Field irrigation management through soil water potential measurements: a review

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Abstract: *The soil water potential (SWP) is a variable that, if correctly measured, allows to improve the irrigation efficiency at the field scale. There are different types of devices currently on the market able to provide in-field measurements of SWP, whose reliability and accuracy are widely investigated by the international scientific literature. In order to convert SWP measurements into an irrigation advice, values have to be compared with a SWP threshold (PT) adopted for the specific crop-soil condition. The PT value represents the lower limit of the SWP below which the plant begins to suffer as a consequence of the decreased availability of water in the soil, with the result of compromising its physiological well-being. Many experiments in the literature focussed on the sustainable irrigation management of different agro-ecosystems based on SWP monitoring with various devices, and on the adoption of specific PTs to drive the irrigation decision.*

The major aim of this work was to extract from the available scientific literature general rules/guidelines to support farmers in the irrigation management with SWP devices. In particular, we attempted to review: i) the most important and currently widespread types of SWP devices and their potential and limitations; ii) the principal factors to be considered when installing a SWP device (proper location within the field, installation depth, irrigation method); iii) the PTs presented in 76 literature studies carried out in different agricultural contexts (in terms of crop type, crop variety, soil texture, irrigation method) and adopting different types of devices and installation depths; iv) the main barriers in the adoption of this technology.

Keywords: *Soil water potential, soil water potential threshold, tensiometer, soil water potential sensor, water saving, irrigation management.*

Riassunto: *Il potenziale idrico del suolo (SWP) rappresenta una variabile che, se correttamente misurata, può consentire di incrementare l'efficienza irrigua a scala di campo. Attualmente sul mercato esistono diversi tipologie di strumenti capaci di fornire misure in situ di SWP, le cui caratteristiche di affidabilità e accuratezza sono largamente riconosciute nella letteratura scientifica internazionale. Il SWP, se confrontato con valori soglia (PT) del potenziale idrico, specifici per ciascuna tipologia di coltura e di suolo, può essere utile per stabilire il momento esatto dell'intervento irriguo. I valori di PT rappresentano il limite di SWP al di sotto del quale la coltura inizia a manifestare i primi sintomi di stress idrico dovuti alla diminuzione della disponibilità di acqua nel suolo. In letteratura sono riportati numerosi esperimenti volti ad una gestione sostenibile dell'irrigazione basta sul monitoraggio del SWP tramite vari strumenti di misura e l'adozione di specifiche soglie (PT).*

L'obiettivo di questo lavoro è stato quello di estrarre dalla letteratura scientifica disponibile indicazioni e regole che gli agricoltori possano adottare per una gestione dell'irrigazione basata sulla misura del potenziale idrico del suolo (SWP). Nello specifico il lavoro si è focalizzato sulla ricerca e l'analisi: i) delle principali e più diffuse tipologie di strumenti di misura del SWP, considerando le loro potenzialità e criticità di utilizzo; ii) dei principali fattori che devono essere valutati nell'installazione dei dispositivi di monitoraggio del SWP (selezione dei punti del campo più idonei all'installazione, profondità dell'installazione, metodo irriguo, ecc.); iii) dei valori di soglia (PT) derivati da 76 lavori presenti in letteratura e condotti in contesti colturali differenti (in termini di specie e varietà coltivata, tessitura del suolo, tecnica irrigua) e con strumenti di misura e profondità di installazione diversi; iv) delle criticità principali alla diffusione di questa tecnologia.

Parole chiave: *Potenziale idrico del suolo, soglia di potenziale idrico del suolo, tensiometro, sensore di potenziale idrico, risparmio idrico, gestione irrigua.*

1. INTRODUCTION

The increasing world population, the changing of eating habits, the pollution, the climate change and the desertification are all factors that contribute to an increasing threat to the water supply, and to make water an increasingly scarce commodity (FAO 2012). Agriculture is the primary sector for water use, accounting for approximately 70% of the total fresh water usage worldwide. Water's increasing scarcity suggests that there is a growing conflict between various water resource uses; therefore, a more rational use of water in the primary sector would clearly provide environmental and economic benefits for both individual farmers and society (FAO 2002). Overwatering not only increases water consumption and energy use (and thus, economic costs for farmers), but also leads to erosion, washes fertilizers out of planted zones, and may exert various forms of stress on crops (Gardner 1986; Ferreres *et al.*, 2003). However, when irrigation does not

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fully satisfy the plant needs, crop yields and the quality of the final products are reduced (FAO 2012; Layne and Bassi 2006).
There are several options to rationally manage irrigation at the field scale in order to improve its efficiency (Pardossi *et al.*, 2009; Thompson *et al.*, 2007, Bianchi *et al.*, 2016). On-site measurement of soil water potential (SWP) is one of the most effective options (Masseroni *et al.*, 2016a, b). The SWP value (generally measured in pressure units) is a fundamental variable to describe the water availability in the soil and, moreover, the capacity for that water to be used by plants (Meyer and Green 1981). SWP can be defined as the amount of work a plant's root system must perform to draw water from the soil (Gonzalez 2003) or, on the contrary, it can be seen as the force exerted by the solid soil matrix to hold water in the soil (Shock and Wang 2011). The SWP reaches a value of zero when the soil is saturated with water, while it assumes negative values in unsaturated soils. More specifically, as the soil water content decreases, the work required by plants to extract the remaining water from the solid soil particles increases, resulting in lower (more negative) SWP values (Gonzalez 2003). In addition to soil water content, the SWP value depends on soil characteristics (soil texture, organic and inorganic colloids content, soil structure). For each crop-soil system, a SWP threshold (hereinafter referred to as potential threshold or PT) can be identified below which cultivated plants begin to suffer as a consequence of the decrease in the available soil water content (Thompson *et al.*, 2007), and this leads to water stress that can compromise the plants' physiological well-being (Shock and Wang 2011). Therefore, the identification of appropriate PT thresholds for different crop types, crop varieties, crop phenological stages and soil characteristics would be a fundamental step in the direction of a more efficient irrigation management (Thompson *et al.*, 2007; Shock and Wang 2011; Hubbel and Sisson 2003; Campbell and Gee 1986).
The main objective of this article is to extract from the scientific literature general rules/guidelines to support farmers in the irrigation management of their fields with SWP devices. The paper firstly describes the SWP devices most commonly used in the operational practice, their functional characteristics and their main potential and limits. Secondly, the most important factors to be taken into account when a SWP device is installed into a field are reviewed. Successively, the paper presents the PTs identified in 76 literature studies conducted in various agricultural systems (characterized by different crop types, crop varieties, soil textures and irrigation methods) and carried out by considering different SWP devices and installation depths. Finally, the main barriers in the adoption of this technology are discussed.

2. MAIN DEVICES FOR MONITORING SWP

This section presents the technical and operational characteristics of the different SWP devices. The main potential and limitations of the devices are briefly summarized in Tab. 1.

2.1 Hydraulic tensiometer

A water tensiometer is a device that consists of a glass or plastic cylindrical tube filled with water, connected to a porous ceramic cup through a watertight connection. As the soil dries out due to plant transpiration, evaporation or percolation, water tends to be sucked out through the porous ceramic cup, creating a partial vacuum inside the tensiometer. When the soil is wetted by sufficient rainfall or irrigation, the vacuum inside the device decreases (Cassel and Klute 1986; Smajastrla and Koo 1986). Thus, at any time, tension inside the tensiometer achieves equilibrium with the SWP in the soil surrounding the porous cup. For this reason, the tension inside the device is a direct measure of the SWP, and can be determined by connecting a vacuum manometer to the device. To use the device for a continuous monitoring of SWP, a pressure transducer must be connected to the tensiometer, in order to convert tension inside the device into an electrical signal that can be registered by a data-logger.
Hydraulic tensiometers do not require any site-specific calibration, are not vulnerable to soil salinity, function within a tension range of 0 to -85 kPa, and cost approximately 40-100 €. The addition of a pressure transducer increases the cost up to 300 €. Their useful life span exceeds 5 years; however, they are extremely difficult to repair because of the risk of compromising the watertight seal (Strebel *et al.*, 1973; Oki *et al.*, 1995). Their reaction time to changes in soil water status is quite slow. It is best to fill tensiometers with water before installing them in the field. The recommended procedure is to immerge them in a vertical position in a bucket containing enough water to cover the porous cup of the instruments for at least one hour, such that the porous cup becomes saturated and the air inside the internal cavities has adequate time to be replaced by water (Cassel and Klute 1986).
The first step of the installation consists in using an earth drill with the same diameter as the tensiometer to drill a hole of the required depth. During the positioning of the tensiometer, perfect adherence between the porous cup and the surrounding soil must be ensured to allow the tensiometer to function correctly (Strebel *et al.*, 1973). For this purpose, a soil-water mixture shall be prepared with the soil of the instal-

Device	Measurement	Operation Range (kPa)	Soil Type	In situ calibration	Life (Years)	Cost (Euros)	Main features
Hydraulic Tensiometer	Direct-Water pressure in the soil	From 0 to -85	No coarse-textured soils	Not required	>5	40-100	1) They require protection from freeze and hot weather conditions 2) They can be integrated in an automated system 3) They can be connected to a datalogger 4) They are not influenced by soil salinity 5) They require continuous maintenance 6) They have a slow response to SWP changes in the soil
Granular Matrix Sensors (GMS)	Indirect-Electric resistance	From 0 to -200	All textured soils	Not required, but possible if accurate measurements are needed	>5	25-40	1) They do not need protection from freeze or hot weather condition 2) They have an optimal response from -10 to -80 kPa 3) They have a soil temperature dependence 4) They are influenced by extremely high soil salinity 5) They can be integrated in an automated system 6) They need to be connected to dataloggers or readout meters 7) They have a relatively quick response to SWP changes
Gypsum Blocks	Indirect-Electric resistance	From 0 to -200	No coarse-texturde soils	Not required, but possible if accurate measurements are needed	1-3	10-40	1) They do not need protection for freeze or hot weather conditions 2) They have a slow response to SWP changes 3) They have a soil temperature dependence 4) They are affected by soil salinity 5) They have a short useful life
Dielectric Sensors	Indirect – Dielectric permittivity of a porous ceramic matrix	From 0 to – 500/-1000	All textured soils	Not required, but possible if accurate measurements are needed	>5	180-250	1) They are subjected to hysteresis 2) They need to be connected to dataloggers of readout meters 3) They have an quick response to SWP changes 4) They do not need protection from freeze and hot weather conditions 5) They can be integrated in automated systems 6) They are highly accurate

Tab. 1 - The four macro-groups of SWP devices and their operational characteristics.
Tab. 1 - Suddivisione degli strumenti SWP in quattro macro-gruppi e loro caratteristiche funzionali.

lation site, and a little amount of this mixture shall be added to the hole before positioning the device. This procedure ensures perfect contact between the porous cup and the soil after the water drains out of the soil-water mixture. After a water tensiometer has been installed in the field, the water in the cylinder may need to be periodically refilled (Hubbel and Sisson 2003).
Tensiometers also require shielding during the winter and summer months (Shock and Wang 2011). More specifically, they must be insulated in wintertime to prevent the water inside from freezing. Shielding tensiometers from direct sunlight during the summer months helps to reduce temperature variations, which determine changes of the volume of the air pocket inside the tensiometer shaft causing deviations of the readings (Cassel and Klute 1986).

2.2 Electrical resistance sensor

Electrical resistance sensors measure SWP indirectly, by quantifying the resistance between two electrodes immersed in a porous block in close contact with the soil and its moisture. The resistance detected at the circuit leads is related to the SWP using a calibration formula whose accuracy depends on the soil temperature (Hawkins 1993; Shock 2003; Larson 1985).
The most widely used electrical resistance sensor is the Watermark 200SS (Irrometer Co., Riverside, CA), where the electrodes are embedded in a granular matrix contained in a stainless steel casing. These sensors are advantageous because of their low price (25-40 €), no specific maintenance requirements, and their ability to be used in either wired mode or as part of a network of wireless sensors (Shock 2003). Depending on the selected solution, data measured by sensors in the field can be read directly by connecting a digital readout meter, or registered on ad-hoc data-loggers and eventually sent via wireless to dedicated servers (which can be also remote) (Oki *et al.*, 1995; Calbo 2004). Electrical resistance sensors generally do not require any site-specific calibration, and may be used in soils with different textural characteristics, ranging from mostly coarse to those with a clay matrix. These sensors respond more rapidly than hydraulic tensiometers to changes in SWP resulting from meteorological events or irrigation within a range of -10 to -80 kPa. However, their estimation of SWP between the field capacity and saturation is less accurate (Fisher and Kebede 2010) and, when low SWP are considered, they may reach -200 kPa with appropriate calibration (Shock and Wang 2011).
Because electrical resistance matrix sensors are positioned completely underground, they do not require any special protection during summer or winter. The sensors tend not to be reparable; they have a useful lifespan exceeding 5 years but are less accurate than water tensiometers (Shock *et al.*, 1998). It has been amply demonstrated that electrical resistance matrix sensors are sufficiently reliable for providing irrigation

guidance at the field scale, allowing for optimal irrigation management to improve crop physiological well-being and production (Fisher and Kebede 2010). Electrical resistance sensors are not affected by changes of nutrient concentrations in the soil solution that, in the form of free ions, could influence the resistance measurement. As for hydraulic tensiometers, it is advisable to immerse these sensors in water for approximately an hour prior to the installation to thoroughly soak the porous matrix. They are installed in the field into holes drilled using a special earth drill with the same diameter of the sensor. The holes are then filled with soil removed during the installation. As for hydraulic tensiometers, it is essential to ensure an adequate contact between the sensor and the surrounding soil.

Gypsum blocks are old electrical resistance sensors. The electrodes in these sensors are embedded within gypsum blocks that attain equilibrium with the moisture in the soil. The electrical resistance measurement is converted to SWP using specific calibration curves (Bouyoucos and Mink 1947; Campbell and Gee 1986; Gardner 1986). They respond somewhat slowly to changes in SWP in comparison to hydraulic tensiometers and more recent electrical resistance sensors (Shock and Wang 2011). Moreover, the gypsum blocks tend to deteriorate and dissolve over time, which changes their characteristics and leads to a gradual loss of functionality. They are available at relatively low cost (10–40 €), but their useful lifespan is short (1-3 years). SWP measurements made with gypsum blocks are affected by soil temperature, by solute concentration in the circulating soil water (they are not compensated for soil salinity), and by imperfect adhesion between the soil particles and the block itself (Campbell and Gees 1986).

2.3 Dielectric sensors

These sensors utilize the dielectric sensing technology currently adopted in many soil moisture sensors, to which ceramic blocks are added. A dielectric sensor is used to measure the dielectrical permittivity of a porous ceramic body, whose value depends on the amount of water inside the matrix pores (in equilibrium with the SWP in the soil surrounding it). The measured value is converted into SWP using a calibration curve. Soil temperature measurements are also taken, which increase the accuracy of the SWP output values. One example of sensors of this type are the MPS-2 and MPS-6 Dielectic Water Potential Sensor manufactured by Decagon Devices, Inc. (Pullman, WA). The sensor output (proportional to the water content within the porous body) is transformed into a SWP value using an appropriate calibration curve (Decagon Device 2008; Maruelli and Calbo 2009; Paschold and Mohammed 2003). These sensors have an extremely wide range of measurement (-10 kPa to -500 kPa) and are highly accurate, with a maximum uncertainty of +/- 0.1 kPa, which is why they are often used for monitoring in scientific experiments (Wang *et al.*, 2007). As for the other devices described above, it is essential to ensure a good contact between the sensor and the surrounding soil during installation. Dielectric sensors can function at temperatures between -40 and +60 °C, and require no special maintenance during their useful lifespan (which exceeds 5 years). Similar to electrical resistance sensors, dielectric sensors can function in wired or wireless mode, and the measured data can be saved by dataloggers, or transmitted via a wireless network to personal computers or dedicated web servers via radio bridges or cellular schemes. Their cost is higher than that of previous sensors (300-400 €); however, they have extremely high acquisition frequency (70 MHz) and fast response time (150 ms). After the installation, they require only a short time to reach equilibrium with the water content of the soil (between 10 minutes and 1 hour, depending on the textural characteristics of the soil) (Decagon Devices, Inc., 2014).

The EQ3 Equitensiometer is a relatively new sensor based on electrical permittivity measurements, manufactured by Delta-T Devices (UK) since 2014. The EQ3's full measurement range is 0 to -1000 kPa, but best accuracy is achieved between -100 and -500 kPa. This makes it well suited to plant water stress studies even in very dry soils. Also for this sensor it is essential to ensure a thorough soaking of the porous matrix before the installation, and a good contact between the surrounding soil and the porous matrix during the sensor positioning. However, unlike the devices described above, the EQ3 can be installed horizontally instead of vertically or at an angle of at least 10° from vertical. It is important to protect the device from strong temperature variations by fully burying the body of the sensor and (if wired) the first portion of the cable. The EQ3 requires little maintenance and can be connected to dataloggers by cables or wireless connections. There are no special constraints on its installation regarding soil types, except highly saline soils, in which the high sodium concentration may negatively affect the accuracy of SWP output values.

3. INSTALLATION AND OPERATIONAL USE OF THE SWP DEVICES

The devices described in Section 2 must be installed at depths that should be representative of the soil zone explored by the root systems of the cultivated plants. The root system of each crop has its own particular growth pattern that depends on the plant's phenological stage (Layne and Bassi 2006). Alan and Rogers

(1997) and Pardossi *et al.*, (2009) recommended the installation of devices in pairs: one at one-third and the other at two-thirds of the maximum depth reached by the root system. Soil water content and potential of soil layers closer to the soil surface vary more widely over time than those of deeper levels, since they are more affected by wetting events and evapotranspiration processes. Thus, the device positioned in the upper part of the soil profile can be used to indicate when an irrigation event should start (i.e., the moment when the SWP drops below a certain SWP threshold fixed for the specific crop) (Shock and Wang 2011). In contrast, the deeper device can be used to determine when the irrigation event should be stopped (i.e., when the measured SWP reaches the field capacity or a predefined value set accordingly to the irrigation purpose) and consequently to control the irrigation amount delivered. This approach allows to minimize deep percolation phenomena, avoiding the increase of soil water content for soil layers not involved in the root system development (Incrocci *et al.*, 2009).

Another factor to be taken into account is the spatial heterogeneity of the agricultural field, both in terms of soil characteristics and crop development. Devices should be positioned in specific points of the field, where plant development and evapotranspiration rates can be considered in some way representative for the entire field. Pardossi *et al.* (2009) recommended to install the devices in areas where plants have a medium-high evapotranspiration rate with respect to the average conditions of plants within the irrigated sector. At the same time, if significant differences in the soil characteristics (usually above the plow sole) can be observed, the recommendation is to install at least one pair of sensors in each homogenous area to account for the field heterogeneity (Peralta and Costa 2013).

Device positioning is also influenced by the irrigation method adopted. Water redistribution in the soil is both spatially and temporally sensitive to the irrigation method used (Feibert *et al.*, 1998). More specifically, when the sprinkler technique is used, installation points are less subjected to restrictions, since this method presumes a homogeneous distribution of water within the field. In contrast, for micro-irrigation systems, SWP devices generally must be positioned perpendicular to the drip line approximately 15-25 cm from the drip nozzle, but other authors suggest to locate them at an intermediate distance between plants and the drip line (Wang *et al.*, 2007). Finally, in the case of border irrigation method, it is advisable to position the devices in the final portion of the field (on the side of the drainage channel) and/or in field zones that are, in the farmer's experience, less reached by irrigation. More information about the device positioning with respect to irrigation methods are reported in Tab. 2. Another point to take into account when considering the SWP devices positioning with respect to irrigation issues, is that PTs may depend also on the irrigation water delivery mode adopted at the farm level. In general, when irrigation water is available "on demand" (i.e., the farmer can irrigate anytime he wants) PT values can be lower than in situations where water is provided with a rotation rule (i.e., irrigation water is delivered to the farmer by an Irrigation Authority on the basis of a fixed calendar schedule). In this last case, in fact, farmer usually prefer to irrigate even if the SWP is still relatively high, in order to minimize the risk of reaching very low SWP before irrigation water is available again.

4. SWP THRESHOLDS FOR THE IRRIGATION MANAGEMENT

Tab. 3 summarizes the main SWP thresholds (PTs) used by various authors as criteria for starting irrigation. Each row reports the PT value for a different crop together with the corresponding literature reference; in addition, when available, also information on the soil type, the irrigation system, the depth of installation, the type of SWP device, the location and the season in which the experiment was conducted are reported.

In Tab. 3 information on approximately 40 different crops located in European and American agricultural

Furrow irrigation	Devices should be placed near the furrow (30-40 cm), slightly inclined towards it. In tree crops, devices must be installed between the rows, in field zones where solar radiation reaches the soil surface only during the central hours of the day.
Flooding or border irrigation	With these irrigation techniques, SWP devices provide a useful tool to check if the entire field is reached by the wetting front, and they can be also used to alert the famer when the soil reaches the saturation and the irrigation should be cut off. Devices should be placed in the final portion of the field (on the side of the drainage channel) and/or in field zones not easily reached by the irrigation, due to topography or imperfect levelling operations. Moreover, in case of soil heterogeneity, SWP devices should be (at least) positioned in field zones characterised by lighter textured soils, lower water-holding capacity and higher drainage in order to prevent crop water stress.
Sprinkler irrigation	In sprinkler irrigation systems SWP devices should be located between plants, approximately in the central part of the area wetted by each single sprinkler, making sure that vegetation would not cover the soil in which they are positioned thus modifying the soil water condition.
Drip irrigation	When drip irrigation is considered, SWP devices should be installed in the wetting zone of the emitters. Before installing the devices it is thus important to evaluate the wetting pattern into the soil, depending on the emitters discharge and position, and on the soil type. Usually, a distance of 15-25 cm from the drip nozzles or an intermediate distance between drip line and the plants can be seen as a good rule.

Tab. 2 - SWP devices positioning for different irrigation techniques.
Tab. 2 - Posizionamento dei sensori di SWP in funzione della tecnica irrigua.

areas subdivided by type (grains, fruits, vegetables, tropical crops and fodder crops) are summarized. Some crops are largely investigated in the literature (e.g., onion, potato, tomato), whereas for others, despite their agricultural and economic interest, there is little (e.g., soy) or even no (e.g., many fruit crops) information available. This reveals that irrigation management through PTs is not yet a widespread practice. The underlying reasons will be addressed in more detail in Section 5.

The experiments summarized in Tab. 3 were performed in different countries. Consequently, they reflect a wide variety of environments, climates and agricultural systems. Soil types vary from sandy to heavy clay soils, and irrigation methods adopted range from gravity-based to high-efficiency pressurized systems. Among the SWP devices, hydraulic tensiometers are the most widely used, while installation depths vary approximately between 10 and 40 cm mainly depending on the crop type. Greater installation depths are uncommon, except for specific fruit crops (e.g., vineyards) characterized by root systems reaching one meter (ore more) in length (Holler 2008).

In Tab. 3 a marked variability in PTs is shown, even for the same crop. This variability may be mainly explained by: (1) different crop species and varieties being considered, and (2) other site-specific factors including soil texture, irrigation system, type of sensor and installation depth. As a general trend, higher PT values (closer to field capacity: -10 to -30 kPa) are usually set for crops more sensitive to water stress, whereas lower PTs (-40 to -60 kPa) are adopted for more resistant crops. Cereals, for example, exhibit PTs of approximately -40 to -50 kPa except for rice, which requires higher thresholds (-15 to -20 kPa).

A marked difference in PTs can be observed also with respect to the irrigation method adopted. For example, in apple orchards PT values of -15 to -20 kPa were adopted with a single lateral drip line, while values of -20 to -25 kPa are found for drip lines installed at both

Crop	SWT (kPa)	Soil type	Irrigation method	SWP device, Installation depth	Literature reference; Geographic location; Period of the year
CEREALS					
Corn for sweet corn (*Zea mays*)	10 to 40	Sandy	Drip	Heat dissipation sensor calibrated to SWP 15 cm	Phene and Beale, 1976
Corn for sweet corn	30	Carsic	Drip	Tensiometer, 30 cm	Rivera-Hernandez, et al., 2010; Champoton, Campeche, Mexico; spring–summer
Corn for grain	30	Loamy fine sand	Sprinkler	Tensiometer, 15 cm	Rhoads and Stanley, 1973; Quincy, FL, spring–summer
Rice (*Oryza sativa*)	16	Sandy loam	-	Tensiometer, 15 to 20 cm	Kukal et al., 2005; Punjab, India; summer-fall
Rice	20	Clay-loam/clay	-	Tensiometer, 20 cm	Yadav et al. (2011), Ludhiana, India
Barley (*Ordeum vulgare*)	40-50	-	-	Tensiometer, 30 cm	Hobbs 1973, Canada
Wheat (*Triticum spp.*)	40-50	-	-	Tensiometer, 30 cm	Hobbs 1973, Canada
Oats (*Avena sativa*)	40-50	-	-	Tensiometer, 30 cm	Hobbs 1973, Canada
FRUITS					
Apple (*Malus domestica*)	15-20	Clay-loam	Single lateral drip irrigation	Tensiometer, 40 cm	Meron et al., 2001
Apple	20-25	Clay-loam	Two lateral drip irrigation	Tensiometer, 40 cm	Meron et al., 2001
Cranberryes (*Vaccinium macrocarpon*)	6(morning)-10(afternoon)	-	-	-	Jeranyama, 2009;
Grape (*Vitis vinifera*)	150	Fine-loam	Drip irrigation	GSM, 60 cm	Holler, 2008; Napa, CA, USA;
Lemon (*Citrus limonum*)	30	Loam	Microsprinkler	Tensiometer, 30 cm	Zermeno-Gonzalez et al. 2007, Mexico, november 1999-september 2001
Pear (*Pyrus communis*)	45-60	Silty-loam	Drip irrigation	GSM	Janssens et al., 2011; Belgium/Netherlands; three successive years
Strawberries (Fragraria ananassa)	10-30	-	Drip irrigation	Tensiometer, 10-20 cm	Serrano et al., 1992; Catalonia, Spagna
VEGETABLES					
Beans, snap (*Phaseolus vulgaris*)	25[a]	Loamy sand	-	Gypsum block, 10 cm	Stansell and Smittle, 1980; Tifton, GA; spring and fall seasons

Crop	SWT (kPa)	Soil type	Irrigation method	SWP device, Installation depth	Literature reference; Geographic location; Period of the year
Beans, snap	45	Sandy clay loam	-	Tensiometer, 15 cm	Hegde and Srinivas, 1990; Bangalore, India; fall–winter
Beans, snap	50	Clay loam	Furrow and drip	Tensiometer and gypsum block, 30 cm	Muirhead and White 1981; Griffin, NSW, Australia; summer
Bell pepper	58	Sandy/ sandy silt	Drip	Watermark, 10 cm	Thompson et al., 2007; Almeria, Spain; greenhouse
Bell pepper (*Capsicum annuum*)	25	Sandy loam	-	Resistance block soil moisture sensors, 10 cm	Smittle et al. 1994; Coastal plain experimental station, Tiston, Georgia; spring-fall
Broccoli (*Brassica oleracea var. italica*)	10 to 12	Sandy loam	Subsurface drip	Tensiometer, 30 cm	Thompson et al., 2002a, 2002b; Maricopa, AZ; fall–winter
Broccoli	50, 20[f]	Silty loam	-	Gypsum block, 10 cm	Maurer, 1976; Agassiz, British Columbia, Canada; spring
Cabbage (*Brassica oleracea var. capitata*)	25	Loamy sand and sand	-	Gypsum block, 10 cm	Smittle et al., 1994; Tifton, GA; spring and fall
Carrot (Daucus carota var. sativa)	30 to 50	-	Sprinkler	TDR[d]	Lada, 2002; Nova Scotia, Canada; spring–summer
Carrot	40 to 50	-	Microsprinkler	GMS, 15 cm	Lada and Stiles, 2004; Nova Scotia, Canada; spring–summer
Cauliflower (*Brassica oleracea var. botrytis*)	10 to 12	Sandy loam	Subsurface drip	Tensiometer, 10 cm	Thompson et al., 2000a, 2000b; Maricopa, AZ; fall–winter
Cauliflower	25y	Sandy loam	Furrow	Tensiometer, 18 cm	Prabhakar and Srinivas, 1995; Bangalore, India; winter
Cauliflower	20 to 40	Sandy loam	-	Tensiometer	Kaniszewski and Rumpel, 1998; Skierniewice, Poland; spring–summer
Celery (Apium graveolens)	10	Sandy loam	-	Tensiometer, 20 cm	Feigin et al., 1982; Santa Ana, CA; fall–winter
Collard (*Brassica oleracea var. Sabauda*)	9	Sandy loam	Subsurface drip	Tensiometer, 30 cm	Thompson and Doerge, 1995; Maricopa, AZ; fall–winter
Cucumber (*Cucumis sativus*)	15–30	Fine sand and sandy clay	Drip	Tensiometer, 20 cm	Suojala-Ahlfors and Salo, 2005;Piikkio, Finland; spring–summer
Eggplant (*Solanum melongena*)	15	-	Drip	Tensiometer	Bilibio et al., 2013. Greenhouse, Minas Gerais, Brasil. April
Lettuce, romaine (*Lactuca sativa*)	<6.5	Sandy loam	Subsurface drip	Tensiometer, 30, cm	Thompson and Doerge, 1995; Maricopa, AZ; fall–winter
Lettuce, leaf	6–7	Sandy loam	Subsurface drip	Tensiometer, 30 cm	Thompson and Doerge, 1996a, 1996b; Maricopa, AZ; fall–winter
Lettuce	<10	Red earth	Drip	Tensiometer, 30 cm	Sutton and Merit, 1993; NSW, Australia
Lettuce	20	Clay loam, sandy loam	Sprinkler, drip	Tensiometer, 15 cm	Sammis, 1980; Las Cruces, NM; summer-fall
Lettuce, romaine	30[a]	Clay loam	Surface	Tensiometer and gypsum block, 30 cm	Aggelides et al., 1999
Lettuce, crisphead and romaine	50	Sandy loam	Sprinkler	Tensiometer, 15 cm	Gallardo et al., 1996; Salinas, CA; spring-summer
Melon (*Cucumis melo*)	35	Sandy/ sandy loam	Drip	Watermark	Thompson et al., 2007; Almeria, Spain; greenhouse
Mustard, greens (Brassica juncea)	6 to 10	Sandy loam	Subsurface drip	Tensiometer, 30 cm	Thompson and Doerge, 1995; Maricopa, AZ; fall–winter
Mustard, greens (*Brassica juncea*)	25[g]	Loam sand and sand	-	Gypsum block, 10 cm	Smittle et al., 1992; Tifton, GA; spring and fall
Onion (Allium cepa)	8.5	Sandy	Microsprinkler	Tensiometer	Coelho et al. 1996, Piauì, Brazil
Onion	10	-	-	Tensiometer	Abreu et al. 1980, Pernambuco, Brazil
Onion	15	Silty loam	Furrow	-	Klar et al. 1976, Sao Paulo, Brazil
Onion	10 to 15	Silty loam	Drip	GMS, 20 cm	Shock et al. 2009, Oregon
Onion	17 to 21	Silty loam	Drip	GMS, 20 cm	Shock et al. 2000a, Oregon
Onion	27	Silty loam	Furrow	GMS, 20 cm	Shock et al. 1998a, Oregon
Onion	45	Sandy clay loam	_	Tensiometer	Hegde 1986, Karnataka, India

Crop	SWT (kPa)	Soil type	Irrigation method	SWP device, Installation depth	Literature reference; Geographic location; Period of the year
Onion	30	Sandy clay loam	Drip	GMS, 20 cm	Enciso et al. 2009, Texas
Potato (*Solanum tuberosum*)	20	Sandy loam	Sprinkler	Tensiometer	Hegney and Hoffman, 1997, Western Australia
Potato	25	Silty loam	Sprinkler	Tensiometer, gravimetric	Epstein and Grant, 1973, Maine
Potato	25	Silty loam	Drip	Tensiometer, 20 cm	Kang et al., 2004; Wang et al., 2007b, Luancheng, Hebei Province, China;
Potato	30	Sandy loam	Sprinkler	Tensiometer, neutron probe, to 90 cm	Lynch and Tai, 1989, Lethbridge, Alberta, Canada
Potato	30	Silty loam	Drip	GMS, 20 cm	Shock et al., 2002c, Oregon
Potato	50	Loam	Furrow	Tensiometer	Timm and Flockner, 1966, California
Potato	50 to 60	Silt loam	Sprinkler	GMS, 20 cm	Eldredge et al., 1992, 1996; Shock et al., 1998b, 2003, Oregon
Potato	60	Silty loam	Furrow	GMS, 20 cm	Shock et al., 1993, Oregon
Radish (*Raphanus sativus*)	35	Silty loam	Drip	Tensiometer, 20 cm	Kang and Wan, 2005; Luancheng, Hebei Province, China; summer-fall
Radish	20	Sandy clay loam	Furrow	Tensiometer, 18 cm	Hegde, 1987; Bangalore, India; winter
Radish	35	Silty loam	Drip	Tensiometer, 20 cm	Kang and Wan, 2005; Luancheng county, China; July-October
Spinach (*Spinacea oleracea*)	9	Sandy loam	Drip	Tensiometer	Thompson and Doerge, 1995; Maricopa, AZ
Squash, (*Cucurbita pepo*)	25[a]	Loamy sand and sand	-	Gypsum block	Stansell and Smittle, 1989; Tifton, GA; spring, summer, and fall seasons
Tomato (*Lycopersicon esculentum*)	10	Fine sand	Drip	Tensiometer, 15 cm	Smajstria and Locascio, 1996; Gainesville, FL; spring
Tomato	20	Sand	Drip	Tensiometer, 15 cm	Oliveira and Calado, 1996; Coruche, Portugal; spring–summer
Tomato	12–35[c]	Clay	Drip	Tensiometer, 10 to 20 cm[e]	Marouelli and Silva, 2007; Federal District, Brazil; fall–winter
Tomato	50	Silty loam	Drip	Tensiometer, 20 cm	Wang, et al., 2007a; Yougledian,Tongzhou, Beijing, China; summer
Watermelon (*Citrullus vulgaris*)	7 to 12.6	Sandy loam	Drip	Tensiometer, 30 cm	Pier and Doerge, 1995a, 1995b;Maricopa, AZ; spring–summer
TROPICAL CROPS					
Papaya (*Carica papaya*)	10	Gravelly-loam	Two lateral drip irrigation	Tensiometers, 16.5 cm	Migliaccio et al.,2010; Homestead, Florida, subtropical marine climate; march-august
Sugarcane (*Saccharum officinarum*)	8	_	_	Tensiometer	Hodnett et al., 1990
Sweet potato (*Ipomea batatas*)	25, then 100[b]	Loamy sand and sand	-	Gypsum blocks, 23 cm	Smittle et al., 1990; Tifton, GA; summer
FODDER CROPS					
Alfaalfa (*Medicago sativa*)	200-800	Fine sandy loam, loam, silty loam	Sprinkler	Tensiometer and gypsum block. 10 to 183 cm	Taylor et al. 1959, Logan, UT; summer season of perennial crop
Castor bean (*Ricinus communis*)	45	Loamy	Drip	Tensiometer, 20 cm	Rios et al., 2013; Lavras, Mians Gearai State,Brazil; January-August
Rape (*Brassica napus*)	20	Heavy clay	Drip	Granular matrix sensors, 12.5 cm	Bilibio et al., 2014; (greenhouse) Germany;
Soybean (*Glicine max*)	60	Silt clay soil	-	Granular matrix sensors, 25 cm	C. Shocket al., 2009. Soybean performance in Ontario in 2009. Malheur Experiment Station, Ontario, OR.
Sugar beet (*Beta vulgaris*)	40	Sandy soil	_	Granular matrix sensors, 30-40 cm	H.Neibling and J.J. Gallian. University of Idaho
Sugar beet (*Beta vulgaris*)	60	Silt loan soil	_	Granular matrix sensors, 30-40 cm	H.Neibling and J.J. Gallian. University of Idaho

Tab. 3 - SWP thresholds (absolute values) used as irrigation criteria for different crops.
Tab. 3 - Soglie di SWP (in valore assoluto) utilizzate come criterio di intervento irriguo per differenti colture.

	SWP thresholds (kPa) for crops with different sensibility to water stress	
Soil type	**High sensibility (Potatoes, Onions, Beans)**	**Low sensibility (Alfalfa, Beets, Grain, Pasture)**
Fine sand	18	25
Sandy loam	24	30
Loam	45	58
Light-textured silt loam	25	40
Heavier-textured silt loam	62	75

Tab. 4 - Soil water potential thresholds suggested as irrigation criteria for different soil types by the Extension Service of the University of Idaho.
Tab. 4 - Soglie di potenziale idrico del suolo suggerite come criterio di intervento irriguo per differenti tipologie di suolo dall'Extension Service dell'università dell'Idaho.

sides of the crop row (Meron *et al.*, 2001). A threshold of -25 kPa is recommended for potatoes in a silty-loam soil with a drip irrigation system, whereas the threshold drops to -50 kPa for a flood furrow irrigated silty soil.
The dependence on soil type is particularly evident for tomato, for which the threshold for a sandy substrate is -20 kPa. In contrast, when other conditions such as the irrigation method, the SWP device and positioning are the same, a PT of -50 kPa is found for a silty-loam soil. Soil type and crop factors are used by some (still very few) public or private Extension or Advisory Services for providing to farmers specific PTs to be adopted for the irrigation management. As an example, Tab. 4 presents PT values recommended by the Extension Service of the University of Idaho. As shown in the table, soil texture is usually the first factor for selecting a PT value, while the sensitivity to water stress of the specific crops is the second. Soils with coarser textures are usually characterized by higher thresholds with respect to heavier and less loose soils. For instance, for sandy soils Tab. 4 recommends a threshold value lower than the field capacity (-20/-30 kPa, when field capacity for sandy soil is around -10/-20 kPa), whereas for heavy soils the PT value reaches -60/-70 kPa.

5. BARRIERS TO THE OPERATIONAL USE OF SWP DEVICES

The scientific literature illustrates technological and operational potentials and limitations of the devices used for on-site SWP measurement (Tab. 1), which are also documented in the user manuals. However, a gap remains between the research in this field and the adoption of such instruments for managing irrigation in the agricultural context. There are more reasons for this fact. A first point is definitely related to the type of crop selected by the farmer. For high-value crops (i.e., those with economically advantageous yields such as vineyards), farmers are more likely to adopt technologically advanced systems to monitor the plant physiological well-being, with the aim of increasing the quality and quantity of the final product also improving the management of the water resource. While considering the irrigated agriculture in Italy, another fundamental factor limiting the application of SWP devices are the prevailing irrigation methods adopted in many agricultural areas, such as the Po Plain. When irrigation is conducted by gravitational methods, the irrigation amount delivered to the field is often unrelated to the actual crop water need. In fact, the water volume delivered must be sufficient to irrigate the entire field, from the edge of the field close to the irrigation channel to that on the opposite side, close the drainage channel. In this case, the amount of water required is more related to the soil type and the size and the slope of the field, than to the crop water requirement. The SWP devices installed in these situations are mainly used to verify that all parts of the field are watered, than to ensure an accurate irrigation supply to the crop (Tab. 2). In contrast, in the case of pressurized methods (microirrigation but also sprinkler irrigation), the irrigation efficiency is one of the main objectives. The irrigation process is usually managed by automated systems (programmable control units) that could be easily integrated with sensors monitoring the SWP or the volumetric soil water content. However, few are still the situations in which these devices are used systematically.
The key aspect in the operational use of SWP devices is that SWP measurements must be translated into irrigation recommendations by setting potential thresholds for each crop. Many scientific studies aimed to select PTs for different crop species and varieties have been conducted in the last decades (Tab. 3). However, it is still difficult to analyze the available research outcomes to identify the main factors influencing the SWP thresholds in order to propose a general criterion that may be useful to support the operational irrigation management in any condition. Therefore, if a farmer buys SWP devices, it is difficult nowadays for him to find operational guidelines for their use in irrigation management.
Other factors that may be taken into account when considering the setting of PTs for managing irrigation,

are the different water stress sensitivities characterizing the various crop varieties, and even the phenological stages of each crop variety. Within the literature, each crop is known to exhibit a specific sensitivity to water stress that depends on the species considered. Within a single species, however, different crop varieties may respond differently to soil water stress. It follows, therefore, that the identification of suitable PTs should concern the specific variety rather than the general species (Medici *et al.*, 2013). In the case of rice crop, for instance, there are varieties less sensitive to water stress used for aerobic rice in upland areas, that can be irrigated with criteria similar to those adopted for others cereals (Bouman *et al.*, 2007). In addition, each phenological stage is characterized by a different sensitivity to water stress (Steduto *et al.*, 2012). In cereals, for instance, the flowering stage is highly sensitive to water shortage (Steduto *et al.*, 2012) and thus requires a PT close to the field capacity (the value of which depends on the soil type); however, during the maturation phase cereals are less vulnerable to low soil water contents, and a PT of approximately -50 kPa can be indicatively set (Farrè and Faci 2009). Crop sensitivity to soil water conditions is the main factor to take into account in deficit irrigation management. Among the others, Jensen *et al.*, (2010) and Kang *et al.,* (2004) demonstrated how deficit irrigation or partial root-drying irrigation strategies could be used to reduce irrigation input during the less sensitive phenological phases for horticultural crops (potato and tomato), by adopting a PT around -60 kPa. Despite what discussed is widely recognized by researchers, PTs for the different crop stages are information missing in many articles examined in this review, and thus irrigation recommendations are not available for farmers.

7. CONCLUSIONS

This article makes and attempt to provide a summary of the criteria for the operational use of SWP measurements to support irrigation management at the field scale proposed by different studies available in the literature. Firstly, the main SWP devices are described, highlighting their technological and operational potentials and limitations (SWP devices characteristics are illustrated in Tab. 1). Secondly, several indications for their proper installation in the field are reported (Tab. 2 illustrates the SWP devices positioning for different irrigation techniques). Successively, SWP thresholds for managing irrigation using SWP devices as reported in 76 scientific case studies are listed (Tab. 3). For each PT, information about the geographic location of the experimental fields, the SWP device, the positioning depth, the irrigation method and the soil type are also reported. Finally, the main barriers to the operational use of SWP devices are discussed.

As shown in this review, SWP measurements can be collected by employing different approaches. The choice of the appropriate one and of suitable PTs for the irrigation management may depend on a variety of factors including:

1. Soil type (texture, bulk density, salinity, shrinking-swelling properties, soil variability within the field)
2. Crop (species and varieties, phenological stage)
3. Irrigation method and delivery mode (surface or pressurized methods, “on demand” or “fixed turn” delivery)
4. Meteorological conditions (air temperatures, freezing)
5. Location (remoteness, accessibility for sensor maintenance, remote transmission of data)
6. Available economic budget
7. Accuracy and precision of the required data
8. Technical knowledge required to operate the devices (operator skills)

The “weight” of each of these factors in the final choice must be evaluated case by case. In particular, regarding the PT thresholds, despite a plethora of information and case studies reporting values for different crops, soil types and irrigation methods, it is currently impossible to extract a general rule useful for supporting irrigation management based on SWP measures in any situation. However, the data reported in this study remain a valid compendium of case studies and constitute a reliable support for decision-making when applied to similar cases, even within different geographical contexts.

To provide an unambiguous assessment of the influence of each factor on PT values, well-designed experiments in controlled facilities should be carried out. Moreover, before adopting a SWP device for the operational irrigation management of a field, an assessment period should be scheduled in order to calibrate the procedure in the site-specific field conditions. In particular, it would be advisable to increase experiments focused on cereals and fruit crops, for which data available in the literature are still scarce. Finally, more research would be needed to support deficit irrigation or partial root-drying irrigation strategies, in order to provide suitable PTs for the different crop growth stages.

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