationship.

In Stage 3 (Section 2.5), we analysed the effects of a large-scale transition from CS to FI water management on the reduction of irrigation deliveries. Two different scenarios have been considered: the former assuming that the depth to the groundwater does not change from the present condition, the latter accounting for the fluctuations of groundwater depth triggered by the significant change of the water management in rice areas. The two cases are referred to as ‘No feedback’, ‘NF’ (Section 2.5.1), and ‘Feedback Accounting’, ‘FA’ (Section 2.5.2), depending on whether the feedback between the amount of water applied for irrigation and the fluctuations of groundwater depth are considered or not. SWAP model simulations were used to investigate both the scenarios. FA scenario, however, required the further application of the PF-GWL relationship in order to identify the target groundwater when CS is replaced by FI.

2.3 Analysis of the present state

2.3.1 Maize, poplar and bare areas

The water balance analysis of maize, poplar and bare areas was performed via model simulation by applying the Soil Water Atmosphere Plant (SWAP) model (Kroes and van Dam, 2003) over the years 2010-2013. SWAP is a well-known physically-based agro-hydrological model that implements a finite difference solution of the Richards’ equation:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta)\left(\frac{\partial h}{\partial z} - 1\right)\right) - S(h) \qquad (1)$$

where θ is the soil water content [-], h is the soil water potential [L], C is the water capacity [L^{-1}], t is time [T], z is the vertical coordinate taken positive in the upward direction [L], K is the unsaturated hydraulic conductivity [LT^{-1}] and S is the sink term [T^{-1}] representing the water extraction by roots and evaporation from the surface soil layer. The water retention curve and the hydraulic conductivity curve are defined through the analytical functions of Van Genuchten (1980) and Mualem (1986).

Weather data used for the simulations were provided by the hourly values of the agrometeorological variables registered in the Castello d'Agogna weather station.

Soil characteristics in the S. Giorgio district are quite homogeneous (ERSAL, 1996), so we assumed that the same profile is representative of the whole district area. The hydraulic parameterization of the profile is reported in Table 3. We obtained the values of the hydraulic parameters of each horizon using the ROSETTA pedo-transfer functions (Schaap et al., 2001) with a soil bulk density estimated according to Baumer (1990). For the numerical solution of the Richards' equation, the profile was discretized into 1 cm-compartments up to 60 cm and into 5 cm-compartments up to 230 cm.

The measured bi-weekly values of groundwater depth recorded at the Ottobiano piezometer were used to derive, by linear interpolation, the daily values that served to set bottom boundary conditions of the SWAP simulations. Measurements taken at Ottobiano instead of those collected in Cascina Stella were used as they were found to be more representative of the groundwater level of the district as explained in Section 2.4.

With respect to crop development, SWAP includes two modules of different complexity for the simulation of crop behaviour: a detailed crop growth simulation model WOFOST 6.0 (Spitters et al., 1989; Hijmans et al., 1994) and a simple crop module, where the time patterns of Leaf Area Index or Soil Cover Fraction, crop height and rooting depth must be provided as input data. Since the former module needs input of many parameters that could not be calibrated due to lack of information, we chose to adopt the simple crop module in the simulation runs. The crop module of maize was parameterized using time patterns of crop variables derived from field observations under similar conditions, while a fixed parameterization from the literature was used for poplar. As regards maize, sowing and harvesting dates, as well as seasonal patterns of biometric parameters, were estimated according to a model based on the temperature sum of each year (Stockle and Nelson, 1996; Gandolfi et al., 2010) with reference values of LAI, crop height and rooting depth that are representative of the Italian environment (Facchi et al., 2013b; Rienzner et al., 2013). This approach enabled to simulate development stages whose lengths are consistent with the thermic conditions of the year and a crop growth that is in agreement with field observations. On the other hand, since little site-specific information was available for poplar, we adopted the generic deciduous forest parameterization suggested by Kroes at al. (2008) (crop file provided with SWAP version 3.2.36), but we modified the pressure heads regulating root water uptake (model of Feddes et al., 1978) according to the specific values for poplars found in Lv et al. (2014). Moreover, the values of specific parameters of young poplars, such as Leaf Area Index, were adapted to account for the smaller crop development. A summary of the crop parameterization adopted for each crop is reported is Table 4.

Mature poplar was treated as rainfed only, while the simulation of the irrigation applications to maize and young poplar was obtained using the irrigation scheduling option of SWAP. We set the timing of irrigation availability and of irrigation depth according to the information provided by AIES i.e. water available on a 15-days turn and amounts of approximately 150 mm to maize and 210 mm to young poplars. In addition, AIES provided information on the number of irrigation supplies to both the crops, which are within a range of 4 to 6 for maize and 1 to 3 for poplars depending on the precipitation pattern. In fact, farmers will probably skip the irrigation in case of high soil moisture after heavy rainfalls. In order to mimic this behaviour, we identified a pair ‘moisture threshold-soil depth’ that triggered a number of irrigation events per season within the ranges stated by AIES. Once the threshold has been identified, we verified that no significant transpirative stress occurred since AIES declared that crop water requirements are substantially satisfied under the current irrigation management.

Table 2 Profile characteristics of the main agricultural soil type in the San Giorgio East district

Horizons*	Soil depth cm	Coarse Sand %	Medium Sand %	Fine Sand %	Corse Silt %	Fine Silt %	Clay %	Organic Carbon %
Apg	0-35	61.3	14.2	10.7	4.3	6.4	2.9	0.80
Bw1	40-50	69.4	15.9	4.2	2.5	2.5	5.6	0.20
Bw2	50-80	75.5	12.9	4.5	0.9	1.3	4.9	0.10
E&Bt	80-230	62.9	28.8	3.8	0.4	0.9	3.2	0.00

**Classification according to USDA (1975)*

Table 3 - Soil hydraulic parameters of the SWAP simulations

Layer	Soil depth (cm)	Field capacity* (cm^3 cm^{-3})	Saturated water content^a (cm^3 cm^{-3})	Residual water content^a (cm^3 cm^{-3})	Van Genuchten-a^a (cm^{-1})	Van Genuchten-n^a (-)	Hydraulic Conductivity^b (cm^3 d^{-1})	Mualem-l^b -
1	0-35	0.13	0.34	0.04	0.041	2.2447	168.9	0.5
2	35-50	0.15	0.34	0.05	0.035	2.3489	197.6	0.5
3	50-80	0.13	0.34	0.05	0.032	2.7794	345.3	0.5
4	80-230	0.12	0.34	0.05	0.031	3.2667	550.5	0.5

** 60 hPa*

[a] parameter of the analytical function of Van Genuchten (1980)

[b] parameter of the analytical function of Mualem (1986)

SWAP simulations provided the scheduling of the irrigation applications, the hourly values of evapotranspiration, and the water fluxes along the profile for all the land uses (maize, young and mature poplar and bare soil). These results are representative of the behaviour of a typical maize or poplar field in the district, but there are obviously variations from field to field due to a number of management factors (scheduling of agricultural operations, water availability on rotation, etc.). However, these differences tend to be filtered out when longer time intervals are considered. Therefore, while a lumped representation of the whole maize or poplar area is inadequate for intervals of hours or days, it becomes acceptable for longer intervals. In our case, we selected a monthly time interval, considering that it is long enough to homogenize the variability of the management factors, but still sufficiently detailed to capture the seasonal fluctuations of the groundwater level and their influence on the soil water dynamics.

2.3.2 Rice areas

The application of physically based models, like SWAP, simulate soil water dynamics in continuously submerged conditions is more difficult than in the case of upland crops, due to the constantly saturated soil profile, the significant role of horizontal components of the flow, and the high influence of the variability of soil characteristics, both natural and induced by agricultural practices. Considering these difficulties and that the objective of our study was the analysis of the seasonal patterns of the rice irrigation volumes and of the net percolation flux, we adopted a different approach, based on the direct application of the monthly water balance equation for a unit of CS rice surface:

$$i_{r,t} + r_t - p_{r,t} - e_{r,t} = \Delta s_{r,t} + \Delta f_{r,t} \qquad (2)$$

in combination with the monthly water balance equation of the irrigation canals network:

$$Q_{i,t} = Q_{o,t} + P_{c,t} + i_{r,t}A_{r,t} + i_{m,t}A_{m,t} + i_{y,t}A_{y,t} + \Delta C_t \qquad (3)$$

The variables in Equations (2) and (3) have the following meaning:
$i_{r,t}$ is the irrigation depth applied [L^3L^{-2}];
r_t is the rainfall depth [L^3L^{-2}];
$p_{r,t}$ is the net percolation depth [L^3L^{-2}];
$e_{r,t}$ is the evapotranspiration depth [L^3L^{-2}];
$\Delta s_{r,t}$ is the specific storage variation in the rooted soil layer [L^3L^{-2}];
$\Delta f_{r,t}$ is the variation of the flooding depth [L^3L^{-2}].
$Q_{i,t}$ is the total inflow to the district through the S.Giorgio and Daglio canals [L^3];
$Q_{o,t}$ is the total surface outflow from the district [L^3];
$P_{c,t}$ is the seepage flux from the canals [L^3];
ΔC_t is storage variation in the canals [L^3];
$A_{r,t}$, $A_{m,t}$, $A_{y,t}$ and $A_{p,t}$ are the surfaces of the rice, maize, young poplar and mature poplar areas, respectively [L^2] (see Table 1).

We used the two equations in cascade: first we solved Equation (3) for the rice irrigation $i_{r,t}$ and then we used the $i_{r,t}$ values to compute the rice percolation $p_{r,t}$ through Equation (2). We derived the values of $i_{m,t}$ and $i_{y,t}$ in Equation (3) directly from the SWAP simulations, as illustrated in the previous section. The inflow Q_i was obtained from the measured daily values of the flowrate in the two canals feeding the district, that were available for the four-year period 2010-2013. According to AIES, approximately one third of $Q_{i,t}$ is lost through seepage from the canal network, due to the high permeability of the soils. Therefore $P_{c,t}$ was assumed equal to 30% of the surface inflow $Q_{i,t}$. Surface outflows $Q_{o,t}$ during the agricultural season are, on the contrary, very small compared to the inflows Q_i, occurring only after significant rainfall events. Following again the indications of AIES, we estimated a value of $Q_{o,t}$ of 5% of the distributed irrigation amount (i.e. of the total supply $Q_{i,t}$ minus the seepage losses $P_{c,t}$) during the irrigation season, while, in the remaining months, we assumed that it consisted of the whole inflow except for the percolation losses, since no distribution takes place, i.e. we considered $Q_{o,t}$ equal to the difference between $Q_{i,t}$ and $P_{c,t}$. Finally, we assumed that the last term in Equation (3), namely the storage variation ΔC_t, is negligible compared to the other terms, considering that water circulation in the canal network is maintained throughout the year and the actual free storage capacity is relatively small.

Going back to the solution of Equation (2), we derived the rainfall depths rt directly from the registrations at the Castello d'Agogna meteorological station (assuming a uniform distribution over the district area).

The evapotranspiration term er,t was derived from the daily estimates obtained with the FAO-Penman-Monteith method (Allen et al., 1998). Reference evapotranspiration (ET0) was computed using the meteorological data registered at the Castello d'Agogna station. Site-specific values of the crop coefficients (Kc-ini, Kc-mid, Kc-end; see Allen et al., 1998) for flooded rice were derived from an intensive 2-years experimental activity (2012 and 2013) carried out in a site close to the San Giorgio-E district (Chiaradia et al., 2015; BioGesteca, 2014), where the daily values of rice evapotranspiration in well-watered conditions, ETc, were obtained by integrating eddy-covariance flux measurements and Penman-Monteith type models, as reported in Facchi et al. (2013a). Kc-ini, Kc-mid, Kc-end values were then derived as the ratio of ETc and ET0 in the different development stages and they were equal to 0.8, 1.1 and 0.9 respectively. The Kc curve for the four years of the study were built using these values in combination with a growing a degree days model to simulate the length of the stages in each year.

The storage variations $\Delta_{s,t}$ and $\Delta_{f,t}$ were considered negligible, except in May and September. In May, $\Delta_{f,t}$ was assumed equal to the average depth of submergence (100 mm) and $\Delta_{s,t}$ to the incremental water amount to reach the saturation of the soil profile from the condition prior to submergence. Soil water content prior to submergence was estimated by running a SWAP simulation for bare soil conditions. In September, $\Delta_{f,t}$ was assumed equal to minus the depth of submergence and $\Delta_{s,t}$ to half of the saturated soil water content.

Lateral-flow components are not included in Equation (2) since their contribution to the total water balance is not supposed to be relevant due to the flat topography of the area (average slope in the district around 1‰).

2.4 Calibration of an empirical relationship between percolation fluxes and groundwater levels

The hypothesis behind this stage of the procedure is that the seasonal fluctuations of the groundwater depth observed in the San Giorgio-E district were mostly driven by the recharge due to rain and irrigation. We primarily focussed on the seasonal fluctuations of groundwater depth caused by the superposition of fluxes deriving from percolation of irrigation water to the natural groundwater recharge, since the scope of our analysis was not to capture the short-term fluctuations of the groundwater depth due to single irrigation or rainfall events.

Groundwater dynamics in the district are also influenced by source and sink terms acting at larger spatial scales and not only by the direct recharge from the district. However, the area included between the Agogna and Terdoppio streams, which represent natural boundaries of the underlying phreatic aquifer, is quite homogeneous in terms of land use and irrigation management, hence the seasonal pattern of groundwater fluctuations is expected to be significantly uniform in space. This is also confirmed by the analysis of the observations at the Ottobiano piezometer and at a second piezometer, at Cascina Stella (correlation coefficient 0.86). In fact, the two series of measurements show very similar fluctuations (not shown), though the absolute values of groundwater depth are different due to the higher elevation of Cascina Stella compared to the rest of the area. Since the conditions in Ottobiano are more similar to the ones of the S. Giorgio-E district in terms of ground elevation and soil characteristics, we assumed that the monthly averages of groundwater depths taken in Ottobiano are representative for the whole district area.

Following the same rationale, we assumed that the average monthly net percolation flux from the S. Giorgio-E district, $p_{s,t}$, is representative of the large-scale pattern of the recharge to the aquifer. So we computed its value for the years 2010-2013 considering the net percolation fluxes for the different crops and the channel seepage flux according to equation (4):

$$p_{s,t} = (p_{r,t}A_{r,t} + p_{m,t}A_{m,t} + p_{y,t}A_{y,t} + p_{b,t}A_{b,t} + P_{c,t}) / A \qquad (4)$$

where $p_{r,t}$, $p_{m,t}$, $p_{y,t}$, $p_{p,t}$ and $p_{b,t}$ are the percolations from rice, maize, young poplars, mature poplars and bare soil respectively [L^3L^{-2}]; $A_{r,t}$, $A_{m,t}$, $A_{y,t}$, $A_{p,t}$ and $A_{b,t}$ are the corresponding areas [L^2]; $P_{c,t}$ is the seepage flux from the canals [L^3] and A [L^2] is the district surface.

Then, we used non-linear regression analysis techniques to calibrate an empirical relationship between the monthly series of net percolation flux and of reference groundwater level (PF-GWL relationship) that can be expressed in the quadratic form:

$$GWL_t = \alpha \cdot p_{s,t}^2 + \beta \cdot p_{s,t} + \gamma \qquad (5)$$

where the first two terms at the right hand-side account for the effect of recharge fluxes, while the third one reflects the background value of groundwater depth, mainly determined by the water levels in the Terdoppio and Agogna streams that represent the aquifer boundaries. The α, β and γ parameters were least-squares calibrated using the first three years of available data (2010-2012) and validated with data of year 2013. The goodness of the fitting was checked using traditional statistical indicators (correlation coefficient and Nash-Sutcliffe coefficient); the calibrated curve is presented in Section 3.2.

2.5 Prediction of the effects of the FI technique

The shift from CS to FI technique may involve a significant reduction of the flows needed for rice irrigation, which in turn may produce a decrease of the percolation fluxes and of the recharge to the groundwater. This is expected to lead to a decrease of the groundwater level and, consequently, to smaller amounts of water retained in the rooted soil layer and, thus, to some increase in the irrigation (i.e. a feedback effect). Therefore, it is necessary to account for the feedback between irrigation and groundwater depth when the effects of the FI adoption are to be investigated on a large scale.

In Stage 3 of our procedure, we first analysed the effects of the shift from CS to FI neglecting these feedbacks (No Feedback scenario or NF scenario). Then, we repeated the same analysis applying an enumerative algorithm that explores a set of different groundwater depth patterns in order to find the one that best accounts for the feedback between irrigation and groundwater triggered by the shift from the CS to the FI (Feedback Accounting scenario–FA scenario).

In either of the two cases, the district percolation was computed by applying Equation (4) with the monthly series of percolations obtained by the SWAP simulations for each land use. The computation of the seepage flux from the canal, $P_{c,t}$ in equation (4) was less straightforward than in the present state since $P_{c,t}$ is a share of the total inflow to the district $Q_{i,t}$ which is unknown under the scenario. $P_{c,t}$ was then obtained as the 30% of the gross amount of water required by the district that, in turn, was computed from the net irrigations to the other crops (i.e. $i_{r,t}$, $i_{m,t}$ and $i_{y,t}$) increased to account for both the seepage flux from canals and surface outflows.

2.5.1 No feedback scenario (NF)

No-Feedback scenario represents a picture of reductions in irrigation deliveries if all the CS rice area is replaced by FI rice and no changes in groundwater levels are accounted for. Therefore, it provides estimates of the reductions in water withdrawals that would be obtained if results of field-scale experiments with a shallow water table are blindly extended to the district scale.

The SWAP model was run with input of the same meteorological data (years 2010 to 2013) and bottom boundary conditions (monthly measures of groundwater level) used for the present state. Maize, young and poplar areas were therefore treated as discussed in Section 3.3.1. We applied the same modelling scheme also to simulate FI rice that can be considered as the other upland crops. Hence, we used the same soil parameterization, bottom boundary conditions and meteorological input data for the years 2010-2013 to run a SWAP simulation of FI rice. The time patterns of Leaf Area Index, crop height and rooting depth were derived from a two-year monitoring activity of FI rice that we conducted nearby the San Giorgio-E district over years 2012 and 2013 (Table 4). In this framework, several campaigns per season were conducted making use of a A LP-80 AccuPAR Ceptometer for measurements of Leaf Area Index and a measuring tape for crop height and rooting depth. Details on the research can be found in Chiaradia et al. (2015); Cesari de Maria et al. (submitted); BioGesteca (2014). Starting from these reference values, the time pattern of crop development was obtained applying the same approach based the thermic sum we explained in Section 2.3.1. Like for maize and young poplar, we assumed that the rice fields are flushed intermittently, with a fixed irrigation depth of 150 cm, but with water applications scheduled on demand for two main reasons: *i*) because water delivery to rice farmers is currently no-stop due to the practice of continuous submergence, *ii*) in order to provide estimates of irrigation requirements to FI rice that are not constrained by any rotational scheme. Finally, we selected as the criterion to trigger irrigation applications for FI rice, the maximum allowed daily stress which requires input of a threshold value given by the ratio between actual and potential transpiration (e.g. with a threshold value of 0.90, the model schedules an irrigation each time the actual transpiration drops below 90% of the potential one).

Table 4 - Crop parameters in input to the simple crop module of SWAP.

	Present State and Scenario			**Scenario**
	Maize	Young Poplar	Mature Poplar	Aerobic Rice
Crop				
LAI max (m^2 m^{-2})	5.20 [c, h]	2.00 [f]	4.00 [e]	4.70 [b]
Root depth max (m)	0.85 [c, h]	1.00 [e]	1.00 [e]	0.40 [b]
Minimum canopy resistance (s m^{-1})	70 [a]	150 [e]	150 [e]	66 [b]
Critical pressure heads for root water uptake (hPa)*				
h_1	-10 [a]	0 [g]	0 [g]	100 [i]
h_2	-40 [a]	0 [g]	0 [g]	55 [i]
h_{3h}	-325 [a]	-330 [g]	-330 [g]	-160 [i]
h_{3l}	-600 [a]	-2000 [g]	-2000 [g]	-250 [i]
h_4	-8,000 [a]	-15,000 [g]	-15,000 [g]	-16,000 [i]
Irrigation Scheduling				
Timing	Fixed interval	Fixed interval	-	On demand
Irrigation depth (mm)	150	210	-	150
Scheduling criteria	Moisture content	Moisture content	-	Daily stress

** h_1: pressure head below which roots start to extract water from the soil; h_2: pressure head below which roots extract water at the maximum possible rate; h_{3h}: pressure head below which roots can no longer extract water at the maximum rate for higher potential transpiration rates; h_{3l} pressure head below which roots can no longer extract water at the maximum rate for lower potential transpiration rates; h_4: pressure head below which root water uptake ceases.*

[a] Baroni et al. (2010); [b] BioGesteca, 2014; [c] Facchi et al. (2013b), [d] Feddes et al. 1978; [e] Kroes et al. (2008); [f] Kroes et al. (2008) [modified]; [g] Lv et al. (2014); [h] Rienzner et al (2013); [i] Singh et al. (2006);.

2.5.2 Feedback accounting scenarios (FA-15 and FA-10)

In order to account for the feedback between irrigation and groundwater depth, we implemented an enumerative algorithm, whose flowchart is shown in Figure 2. The algorithm is based on two assumptions: *i)* the changes of percolation during the agricultural season due the shift from the CS to FI technique may alter the amplitude of the seasonal groundwater fluctuation but do not modify significantly its shape; *ii)* the effects of the same changes will gradually fade after the end of the irrigation period and they will not influence the minimum value of groundwater depth, occurring in the fallow season.

The rationale of the algorithm and the steps for its implementations are explained in the following. The groundwater depth of the district can be expressed as a function of the groundwater recharge, which, in summertime, depends mainly on the amount of water used for irrigation purposes. Therefore, if it is possible to identify an empirical model describing the relationship between the two variables in the present state, then the model is supposed to hold also under scenario land use, where a “new equilibrium” between groundwater depth and groundwater recharge is expected. It follows that the calibrated empirical relationship can be used to foresee the groundwater level resulting from a specific groundwater recharge (i.e. district percolation). The district percolation is however dependent on the groundwater level itself, which is unknown. To overcome this cross feedback, we generated N patterns of 12 monthly groundwater levels (where N = 16) with summer maximums ranging from –0.50 m (very shallow GWL for N = 1) to –2.00 m (relatively deep GWL for N = 16) and the remaining (N-2) patterns with summer maximums in between these two extremes. On the other hand, the winter minimum was fixed at -2.00 m for all the N patterns, corresponding to the average winter minimum over the years 2010-2013. The 16 sets were obtained by applying equation (6) to the monthly average data recorded at Ottobiano over the years 2010-2013.

$$v_{i,j} = \overline{d_2} + (v_{i,8} - \overline{d_2}) \frac{\overline{d_j} - \overline{d_2}}{\overline{d_8} - \overline{d_2}} \quad \textit{with} \quad v_{i,8} = -2.0 + 0.1(i-1) \qquad (6)$$

where

i=1, 16 is the variant index;

j=1, 12 is the month index (from January to December);

$v_{i,j}$ is the average value of groundwater depth (m) of variant i in the month j;

$\bar{d}_j$ is the average observed value of groundwater depth (m) in month j at Ottobiano (subscript 2 for February and 8 for August).

We will refer to the N patterns of groundwater levels computed according to Equation (6) as the *a priori* variants. These 16 patterns were used as bottom conditions to run as many simulations for each land use of the scenario (i.e. FI rice, maize, young poplar, mature poplar and bare soil). The same simulation period going from 2010 to 2013 was considered.

For each of N *a priori* variants, we obtained the series of irrigation requirements ($i_{r,t}$, $i_{m,t}$,, $i_{y,t}$) that are scheduled by SWAP taking into consideration that specific groundwater level set as bottom boundary condition. The simulations provided also the monthly specific net percolations $p_{r,t}$, $p_{m,t}$, $p_{y,t}$, $p_{p,t}$, and $p_{b,t}$, which were used to compute N series of district percolation $p_{s,t}$ through the application of Equation (4) (where N is still equal to 16).

Next step was the application of the PF-GWL relationship (Equation (5)) with input of the N series of $p_{s,t}$ in order to obtain as many patterns of groundwater levels according to the PF-GWL relationship. These N patterns of groundwater levels will be referred to as *a posteriori* variants. The simulation better accounting for the scenario is the one where the *a priori* pattern (in input to SWAP) is as close as possible to the *a posteriori* pattern (from the PF-GWL relationship with input of district percolation obtained aggregating results from SWAP). In other words, when the *a priori* and the *a posteriori* groundwater levels fit, it means that this specific pattern of groundwater levels determines water requirements that, in turn, generate percolation fluxes maintaining that very same levels used in input. In order to identify the best fit between the *a priori* and *a posteriori* series, we select the pair with the smallest distance between the two summer maximum levels. An overview of the enumerative algorithm is reported in Figure 2.

Two different study cases with respect to FA scenario were considered that differ in the rotational irrigation of maize. In the former (Feedback Accounting–15, FA-15), the interval between two subsequent irrigation of maize was equal to 15 days like in the present state, whereas in the latter (Feedback Accounting–10, FA–10) the interval was shortened to 10 days.

FA-10 was introduced since quite a significant stress, especially in the month of July, appeared to occur under FA-15.

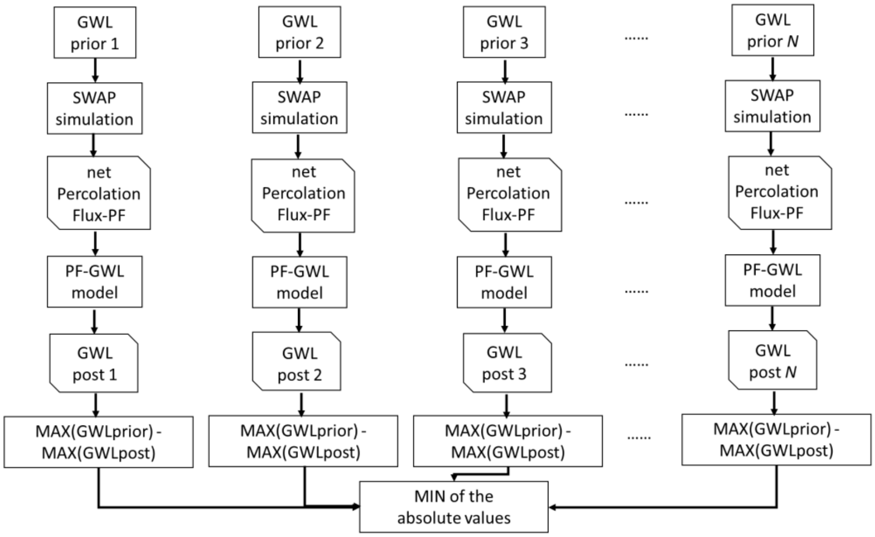

Figure 2 - Scheme of the enumerative algorithm used to select the best groundwater level (GWL) variant for the simulation of the different crops in each year

3 RESULTS AND DISCUSSION

3.1 Analysis of the present state

3.1.1 SWAP simulations for maize and poplar areas

Results from SWAP simulations provided the irrigation water requirements of maize and young poplars, as well as all the other water balance terms of maize, poplar and fallow areas over the agricultural seasons 2010-2013.

To obtain a number of irrigation events consistent with the criteria explained in Section 2.3.1, we manually calibrated the pair “soil moisture-soil depth” triggering the application of water, which is allowed only every 15 days. The best combination was found to be a soil water content of 0.13 $cm^3 cm^{-3}$ at the depth of 10 cm, which corresponds to the soil moisture at field capacity given the high percentage of sand (more than 70%, see Table 2). The threshold identified therefore suggests that the irrigation is applied even at high soil water contents, in order to avoid the risk of incurring in water stress conditions during the 15 days passing before the next turn. The same criterion was adopted for poplar, but with a rotation of 30 days in order to reproduce an average number of 2-3 irrigations per season that AIES indicated as the mean values per season. The calibrated threshold determined 5 irrigation events to maize in all years but 2010, when favourable amounts and distribution of rainfall during the irrigation season significantly reduced the number of irrigations to 3 per season. Such results are in agreement with the average number of irrigations in the area (AIES, personal communication) and enabled to prevent significant water stresses as shown by the transpirative ratio of the month of July which was on average higher than 0.85. As regards young poplars, 3 irrigation applications were scheduled in each season for 2011 to 2013, while again a smaller number amounting to 2 was needed in 2010 because of the particular weather conditions.

Table 5 reports the main water budget components for a unit surface of maize, young poplar and mature poplar, cumulated over the months May to August corresponding to the irrigation season. The average water use (irrigation plus rainfall) of maize over the period 2010-2013 was around 900 mm, of which 35% was provided by rainfall and the remaining part was supplied through border irrigations of 150 mm each on a 15-days turn. Quite significant variations however occurred in 2010 (as mentioned above), when heavy rainfalls during the irrigation period made the irrigation requirements drop to 450 mm (443 mm of rainfall against an average of 180 mm over the same period in the years 2011-2013). Instead, actual evapotranspiration is rather constant, being around 460 mm (±53 mm) against a potential evapotranspiration of 646 mm (±54).

Table 5 - Present state: main water budget components for a surface unit of maize, continuously submerged rice, young poplar and mature poplar for the years 2010 to 2013 (values are cumulated over the months May to August). The last block, referring to the whole period 2010-2013, reports averages and standard deviations.

	Crop	Rain (mm)	Irrigation (mm)	ET potential (mm)	ET actual (mm)	Net Percolation (mm)
2010	Maize	443	450	575	386	356
	Continuously Submerged rice		3,399	537	537	2,942
	Young poplar		420	450	364	309
	Mature Poplar		0	442	393	-145
2011	Maize	200	750	632	449	434
	Continuously Submerged rice		3,882	608	608	3,175
	Young poplar		630	497	270	454
	Mature poplar		0	491	338	-221
2012	Maize	148	750	694	480	339
	Continuously Submerged rice		3,904	646	646	3,097
	Young poplar		630	520	291	380
	Mature poplar		0	510	383	-329
2013	Maize	195	750	682	510	353
	Continuously Submerged rice		4,373	636	636	3,630
	Young poplar		630	512	328	390
	Mature poplar		0	501	415	-320
2010-2013	Maize	247 (±133)	675 (±150)	646 (±54)	456 (±53)	371 (±43)
	Continuously Submerged rice		3,889 (±398)	607 (±49)	607 (±49)	3,211 (±295)
	Young poplar		578 (±105)	495 (±31)	313 (±41)	383 (±60)
	Mature poplar		0 (±0)	486 (±30)	382 (±32)	-254 (±87)

Although the actual evapotranspiration is lower than the potential one by 30%, most of this deficit is due to a decrease of evaporation, since actual transpiration is on average the 85% of the potential one during the whole period (May to August) and, especially, during the critical month of July when flowering occurs. The transpirative stress occurred in July 2010 is in fact due to excess of water rather than lack of water, as the groundwater levels reaching a maximum of -60 cm in the month of August determined a reduction of the transpiration rate by 27% .

Irrigation requirements of young poplars were 630 mm in the years 2011 to 2013 and 420 m in 2010

3.1.2 Water balance of rice areas

Water balance terms for a unit surface of submerged rice were obtained through the application of Equation (2) and (3), where the amount of rice irrigation was obtained by subtracting to the measured flow discharges the following components: i) amount of water lost via seepage and percolation from the canals, ii) amount of water required to satisfy the other crop water requirements (as obtained by the SWAP simulations), and iii) amount of water flowing out from the district.

Results showed that average irrigation requirements under continuous submergence conditions range from 3,400 mm in 2010 to more than 4,300 mm in 2013, whereas the rice cropped surface showed the opposite trend decreasing from 240 ha to 136 ha over the same period. On the one hand, some underestimation of irrigation provided to the other crops could potentially bring to an overestimation of rice irrigation, since the amount of water applied to rice was estimated as the residual term of the irrigation network balance (see Equation (3)). However, the 4-years average irrigation of 3,800 mm is a consistent value considering the very high sand percentage of the soils and it is in very good agreement with what found also by INEA (2013) who reports water requirements in the same area in excess of 4,000 mm. Moreover, the higher value estimated in 2013 could be due to two different issues both related to the contraction of the rice area. First, the replacement of submerged fields with flush irrigated ones occurred with a sparse pattern, which may contribute to increasing the local seepage fluxes and then the water requirements per unit of rice surface. In addition, the water supply in the area has been planned for many decades under conditions of predominance of CS rice. In the last three years, however, rice has been progressively replaced by maize and it is not unlikely that the irrigation management still has to fully adjust to the changes in water requirements occurring after a significant rearrangement of land uses in the area. This inertia in adaptation implies that more water than the amount actually needed by the reduced rice surface would be diverted, with outflows possibly higher than the share we considered.

Evapotranspiration from the rice surfaces in the months from May to August amounted to 607 mm on average and was assumed to be equal to the potential one, since flooding conditions are maintained throughout the growing season.

The net percolation trend reflects that of irrigation with an overall increase from 2010 to 2013 and an average value of 3,200 mm over the years considered. Such relevant downward water fluxes provide a significant recharge to the groundwater and are responsible for the shallow water table in the summer period.

3.1.3 Allocation of water resources in the district

Figure 3 shows the monthly allocation of water resources among the different components namely outflows from the district, percolation from the channels, rice irrigation, maize irrigation, and young poplar irrigation. The irrigation season goes from May till August when flow rates diverted are used for farming purposes, while, outside this period, the amounts circulating are mainly due to the drainage of rainfall and waste waters. During the month of May, water amounts ranging between 1 and 3.5 million cubic metres are required for flooding the rice fields of the area, determining an increase of the groundwater of about 40 cm on average. During the rest of the irrigation season, amounts of water comprised between 3 and 4 million cubic metres per month are used to satisfy water demands from farmers. Out of this amount, 30% percolates due to the coarse soils in the area and the remaining part is allocated between rice, maize and poplars with a predominant use for rice farming. The share of irrigation to satisfy maize water requirements however increased from 2010 to 2013 due to the expansion of the maize area. A certain inter-annual variability is also worth noting, which mainly depends on weather conditions. For instance, in May 2010, in spite of the large rice area, the amount of water required to flood all the rice fields is lower than the following years, since around 1 million cubic metre (200 mm of rainfall depth) was provided by the rainfall occurred in the month. Likewise, a very cold and wet spring in 2013 delayed the irrigation requirements, with a peak demand in August similar to the previous years in spite of the smaller rice surface.

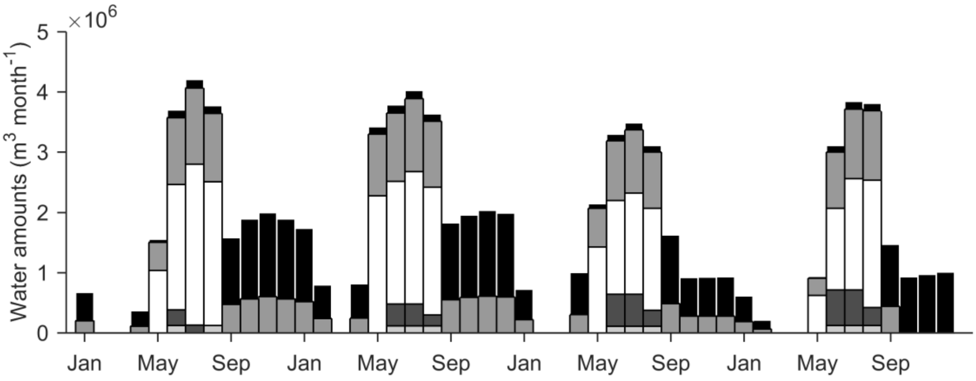

Figure 3 - Monthly allocation of water resources among the different components: outflows from the district (black), percolation from the channels (grey), rice irrigation (white), maize irrigation (dark grey), young poplar irrigation (light grey)

3.2 Relationship between percolation fluxes and groundwater levels

From estimates of the amounts of water percolating from each land use in the present state, it was possible to compute the monthly district percolations representing the recharge to groundwater (see Equation (4)).

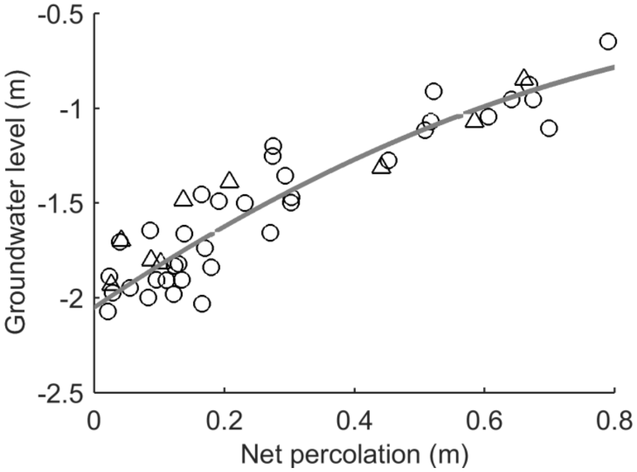

Figure 4 – Monthly averages of the measured groundwater levels vs monthly district percolations for the calibration (circles) and the validation periods (triangles), and calibrated regression curve (grey line).

Figure 4 shows, in a Cartesian coordinate system, the pairs of monthly net percolation fluxes $p_{s,t}$ (simulated), versus the monthly reference groundwater levels GWL_t (measured) and the PF-GWL relationship obtained calibrating Equation (5). Values of the parameters are: α = -0.92 m^{-1}, β = 2.32 and γ = -2.06 m (correlation coefficient R^2 = 0.86 in calibration and 0.90 in validation). Instead, Figure 5 shows a comparison of the pattern of measured and simulated groundwater levels. The agreement between the two patterns, as expressed by the Nash-Sutcliffe index, is satisfactory (0.87 and 0.82 in the calibration and validation respectively). The validity of the model has been also checked for the optimality conditions according to the regression theory (negligible sequential correlation of the residuals assessed by the runs test (Bradley, 1968) and the normality of the residuals assessed by the Lilliefors (Lilliefors, 1967): p-values > 0.1 in both cases).

According to the calibrated relationship, the deeper the water table, the greater is the increase of the GWL in response to a unit percolation. Conversely, when the water table is shallower, the response is flatter; i.e. a smaller GWL increase is observed for the same increase of the percolation rate. This behaviour is in good agreement with the orography of the study area that is crossed by a number of differently engraved channels. That is, the higher the GWL, the more the channels will drain water from the aquifer and the greater the number and the effect of the sinks.

As usual in case of empirical regressions, the relationship is reliable only within the range of the dataset, while no applications outside this range are to be considered reliable. In our study case, the quadratic relationship reaches its maximum at around -0.60 m for a percolation of 1.30 m; as the percolation exceeds this value, the estimated GWL starts to decrease and the calibrated relationship gives meaningless outcomes. However, in the scenario we are investigating, we expect the percolations to be fairly within the range of the percolations estimated for the present state, i.e. anywhere between the low percolations occurring in winter and the high summer values due to the continuous submergence of rice fields.

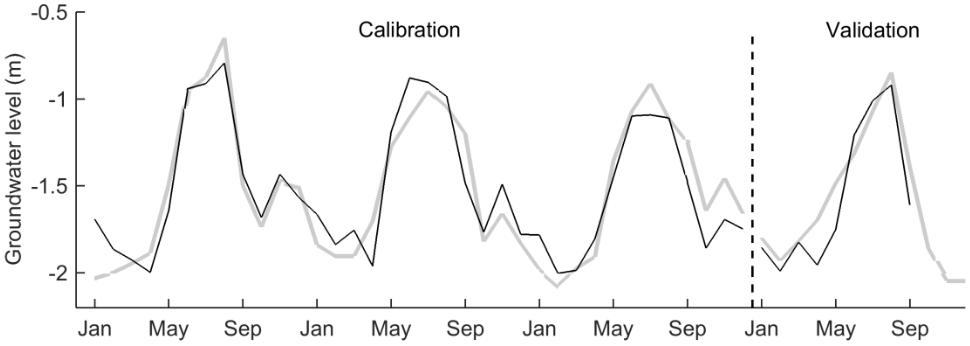

Figure 5 – Measured groundwater level (grey line) and estimated groundwater level (black line) for the calibration (years 2010-2012) and the validation (year 2013).

3.3 Prediction of the effects of FI technique

For the scenario analysis, water balance terms of all the crops, included FI rice, were simulated by application of the SWAP model. Irrigation of FI rice was scheduled by SWAP considering fixed amounts of 150 mm, but with a constant water availability instead of a 15-days turn. Being the water supply on demand, we adopted the daily stress criterion and we scheduled an irrigation every time the daily transpiration dropped below 70% of the potential one (i.e. ratio actual transpiration over potential transpiration equal to 0.70). This value enabled to maintain the mean transpirative stress as low as possible, especially in the month of July (average values greater than 0.90), and avoided at the same time an excessive number of irrigations.

3.3.1 No feedback scenario (NF)

As expected, the amount of water required by FI rice is much lower than in case of CS, decreasing from an average of 3,800 mm to an average of 825 mm, nonetheless with a very high variation among the years (±719 mm) (Table 6). In fact, while in 2011 and 2012 the irrigation amounts reached 1,350 and 1,500 mm respectively, no irrigations were scheduled in 2010 and just 450 mm were required in 2013. Reduction in water withdrawals achieved in 2010 were mainly due to the presence of shallow groundwater (summer maximum level of -0.60 m below the soil surface) and the higher rainfall that in August reached 155 mm. Similarly, the high water table levels that occurred in 2013 (summer maximum level of -0.80 m) reduced the number of irrigation events to 3 per season. As shown by the results, the groundwater table depth in such a coarse soil plays a significant role in determining the overall irrigation requirements due its effect in compensating for the low retention attitude of the soil.

However, estimates obtained in this scenario are utopic as shown in Figure 6 panel a, which highlights the incongruity between groundwater levels and groundwater recharge. The continuous line represents the measured groundwater level in the present state (i.e. with submerged rice) that was used as bottom boundary condition to estimate irrigation requirements and percolation fluxes of aerobic rice. The dashed grey line instead represents the a posteriori groundwater level resulting from the percolation fluxes as obtained by the PF-GWL relationship explained in Section 3.3.2. It is evident that the percolations occurring in NF scenario (i.e. with invariant groundwater level from the present state) do not provide a recharge to the groundwater that is sufficient to maintain the shallow table that used in input to the model. The greater the difference between the two lines, the more inconsistent the investigated scenario is. The figure clearly shows that there is no agreement between percolations and groundwater levels in all the years, and especially in 2010 and 2013 when the lowest irrigation requirements were estimated (see Table 6). In 2010 in particular, the PF-GWL model is inappropriate as the percolation fluxes are even lower than the winter values we used for calibrating and validating the model, with a consequent drop of the groundwater below the winter minimum of -2.00 m. The increase of the a posteriori groundwater level is delayed compared to the a priori in all the years because water for flooding rice paddies in May is no longer supplied in case of flush irrigated rice with a consequent delay in the increase of the groundwater table depth.

3.3.2 Feedback accounting scenario (FA-15 and FA-10)

The need to consider a 10-days rotation of maize irrigation (FA-10 scenario) was justified by the fact that a 15-days rotation, which enabled to achieve an almost complete satisfaction of crop water requirements under the present conditions, was found to be no longer adequate with FI rice due to average transpiration rates in the critical month of July that were lower than 0.80. Conversely, shortening the turn by 5 days (from 15 to 10 days) increased the ratio of actual transpiration over potential transpiration of maize by 9% on average, with values close to 0.90 in all the years. Such effect is caused by a decrease of the summer maximum level of about 25-30 cm compared to present state as discussed further on in this section. At the same time, also mature poplars benefitted from increasing the water amounts to maize due to the higher retention of soil moisture in the rooted soil layer and the greater root water uptake from the groundwater that gets shallower (the ratio increases from 0.81 to 0.87 moving from FA–5 to FA–10 respectively). FI rice, on the other hand, had always values higher that 0.90 since irrigation is scheduled on the demand and not according to any rotations.

The Feedback Accounting scenario with a 15 days rotation for maize and poplar (FA-15) showed a decrease of the summer maximum level of about 25-30 cm compared to present state, as discussed further on in this section. This decreases the capillary rise contribution reaching the maize roots and brings, in the critical month of July to average transpiration rates lower than 0.80. Therefore, a 15-days rotation, which enabled to achieve an almost complete satisfaction of crop water requirements under the present conditions, is not sustainable for maize with FI rice.

The case study FA-10 (just like FA-15 but a 5 days shortening in the maize turn) increases the ratio of actual transpiration over potential transpiration for maize reaching values close to 0.90 in all the years.

In changing from FA-15 to FA-10, also mature poplars benefit from the slightly increased GWL and their average transpiration rate increases from 0.81 to 0.87 respectively. FI rice, on the other hand, had always values higher that 0.90 since irrigation is scheduled on the demand and not according to any rotations.

Table 6 reports the irrigation water requirements we estimated for both FA–15 and FA–10. When moving from a 15-days rotation to a 10-days rotation, irrigations amounts increased from 750 mm per season (i.e. 5 irrigations) to 1,050 mm (i.e. 7 irrigations) per season. Flush irrigated rice required water amounts comprised between 1,350 mm in 2010 (9 irrigations) to 1,800 mm in 2013 (12 irrigations). Irrigation supplies to FI rice, according to the FA simulations, needed to be provided on a weekly basis or slightly less like for instance in August 2013. District water withdrawals under FA–10 scenario were estimated to be on average the 41% less than the present state, while in case of FA–15 and NF they were lower by 46% and 67 % respectively. The average of 67% for NF scenario was influenced by the very high reduction we estimated for 2010 (up to the 90%). Nonetheless, disregarding results of 2010 that was a very particular year, the average reduction in the period 2013-2013 was still higher by 17 % than what we obtained under FA–10 scenario. Differences in the summer maximum of groundwater level between FA–10 and the NF scenario ranged between 40 cm in both 2010 and 2013 to 20 and 30 cm in 2011 and 2012 respectively. Therefore, it is evident how neglecting the feedback effects may be quite imprecise and lead to an overestimations of potential gains in case of FI adopted over large areas.

Figure 6 panel b shows the fitting of the *a priori* variant and *a posteriori* pattern for the FA–10 scenario. The agreement between the two, as measured by the correlation coefficient (R^2=0.52) and by the Nash-Sutcliffe index (N-S=0.42), is quite good especially during the central months of the irrigation season, namely June, July and August, when the two summer peaks are very similar. Greater differences can be noticed during winter time, but this is not going to affect the irrigation water requirements in summertime and the PF-GWD relationship is supposed to reproduce fairly well the groundwater behaviour in response to the superposition of fluxes deriving from the irrigation practice. Quite interesting is the behaviour of the two lines at the beginning of the irrigation season, during May, as the dashed line (i.e. the *a posteriori* GWL) shows a delayed increase if compared to the continuous line (i.e. the *a priori* GWL). The *a priori* GWL was obtained from the average measured groundwater level in the years 2010-2013 through the application of Equation (6). Therefore, the *a priori* pattern shows an increase of the level starting from May due to the submergence of rice fields. In the FA scenario, however, no significant recharge to the groundwater occurs in May with a consequent gap between the *a priori* and the *a posteriori* GWL at the beginning of the season that cannot be reduced because of the different distribution of irrigation supplies during the season. It follows that, under a scenario of FI rice, water requirements of maize and rice would tend to coincide, with possible consequences on the water availability, especially early in the season (namely June) when the groundwater is still relatively deep and the percolation from seepage and channels may be consequently higher.

Table 6 - Irrigation amounts for the different crops and the whole district, obtained from the different case studies in the years 2010-2013. The last block, referring to the whole period 2010-2013, reports averages and standard deviations. Feedback accounting 15 and Feedback accounting 10 differ in the length of the irrigation turn for maize, which is equal to 15 and 10 days respectively

	Case studies	Maize (mm)	Continuously submerged rice (mm)	Flush irrigated rice (mm)	Young Poplar (mm)	District Irrigation (10^3 m^3)
2010	Present state	450	3,399	-	420	13,244
	No feedback	450	-	0	420	954
	Feedback accounting 15	750	-	1,500	630	7,494
	Feedback accounting 10	1,050	-	1,500	630	7,881
2011	Present state	750	3,882	-	630	14,877
	No feedback	750	-	1,350	630	6,406
	Feedback accounting 15	750	-	1,500	630	7,043
	Feedback accounting 10	1,050	-	1,500	630	7,593
2012	Present state	750	3,904	-	630	12,049
	No feedback	750	-	1,500	630	6,171
	Feedback accounting 15	750	-	1,800	630	6,905
	Feedback accounting 10	1,050	-	1,800	630	7,705
2013	Present state	750	4,373	-	630	11,711
	No feedback	750	-	450	630	3,693
	Feedback accounting 15	750	-	1,800	630	6,452
	Feedback accounting 10	1,050	-	1,800	630	7,340
2010-2013	Present state	675 (±150)	3,889 (±398)	-	577 (±105)	12,970 (±1,431)
	No feedback	675 (±150)	-	825 (±719)	577 (±105)	4,306 (±2,549)
	Feedback accounting 15	750 (±0)	-	1,650 (±173)	630 (±0)	6,974 (±429)
	Feedback accounting 10	1,050 (±0)	-	1,650 (±173)	630 (±0)	7,629 (±226)

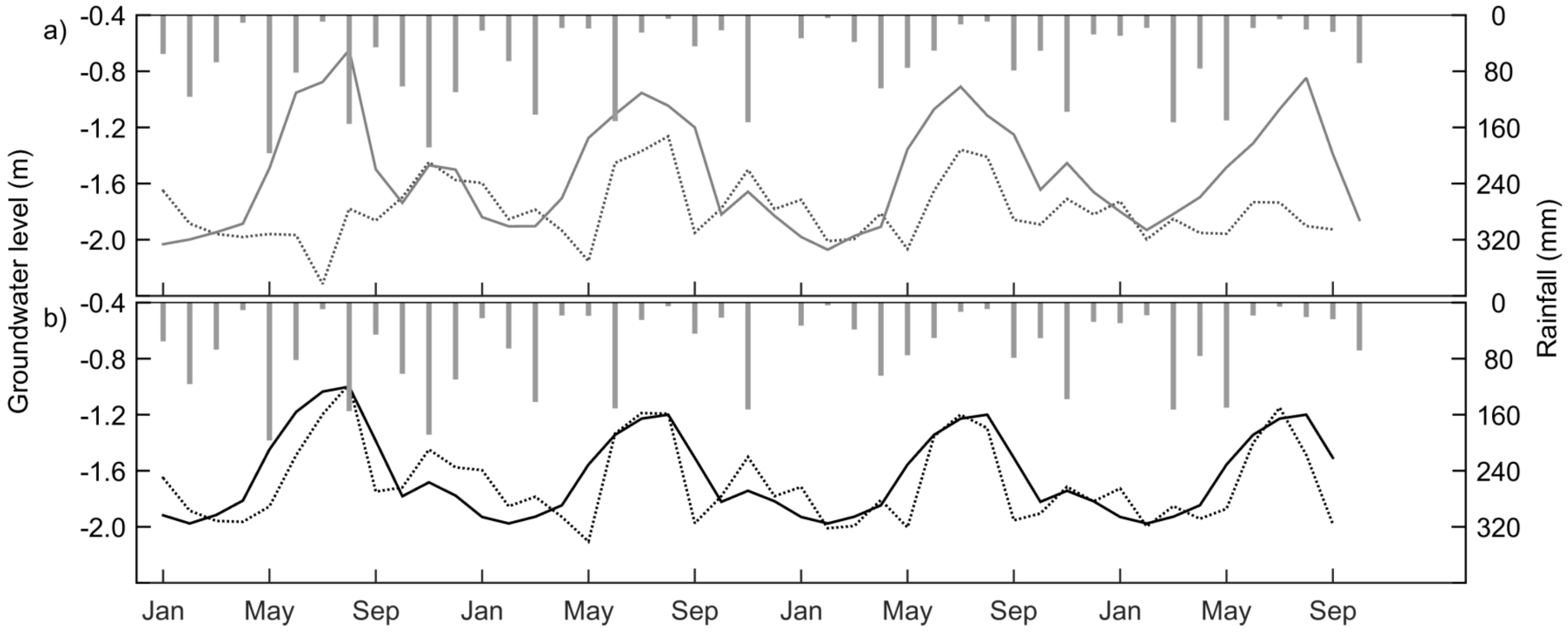

Figure 6 – Panel a): observed groundwater level (continuous line) and a posteriori pattern of groundwater level computed in the No Feedback scenario (dashed line); panel b): best fitting a priori variant (continuous line) and a posteriori pattern (dashed line) of groundwater level for the feedback accounting scenario with 10-days rotation for maize irrigation. Grey bars represent monthly rainfalls. Results of years 2010 to 2013.

Water use efficiencies of the different case studies

Table 7 presents the values of water use efficiencies (WUE) of each land use, i.e. the ratio of actual evapotranspiration over the net water inputs given by irrigation plus rainfall. The last column reports values aggregated at the district scale and includes also the evapotranspiration of mature poplars, which are not irrigated, but benefit from the effects of the irrigations provided to the other crops through their effect on the groundwater table depth. Out of all the crops, CS rice grown in the present state had the lowest WUE (0.15 on average) due to the need of continuously supply water in order to maintain ponding water in a coarse soil. It follows that WUE of the district in the present state reflected that of CS rice (0.17 on average) due the large area occupied by CS rice (up to the 48% in 2010). WUE of maize in the present state was around 0.50, again because of the combination of the soil type, of the groundwater table depth and of the efficiency of the irrigation practices that implies border irrigations 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), WUE of rice increased to 0.47 and WUE referred to the whole district reached 0.38. Results obtained for FI rice are fairly within ranges reported in literature for field-scale studies.

However, when the feedback effects between irrigation and groundwater level are accounted for (see FA–15 and FA–10), WUE of FI rice decreased to an average of 0.20, being just 5% higher than CS rice. Such increase of WUE is relatively low because, although irrigations decreased by an average of 57% from CS to FI, as also actual evapotranspiration had a decrease of 35% on average. However, the reduction was mostly due to a reduction of evaporation (because of the lack of continuous ponded water) rather than transpiration, as demonstrated by the values of actual transpiration (average ratio between actual and potential fluxes in in the month of July of 0.94 (±0.01)).

Table 7 - Values of water use efficiency (actual evapotranspiration divided by irrigation plus rainfall) (mm mm^{-1}) for the different crops and the whole district obtained from the different case studies in the years 2010-2013. The last block, referring to the whole period 2010-2013, reports averages and standard deviations. Feedback accounting 15 and Feedback accounting 10 differ in the length of the irrigation turn of maize, which is equal to 15 and 10 days respectively

	Case studies	Maize (-)	Continuously submerged rice (-)	Flush irrigated rice (-)	Young Poplar (-)	District Irrigation (-)
2010	Present state	0.43	0.14	-	0.42	0.14
	No feedback	0.43	-	0.84	0.42	0.57
	Feedback accounting 15	0.34	-	0.17	0.26	0.17
	Feedback accounting 10	0.29	-	0.17	0.26	0.16
2011	Present state	0.47	0.15	-	0.25	0.15
	No feedback	0.47	-	0.24	0.25	0.24
	Feedback accounting 15	0.45	-	0.22	0.24	0.22
	Feedback accounting 10	0.35	-	0.22	0.24	0.20
2012	Present state	0.53	0.16	-	0.27	0.18
	No feedback	0.53	-	0.24	0.27	0.28
	Feedback accounting 15	0.46	-	0.21	0.24	0.23
	Feedback accounting 10	0.39	-	0.21	0.25	0.22
2013	Present state	0.54	0.14		0.30	0.19
	No feedback	0.54	-	0.56	0.30	0.44
	Feedback accounting 15	0.47	-	0.21	0.25	0.25
	Feedback accounting 10	0.40	-	0.21	0.26	0.24
2010-2013	Present state	0.49 (±0.05)	0.15 (±0.01)	-	0.31 (±0.08)	0.17 (±0.03)
	No feedback	0.49 (±0.05)	-	0.47 (±0.29)	0.31 (±0.08)	0.38 (±0.15)
	Feedback accounting 15	0.43 (±0.06)	-	0.20 (±0.02)	0.25 (±0.01)	0.22 (±0.04)
	Feedback accounting 10	0.36 (±0.05)	-	0.20 (±0.02)	0.25 (±0.01)	0.21 (±0.03)

If an increase of WUE for FI rice was assessed in the FA scenario compared to the present state, 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 amounted to 0.21 against 0.17 in the present state. Obviously, root growth adaptation to the changing conditions, which we did not consider, may determine some small variations in WUEs we estimated. However, it is clear that FI rice is not as effective in all the situations as results obtained from experiments with shallow water tables would suggest.

4 CONCLUSIONS AND GENERAL REMARKS

According to numerous field-scale studies, flush irrigation management in rice farming has the potential to significantly reduce the water amounts required by the practice of continuous flooding. However, when such technique is adopted over large paddy areas, reduction in water withdrawals may be of different extent because of the effects on the groundwater resources caused by a decreased recharge to the groundwater. In fact, in areas with shallow groundwater, even a decrease of few tens of centimetres may have relevant impacts on the irrigation requirements because of the reduction of the capillary rise contribution.

In this context, the study presents a multiple-stage approach to studying the large-scale effects of shifting the irrigation technique in a rice area from continuous submergence to flush irrigation. Stages include: i) the estimation of the percolation fluxes at the scale of an irrigation district under the present conditions, ii) the calibration of an empirical relationship between the same fluxes and the groundwater level, and iii) the prediction of the effects of the extensive adoption of flush irrigation. The approach makes a combined use of observative data (from monitoring data to knowledge of irrigation scheduling, canal seepage etc.), physically-based models (SWAP), water balance equations, and empirical relationships (percolation-groundwater levels). Through the application to a study area in Northern Italy, the S.

Giorgio-E district, over a four-year period (2010-2013), we show that when good quality data on irrigation supply and groundwater depth are available, robust results can be achieved in the simulation of the water fluxes under present conditions and in the prediction of the effects of changes in the irrigation practices.

In the case of the S. Giorgio-E district, reductions in water withdrawals drop from an expected 67% when blindly extending to the whole district the results for an individual field, to 41% when fully considering the effects of groundwater drawdown due to the decrease of recharge after the extensive adoption of flush irrigation. This highlights the importance of considering groundwater fluctuations in order to avoid overestimates in the reductions of irrigation deliveries.

Moreover, the current irrigation scheduling of maize, based on a 15-days rotation, is likely to be not sufficient to the satisfaction of the crop water requirements in the scenario. Rather, a 10-days turn was found more effective in reducing the transpirative stress, especially during the month of July.

Gains in water use efficiency at both the field and the district level are possible after a conversion to flush irrigated rice, but, in our study, the scenario water use efficiency of the whole district was greater than that of present state by just 4%. Again, neglecting the groundwater response to the different water management brought to an overestimation of 17%. The feedbacks are particularly relevant in the S. Giorgio-E district due to the high permeability of soils in the area and may have substantially different impacts in less permeable areas, even if groundwater depth is similar. Therefore, we do not imply in any way that water saving techniques are ineffective. We rather stress the importance of carefully analysing all the consequences of their extensive adoption as several issues need to be considered.

With respect to water resources aspects specifically addressed here, results from our simulations suggested that changes in the irrigation turns may be required. As a consequence, significant adaptations of the planning and management of irrigation deliveries to farmers would need to take place. In fact, rice growers currently receive small flow rates and without interruption. However, the shift to flush irrigation practice would imply to deliver higher flow rates on a weekly basis, with possible need to rearrange dimensions of irrigation channels accordingly. Moreover, no significant competitions between rice and maize is occurring under the present management and it is yet to assess whether this will be the case under the scenario investigated. In fact, interrupting the flooding of rice paddies determines a delay in the rise of the regional groundwater table from May in the present state, to June-July in the scenario, with possible competitions between rice and maize in the first part of the season. Also poplars, which are currently benefitting from the shallow groundwater, could suffer from a decrease of the water table. If more irrigations will be required, the economic return of poplars plantation could be questioned.

Furthermore, a large conversion to flush irrigated rice involves several issues that we did not address, as beyond the scope of this paper, but that need to be carefully considered too. Such issues include, for instance, yield gaps between submerged rice and flush irrigated rice, the susceptibility of rice to temperature stresses, the environmental impacts of different agronomic practices and the nutrient dynamics due to the shift from anaerobic to aerobic soils etc. Water productivity (defined as the amount of food produced per unit volume of water used, Molden, 1997), is determined not only by the amount of water contributing to seepage and percolation, but depends also on yield potential as determined by variety and climate, and on the input of other production factors such as nutrients, pesticides etc. (Bouman and Tuong, 2001). The value of indicators like the water productivity is highly influenced by the scale of analysis and net gains with respect to a specific domain (e.g. at the farm level) may determine off-site effects that not necessarily lead to an increase of the efficiency and the productivity of whole the system (Guerra et al., 1998). Our study suggests indeed that reducing the irrigation supplies to rice at the field level may determine an increase of the amount needed by the other crops because of the feedbacks effects on the groundwater dynamics at larger scales. It follows that the reductions of water withdrawals cannot be the only goal when the efficiency of rice-based systems is under evaluation.

In this framework, our study stresses the importance of specifically considering the large-scale effects that massive changes in the irrigation practice have on the groundwater system, especially in areas characterised by strong interconnections between surface water dynamics and the groundwater system.

Acknowledgements

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CHAPTER 6

Linking dissolved organic carbon cycling to soil functions in rice paddies under different water management practices[4]

D. Said-Pullicino[a], E.F. Miniotti[a, c], M. Sodano[a], C. Bertora[b], C. Lerda[a], E.A. Chiaradia[d], M. Romani[c], S. Cesari de Maria[d], D. Sacco[b], L. Celi[a]

[a] Soil Biogeochemistry, Dept. of Agricultural, Forest and Food Sciences, University of Turin, Grugliasco, Italy.

[b] Environmental Agronomy, Dept. of Agricultural, Forest and Food Sciences, University of Turin, Grugliasco, Italy.

[c] Rice Research Centre, Ente Nazionale Risi, Castello d'Agogna, Italy.

[d] Department of Agricultural and Environmental Sciences, Universitá degli Studi di Milano, Milan, Italy

Abstract

Aims: Although paddy soils are generally characterized by relatively high dissolved organic carbon (DOC) concentrations and fluxes, little is yet known on how water management influences the cycling of this important organic C pool. This work aims at providing insights into the link between DOC cycling during rice cropping and organic C input to the subsoils and export with surface waters, as well as methane (CH_4) emissions in a temperate paddy soil as a function of different water management practices.

Methods: DOC quantity, quality and fluxes, as well as CH_4 emissions were evaluated at field-scale over two cropping seasons for three water management systems including continuous flooding, dry seeding with delayed flooding, and intermittent irrigation.

Results: DOC cycling in the different water management systems were strongly linked to the reducing soil conditions resulting from field flooding. In contrast to dry seeding or intermittent irrigation, adoption of continuous flooding not only favoured the accumulation of DOC in the topsoil (>10-20 mg C l^{-1}), but also enhanced C inputs to the subsoil (14-51 g C m^{-2}), and exports with surface waters (14-44 g C m^{-2}). Moreover, changes in DOC quality in paddy soils were linked to a positive feedback on the abiotic release of soil-derived DOC, and substrate availability for CH_4 production.

Conclusions: Water management practices in rice paddies strongly affect the temporal trends in DOC quantity and quality over the cropping season, with important implications on organic C fluxes.

Keywords: organic carbon fluxes, soil redox conditions, reductive dissolution, surface waters, subsoil, methane emissions

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[4] Plant and Soil (accepted)

1 INTRODUCTION

1.1 Introduction

Rice paddy soils are generally characterized by large concentrations and fluxes of dissolved organic carbon (DOC) in comparison to other ecosystems (Kögel-Knabner et al., 2010; Krupa et al., 2012). Being a relatively mobile and the most bioavailable fraction of soil organic carbon (SOC; Marschner and Kalbitz, 2003), DOC plays a role in many chemical and biological processes, and therefore the most dynamic in terms of ecosystem functionality. In particular, soil processes involving this organic C pool may strongly control the C source/sink functions of paddy soil agro-ecosystems.

Indeed, paddy rice cultivation represents the major source (11%) of global methane (CH_4) emissions, one of the principal greenhouse gases, with annual emissions estimated to range between 493 and 723 Mt CO_2-eq yr^{-1} in 2010 (Kimura et al., 2004; Smith et al., 2014). Seasonal patterns of CH_4 emissions from these soils generally follow the pattern of DOC in the root zone (Lu et al., 2000), suggesting that this labile C pool may serve as a major C source for methanogenic microorganisms. Moreover, DOC may also be responsible for significant C exports to adjacent water bodies with important implications concerning fluvial water quality and agricultural catchment C budgets (Abe et al., 2011; Krupa et al., 2012). Paddy soils are also often associated with a large accumulation of SOC compared to other arable ecosystems (Kögel-Knabner et al., 2010). Recently, Hanke et al. (2013) challenged the general assumption that increasing SOC contents with paddy soil development is due to a smaller C mineralization under anoxic conditions. They provided evidence showing how successive cycles of DOC desorption and partial mineralization under anoxic conditions, followed by re-adsorption and selective preservation under oxic conditions, may drive the long-term accumulation of more stable organic C and contribute to increasing topsoil C stocks in well-established paddy soils. Moreover, recent studies have shown that, whereas topsoil organic C stocks and concentrations increase with years of paddy management, accumulation of organic C in the subsoils is slower (Kalbitz et al., 2013). This has been attributed to the low-permeability of the plough pan, particularly in finely textured soils, that could limit DOC input into the subsoil (Wissing et al., 2011).

Various studies have shown that the degradation of incorporated crop residues may contribute significantly to DOC (Katoh et al., 2005; Ruark et al., 2010), and also influence its heterogeneity in terms of chemical composition and molecular structures due to the diverse biodegradability as a function of soil redox conditions (Chen et al., 2010). Rice growth is also an important factor affecting DOC in paddy soils through the release of soluble root exudates and rhizodeposits (Ge et al., 2012), although root-derived DOC has been shown to be rapidly mineralized contributing only marginally to DOC fluxes (He et al., 2015). Moreover, the increase in soil pH and the dissolution of Fe and Mn oxyhydroxides when acidic soils are subjected to anoxic conditions may result in the release of significant amounts of DOC previously stabilized on the mineral matrix (Grybos et al., 2009). These mechanisms, are all considered to affect DOC concentrations and fluxes in rice paddies. However, little is yet known on the numerous biotic and abiotic factors that control the temporal and spatial variations in DOC quantity and quality in soils subjected to alternating redox conditions (Kalbitz et al., 2000), particularly for rice paddies (Hanke et al., 2013).

Agricultural practices in rice cropping systems are expected to influence DOC cycling and related ecosystem functions. In the last decades, various studies have shown that management options involving the adoption of water systems alternative to continuous flooding have a high potential to mitigate CH_4 emissions (Corton et al., 2000; Wassmann et al., 2004; Liu et al., 2014) and impact the timing and magnitude of DOC exports from soils to rivers (Abe et al., 2011; Krupa et al., 2012; Oh et al., 2013; Xu et al., 2013). In fact, water management practices play an important but still not well understood role in the production, mineralization and leaching of DOC in paddy soils, although they are crucial processes affecting the ecosystem C balance (Kindler et al., 2011). On the basis of a two-year field experiment carried out in a temperate paddy field (NW Italy), the objectives of this study were to: (i) evaluate the trends in DOC concentrations, composition and fluxes in paddy soil solution, water supply and drainage canals during rice cropping, and (ii) identify the main mechanisms and drivers that link soil solution DOC cycling to the input of organic C to subsoils, export to surface waters, and CH_4 emissions, as a function of different water management practices.

2 MATERIALS AND METHODS

2.1 Experimental site description

The field experiment was carried out over two rice cropping seasons (2012 and 2013) at the Rice Research Center of Ente Nazionale Risi, Castello d'Agogna, Pavia (45°14'48"N, 8°41'52"E), located in the plains of the river Po (NW Italy).

The study area has a temperate climate with a mean annual temperature of 12.4°C and annual precipitation of 684 mm over the experimental period.

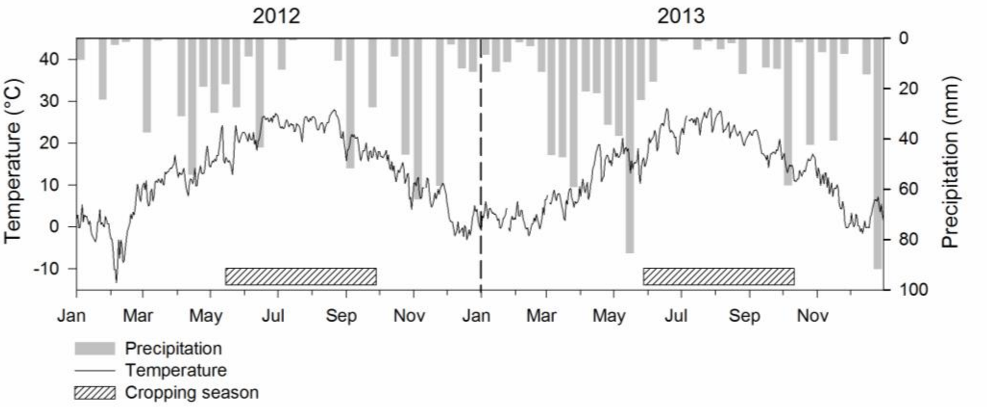

Figure 1 -Variations in mean daily air temperatures and cumulative precipitation (over 10 consecutive day periods) during the experimental period

Mean daily air temperatures and cumulative precipitation over the experimental period are shown in Fig. 1 (data from Meteorological Station

125, ARPA Lombardia). The soil of the experimental field was classified as a Fluvaquentic Epiaquept coarse silty mixed mesic (Soil Survey Staff, 2010), while general soil properties are reported in Table 1.

2.2 Experimental design and irrigation management

Field treatments involved the comparison of three water management systems including water seeding with continuous flooding (WFL), dry seeding with flooding at tillering stage (DFL), and dry seeding with intermittent irrigation (DIR), with two replicate plots for each treatment. Each plot was hydrologically-isolated, had an area of 2000 m^2 (20 × 80 m), and was seeded with rice (*Oryza sativa* L. cv. Gladio; 160 kg ha^{-1}). In all plots, crop residues were incorporated with tillage in spring (2 April 2012 and 9 May 2013).

In the WFL treatment, water seeding was carried out on May 28 and June 7, for the 2012 and 2013 cropping seasons, respectively. A 6–18 cm standing water depth was constantly maintained during the cropping season, except for two 5-day mid-season drainage periods about 18-23 and 45-50 days after seeding (DAS). In the DFL treatment, dry seeding was carried out on May 15 and May 28, and the field kept without standing water for 35 and 24 DAS, for the 2012 and 2013 seasons, respectively. Subsequently, water management followed the same regime as for WFL. In the DIR treatment, dry seeding was carried out on May 15 and May 28 for the two cropping seasons. Ponding water was not maintained throughout the cropping season, and irrigation was applied when the soil moisture tension at a depth of 10 cm approached –30 kPa (9 events in 2012, and 12 events in 2013). In all treatments, drainage was allowed at the ripening stage, 20–30 days before harvest that was carried out between the end of September and the first 15 days of October. Throughout the cropping seasons, soil pH and Eh were measured potentiometrically in each plot at a soil depth of 10 cm.

Table 1 - Basic properties of the soil horizons in the site

Horizon	Depth (cm)	Soil colour	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Texture class[a]	pH_{H2O}	pH_{KCl}	CEC[b] (cmol$_{(+)}$ kg ^{1})
Apg1	0 30	5Y4/1	405	477	118	L	5.9	4.4	10.2
Apg2	30 40	5Y4/1	387	513	100	SiL	6.6	5.0	11.1
ABg	40 55	5Y3/1	309	554	137	SiL	6.6	4.9	17.1
Ab1	55 70	10YR3/2	327	562	111	SiL	6.3	4.9	17.8
Ab2	70 90	1.25Y3.5/2	333	574	93	SiL	6.3	5.0	16.6
Bwgb	90 130	5Y5/1.5	279	558	163	SiL	6.5	4.6	11.0
CBgb	130 200	5Y5/2	155	652	193	SiL	6.7	4.3	17.8
2C	>200	2.5Y5.5/2	445	488	67	SL	6.7	4.4	9.1

Table 1 (continued)

Horizon	Depth (cm)	OC[c] (g kg ^{1})	N_t[d] (g kg ^{1})	Fe_o[e] (g kg ^{1})	Fe_d[f] (g kg ^{1})	Fe_o/Fe_d	Mn_o[e] (g kg ^{1})	Mn_d[f] (g kg ^{1})	Bulk density (g cm ^{3})
Apg1	0 30	9.5	0.83	3.55	9.40	0.38	0.07	0.08	1.44
Apg2	30 40	7.1	0.66	3.11	10.18	0.31	0.10	0.13	1.47
ABg	40 55	14.3	1.29	2.60	5.30	0.49	0.08	0.12	1.30
Ab1	55 70	20.6	1.78	3.09	5.42	0.57	0.10	0.13	0.97
Ab2	70 90	13.8	1.19	3.62	5.18	0.70	0.13	0.13	1.10
Bwgb	90 130	2.6	0.19	6.81	30.53	0.22	0.28	0.53	1.51
CBgb	130 200	1.0	0.10	3.29	13.90	0.24	0.12	0.18	n.d.
2C	>200	0.3	0.10	0.80	4.43	0.18	0.05	0.05	n.d.

n.d. not determined

[a] Texture: L, loam; SiL, silty loam; SL, sandy loam

[b] Cation exchange capacity

[c] Organic carbon

[d] Total nitrogen

[e] NH_4-oxalate-extractable Fe and Mn

[f] Dithionite-citrate-bicarbonate extractable Fe and Mn

For each field treatment 160 kg N ha^{-1} of urea were applied and split between basal, tillering, panicle differentiation and booting stages as follows: 60-60-40-0 kg N ha^{-1}, 40-70-50-0 kg N ha^{-1} and 50-40-40-30 kg N ha^{-1} for WFL, DFL and DIR, respectively. All fertilizer applications were top-dressed except for the basal fertilization that was incorporated. A different fertilizer N split rate was adopted to optimize crop growth and yield performance, as well as limit N losses for each water management. All plots also received 18 kg P ha^{-1} and 70 kg K ha^{-1} as basal fertilization.

2.3 Water sampling and analyses

Ceramic suction cups were installed vertically at 25, 50 and 75 cm depths to collect soil solutions, with two replicates per plot. Surface water samples were collected from supply canals and flumes channelling outflow waters from each plot to drainage canals. All water samples were collected on a weekly basis, filtered through a 0.45 µm nylon membrane filter, and subsequently analyzed for DOC, specific ultraviolet absorbance at 254 nm (SUVA), and Fe(II). Dissolved organic carbon was determined using Pt-catalyzed, high-temperature combustion (850°C) followed by infrared detection of CO_2 (VarioTOC, Elementar, Hanau, Germany), after removing inorganic C by acidifying to pH 2 and purging with CO_2-free synthetic air. UV absorption at 254 nm was measured (Helios Gamma Spectrophotometer, Thermo Electron, Waltham, MA) after appropriate dilution to DOC <50 mg l^{-1}. The SUVA values calculated by normalizing measured absorbance values to the concentration of DOC, were used as an estimate for the aromatic content of water samples (Weishaar et al. 2003). Dissolved Fe(II) concentrations were measured colorimetrically immediately after sampling, using the 1,10-phenanthroline method (Loeppert and Inskeep 1996).

2.4 Calculation of DOC fluxes

Daily dissolved organic C concentrations in surface (inflow and outflow) and subsurface (25 cm) waters were extrapolated for the entire cropping season by assuming a linear change in concentration between two successive measured data points. Water fluxes for each irrigation management were determined for both cropping seasons as described in Chiaradia et al. (2013; 2015). Briefly, irrigation inflow (*I*) and outflow discharges (*D*) for each plot were measured by long-throated flumes equipped with a level gauge, while net percolation (*P*) was obtained as the residual term of the water balance according to the equation:

$$I + R = \Delta S + ET + P + D$$

where *R* is the precipitation, *ET* is the crop evapotranspiration estimated by the application of Penman-Monteith type models previously calibrated using a discontinuous data series obtained through eddy-covariance measurements as described by Facchi et al. (2013a) and Gharsallah et al. (2013), and ΔS is the change in the field soil water storage (including the soil water content of the root zone up to 40 cm depth, and ponded water depth during flooding). The experimental fields were also instrumented with piezometers in order to monitor the groundwater depth and with tensiometers at different depths in order to assess the soil pressure profile. Net percolation was used to compute the percolation fluxes of DOC at 25 cm. Concentrations at 25 cm instead of those at 50 cm have been chosen in light of the following considerations: (i) fluxes in the topsoil were mainly downward, as evidenced by data obtained from piezometers and tensiometers (data not shown), while horizontal water movements may not be excluded at depths > 40 cm, and (ii) the root water uptake between 25 and 40 cm are in any case negligible compared to the magnitude of percolation fluxes, so no significant differences in percolation fluxes between these two depths were expected. Daily inflow, outflow and percolation fluxes of DOC (g m^{-2} d^{-1}) were then calculated by multiplying the concentration of DOC (mg C l^{-1}) by the water flux (l m^{-2} d^{-1}), while cumulative fluxes over the cropping season were calculated as the sum of all daily fluxes. Flow-weighted DOC concentrations for each irrigation management were calculated by dividing the total DOC flux by the total water flux in the same time period.

2.5 Gas sampling and methane flux measurements

Methane emissions were measured over the whole rice cropping season by the non-steady-state closed chamber technique. Stainless steel flux anchors were permanently installed into the soil (40 cm deep) prior to seeding, to ensure reproducible placement of gas collecting chambers during successive emission measurements. The top edge of the anchor had a groove for filling with water to seal the rim of the chamber. The chamber was equipped with a circulating fan to ensure complete gas mixing and was wrapped with a layer of polystyrene and aluminium foil to minimize air temperature changes inside the chamber during the gas sampling period. The cross-sectional area of the chamber was 0.27 m^2 (0.75 × 0.36 m). During gas sampling, the chamber was placed over the vegetation with the rim of the chamber fitted into the groove of the anchor. Extension collars were added to increase chamber height in order to accommodate the growing rice plants. During this study, CH_4 efflux was usually measured once a week, except during drainage periods, when a higher sampling frequency was adopted. Gas samples (30 ml) were drawn with airtight syringes at 0, 15 and 30 min after chamber closure, and transferred into 12 ml pre-evacuated vials (Exetainer®, Labco Limited, UK). Gas samples were analysed by gas chromatography with flame ionization detection (Agilent 7890A, Santa Clara CA, USA). Methane emission flux (*F*, expressed in g C m^{-2} d^{-1}) was calculated from the linear resolution of the rate of increase in gas concentration in the chamber (*dC/dt* in ppm h^{-1}), according to the following equation (Yang et al., 2012):

$$F = \frac{dC}{dt} \cdot H \cdot \frac{\mu \bar{P} \cdot 24 \cdot 10^{-6}}{R(\bar{T} + 273.2)}$$

where *H* is the effective height of the static chamber (m), $\bar{P}$ is the mean air pressure in the chamber (Pa), $\bar{T}$ is the mean air temperature in the chamber

(°C), R is the universal gas constant (R = 8.31441 J mol^{-1} K^{-1}) and μ is the molecular weight of C. When the rate of increase in gas concentration between the 2nd and 3rd sampling points was lower with respect to that between the 1st and 2nd points, fluxes were calculated by applying the nonlinear Hutchinson and Mosier (1981) model.

3 RESULTS

3.1 Soil redox conditions and pH

Field flooding in both WFL and DFL treatments led to the establishment of anoxic conditions evidenced by a decrease in soil Eh and a corresponding increase in pH values (Fig. 2). Eh values below –300 mV were observed for WFL over most of the cropping season, except for a couple of more positive peaks in correspondence with mid-season field drainage, while pH values tended to increase from around 5.0 before flooding to a maximum of 6.3-6.9 before final field drainage (Fig. 2a). In DFL, the drop in Eh values and increase in pH occurred later on in the cropping season with respect to WFL, in correspondence with field flooding at tillering stage (Fig. 2b). However, once the fields were flooded, Eh values below –250 mV were recorded, while pH values tended to increase reaching maximum values of 6.3-6.4. In both WFL and DFL treatments, Eh values gradually returned to positive values after final field drainage towards mid-September (only observed in 2012 due to missing data in 2013). In contrast, redox potentials in DIR were generally positive throughout the cropping season with only a number of temporary drops in Eh in correspondence with some irrigation events, particularly in the 2013 season (Fig. 2c). pH values for this treatment were relatively constant with an average value of 5.3.

3.2 Soil solution dissolved organic carbon

DOC concentrations generally tended to increase with the onset of anoxic soil conditions during field flooding, although different trends in time and with soil depth were observed among the three management practices (Fig. 3).

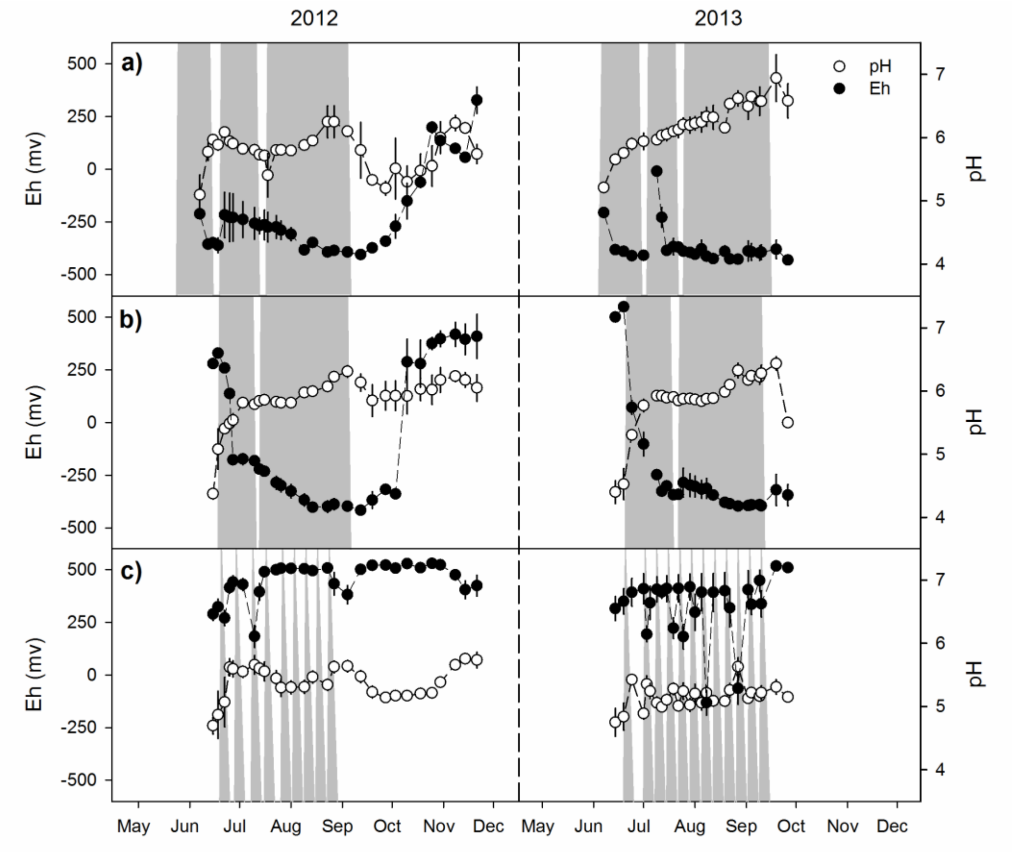

Figure 2 -Variations in topsoil pH (open symbols) and Eh (closed symbols) values over two rice cropping seasons as a function of water management practices involving a water seeding and continuous flooding (WFL), b dry seeding and flooding at tillering stage (DFL), and c dry seeding and intermittent irrigation (DIR). Shaded areas represent the presence of flood water. Error bars represent the standard error of replicated measurements (n=3)

Moreover, temporal variations in DOC at this depth followed a bimodal trend, more evident in 2013, with maxima at the beginning (mid-June) and towards the later stages (beginning September) of the cropping season (Fig. 3a). In both years, increasing DOC concentrations during flooding were also observed at 50 cm (11-29 mg C l^{-1}; mean 18.4 ± 7.2 mg C l^{-1}), and to a lesser extent, at 75 cm (8-23 mg C l^{-1}; mean 13.0 ± 4.3 mg C l^{-1}).

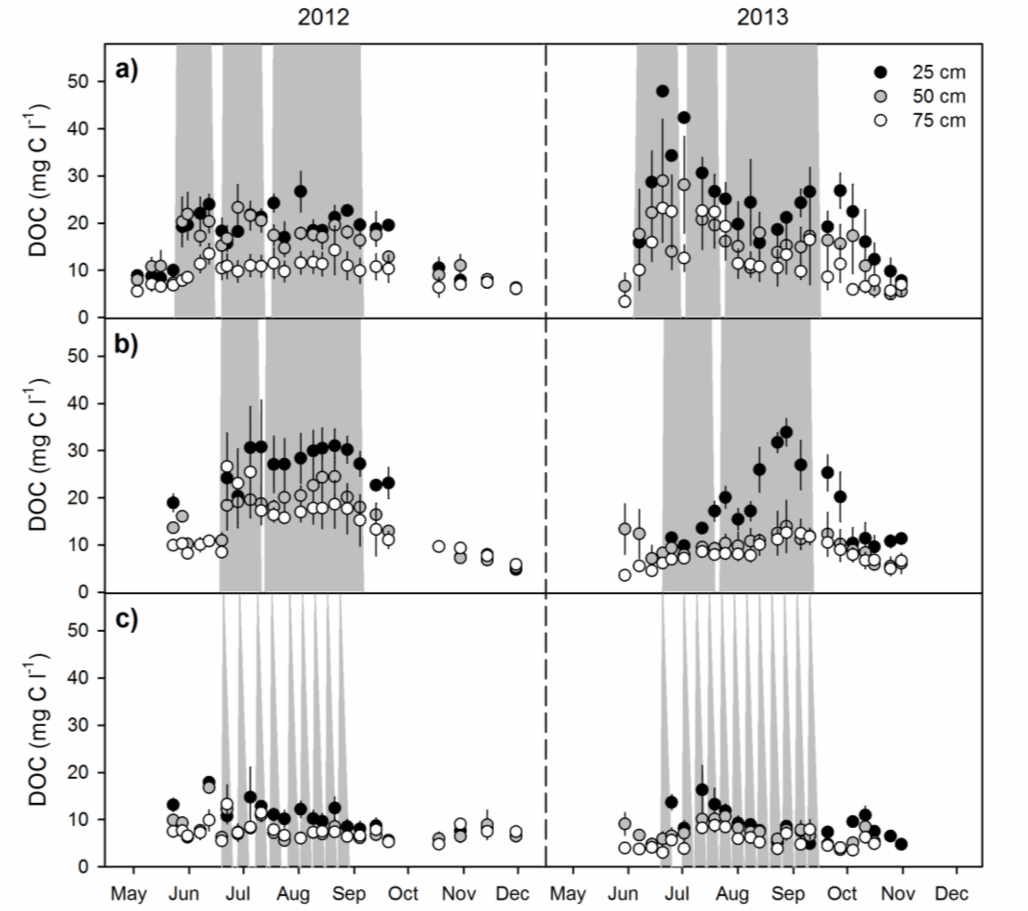

Figure 3 -Variations in DOC concentrations at different depths over two rice cropping seasons a sa function of water management practices involving a water seeding and continuous flooding (WFL), b dry seeding and flooding at tillering stage (DFL), and c dry seeding and intermittent irrigation (DIR). Shaded areas represent the presence of flood water. Error bars represent the standard error of replicated measurements (n=4). The effects of water management, sampling date and depth, as well as water management×date, and water management×depth interactions, on DOC concentrations analysed by ANOVA for both years were all significant (p=0.000)

In DFL, topsoil DOC concentrations also increased with the onset of flooding though later on in the cropping season with respect to WFL (Fig. 3b). Under flooded conditions DOC concentrations at 25 cm ranged between 9.8 to 33.9 mg C l^{-1} with maximum values occurring towards the end of August just before final field drainage (Fig. 3b).

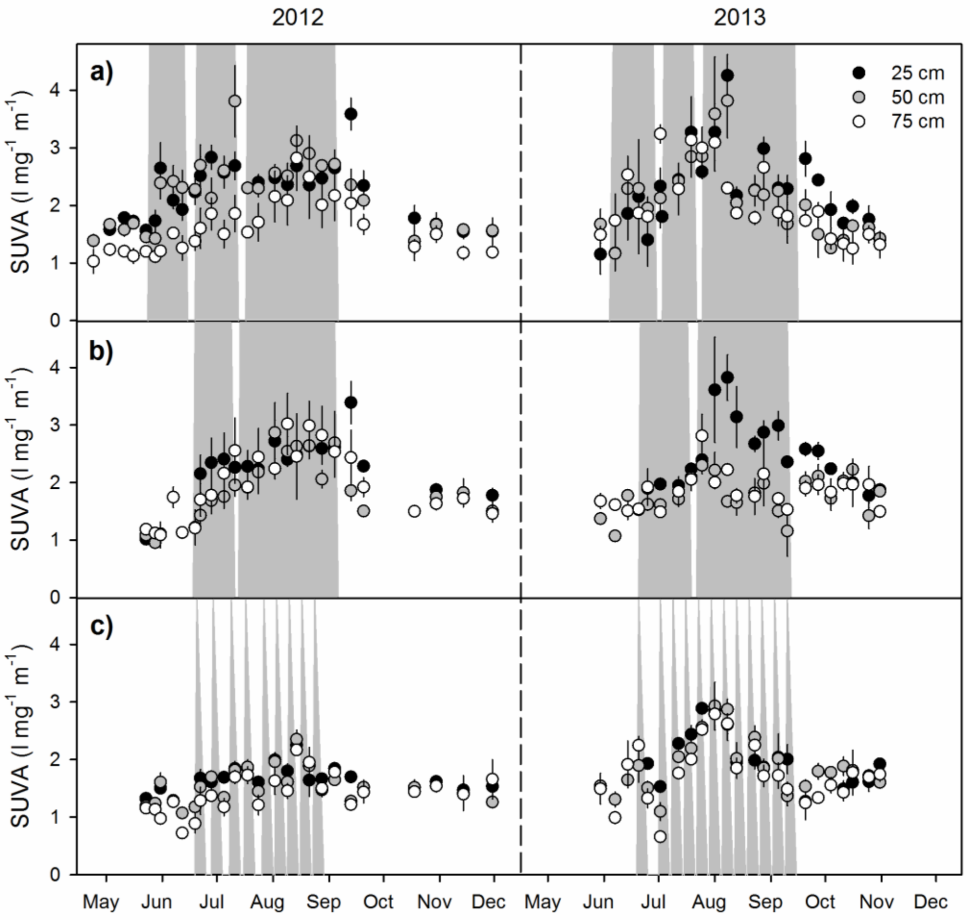

Figure 4 - Variations in soil solution specific UVabsorbance (SUVA) values at different depths over two rice cropping seasons as a function of water management practices involving a water seeding and continuous flooding (WFL), b dry seeding and flooding at tillering stage (DFL), and c dry seeding and intermittent irrigation (DIR). Shaded areas represent the presence of flood water. Error bars represent the standard error of replicated measurements (n=4). The effects of water management, sampling date and depth, as well as water management×date, and water management×depth interactions, on SUVA analysed by ANOVA for both years were all significant (p=0.000)

DOC concentrations at greater depths also tended to increase during flooding, although this increase was more evident in 2012 than 2013. In the former, maximum concentrations of 24.5 mg C l^{-1} were measured in correspondence with the highest concentrations at 25 cm (end of August; Fig. 3b).

In DIR, maintenance of oxic conditions through intermittent irrigation resulted in relatively lower DOC concentrations throughout the cropping season and at all soil depths with respect to the other treatments ($p < 0.001$; Fig. 3c). Over both cropping seasons, mean DOC concentrations were 9.7 ± 3.1 mg C l^{-1} at 25 cm, 7.4 ± 2.3 mg C l^{-1} at 50 cm, and 6.5 ± 2.1 mg C l^{-1} at 75 cm with little variation in time.

The increase in DOC during field flooding was generally accompanied by an increase in its aromatic character evidenced by increasing SUVA values at all soil depths (Fig. 4). In WFL, mean SUVA values at 25 cm increased from 1.51 l mg^{-1} m^{-1} before flooding to 2.51 l mg^{-1} m^{-1} during flooding and down to 1.91 l mg^{-1} m^{-1} after final field drainage (Fig. 4a). Maximum values of 3.59 and 4.26 l mg^{-1} m^{-1} were observed towards the later stages of the cropping season in 2012 (mid-September) and 2013 (beginning August), respectively. This increase in SUVA values with flooding was not limited to the topsoil since similar trends and maximum values were also observed at 50 cm and, to a lesser extent, at 75 cm.

In DFL, relatively low SUVA values were obtained at all depths at the beginning of the cropping season when the fields were still drained (mean 1.31 ± 0.27 l mg^{-1} m^{-1}), and again after final field drainage before harvest (mean 1.94 ± 0.38 l mg^{-1} m^{-1}; Fig. 4b). With the onset of flooding SUVA values at 25 cm tended to increase steadily reaching maximum values of 3.39 and 3.82 l mg^{-1} m^{-1} in 2012 (mid-September) and 2013 (beginning August), respectively. A similar trend was also observed at the greater soil depths although this was more evident in 2012 when maximum values at 50 and 75 cm corresponded to peak values observed at 25 cm.

In contrast to the other two management systems, significantly lower SUVA values were observed in DIR ($p < 0.001$), although changes over the rice cropping season showed similar trends (Fig. 4c). In 2012, SUVA values at all depths ranged between 1.07-2.25 l mg^{-1} m^{-1} with mean values of 1.70 ± 0.21, 1.53 ± 0.30 and 1.41 ± 0.33 l mg^{-1} m^{-1} at 25, 50 and 75 cm, respectively. In 2013, average values were slightly higher than 2012 mainly due to a small increase in absorbance values towards the middle of the cropping season (beginning August) at all depths. Maximum values during this period reached 2.89, 2.93 and 2.79 l mg^{-1} m^{-1} at 25, 50 and 75 cm, respectively.

3.3 Surface water dissolved organic carbon

Inflow and outflow DOC concentrations over the cropping seasons did not show any particular trend over time, and therefore collected data were grouped together (Table 2). Inflow DOC concentrations were significantly lower than those measured in outflow waters from each of the water management treatments. Over the two cropping seasons DOC concentrations in the supply canals ranged from 2.7-7.9 mg C l^{-1} with an average value of 5.1 ± 0.2 mg C l^{-1} (Table 2). Outflow waters showed higher mean DOC concentrations ranging from 6.1 to 6.8 mg C l^{-1} with no significant differences between treatments (Table 2), even though slightly higher maximum DOC concentrations were observed for WFL with respect to DFL and DIR (14.1, 8.9 and 10.9 mg C l^{-1}, respectively). Only for WFL, maximum DOC concentrations in the outflow waters corresponded to the peak values in topsoil DOC observed in the first phase of the cropping period (end June; data not shown). No significant differences were observed in SUVA values between inflow and outflow waters from the three water management practices (Table 2). Compared to soil solutions, mean SUVA values in surface waters were relatively low and ranged between 1.91 and 2.20 l mg^{-1} m^{-1}.

Table 2 - Mean DOC concentrations and specific UV absorbance (SUVA) values for inflow and outflow waters from the three water management practices.

	n	DOC (mg C l^{-1})	SUVA (l mg^{-1} m^{-1})
Inflow	54	5.1 ± 0.2 b	2.10 ± 0.08
Outflow WFL	35	6.8 ± 0.3 a	1.91 ± 0.10
Outflow DFL	26	6.1 ± 0.3 a	2.01 ± 0.13
Outflow DIR	22	6.5 ± 0.3 a	2.20 ± 0.10

Values represent the mean of *n* measurements over two cropping seasons ± standard error. Different letters indicate a significant difference between inflow and outflow waters tested by repeated measures, one-way analysis of variance and the Bonferroni post-hoc test ($p < 0.05$)

3.4 Dissolved iron(II) concentrations

Soil solution Fe^{2+} concentrations generally depended on soil redox conditions therefore resulting in different trends in time and with soil depth among water management practices (Fig. 5). In WFL, Fe^{2+} concentrations in the topsoil (25 cm) increased rapidly with field flooding reaching maximum values of around 24-27 mg Fe l^{-1} in less than 20 days (Fig. 5a). These concentrations were sustained for most of the cropping season except for short periods in correspondence with mid-season drainage and after final drainage before harvest, when Fe^{2+} concentrations dropped rapidly. Mean topsoil Fe^{2+} concentrations over the flooded period were 17.5 ± 8.2 and 22.2 ± 6.0 mg Fe l^{-1} for 2012 and 2013, respectively. Also subsoil Fe^{2+} concentrations tended to increase during flooding reaching maximum values of 23-25 and 9-28 mg Fe l^{-1} at 50 and 75 cm respectively.

Flooding also resulted in an increase in soil solution Fe^{2+} concentrations in DFL, though this was more contained and clearly slower with respect to WFL (Fig. 5b). In fact, maximum Fe^{2+} concentrations of 28.3 and 20.7 mg Fe l^{-1} at 25 cm, were only observed after 35 (end July) and 68 (end August) days from initial field flooding in 2012 and 2013, respectively. Similarly, at 50 and 75 cm soil solution Fe^{2+} concentrations tended to increase only slowly, reaching peak values later on during the cropping season (end August). In this treatment, mean Fe^{2+} concentrations during field flooding tended to decrease with soil depth.

Maintenance of oxic soil conditions for most of the cropping season in the DIR treatment resulted in significantly lower soil solution Fe^{2+} concentrations compared to WFL and DFL ($p < 0.001$; Fig. 5c). Over the two years Fe^{2+} concentrations t 25 cm did not exceed 1.0 mg Fe l^{-1}, while at deeper soil depths (50 and 75 cm) concentrations were generally below or close to detection limits (0.2 mg Fe l^{-1}).

Over both cropping seasons and for all water management practices, mean Fe^{2+} concentrations in surface waters (inflow and outflow) were negligible and never exceeded 0.5 mg Fe l^{-1} (data not shown).

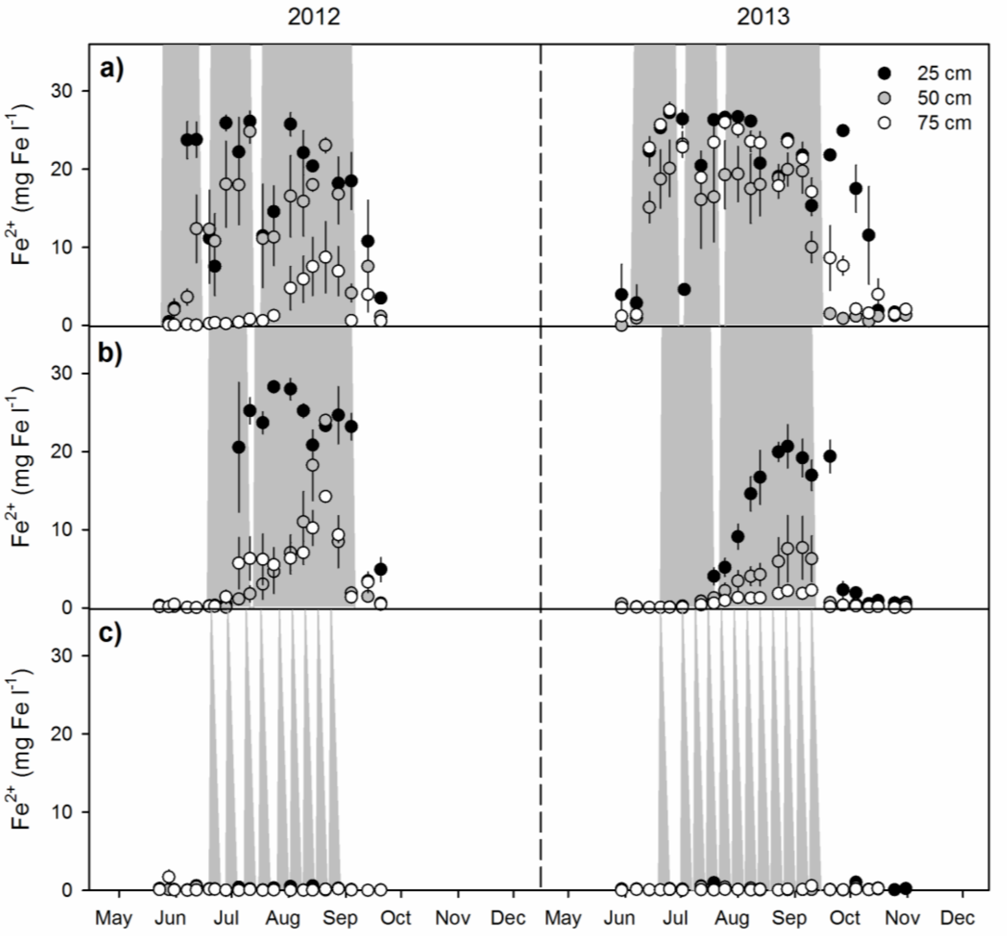

Figure 5 -Variations in soil solution Fe2+ concentrations at different depths over two rice cropping seasons as a function of water management practices involving a water seeding and continuous flooding (WFL), b dry seeding and flooding at tillering stage (DFL), and c dry seeding and intermittent irrigation (DIR). Shaded areas represent the presence of flood water. Error bars represent the standard error of replicated measurements (n=4). The effects of water management, sampling date and depth, as well as water management×date, and water management×depth interactions, on Fe2+ concentrations analysed by ANOVA for both years were all significant (p=0.000)

3.5 Dissolved organic carbon fluxes

The combined effect of water management practices on DOC concentrations and components of the water balance resulted in a strong influence on DOC fluxes in terms of both the total amounts as well as temporal variations. Over both cropping seasons, mean daily inflow of DOC with the water supply for the three treatments ranged between 0.04 and 0.26 g C m^{-2} d^{-1}, with maximum fluxes of 1.32 g C m^{-2} d^{-1} for WFL and DFL, and 0.84 g C m^{-2} d^{-1} for DIR (Fig. 6). As expected, these peak fluxes were mainly recorded in correspondence with the beginning of field flooding in WFL and DFL, or irrigation events in DIR. Cumulative input fluxes calculated over the entire cropping seasons evidenced a greater input of DOC (17.5-46.3 g C m^{-2}) in the WFL and DFL treatments with respect to the DIR treatment (4.8-6.9 g C m^{-2}; Table 3). However, similar flow-weighted DOC concentrations across treatments (4.6-5.1 mg C l^{-1}) suggests that these differences were mainly linked to the different water flow rates in each treatment.

Mean daily DOC fluxes of 0.24, 0.18 and 0.02 mg C m^{-2} d^{-1} with outflow waters were measured over both cropping seasons for WFL, DFL and DIR, respectively, with maximum fluxes reaching values of 1.56, 1.48 and 0.56 g C m^{-2} d^{-1} for the three treatments respectively (Fig. 7). Highest DOC outflow was generally observed during field drainage (WFL and DFL) or irrigation events (DIR). In both years, cumulative DOC outflow over the cropping season were generally greater in WFL and DFL (between 4-18 times) with respect to DIR, although greater cumulative fluxes were measured in 2012 with respect to 2013 (Table 3). For all treatments, flow-weighted DOC concentrations in outflow waters (5.6-6.4 mg C l^{-1}) were slightly greater that the respective concentrations in inflow waters (4.6-5.1 mg C l^{-1}).

In general, higher DOC percolation fluxes were obtained during flooded with respect to drained periods of the cropping season (Fig. 8). In fact, over both cropping seasons, higher mean daily percolation DOC fluxes were obtained for WFL and DFL (0.32 and 0.23 g C m^{-2} d^{-1}, respectively) with respect to DIR (0.03 g C m^{-2} d^{-1}), as were maximum percolation fluxes (1.68, 2.07 and 0.73 g C m^{-2} d^{-1} for WFL, DFL and DIR respectively; Fig. 8). Cumulative percolation DOC fluxes over the entire cropping season ranged from 3.7 to 51.1 g C m^{-2} and tended to decrease in the order WFL>DFL>>DIR, although greater cumulative fluxes were measured in 2012 with respect to 2013 (Table 3).

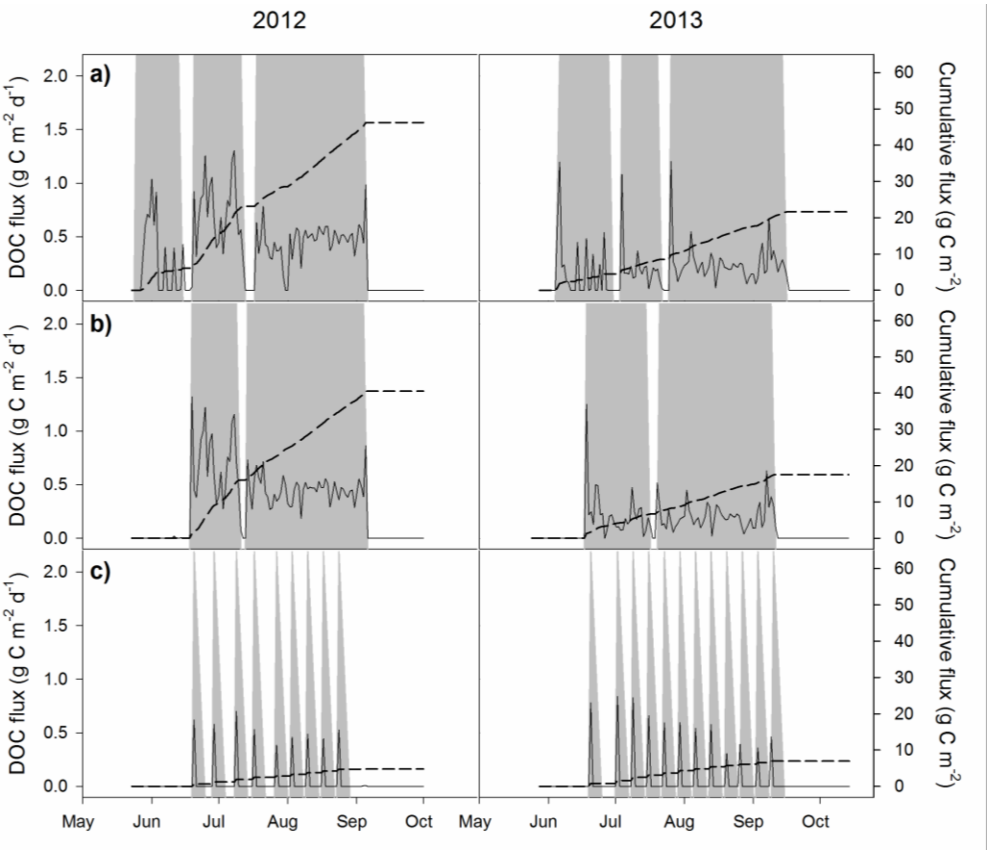

Figure 6 - Variations in estimated DOC inflow fluxes from supply canals over two rice cropping seasons as a function of water management practices involving a water seeding and continuous flooding (WFL), b dry seeding and flooding at tillering stage (DFL), and c dry seeding and intermittent irrigation (DIR). Dashed line represents cumulative fluxes over the cropping season, while shaded areas represent the presence of flood water

In the WFL treatment, the greatest amount of DOC percolation occurred during the first 30 DAS, accounting for 39-45% of the total cumulative flux (Table 3). In contrast to WFL, percolation of DOC at the beginning of the cropping season (0-30 DAS) in the DFL treatment was relatively limited, accounting for only 1-2% of the total flux, but increased rapidly with the onset of flooding at tillering stage. Much lower amounts of DOC were percolated in DIR and most of this was concentrated between 31-60 DAS (44-51% of the total DOC percolation flux).

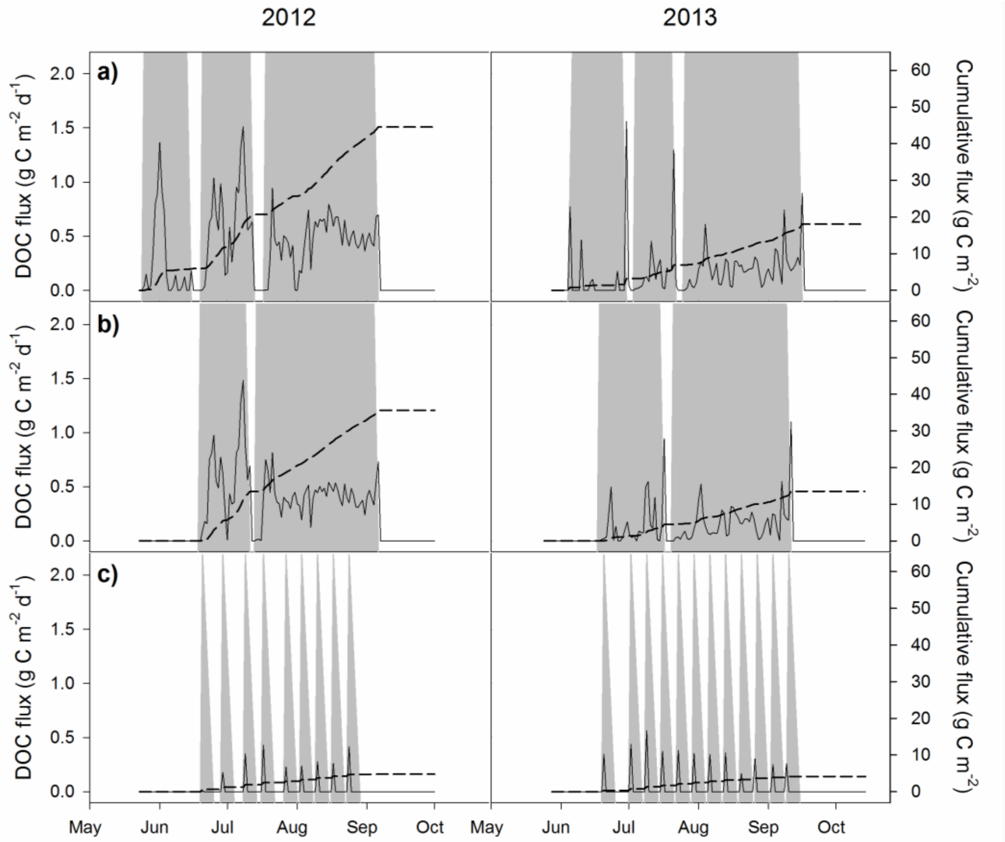

Figure 7 -Variations in estimated DOC outflow fluxes from drainage canals over two rice cropping seasons as a function of water management practices involving a water seeding and continuous flooding (WFL), b dry seeding and flooding at tillering stage (DFL), and c dry seeding and intermittent irrigation (DIR). Dashed line represents cumulative fluxes over the cropping season, while shaded areas represent the presence of flood water

Flow-weighted DOC concentrations in percolation waters were markedly higher than those obtained in inflow and outflow waters for all treatments under study (Table 3). Moreover, higher values were obtained for WFL and DFL (18.5-27.0 mg C l^{-1}) with respect to DIR (9.7-12.1 mg C l^{-1}; Table 3). The high flow-weighted DOC concentrations obtained for WFL were generally maintained throughout the cropping season. In contrast, DFL showed relatively lower concentrations in the first 30 DAS with respect to the rest of the season, in both years studied.

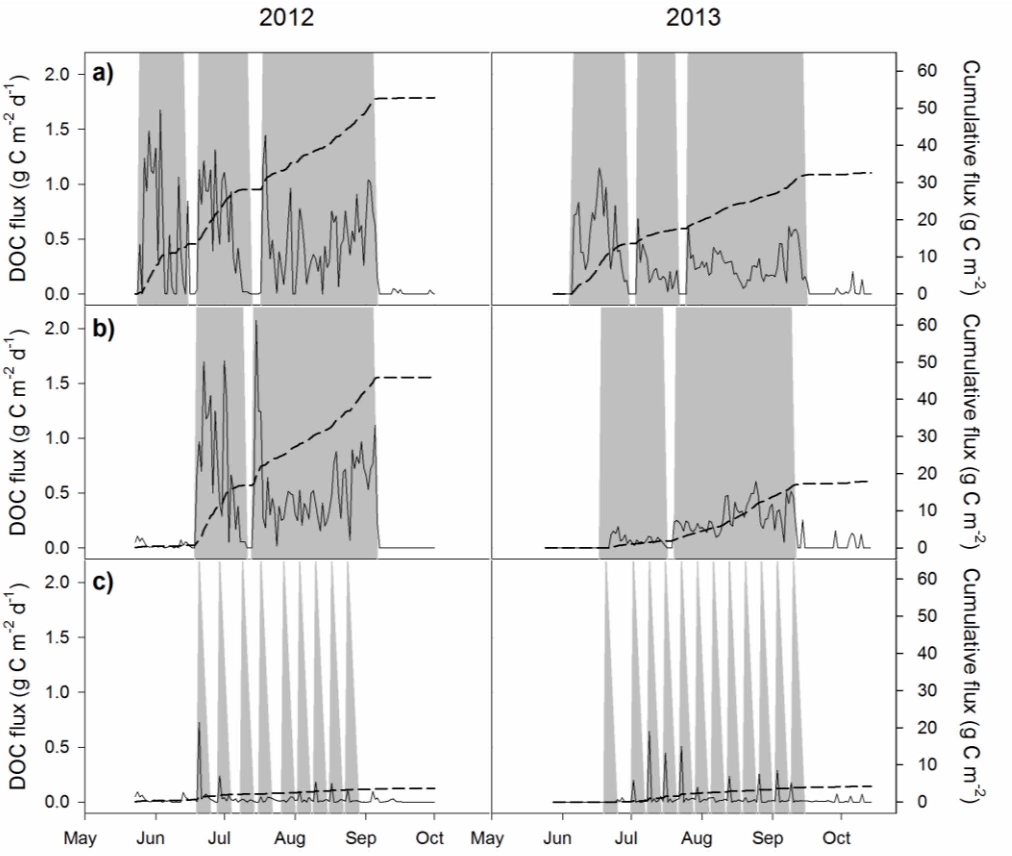

Figure 8 - Variations in estimated DOC percolation fluxes (at 25 cm) over two rice cropping seasons as a function of water management practices involving a water seeding and continuous flooding (WFL), b dry seeding and flooding at tillering stage (DFL), and c dry seeding and intermittent irrigation (DIR). Dashed line represents cumulative fluxes over the cropping season, while shaded areas represent the presence of flood water

Flow-weighted DOC concentrations in DIR were generally similar throughout the cropping season, except for the beginning of the 2013 cropping season where lower than average concentrations were observed in the first 30 DAS and higher concentrations in the 31-60 DAS period.

Table 3 - Cumulative DOC fluxes and flow-weighted DOC concentrations in inflow, outflow and percolation waters over the two cropping seasons as a function of water management practices

	DOC flux (g C m^{-2})			Flow-weighted DOC (mg C l^{-1})		
	WFL	DFL	DIR	WFL	DFL	DIR
2012 cropping season						
Inflow[a]	46.3	40.5	4.8	4.8	4.7	4.6
Outflow[a]	44.3	35.6	2.4	6.4	5.6	5.8
Percolation[a]	51.1	45.9	3.7	20.8	25.2	12.1
0–30 DAS[c]	19.7	0.7	0.5	19.1	13.7	13.8
31–60 DAS	11.9	16.7	1.6	21.4	20.2	11.9
61–90 DAS	12.3	14.1	0.8	21.7	28.3	12.0
91–120 DAS	7.2	14.5	0.7	23.6	30.6	10.9
2013 cropping season						
Inflow[b]	21.6	17.5	6.9	5.0	5.1	5.0
Outflow[b]	18.1	13.5	4.1	6.4	6.2	6.3
Percolation[b]	32.6	17.9	4.2	27.0	18.5	9.7
0–30 DAS[c]	14.6	0.4	0.1	32.8	1.8	1.4
31–60 DAS	5.8	2.8	2.1	26.5	15.5	14.4
61–90 DAS	7.0	8.4	1.1	20.3	24.0	8.1
91–120 DAS	4.1	5.7	0.7	30.8	32.7	7.4

[a] Calculated over entire cropping period (between 15/05/12 and 28/09/12)
[b] Calculated over entire cropping period (between 28/05/13 and 15/10/13)
[c] 30-day cumulative data for percolation flows; DAS, days after seeding

3.6 Net methane emissions

Water management practices strongly influenced both the extent and temporal variations in net CH_4 fluxes from the soil during the rice cropping season (Fig. 9) that were generally related to the establishment of anoxic soil conditions and therefore linked to the duration of field flooding. In WFL, CH_4 emissions were recorded a few days after initial field flooding, and rapidly increased to reach maximum fluxes of 0.59 and 0.69 g C m^{-2} d^{-1} within 15-20 days in 2012 and 2013, respectively (Fig. 9a). Emission rates fell drastically in correspondence with mid-season drainage events, only to increase again with subsequent flooding. However, during the cropping season, emission fluxes generally tended to decrease with time and returned to background levels (< 0.01 g C m^{-2} d^{-1}) when fields were drained prior to harvest (end September). Mean CH_4 fluxes over the flooded period were 0.19 ± 0.03 and 0.30 ± 0.03 g C m^{-2} d^{-2} in 2012 and 2013, respectively.

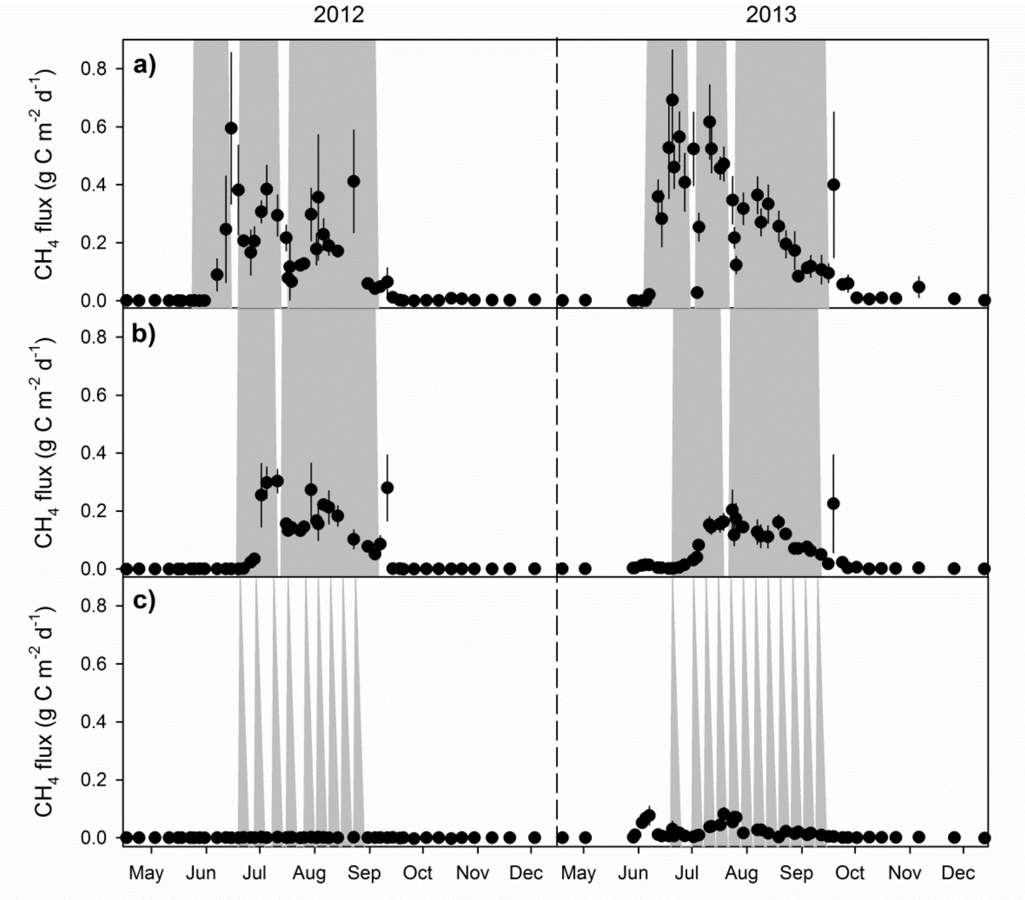

Figure 9 - Variations in net CH_4 emission fluxes over two rice cropping seasons as a function of water management practices involving a water seeding and continuous flooding (WFL), b dry seeding and flooding at tillering stage (DFL), and c dry seeding and intermittent irrigation (DIR).Shaded areas represent the presence of flood water. Error bars represent the standard error of replicated measurements (n=4). The effects of water management and sampling date, as well as their interaction, on net CH_4 emission fluxes analysed by ANOVA for both years were all significant (p=0.000)

Similarly, in DFL, CH_4 emissions increased in correspondence with field flooding, and, after reaching maximum fluxes towards mid-July, tended to decrease with time (Fig. 9b). However, mean CH_4 fluxes during field flooding (0.14 ± 0.02 and 0.10 ± 0.01 g C m^{-2} d^{-2} in 2012 and 2013, respectively) were smaller, and lower maximum emissions were measured (0.30 and 0.20 g C m^{-2} d^{-1} in 2012 and 2013, respectively), with respect to WFL ($p < 0.001$). In both years we observed singular high emission peaks just after final drainage in September, probably due to the release of methane trapped in the soil or dissolved in soil solution during drainage.

The maintenance of oxic soil conditions in DIR resulted in measured fluxes that were generally below detection limits, except for some sporadic emissions in 2013 that however, did not exceed 0.08 mg C m^{-2} d^{-1} (Fig. 9c).

4 DISCUSSION

4.1 Quantity and quality of DOC in paddy soils

Water management strongly affected trends in pore-water DOC concentrations with time and depth, clearly showing a dependence on soil water status, and consequently redox conditions. Cropping systems managed under continuous flooding led to the accumulation of important amounts of DOC, with mean topsoil concentrations of 19.4 mg C l^{-1} and maximum values up to 48 mg C l^{-1}. High DOC concentrations in flooded rice paddies have frequently been reported with values often in excess of 10-20 mg C l^{-1} (Katoh et al., 2004; Maie et al., 2004; Xu et al., 2013; He et al., 2015). This has generally been attributed to the limited or incomplete decomposition of organic matter and accumulation of water soluble intermediate metabolites under anoxic conditions (Sahrawat, 2004). Moreover, although similar C mineralization rates have been reported under both anoxic and oxic conditions (Hanke et al., 2013), the higher substrate use efficiency by the microbial biomass under anaerobic conditions may lead to a reduced mineralization of straw-derived C with an enhanced preference for the most labile C pools (Devêvre and Horwáth, 2000). The relatively high DOC concentrations and low SUVA values observed at the beginning of the cropping season under continuous flooding seem to suggest that most of the accumulated soluble organic C derived from decomposing crop residues.

Post-harvest incorporation of crop residues represents the main input of organic C into paddy soils (Kimura et al., 2004), which in our experimental platform, accounted for a organic C input of 270-385 g C m^{-2} yr^{-1} in the form of rice straw alone (i.e. excluding below-ground biomass C; *unpublished*). The decomposition of these residues may supply important amounts of DOC, predominantly during the first stages of the cropping season (Katoh et al., 2005). However, the extent of this contribution also depends on the timing of crop residue management practices. In fact, we attributed the generally higher DOC concentrations observed in 2013 (Fig. 3a) to the shorter time span between crop residue incorporation and field flooding with respect to 2012 (27 and 53 days, respectively). As a consequence of the particularly abundant precipitation in the spring of 2013, soil tillage had to be delayed, probably influencing the amount of labile straw-derived C present in the soil during the cropping season.

The increasing trend in SUVA with time under flooded conditions (up to values of 3.6-4.3 l mg^{-1} m^{-1}) points to an increasing contribution of more aromatic, soil-derived organic C, although the selective preservation of aromatic, residue-derived constituents under anoxic conditions could have also partly contributed to this increase. The important release of Fe^{2+} due to the reductive dissolution of Fe (hydr)oxides as well as the increase in soil pH towards neutral values, suggest that anoxic conditions could indeed lead to the abiotic release of DOC previously stabilized on the mineral matrix (Grybos et al., 2009). This was further supported by the significant correlation between DOC and Fe^{2+} concentrations in the topsoil ($r = 0.639$; $p < 0.001$; Fig. 10a). Continuous flooding also resulted in an increase in DOC contents, SUVA values and Fe^{2+} concentrations in the subsoil. This points to the mobility of DOC along the soil profile, not only as a consequence of the higher concentrations in the topsoil, but also due to a limited retention of aromatic constituents during passage through the reduced mineral horizons. Moreover, maintaining anoxic soil conditions for relatively long periods of time could result in an important transfer of pedogenic Fe from the topsoil to the subsoil, with important implications on C stabilization (Wissing et al., 2013; Sodano et al., 2016). Fe redox transformations, transport of soluble Fe^{2+}, and redistribution of pedogenetic Fe (hydr)oxides along the soil profile may have a profound, but still not well understood, influence on DOC cycling and C sink potential of paddy soils subjected to frequent changes in redox conditions (*c.f.* Kalbitz et al., 2013; Winkler et al., 2016).

Adoption of dry seeding and delayed flooding resulted in much lower DOC concentrations in the first part of the cropping season with respect to water seeding and continuous flooding. Oxic soil conditions present during this period probably favoured the rapid turnover of this labile organic C pool preventing its accumulation. Nonetheless, with the onset of flooding at tillering stage, the concentration of DOC and its aromatic character tended to increase suggesting an important release of soil-derived DOC in this water management too. This was consistent with the corresponding increase in pore-water Fe^{2+} concentrations observed in the later stages of the cropping season. Moreover, variations in Fe^{2+} concentrations in the dry seeded treatment explained 71% of the variability in DOC concentrations ($p < 0.001$), compared to only 41% in the water seeded treatment (Fig. 10a) supporting our hypothesis that DOC accumulated under the former water management was mainly soil-derived.

The release of Fe^{2+} in solution during field flooding was however, more limited and clearly slower in the dry with respect to water seeded treatment. In the former, the oxic soil conditions together with the warmer ambient temperatures during the first 25-35 DAS probably favoured the decomposition of the straw-derived C incorporated into the soil. This could have limited the availability of labile C once the fields were flooded, partially reducing the supply of electrons from organic matter degradation to Fe-reducing microorganisms. Moreover the lower pH values and slower decrease in Eh observed with the onset of field flooding in the dry with respect to the water seeded treatment, lends support to this interpretation. These observations suggest that whereas crop residue incorporation in proximity of field flooding (water seeded) could actually result in a positive feedback on DOC concentrations by stimulating the microbially-driven, reductive dissolution of Fe (hydr)oxides and the consequent release of soil-derived DOC, dry seeding could limit this effect. This was further corroborated by the generally higher DOC concentrations and maximum SUVA values observed under continuous flooding in the 2013 with respect to the 2012 cropping season as a consequence of the closer temporal proximity between residue incorporation and flooding in 2013.

In contrast to the other two water management practices, maintaining rice cropping under aerobic conditions by intermittent irrigation resulted in relatively low DOC contents throughout the soil profile with concentrations generally <10 mg C l^{-1}. Specific UV absorption values and Fe^{2+} concentrations were relatively low, never exceeding 2.25 l mg^{-1} m^{-1} and 1.0 mg Fe l^{-1}, respectively. These results suggest that maintaining oxic conditions not only enhanced the turnover, but also limited the release and mobility of DOC throughout the cropping season.

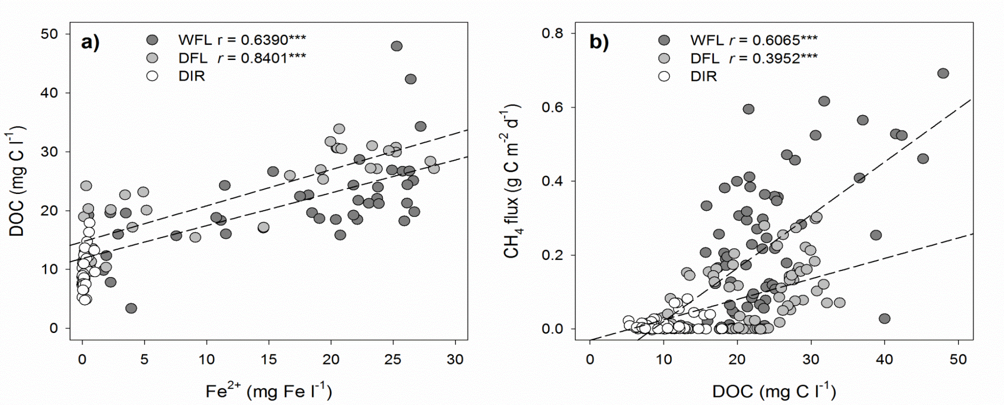

Figure 10 - Correlations between topsoil DOC concentrations, and a Fe2+ concentrations or b CH_4 fluxes for the three water management practices

4.2 DOC export and transport from topsoil to subsoil

Water management practices may have an important effect on the hydrology of paddy soils (Sacco et al., 2012; Chiaradia et al., 2014; Zhao et al., 2015), and consequently on DOC fluxes. In fact, rice paddies may contribute significant amounts of DOC to surface waters with important impacts on catchment C budgets and downstream water quality in rice-dominated areas (Ruark et al., 2010). All three water management practices studied evidenced higher DOC concentrations in the outflow with respect to inflow water. However, for all treatments, cumulative DOC fluxes in the outflow were generally lower than DOC fluxes entering the rice paddies with inflow waters, and decreased drastically on going from continuous flooding (18-44 g C m^{-2}) to intermittent irrigation (2-4 g C m^{-2}). This suggests that outflow rather than DOC concentrations, mainly governed organic C exports with surface waters from the different water management practices. This is consistent with the findings of other studies regarding DOC exports from agricultural watersheds (Hernes et al., 2008) and rice fields (Ruark et al., 2010) in particular. Nonetheless, the slightly higher flow-weighted DOC concentrations in output with respect to input waters suggests that rice paddies could represent a net source of organic C to surface waters at field-scale. Although Krupa et al. (2012) reported an increase in the fraction of aromatic and high molecular weight moieties lost with outflow waters over the course of the growing season, we did not observe any differences in the quality of DOC neither between inflow and outflow waters, nor between outflow waters from the different water management practices. This suggests that enrichment of surface waters in aromatic components is strongly linked to soil processes occurring in the topsoil and their contribution will depend on flow through these horizons.

Leaching losses of DOC from paddy topsoils may represent a crucial component of the ecosystem C balance, although this is often overlooked. Very few studies have attempted to quantify these fluxes (Katoh et al., 2004; Maie et al., 2004), and even less have evaluated the influence of water management (Xu et al., 2013). Our results evidenced that the transport of DOC from the topsoil to the subsoil was dependent on the combination of hydrological flow regime and the resulting soil moisture conditions. The former was mainly responsible for the differences in measured fluxes between the two years within each water management. In fact, the different water fluxes we observed between cropping seasons was mainly attributed to the higher water table depth in 2013 with respect to 2012. Over a cropping season, as much as 32.6-51.1 g C m^{-2} were lost by percolation from the silty-loam textured topsoil under continuous flooding. This could represent an important input of organic C into the subsoil particularly in coarse textured paddy soils where the plough pan does not act as a transport barrier for DOC between topsoil and subsoil (*c.f.* Wissing et al., 2011). Large vertical fluxes of DOC in rice paddies may strongly contribute to the formation of stable SOC in the deeper mineral horizons resulting in an increase in C stocks, as already postulated for oxic soils (Kalbitz and Kaiser, 2008). However, the interaction of DOC with soil minerals and its subsequent stabilization against microbial mineralization (Eusterhues et al., 2014) could largely depend on soil redox conditions. Moreover, a significant proportion of this C flux (40-45%) occurred during the first month of rice cropping. Considering the variations in SUVA values with time, the distribution of C percolation fluxes over the cropping season could strongly influence the source and chemical composition of DOC reaching the subsoil, and consequently its retention on mineral surfaces.

Total DOC percolation was reduced by about 25% with the adoption of dry seeding (17.9-45.9 g C m^{-2}), and by 90% with rotation irrigation (3.7-4.2 g C m^{-2}). This was in accordance with the findings of Xu et al. (2013) that observed a 46% decrease in DOC leaching under non-flooded, controlled irrigation (6.3 g C m^{-2}) with respect to continuous irrigation (11.8 g C m^{-2}). The relatively high flow-weighted concentrations >20 mg C l^{-1} observed during field flooding suggest that soil processes that led to the elevated DOC concentrations in topsoils under anoxic conditions, can also be responsible for important inputs of organic C to the subsoils. Lower, but not negligible flow-weighted DOC concentrations were observed during the first month of dry seeded rice cropping, and throughout the season where intermittent irrigation was adopted. These results confirmed that the differences in DOC percolation we observed among treatments were not exclusively due to different water flows.

4.3 Substrate availability for methane production

Since both the production and oxidation of CH_4 are known to be influenced by oxygen availability (Conrad, 2002; Ma et al., 2013), water management is one of the most important factors influencing net CH_4 emissions from paddy fields (Neue, 1997). With respect to continuous flooding, dry seeding, and particularly, intermittent irrigation resulted in important reductions in net CH_4 emissions throughout the cropping season. This was in line with the findings of various authors (Tyagi et al., 2010; Yang et al., 2012; Ma et al., 2013; Liu et al., 2014) who showed that frequent field drainage during the cropping season could effectively mitigate CH_4 emissions by reducing the production and also enhancing the oxidation of CH_4.

Dissolved organic C may represent the primary carbon source for CH_4 production, leading to a strong positive correlation between the seasonal pattern of DOC concentrations and CH_4 emissions, particularly in the root zone (Lu et al., 2000). In fact, we observed strong correlations between DOC concentrations in the topsoil and CH_4 fluxes in the fields managed under continuous flooding and dry seeding (r = 0.607 and 0.395, respectively; $p < 0.001$), but not for the intermittent irrigation treatment where CH_4 emissions were often absent (Fig. 10b). Our findings suggest that under continuous flooding, the presence of a more readily mineralizable, residue-derived DOC pool was probably linked to a greater substrate availability for methane production, particularly at the beginning of the cropping season (Watanabe et al., 1999; Katoh et al., 2005). We do not, however, have substantial evidence to confirm that any positive feedback of residue-derived C on the release of presumably, less labile, soil-derived DOC could lead to a corresponding increase in CH_4 production as reported by Yuan et al. (2014). Nonetheless, maintaining aerobic soil conditions at the beginning of the cropping season with dry seeding may have led to a preferential mineralization of the more labile constituents of the incorporated crop residues before the onset of flooding, consequently resulting in a lower amount of CH_4 emitted per unit DOC (Fig. 10b).

5 CONCLUSIONS

Understanding how water management practices influence DOC cycling during the rice cropping season can provide important insights into the functions of this labile SOC pool in paddy soils. Our results confirm that the typically high DOC concentrations observed in paddy soils (>10-20 mg l^{-1}) are strongly linked to the reducing conditions resulting from field flooding. Adopting water regimes that maintain the soil under anoxic conditions from most of the cropping season, not only enhance CH_4 emissions, but also lead to important DOC fluxes with surface and subsurface waters. In particular, we showed that vertical fluxes of DOC could be rather consistent, and together with the enhanced mobility of Fe^{2+} under reducing conditions, could possibly have important implications on C inputs and accumulation in the subsoil. However, as for CH_4 emissions, these fluxes are strongly dependent on water management.

The cycling of DOC in paddy soils is intimately linked to Fe cycling. In fact, our results indicated that the presence of important amounts of labile, residue-derived organic C in correspondence with field flooding may result in a positive feedback on the abiotic release of soil-derived DOC by promoting the microbially-driven reductive dissolution of Fe (hydr)oxides present in the soil. Moreover, the progressive release of soil-derived DOC under anoxic conditions, probably responsible for the increase in aromatic character during the cropping season, indicated that water management can also influence DOC quality with important implications on the chemical composition of DOC reaching the subsoil.

Acknowledgements

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CHAPTER 7

Estimating the contribution of rainfall, irrigation and upward soil water flux to crop water requirements of a maize agroecosystem in the Lombardy plain[5]

M. Rienzner [a], S. Cesari de Maria [a], A. Facchi [a], F. Wassar [a], C. Gandolfi [a]

[a] Department of Agricultural and Environmental Sciences, Universitá degli Studi di Milano, Milan, Italy

Abstract

In agricultural areas with shallow groundwater tables, capillary rise plays a crucial role in the satisfaction of crop water requirements. While monitoring the root zone inflows and water status allows the evaluation of most of the water balance variables, capillary rise cannot be directly measured; therefore, hydrological models are often employed for its estimation. In the agricultural seasons 2010 and 2011, an intensive monitoring activity (founded under the Lombardy Agricultural Research Program 2007-2009) was carried out in a 10 ha experimental field located in Landriano (Pavia), characterized by a shallow groundwater table depth (0.6 to 1.5 m). The site included six Intensive Monitoring Plots (IMPs in the following), each equipped with instrumentation for continuous monitoring of moisture, water potential and groundwater table depth, and an eddy covariance tower. In the two seasons, periodic campaigns were conducted in the IMPs measuring crop biometric parameters and soil hydrological parameters. In 2010 the field was watered by border irrigation, while in 2011 no irrigation was applied.

Monitoring data were used to carry out simulations with the physically based hydrological model SWAP, in order to assess the relative contribution of the various water fluxes to maize water requirements. While most parameters and inputs necessary for the SWAP implementation were directly measured in the field, it was impossible to detect with sufficient accuracy the saturated hydraulic conductivity (Ks) of a four layered profile. An automatic calibration of these variables was then performed using the optimization algorithm SCEM-UA, which is one of the most powerful algorithms for the search of the global optimum currently available. Results presented in this contribution involves one of the IMPs for year 2010. The calibration procedure identified narrow Ks ranges for all the layers well in agreement with some Ks measurements carried out in the top soil. SWAP simulations run with the 100 best Ks sets show a mean contribution of capillary rise amounting to 50% of the crop water requirements.

Keywords: SWAP, calibration, SCEM-UA, maize water requirements, capillary rise

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1 INTRODUCTION

The unsaturated zone plays an important role in the hydrological cycle, since it is at the interface between atmosphere and groundwater circulation. Water fluxes in the unsaturated zone affect water status, development and production of crops; by an environmental point of view, these fluxes determine mobilization and transport of solutes and pollutants from the soil surface to the aquifer system.

There are several reasons for modelling hydrological processes in the unsaturated zone, one of them is definitely the existing limit at the possibility of measuring all the variables we need to know about the physical system. The models are used to perform extrapolations or predictions that, reasonably, are expected to be useful in decision-making processes focused on hydrological issues (Beven, 2001).

Water movements in the unsaturated zone can be described with mathematical formulations based on different approaches (e.g. Gandolfi et al., 2006) going from very simplified conceptual schemes to models, as SWAP (Kroes and van Dam, 2003), Hydrus-1D (Šimůnek et al., 2008), U3M-1D (Vaze et al., 2004), implementing the numerical solution of the Richards' differential equation. The latter set of models simulates soil, plant and atmosphere as a continuous system in which water movements are driven by potential gradients. In case a thorough analysis of the physical processes is required and all the needed information is available, complex models are usually preferred.

A modelling approach is particularly interesting in sites where there is a strong interaction between the processes occurring at the soil surface and the groundwater, as in areas characterized by shallow groundwater tables. In such situations, a water flow towards the root zone is triggered by the strong potential gradient that occurs when the soil water content nearby the roots becomes very negative. A model simulation can be very useful in the estimation of this upward flux since a reliable direct measurement is at least a complex task.

Numerous studies, performed by different approaches, attempted to quantify the contribution of the capillary rise to the root zone soil water balance, taking into account several variables including, particularly, the crop type and the groundwater depth. Kahlown et al. (2005) reported that with a groundwater depth of 0.5 m irrigation of wheat was no longer required, while in the case of sunflower an irrigation supply equal to the 20% of the evapotranspiration volume showed to be sufficient. Prathapar and Qureshi (1999) showed that with a groundwater depth within 2 m from the topographic surface, crops were able to extract a considerable fraction of the water they needed. Kahlown et al. (1998) illustrated how a groundwater depth of 1 m represents the optimum situation for the growth of many crops, while the capillary rise contribution to the root zone water balance becomes negligible when the groundwater depth becomes 2-3 m. Liu and Luo (2011) suggested a groundwater table at 1.5 m from the soil surface as the optimum for the winter wheat, since this depth allows its complete root development. Kahlown et al. (2005) suggested the optimal groundwater depth to be between 1 and 2 m for all the crops they investigated. For the maize crop, the same authors reported a required irrigation contribution of 75 mm when the groundwater depth was 1 m, this contribution was shown to decrease approximately linearly with the increasing of the water table depth (the linear decrease was highlighted for all the crops examined). A linear relationship between the groundwater depth and the required irrigation amount was also detected by other authors, including Sepaskhah et al. (2003). Authors, however, came to different conclusions, since factors such as climate of the experimental areas or soil types therein play a non-negligible role.

Although maize is a crop fairly affected by water ponding (often happening when shallow groundwater combines with heavy rains or abundant irrigation), massive roots uptake and yields are documented also with groundwater depths of few tens of centimetres. With a water table depth of 0.5 m several authors found groundwater contributions around 40% of the crop water requirements and an increase in yield (Follett et al., 1974; Cavazza and Pisa, 1988; Pisa and Ventura, 1991). The same contribution was observed by Kahlown et al. (2005) for maize in an arid region of Pakistan. These authors also reported that the contribution decreases to 30% of the crop water requirements with a groundwater depth of 1 m and to 7.5% with a groundwater depth of 1.5 m. Soppe and Ayars (2003) showed that the contribution of shallow water tables is not constant in time but increases with the increasing of the rooting depth, reaching its maximum value at the end of the growth phase of the plant, when roots are fully developed. Liu and Luo (2011) concluded their study proposing irrigation systems in which the water table depth could be maintained at a depth of 1.5 m or less, allowing an increase in crop production and a reduction in the use of surface irrigation.

In order to have a reliable model estimation of the water fluxes, especially in case of complex physically based models (i.e. implementing the Richards' equation), a relevant effort has to be spent for the quantification of the model parameters. Some of the needed parameter values are difficult to be quantified, even in presence of in-field or lab measurements. Among them, the effective soil saturated hydraulic conductivity (K_s), which is the value needed by the model (valid under the hypothesis of spatial homogeneity), is actually a virtual value since it does not correspond to any specific conductivity that can be measured in the field where a relevant spatial variability usually exists. The calibration of K_s can be done through inverse modelling (i.e. finding the value of the parameters giving the best fit between field measurements and model outputs) adopting the algorithms available in literature for the global optimum search (e.g. SCE-UA, SCEM-UA, PEST, SWARM).

This research aims at estimating the upward groundwater flux in an experimental case characterized by a shallow groundwater table (as it is typical for large areas of the Po valley plain) in order to assess its contribution to the satisfaction of maize water requirements among the other water inputs (rain and irrigation). For this purpose, the hydrological model SWAP (Soil Water Atmosphere Plant model, Kroes and van Dam, 2003) has been implemented using detailed monitoring data collected in field. For the calibration of the saturated hydraulic conductivity, the model has been coupled with the algorithm SCEM-UA (Vrugt et al., 2003), which is effective and efficient in locating the optimal values in multidimensional parameters spaces in case of highly-non-linear systems. In this paper, preliminary results concerning one site and one year are presented and discussed.

2 MATERIAL AND METHODS

2.1 Monitoring activity

In the agricultural seasons 2010 and 2011, an intensive monitoring activity was carried out for quantifying fluxes and storage of water and carbon in two maize agro-ecosystems of the Lombardy plain, according to the purpose of the AC-CA project (Gandolfi et al., 2012), funded under the Lombardy agricultural research program 2007-2009. The experimental site this paper is concerned is a 10 ha field located in Landriano (Figure 1 – 45°19’ N, 9°15’ E, 88 m a.s.l), characterized by a shallow groundwater table depth (0.6 to 1.5 m). In both the years the field was seeded with a long season Zea Mays variety (class 600-700) and a border irrigation was applied just in the first one. The monitoring setup involved an eddy covariance tower measuring water and carbon fluxes and instruments for the continuous monitoring of the soil water status installed in six Intensive Monitoring Plots (IMPs hereafter). Each IMP was provided with: (i) a FDR Sentek soil water content probe (sensors placed at 7, 27, 47, 67 cm depth), (ii) 4 tensiometers (installed at the same depths of the soil water content sensors) and (iii) a 3 m piezometric pipe equipped with a STS pressure transducer.

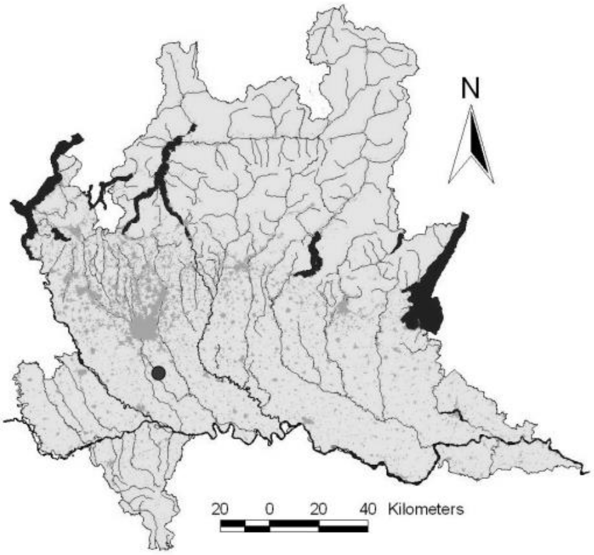

Figure 1 - Location of the experimental site (black dot) within the Lombardy region

Moreover, about 8 campaigns per agricultural season were carried out in each IMP to measure crop biometric parameters (leaf area index, crop height and rooting depth) and to collect soil samples for assessing soil physico-chemical properties (soil texture, organic matter content, bulk density). At the same dates also saturated hydraulic conductivity measurements with two Guelph permeameters and one tension infiltrometer were carried out at the same sites (Rienzner et al., 2011). Finally, undisturbed soil samples were extracted in September 2010 for the laboratory determination of soil retention curves (by tension plates and the Richards' pressure plate apparatus).

2.2 The SWAP hydrological model

Among the numerical models solving the Richards' equation in the one-dimensional vertical form, SWAP (Soil Water Atmosphere Plant model, Kroes and van Dam, 2003) is one of the most widely used and best documented. It adopts the modified differential Richards' equation which includes a sink term representing the macroscopic flow extracted by the vegetation (depending on plant characteristics, local soil water potential and transpiration demand due to climate). SWAP solves the Richards' equation by a finite difference scheme adapted from those described by Haverkamp et al. (1977) and Belmans et al. (1983); initial and bottom boundary conditions must be provided as input.

The soil profile is modelled as a sequence of layers, each one with its own hydraulic characteristics. The layers are further discretized into smaller compartments adopted in the finite differences solution scheme. Soil retention curves θ(h) and unsaturated hydraulic conductivity K(θ) of the layers are described by the analytic equations of Van Genuchten (1980) and Mualem (1976) respectively.

Regarding the crop development, SWAP includes a detailed crop growth model (WOFOST 6.0, Spitters et al., 1989; Hijmans et al., 1994) and, alternatively, a simple module needing the time series of leaf area index (LAI) or soil cover fraction (CF), crop height, roots depth and distribution. The interception is modelled by the analytical model proposed by Von Hoyningen-Hune (1983) and Braden (1985). The potential evapotranspiration can be calculated either by the Penman-Montieth equation (Allen et al., 1998) or by applying crop factors to a reference evapotranspiration given in input. Then, the actual transpiration is derived from the potential accounting for soil cover, moisture and salinity conditions in the root zone (weighted by the root density), while the actual evaporation depends on the capacity of the soil to transport water to the soil surface.

As regards irrigation, it can be fixed or scheduled by SWAP choosing among different time and depth criteria.

2.3 Input data and SWAP parameterization

Among the collected data (6 IMPs and two years), IMP-5 year 2010 was chosen as case study for this contribution. The chosen simulation period starts on 08/05/2010 (2 days before crop emergence) and ends at the maize harvesting (11/09/2010). The initial conditions of soil water potential were fixed according to the groundwater level measured in the day the simulation starts (1 cm below the soil surface) and the bottom boundary condition was fixed by the daily series of groundwater depth.

Soil profile was divided into four layers having their centre at the sensors depth (Section 2.1), further divided in 1cm-thick compartments; the fourth layer was extended up to the bottom of soil profile (4 m).

The four retention curves were obtained by least squares regression, on the pairs of water content (θ) and water potential (h) values measured at the four different depths, with the Van Genucthen curve. The calibration values were the collected field measurements (along the season) and the laboratory test out comes made with tension and Richards' plates apparatus on undisturbed soil samples taken in September 2010 at the same depths of the sensors. Van Genucthen curve calibration was performed by using a MATLAB algorithm solving nonlinear curve-fitting problems in least-squares sense (lsqcurvefit.m of the MATLAB Optimization Toolbox; Coleman and Li, 1996) for all the parameters except of the saturated water content, which was selected according to field measurements.

Maize growth was computed using the simple crop module since the crop biometric measurements were directly collected in field (linear interpolation was used to obtain the complete time series).

Daily meteorological data recorded by a 200m-far meteorological station were used, i.e. solar radiation (KJ m^{-2}), maximum and minimum temperature (°C), air humidity (KPa), wind speed (m s^{-1}) and rain (mm).

As regards irrigation, on day 25/07/2010 a water amount was supplied by border irrigation which produced in IMP-5 an estimated infiltration of 65.9 mm (obtained assessing local water table fluctuations and changes in soil moisture).

2.4 SCEM-UA

SCEM-UA (Shuffled Complex Evolution Metropolis - usable algorithm (Vrugt et al., 2003a; Vrugt et al., 2003b) is an algorithm for optimization, inverse modeling and assessment of hydrologic model parameters. It provides an estimate of the most likely parameter set and its underlying posterior probability distribution. The algorithm is a Markov Chain Monte Carlo (MCMC) sampler, which generates multiple sequences of parameter sets that converge to the stationary posterior distribution for a large enough number of simulations. For further details of SCEM-UA's functioning the reader should refer to Vrugt et al., 2003a; Vrugt et al., 2003b.

Among the automatic calibration procedures, SCEM-UA has been chosen as it is consistent, effective and efficient in locating the optimal model parameters in multidimensional parameters spaces which may not be smooth. As a matter of fact, the case study performed required a calibration of a highly-non-linear system with a four-dimensional parameters space (saturated hydraulic conductivity at four depths).

A pre-alpha version of SCEM-UA (MATLAB version) was used and coupled with the stand-alone model (SWAP.exe) through a set of MATLAB functions and scripts written in order to virtually make SWAP running within the MATLAB environment.

The objective function leading the assessment of the "best" parameter set was defined as a weighted mean of the squared error between measured and simulated values (i.e. soil water potential, soil water content and water table depth). The weight of each term was set according to the reliability of the corresponding measured data. Results of the calibration procedure are described in Section 3.

3 RESULTS

In this section are presented both the optimal K_s sets given by SCEM-UA for the four soil layers the profile was divided in, along with some details of the calibration, and an analysis of the corresponding SWAP outputs.

3.1 Estimation of the saturated hydraulic conductivities

A wide range of K_s values, going from 0.01 to 1000 cm d^{-1}, was given to SCEM-UA as prior distribution of the parameters (actually the inverse problem was performed on decimal log-transformed K_s ranging from -2 to 3). After some exploratory SCEM-UA applications (changing e.g. the weights in the objective function), a suitable inverse solution was obtained with a 15,000 simulations run. The main SCEM-UA output is a matrix having in each row the four parameters corresponding to each SWAP run and the resultant value of the objective function. A selection of 100 parameter sets (100-Opt hereafter) was obtained by extracting the rows having the best 100 values of the objective function, the same was done for the 20 best sets (20-Opt hereafter).

Figure 2 shows the four frequency distributions, one for each layer, of 100-Opt (light grey) and 20-Opt (dark grey). The distributions are bell-shaped and their ranges, compared with their mean values, are quite narrow indicating that the optimization, after a thorough investigation of the whole space, converged to a small area corresponding to the optimal solution in the 4D parameter space.

The values of the objective function of 100-Opt, divided by the overall worst value, ranged from 0.0128 to 0.0132. As different combinations of the four parameters gave nearly equivalent scores of the objective function, the results of the inverse problem consist of multiple solutions for the saturated hydraulic conductivities of the soil profile. The means of the calibrated K_s (100-Opt), going from the first layer (close to the soil surface) to the fourth one, are 10.96, 1.76, 3.74 and 4.79 cm d^{-1} showing some variation along the profile. Notice the conductivity is smaller in the layers containing the plough pan.

A confirm of the SCEM-UA estimation for the shallower layers is found in the results of the Guelph permeameter campaigns (Rienzner et al., 2011; Gandolfi et al., 2012) conducted in the same period and IMP. In fact, the measured values of K_s, involving the first 30 cm, ranged from 2.8 to 9.1 cm d^{-1}, in agreement with the calibration results for the first two layers.

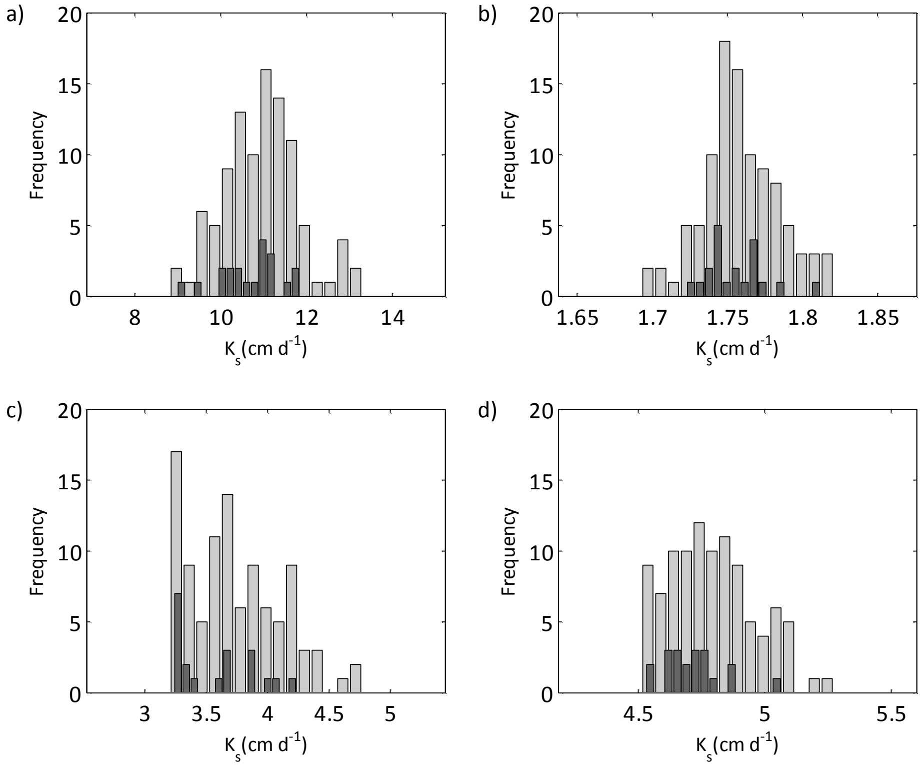

Figure 2. Posterior distribution of the Ks values estimated for the layers: (a) 0-17 cm, (b) 17-37 cm, (c) 37-57 cm, (d) 57-77 cm

3.2 SWAP outputs

The SWAP model was run with the 100-Opt K_s set in order to quantify the upward flux. Capillary rises were thus computed on each day of simulation as the upward fluxes pouring out from the model compartment immediately below the root depth (which changes in time according to the field measurements). The 100 total upward fluxes were then replicated proportionally to their objective score (100 replicates for the best simulation and 1 to the 100th); the histogram of the upward flux is reported in Figure 3.

As an example of the model fitting, Figure 4 shows the measured and simulated soil water contents along the crop season for the 20-Opt K_s set. In the figure, the 20 lines cannot be distinguished due to an overlying of the results, confirming the modelling error to be equivalent in the set.

Finally, Table 1 reports the different contribution to the maize water requirements due to rain, irrigation and capillary rise (100-Opt set), and the water percolation computed in the same way of the upward flux.

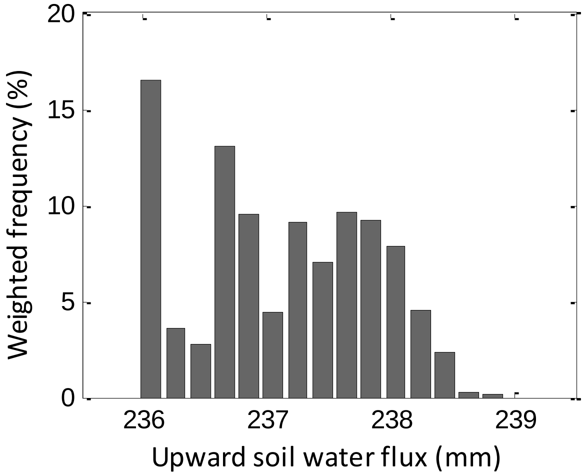

Figure 3 - Histogram of the 100-Opt upward flux, weighted in frequency proportionally to the corresponding value of the objective function

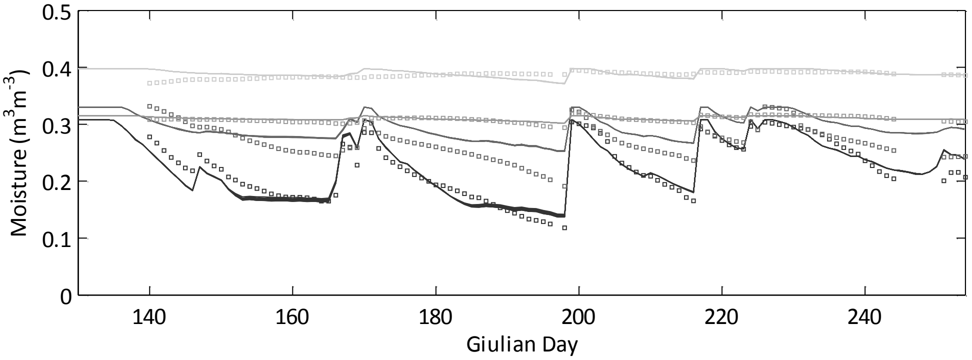

Figure 4 - Moisture trends for the four layers: measured data at the sensors depths (squares) and model outputs for the 20-Opt set at the same depths (straight lines); grey getting lighter moving downward the soil profile

Table 1. Average fluxes as obtained by the 100-Opt SWAP simulations, percentage of satisfaction of the potential evapotranspiration are also provided (E and T are the evaporation and transpiration components)

Potential ET (mm)	Net rain (mm)	Irrigation (mm)	Mean Actual ET (mm)	Mean percolation (mm)	Mean upward flux (mm)
464	313	66	403	-308	237
(E 293, T 171)			(E 255, T 148)		
	(67%)	(14%)	(86%)	(-66%)	(51%)

4 CONCLUSIONS

In order to compute a complete water balance of a Lombardy maize field, including percolation and capillary rise, the SWAP model was implemented with a complete set of field measurements accounting for meteorology, soil properties, measurable water fluxes and crop features. Nevertheless, a calibration procedure of the saturated soil hydraulic conductivities along a layered profile was needed for a reliable application of the model, since it is rather unrealistic to measure directly the effective values of K_s within some square meters and at different depths without disturbing the cropped soil. For this purpose, the MATLAB SCEM-UA toolbox was coupled with the SWAP model in order to obtain an optimal estimation of K_s sets able to represent the experimental soil profile.

The preliminary results for IMP-5−year 2010 show that the potential evapotranspiration (464 mm) is not fulfilled since actual transpiration amounts to 403 mm. It is worth to stress that, while irrigation and rain contribute to the satisfaction of both the soil evaporation and the plant transpiration, the upward flux (237 mm) contributes mainly to transpiration. Moreover, most of rain and irrigation (379 mm) percolate (308 mm) but, due to the shallow groundwater table, capillary rise compensates almost 80% of the same percolation losses, greatly increasing the water efficiency of the whole system.

Rain, irrigation and capillary rise account, respectively, for 67%, 14% and 51% of the crop water requirements represented by the potential evapotranspiration. A significant contribution of capillary rise was thus noticed in case of shallow groundwater which ensured about half the potential evapotranspiration flux; this percentage is even greater than the values found by other authors (i.e. up to 40% with a water table 50 cm below the soil surface in Follett et al., 1974; Cavazza e Pisa, 1988; Pisa e Ventura, 1991; Kahlown et al., 2005).

Concluding, the adopted approach involving the inverse calibration of a physically based model is a promising tool to enhance the analysis of the soil-water-plant system with particular reference to the interactions between the groundwater and the root zone which significantly influence the whole system.

CHAPTER 8

Summary and conclusions

The research work presented in the Thesis has addressed the issue of water management in irrigated rice system in light of the call for improving their water productivity. Three interlinked focus areas have been evaluated: (i) role of monitoring techniques in improving knowledge of rice systems, (ii) field-scale considerations relating to water management in rice cultivation, (iii) impacts on water withdrawals induced by the adoption of “water-saving” regimes over large domains.

This final chapter reviews and summarizes the main achievements obtained in each focus area and presents general considerations on the research question that propelled our work.

Monitoring techniques in rice systems

Identifying the scope for improvement in the efficiency of a system requires the adoption of monitoring techniques as an essential starting point. The combined use of on-ground measurements, providing detailed data though costly and time-consuming, with remote sensed data, less accurate but conveying spatial information, does offer outstanding opportunities to improve knowledge of agricultural systems.

Our Thesis provided evidence that several on-ground monitoring devices can be effectively used in rice paddies to collect data capturing different processes with a high temporal resolution (data acquisition at hourly or sub-hourly time steps). With a proper preliminary design, it is possible to implement an integrated system at reasonable cost, by using a combination of specific devices directly purchased from different manufacturers. However, savings on the total cost of the system are counterbalanced, to a certain extent, by the amount of time required to choose the right combination of instruments that enables a proper communication between sensors and dataloggers.

Another important aspect of in-field monitoring set-ups is the adoption, when possible, of systems to remotely check the functioning of the instruments. In fact, devices are subject to a series of disturbances such as high temperatures, humidity and damages from animals, so it is crucial to promptly detect any anomalies in the data acquisition and take actions timely.

In spite of their potentialities, the use of integrated multi-sensor systems is reasonably limited to research purposes. However, different monitoring approaches can be effectively adopted by rice farmers who are seeking for solutions to improve water productivity. Besides point measurements, information provided by satellite images can be used to compute vegetation indices such as the Normalized Difference Vegetation Index (NDVI) that can be successfully used to evaluate crop development across space and time. Real-time data on crop development are of great importance for identifying areas with a stunted growth that can be managed according to precision agriculture techniques. Moreover, remote sensed information can be used as input data to spatialized models requiring knowledge on crop development.

Future challenges

- Development of monitoring set-ups based on low cost sensors and “open” acquisition systems in order to reduce costs and increase the monitoring performances;
- Massive integration of remote sensed data of high spatial resolution (down to 10 m) in monitoring plans performed for both research and farming purposes.

Water management of rice at the field scale

Several field-scale experiments show that higher water productivities can be achieved when less water-demanding regimes replace traditional flooding.

This general evidence was indeed confirmed by results of the field experiment we conducted in Northern Italy where the following water managements were evaluated and compared: (i) continuous flooding of water-seeded rice (“traditional” flooding), (ii) delayed flooding of dry-seeded rice and (iii) intermittent irrigation of dry-seeded rice. In fact, intermittent irrigation and delayed flooding enabled to achieve higher water productivities than traditional flooding in both the years we considered (water productivities in the order: Intermittent Irrigation > Delayed flooding > Traditional Flooding). However, focussing on just a synthetic index could be indeed reductive.

First, we observed irrigation requirements of the flooded treatments to vary significantly between years, with a variation of irrigation requirements by 40% to 50%, mostly occurred in the first part of the season. Variations were attributed to a combination of abiotic and biotic factors including the groundwater level at the beginning of the rice season, the soil moisture antecedent to the tillage operations; the rainfall intensity occurred between soil tillage and the first irrigation; and the possible occurrence of preferential macropore fluxes due the activity of earthworms. Therefore, our study suggests that water applications related to a specific water treatment does not depend only on the water regime itself or on the soil type where rice is grown. In fact, even when the same water regime is applied to the same rice field, water requirements can halved in two subsequent seasons by the effect of environmental factors. Water productivity is therefore expected to vary accordingly if yield is not subject to relevant variations.

Another aspect to consider is related to the decrease in yield that was observed with the water saving regimes. If delayed flooding determined average yield reductions by 3% against a decrease of water applications by 20%, the reduction by 65% of water applications in intermittent irrigated rice was counterbalanced by yield losses close to 30%. The sustainability of a water management such as intermittent irrigation should be therefore evaluated by making a balance between the costs of the productive factors (of which water is just one component) against the income obtained from grain production. These economic considerations are beyond the scope of this work, however it is worthwhile mentioning that water productivity does not convey any information on the profitability of the productive system.

In addition to impacts on water amounts and yield productions, changes in the water management could have positive or negative impacts on other components that have to be evaluated when seeking for a sustainable alternative to traditional flooding. In fact, the presence of ponded water determines continuous downward water fluxes and maintain anaerobic soil conditions, which both affect the nutrient cycling and the environmental fate of organic chemicals. In this context, our work focussed on just one of these aspects by investigating the dynamics of dissolved organic carbon in relation to the water management. Results of the study suggest that there is a strong link between dynamics of dissolved organic carbon and the reducing soil conditions resulting from field flooding. In fact, the adoption of continuous flooding not only favoured the accumulation of dissolved organic carbon in the topsoil, but also enhanced the inputs of organic carbon to the subsoil and the exports with surface waters. On the other hand, maintaining oxic conditions through a regime of intermittent irrigation increased the turnover and limited the release and mobility of dissolved organic carbon throughout the cropping season.

Future challenges

- Investigate, and possibly quantify, the role of factors including groundwater levels, changes in bulk density and macroporosity on the irrigation requirements of the flooded treatments via modelling simulations.

District-scale implications

As mentioned before with respect to field-scale studies, intermittent irrigation enables to reduce significantly the water requirements for rice cultivation. However, a blind extension of these results to larger scales could be inappropriate. Our study showed that the magnitude of these reductions in a rice district converting to intermittent irrigation was of different extent than what observed at the field scale because of variations in the groundwater levels.

Under the present conditions, a total irrigation depth greater than 3,000 mm per season is required for growing flooded rice due to the coarse texture of the soils. But, at the same time, 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. Such contribution can reach some 50% of the water requirements for crops like maize, as demonstrated by the case study presented in this Thesis. Moreover, a high water table limits the deep percolation fluxes, thus further reducing the irrigation requirements. Therefore, irrigation applications and groundwater levels are related by a feedback mechanism that cannot be ignored when considering relevant changes in the irrigation practices over large areas. Our scenario analysis, which assumed a large conversion to intermittent irrigation, showed that irrigation withdrawals of the district decreased by up to 70% when the feedback mechanism was neglected. However, the reduction amounted to around 45% when the feedback was accounted for, i.e. when the irrigation applications were estimated on the basis of the “new” equilibrium between groundwater levels and groundwater recharge. In addition to that, the second main crop of the district (maize) was found to suffer from some degree of water stress under the scenario. In fact, maintaining the original turn of 15 days for the irrigations of maize was no longer enough to guarantee timely irrigation supplies and avoid crop water stress due to the decrease of the groundwater level. Shortening the irrigation turn to 10 days further decreased the estimate of the savings achievable in the total irrigation withdrawals to around 40%. This is still very significant, but it should be viewed in a wider perspective, including the consideration of the decrease of rice yield under the intermittent irrigation regime and the loss of the ecosystem services of the continuous flooding regime.

Feedback effects are particularly relevant in our study area due to the high permeability of the soils and may have a substantially different magnitude in less permeable areas, even if groundwater depth is similar. Therefore, we do not imply that water saving techniques are ineffective. We rather stress the importance of carefully analysing all the consequences of their extensive adoption as several issues need to be considered. Besides considerations on yield losses and environmental aspects, one additional important issue regards the adaptations in the planning and management of water resource that may be required. In fact, rice growers currently receive relatively small flow rates and without interruption, but a shift to flush irrigation would imply to deliver higher flow rates on a weekly basis, with the possible need to rearrange the dimensions of the irrigation channels accordingly. Moreover, some competition for water between rice and maize could occur due to the overlap of the peak demands.

Future challenges

- Refine the methodology for the estimation of irrigation requirements of flooded rice;
- Perform the same analysis on the adjacent rice district that is characterised by finer soils and different groundwater levels in order to evaluate the role of these two factors in the estimates we presented;
- Simulate the variations of rice yields along with the variations of irrigation requirements.

Is reducing water inputs the key?

In spite of the tendency to seek for general and global solutions, the research activities presented in the Thesis clearly highlighted the difficulty to provide a univocal response to the question we posed. Different conclusions in fact could be drawn depending on the specific stakeholders (farmers, water planners, politicians) and on the domains of analysis (single field, farm, irrigation district, basin).

In areas suffering from water scarcity, water saving regimes likely represent the only option rather than a deliberate choice to save water. In other contexts where water shortages are not a major issue and water availability is fostered by the strong interconnection between surface and subsurface water reserves, the call for water savings cannot be the only driving force to radical changes in the water management of rice farming. Extremely important are therefore research activities that look at the system as a whole by integrating knowledge on hydrology and crop physiology, soil chemistry and biology, as well as ecology and economics.

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