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# Evaluating performances of the first automatic system for paddy irrigation in Europe

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ABSTRACT

Italy is the leading rice producer in Europe, accounting for more than half of the total high-quality production of this crop. Rice is traditionally grown in fields that remain flooded starting with crop establishment until close to harvest. The water management in rice areas requires a high level of labor because it is based on maintaining a predetermined water height in paddy fields and because the regulation of input and output flow is typically operated manually by the farmers. This study aims to evaluate the hydraulic, control and economical performances of the first automatic and remote-controlled system applied for traditional rice irrigation in Europe and tested in Italy during 2016 agricultural season. In particular, (i) the effects of automation on the water balance; (ii) the reliability of the irrigation system for a real-time control of flow regulation and water level management in the field and (iii) the economic viability of the investment are investigated.

The results show that, despite the automatic system has not proven a decrease of water consumptions (ranging from 2000 to 3700 mm) or a significant increase of rice yield (of about 8 ton hectare$^{-1}$), it has not revealed any mechanical malfunctioning during the irrigation season and it allows to drastically reduce the time spent by workers for water level control and flow regulation. Lastly, the price of the automatic irrigation system (ranging from 638 to 689 € hectare$^{-1}$) appears to be in good agreement with respect to the willingness of farmers for innovation.

## 1. Introduction

### 1.1. Rice irrigation features in the Italian agricultural context

Rice is a staple crop for more than half the world's population. Approximately 90% of world rice production is grown in Asia, while the quantities produced in Europe are relatively limited (approximately 2 million tons). Italy, with more than half of the total European rice production, is the first producer of the old continent, while Spain, Greece, Portugal and France appear in the top five producers providing about 30%, 10%, 5% and 3% of the total European rice production, respectively (EUROSTAT, 2013; ISTAT, 2009) (Fig. 1).

The most important rice-growing area in Italy is a portion of the Padana plain located to the east of Ticino river, straddling the regions of Lombardy and Piedmont in northern Italy (more than 200.000 ha, 92% of the Italian rice surface; National Rice Centre, 2015). Although the main objective of the rice farms is productive, areas in which the prevailing crop is rice create a peculiar agro-ecosystem characterized by the presence of water in the fields for several months each year (Leibundgut and Kohn, 2014). This extensive water presence endows these areas with significant landscape and natural heritage values, ranging from the preservation of traditional rural landscapes to the safeguarding of different animal and plant species typical of wetland areas (Cesari de Maria et al., 2016; Masseroni et al., 2017b). The prolonged presence and circulation of water, due to continuous flooding of fields from wet-sowing until close to harvest, represents a distinguishing feature of these rice areas, some of which have also been included in the European ecological network NATURA 2000 and on the official list of the European Special Protected Areas (Habitat Directive, 92/43/EEC; European Commission, 1992) (Chiaradia et al., 2013). However, the traditional irrigation technique, based on continuous flooding during the growing season, still dominates in most areas (for exam-

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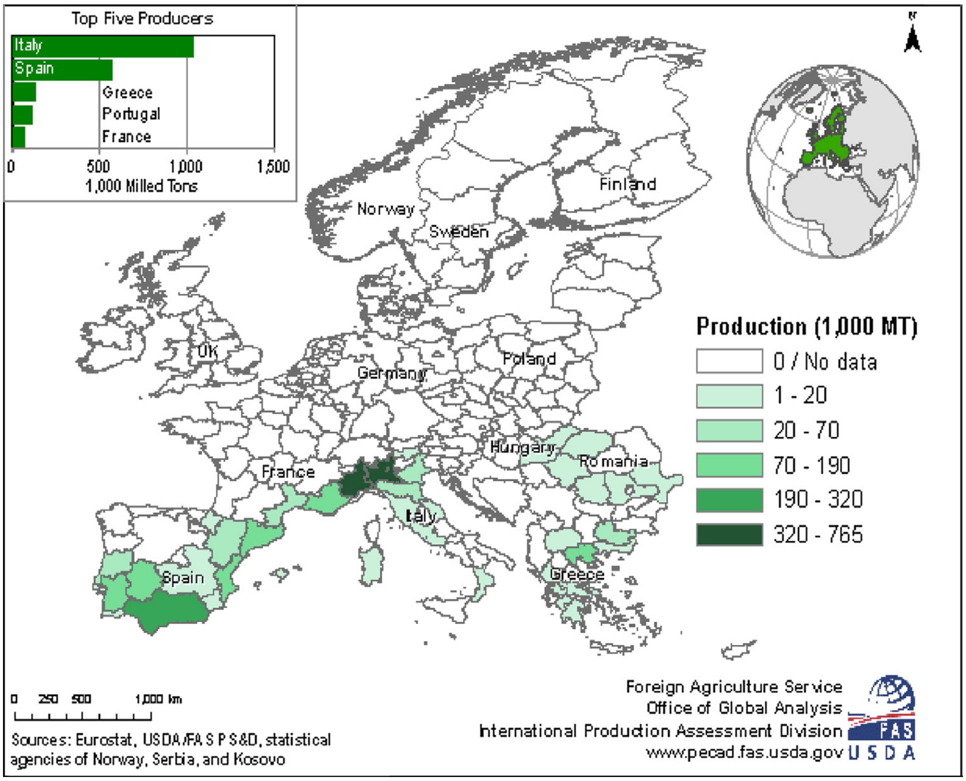

**Fig. 1.** Harvested rice production (2001–2010 average) in Europe.
Source: United State Department of Agriculture (USDA), Foreign Agricultural Service http page (https://www.pecad.fas.usda.gov/rssiws/al/europe_cropprod.htm?country=Europe&commodity=Rice)

ple, in 85% of the northern Italy rice area) and is characterized by very low irrigation efficiencies and a high level labor requirement performed by workers (named in Italian “acquaioli”), which combine rich hands-on experience and local traditional knowledge. Although there are no accurate literature measurements related to the time that farmers spend for irrigation management of their fields, it may be estimated that a significant fraction of the working day during the agricultural season is dedicated to the manual control and adjustment of the gates to maintain the correct levels of water inside the paddy fields. This fraction of the day can vary considerably depending on the extension of the cultivated area, the growing period and the fragmentation of the rice-growing property. Consequently, these features affect the fixed costs of individual companies, primarily for the assumption of seasonal workers’ time that is dedicated full-time or part-time to irrigation management. The implementation of reliable automatic irrigation systems which support the manual operations of these workers is strictly encouraged especially by farmers in order to ensure a more rational allocation of water in the fields according crop conditions. Moreover, from the legislative point of view, the recommendations provided in the European Water Framework Directive (2000/60 CEE) (recently transposed into the Italian national law n°213 of the 15 July 2015) stress on the necessity to reduce the water consumptions through (i) the measure of irrigation consumptions, (ii) the improvement irrigation efficiency and (iii) the development of new irrigation management framework and tools.

### *1.2. Compendium of applications of automatic gravity-fed irrigation systems*

Various attempts to develop and apply automatic gravity-fed irrigation systems have been reported in the literature (Niblack and Sanchez, 2008; Dassanayake et al., 2010; Shahidian and Serralheiro, 2012). In particular, automatic systems for bay irrigation, such as FarmConnect® (Rubicon Water, 2013) and Aquator® (GM Poly, 2013), are commercially available in Australia and North America. Adoption of these systems is growing, particularly in northern Victoria, in response to the combined influences of a modernised and automatic supply system, growers’ access to higher and more consistent flow rates, increasing labour costs, and government incentives for on-farm improvements. To date, these systems have been largely applied for furrow or border irrigations, with suitable infrastructure to deliver water to the field in a controlled and uniform manner. Preliminary trials obtained by Koech et al. (2014a, 2014b) have shown that on maize, soybean, lucerne, pasture and cotton these systems are effective in improving application efficiency above the values routinely achieved by the growers. Along with these developments, in Australia, the cotton industry has been funding the development of a real-time optimisation system for furrow irrigation (Khatri and Smith 2006, 2007). Smart automated furrow irrigation of cotton are widely adopted on farms in the southern part of Australia (mainly in the state of Victoria) and in California (United States of America) where gravity-fed surface irrigation methods are currently adopted to irrigate large portions of cultivated areas (Gillies et al., 2010; Uddin et al., 2015). Different case studies in which these systems are adopted for wheat, barley, faba bean, canola and maize crops demonstrated that the application of automatic systems leads to a reduction of the time spent by the farmer for irrigation (Koech et al., 2014a,2014b) and to an increase in water application efficiency (Smith et al., 2016a,2016b). In these areas, farmers managed properties ranging from 200 to 800 hectares, with single fields characterized by a surface of approximately 8-10 ha. Irrigation of each field requires several hours and interviews with farmers show that they have to interrupt other farm chores to close and open the bay gates. These gates are habitually closed later than the optimal cut-off time, leading to a

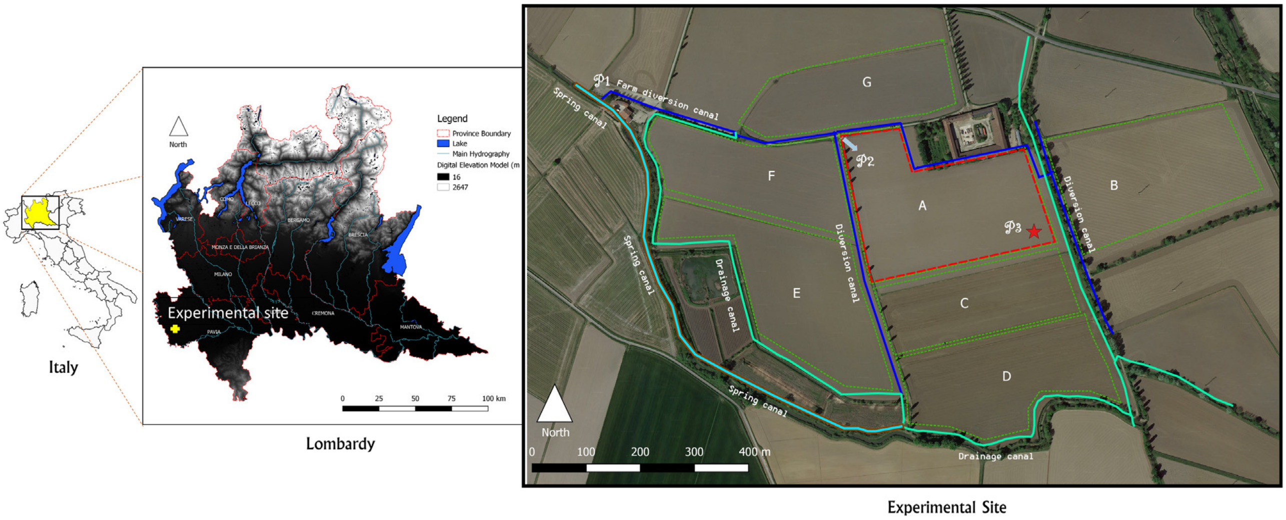

**Fig. 2.** Experimental site of Cerino farm and monitored fields.

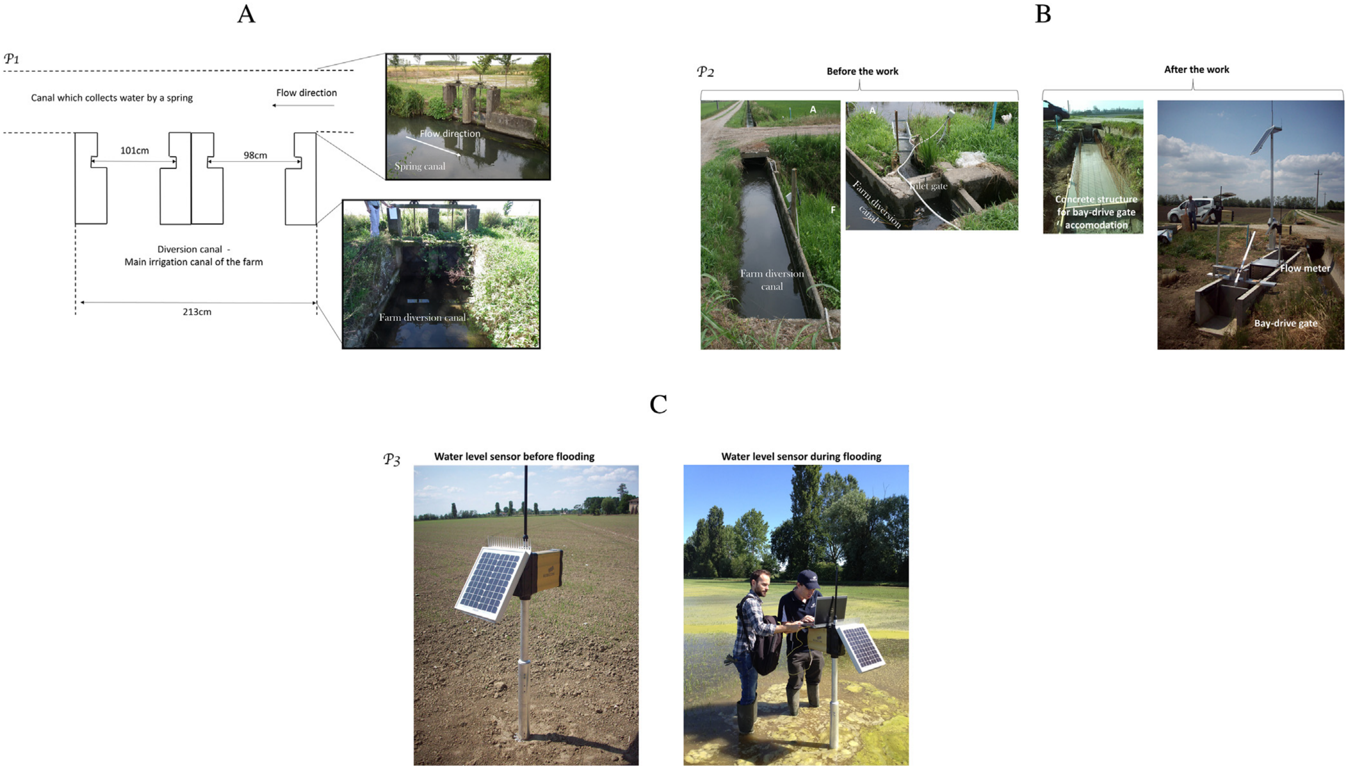

**Fig. 3.** (a) Diversion point between Roggia Raina spring canal and main diversion canal of the farm. (b) comparison between before and after gate installation: inlet point of field A, concrete structure for the gate accommodation, BayDrive® gate, Flow Meter® and FarmConnect Gateway® transmission antenna are shown. (c) FloodTech® sensor before and after flooding.

water wastage of approximately 20% compared with the real crop requirements of each irrigation event (Gillies and Smith, 2015). The introduction of well-designed and well-managed gravity-fed surface irrigation systems using automatic and remote controlled gates can increase application efficiencies and reduce very significantly the labour requirements. For example, an extensive number of furrow irrigation evaluations in the Australian sugar and cotton industries during the 1990s (Raine and Bakker, 1996; Smith et al., 2005) found application efficiencies for individual furrow irrigations averaging approximately 50% and ranging from 10 to 90%. In cotton production, an increase in the furrow inflow rates of $6\,\mathrm{l\,s^{-1}}$ combined with a reduction in the irrigation duration (time to cut-off) enabled attaining an average application efficiency of approximately 75% (Smith et al., 2005). The analysis of the cotton industry irrigation water consumption showed that over a 16-year period, the wide adoption of automatic irrigation systems allowed a water savings of approximately 28.5 million of $\mathrm{m^3\,year^{-1}}$, which contributed to an industry improvement in water use efficiency of 10% (BDA Group, 2007).

A similar situation occurred for the dairy industry in the Goulburn-Murray Irrigation District (GMID) in northern Victoria, Australia. A study by the Cooperative Research Centre for Irrigation Futures (Smith et al., 2009; Gillies et al., 2010) demonstrated that significant gains in application efficiency (approximately 20%) can be reached in the bay irrigation of pasture and fodder crops simply by doubling the flow rates (to at least 0.2 million $m^3$ $day^{-1}$ $m^{-1}$ width) and reducing the irrigation durations. Generally, in these cases, the type of flow control was dependent on the soil water content, which was monitored using multi-level sensors placed within each field. The continuous monitoring of the soil water content compared with the crop-specific water stress threshold provided a framework for when to irrigate and how much water to apply.

Despite the encouraging results obtained in the Australian and United States agricultural contexts, currently, the literature does not show any trials of these systems in Europe. Only two experiments were contemporaneously running in Spain and Italy in the year 2016 for supplying irrigation requirements to crops using automatic and remote controlled gate prototypes. In Spain, the automatic gate was tested on maize and grass providing furrow and basin irrigations, respectively. Soil moisture probes located at different depths in the field assured a real-time flow control in order to schedule irrigations according crop requirements. While, in Italy, the automatic gate was tested on a rice field with traditional irrigation management, with the aim to maintain optimal flooding conditions during the growing season. In this case, the flow control at the field inlet was provided by a water level sensor located close to the field outflow (Masseroni et al., 2017a).

### 1.3. *Objectives*

The purpose of this study concerns the evaluation of (i) hydraulic, (ii) control and (iii) economic performances of the first automatic and remote controlled gate prototype (already described in its hardware and software components in Masseroni et al. (2017a)) originally designed for furrow, basin or border irrigations and rearranged for a traditional rice irrigation in Europe and tested with a pilot project in Italy. In particular, the specific objectives of the paper are: (i) to analyze the effects of automation on the water balance; (ii) to critically discuss the reliability of the gate for a real-time control of flow regulation and water level management in the field and (iii) to evaluate the economic viability of the investment for the European farmers.

## 2. Material and methods

### 2.1. *Experimental site*

The experimental campaign was carried out in the agricultural season 2016 (from April to September). The experimental site of Cerino farm (45° 08′ 00.00′′ N; 8° 44′ 42.15′′ E) (Fig. 2) is composed by 7 fields, each of about 5–8 ha provided with one inlet and one outlet for irrigation and runoff respectively, cultivated with two similar rice cultivar (Terra and Sole registered trademarks) in monoculture. *Dry seeding and delayed FLooding (DFL)* method is applied in all fields i.e. rice is seeded in dry soil and the field is flooded when rice is approximately around the three-leaf stage, about one month after the seeding.

The availability of water for the farm irrigation is continuous during the year, because the water is supplied from a spring canal (named Roggia Raina) with a mean flow during the agricultural season of about 2.5 $m^3$ $s^{-1}$ and delivered by a main farm canal (with a maximum flow capacity of about 1 $m^3$ $s^{-1}$) up to the single fields (point P1 in Fig. 3a). In the experimental farm, the hydraulic structure in inlet to each field is constituted by a concrete structure supporting a 50 cm wide and 60 cm high iron gate which regulates the flow through an orifice with diameter of 40 cm. The farmer opens and closes the gates manually many times a day, according to the water level in the fields and taking into account the crop conditions, assessed through a combination of visual judgment and personal experience.

**Table 1**
Irrigation management in the experimental fields.

| | Year | |
|---|---|---|
| Field | 2015 | 2016 |
| A | Manually | Automatic |
| B | Manually | Manually |

Before the irrigation season 2016, at the inlet point of the field A (7.8 ha), a rectangular concrete structure of 720 mm width, 650 mm high and 5500 mm long was built and connected in front of the traditional hydraulic structure for accommodating one automatic gate (BayDrive®) and one sonary box flow meter sensor (FlumeMeter®). The former was designed for the case study by Rubicon Water industry and traditionally applied for furrow, basin or border irrigations, while the latter is a standard meter box for measuring the velocity profile through ultrasonic array principle. Specifically, the FlumeMeter® sensor and the BayDrive® gate were located downstream the orifice of the field A (point P2 in Fig. 3b) at a distance about 2 m and 4 m respectively, in order to reduce the flow turbulence in input to the FlumeMeter® during irrigations. This device configuration provides a good level of precision of the flow measurements maintaining their accuracy in the range of +/− 2.5% as reported in the FlumeMeter® fact-sheet.

A water level sensor (FloodTech®), for a continuous monitoring of the water level in the field, was located at the end of the south-east part of the field A (point P3 in Fig. 3c) providing the data required to govern the BayDrive® gate in real-time, according to the precise time to cut off the flow rate. The sensor was located at the end of the field in order to guarantee and homogeneous water level conditions all over parts of the plot. The aim of the system automation was the control and adjustment of the gate for maintaining the correct levels of water inside the paddy field according to the farmer settings scheduled during the growing season. For a detailed description of the installed instrumentations, transmission procedures and operation scheduling, the reader can refer to Masseroni et al. (2017a,2017b).

In the field A, seeding was the 12th of April while harvesting was the 10th of September. The field was maintained completely flooded from about the 12th of May to the 15th of August. The soil can be classified as sandy-loam with a mean saturated hydraulic conductivity ($K_{sat}$) of about 1.0 cm $day^{-1}$ evaluated in a soil horizon that reaches the 80 cm below the ground level. The plow sole is located at about 30–35 cm below the ground level, while the groundwater level is about 100 cm below the ground level on average throughout the agricultural season.

### 2.2. *Instrumentation*

The Cerino farm was part of a project aimed at quantifying the water efficiency in paddy areas of northern Italy at the changing of the spatial scale (WATPAD project, funded by Fondazione Cariplo, grant number 2014–1260). In this contest, an intense monitoring activity was conducted in the farm in the years 2015 and 2016.

At the Cerino farm a detailed soil survey was carried out in more than 50 points of the farm (about 10 for each field) and in many soil horizons for detecting soil textures and soil hydraulic properties. Nonstandard and innovative prototype system specifically designed for the case study was implemented for the monitoring of paddies' water fluxes. Details about the adopted monitoring systems are provided by Chiaradia et al. (2015); therefore, just a brief summary is given in the following.

Inflow and outflow discharges in each plot were measured by a Parshall long-throated flume associated with a specific

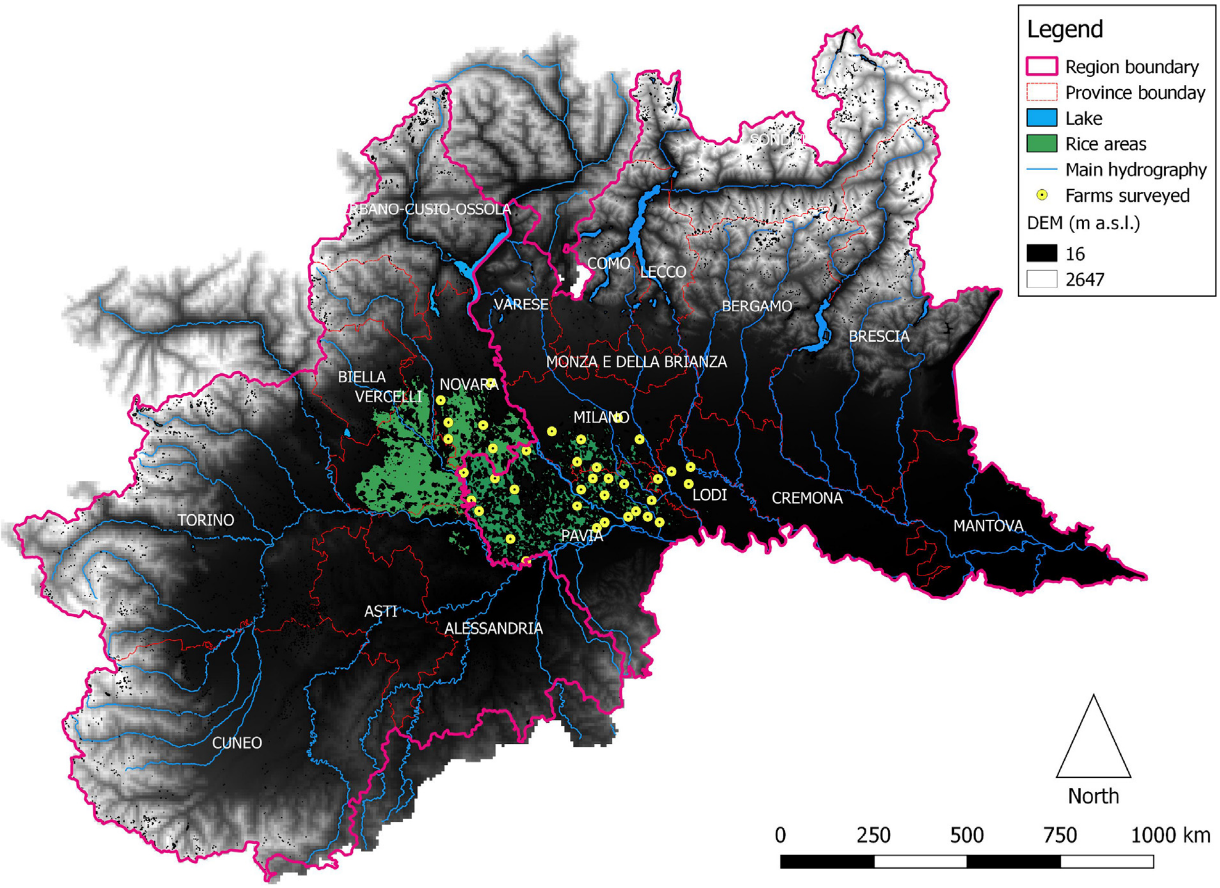

**Fig. 4.** Location of surveyed rice farms (yellow points) within the northern Italy areas where the rice is cropped (green zones). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

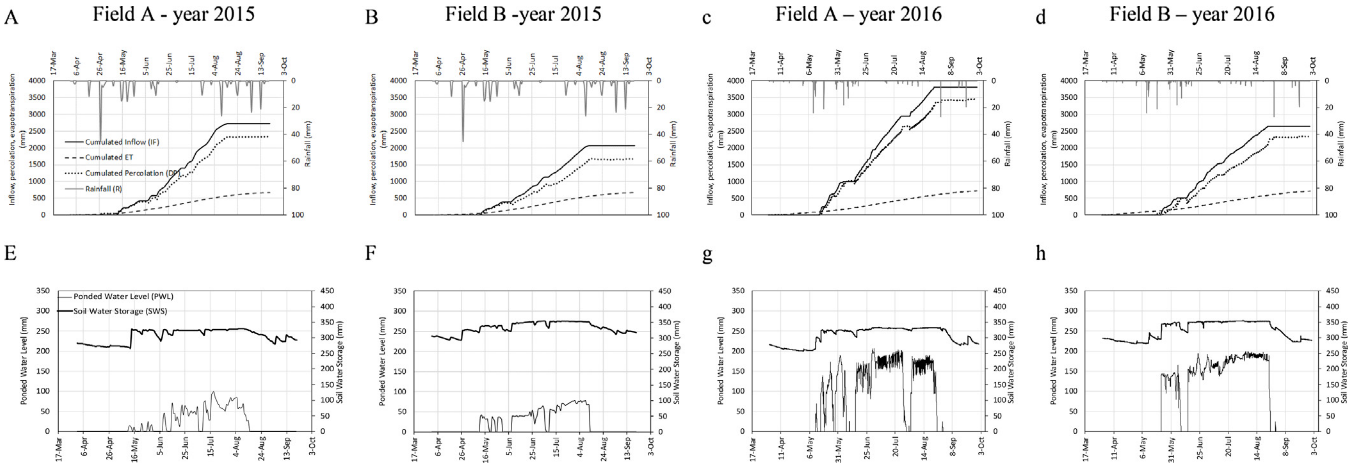

**Fig. 5.** Water balance terms in years 2015 and 2016 for fields A and B. SWS within the root zone (between 0 and 80 cm depth) and percolation out of the root zone.

stage–discharge relationship. Only the Parshall flume at the inlet point of the field A was replaced with the FlumeMeter® in the year 2016. Groundwater levels were monitored by a series of 19 piezometric wells (3 m depth) positioned along the bunds dividing the plots. In each well a capacity pressure probe (41X by Keller or MTM/N10 by STS Instruments) was installed for detecting in continuous groundwater level. The same typology of probes was used to monitor the water level in the field during flooding periods. In particular, one water level sensor per plot was placed close to the inlet point. Soil water contents were measured in each field by 7 soil moisture multi-level probes (depths: 10, 30, 50 and 70 cm) (EnviroSCAN by Sentek) calibrated by volumetric measures on undisturbed soil samples collected at the beginning of the seasons.

Data of the probes and devices were recorded every ten minutes and stored in a set of Campbell Scientific dataloggers (3 CR1000, 5 CR200 and 1 CR800) self-powered by solar panels. Data were checked and downloaded on-field more or less one time a week, except for the BayDrive®, FlumeMeter® and FloodTech® sensors, where the data were send via wireless to the FarmConnect Gateway® mother station and then sent via GSM to a dedicated FarmConnect® web-page to be remotely available in real-

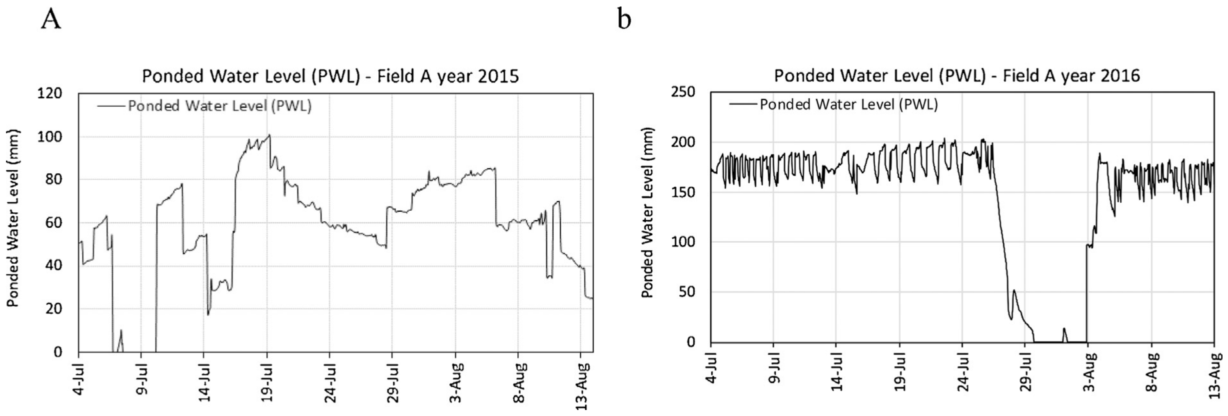

**Fig. 6.** Ponded water level in the field A in the year 2015 (a) and 2016 (b).

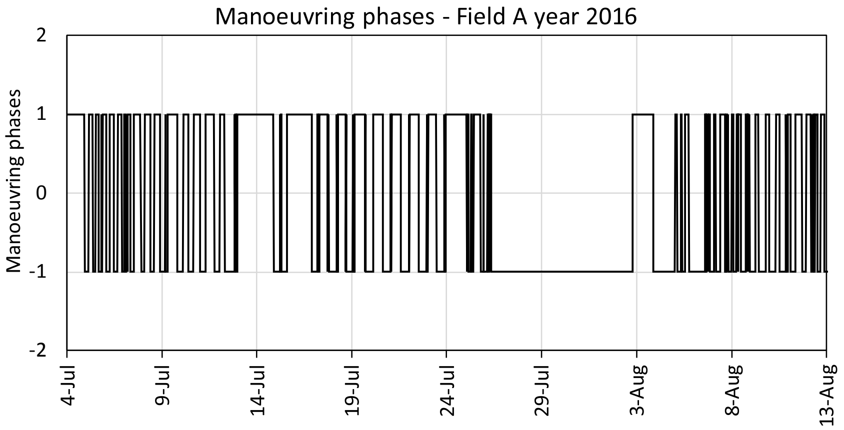

**Fig. 7.** Example of BayDrive® maneuvering phases between 4th of July to the 13th of August.

time. Meteorological data were provided by a Davis Vantage Pro2 Weather Station located in the middle of the farm at a height of 2 m from the ground level.

These great amount of experimental data were needed for calculating the terms of the water balance in each field, in particular amount of irrigation supply, tail water drainage flowing out from the fields, rainfall, crop evapotranspiration, change in soil water storage within the root zone (between 0 and 80 cm depth) and in ponding water over the field, percolation out of the root zone.

### 2.3. Automatic irrigation system performances

The hydraulic performance of the automatic irrigation system is assessed by comparing the water balance terms determined for field A in the years 2015 and 2016, while during year 2016 a comparison of water fluxes between field A (automatically managed) and field B (manually managed) is carried out, since very similar topographical, soil and hydrological features were assessed for the two fields during 2015 (Table 1).

The control performance of the BayDrive® gate is assessed as follows:

(i) analyzing the ability of the gate to maintain autonomously optimal flooding conditions (i.e. a constant water level in the field) according the farmer's scheduling;
(ii) checking if any hardware malfunctions or communication breaks occurred during the growing season.

The assessment of the economical performance is performed analyzing the improvements achieved by the automated irrigation system with respect to traditional rice irrigation management features. In particular, traditional rice irrigation management practices were extrapolated from questionnaires distributed by the National Rice Center technicians to 45 farmers homogenously spread over a rice area of about 1500 km$^2$ located between the Ticino and Sesia rivers (Fig. 4). The 13 questions listed in the interview are the following and the answer referring to the agricultural season 2016:

1) Municipality where the farm is located;
2) Utilized Agricultural Area (UAA) for rice cultivation within the farm
3) Type of seeding method, surface devoted to each method, and irrigation management. In particular:
    a Dry seeding and delayed FLooding (DFL)
    b Water seeding and continuous FLooding (WFL)
    c Dry seeding and intermittent IRrigation (DIR)
4) Number of diversion canals used for the farm irrigation supply
5) Methodology of water delivering to the farm (i.e. continuous or rotational)
6) Level of farm fragmentation (i.e. time the farmer spends to reach the farthest rice field)
7) Type of irrigation:
    a Gravity irrigation
    b Tractor with water pomp (pumped irrigation).
8) Irrigation management (i.e. manually or based on automatic systems)
9) Number of times per day that the inlet gate to a generic rice field needs to be maneuvered/adjusted

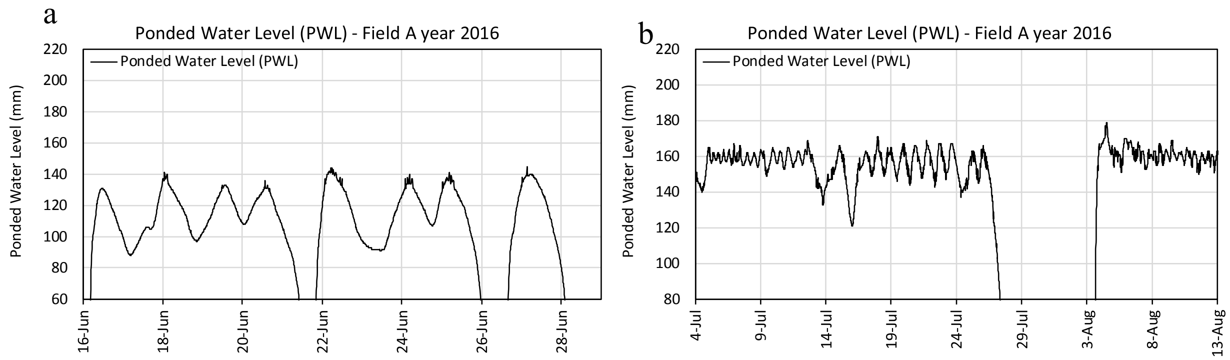

**Fig. 8.** Ponded water level in the field (at FloodTech® sensor position). From the 16th of June to the 28th of June the range was set between 115 and 125 mm (a). From the 4th of July to the 13th of August the range was set between 159 and 160 mm.

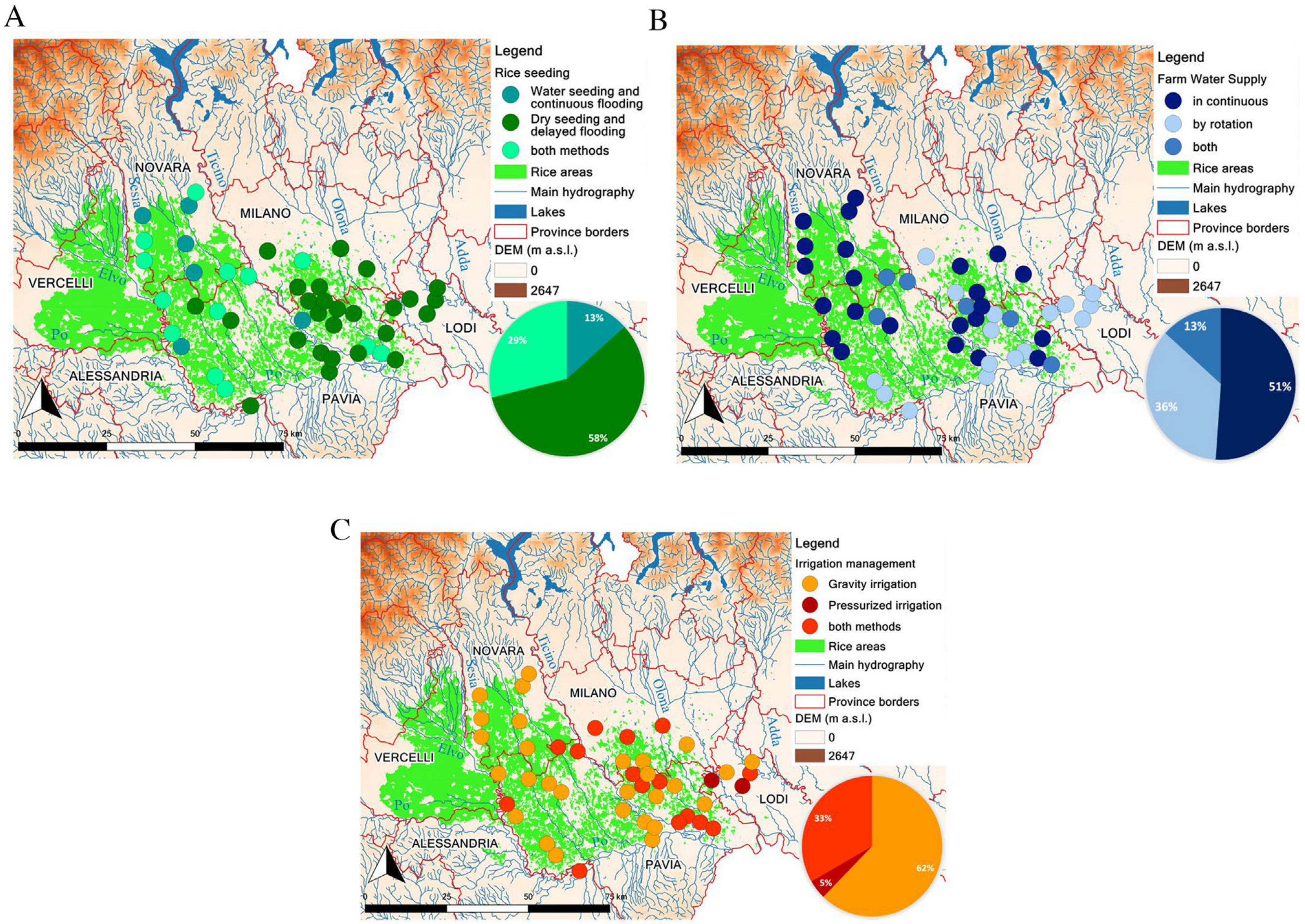

**Fig. 9.** Spatial distribution of questionnaire data resuts. (a) Rice seeding and irrigation methods; (b) Water delivering methods; (c) Type of irrigation.

10) Man-hours a day required for farm irrigation
11) Number of workers involved in the irrigation procedures
12) Number of times the irrigation system requires maintenance in an year
13) Annual average cost for the irrigation network maintenance (e.g. gate replacement, canal relining etc.).

Starting from questionnaire responses, a cost-benefit analysis of the economic impact of automation on farmer's income is performed through Net Present Value (NPV) methodology (Khan 1993).

## 3. Results and discussions

### 3.1. Hydraulic performance

The amount of irrigation (Cumulated Inflow – IF) applied to field A was about 2700 mm and 3700 mm respectively in years 2015 and 2016 (Fig. 5a and c), while in field B in the year 2015 and 2016 the irrigation inflow was respectively about 2000 mm and 2600 mm (Fig. 5b and d). Rainfall was lower than 500 mm in both seasons. Cumulated evapotranspiration (ET) was about 700 mm in both fields and years. The soil water storage (SWS) (between 0 and 80 cm depth) in the fields under saturated condition was about

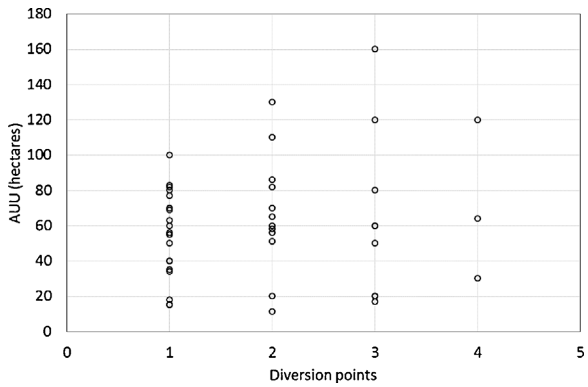

**Fig. 10.** Comparison between Utilized-Agricultural-Area (UAA) devoted to rice and the number of diversion canals per farm.

250 mm for both fields and years (Fig. 5e–h), confirming the attendance in the field of the same soil hydraulic features despite the soil preparation works before the seeding. Values of percolations (DP) (obtained as residual terms in the water balance computation) for fields A and B respectively in years 2015 and 2016 amounted ranging from 1700 to 2500 mm (Fig. 5a, b, d), while in the field A in the year 2016 the percolation was about 3500 mm (Fig. 5c). In both fields the irrigation outflow was negligible.

Values of irrigation supply for fields A in the year 2015 and for the field B in the years 2015 and 2016 are in good agreement with results found in the literature, which reports water consumptions ranging from 1500 to 3000 mm (Singh et al., 2001, Tabbal et al., 2002; Zhao et al., 2015). The amount of irrigation in the field A in the year 2016, instead, is in reasonable agreement with the results of previous water balance experiments carried out in the northern-Italy rice area, with irrigations sometimes exceeding 3000 mm (Cesari de Maria et al., 2016, de Maria et al., 2017).

Concerning water levels in fields A and B, they were maintained on average equal for both the fields during the entire 2015 and then 2016 growing seasons (about 50 mm for both fields in the year 2015 (Fig. 5e and f) and 150 mm for both fields in the year 2016 (Fig. 5g and h)). Despite the water levels in the year 2016 are generally greater than those maintained in the year 2015, comparing the water levels in the field A, the average water level in 2016 was higher than in 2015 of about 70 mm. In view of the fact that water level in field A in 2016 (when BayDrive® gate was operating) was scheduled by the farmer during the growing season, the reasons of this gap could be explained mainly by farmer's lack of knowledge of the actual water levels in the fields, as well as to a natural proclivity to increase the water supply in order to avoid any crop water stress when a new irrigation technology was adopted. As a matter of fact, water levels which the farmer believed to have maintained in the field according to his visual judgment and experience are far from the actual conditions. In the year 2016 the farmer set a mean water level of 150 mm within the field A, to obtain the water level achieved in 2015 by manually regulating the inflow gate. This factor led to an increase of water supply in field A in 2016 which, however, cannot be ascribed to the automated irrigation system itself, but to the way in which the system was set.

In Fig. 6 water levels monitored near the inlet point of the field A in years 2015 and 2016 between the 4th of July and the 13th of August are shown. While in the first case (Fig. 6a) the water level fluctuations are evident and ranging between 20 mm and 100 mm, in the year 2016 (Fig. 6b), even if the water level in the field is higher than in the previous year, water level fluctuations are restricted in a range between 150 mm and 200 mm.

The field A provided an average yield of 8.8 ton hectare$^{-1}$ in 2015 and 8.4 ton hectare$^{-1}$ in 2016. The field B provided an average yield of 8.4 ton hectare$^{-1}$ in 2015 and 8.7 ton hectare$^{-1}$ in 2016. Applying the Fisher test on average productions, the difference in rice yield occurred between 2015 and 2016 is not significant for both fields ($p$-value < .001).

### 3.2. Control performance

The complex of automatic irrigation system components constituted by the BayDrive® gate, the FloodTech® sensor and the FlumeMeter® device proved to reliable, since no malfunctioning occurred during the whole experimental campaign. The FarmConnect® software uploaded online sensor readings every ten minutes as planned, and by means of a web-based interface the farmer was able to manage the irrigation using his computer and smartphone. In particular, each irrigation event consists of a single cycle of gate opening and closing, then the program is aborted. This type of scheduling was designed in-primis for furrow and basin irrigations, as well as for rotational water supplies (i.e. where the number of irrigations in a growing season is relatively low, no more than 10–12 irrigations) (Koech et al., 2014a, 2014b). In field A, the high soil conductivity ($k_{sat}$ = 1.02 cm day$^{-1}$) requires to schedule multiple irrigation events in a day in order to maintain the fixed water level threshold within the field. In Fig. 7 the gate maneuvering sequences in 45 days (from the 4th of July to the 13th of August) are shown. In particular when maneuvering phase is 1 the gate is completely open, while when maneuvering phase is −1 the gate is completely close. In this period, 167 irrigation events occurred with

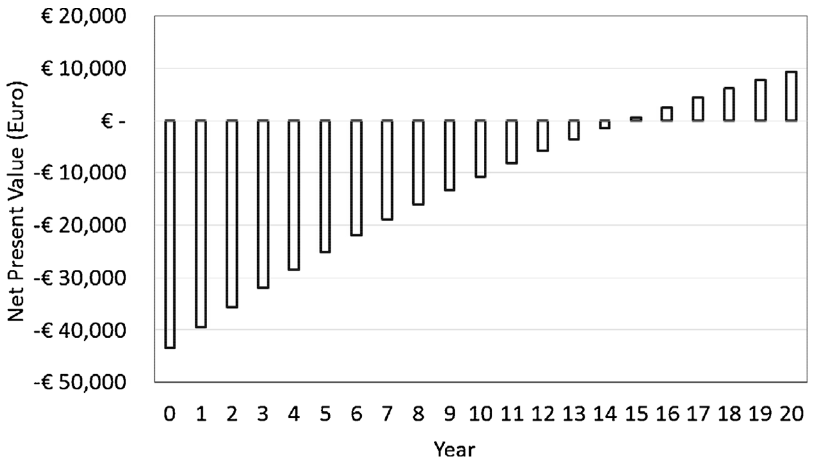

**Fig. 11.** Cost-benefit analysis over 20 years of the device life time.

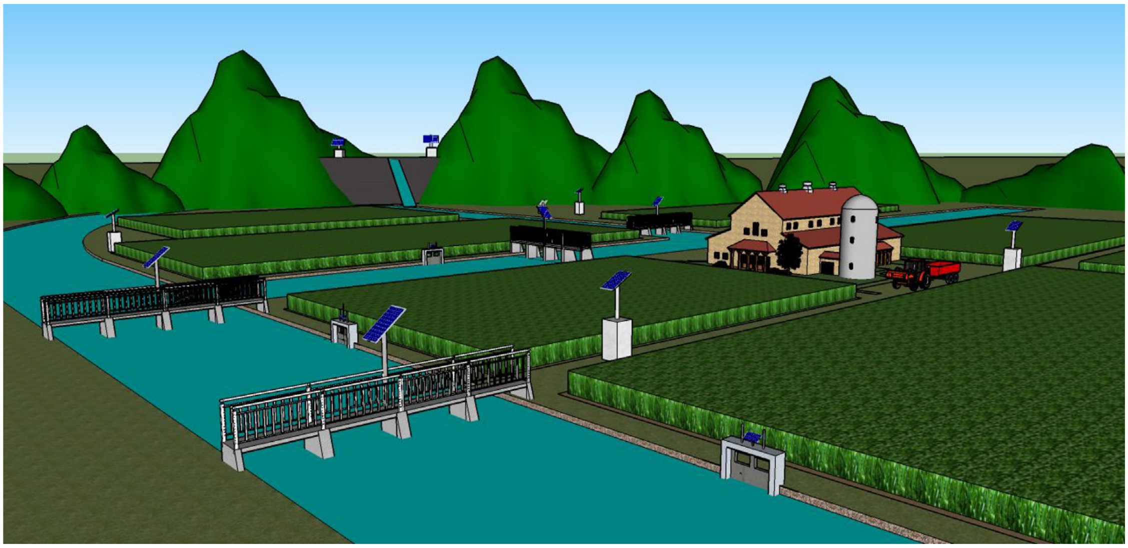

**Fig. 12.** Rendering of an automatic gravity-fed irrigation network system.

a mean of about 3 irrigation events per day (value that is maintained also for the entire agricultural season). According the current characteristics of the irrigation program setting procedure used in this pilot project require the farmer to initiate repetitive sub-weekly scheduling procedure with a considerable amount of time spent for programming.

Concerning the ability of the BayDrive® gate to maintain optimal flooding conditions, the real-time communication between FloodTech® sensor and BayDrive® gate allows to optimize the binomial flow rate-cutoff time, thus minimizing the water level fluctuations in the field. For this pilot project, the gate worked only in two positions i.e. fully opened or fully closed as the vendor is yet to commercialize a solution for rice which would include autonomous multiple events within its program. As a result, a lag-time has to be taken into consideration in the choice of the optimal water level range to be preserved in the field. The lag-time consists in the time needed for water to flow from the inlet point of the field (where the BayDrive® gate is located) to the end of the field (where the FloodTech® sensor is installed). In fact, as shown in Fig. 8a where a range of 115–125 mm was set in the program, the water level fluctuations in the field are on average of about 40 mm (between 100 mm and 140 mm). Conversely, as shown in Fig. 8b where a range of 159–160 mm was set in the program, the water level fluctuations in the field are on average only about 5 mm (between 158 mm and 163 mm). This means that for minimizing water level fluctuations in the field a narrow range of water levels has to be set. However, this setting operation leads to an increase of the number of gate openings and closings.

In Fig. 8a and b, three drying periods for agronomic treatments are shown (on June 21st and June 26th during the first period, and from the 28th of July to the 3th of August in the second period).

## 3.3. Economical performance

### 3.3.1. Results of questionnaires

The UAA devoted to rice cultivation in the surveyed farms is on average 63 ha, with a minimum and a maximum size of 11 and 160 ha. The overall UAA of the surveyed farms is about 2837 ha. The overall surface with DFL seeding method is about 1940 ha (68.4% of the total area), while that the WFL method is adopted only on 816 ha (28.8% of the total area). The remaining surface (about 81 ha, i.e. 2.8% of the total area) is devoted to other types of seeding and irrigation management not specified in the questionnaires. Referring the number of farms preferring DFL or WFL methods, the 58% of farms adopted for all fields the DFL seeding and irrigation method, while the 29% of farms adopted for all the fields the WFL method. The 13% of farms adopted both methods of rice seeding (Fig. 9a).

Two diversion canals on average supply water to each farm, independently from the UAA size, as shown in Fig. 10. This is probably due to a high level of farm fragmentation (ISTAT, 2010) aggravated by an agrarian context where land reorganization plans and rational allocation of water resource are extremely difficult to achieve. In 20 farms the water is delivered in continuous, while in 16 farms the water is delivered following a rotational schedule. In 9 farms both the modes are present, depending on the type of irrigation license granted by the Regional authority or by the Irrigation Consortium to each farm diversion canal. In general, between Ticino and Sesia rivers the continuous method of supply prevails, while between Ticino and Adda rivers supply by rotation is preferred also in according to the prevailing seeding and irrigation method i.e. the DFL (Fig. 9b).

Irrigation in the surveyed farms is entirely manually managed, and the gravity-fed systems prevail over pumped irrigation systems (28 farms adopt gravity-fed irrigation systems, 2 farms adopt pumped systems, 15 farms adopt both methods) (Fig. 9c). Regarding the gravity-fed distribution system, the water is delivered to the field by a network of canals. The flow regulation is performed opening and closing sluice gates located along the canals. At the inlet of each field flow regulation is performed according to water availability and crop status. Flow regulation is performed on average 2 times per day (during the entire growing season), and 3 man-hours is the average labor requirement for flow regulation in a day. Generally, 2 workers per farm are involved in the irrigation management.

### 3.3.2. Cost-benefit analysis

The average cost for a complete automated irrigation system composed by one BayDrive® gate, one FloodTech® sensor, transmission antenna, communication and actuation protocols, power supply, and FarmConnect® software is about 7704 € (subdivided in 1540 € for the gate, 700 € for the rubber insert, 1806 € for the water level sensor, 3224 € for the antenna, communication protocols, 245 € for installation and finally 189 € for FarmConnect® software and commissioning). The gate cost can vary considerably in function of the BayDrive® width, however, in this study we chose the price of a generic gate of about 70 cm width according the dimension of the inlet point of the field A. In addition to this cost, an annual maintenance fee for automation of about 21 € gate$^{-1}$ year$^{-1}$ and FloodTech$^{-1}$ year$^{-1}$ is required, which include software upgrade services, gates maintenance and data storages. An annual SIM card recharge service of about 315 € year$^{-1}$ has to be included.

The cost of the initial investment for the surveyed farms is on average 43,474€. This cost was obtained by multiplying the fixed costs for the automation system (i.e. 1540 € for gate, 700 € for rubber insert 1806 € for the water level sensor, 378 € for software and commissioning) for the mean number of fields per farm (supposing one field – one gate). The mean number of fields per farm is about 9, the latter calculated as the ratio between the mean UAA for the surveyed farms (about 63 ha) and the mean size of a rice field (about 7 ha). Furthermore, to the previous costs, 3224 € plus 245 € respectively for central gateway transmission device and for installation (both costs are independent by the number of fields) are summed.

The life-time of the whole automatic system is supposed to be 20 years, after which all the devices should be replaced with new equipment.

Regarding the management costs of a traditional rice irrigation system, the overall hours invested in a day for the farm irrigation were multiplied for (i) the hourly cost of a non-specialized agricultural worker (13.73 € hour$^{-1}$ by ISTAT information), (ii) the days of an irrigation season (about 90 days) and, lastly, (iii) the number of workers involved in irrigation procedures. The irrigation management cost amounts to 3400 € year$^{-1}$ as well as 2300 € year$^{-1}$ for the irrigation network maintenance (as sum of farm canals and gates maintenance).

The NPV methodology was applied to quantify the profitability of the automation adoption and separately the manual option, by subtracting the actual value of cash outflows (including initial cost) from the actual value of cash inflows over the life time of devices (20 year). A discount rate of 5% is supposed.

The cash outflows for the automation solution are:

(i) The initial investment (43,474 €) at the first year;
(ii) The annual fee for automation and SIM card recharge service (688 € year$^{-1}$);
(iii) The cost for farm canals maintenance (about 460 € year$^{-1}$) supposed to be 20% of the total cost of the irrigation network maintenance;
(iv) The cost for the gates tele-control (supposed about 15 min day$^{-1}$) of about 309 € year$^{-1}$ (i.e. 13.73 € hour$^{-1}$ × 15 min day$^{-1}$ × 90 days year$^{-1}$ × 60$^{-1}$ h min$^{-1}$).

While the cash outflow for the manual solution are:

(i) The labor cost for traditional rice irrigation (3400 € year$^{-1}$);
(ii) The cost of irrigation network maintenance (2300 € year$^{-1}$).

The results show that the NPV at the end of the 20th year is positive (about 9400 €) for the automation solution and therefore the investment can be accepted and can be selected over the manual option (Fig. 11). The investment is fully repaid at the end of the 14th year, with a total capital cost of ranging from 638 to 689 € hectare$^{-1}$ the former in the case where Gateway® and installation costs are amortized across 12 properties as usually performed in the Australian installations.

A factor that should be taken into account is that no significant increase of rice production occurred in the field A between 2015 and 2016 agricultural season, as well as no significant reduction in water consumptions were observed (as shown in section 4.1 by the comparison between the water inflow rate at the field A – automatically managed, and at the field B – manually managed). Generally, in literature is commonly known that automatic systems for gravity-irrigation allow to achieve an increase of application efficiency and uniformity distribution up to 40–50% (in cases of furrow or basin irrigations) as a consequence of a real-time selection of the optimum combination between irrigation flow rate and cut-off time (Smith et al., 2016a,2016b). In the case of flooding irrigation (rice fields) flow rates and cutoff times are usually replaced with a constant water inflow to the field. This allows to achieve both application efficiency and distribution uniformity at the maximum possible level also with a traditional and manually managed irrigation management. Furthermore, if an adequate water level in the field is maintained during the growing season (generally between 5–20 cm), water stress should not occur and the quality and quantity of production should not be subject to evident changes (Bouman et al., 2007). In our case, for both years, the mean water level in the field A was maintained within the optimal range (about 10 cm on average in the year 2015 and 15 cm on average in the year 2016) and only a decrease of water level fluctuations was provided by the automatic system. These findings from one season only, suggest that only small variations in water consumption and rice production might be envisaged over consecutive years, and the profitability derived from potential reduction of water consumptions or by the increase of rice production probably will not improve the economic balance (for example reducing the time of investment repayment). This fact is also amplified by a low water price for irrigation that is about 17 10$^{-3}$ € m$^{-3}$ in respect to that of other European countries such as Spain and Greece where the costs are about 100 10$^{-3}$ € m$^{-3}$ and 82 10$^{-3}$ € m$^{-3}$ respectively (Bardarska and Hadjieva 2000). This implies that, even if a relevant reduction of water uses for farm irrigation would occur, the economic benefit would be relatively low. It follow that, the mainly advantage provided by the automatic system adoption in Italian paddy fields would concern almost exclusively the reduction of labor cost of the workers involved in irrigation procedures, but would probably not provide improvements in terms of rice production or irrigation efficiencies. Nevertheless, both these aspects (improvement of yield and decreasing in water consumption depending on automation) should be analyzed in detail considering more than one year of experimental data.

## 4. Conclusion remarks

In this work the performances of an innovative automatic irrigation prototype originally designed for furrow, basin or border irrigations and rearranged for the traditional rice irrigation in Europe are evaluated. The experimental activity was carried out in the agricultural season 2016 in a paddy field located in the most important rice-growing area in Italy, specifically in the municipality of Semiana. The system was composed by one BayDrive® gate for automatic and remote-controlled flow regulation, one FlumeMeter® box for inlet flow measurements, one FloodTech® sensor for the real-time monitoring of water level in the field, and lastly one FarmConnect Gateway® as a connection device to the cellular network.

The outcomes show the following positive aspects:

(i) The automatic irrigation system did not reveal any mechanical malfunctioning during the irrigation season, as well as good communication protocols provides reliable data transmission on the server web.
(ii) The web interface can be considered a valuable tool for an easy real-time control of gate position, flow regulation and water level measurement in the field.
(iii) The automatic irrigation system allows to reduce the time spent by workers for water level control and flow regulation.

(iv) The automatic irrigation system allows for constant flow to maintain a constant water level with a narrow operational band compared to the manually operated system the previous year (Fig. 6).

(v) The current price of the automatic irrigation system (ranging from 638 to 689 € $hectare^{-1}$) is suitable with respect to the willingness of farmers to spend for innovation inferred by questionnaires data. This result is in line with what achieved by the researches of University of Lleida for two agrarian districts in Lleida (Spain): considering the current labor cost for irrigation, the profitable investment for farm modernization with automatic irrigation system was assessed to be lower than 1000 € $hectare^{-1}$.

Conversely, no significant reduction of water consumptions (ranging from 2000 to 3700 mm) or a significant increase of rice yield (of about 8 ton $hectare^{-1}$) occur in this experimentation but, as shown in Fig. 5, a good correlation between water levels in the field and the amount of percolations suggests that a good water level maintenance in the field by automatic irrigation systems might lead to a stabilization of water losses (e.g. percolations or runoffs).

Some lessons learned from this pilot project for future development of a specific paddy automatic irrigation system could be:

(i) Future development of software would require for traditional rice irrigation in Europe that irrigation program settings incorporate the possibility to set different water levels according to specific period of time, with respect to a regulation based on a number of cycles (i.e. gate openings and closings). In particular, the farmer should be allowed to plan, at the beginning of each agricultural season, the water level in the field according to the crop growing phases, or dry periods for agronomic treatments.

(ii) In the web-page the farmers should set only two basic information for each scheduling i.e. the optimal range of water level in the field and the date of start and end of each scheduling, independently by the number of opening and closing cycles of the gate.

(iii) Regarding the automatic gate opening operation features, the number of gate openings and closings could be drastically decreased if a self-learning process is implemented in the gate program, allowing, thus, the regulation of a constant flow in inlet to the field. In this case, the gate should change its degree of opening in function of the upstream (at the canal) and downstream (in the field) water levels. This type of flow regulation could remedy the difficulties of a traditional rice irrigation especially in permeable soils that are typical in northern Italy rice areas (more than 40% of sandy and sandy-loam soil textures). Moreover, decreasing the number of gate opening and closing, the wear of mechanical components and the ordinary maintenance costs could be minimized. Another setting typology able to simplify the automatic gate opening operation features, could be the maintenance of a certain degree of gate opening related to the mean infiltration capacity of the field, in order to maintain a constant flow in inlet to the field which compensates for the losses terms into the hydrological balance.

(iv) Lastly, the current costs for the automation appear affordable for the Italian rice farmers since the NPV of the automatic solution is positive even though this one year pilot project did not demonstrate a decrease of water consumptions or a significant increase of rice yield.

Many externalities connected with an automatic and remote controlled management of irrigation should be taken into account if the performances of these systems are evaluated on a wider spatial scale (i.e. irrigation district or basin scales). In these cases, the maintaining of the ecological, landscape and environmental functions of the gravity-fed irrigation systems and the continuous monitoring of the binominal crop water requirements – water availability, give to the irrigation water managers the possibility to plan the water allocation and to regulate water distribution in function of farmer requirements. This overall improvement of the management performance could provide a profitable growth in revenue of irrigation consortia, in particular reducing the time spending for gates maneuvering especially in the context of Padana plain where the length of the irrigation network exceeds the 40,000 km. Lastly, the combination of flow regulation and measurements provided by the automatic irrigation system, can be a valuable support for the regional water authorities in order to evaluate the actual water consumptions according to the national law and European Union recommendations. This might provide an overview on irrigation efficiencies over the territories allow a more rational planning of irrigation resources. In a more general prospective, automatic gravity-fed irrigation systems could automatically control the water deliver, irrigation time, irrigation water quantity according to soil conditions and crop requirements. However, in order that the system would be able to perform an irrigation control based on its management potentiality, an integrated gravity-fed irrigation system from storages (or main rivers) to the farms and finally to the fields should be designed (Fig. 12).

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