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REAL TIME MONITORING OF WATER QUALITY IN AN AGRICULTURAL AREA WITH SALINITY PROBLEMS

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Abstract

Agriculture is a highly water-demanding sector. Developed in recent years, the precision farming approach allows to optimize irrigation without compromising crops productivity. WSN networks are a key element of this approach because they allow to monitor continuously large number of parameters providing the possibility of a real-time intervention on field management practices. The WSN networks can be used to measure traditional parameters such as precipitation, soil moisture, or irradiation and others such as the quality of irrigation water and groundwater. The qualitative monitoring of these parameters is essential when the cultivation is carried out under complex conditions such as those represented by soils with salinization problem. This work fits this context by presenting the results of the first 13 months of an experimental campaign aimed at the measurement of soil, water (quality of irrigation and drainage water of the fields) and groundwater parameters by a WSN system. This paper analyzes results of this activity and provides practical suggestions to ensure a more efficient system.

Keywords: Monitoring Precision Farming; salinity; water management; WSN

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1. Introduction

Agriculture, and irrigated agriculture in particular, is by far the sector with the highest use of water. Globally it accounts for around 70% of world water withdrawal (WWAP, 2015). Irrigated agriculture represents 20 % of the total cultivated land but contributes 40 % of the total food produced worldwide (www.fao.org). Irrigation water withdrawal greatly exceeds the need for irrigation water due to significant losses in both fields and distribution systems. Consequently not all water taken from a source reaches the root zone of the plants and so irrigated land does not fully meet its production target (Afrasiabikia et al., 2017). In many countries including Italy (Canone et al., 2015) and others in the Mediterranean area (Iglesias et al., 2007; Levidow et al., 2014), efficient water use and management are today's majors concerns. In recent years this has pushed farmers to investigate the possibility of using moderately saline water for irrigation purposes (Wang et al., 2017), however by adding salts to the soil via irrigation, it may lead to soil salinization and crop yields reduction. It should also be considered that especially in the Mediterranean region, many aquifer systems, that naturally contain vast quantities of brackish water, have limited possibilities for exploitation for human or agricultural uses, imposing so, additional demand stress to neighboring aquifers with higher water quality. Also saline intrusion is an important concern in aquifers, where as a result of the high seasonal water demand, mainly for tourism, they have been over pumped (Iglesias et al., 2007).

New technologies (e.g. soil moisture, water table depth, electrical conductivity and canopy sensors) can allow scheduling irrigation by following

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plant needs. This together with good agricultural practices will consent to reduce water withdrawal and chemicals without compromising crop productivity (Levidow et al., 2014). The use of information technologies (IoT) in agriculture is frequently known as "Precision farming" (Auernhammer, 2001). The key component of this farm management approach is the use of IoT and a wide array of items such as control systems, sensors, robotics, drones, autonomous vehicles, variable rate technology, GPS-based soil sampling, automated hardware, telematics, and software to optimize the growing of crops (Barnes et al., 2019; Zamora-izquierdo et al., 2018).

Sustainable irrigation is a key element of precision farming and it mainly relies on the efficient use of water avoiding soil degradation. A sustainable use of water resources, for the irrigation of soils suffering of problems connected with salinization, must take into account different factors such as: the quality of irrigation water, crop requirements, and salt concentrations in soils (Libutti et al., 2018; Peragón et al., 2018) The measurement of all these parameters through a sensor network offers the possibility to optimize irrigation while protecting the overall environment. Wireless sensor networks (WSNs) can be used in agriculture to provide farmers with a large amount of information. Jawad et al. (2017) provided a detailed review of the WSN-based agriculture applications by comparing communications protocols, energy harvesting techniques and presenting the most used sensors and actuators. However, this document does not contain any information concerning the use of WSNs for monitoring parameters related to water salinity.

Salinity problems exist when the concentration of salt accumulated in the crop’s roots zone causes a loss in yield. It may be caused by 2 main factors: a) primary salinity due to natural causes; and b) secondary salinity due to irrational land use and inappropriate agricultural practices. The first occurs in both soils and waters, and it is often associated with certain types of relief, geomorphological and hydrogeological conditions such as a high groundwater table and impeded drainage or poor drainage. Secondary salinity is caused by an excessive water inputs via irrigation that, in the absence of appropriate drainage systems, leaches the soils causing a rapid raising of the groundwater table (Tables 1, 2)(Vargas et al., 2018).

The accumulation of salt in the root zone causes the impossibility of extracting enough water from the salty soil solution by roots, resulting in a water stress (Ayers and Westcot, 1985). Salts that contribute to a salinity problem are water soluble and readily transported by water. The electrical conductivity (EC) is the parameter used to measure the water and soil salinity, and it is usually reported in deciSiemens per meter at 25°C (dS/m).

Waters and soils salinity classes generally recognized are given in Tab. 1 and Tab 2 respectively, while a detailed description of the grade of soil salinity as a function of the chemistry of salinization is presented in Vargas et al. (2018). Usually water sourced from snow-fed rivers, has a total salinity of less than about 0.5 to 0.6 dS/m, groundwater in semi-arid region has a salinity in the range 1-15 dS/m, and sea water has an average total soluble salts content of about 35 g/l corresponding to an electrical conductivity of about 50 dS/m. As a result of this irrigation water ranges between a wide range of salinity values. The higher the total salinity of an irrigation water, the higher is its salinity hazard for the crops if the soil and climatic conditions and the cultural practices remain the same.

When farmers deal with problems connected to salinity, it is important to evaluate all the factors that caused them such as: soil salinization, poor quality of irrigation water, unfavorable climatic conditions, seawater intrusion, and poor management; in order to identify the factors on which to intervene. The precision farming approach combines perfectly with this process because it allows to monitor all the variables and therefore to understand where, how, and when to act.

Table 1. Classification of saline waters, adapted from Rhoades et al. (1992)

Water class	*Electrical conductivity dS/m*	*Salt concentration mg/l*	*Type of water*
Non-saline	<0.7	<500	Drinking and irrigation water
Slightly saline	0.7 - 2	500-1500	Irrigation water
Moderately saline	2 - 10	1500-7000	Primary drainage water and groundwater
Highly saline	10-25	7000-15 000	Secondary drainage water and groundwater
Very highly saline	25 - 45	15000-35 000	Very saline groundwater

Table 2. Classification of saline soils (adapted from Rhoades et al. (1992))

Soil Salinity Class	*Conductivity of the Saturation Extract (dS/m)*	*Effect on Crop Plants*
Non-saline	0 - 2	Salinity effects negligible
Slightly saline	2 - 4	Yields of sensitive crops may be restricted
Moderately saline	4 - 8	Yields of many crops are restricted
Strongly saline	8 - 16	Only tolerant crops yield satisfactorily
Very strongly saline	> 16	Only a few very tolerant crops yield satisfactorily

Integrated in this context, the LIFE AGROWETLANDS II research project – SMART WATER AND SOIL SALINITY MANAGEMENT IN AGRO-WETLANDS – aims to counteract the soil degradation and the wetlands natural ecosystems alteration through a targeted and efficient management of the water resources (precision farming approach). The project provides for the implementation of a smart irrigation management system - SMART AGROWETLAND - that, by monitoring weather, soil, groundwater, channel water and crops parameters will formulate irrigation recommendations (decision support systems, DSS) to support farmers' decisions (Masina et al., 2019).

In this frame, this paper will present the architecture and the results obtained after 13 months of monitoring activity of the wireless sensor network (WSN) developed within the described project, highlighting benefits, limits of applicability, possible improvements, and strategies to optimize the operational costs.

2. Material and methods

2.1. Project architecture

The overall architecture of the SMART AGROWETLANDS II is depicted in Fig.1. It is essentially organized into three modules: the monitoring system, the data cloud and analytics, and a Decision Support System (DSS) into a web environment which provides irrigation recommendations.

The monitoring system consists of two subsystems: a) a monitoring via WSN, b) and a traditional manual monitoring (Fig. 1). The first deals essentially with real-time monitoring of environmental data (soil, ground water, canal water, irrigation water); the other consists of a manual data collection of field data, the post processing and the upload into the cloud. This last sub-system includes measurements of agricultural (agricultural workings, fertilization, canopy cover, etc.) and ecological parameters (William et al., 2001).

The WSN is an innovative on-line system composed by a group of spatially dispersed and dedicated sensors for monitoring and recording the physical parameters of soil, ground water, surface water and weather. The WSN is based on IEEE standard 802.15.4 (Adams, 2006), which focuses on a low-cost and low-speed communication between nearby devices with little to no underlying infrastructure, and lower power consumption.

The WSN is composed by different nodes, which basically are measurement points. There can be three type of nodes (Fig. 2): the "*S*-node" that is equipped only with sensors for soil monitoring, the "*P-node*" which is equipped with a soil sensor and a water sensor inserted in a nearby piezometer; the "*I-node*" which is located close to a canal and has only water quantity and quality sensors. Each WSN node can serve as router or gateway. A router is a node which collects and transmits information to another router or to a gateway. A gateway is a coordinator node, and usually it integrates a weather station *"M-node"*, and it is responsible to the sending of monitoring data to the cloud.

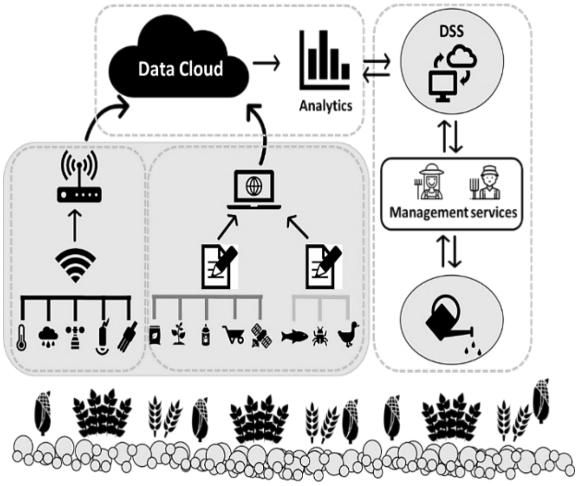

Fig. 1. Overall architecture of the SMART AGROWETLANDS platform

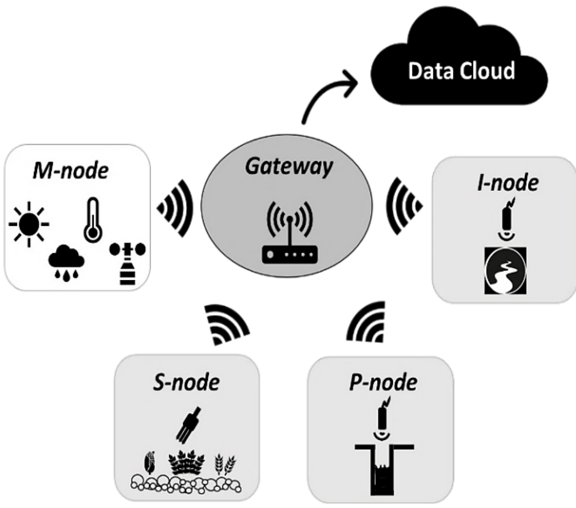

Fig. 2. Overall structure of the Wireless Sensor Network (WSN)

Nodes have been equipped with the following sensors:

- **Decagon CTD-10 -** The Decagon CTD-10 sensor is a low cost, accurate tool for monitoring water level, electrical conductivity, and temperature in both ground water and surface water. The sensor utilizes a vented pressure transducer to obtain an accurate water level measurement from 0 to 10 m while removing the effects of barometric pressure. With a range of 0 to 120 dS/m, the CTD sensor has the ability to make accurate electrical conductivity measurements in a broad range of applications.

- **Decagon GS3** - The GS3 soil moisture, temperature, and EC sensor is built with an epoxy body and stainless-steel needles. The internal circuitry is the same cutting-edge design that you can find in other Decagon soil moisture sensors, but the form factor has been optimized for use in soilless substrates or harsh environments, giving it a wider range of EC measurement and an increased temperature range. Not only do the steel needles improve sensor contact, but they also improve the sensor's ability to measure EC in porous substrates such as peat or perlite.

2.2. Case study

The study area (Fig. 3) is located in the northern part of Italy, between the Reno River to the north, the Lamone River to the south, and the coastline of the Adriatic Sea. It includes rural and agricultural land, with a high landscape value, as well as a significant number of coastal wetlands, brackish and otherwise where salinity is a fundamental controlling factor for wetland water chemistry and biodiversity (Antonellini and Mollema, 2010; Smith et al., (2007); Turnbull et al., 2007).

The pilot site is composed by 5 farms managed by a co-operative (Agrisfera, 2019) for a total surface of 609 ha mostly located close or below the sea level. The area is affected by soil salinization, salt water intrusion, and it has a shallow water table (Antonellini and Mollema, 2010; Giambastiani et al., 2007; Lamberti et al., 2018). This is essentially due to the fact that, during the second half of the 19th century, the area was converted from a wetland to an agricultural zone through hydraulic land reclamation. Soil texture ranges from clay loam to sandy loam with poor internal drainage. There is a shallow water table present within 2.5 metres from the surface in most of the study area. The climate is humid subtropical and rainfall ranges between 800-900 mm per year (Felisa et al., 2013).

The drainage system consists in 69 km of canals of different sizes (the lower the width the higher the order of the canal indicated in Fig. 3) and two dewatering pump systems (the main characteristics are summarised in Table 3) which guarantee the minimum depth to water table in the fields, it means that drainage is carried out almost exclusively mechanically. Canals have a primary function of drainage and, some of them, a secondary of irrigation (Cipolla et al., 2018a).

Table 3. Characteristics of the pump systems

ID Pump systems	***Drained area [km^2]***	***Head [m]***	***Flow rate [m^3/s]***
1° Bacino Mandriole	18.99	4.35	6.00
2° Bacino CasalBorsetti	47.38	2.96	0.87

Among all canals, only the “Canale di Bonifica Destra Reno (CBDR in Fig.3) which runs through the study area in an east-west direction and it is parallel to the Reno river, drains naturally to the Adriatic Sea. It is dammed on both banks along its whole extension and it equips a water control gates to avoid conveying seawater inland (red line in Fig. 3). During the summer season the water control gate is closed to guarantee a higher upstream water level, and so the possibility to use the water for irrigation purposes (Cipolla et al., 2018b).

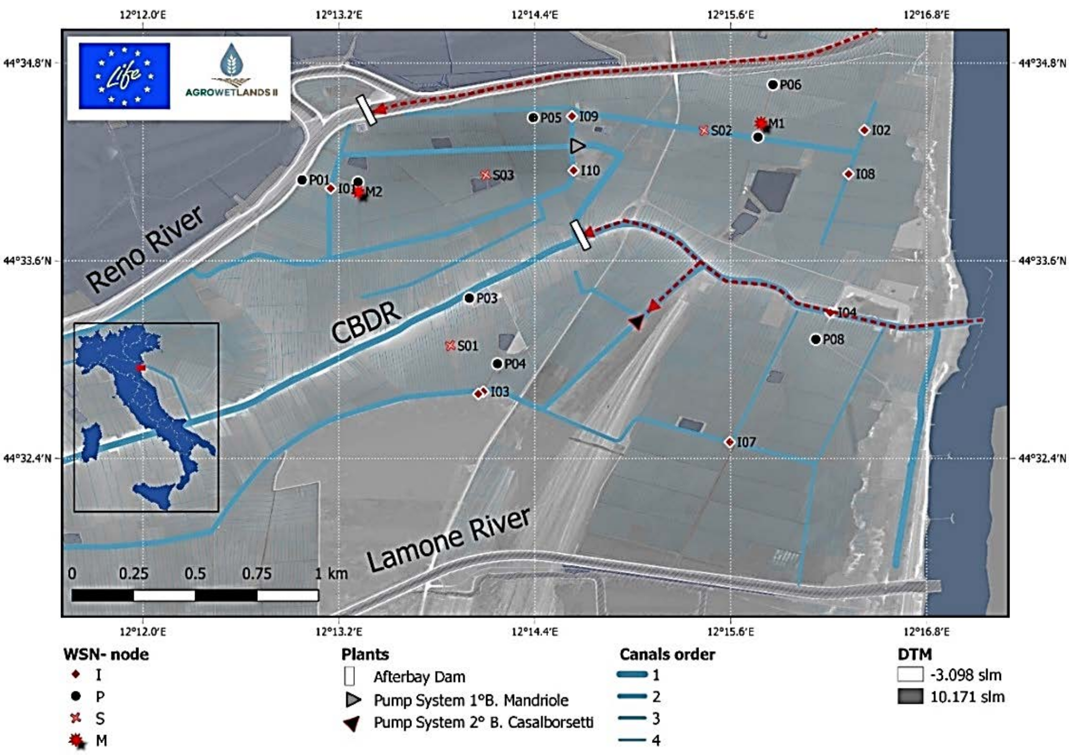

Fig. 3. Case study area

The study area is mainly cultivated with summer crops such as: maize, alfalfa, sorghum and sunflower both in traditional and organic way. Rainfall does not play a significant role in meeting crop water demand or leaching requirement and then irrigation season begins on April and finishes on the end of July/August depending on the crop.

Irrigation water comes from surface water and it is withdrawn from the Reno River and the CBDR. The first source serves, through two pump systems, a pressurised irrigation networks called "distretto irriguo in pressione", and a gravity open pipe called "Canaletta Mandriole". The second source is the CBDR and the water withdrawn through a pump and a complex systems of sluice gates is sent to the Rivalone canal. The most used irrigation systems are: traveling sprinklers and centre pivots with drop sprinklers.

2.3. Wireless Sensor Networks

The WSN is composed by 19 nodes organised into 6 subnetworks. It means that 6 gateways guarantee the transmission of monitoring data to the cloud once per hour. Fig. 3 shows the positions of the 11 *I-nodes*, 8 *P-nodes*, and 3 *S-nodes*, while Table 4 illustrates the type of sensors installed in each node and the date of installation. Monitoring data are acquired with a 10 minutes time step. The CTD10 sensors allow measuring the temperature, the water depth and electrical conductivity. They are installed in both *P-node* and *I-node*. In-canal installations were carried out by positioning the sensors in the centreline of the channel, when possible, or near a bank otherwise. *P-node* installation of CTD10 sensors was realised between 2 and 3 meters below the ground level. GS3 soil sensors were located 50 cm below the ground level.

3. Results and discussion

3.1. M-node and weather data

The WSN network is equipped with 2 weather stations 3.2 km away from each other. The M2 and M1 weather station are respectively 5 and 1.5 km from the Adriatic Sea. The traditional wind rose plots, illustrated in Fig. 4, show how wind speed and direction are distributed at M1 (a) and M2 (b) weather stations. The prevailing winds recorded on M1 come from the NW and NE with maximum speeds reaching 130 m/s. M2 station is more sheltered from the wind, the maximum speed measured is less than half (52 m/s) and the prevailing winds come from the SE.

This is likely because the right bank of the Reno river and the weather station are only 400-500m distant and the first is 4-5m higher than the second, sheltering the weather station form winds coming from NE and NW. Fig. 5 shows the cumulative daily rainfall (a and c) and the average, maximum and minimum daily air temperature (b and d) recorded at M1 and M2 stations respectively.

It may be observed that there are almost no differences in terms of temperature. On the contrary, the rainfall variability between the two stations is really accentuated.

Table 4. Characteristics of the WSN nodes

SUB-NETWORK	***ID***	***Type***	***CTD-10***	***GS3***	***Weather***	***Role***	***Date Installation***
GATTOLO INFERIORE	P02	P-node +S-node +M-node	1	1	1	G	10/11/2017
	P01	P-node +S-node	1	1	-	R	10/11/2017
	I01	I-node	1	-	-	R	01/01/2018
AUGUSTA	S01	S-node	-	1	-	G	29/03/2018
	P03	P-node +S-node	1	1	-	R	29/03/2018
	P04	P-node +S-node	1	1	-	R	06/04/2018
	I03	I-node	1	-	-	R	29/03/2018
	I11	I-node	1	-	-	R	29/03/2018
MARCABO' EAST	P07	P-node +S-node +M-node	1	1	1	G	10/08/2017
	P06	P-node +S-node	1	1	-	R	10/08/2017
	I02	I-node	1	-	-	R	01/01/2018
	I08	I-node	1	-	-	R	16/03/2018
	S02	Soil	-	1	-	R	06/04/2018
MARCABO' WEST	I10	I-node	1	-	-	G	06/04/2018
	I09	I-node	1	-	-	R	06/04/2018
	P05	P-node +S-node	1	1	-	R	06/04/2018
	S03	S-node	-	1	-	R	06/04/2018
BARONIA	P08	P-node +S-node	1	1	-	G	16/03/2018
	I04	I-node	1	-	-	R	04/12/2018
	I07	I-node	1	-	-	R	16/03/2018
S. ALBERTO	I05	I-node	1	-	-	G	04/12/2018
	I06	I-node	1			R	04/12/2018
TOTAL			19	11	2	6 G+16 R	

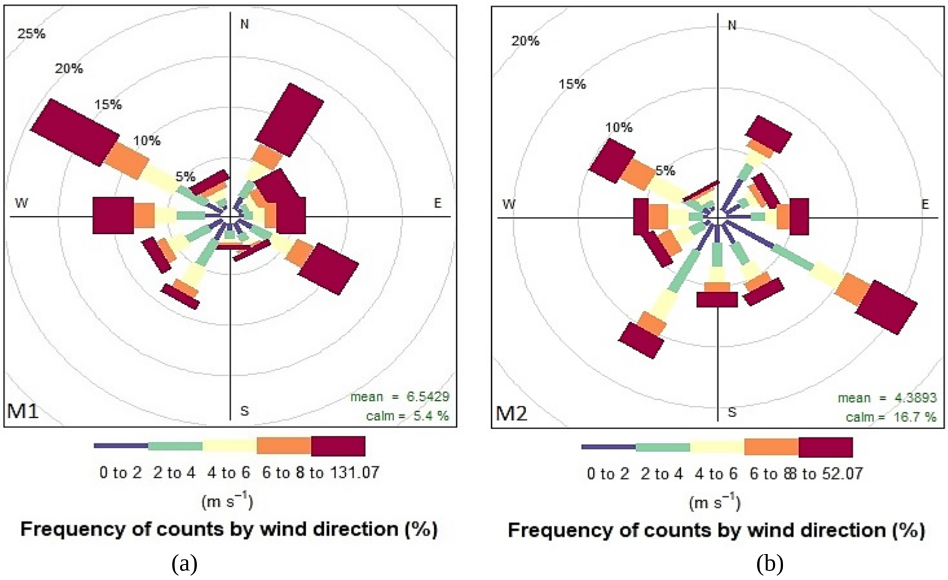

Fig. 4. Wind rose plot for the M1 (a) and the M2 M-node (b)

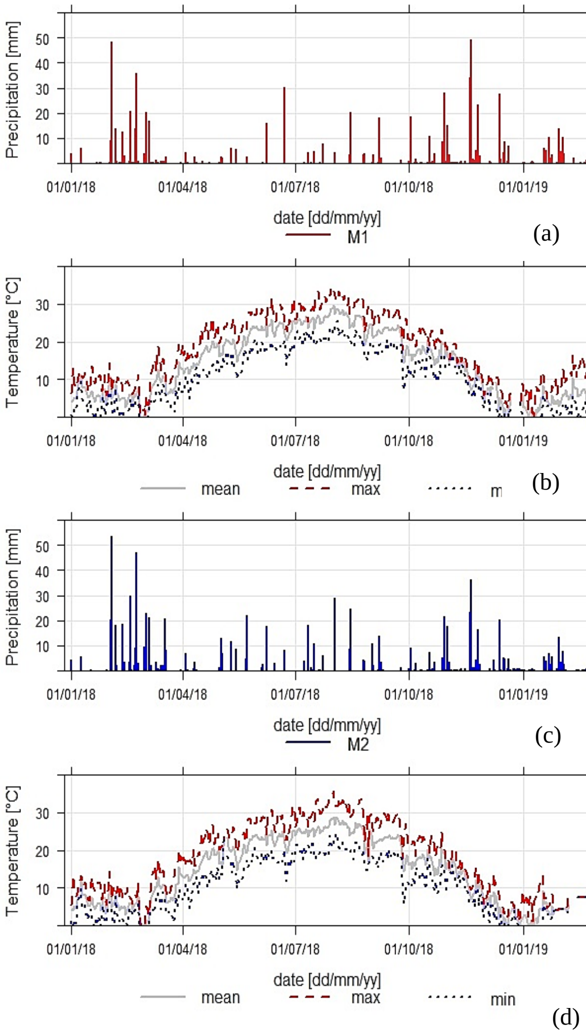

Fig. 5. Representation of: (a) the daily cumulative rainfall depth and (b) the minimum, average and maximum air temperature for the weather station M1; and of the daily cumulative rainfall depth (c) and minimum, average and maximum air temperature (d) for M2 weather station

Both rain gauges installed in the two weather stations are "tipping bucket" and have a tolerance depth of 0.1 mm. The cumulative rainfall recorded during the observation period (01/01/2018-22/02/2019, 417 days) for M1 and M2 was respectively equal to 715.3 and 854.3 mm, which corresponds to a percentage variation of 16% (Table 5).

The measurement of precipitation is very sensitive to exposure, and to wind. The differences in terms of wind exposure described above could therefore be the main cause of this difference.

Table 5. Cumulative monthly rainfall depth for weather station located on M1 and M2 and differences between them

NODE-ID	*M1*	*M2*	*M1-M2*
SU	mm	mm	Mm
Jan-18	11.0	10.5	0.5
Feb-18	162.0	210.8	-48.8
Mar-18	49.0	103.5	-54.5
Apr-18	8.5	11.5	-3.0
May-18	19.8	68.5	-48.8
Jun-18	46.5	32.5	14.0
Jul-18	18.0	41.5	-23.5
Aug-18	35.8	70.3	-34.5
Sep-18	25.5	32.0	-6.5
Oct-18	76.8	53.8	23.0
nov-18	141.3	111.5	29.8
Dec-18	51.3	46.5	4.8
Jan-19	48.8	45.3	3.5
Febr-19	21.3	16.3	5.0

Making an analysis only during the irrigation period (Apr-Aug) the differences sharpen considerably. The cumulative rainfall recorded in this period is equal to 128.5 and 224.3 mm on M1 and M2 respectively, which corresponds to a percentage variation of 42%. The high variability of rainfall data between the two stations, particularly during the irrigation period, suggests the importance of installing a dense network of rain gauges in the area that is grown using the precision farming approach. In the near future the use of precipitation radar data, which in Emilia Romagna region are supplied free of charge with a resolution of 500*500m could be exploited to reduce the costs associated with the installation of multiple rain gauges (Cipolla et al., 2019).

3.2. *Water level and salinity in I-node*

All sensors located in *I-nodes* allow estimating the quality of water returned to the sea by the canal system, while some of them (I03, I05, I06), located in canals used for both irrigation and drainage purposes, provide information also on the irrigation water quality.

Fig. 6 depicts the monitoring data collected by the *I-node* of the WSN. Water levels in canals generally vary proportionally to rainfall volume, rising during intense meteoric events, and lowering in dry weather. However, many canals (I01, I09, I07) show an artificial level variation which is caused by the pump system downstream. Moreover, during the irrigation season, the water levels are kept high thanks to the introduction of fresh water into the network through the irrigation systems, following the purpose of countering the shallow water table. This management practice is clearly visible in node I01, I02, I07 and I09.

EC values are strongly variable. Generally, the highest values are in winter and the lowest in summer, as showed in Fig.7 for nodes I01, I03, I07, and I10. The highest EC values were recorded almost in each sensor in winter 2017/2018 probably because 2017 was much drier than 2018.

This behaviour may be mainly caused by 4 factors: a) in winter the canals collect the waters that leach the soils; b) since all the canal beds range between -2.39 and -0.34 s.l.m., they collect also saline groundwater; c) in summer a large amount of fresh water is pumped in canals; 4) irrigation water has a good quality.

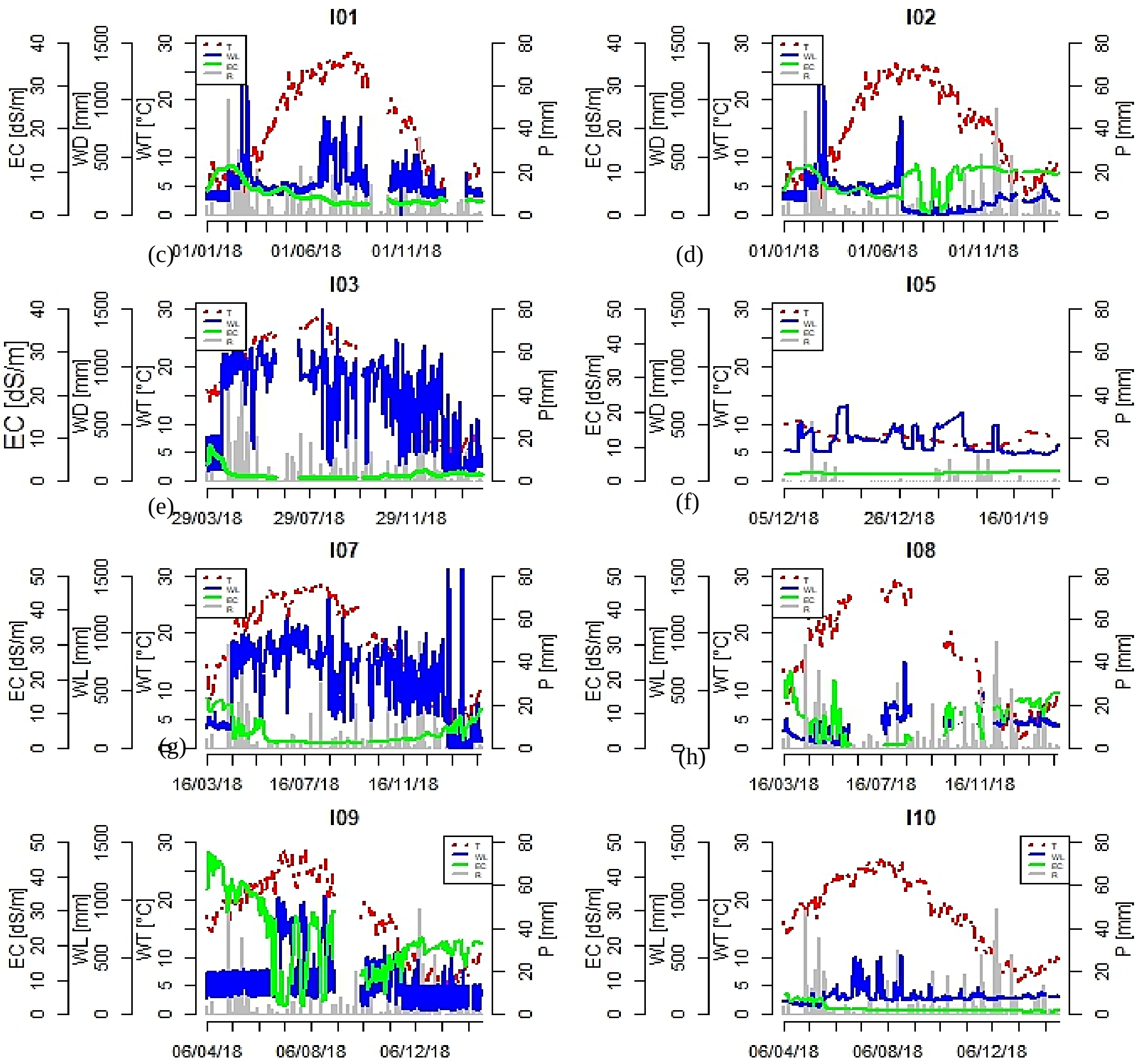

Fig.6. Daily cumulative rainfall depth of the weather station closer to the I-node (P, gray), average daily air temperature (T, red); average hourly water level in canal (WL, blue); average hourly electrical conductibility (EC, green) measured in nodes I01 - I10 during the monitoring period

The use of a real time control system, such as the one provided by the WSN, makes it possible to monitor the operation of the sensors in each moment. This allows to highlight both punctual anomalies and long-term anomalies of the data acquired. For example, the nodes I02, I08 and I09 present anomalies in terms of EC. Regarding the first two nodes, these anomalies are found between July and September 2018 and in all the months except July 2017 for node I08. I02 presents very uneven EC values during the summer, this is because the presence of water depth close to zero, as often happens in summer, the sensor measures the EC value of stagnant water, and these values should be analyzed with caution.

The behavior of node I08 is the opposite, during the winter the level is almost always close to zero and then EC rises, while during storms it drops. Upstream of the I08 there is the outfall of the "Canaletta Mandriole" irrigation system, and the low EC value indicate that during July and August a good amount of fresh water was discharged into the canal. Such water may be used by farmer for irrigation purposes. The I09 hydrometer, whose EC values reach peaks above 50 dS/m as well as an important monthly and daily variability provides an alert. Through punctual data withdrawals and inspections, the origin of such anomalies could be understood.

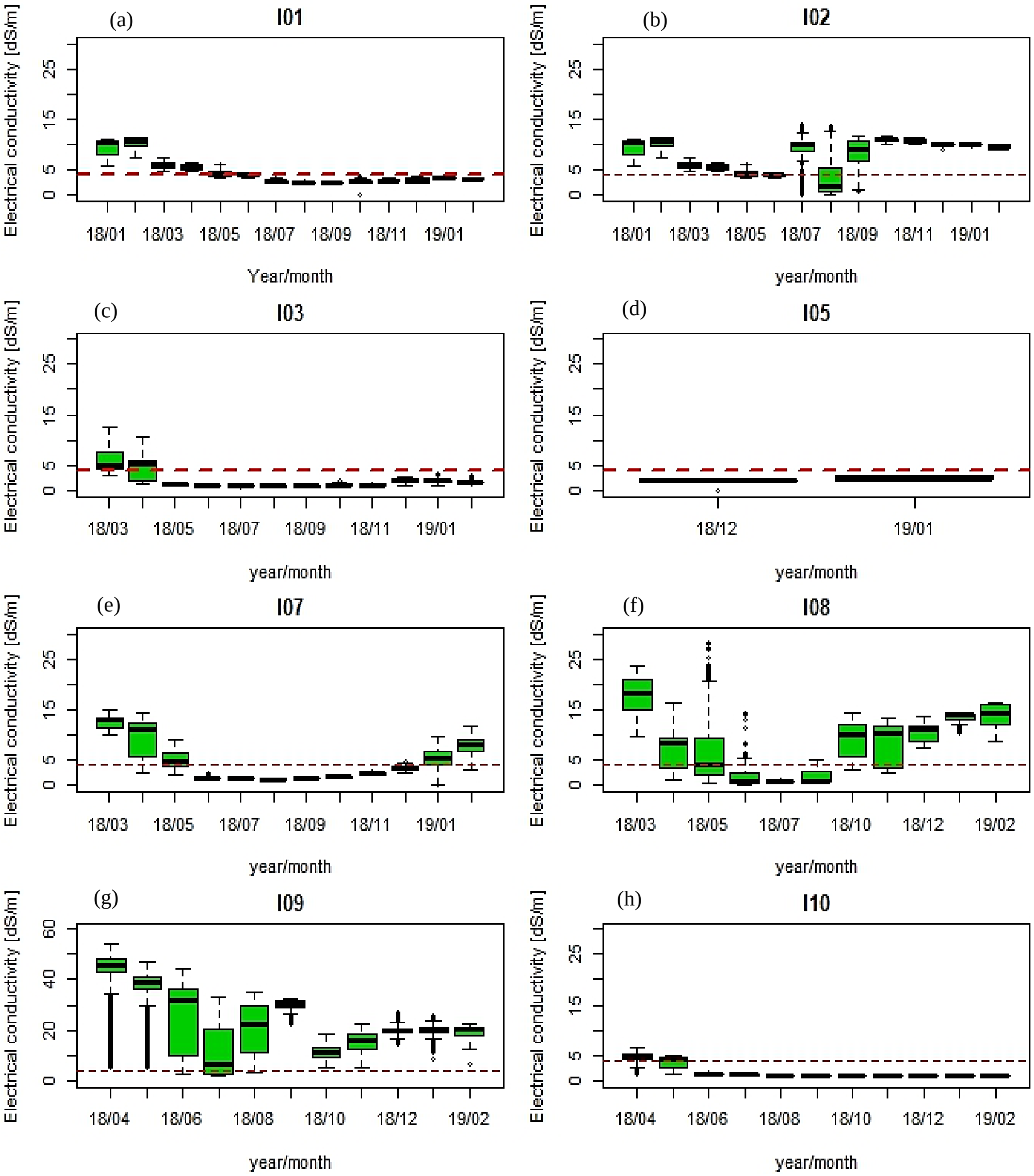

Fig. 7. Monthly boxplots of EC values in in nodes
I01 (a), I02 (b), I03 (c), I05 (d), I07 (e), I08 (f), I09 (g), and I10 (h) during the monitoring period

3.3. Water level and salinity in P-node

Groundwater table has been monitored in terms of depth from the ground level and EC by 8 P-node and 8 piezometers (see Fig. 3 for their positions). Fig. 8 shows the monthly box plots of the level and EC values for 4 of the 8 monitored piezometers. Piezometers show a marked seasonality in the watertable depth pattern and a low monthly variability of EC values since sensors have a fixed position inside the piezometer.

Rising brackish groundwater level, as the case of almost all the monitored piezometers (the piezometer P01 is in fact close to the Reno river), is a major indicator of the risk of salinity. Once the watertable rises to within 2 meters of the soil surface there is large risk of soil salinization. The fixed depth of installation of the sensors greatly affects the measurement of EC so it must be selected with due attention. Table 3 sums up the monthly mean values of the depth, temperature, and electrical conductivity of water. The red line of each graphs shows the sensor position and the brown one the ground level.

In conclusion all groundwater monitored are strongly saline. Lowering the watertable is the first step to effectively reclaim a saline site, and this the motivation that, during the monitoring period, has pushed farmers to install agricultural drains.

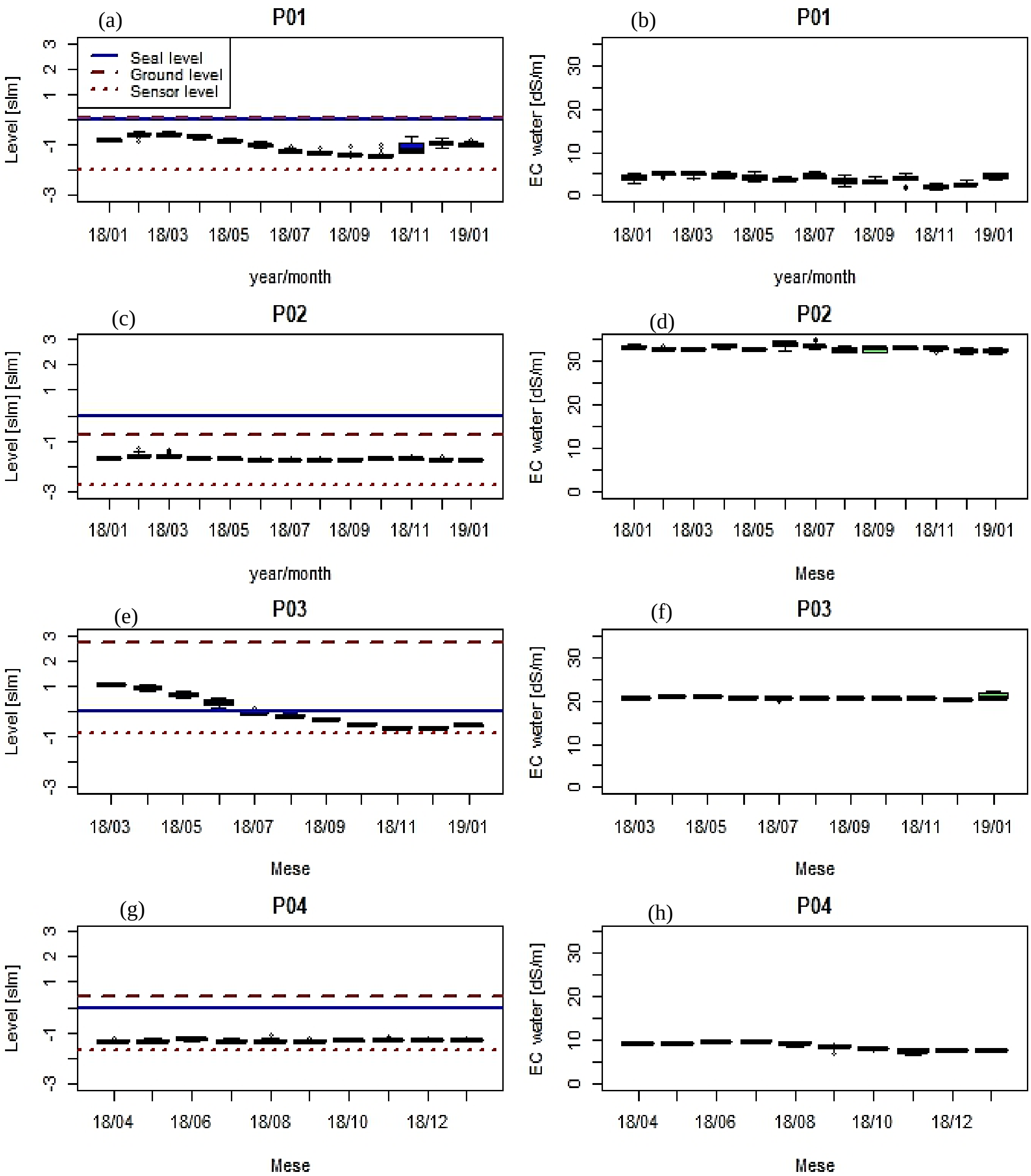

Fig. 8. Monthly boxplots of water depth (left) and EC (right) values in P01 (a and b), P02 (b and c), P03 (e and f), and P04 (g and h). The brown line of each figure represents the ground level, the red line is the level in which the sensor has been installed, and the blue line corresponds to the sea level

Table 6. Average monthly EC, water level, and water temperature values and sensor altitude for each P-node

ID	Sensor	01/18	02/18	03/18	04/18	05/18	06/18	07/18	08/18	09/18	10/18	11/18	12/18	01/19
P01	CTD10_Ew mS/cm	4.2	5.0	5.0	4.7	4.2	3.8	4.6	3.5	3.4	3.9	1.9	2.7	4.5
	Water Table [slm]	-0.8	-0.6	-0.6	-0.7	-0.8	-1.0	-1.2	-1.3	-1.4	-1.4	-1.1	-0.9	-1.0
	CTD10_Tw Â°C	12.8	11.8	10.9	12.0	14.2	16.3	19.1	20.7	21.2	20.2	18.2	14.9	13.1
	Level [slm]	-1.95	-1.95	-1.95	-1.95	-1.95	-1.95	-1.95	-1.95	-1.95	-1.95	-1.95	-1.95	-1.95
P02	CTD10_Ew mS/cm	33.3	32.9	32.8	33.4	32.7	34.0	33.5	32.5	32.8	33.1	32.9	32.5	32.5
	Water Table [slm]	-1.7	-1.6	-1.6	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.8
	CTD10_Tw Â°C	12.6	11.7	11.0	11.9	13.4	15.4	17.3	19.1	20.0	19.6	17.9	15.4	13.3
	Level [slm]	-2.75	-2.75	-2.75	-2.75	-2.75	-2.75	-2.75	-2.75	-2.75	-2.75	-2.75	-2.75	-2.75
P03	CTD10_Ew mS/cm	NA	NA	20.7	20.9	21.0	20.8	20.6	20.6	20.6	20.5	20.5	20.3	21.0
	Water Table [slm]	NA	NA	1.1	0.9	0.7	0.3	0.0	-0.2	-0.3	-0.5	-0.6	-0.6	-0.6
	CTD10_Tw Â°C	NA	NA	12.8	12.6	13.1	14.0	15.1	15.9	16.8	17.3	17.3	16.9	16.1
	Level [slm]	NA	NA	-0.83	-0.83	-0.83	-0.83	-0.83	-0.83	-0.83	-0.83	-0.83	-0.83	-0.83
P04	CTD10_Ew mS/cm	NA	NA	NA	9.3	9.3	9.5	9.8	9.2	8.5	8.1	7.5	7.6	7.8
	Water Table [slm]	NA	NA	NA	-1.3	-1.3	-1.2	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3
	CTD10_Tw Â°C	NA	NA	NA	12.2	14.3	15.8	19.4	20.7	21.1	20.2	18.7	16.3	14.1
	Level [slm]	NA	NA	NA	-1.66	-1.66	-1.66	-1.66	-1.66	-1.66	-1.66	-1.66	-1.66	-1.66
P06	CTD10_Ew mS/cm	31.3	30.5	32.2	31.3	30.5	30.8	29.9	26.5	20.1	19.2	19.1	13.8	11.9
	Water Table [slm]	0.13	0.37	0.35	0.12	0.04		-0.23	-0.62	-0.51	-0.35	-0.33	-0.23	-0.16
	CTD10_Tw Â°C	14.1	13.2	12.5	12.3	12.6	14.8	16.7	19.1	19.8	19.0	17.5	15.1	12.3
	Level [slm]	-2.34	-2.34	-2.34	-2.34	-2.34	-2.34	-2.34	-1.81	-1.81	-1.81	-1.81	-1.81	-1.81
P07	CTD10_Ew mS/cm	NA	36.2	36.1	36.3	36.5	36.5	29.9	16.2	17.6	17.9	18.3	18.6	18.2
	Water Table [slm]	NA	-0.9	-0.9	-1.2	-1.2	0.0	-1.3	-1.6	-1.5	-1.5	-1.5	-1.5	-1.4
	CTD10_Tw °C	NA	14.0	12.8	12.4	13.1	14.1	15.9	18.1	18.9	18.7	17.8	16.3	14.0
	Level [slm]	-2.72	-2.72	-2.72	-2.72	-2.72	-2.72	-2.72	-1.85	-1.85	-1.85	-1.85	-1.85	-1.85
P08	CTD10_Ew mS/cm	NA	NA	1.90	4.10	4.10		6.70	9.90	6.30	9.40	12.00	10.30	3.90
	Water Table [slm]			-0.48	-0.89	-0.96		-1.03	-1.19	-1.46	-1.43	-1.36	-1.18	-1.02
	CTD10_Tw °C			10.10	11.30	13.80		16.20	18.00	19.50	20.00	19.30	17.90	15.00
	Level [slm]	-1.82	-1.82	-1.82	-1.82	-1.82	-1.82	-1.82	-1.82	-1.82	-1.82	-1.82	-1.82	-1.82

3.3. Moisture and salinity in S-node

S-nodes allow estimating the moisture content (U_S) and measuring the bulk conductivity (EC_b). The pore water EC (EC_w) has been then estimated, as a function of the previous illustrated parameters, based on an empirical equation provided by the company that made the sensors. EC_w provides information about the soil solution, and then of the water that the plant roots actually experience during the transpiration process. Salinity sensors may be used for continuously monitoring electrical conductivity of soil water at selected depths over relatively long periods of time, as illustrated in Table 7. Soil moisture content generally decreases during the summer period and in fact all the sensors show this trend. An exception is represented by S03 sensor, which is located in the middle of an irrigated field and moreover it is close to an artificial wetland.

As the soil moisture decreases, the concentration of the salts is increased, causing an increase in the ECw, and this causes a poor crop yield. During the monitoring period the field located near the P02 was cultivated with sunflower, and the low yields achieved are certainly attributable to elevated ECw measured. On the contrary, the sorghum cultivated near the P08 has obtained a good yield demonstrating to better tolerate the high values of ECw.

Table 7. Average monthly moisture content (US), bulk conductivity (EC_b), pore water conductivity (EC_W) and relative statistics for some **S-node**

ID	S01			S03			P02			P08		
Parameter	**GS3_EC_b**	**GS3_EC_W**	**GS3_U_S**	**GS3_EC_b**	**GS3_EC_W**	**GS3_U_S**	**GS3_EC_b**	**GS3_EC_W**	**GS3_UC_S**	**GS3_EC_b**	**GS3_EC_W**	**GS3_U_s**
SU	***mS/cm***	***mS/cm***	***%***	***mS/cm***	***mS/cm***	***%***	***mS/cm***	***mS/cm***	***%***	***mS/cm***	***mS/cm***	***%***
01/18	-		-	-		-	1.460	6.421	46.060	-	-	-
02/18	-		-	-		-	1.630	6.425	48.010	-	-	-
03/18	0.320	2.301	36.840	-		-	1.410	5.611	47.840	0.630	4.151	38.580
04/18	0.330	2.321	37.220	0.860	3.326	47.980	1.240	4.886	47.640	0.660	4.505	37.550
05/18	0.380	2.825	35.840	0.930	3.160	49.790	1.380	4.570	50.110	0.730	4.449	39.130
06/18	0.340	4.614	26.710	1.010	3.073	51.210	1.370	4.790	48.880	0.810	5.148	38.110
07/18	0.220	5.033	21.090	1.160	3.230	52.330	0.840	11.456	26.170	0.570	8.160	25.640
08/18	0.310	4.673	25.480	1.030	3.153	50.780	0.710	10.371	25.080	0.650	9.073	25.830
09/18	0.220	4.858	21.140	0.980	3.236	49.660	0.460	7.091	25.150	0.720	7.960	29.130
10/18	0.200	4.819	20.850	0.900	3.949	45.180	0.110	1.561	26.170	0.630	7.163	28.820
11/18	0.250	4.686	23.330	1.100	3.870	49.370	0.670	4.928	32.880	0.690	6.656	31.730
12/18	0.320	3.172	31.680	1.110	4.293	48.340	1.390	6.304	45.320	0.650	5.095	35.410
01/19	0.370	3.060	33.780	1.080	4.368	47.540	1.350	6.444	44.010	0.590	4.773	35.250
Average	0.296	3.851	28.542	1.016	3.566	49.218	1.078	6.220	39.486	0.666	6.103	33.198
Max	0.380	5.033	37.220	1.160	4.368	52.330	1.630	11.456	50.110	0.810	9.073	39.130
Min	0.200	2.301	20.850	0.860	3.073	45.180	0.110	1.561	25.080	0.570	4.151	25.640
Var	0.004	1.219	44.409	0.010	0.252	4.229	0.218	6.320	109.925	0.005	3.072	26.561

4. Conclusions

This study shows the results of 13 months of monitoring activity realized by means of a wireless sensor network in an area affected by water and soil salinization. The WSN system is equipped with *M-nodes* to monitor the weather parameters, *S-node* to monitor moisture and electrical conductibility of soils; and *P-node* and *I-node* to monitor the water table and the electrical conductibility of groundwater and surface water respectively.

The network, currently set up with a 10-minute acquisition time step, is able to provide a wide range of data through which irrigation can be optimized. Furthermore *I-nodes* may allow optimizing the management of both irrigation and drainage systems by reducing for example the amount of fresh water get into the system to reduce the EC in canals with irrigation functions, or by optimizing the operation of pumping systems during wet weather.

Overall the network worked without major concerns, except for P05 node in which cables have been cut out by a farmer during plowing, and for I08 node that had a problem of data transmission caused by vegetation growth. In conclusion, the network as a whole turns out to be an excellent tool to support the precision farming, however during the installation of the sensors it would be advisable to take the following precautions:

1) The high variability of precipitation, in particular during the irrigation season, suggests the need of installing an adequate number of rain-gauges;
2) The sensors located in canals should always be covered by a minimum water depth, and water stagnation should be avoided.
3) Water density rises proportionally to salt content. In the piezometer water column, there is often a clear interface between the fresh and the salt water. The depth of this interface depends on the volume of fresh water in the piezometer, which in turn depends on rainfall and irrigation. However, it often happens that the probes placed at lower depth measure highest EC values. For this reason, the continuous measurement of EC at a given fixed level must be integrated with measurements along the water column to evaluate the salinity gradient.

In the near future, in situ measurement through the WSN must be integrated with satellite data (e.g. rainfall, soil moisture, NDVI etc). Those last family of measurements are frequently free of charge, and moreover, the resolution is continually improving in terms of both space and time. This will provide distributed information that will allow to extend the information acquired by a wireless sensor network system.

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