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ARTICLE

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ABSTRACT

A comprehensive review of automation of irrigation based on volumetric soil water content (VSWC) in the framework of IoT (Internet of Things) is presented. The fundamentals of electromagnetic sensors based on soil dielectric permittivity and the techniques used for measuring the VSWC are briefly described. Factors affecting sensor performance that have to be considered for selecting the appropriate sensor along with a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis are outlined. Special attention must be paid to the small soil volume explored by these sensors, installation accuracy, calibration, power supply and consumption and the effects of salinity on the soil water content. Since it is connected to a telemetry system, a wireless sensor network should include robust transmission units, energy-efficient processor, flexible configuration of the I/O ports, long-life battery, and a friendly software platform. A bidirectional wireless network layout allows sensor activity to be monitored, acts on solenoid valves to trigger irrigation (based either on direct VSWC values or algorithms) and provides real-time feed-back information of the soil-plant-atmosphere continuum. As revealed by the field research studies, significantly higher water, energy and labour savings were possible using automated irrigation based on VSWC sensors than with conventional irrigation scheduling based on computed evapotranspiration.

Introduction

Substantial water savings in agriculture have been made possible by switching the concept of 'irrigation of land' towards 'irrigation of crops' using irrigation techniques, ranging from traditional gravitational irrigation to micro-irrigation, which have resulted in higher productivity and lower water and energy consumption (Jackson, Khan, & Hafeez, 2010). The most used form of micro-irrigation is drip irrigation, whereby water is delivered to the crops via holes made in pipes and tubes or via in-line emitters (Burt & Styles, 2007). This type of irrigation system allows precise irrigation with the regular and slow application of small volumes where it is most needed. Then, the water that reaches the plant is maximised (Ayars, Bucks, Lamm, & Nakayama, 2007; Postel, Polak, Gonzales, & Keller, 2001; Vera, Conejero, Conesa, & Ruiz-Sánchez, 2019).

Under the increasing pressure of less water available for higher food demand (Mekonnen & Hoekstra, 2016), new technologies aim to improve irrigation management, increasing water use efficiency and confronting the challenge of better food and lower environmental impact (Casadesus et al., 2012; Osroosh, Peters, Campbell, & Zhang, 2016; Velasco-Muñoz, Aznar-Sánchez, Batlles-delafuente, & Fidelibus, 2019; Vera et al., 2019).

Drip irrigation management requires the timely application of the right amount of water, which, put simply, consists of knowing when to irrigate and how much water to apply. Moreover, irrigation efficiency depends on the management of water inputs to satisfy crop needs (Fereres & Soriano, 2007). One way to increase the efficiency of irrigation management is to determine the soil water content, commonly expressed as the ratio between the mass of water in the soil sample and its dry mass 'gravimetric water content' or, in terms of the volume of water in a given volume of dry soil, 'volumetric soil water content' (VSWC). Because gravimetric methods are destructive, not repeatable, and time-consuming, indirect methods based on some physical or chemical soil properties such as soil dielectric permittivity, heat capacity or H^+ content have become to be considered as alternative methods (Topp & Ferré, 2002). Recently, Hardie (2020) made a review of the novel and emerging proximal soil moisture sensors for use in agriculture.

For such indirect methods, a variety of sensors based on different physical principles, electronic designs and architecture have been developed and made available to the irrigation sector over the last three decades (Lekshmi, Singh, & Baghini, 2014; Vera, Abrisqueta, Conejero, & Ruiz-Sánchez, 2017).

Basically, these sensors measure a surrogate property of the soil related to the soil water content, the most common one being the electrical permittivity.

This paper is focused on a review of VSWC dielectric permittivity sensors and the measurement techniques used for the automation of irrigation. Also, the main factors affecting sensor performance that must be considered when selecting the most appropriate sensor in the framework of IoT (Internet of Things) in irrigated agriculture are depicted. Finally, a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis is presented based on experimental field results.

Basics of soil water content sensors

Soil and air are largely non-polar, but water is a polar molecule with a negative and positive charge which, in the presence of a magnetic field, will rotate holding an electrical charge at the frequency of the magnetic field.

The concept of dielectric permittivity (ε) is simply the ability of a substance to hold an electrical charge. Relative permittivity or dielectric constant (κ), which is dimensionless, is defined as:

$$\kappa = \varepsilon / \varepsilon_o \qquad (1)$$

where: ε_o is the permittivity of a vacuum.

Since the κ of air and water are 1 and 80, respectively, these values are the base of all the electromagnetic methods for estimating VSWC.

The dielectric permittivity of any material is a complex number:

$$\varepsilon = \varepsilon_r - j\varepsilon_i \qquad (2)$$

where: ε_r represents 'energy storage' in the form of rotational polarisation, which is closely related to VSWC (θ_v); ε_i represents the 'energy loss', and $j = \sqrt{-1}$

Energy loss is the sum of a conductivity term and a relaxation term (Kraus, 1984):

$$\varepsilon_i = \varepsilon_{i._{m.rel}} + \sigma / (2\pi f \varepsilon_o) \qquad (3)$$

where: $\varepsilon_{i._{m.rel}}$ is the soil molecular relaxation, which in non-dispersive soils is near to zero; σ is the bulk dielectric conductivity; f is the frequency; ε_o is the dielectric constant of vacuum = 8.544×10^{-12} F m^{-1}.

Therefore, ε_i allows a good estimation of the soil bulk salinity and, when $\varepsilon_r \gg \varepsilon_i$, then $\varepsilon_r = f(\theta_v)$ is robust (Seyfried & Grant, 2007).

The electromagnetic sensor responds to the apparent relative permittivity of the soil or apparent dielectric constant (ε_a) (Ferre & Topp, 2002):

$$\varepsilon_a = (\varepsilon_r/2) \left\{ 1 + \left[1 + (\varepsilon_i + (\sigma/\omega\varepsilon_o)/\varepsilon_r)^2 \right]^{1/2} \right\} \qquad (4)$$

This equation shows that the apparent permittivity depends on the ω -operating frequency of the sensor-

, the bulk electrical conductivity of the soil, and the soil temperature, which affects both ε_r and ε_i.

If $[\varepsilon_i + (\sigma/\omega \varepsilon_o)]/\varepsilon_r \ll 1$, then, ε_a is a good estimator of ε_r, as it is the case of most cultivated soils, but if ε_i is high it will introduce an error, increasing the VSWC value. This can be overcome if the sensor operates at high frequencies providing a more real character to ε_a.

The term 'energy storage' can be characterised by its capacitance (C) (Kelleners, Robinson, Shouse, Ayars, & Skaggs, 2005):

$$C = g\varepsilon_a\varepsilon_o \qquad (5)$$

where: g is a geometrical factor of the capacitor (constant).

Therefore, C is also a complex number whose imaginary part depends on the frequency of the sensor, bulk electrical conductivity, and the actual temperature of the sensor in the soil.

Techniques for permittivity and soil water content estimation

Permittivity sensors

The main techniques used for permittivity and soil water content estimation can be classified into four groups: (i) Time Domain Reflectometry (TDR), (ii) Time Domain Transmission (TDT), (iii) Capacitance or Frequency Domain Reflectometry (FDR), and (iv) Impedance. Table 1 shows the links of the main current dielectric sensors including brand, models, designs, interfaces and website for more technical information. In addition, Charlesworth (2005) compiled the features of the sensors used for soil water monitoring.

(i) In **Time Domain Reflectometry (TDR)** the wavefront of a pulse passes along the rod with a velocity, which is determined by the dielectric permittivity provided by the soil. A proportion of the signal is reflected back along the rod, which is used in determining soil conductivity. The speed and strength of the wave are causally related to ε_r, being:

$$\varepsilon_r = (ct/2L)^2 \qquad (6)$$

where: ε_r is the apparent relative dimensionless permittivity measured by TDR; c is the velocity (m/s) of an electromagnetic wave in free space; t is the travel time (s) of the electromagnetic wave along the probe, and L is the length (m) of the transmission-line rod in the soil.

Topp, Davis, and Annan (1980) was the first to propose a method to measure VSWC based on soil electromagnetic properties, virtually independent of soil texture. The author proposed a polynomial

Table 1. Main current volumetric soil water content (VSWC) sensors.

Technique	Brand	Model	Design	Interface	Website
(i) **TDR**	Acclima, Inc.	TDR 315 H TDR 310 H TDR 305 H	Parallel rods & Portable	SDI-12	www.acclima.com
	Campbell Scientific, Inc.	SoilVUE	Screw probe with cylindrical metal rings	SDI-12	www.campbellsci.com
		CS650, CS655	Parallel rods & Portable	SDI-12, RS232	
(ii) **TDT**	Acclima, Inc.	Acc TDT	Parallel rods & Portable	SDI-12	www.acclima.com
	Vegetronix, Inc.	VH400	Prong & Portable	0–3 V	www.vegetronix.com
	OnFarm Data Ltd.	Aquaflex	Belt (3 m)	SDI-12, 4–20 mA	www.aquaflex.co.nz
	RioT Technology Corp.	GroPoint	Probe, Parallel rods & Portable	SDI-12, 4–20 mA, RS-485	www.gropoint.com
(iii) **Capacitance**	Sentek Sensor Technologies	EnviroSCAN	Probe with cylindrical metal rings	RS232, RS485, SDI-12, 0–5 V	www.sentektechnologies.com
		Drill & Drop	Encapsulated probe		
	Metre Group Devices, Inc.	5TE	Parallel rods & Portable	RS232, SDI-12	www.metergroup.com
		10 HS	Parallel rods	300–1250 mV	
		Teros 12	Parallel rods & Portable	SDI-12	
	AquaCheck, Pty Ltd.	AquaCheck	Encapsulated probe cylindrical metal rings	SDI-12, RS-485	www.aquacheck.co.za
	Entelechy Pty Ltd.	EnviroPro	Encapsulated probe cylindrical metal rings	SDI-12	www.enviroprosoilprobes.com
(iv) **Impedance**	Stevens Water Monitoring Systems, Inc.	Hydraprobe	Parallel rods & Portable	SDI-12	www.stevenswater.com
	Delta-T Devices Ltd.	PR2 Profile	Encapsulated probe cylindrical metal rings	SDI-12, 0–1 V	www.delta-t.co.uk
		ML3 ThetaProbe	Parallel rods & Portable	0–1 V	

equation, which was later simplified by Topp and Reynolds (1998) to the following equation:

$$\theta_v = 0.115\sqrt{\varepsilon_r} - 0.176 = 0.115(ct/2L) - 0.176 \quad (7)$$

It is important to note that the θ_v is linear with the travel time of the electromagnetic pulse, which makes the calibration procedure easier with just two points.

In recent years, Acclima Inc. (Meridian, USA) launched a 'second generation' of TDR sensors based on nano-electronics with much lower price and superior accuracy, for both soil water content and soil electrical conductivity, of its predecessors (e.g. Tektronik 1502B).

See trademark models in Table 1.

(ii) In **Time Domain Transmission** (TDT) the measurement is based on the time taken for the pulse wave-front to travel along the rods connected beginning and end to the electrical source.

In contrast, TDR sensors are open-end rods measuring transmission time and reflected pulse. This is a closed circuit where the time difference is measured at different ends of the rod. See trademark models in Table 1.

(iii) For the **capacitance** techniques, the sensors use the soil as a capacitor, which stores part of an electric charge. The measured frequency (F) depends on the capacitance C, as the inductor (L) is a constant linked to the sensor design, as follows:

$$F = 1/\left(2\pi\sqrt{LC}\right) \quad (8)$$

In the case of the *EnviroSCAN* sensor, the Scaled Frequency (SF) or normalised frequency of the soil related to the air and to the water is defined as in the equation:

$$SF(\text{dimensionless}) = (F_{air} - F_{soil})/(F_{air} - F_{water}) \quad (9)$$

where: F_{air} is the frequency reading inside the PVC access tube while suspended in air; F_{water} is the reading inside the PVC access tube in the water bath, and F_{soil} is the reading inside the PVC access tube installed in the soil.

Because the frequency is a function of θ_v, calibrations are made using the normalised values (SF) *versus* a range of volumetric water content and temperature values for specific soils, leading to a nonlinear relationship (Paltineanu & Starr, 1997).

Other capacitance sensors, such as *EnviroPro*, or *Aquacheck*, provide a direct estimation of θ_v, but little technical information is available and specific calibrations are needed.

The *10HS* capacitance sensor is pre-calibrated to estimate the apparent constant permittivity ε_a = f(mV). It is assumed that the capacitance level relates to capacitor charging time. See trademark models in Table 1.

In recent years, Sentek Sensor Technologies Inc (Stepney, Australia) launched encapsulated probe type 'plug and play' as an alternative of the well-known *Enviro*SCAN soil moisture probe, sold as a kit composed of access tube, probe rod, probe sensor, cutting edge, and various interfaces outputs.

Other companies have made efforts in developing and selling low-cost sensors but with poor results in the field.

(iv) The **impedance** technique also has two components: the dielectric constant and the soil electrical conductivity. A numerical solution of the Maxwell equation is contained in the microprocessor inside the probe providing real and imaginary dielectric permittivity and VSWC values for selected soil textures (Campbell, 1990; Seyfried & Murdock, 2004). See trademark models in Table 1.

Calibration of permittivity sensors

Since none of the sensors can directly measure the water content in the soil profile, calibration is necessary. Using manufacturer´s default calibration equations might result in inappropriate VSWC estimations and a site-specific analysis should be then performed (Evett, Tolk, & Howell, 2005; Plauborg, Iversen, & Laerke, 2005). Jones, Blonquist, Robinson, Rasmussen, and Or (2005) proposed a methodology for standardising the characterisation of seven electromagnetic water content sensors, using relaxing, non-relaxing conductive and non-conducting fluids.

The sensor calibration procedure consists of two steps: first, relating the electrical output of the sensor to ε_r and then relating ε_r to θ_v. In this sense, standard procedure for the laboratory calibration of 'prong' and 'ring' type capacitance probes has been developed by Paltineanu and Starr (1997), Young, Fleming, Wierenga, and Warrick (1997) and Starr & Paltineanu (2002). Their approach focused on single sensor calibration, but when dealing with the whole probe, a horizontal soil container prevents the water from moving by gravity; this method is suitable for encapsulated probes (see trademark models in Table 1) as they are waterproof.

All studies that involve laboratory or field calibration are highly demanding in terms of labour and time, and many commercial farms use tendencies in the soil water content for irrigation management purposes without any field calibration. Raw data tendencies are useful to know the depth of the wetting front, maximum soil water storage and the time when daily variations in the soil water content start to limit plant water (Vera et al., 2017).

Factors affecting sensor performance

In an appraisal of how to find the best soil water content sensor for a given application, Ritter (2016) concluded that all soil water content sensors have their particular advantages and disadvantages. In this sense, the main features of the commercially available soil water content sensors were included in Charlesworth (2005) and Sample, Owen, Fields, and Barlow (2016). Also, a useful link on soil water sensors can be found at https://soilsensor.com, updated with new sensors.

The main factors affecting sensor performance to consider when selecting the most appropriate soil water sensor are:

- Soil texture, bulk density, bulk salinity, the presence of stones and soil spatial variability. Sensors must cope with those specific soil properties that must be beforehand identified.
- Depth pattern and distribution of roots (plant species) and irrigation system (hydraulic design). This feature is crucial for properly placing the sensors within the area of the main root water uptake.
- Soil volume explored by the sensor. For this feature, it has to be considered both radial and axial sensitivity, which depend on the soil water content (Paltineanu & Starr, 1997). Axial sensitivity for cylindrical rings separated 10 cm apart is ±5 cm, centred between both metallic rings. The 99% of the radial sensitivity range is less than 10 cm, in the case of cylindrical capacitance sensors embedded in a PVC access pipe. A variety of fork shape capacitance and TDR sensors, with prongs from 5 to 30 cm long, will explore a radial volume 1.4 times that of the distance between prongs. We can conclude that the relative low soil volume explored by a dielectric sensor is the main limitation.
- Temperature effects. Diurnal fluctuations in VSWC values have been observed in all dielectric sensors with TDR, TDT, capacitance and impedance techniques (Chanzy, Gaudu, & Marloie, 2012; Paltineanu & Starr, 1997; Seyfried & Murdock, 2004; Wraith & Or, 1999). According to Wraith and Or (1999), the apparent dielectric permittivity (ε_a) is determined by an interplay between two competing phenomena: the reduction in the dielectric constant of bulk water with increased temperature, and the increase in ε_a-TDR measured with increased temperature due to release of bound water.
- Design options: fixed single point sensor (e.g. *HydraProbe*), soil profile sensors named as probe (e.g. *Enviro*SCAN), or portable sensor (e.g. *Acclima*´s field kit).
- Type of sensor included in the device. Does it measure only the soil water content or

a combination of soil water content, temperature, and salinity?

- Accuracy. Usually defined as a percentage for the range of measurements, e.g. ±2% for a range of 0–50% VSWC (e.g. *EnviroPro*).
- Working frequency of the sensor. The higher frequency the better for VSWC values, as it reduces the permittivity imaginary component (see Equation (3)). Although manufacturers provide this information rarely, usually it varies from 20 MHz to 1 GHz.
- Calibration accuracy. Soil-specific calibrations reported in the literature are in the range of 0.02 to 0.03 $m^3 m^{-3}$, somewhat larger than the values ≤0.01 $m^3 m^{-3}$ reported for the neutron moderation method and TDR (Evett et al., 2005). Some manufactures provide the sensor accuracy for ranges of salinity, which may be of relevance when dealing with saline soil and/or water.
- Sensor power supply. This varies from +3.5 to +15 V. Sensor low excitation voltage is a desirable feature and does not affect the soil volume explored.
- Sensor power consumption. This is also important because data logger's battery supports both idle and active modes.
- Sensor communication interface. Serial Digital Interface SDI-12 is becoming a widely used protocol, its bus address, 0 by default, can be changed using SDI-12 commands (www.sdi-12.org).
- Difficulties involved in sensor installation and uninstallation. Permittivity sensor installation is a critical issue and therefore it must assure a close contact of the sensor or access tube with the soil. Different installation protocols depend on the sensor format: parallel electrodes in direct soil contact and cylindrical metal ring electrodes inside a PVC access pipe. Coelho and Or (1996) applied physically based principles to the sensor placement under various drip irrigation scenarios. They concluded that regions deemed suitable for sensor placement are influenced mostly by irrigation interval.
- Salinity of both of soil and irrigation water. Because salinity greatly affects VSWC values, capacitance systems typically exhibit increasing degrees of error as the salinity of soil or water increases (Campbell, 1990; Evett, Laurent, Cepuder, & Hignett, 2002; Kargas, Kerkides, & Seyfried, 2014; Kelleners et al., 2004). See Equation (4).
- Costs. The cost of a TDR sensor is ≈250 €, whereas the capacitance sensors, usually manufactured in probes of 0.4 to 1.6 m long, with sensors separated 0.1 m, vary between 600 and 1000 €. Capacitance sensors standalone fork design cost is ≈200 €. In addition, the costs associated with loggers/readers, communication and SCADA software increases by about 600–1200 €.

Using permittivity sensors in the IoT framework

Currently, soil water content sensors connect to a telemetry system by means of a Wireless Sensor Network (WSN), which is composed of transceivers, sensors, microcontrollers and a battery for power source. Such WSNs have recently come to the forefront in irrigation research. The system should include robust transmission units, an energy-efficient processor, flexible configuration of I/O ports, a long-life battery, and a friendly software platform. Wang, Liang, Ye, Lu, and Pan (2006) reviewed the state of the art on wireless sensors in the food industry and agriculture, including a section devoted to precision irrigation.

For the transmission unit, the main features to consider include the operating frequency, power consumption, analogue and digital inputs and outputs, pulse frequency counter, waterproof connectors and box with IP65 class protection.

A WSN is built of 'nodes', ranging from a few to several hundred, each node connected to one or several sensors which communicate wirelessly (Navarro-Hellín et al., 2015). Each node typically has a transmission unit with an antenna, an electronic circuit for interfacing with the sensors, and an energy source, usually a battery recharged by a solar panel. The radio transmission units send data to a gateway connected via TCP/IP to a web server program, commonly called Supervisory Control and Data Acquisition (SCADA). Currently, with the growth of de IoT technologies, an increasing number of practical applications can be found in many fields including agriculture: short-range radio technologies (e.g. Bluetooth, ZigBee), cellular communications with high device energy consumption (e.g. 3 G, 4 G, 5 G), and new technologies of low power wide area network (e.g. LoRaWAN, SigFox, NB-IoT). A comparative study on communication technologies can be found in Mekki, Bajic, Chaxel, and Meyer (2019).

A unidirectional WSN is a set of spatially distributed autonomous sensors that monitor physical or environmental conditions, such as soil water content, rainfall, soil water potential, irrigation events, leaf temperature, and meteorological conditions. Using unidirectional WSN systems to control irrigation requires a remote server, and sensor readings of the soil-plant-atmosphere continuum that consider

temporal and spatial variability, to be transmitted in quasi real-time to the server, and access to the data over the Internet.

A step forward in irrigation automation is a bidirectional WSN named as Wireless Sensor and Actuator Network (WSAN), a variant of WSN that has one additional type of component that is an actuator (Figure 1).

Inclusion of an actuator increases the capability of WSN from monitoring to system control (Aqeel-ur-rehman, Zafar, Islam, & Zubair Ahmed, 2014). It adds the ability to control sensor activity, typically by means of electro-valves to trigger irrigation based on specific algorithms, and, in addition, to detect failures of the system, which will allow real-time feedback information and action. Yunseop, Evans, and Iversen (2008) reported a WSN combining spatial soil variability with a site-specific linear-move irrigation system georeferenced by GPS.

The information and communication technology industry are very dynamic and usually, data are stored in the cloud. Several commercially available software solutions to process those WSN have been developed: Libelium (www.libelium.com), addVANTAGE (www.adcon.com), GP2 (www.delta-t.co.uk), Irrimax (www.sentektechnologies.com), Zentra Cloud (www.metergroup.com), Evvos Cloud (www.eccos.com), among others.

One of the main concerns of wireless communication is the security of the data. Since the signals are transmitted in open space, it is possible that an intruder can intercept the signals and copy sensitive information. Providing security to the entire process of communication and data management is difficult, as the CIA-triad principle of security (Confidentiality, Integrity and Availability) is applied (Andress, 2014). When managing large amounts of data, different communication protocol in different channels, with multiple sources sending data in a huge variety of data formats, provide security becomes a challenge, which is out of the scope of this paper.

Automatic irrigation management

A quick review of approaches for irrigation management based on soil water content would start with the definition of the concept of available water content (AWC) given by Veihmeyer and Hendrickson (1949): field capacity minus permanent wilting point, which has long served as a criterion for irrigation management. The AWC concept assumes a spatially uniform storage 'bucket' of invariant size to which plant roots have access (Guswa, Celia, & Rodríguez-Iturbe, 2002). The bucket representation of the rhizosphere includes uncertainties in determining the maximal effective rooting depth of plants and setting realistic values for field capacity and the water extraction limit for plants (Federer, Vorosmarty, & Fekete, 2003).

Tanner (1982) made a review of the effect of soil water content on the real to the potential crop evapotranspiration ($ET_{relative}$ etc.), as depicted in Figure 2. Line A represents the Veihmeyer and Hendrickson's theory, whereby plant evapotranspiration remains constant up to the wilting point. Line C, in accordance with Thornthwaite and Mather (1955), depicts the linear decrease in evapotranspiration as the soil water content decreases. Allen, Pereira, Raes, and Smith (1998) defined the concept of Readily Available Water (RAW), as a fraction of Total Available Water (TAW) depleted. This concept of
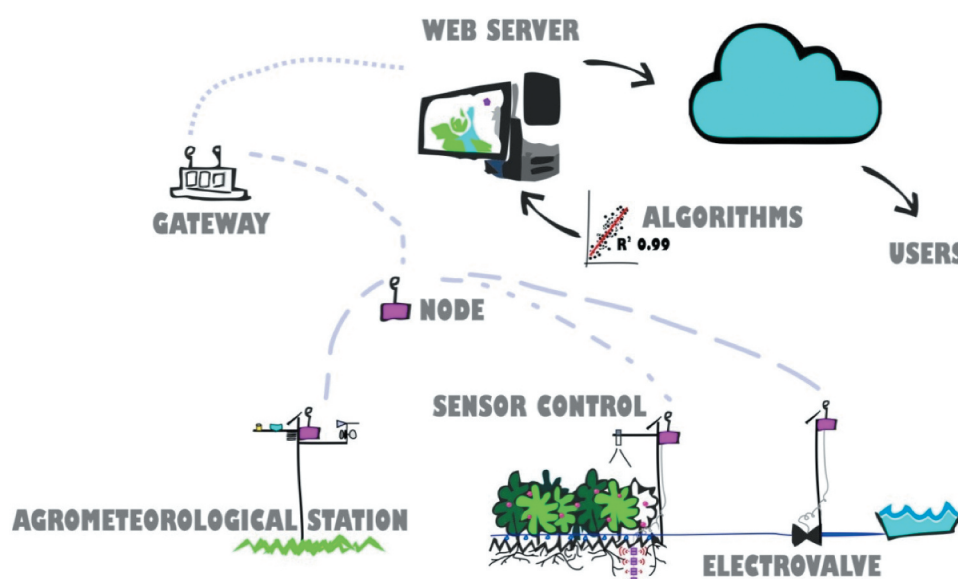

Figure 1. Components of a Wireless Sensor and Actuator Network (WSAN) for automated irrigation (By W. Conejero).
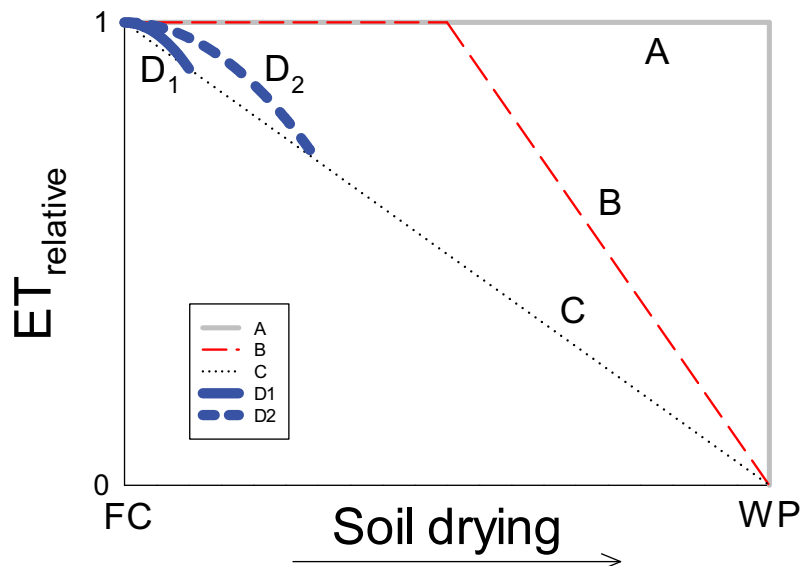
Figure 2. Relative crop evapotranspiration (ET_relative) related to soil water content (Adapted from Tanner, 1982). FC: field capacity, WP: wilting point. Lines A-D (see text).

RAW is similar to the Management Allowed Deficiency (MAD) defined by Merriam (1966), determining the depth and frequency of irrigation. This corresponds also to Line B (Figure 2).

Following those concepts, irrigation automation acts on an upper limit, around field capacity, and lower limit threshold VSWC values. Nonetheless, under high irrigation frequency conditions, an intentional water stress applied in situations of water scarcity and/or controlled deficit irrigation practices, saving water while maintaining high yields and good quality (Ruiz-Sánchez, Abrisqueta, Conejero, & Vera,

2018; Ruiz-Sánchez, Domingo, & Castel, 2010). Under this scenario, two MAD values of 10% and 30% defined for the different water stress sensitivity phenological stages, as depicted by Lines D1 and D2 (Figure 2). This new MAD approach based on the hypothesis that the soil never becomes dry enough to limit plant yield, in spite of some limitation in vegetative growth (Vera et al., 2019).

Without sensors, timers allow irrigation being automated; this is an 'open-loop irrigation' (Table 2), with a sequential control ON/OFF measuring the elapsed time of irrigation. The irrigation duration

Table 2. Automated irrigation control.

Control	Type	Parameter	Device	Algorithm	Telemetry	Time-step	WUE[a]	References
Schedule time: sequential control (On/Off)	Open-loop	ETc (mm/week) (hh:mm)	Timer	None	None GPRS	Week	+	Most commercial farms
	Feed-forward	ETc + Field monitoring	Timer Datalogger Computer	Sometimes	WSN GPRS	Hours	++	Fernández et al., 2008 Mounzer et al., 2008 Vera et al., 2010 Casadesús et al., 2012 Callejas, Vera, & Kremer, 2014 Domínguez-Niño, Oliver-Manera, Girona, & Casadesús, 2020 Navarro-Hellín et al., 2015 Osroosh et al., 2016 Millán, Casadesús, Campillo, Moñino, & Prieto, 2019 Martínez-Gimeno et al., 2020
System State Control: upper/lower limits or PID	Feed-back	VSWC SWP Drainage Weight Plant monitoring	SCADA	Yes Actuators Alarms	Bidirectional WSN TCP-IP UHF	Real-time	+++	Muñoz-Carpena & Dukes, 2008 Dursun & Ozden, 2011 Romero et al., 2012 Gutiérrez et al., 2014 Goodchild et al., 2015 Montesano et al., 2018 Pascual-Seva, San Bautista, López-Galarza, Maroto, & Pascual, 2018 Vera et al., 2013, 2017, 2019 Conesa et al., 2019, 2021

[a]WUE: water use efficiency.

calculated upon crop evapotranspiration, obtained from agro-meteorological data and crop coefficients (Allen et al., 1998), but regardless of the soil water conditions. These units are located in the field and some of them accessed by telemetry. When this sequential control is readjusted by any field-monitored parameter, it becomes a 'feed-forward irrigation'. Table 2 summarises the main control systems for automated irrigation and includes some relevant references.

Another automated irrigation control considers irrigation based on the system state. This refers to the various conditions: VSWC, soil water potential (SWP), drainage, sap flow, among others, that accumulates or depletes state variables over time (Forrester, 1994). This technique named 'feed-back irrigation' where the target is an upper and a lower limit of each system state (Table 2). When the target consists of a specific value a proportional-integral-derivative (PID) controller was tuned by its corresponded coefficients (Goodchild, Kühn, Jenkins, Burek, & Dutton, 2015; Romero, Muriel, García, & Muñoz-de la Peña, 2012), although we consider not a good option for large field irrigation sector management.

At the CEBAS-CSIC experimental field station in Murcia (Spain), different automated irrigation strategies have been designed for application in stone fruit tree orchards (Abrisqueta et al., 2015, 2010; Conesa et al., 2021; Conesa, Conejero, Vera, Ramírez-Cuesta, & Ruiz-Sánchez, 2019; Mounzer et al., 2008; Vera, Abrisqueta, Abrisqueta, & Ruiz-Sánchez, 2013; Vera et al., 2019, 2010). In these field trials, a wireless sensor network was set up, whereby irrigation was automatically managed by monitoring the soil water content with several encapsulated multi-depth capacitance probes located in the main root zone (Abrisqueta, Conejero, López-Martínez, Vera, & Ruiz-Sánchez, 2017), thus the soil sensor became a biosensor data of plant-root water uptake. Integration of the profile soil water content and desired threshold values trigger solenoid valves by means of a real-time telemetry system enhanced by various alarm controls. The VSWC threshold values were based on soil field capacity (FC) values, which were adjusted for the different phenological stages of the cultivar studied according to their water stress sensitivity (Pérez-Pastor, Ruiz-Sánchez, & Conesa, 2016; Ruiz-Sánchez et al., 2010) as 95% and 85% FC for pre- and post-harvest periods, respectively, corresponding to management allowed depletion (MAD) values of 10% and 30%, respectively. In nectarine trees, an automated sensor-based irrigation management system was compared with conventional irrigation scheduling (based on crop evapotranspiration calculations (Allen et al., 1998)), allowing a water saving of about 40% with no yield penalty (Conesa et al., 2019).

Gutiérrez, Villa-Medina, Nieto-Garibay, and Porta-Gándara (2014) reported an automated irrigation system in a sage crop field in Mexico, based on an algorithm with threshold values of temperature and VSWC with up to 90% water savings compared with traditional irrigation practices. Sui (2018) evaluated VSWC sensors determining threshold values for irrigation scheduling of cotton cultivated in the humid region of the Mid-South US. In an automatic irrigation in potted plants (Nemali & van Iers, 2006), data-logger was programmed to increase only a 2–3% VSWC every irrigation event, allowing to keep nearly constant VSWC values.

A wireless application of drip irrigation automation supported by soil moisture sensors was implemented to dwarf cherry trees in central Anatolia Turkey by Dursun and Ozden (2011). The demonstration field experiment with capacitance sensors, site-specific network and simple low-cost electronic components provided irrigation automation and improved water use efficiency. In a drip irrigated paddy field, Barkunan, Bhanumathi, and Sethuram (2019) propose an automation of drip irrigation based on the wetness level of soil images, transmitted onto a microcontroller that decides the irrigation. The automatic system saved 40% compared to the conventional flood irrigation, and 13% compared with conventional timer-based drip irrigation schedule.

Reclaimed water source is currently providing a significant amount of water for agriculture, being salts and nitrogen the major risk sources (Weiping, Sidan, Wentao, Meie, & Andrew, 2013). Studies of Mounzer et al. (2013) and Pedrero et al. (2015) showed that saline reclaimed water can be managed to save irrigation water in citrus trees. However, up to our knowledge no studies on the use of soil sensors for automated irrigation with saline water are offered. More research is needed with sensitive specific-ion content sensors. We point to the use of TDR sensors, that better discriminate soil water content from salinity measurements (see Equation (4)), for automated irrigation soil–sensor-based using poor quality water (Hardie, 2020).

Strengths, Weaknesses, Opportunities and Threats (SWOT) of sensor-based irrigation

An approach SWOT analysis of VSWC sensor-based automated irrigation experiments, showing strengths, weaknesses, opportunities, and threats, can be summarised as follows:

Strengths

- Water, energy and labour savings reported of about 40% for irrigation based on soil water content sensors compared to conventional irrigation scheduling based on computed ETc.

- Data and information from the field reaches real-time interested parties in a user-friendly way allowing on-line irrigation decisions.
- In addition to VSWC data, field monitoring may include volumetric counters, soil water potential, soil temperature, soil salinity, meteorological conditions, electro-valves status that can be accessed on-line in real-time anywhere.
- Alarms based on simple algorithms can be included in the system in order to prevent losses of water and fertiliser resulting from failures of the irrigation system (electro-valves, pipes, drippers).

Weaknesses

- All electromagnetic sensors explore a relatively small volume of soil depending on their design, and for vertisols or stony soils installation and measurements could be a limiting factor.
- The spatial variability of soil properties within fields and between farms must be considered. A minimum of three probes should be installed in the wet bulb area evenly distributed in each homogenous irrigation sector to represent the soil-root system.
- From an economic point of view, the investment needed to purchase the equipment (sensors, transmission units, SCADA, and software), maintenance, and consultancy costs must be considered.
- Maintenance of the different components of the field devices (sensors and irrigation networks) requires qualified staff for technical surveillance.
- The variety of soil water content sensors, radio transmission units and visualisation software can make the choice difficult for the users. Moreover, usually, they are not offered as part of a 'turnkey' project but by a chain of different companies that include sensor providers, sensor installation operators, transmission unit manufacturers, communication service technicians, and data visualisation and data interpretation consultants.

Opportunities

- IoT is a valuable tool for having real-time information of the soil-plant-atmosphere water continuum.
- The Wireless Sensor and Actuator Network (WSAN = bidirectional WSN) provides feedback actions.
- Public administrations, such as irrigation advisory services, whose knowledge is commonly based on networks of meteorological stations and plant phenology, could go one step further by including soil water status monitoring.

Threats

- Compliance with data protection when using cloud services of intermediary companies could be a concern, even using username and password and distributed privileges.
- A change in technology might render current sensors redundant.
- WSNs and WSANs can lead to data overflow, so efforts are needed to translate data into information.
- Climatic change could modify the economic viability of crop production and the described techniques or threshold values.

Conclusions

This work has attempted to review the current knowledge of the volumetric soil water content (VSWC) concept and monitoring by means of electromagnetic sensors for irrigation management. Capacitance, impedance, and the more reliable TDR sensors are analysed in the framework of IoT for facilitating automated irrigation.

Attention to the small volume of soil explored by these sensors, the accuracy of installation, calibration issues, power supply and consumption and the effects of salinity on the soil water content have to be considered. A telemetry system of a wireless sensor network includes robust transmission units, energy-efficient processor, flexible configuration of I/O ports, long-life battery, and a friendly software platform. A bidirectional wireless sensor network, WSAN layout, allows the monitoring of sensor activity and the ability to activate solenoid valves to trigger irrigation (based on VSWC values or algorithms), with real-time feedback information and action on the soil-plant-atmosphere water continuum.

The manuscript shows the technical challenges that can be addressed through an approach to SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis. To underline the effectiveness and accuracy of the developed automated system, some field experiments with different crops are described. The experiments pointed to the water, energy and labour savings that are possible with an automated irrigation system based on precise 'second generaton' soil water content sensors compared with conventional irrigation scheduling (based on crop evapotranspiration, ET_c). Most importantly, system state control represents a step forward in irrigated agriculture

practices that are threatened by climate change.

Disclosure statement

No potential conflict of interest was reported by the authors.

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