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

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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, multisensor system for the continuous monitoring of water dynamics in rice fields under different irrigation regimes. The system consists of the following: (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) multilevel tensiometers and moisture sensor clusters to monitor soil water status; (5) eddy covariance station for the estimation of evapotranspiration fluxes and (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 2-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 interconnections 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

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. 2007). 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. 2007) and that the total seasonal water input to irrigated rice (rainfall plus

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irrigation) can be up to two–three 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. 2007; 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 ecosystem 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 recognized 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 flux 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.

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 as follows:

1. Wet seeded, 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.
2. Dry seeding and delayed FLooding (DFL)—seeding is made before flooding, which takes place approximately when rice is around the three-leaf stage; water management is then similar to WFL.
3. 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, and 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

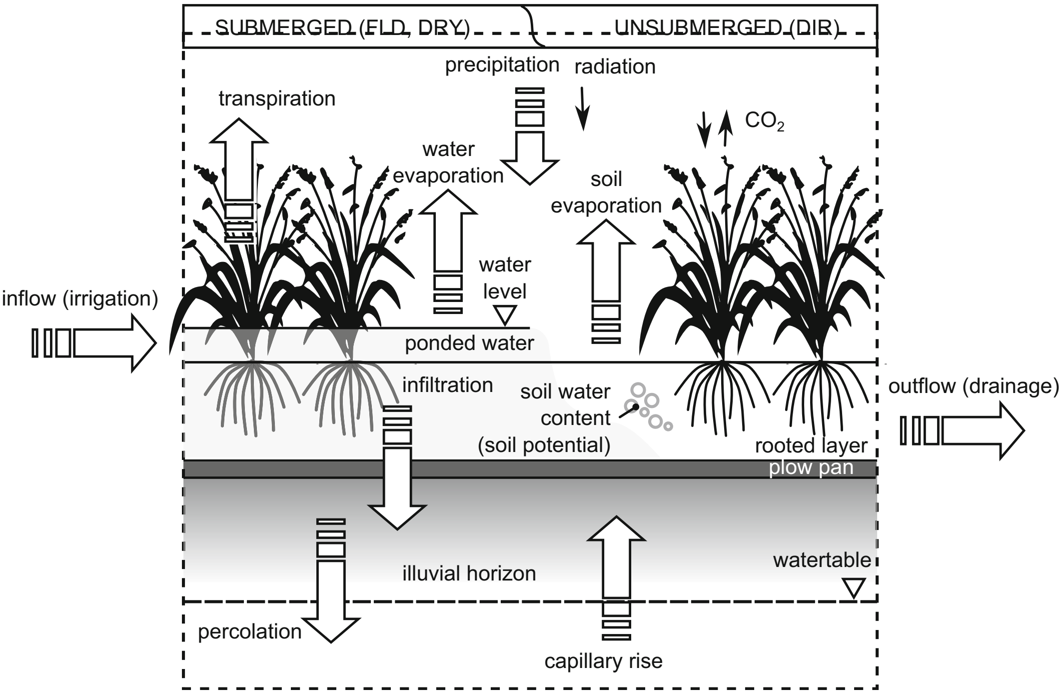

Fig. 1 Water fluxes and storages in flooded (*on the left*) and aerobic (*on the right*) rice fields

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 a 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.

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 Fig. 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 "Water fluxes in irrigated rice fields", 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 1990s 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). The average wind velocity is 2.1 m s^{-1}.

Six laser-levelled fields were selected for the experiments. Each of them was approximately 20 × 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

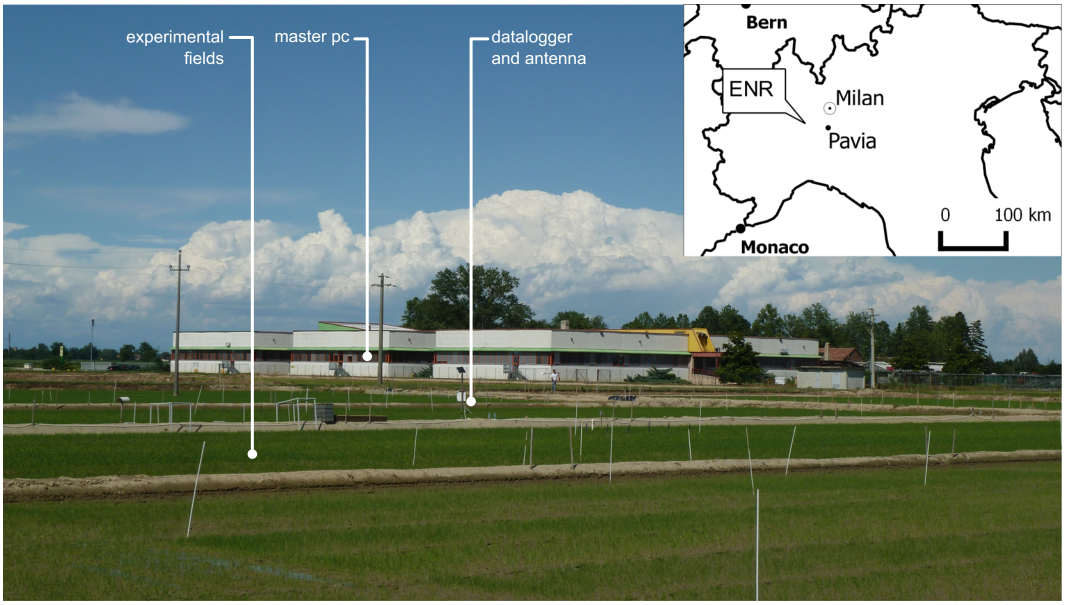

Fig. 2 Picture of the experimental area, located west of Milan. In the foreground: the experimental fields; in the background: the ENR offices were the remote control is placed

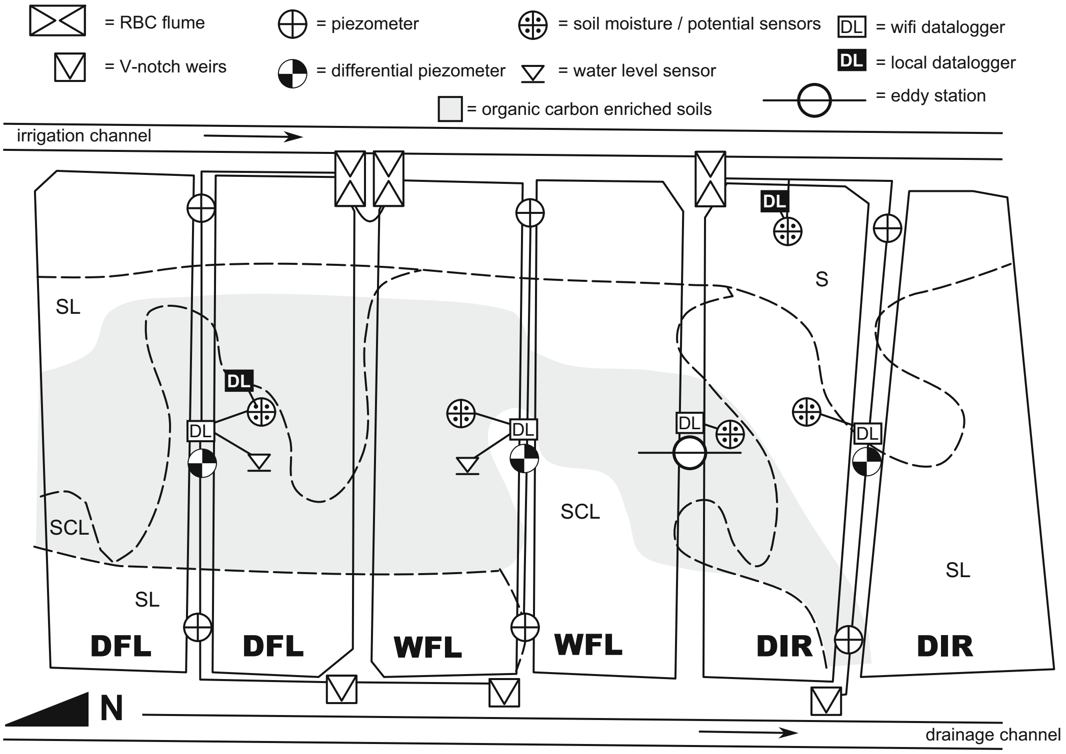

Fig. 3 Scheme of the experimental installation, showing the position of the instruments and the soil type distribution. WFL, DFL and DIR are the three different irrigation treatments. *S* sand soils, *SL* silty loam soils, *SCL* silty clay loam

horizon along the profile. Standard physical and chemical analysis was 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. 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} and by 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 Fig. 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.

Characteristics of the prototype monitoring system

The integrated, multisensor 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 multilevel

Table 1 Average particle size distribution of each explored soil layer

Soil unit	Layer 0–35 cm			Layer 45–70 cm			Layer 90–120 cm		
	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

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

probes, 1 thermohygrometer, 1 four-component 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 simplify the connection of several of them to a single data logger.

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; 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).

Table 2 List of installed sensors (details can be found on websites 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, SDI-12	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
CO_2/H_2O fluxes	Li-7500	LICOR	Digital, SDM	1
3D wind velocity	Ultrasonic anemometer 81000	R.M. Young Company	Analogical	1
Air temperature and moisture	HMP 155 thermohygrometer	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

V-notch 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 Replogle, Bos and Clemmens (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 and (5) the possibility to install and remove easily the devices, in order to allow the annual agricultural works.

The 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^{-1} ha^{-1}, 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^{-1}. 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 1-h time, which leads to a value of 30 l s^{-1}. 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.'s (2001) guidelines. In our case, the 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 no. 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 in length, 1.0 m in width and 0.4 m in 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^{-1}) 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 min 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 bubble formation when the stilling well dried.

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 (Fig. 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 the 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 piezometers 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 transmitter (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 frequency domain reflectometry (FDR) 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 and 70 cm. At the same depths, we placed four tensiometers, as close as possible to the FDR sensors, in order to measure the combined values of soil water content and potential (see Fig. 3).

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

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 agrometeorological weather stations (Bouman et al. 2005; Xiaoguang et al. 2005). Advanced micrometeorological 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 time series 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 1990s. 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 and (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 (H_2O, CO_2) were held at 1 m 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° 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 (CGR 3 and CMP 3, 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 1 m 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 (Fig. 5) which are about 300 m distant from the web-connected PC, which was placed in the ENR building (Fig. 2).

A special attention was devoted to the positioning of the eddy covariance tower. As shown in Table 1, 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 Fig. 3.

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 not only 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) and 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 1) were connected directly to DL ports in order to make distances as short as possible (less than 5 m) to limit signal noise.

Pressure transmitters (maximum seven for one DL) were connected through a local area network, built through an industrial Ethernet cable 72001NH (Belden) with solid bare copper conductors. This type of cable was chosen because of its resistance to high temperatures and to high levels of ambient moisture.

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 × 0.25 conductor cable (C3025, Tasker) of a maximum length of 54 m.

Each CR1000 DL was powered by a 12-V/12-Ah rechargeable sealed lead-acid battery automatically recharged by a standard solar panel (Canadian Solar Mo. Type CS5F-14M) with a nominal maximum power of 14 W through a 12-V charge controller (Steca Solsum 8.8A). All groups were protected by an industrial control panel enclosure (Stahlin).

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

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 Scientific, Inc., 2011), to a RF432 radio (Campbell Scientific, Inc., 2011) installed on a local PC with access to the web.

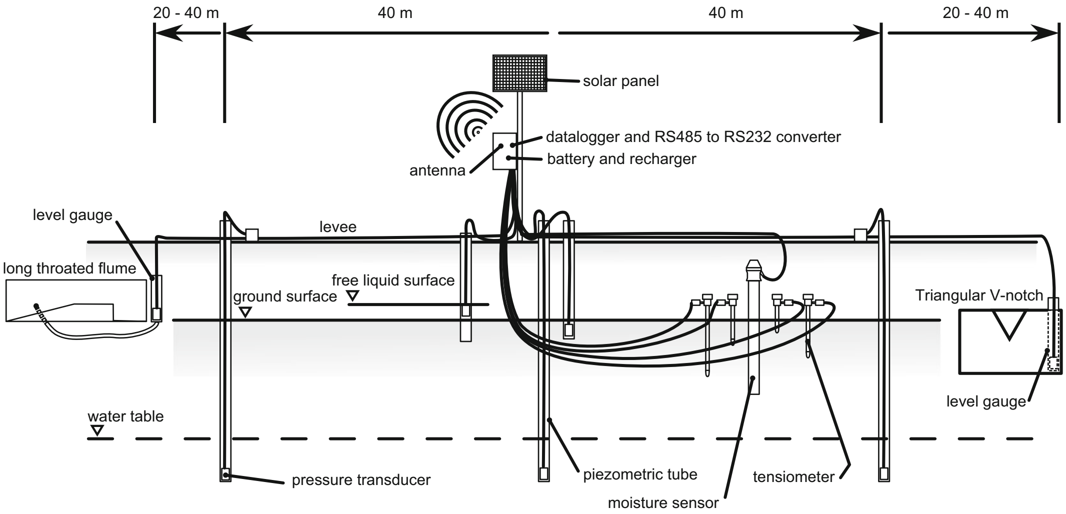

Fig. 4 General scheme of sensors and devices connected to the CR1000 dataloggers

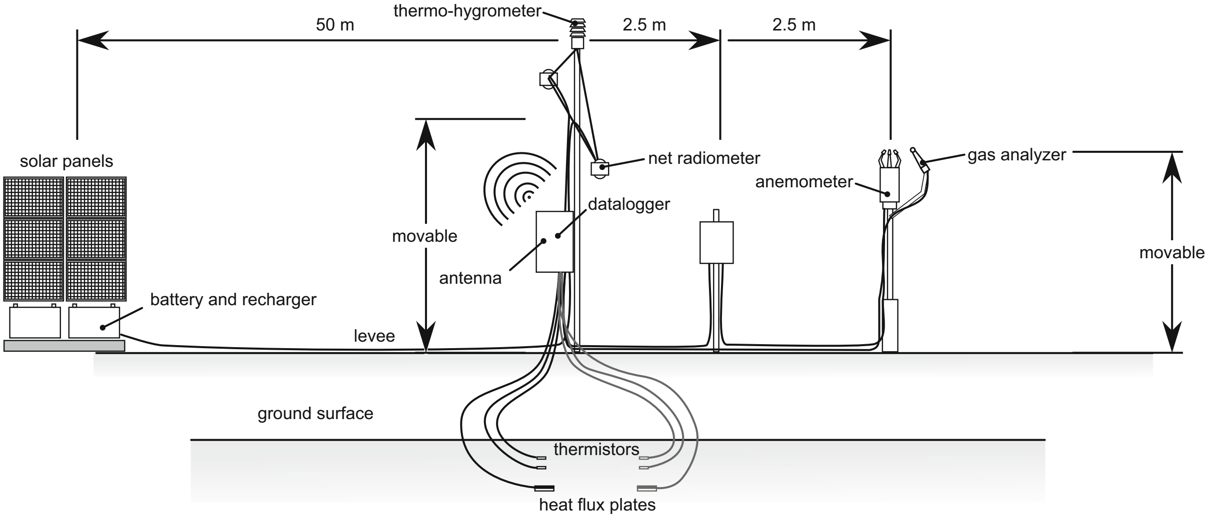

Fig. 5 General scheme of sensors and devices connected to the CR5000 datalogger

The radio is coupled with a 0-dBd, one-fourth wave whip antenna (model no. 15730).

Figure 6 shows the steps followed by the acquisition system and all the preliminary checks applied to the data series 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. In case of failures, the system sent an error message to the maintainer. Otherwise, the process checked the state of the new time series. Checks were about (1) the state of the batteries to prevent energy supply drawbacks at each datalogger, (2) the lack of data in the time series (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, the field trips to the experimental area were limited to what is 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 time series, for post-acquisition data corrections and export in text file format.

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 flux monitoring devices (eddy covariance station), approximately 25 % to the soil water status probes (soil water content and potential), 16 % to dataloggers and 12 % to surface water flux 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 Penman-Monteith equation applied by a standard meteorological station can be an adequate tool

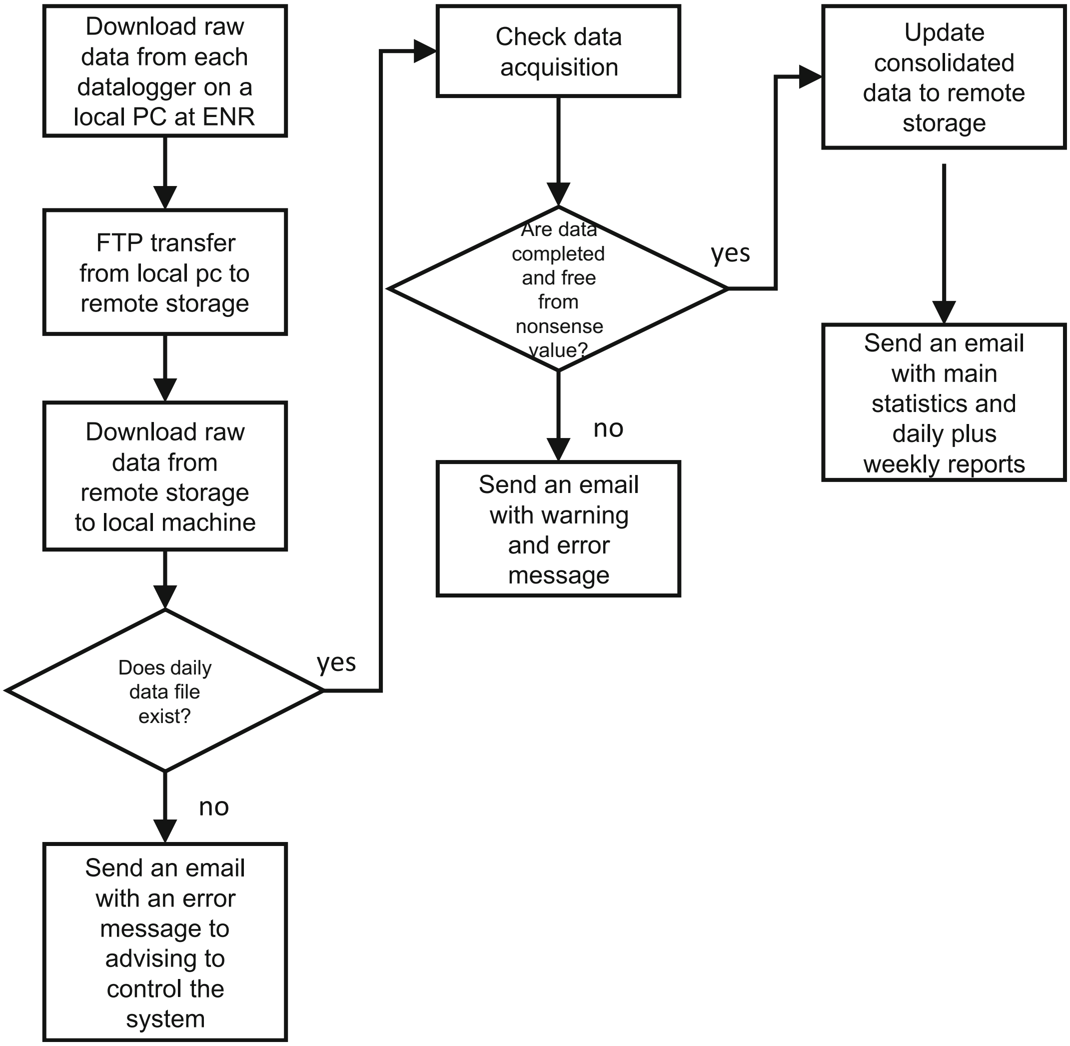

Fig. 6 Flowchart of the process of data acquisition, storage and checking from dataloggers to the central storage. The system performed a download of the data every day at 8:00 a.m. Afterwards, the system uploaded raw data to the remote storage system. A chain of functions verified if the connection to the datalogger was successful and if error in the time series 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

(Facchi et al. 2013). 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 and 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

Material	Individual cost (€)	Number	Total cost (€)
Surface flow			
Keller pressure sensor 41 X	310.00	8	2480.00
Material for RBC flumes and V-notch weirs			1138.51
Total			3618.51
Groundwater			
Keller pressure sensor PR-46X	300.00	12	3600.00
Piezometer wells			531.19
USB driver for interface converter K-104	80.00	1	80.00
Additional cables			228.00
Total			4439.19
Soil water			
EnviroSCAN	*2400.00*	*5*	*12,000.00*
Irrometer tensiometers with manometer (manual recording)	*150.00*	*20*	*3000.00*
Pressure transducers for tensiometers	*350.00*	*2*	*700.00*
Pressure transducers for tensiometers	392.00	4	1568.00
Total			17,268.00
Eddy station			
3D sonic anemometer	*7500.00*	*1*	*7500.00*
Infrared gas analyser	*18,120.00*	*1*	*18,120.00*
CGR 3 pyrgeometer	1300.00	1	1300.00
CMP 3 pyranometer	760.00	1	760.00
Heat flux plate HFP01	512.00	3	1536.00
Thermistors	53.00	6	318.00
Total			29,534.00
Datalogger			
CR1000	1438.00	3	4314.00
CR5000	*3500.00*	*1*	*3500.00*
Case	270.00	3	810.00
Mast Mount bracket	79.00	3	237.00
SDI-12 interface for EnviroSmart devices	438.00	3	1314.00
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
Remote transmission			
RF416 radio	466.00	3	1398.00
RF432 radio	486.00	1	486.00
Whip antenna	35.00	4	140.00
Total			2024.00
Cables, etc.			
Cables			708.29
Connectors and other material			597.00
Total			1305.29
Grand total			69,446.39

Entries in italics indicate that instruments and sensor were already available for the research

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

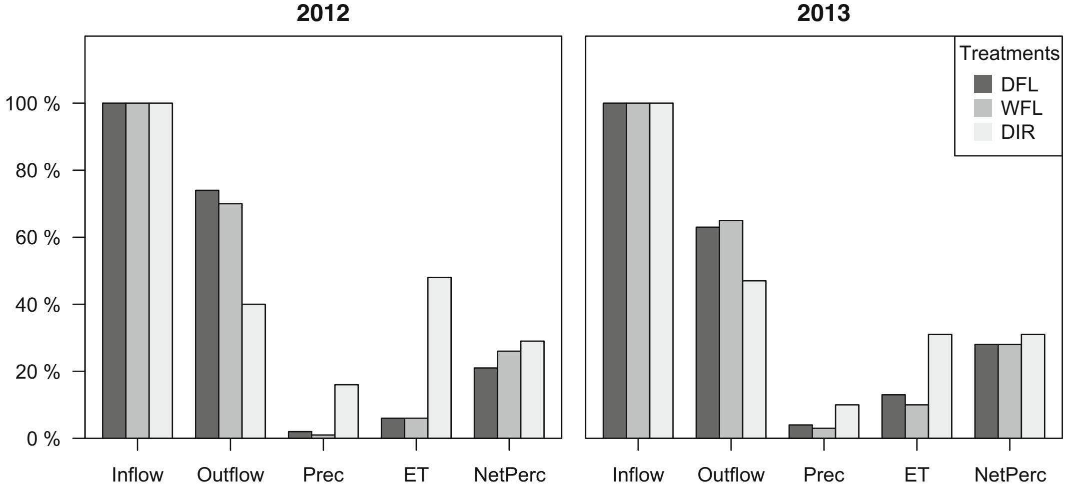

Fig. 7 Cumulative water balance volumes distinguished by each terms and years: superficial inflow and outflow, precipitation (*Prec*), evapotranspiration (*ET*) and the difference between the percolation and the capillary rise, i.e. the residual term of the balance, net percolation (*NetPerc*)

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

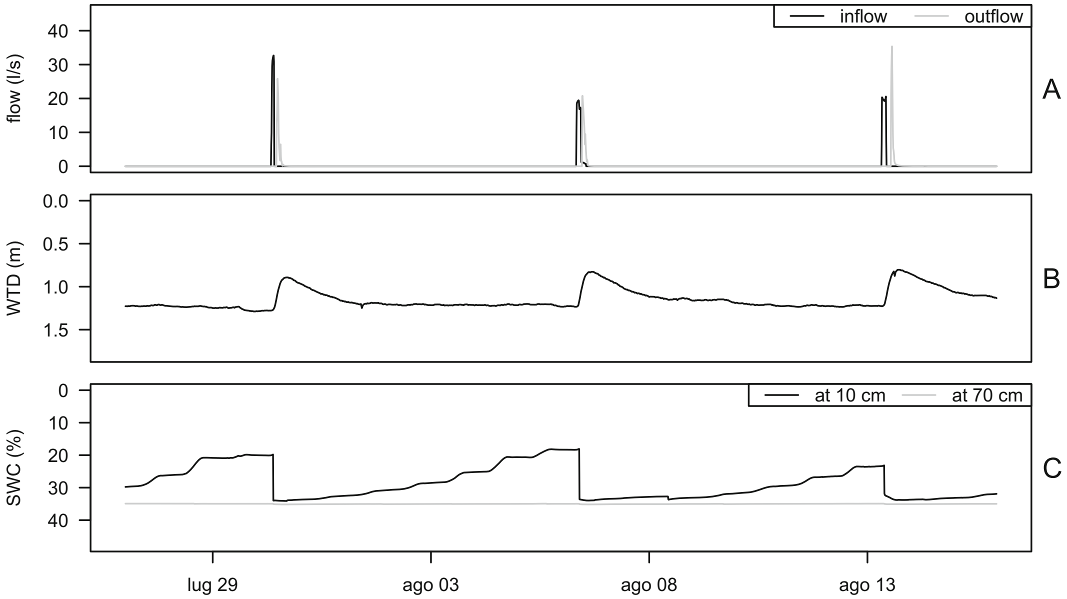

Fig. 8 Temporal pattern of some monitored variables in DIR experimental field: discharge (inflow and outflow, **a**), water table depth (*WTD*, **b**) with respect to the field bed and soil water content (*SWC*, **c**) for a selected time period in 2013. Continuous monitoring activity permits to control all the irrigation practice (three peaks in (**a**)), the following depletion of the paddy (*light grey 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 and 70 cm

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 Fig. 8a, 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^{-1} while outflow peak was 35.37 l s^{-1}). 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 %). 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.

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 researchers 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.

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Disclaimer The brand names of sensors and any commercial products or materials mentioned in this publication are for identification purpose only and do not constitute any endorsement or recommendation for use, by the University of Milan and the coauthors’ institutions.

Authors’ contributions The authors contributed equally.

Conflict of interests The authors declare that they have no competing interests.

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