Proposing an appropriate soil water content estimation technique for Iran

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Abstract: Shortage of water resources is one of the major limiting factors for agricultural development in semi-arid regions, e.g. Iran. Meanwhile, in recent years, Iran has been suffering from increases in water consumption and drought conditions; therefore, efficient use of irrigation water has become a key issue in agricultural production. One of the main aspects of water management in agriculture production is operating irrigation systems efficiently. A proper irrigation water management on-farm requires a routine monitoring of Soil Water Content (SWC). During the past decades, a substantial number of different experimental methods including, direct and indirect which are determined as well as ground based and remote sensing of SWC have been developed, and a large amount of theory and knowledge is now available for application. The need for indirect ground-based methods for obtaining water content or indices of water content is evident when the time and labor involved in direct sampling is considered. Selecting the best soil water measurement technology for optimal management of irrigation system in Iran is a great challenge for managers and decision makers. To propose an appropriate system in view of Iran conditions, besides technical parameters, region related parameters such as purchasing power and lack of technical knowledge of farmers, problems associated with after sale services and good performance in saline soils, are issues that must be taken into account. This article aims to (i) discuss the advantages and limitations of available ground based SWC measurement methods and, (ii) propose a technique that will best fit to conditions in Iran. Considering regional parameters of Iran, it was found out that the tensiometer is the most proper technique for efficient SWC measurement. This is a low cost technique and could be afforded by most farmers in Iran.

Keywords: Iran, water management, soil water content, water estimation technique

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1 Introduction

Iran is faced with a serious water shortage crisis. According to Iran's geographic information, the country is located in a semi-arid region on the earth with normal annual average of 250 mm precipitation. Therefore, it can easily be claimed that the limitation of water resources is one of the main obstacles in the way of agricultural development in Iran.

One third of Iran’s economy relies on agricultural production. Since 1979Iran’s economic policy has been heavily focused on agricultural production (non-oil export policy). Therefore, agricultural production has been playing a vital role in Iranian economy. While there is an abundant access to land and labor, water has been the major limiting factor for Iranian agriculture (Larijani, 2005). About 92.8% of Iran’s water consumption belonged to agricultural activities, while only 1.2% and 6% was consumed by industry and domestic sectors, respectively. With respect to drought conditions in recent years, water management is inevitable in the agricultural sector (Mohammadiet al., 2009; Rezadoost and Allahyari, 2014).

One of the main aspects of water management in agricultural production is efficiently operating of irrigation systems. An efficient on-farm irrigation water management requires a routine monitoring of soilwater content (SWC). SWC is a highly dynamic variable that

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depends on plants evapotranspiration, irrigation frequency, drainage and rainfall. Measurements of SWC have been gaining more popularity as a means to estimate plant water use and to properly schedule agricultural and residential water supply programs (Daneet al., 2002).Such measurements not only conserve water, but also save money for farmers by avoiding the economic losses due to the undesirable effects of under-irrigation on crop yield and crop quality. In addition, SWC Measurements would reduce the adverse impacts of over-irrigation on environment caused by the wasted water and energy standpoints. It also can be considered as a solution for the wasted water problems associated with leaching of nutrients or chemicals into groundwater supplies.

Soil moisture measurement methods can be classified as: (i) direct methods and (ii) indirect methods. In direct methods, the soil moisture content is calculated from the mass of water removed and the mass of the dried soil; indirect methods involve measurement of some property of the soil that is affected by soil water content. The only direct method is the thermogravimetric (Dobriyal et al., 2012), that involves oven drying of a soil sample of known volume at 105℃ for 24 h. SWC is calculated by subtracting the oven dry weight from the initial field soil weight (Lunt et al., 2005). Thermogravimetric is indispensable as a standard method for calibration and evaluation purposes (Walkeret al., 2004).Despite its advantages of accuracy and high reliability, the gravimetric method is time as well as resource consuming, destructive, and unrepeatable(Yin et al., 2013),so it is not considered in this review. Indirect methods to determine SWC are widely used in research and also in practical applications as an alternative to thermogravimetric determination. These methods are called "indirect" because they do not measure SWC directly, but they measure some other variable from which the SWC can be calculated. Based on a known relationship between the actual water content of soil and this variable, the SWC can be determined more or less with accuracy.

The advantages of using indirect methods are clear: the indirect methods are non-destructive, measured data are immediately available, the measurement can be repeated several times in the same spot or the data can be taken and processed by a computer continuously. When the sensors are well calibrated, the measured data are accurate enough for most applications. The calibration is always carried out through comparison with the thermogravimetrical method. The need for indirect methods for obtaining water content or indices of water content is evident when the time and labor involved in direct sampling is considered.

SWC measurements can also be divided into two groups: ground-based and remote sensing measurements (Walker et al., 2004).Remote measurement of SWC, include the use of satellites, microwaves and active and passive sensors (Pumaet al., 2005). It is dependent on the electromagnetic energy that is either reflected or emitted from the soil surface, and is most suitable for determining the average soil water situations over large areas. However, it is complex, expensive and need ground truthing. The uncertainty in the relationship between the brightness, temperature and soil moisture limits the accuracy (Wang and Qu, 2009). Considering mentioned disadvantages, this method also has not been included in our review.

In view of the circumstances of Iran, selecting the best soil water measurement technology for the optimal water management of irrigation system is a challenge for managers and decision makers. This research aims to (i) compile the available ground based soil water content measurement methods and discus their advantages and their limitations, (ii) propose a technique that has best fit to conditions in Iran.

2 Methods

Papers for this review were collected utilizing different combinations of sets of keywords in Scopus, for example “soil water content measurement”, “soil moisture measurement techniques”, “soil moisture sensors" and "water shortage in Iran" searched in scientific databases such as Science Direct and Google Scholar. A large number of papers and research outcomes about soil water measurement were found. Then, for review proposes research articles were filtered by selecting only indirect and ground-based SWC measurement.

Benefits and limitations were discussed by consulting various peer-reviewed journals such as Computers and Electronics in Agriculture, Agriculture Water Management, Journal of Hydrology, Geoderma, Soil Use and Management, C. R. Geoscience, Water Resource Management, Soil & Tillage Research, Water Resource Research, and Sensors and Actuators.

2.1 Ground-based in direct method

Ground-based indirect methods are the techniques for estimating SWC in which the instruments is directly in contact with soil particles. These instruments can be logged at any time with accurate data of SWC.

2.1.1 Time domain reflectometry

In recent years, SWC estimates have advanced to include electromagnetic techniques such as time domain reflectometry (TDR) (Topp et al., 1980; Inoue et al., 2001; Dane et al., 2002; Robinson et al., 2003; Walker et al., 2004), in TDR, parallel-wire lines in a two or three-line fork structures are inserted into the soil to the depth at which the average water content is desired. The fork structures are connected to an instrument that sends an electromagnetic wave of energy along the forks. The rate at which the wave of energy is conducted into the soil and reflected back to the soil surface is directly related to the average SWC.

The TDR technique is highly accurate. Precise measurements may be made near the surface, which is an important advantage compared to other techniques such as the neutron probe. Research has shown (Evett, 2003) that the dielectric permittivity of the soil is nearly independent of soil type and bulk density. Recently Inoueet al. (2008) evaluated the performance of commercially available, low-cost soil moisture sensors time domain reflectometry (TDR), PR1 and WET (commercial dielectric sensors), all measuring changes in the dielectric constant of the soil water, was evaluated under laboratory conditions in a saline sandy soil. The results showed that measurement accuracy was strongly dependent on the salinity of the soil. The TDR sensor estimated volumetric water content with more accuracy and thus can be considered as more reliable than the other two sensors. Other studies (Jacobsen and Schjønning, 1993) found that inclusion of soil bulk density, clay and organic matter content in the calibration equation improves the correlation, suggesting that complex interactions between the soil components affect the electric properties of the soil.

The main advantages of this method are: it measures water content in large soil volume so reduces interference due to heterogeneity; it can be automated for continuous readout, relatively stable over time. However, there are some disadvantages about TDR method, in TDR insertion of rods may be difficult, may sample excessively large soil volume, requires the use of a datalogger and in order to have accurate results, a precise and complex electronics is needed. Therefore, due to the complexity, cost, and high power required by the TDR measuring systems, the existing systems are not economical and are not easy to use in practical applications (Huebner et al., 2005).

2.1.2Capacitance and frequency domain reflectometry

The electrical capacitance of a capacitor that utilizes the soil as a dielectric depends on SWC. When this capacitor, which is made of metal plates or rods imbedded in the soil, is connected to an oscillator to form an electrical circuit, changes in soil moisture can be detected by changes in the circuit operating frequency. This is the basis of the Frequency Domain (FD) technique used in Capacitance and Frequency Domain Reflectometry (FDR) sensors. In capacitance sensors the dielectric permittivity of a medium is determined by measuring the charge time of a capacitor made with that medium. In FDR the oscillator frequency is swept under control within a certain frequency range to find the resonant frequency (at which the amplitude is greatest), which is a measure of water content in the soil (Muñoz-Carpenaet al., 2004).

Skierucha and Wilczek (2010) concluded that the soil moisture values determined for the chosen mineral soil samples by the applied FDR method and sensors are comparable to the ones determined by the TDR method. This method renders accurate results (±0.01 ft^3) but needs soil specific calibration. The ambiguity in measurement of the automatic travel time of the instrument, limited sphere of influence, air gaps sensitivity, soil salinity, temperature, bulk density and clay content restrict the application of this technique (Erlingssonet al., 2009).

2.1.3 Capacitive probes

SWC may be determined via its effect on dielectric constant by measuring the capacitance between two electrodes implanted in the soil. Where soil moisture is predominantly in the form of free water (e.g., in sandy soils), the dielectric constant is directly proportional to the moisture content. The probe is normally given a frequency excitation to permit measurement of the dielectric constant. Resolution of Capacitance probes depends on their dimension, so sphere of influence or measurement is adjustable by variation in size. Capacitance probes do not need maintenance after installation (Dukes et al., 2010).With this method water content of soil can be determined at any depth and high level of precision when it is expected that ionic concentration of soil does not change. However, its flaws will be stated in the following way, the readout from the probe is not linear with water content and is influenced by soil type and temperature. Thus, careful calibration is needed (Deanet al., 1987), the results of this technique are soil and temperature specific, requiring soil specific calibrations. Sensors are expensive and their long term stability is questionable (Pardossi et al., 2009) and as the zone of measurement surrounding the capacitance probe is quite small (80% of signal sensitivity occurs within 25mm of the outside of the casing,Paltineanu and Starr, 1997) the installation that results in good soil/device contact, without the creation of air voids, is essential for accurate SWC.

2.1.4Tensiometers

Tensiometric methods estimate the soil water matric potential that includes both adsorption and capillary effects of the soil. The matric potential is one of the components of the total soil water potential that also includes gravitational (position with respect to a reference elevation plane), osmotic (salts in soil solution), gas pressure or pneumatic (from entrapped air), and overburden components. The sum of matric and gravitational potentials is the main driving force for water movement in soils and other soil-like porous media (Muñoz-Carpena et al., 2004). A tensiometer operates like an artificial root that measures how easily plant roots can pick up water from their surrounding growing media. It operates by allowing soil water to come into equilibrium with a reference pressure indicator through a permeable ceramic cup placed in contact with the soil. Drier soil has higher tension; wetted soil has lower tension values (Ling, 2004). The main advantages of this method are: direct reading of soil water matric potential, inexpensive, non-destructive, automatic for continuous reading, relatively reliable (Squireet al., 1981).Moreover tensiometers are not affected by the temperature of the soil water solution or the osmotic potential (the amount of salts dissolved in the soil water), as the salts can move into and out of the ceramic cup freely. Therefore tensiometer readings are not affected by electro conductivity or soil temperature. The tensiometers need the soil moisture characteristic curve to relate to SWC, samples a small portion of soil near the cup may take a long time to reach equilibrium with the soil (Zermeño-González et al., 2012) and requires high maintenance (Dukeset al., 2010), which restrict the application of this technique.

2.1.5 Neutron probe

The neutron probe uses a radiation source to measure SWC. With this technique, fast neutrons emitted from a radioactive source are thermalized or slowed down by hydrogen atoms in the soil. The number of slow neutrons counted in a specified interval of time is linearly related to the total volumetric SWC. A higher count indicates higher SWC (Chanasyk and Naeth, 1996). The neutron probe has a wide range of measurement capability with reasonable accuracy. However, it also has a number of disadvantages: the high cost of the instrument, radiation hazardous to health and the environment, requirement to a trained operator due to the use of a radioactive source (Tarantinoet al., 2009), equipment is expensive and needs extensive soil specific calibrations (Baker, 1990). Insensitivity near the soil surface, insensitivity to slight variations in moisture content at different points within a 30 to 40 cm radius, and variation in readings due to soil density changes, that may cause an error rate of up to 15%(Phene, 1988). Because of its cost, a neutron probe is not as practical as other methods for on-farm use. It may be a viable option for operators with large acreages of irrigated land. At present, it is used by some irrigation consultants to perform the technical tasks required to schedule irrigation.

2.1.6 Gamma ray attenuation

Principles of absorption by matter of gamma rays are well-known. The amount a beam of monoenergetic gamma rays is attenuated or reduced in intensity in soil depending upon the soil’s constituent elements and the density of the soil column. Gamma ray attenuation assumes that scattering and absorption of gamma rays is related to the density of matter in their path. Gamma ray attenuation also assumes that the specific gravity of a soil remains relatively constant as the wet density changes with moisture content. Changes in wet density are measured by the gamma transmission technique and the moisture content determined from this density change. Simply, if soil constituents and bulk density without water remain constant, then changes in gamma ray attenuation represent changes in water content (Reginato and Van Bavel, 1964). If measurements are made at two different gamma ray energies, attenuation equations may be solved simultaneously to provide both water content and soil bulk density. Bulk density often changes with the wetting and drying of a soil. By using the dual gamma technique the accuracy of water content measurements improves compared to when bulk density must be assumed to remain constant. The gamma ray attenuation method is capable of determining the moisture content at soil surface layers (up to 1-2 cm), but high cost and difficulty of use limit the applicability of this technique (Dobriyalet al., 2012). The radioactive source also poses a big risk to human health and the environment.

2.1.7 Gypsum block measurement

Gypsum blocks consist of two electrodes embedded in a block of gypsum to measure soil water tension. Wires connected to the electrodes are connected to either a portable hand-held reader or a data logger. The amount of water in the soil is determined by the electrical resistance between the two electrodes within the gypsum block. As the soil dries out, water is extracted from the gypsum block and the resistance between the electrodes increases. Conversely as the soil wets, water is drawn back into the gypsum block and the resistance decreases. Gypsum block sensors are able to provide a reasonable estimate of volumetric water content when soils are wet (higher matric potentials) but are not well suited to measurement at lower potentials (dry soils) making the device less suited to dryland systems. Because the units are installed from the soil surface, this device also suffers from preferential water flow and soil/device contact issues in cracking soils, thus it is unsuitable for sandy soils, where water drainage is fast (Zazueta and Xin, 1994).Requirement for recalibration with time caused by degradation of gypsum block is the biggest restriction of this method (Bulut and Leong, 2008).Furthermore, salt and temperature decrease the gypsum block precise in estimating SWC (Erlingsson et al., 2009).

2.1.8 Thermal method

Measurement of soil thermal properties is an indirect ground based method that exploits changes in soil thermal properties due to variation of SWC. The two main techniques are heat dissipation and heat pulse (Bittelli, 2011). The heat dissipation technique uses a heat source and temperature sensors, immersed into a porous ceramic that equilibrates with the surrounding soil at given water content. The source is heated, and the rate of heat dissipation is sensed by the temperature sensors. These changes are affected by the thermal conductivity, which depends on the ceramic water content. A significant advantage of Heat Dissipation Sensors is their insensitivity to dissolved salt content, in contrast to electric conductivity-based sensors. Moreover, sensors are relatively inexpensive (<$100 per sensor)(Flintet al., 2002). Often, variations in heat transfer properties between heater and ceramic of different sensors necessitates individual calibration. Flintet al. (2002) developed a normalization procedure that simplified calibration and presented temperature correction, using sensors from three sources and different calibration methods. The thermal conductivity is then obtained through measuring the differential temperature before and after heating (Shiozawa and Campbell, 1990; Young et al., 2008). In the heat flux method, the pulse of heat is applied at one location and its arrival at another location is determined by measuring the soil temperature at the other location. The time required for the pulse of heat to travel to the second location is a function of soil thermal conductivity, which is related to water content. The heat dissipation sensors are also used to estimate soil water potential, through calibration of the sensors at specific soil water potentials (Reece, 1996). This technique enjoys advantages such as wide measurement range ability, No maintenance requirement, up to 4 inch measurement cylinder radius, possibility of continuous reading and not affected by salinity because measurements are based on thermal conductivity. It also suffers from several drawbacks such as requiring a sophisticated controller/logger to control heating and measurement operations, slow reaction time, not working well in sandy soils, where water drains more quickly than the instrument can equilibrate and fairly large power consumption for frequent readings (Muñoz-Carpenaet al., 2004).

2.1.9 Acoustic technique

Lately, non-destructive acoustical experiments have been progressively executed in agricultural engineering and its accuracy is proven in detection and classification application (Pearsonet al., 2005; Karimiet al., 2012;2015). Several researchers investigated acoustic technique usagein SWC estimation, it is well established theoretically (Brutsaert, 1964) and experimentally (Flammeret al., 2001; Adamoet al., 2004) that some characteristics of acoustic in soil depends significantly on its water content. Sharma and Gupta (2010) used a method based on the propagation of an acoustic continuous wave with frequencies below 900 Hz through the soil and the result showed that the agreement between the experimental results obtained from the laboratory prototype and those obtained theoretically from Brutsaert's model for elastic wave propagation in soil-air-water system is presented. More recently Meisami-asl et al. (2013) investigated the measurement of moisture content in soil using some properties of acoustic waves such as peak amplitude(A), total power (TP), total harmonic distortion and signal to noise ratio. The results showed that the best model for estimating the soil moisture content was the model that expressed relationship between A and soil moisture content with R2 = 0.999 (using sweep frequency) and relationship between TP and soil moisture content with R2 = 0.999 (using multiple tone). It has been concluded that some characteristics of acoustic in the soil can be used to determine the water content of the soil.

In the mentioned studies the dependence of the acoustic characteristics on water content of compressed soil has been investigated. The speed of acoustic in all the experiments, has been observed to decrease with the increase in water content of the soil. The reported results however cannot be directly applied for the agriculture soil because it is intentionally kept loose for better plant growth. There are also some issues such as effect of acoustic noise in open agriculture, temperature dependence of speed of sound, distortions in received signal waveform, degree of saturation of soil, which makes the use of this in the field technique questionable (Sharma and Gupta, 2010).

3 Discussion

During the past six decades, economic development, land-use policies, and population growth and its pressures have affected agriculture as a main sector in Iran's economy. From the 1940s until 2010, the percentage of the total urban population of Iran increased from about 21% to around 72%. Urbanization, industrialization, and intensive cultivation have dramatically affected soil and water resources (Emadodinet al., 2012). In addition, Iran as a developing country is located in arid and semi-arid areas in which water scarcity is a major issue and regarding to the highest level of water shortage is in the agricultural sector, the need for efficient use, or in other words, efficient management of agricultural water consumption is inevitable. This goal cannot be met unless the appropriate technology is provided for SWC measurement.

In typical case, while selecting a technique for SWC measurement, several issues such as the accuracy, replicability, response time, calibration requirements, spatial resolution, cost, ease in using the methods, effort required in installation, management and durability of the equipment should be considered (Baker, 1990). While, to mechanize the Iran irrigation system faster due to low purchasing power of farmers, lower cost of technique should be paid with more attention. Furthermore, localization capability of SWC estimation technology to deal with technological backwardness of Iran as a developing country should be taken with high consideration.

In addition, the general circumstances of Iran soils arean important factor for selecting appropriate SWC measurements technology. Due to its topographical, climatic and particularly its lithologic diversity, Iran displays a rich mosaic of soils. Arid farm soils in central Iran are intensively tilled, low in soil organic matter level and consequently have a weak structural stability (Mosaddeghi et al., 2000).Salinity of soil is observed in many parts of the country. Although salt-affected soils exist throughout Iran, slightly and moderately salt-affected soils are mostly found in the northern part, while soils with high salinity levels are prevalent in the central part(Qadir et al., 2008). In Iran approximately 77% of the agricultural land under irrigation suffers from different levels of salinity (Emadodin and Bork, 2012).Therefore, salinity of soil and water resources as an important issue in many parts of Iran should be paid with specific attention.

Generally, it can be argued that, in proposing an appropriate SWC estimation technique in view of Iran conditions, some additional factors such as cost, localization capability, simplicity, technical support, easy servicing and good performance in saline soils besides the other mentioned characteristics are more highlighted.

Dobriyal et al. (2012) reviewed the methods available for soil moisture estimation and concluded that the TDR technique is more efficient in comparison with other reviewed methods. However, TDR measuring systems requires the use of a datalogger and in order to have accurate results, a precise and complex electronics is needed. In addition Inoueet al.(2008)reported that the performance of commercially available TDR measurement is strongly dependent on the salinity of the soil. Therefore, due to the complexity, cost, sensitivity to soil salinity and high power required by the TDR measuring systems, the existing systems are not economical and they are not suitable instruments in Iran.

By reviewing other described methods with regard to their benefits and costs, it was found that tensiometers are the most efficient SWC measurement device that can widely be used in Iranian farms. Given the theoretical considerations discussed, tensio meters provide a direct measurement (the physical force that plants exert removing water from the soil) of soil water tension.

Tensiometers do not require site-specific calibrations (Shock and Wang, 2011).Tensiometers last for many years and they can be repaired. Tensiometers are suitable for manual or electronic data collection. Manual reading of a tensiometer gauge requires no electrical power. Tensiometers can be equipped with pressure transducers or other devices for automatic readings (Klute, 1986; Hubbell and Sisson, 2003). Moreover tensiometers are not affected by the temperature of the soil water solution or the osmotic potential which are desired features due to the existence of vast Saline soil fields and temperature variation in Iran (Pazira and Homaee, 2010). Muñoz-Carpena et al. (2004)stated the desirable features of tensiometers as: direct reading, up to 4 inch measurement sphere radius, continuous reading possible when using pressure transducer, no electronics and power consumption, well-suited for high frequency sampling or irrigation schedules, minimal skill required for maintenance, not affected by soil salinity; because salts can move freely in and out across the porous ceramic cup and finally, low cost.

4 Conclusion

The efficient water content of soil estimation can be achieved by choosing proper sensing technology. SWC can be measured in the field using various ground-based indirect techniques. To select suitable technique besides characteristics such as accuracy, spatial scale, response time and the measured parameter, other region related parameters like purchasing power and lack of technical knowledge of farmers, problems associated with after sale services and good performance in saline soils, are issues that must be taken into account.

In the present review owing to the particular regional conditions, it was found that the using tensiometers are the most suitable method for efficient measurement of SWC in Iran. This technique due to advantages such as good accuracy, lower cost, simple instruction, direct reading of soil water matric potential, non-destructive, automatic for continuous reading, reliability, no requirement for site-specific calibrations, durability, easy repairable, no electrical power requirement and insensitivity to saline soil and temperature variation in addition with other introduced advantages could be more effective in development of Iran agriculture mechanization.

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