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Indirect Methods of Measuring Soil Moisture Content Using Different Sensors

[1]*Saketu Hunduma and* [1,2]*Gezahagn Kebede*

[1]Ethiopian Institute of Agricultural Research, Holetta Research Center,
P.O. Box: 31, Holetta, Ethiopia
[2]Hawassa University College of Agriculture, P.O. Box: 05, Hawassa, Ethiopia

Abstract: Soil moisture content is a soil property that plays a crucial role in a large variety of biophysical processes, such as seed germination, plant growth and plant nutrition. Soil moisture content affects water infiltration, redistribution, percolation, evaporation and plant transpiration. Soil moisture is very dynamic, both temporally and spatially, therefore its continuous monitoring is necessary. Soil moisture measuring devices can be classified into direct and indirect monitoring methods. The direct method uses weight to determine how much water is in a sample of soil. A soil sample is collected, weighed, oven-dried and weighed again to determine the sample's water content either by mass or by volume. The volume of water in the soil as determined by weight is the standard against which the indirect methods are calibrated. Indirect techniques can be classified into volumetric and tensiometric methods. The indirect methods monitor soil water content by estimating the soil moisture by a calibrated relationship with some other measurable variable. Studies comparing direct and indirect methods have found that all soil water sensing methods must be calibrated, despite the efforts of manufacturers to provide calibration curves. All these methods have their advantages and disadvantages and should be used with caution depending upon the requirements and demands of the users. The suitability of each method depends on several issues like cost, accuracy, response time, installation, management and durability. Almost all suction measurement methods have shortcomings including such aspects as reliability, cost, range of application and practicality. Therefore, there is still a need for improving these soil suction measurement techniques. Different soil moisture estimation methods have been developed and the most common instruments used for estimating soil moisture by indirect methods are neutron probe, time-domain reflectometry, frequency domain reflectometry, tensiometer and gypsum block apparatus. By understanding basic soil water concepts, the strengths and weaknesses of different types of soil water sensors and methods of installing them, we can irrigate crops more efficiently, improve water conservation and make our farm more profitable. In this review, the main indirect techniques used to determine the soil moisture content are discussed, first by describing the physical principles behind the most popular indirect methods and then by addressing the various strengths and limitations of the selected methods.

Key words: Indirect Methods · Soil Moisture Measurement · Tensiometric Method · Volumetric method

INTRODUCTION

The water content in the soil surrounding the crop roots determines crop growth and influences the fate and movement of fertilizers and agricultural chemicals. Accurate measurement of soil water content is therefore important to maximize yield and quality of the crop, to minimize water loss and hence to optimize the water use efficiency. Knowing how much water to apply and when to apply it are prerequisites to effective water management. The amount of water required by a crop is dependent on crop type, its growth stage, its sensitivity to water stress, the environment in which it grows, the depth of the water table, soil health and management options such as fertilizer application and yield target. It is particularly important to maintain the optimal soil water content during the water-sensitive stages of growth, as any damage during these stages cannot be compensated

Corresponding Author: Gezahagn Kebede, Ethiopian Institute of Agricultural Research, Holetta Research Center, P.O. Box: 31, Holetta, Ethiopia & Hawassa University College of Agriculture, P.O. Box: 05, Hawassa, Ethiopia.

at other stages. As soil water status and mineral nutrition of plants are interrelated, optimal soil fertility will enhance crop water uptake and ensure that a maximum of water is used for crop growth. The measurement of soil water content is therefore essential to enhance water management strategies that will enable farmers to schedule irrigation according to soil water holding capacities, plant water use and prevailing weather conditions. Monitoring soil-water content for irrigation scheduling, based on a measurement and control system, requires fast, precise, non-destructive and *in-situ* measurement techniques [1, 2].

Soil moisture is an inevitable part of the three-phase system of the soil, which comprises soil minerals (solids), moisture and air [3, 4]. Hence, soil moisture content has quite significant influence on engineering [5], agronomic [6, 7], geological, ecological, biological and hydrological behavior of the soil mass [8-10]. Mechanical properties of the soil viz., consistency, compatibility, cracking, swelling, shrinkage and density are dependent on the soil moisture content [5, 11]. Furthermore, it has a major role to play as far as the plant growth [7], organization of the natural ecosystems and biodiversity [12] is concerned. In the agriculture sector, the application of adequate and timely moisture for irrigation, depending upon the soil-moisture-plant environment, is essential in crop production [13-16]. Effective irrigation scheduling requires an understanding of the dynamics of soil-water storage in the plant root-zone and soil-water availability and use by plants, which relies on the accurate measurement of soil moisture. Sensors may differ in performance under conditions specific to different local measurement locations due to several environmental factors. For example, clay content, soil temperature, texture, salinity, the air gap between the soil and the sensor, porosity and bulk density can exert different levels of influence on the sensor performance [17-20].

Soil moisture is estimated both by the direct and indirect methods. The direct method involves the determination of moisture in the soil while indirect methods estimate the amount of water through the properties of water in the soil. In the direct methods moisture is estimated thermo- gravimetrically either through oven– drying or by volumetric method. The soil sample is taken with a core sample or with a tube auger whose volume is known. The amount of water present in the soil sample is estimated by drying in the oven. The volumetric moisture content can also be estimated from the moisture content estimated on a dry weight basis. The main advantages of direct methods are its accuracy and low cost. However, the drawbacks are destructive, slow, time-consuming and do not allow for making repetitions in the same location. Indirect techniques can be classified into volumetric (gives volumetric soil moisture) and tensiometric methods (yields soil suction or water potential). The indirect methods monitor soil water content by estimating the soil moisture by a calibrated relationship with some other measurable variable. The most common instruments used for estimating soil moisture by indirect methods are tensiometer, gypsum block, neutron probe, time-domain reflectometry and frequency domain reflectometry apparatus. The suitability of each method depends on several issues like cost, accuracy, response time, installation, management and durability.

Most practical techniques for soil water monitoring are indirect [21, 22]. Numerous sensor performance and performance influencing factors experiments have been conducted under laboratory and field conditions [23-30]. The soil-water status is also measured manually as well as automatically with tensiometers [31-33], soil psychrometers [34] and gypsum blocks [35]. But these methods measure the soil-water potential rather than measuring the soil-water content directly. These methods need individual calibration of the soils and the characteristic curves for them and may be confounded by hysteresis. Different volumetric and tensiometric technologies (Neutron probe; TDR (Time Domain Reflectometry); FDR (Frequency Domain Reflectometry); gypsum blocks; tensiometers etc.) used to estimate the volume of water in a sample volume of undisturbed soil. Therefore, this paper reviews the indirect soil moisture measurement techniques and summarizes basic working principles, measurement, strengths, limitations and application of indirect soil moisture measurement methods.

Volumetric Methods

Neutron Probe: Neutron probe technology, also known as a neutron scattering method, is an indirect method of measuring soil moisture content. Soil moisture can be estimated quickly and continuously with neutron moisture meter without disturbing the soil. Neutron probes are considered among the most accurate methods for measuring soil water content when properly calibrated. A radioactive source emits neutrons through the media and its moisture content is measured by the thermal or slow neutron density at the collector [36]. Garner and Kirkham [37] first defined the principles of the neutron scattering method. The neutron probe has found wide use in hydrological and civil engineering applications [38]. Smaller and safer radioactive sources have evolved as a result of technological advancements in neutron probe technology [39]. This meter scans the soil about 15 cm diameters around the neutron probe in wet soil and 50 cm in dry soil. It consists of a probe and a scalar or rate meter. Access tubes are aluminum tubes of 50-100 cm length and are placed in the field when the moisture has to be estimated. The neutron probe is lowered in to access tube to the desired depth. Fast neutrons are released from the probe which scatters into the soil. The scalar or the rate meter counts of slow neutrons which are directly proportional to a water molecule. The moisture content of the soil can be known from the calibration curve with the count of slow neutrons. Application of neutron probe technology is not feasible for certain moisture-measuring situations due to high regulatory standards for use of radioactive materials. These requirements result in costly licensing and training for both the companies and the operators and storage of the equipment and disposal of the probe with its radioactive source is also expensive and highly regulated [39].

Neutron probe moisture meters involve the detection of soil moisture using radioactive elements. In this method, the amount of water in a volume of soil is estimated by measuring the amount of hydrogen it contains, expressed as a percentage. Because most hydrogen atoms in the soil are components of water molecules, the back scatter of the thermalized neutrons from a radioactive source emitted and measured by a detector in the probe directly corresponds to water content in the soil. A neutron probe can measure total soil water content if it is properly calibrated by gravimetric sampling. Depth probes and surface probes are available that measure the soil moisture content at the required depth, or in the uppermost layer, respectively [40, 41]. A probe is fed deep into the soil and connected to the power supply, micro controller, display and keypad via a wire. Neutron probes emit fast-moving neutrons. The fast neutrons are emitted by the source and the detector detects the neutrons that come back after collision and absorption with nuclei of soil and water. The number of neutrons that come back to probe depends upon the hydrogen and oxygen atoms present in the soil. When the neutrons collide with hydrogen in the soil they are slowed and deflected. A detector on the probe counts returning slow neutrons. The number of slow neutrons detected can be used to calculate soil water content because changes in the amount of hydrogen in the soil between readings will only come about from changes in water content. Wet soil will contain more hydrogen than dry soil and therefore more slow neutrons will be detected.

Neutron probes consist of a probe and an electronic counting scale, which are connected by an electric cable (Figure 1). To measure the moisture content of a medium at the desired depth, the probe is lowered down an access tube to the required depth. Access tubes are made of materials that do not slow the neutrons emitted by the source. Neutrons with high energy are emitted by a radioactive source into the soil and are slowed down by elastic collisions with nuclei of atoms and become thermalized. The average energy loss is much greater when neutrons collide with atoms of low atomic weight than collisions with heavier atoms. The hydrogen atom with its low atomic weight can slow down neutrons more effectively than other elements. The density of the resultant cloud of slowed neutrons (which are detected by the counter) is taken to be proportional to the total number of hydrogen atoms per unit volume of the soil [42]. The volumetric moisture content can then be determined by an established calibration curve, assuming that these hydrogen atoms have a direct correlation with soil moisture. Thomas [43] documented some of the problems of the neutron probe that include: All hydrogen atoms slow the high-energy neutrons. These involve both free water atoms and bound hydrogen atoms that are part of the molecular structure of compounds that are not water molecules [42]; some elements other than hydrogen have a propensity to absorb the high-energy neutrons [42]; and changes in the density of the medium may affect the transmission of the neutron particles [42]. Evaluation criteria for neutron probe soil moisture measurements are summarized in Table 1.

Fast neutrons, emitted from the source and passing through the access tube into the surrounding soil, gradually lose their energy through collisions with other atomic nuclei. Hydrogen molecules in the soil (mostly in soil water) are particularly effective in slowing the fast neutrons since they are both of near-equal mass. The result is a "cloud" of slow or thermalized neutrons some of which diffuse back to the detector. The size and density of the cloud depend mainly upon soil type and soil water content is spherical and ranges in size from 6 to 16 inches. Thermalized neutrons that pass through the detector create a small electrical impulse. These electrical pulses are amplified and then counted. The number of slow neutrons counted in a specified interval of time is linearly related to the total volumetric soil water content.

Table 1: Summary of evaluation criteria for neutron probe soil moisture measurements

SN	Evaluation parameters	Performance of the technique
1	Principles used and methodology	Depends on the amount of collision between fast neutrons and Hydrogen atoms in moisture. Insert the probe into an access tube installed in soil. Linear calibration between the count rates of slowed neutrons gives the reading of % moisture content.
2	Logging capacity	No
3	Installation method	Access tube
4	Soil type not recommended	None
5	Affected by salinity	No
6	Field maintenance	No
7	Accuracy	±0.005 ft^3ft^{-3}
8	Safety hazard	Yes
9	Advantages	High accuracy, relative ease of deep readings, repeatable.
10	Disadvantage	High cost, regulatory requirements.

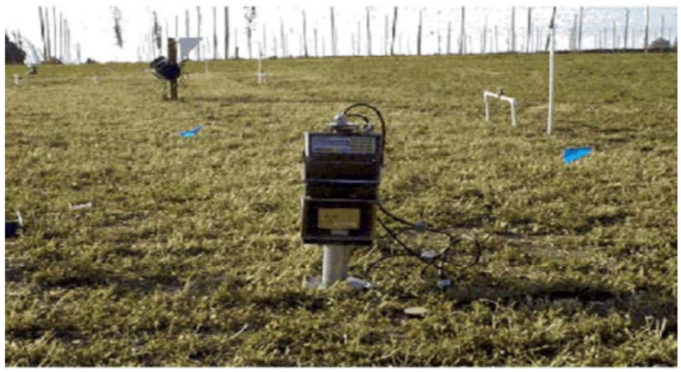

Fig. 1: Neutron probe

A higher count indicates higher soil water content and vice versa. The neutron probe allows relatively rapid and repeatable measurements of soil water content to be made at several depths and locations within a field. Being able to repeat measurements at the same location through the growing season minimizes the effects of soil variability on the measurements. Depending on the number of access tube installations per field and number of fields, the time required to take probe readings and analyze the data may become extensive. A minimum of three access tubes per field is recommended. Readings should be taken in 6-inch increments to the bottom of the expected rooting depth.

Neutron probe technology assumes that hydrogen atoms from the water molecules thermalize the neutrons. This technology cannot measure accurate moisture content if atoms of any other elements are involved in thermalizing the neutrons. When the neutrons are slowed, some of them are captured by various elements that have an affinity towards the neutrons. Neutron absorption elements decrease the number of thermalized neutrons and this reduction is proportional to the moisture content. Apart from bounding hydrogen and neutron capture effects, the changes in the density of the medium also affect the thermalization of the neutrons and their transport to the detector, thus affecting the neutron count rate at the detector. An increase in the density of the medium containing bound hydrogen will increase the count rate due to the presence of more hydrogen per unit volume of the medium [42]. On the other hand, increasing the density of soil containing neutron absorption elements would decrease the count rate due to more neutron capture per unit volume of the medium [42]. The probe configuration is in the form of a long and narrow cylinder, containing a source and detector. Measurements are made by introducing the probe into an access tube (previously installed into the soil). It is possible to determine soil moisture at different depths by hanging the probe in the tube at different depths. The soil moisture is obtained from the device based on a linear calibration between the count rate of slowed-down neutrons at the field (read from the probe) and the soil moisture content obtained from nearby field samples.

Advantages and Disadvantages: The neutron probe method gives fast and reliable measurements. Repeated measurements can be taken at any depth of soil and any location. The method is relatively easy and straightforward to use. Furthermore, it is a nondestructive technique that enables the measurement of soil moisture distribution profiles at several depths. The method is also accurate—a properly calibrated instrument is capable of an accuracy of better than ±0.02 in volumetric water content [44] and capable of measuring surface soil moisture content in real-time conditions [45]. The major disadvantage of a neutron moisture meter is the involvement of radioactive elements. This radioactive element requires extensive care to handle and licensed, efficiently trained operators. The equipment is of very high cost and requires proper calibration according to each soil type in which they will be used, which, in practice, increases the time it takes to collect data. Furthermore and perhaps most importantly, they are insensitive in measuring soil moisture near the surface (top 20 cm) because fast neutrons can escape into the atmosphere [46]. This technique is not common when frequent and automated observations are required and its use has been proven most useful in measuring relative soil moisture differences rather than absolute soil moisture content [45].

Time Domain Reflectometry: The time-domain reflectometer (TDR) is a new device developed to measure soil-water based on soil electrical conductivity measurements belonging to the dielectric group content [47]. Two parallel rods or stiff wires are inserted into the soil to the depth at which the average water content is desired. The rods are connected to an instrument that sends an electromagnetic pulse (or wave) of energy along the rods. The rate at which the wave of energy is conducted into the soil and reflected the soil surface is directly related to the average water content of the soil. One instrument can be used for hundreds of pairs of rods. The TDR probe usually consists of 2–3 parallel metal rods that are inserted into the soil acting as wave guides similarly as an antenna used for television reception. This is a dielectric method that estimates soil water content by measuring the soil bulk permittivity (or dielectric constant), Ka, that determines the velocity of an electromagnetic wave or pulse through the soil. In a composite material like the soil (i.e., made up of different components like minerals, air and water), the value of the permittivity is made up of the relative contribution of each of the components. Since the dielectric constant of liquid water (Ka= 81) is much larger than that of the other soil constituents (Ka= 2–5 for soil minerals and 1 for air), the total permittivity of the soil or bulk permittivity is mainly governed by the presence of liquid water. The speed of an electromagnetic signal passing through a material varies with the dielectric of the material. TDR instruments send a signal down steel probes, called wave guides, buried in the soil. The signal reaches the end of the probes and is reflected in the TDR control unit. The time taken for the signal to return varies with the soil dielectric, which is related to the water content of the soil surrounding the probe.

Time-domain reflectometry (TDR) has been used widely in laboratory and field studies to measure the soil water content, electrical conductivity and other soil hydraulic properties [48-60]. TDR has the advantage of allowing for continuous and simultaneous measurements of the soil water content and the electrical conductivity [61] and usually does not require site-specific calibration [62]. TDR has been used to determine and investigate soil hydraulic properties [52, 53, 63-66]. TDR is a method that uses a device that propagates a high-frequency transverse electromagnetic wave along a cable attached to a parallel conducting probe inserted into the soil. The signal is reflected from one probe to the other before being returned to the meter that measures the time elapsed between sending the pulse and receiving the reflected wave. Assuming that the cable and wave guide length is known, the propagation velocity, which is inversely proportional to the dielectric constant, can be directly related to soil moisture content. By measuring the travel time, the velocity and hence the apparent dielectric constant of the soil can be estimated. This provides a measurement of the average volumetric water content along the length of the wave guide.

Two or three parallel metal rods are often used as a conventional TDR probe for measuring dielectric constant, while a variety of customized probes have been developed for different purposes [67-69]. Although a vertical water content profile can be measured by setting several probes with different depths horizontally, the space between the probes should be at least a few centimeters to avoid interference between them [68, 70]. The effect of clay, soil organic matter content and soil bulk density on TDR measurements has been reported [48, 70-72]. A temperature effect has been reported by Topp *et al*. [48], while an iron influence on the dielectric constant has been discussed by Robinson *et al*. [74]. Evett *et al*. [75] found that TDR measurements may be affected by soil salinity, soil temperature, clay type and clay content. The TDR technique may over estimate soil-water content in saline soils because the apparent dielectric constant also depends on the electrical conductivity of the soil [76]. For example, Wyseure *et al*. [76] used a dielectric-based technique to estimate the electrical conductivity. Miyamoto and Maruyama [77] found that by coating the TDR rods, more accurate measurements in a heavily fertilized paddy field was possible. Roots, earthworm channels, cracks and stones can also cause small variations in soil-water content estimated using the dielectric-based technique [78]. Furthermore, old root channels would affect dielectric measurements if these were within the measurement volume of the sensor.

The water content of the soil is calculated by using the travel time readings. The TDR system consists of a pulse generator that generates a square wave and an oscillator that captures the reflected pulse, from many points along with the probe. The probes are inserted into the soil; the travel time depends upon the complex permittivity of the soil. The reflection of the original signal will occur when there is any change in the impedance. The water present in the soil will change the dielectric constant of the soil. Due to changes in a dielectric, the impedance variations occur and affect the shape of the reflected signal. The reflected signal's shape is used to obtain information about the water content present in the soil. For soil water content measurement, the device propagates a high frequency transverse electromagnetic wave along a cable attached to parallel conducting probes inserted into the soil. The signal is reflected from the end of the waveguide back to the cable tester where it is displayed on an oscilloscope and where the time between sending the pulse and receiving the reflected wave is accurately measured by the cable tester. By knowing the length of the transmission line and wave guide, the propagation velocity of the signal in the soil can be computed The dielectric constant is inversely related to this propagation velocity, i.e., faster propagation velocity indicates a lower dielectric constant and thus a lower soil water content or, as soil water content increases, propagation velocity decreases and dielectric constant increases.

The application of this technology involves the use of finite transmission lines (coaxial or parallel). An electromagnetic pulse is transmitted through these lines and its reflection is analyzed to obtain the complete dielectric frequency spectrum. TDR technology is similar to the concept that the physical characteristic of the medium in which an electromagnetic signal is emitted can be found by analysis of the reflection of this signal. In TDR technology, the physical characteristic of the medium that is analyzed by the propagated electromagnetic wave is the relative permittivity or the dielectric constant of the medium. TDR theory states that the time for a transmitted electromagnetic pulse to be reflected is dependent on the relative permittivity or dielectric constant of the medium [43]. A basic capacitor theory can be used to explain the concept of relative permittivity. Various studies have documented the concept of relative permittivity and the TDR theory [43, 50, 51, 79-81]. The TDR instrument consists of a voltage source and a coaxial cable that is attached to parallel probes at its end. The probes are inserted into the media in which moisture content is to be determined. The voltage source produces a fast rise step voltage pulse (V). This voltage pulse propagates through a coaxial cable and part of this voltage pulse is transmitted (VT) as an electromagnetic wave along the parallel electrodes that are inserted into the test medium [51]. If during propagation the electromagnetic wave passes an interface of changing impedance (when the voltage leaves the coaxial cable and enters the parallel probes), a portion of the signal is transmitted through the interface and a portion is reflected. The first change of impedance is at the beginning of the parallel probes when a portion (VT) is transmitted. At the end of the parallel probes, part of the transmitted pulse (VT) is reflected by the waste (again due to a change of impedance) and is shown as VR. If the medium is a perfect insulator, the reflected voltage will be of the same intensity as the transmitted voltage but if the medium is conductive, the reflected electromagnetic wave will be attenuated.

Seyfried and Murdock [82] suspended six water content reflectometers (WCR) simultaneously in air and subjected them to temperature changes from -5°C to 45°C to investigate the response of the sensor electronics to temperature changes independent of potential soil medium effects. The temperature had a minor effect on the sensor response in air. However, when the sensors are installed in the soil, the sensor response was significantly affected by the temperature and this effect increased in absolute value with the volumetric soil water content. Also, the effect of temperature on sensor response was significantly different for different soils tested. Persson and Berndtsson (1998) quantified temperature dependence of the apparent dielectric constant and electrical conductivity in wet soils by using an automated TDR system in sandy, clay and organic soils. They confirmed the findings of Pepin *et al*. [83] that change in apparent dielectric constant with temperature was lower in fine-textured soils and also found that a high concentration of electrolytes (high EC) in combination with fine-textured soils can lead to positive temperature dependence (i.e., volumetric soil water content increases with increase in temperature). They also showed that the temperature effect on bulk electrical conductivity was independent of soil texture; and if high accuracy for volumetric soil water content measurement is needed, the temperature dependence of electrical conductivity needs to be measured specifically.

Table 2: Summary of evaluation criteria for time-domain reflectometry soil moisture measurements

SN	Evaluation parameters	Performance of the technique
1	Principles used and methodology	Depends on the propagation time required by EM wave to transmit and reflect from sensor transmission wave guide. Insert the probe into the access tube & transmit EM wave. The propagation time required for transmitting & reflect gives the % moisture content depending on the dielectric constant.
2	Logging capacity	Depending on instrument
3	Installation method	Permanently buried *in-situ*
4	Soil type not recommended	Organic, dense, salt or high clay soil
5	Affected by salinity	High level
6	Field maintenance	No
7	Accuracy	±0.001 ft^3ft^{-3}
8	Safety hazard	No
9	Advantages	High accuracy, volumetric water content and salinity, robust calibration.
10	Disadvantage	Highly influenced by adjacent moisture/voids.

Fig. 2: TDR equipment

Advantages and Disadvantages: The main advantages of TDR over other soil water content measurement methods are: (i) superior accuracy to within 1 or 2% volumetric water content; (ii) calibration requirements are minimal-in many cases, soil-specific calibration is not needed; (iii) lack of radiation hazard associated with neutron probe or gamma-attenuation techniques; (iv) TDR has excellent spatial and temporal resolution; and (v) measurements are simple to obtain and the method is capable of providing continuous measurements through automation and multiplexing. A variety of TDR systems are available for water content determination in soil and other porous media (Figure 2). Among the most important advantages of this technique are that it is non-destructive to the study site and is not labor-intensive [41]. The ability to automate TDR measurement and to multiplex many wave guides through one instrument [44] are further advantages of TDR because they allow unattended measurement at multiple points, either on a scheduled interval or in response to events such as rainfall. When it is properly calibrated and installed, it is a highly accurate method for measuring soil moisture content [44, 84]. It requires complex electronic equipment and it is an expensive system. The dielectric constant of a material is a measure of the capacity (or electrical permittivity) of non-conducting material to transmit high-frequency electromagnetic waves or pulses. The dielectric constant of dry soil varies between 2 and 5, while the dielectric constant of water is 80 at frequencies between 30 MHz and 1 GHz. A large volume of research has shown the measurement of the dielectric constant of the soil water media to be a sensitive measurement of soil water content. Relatively small changes in the quantity of free water in the soil have large effects on the electromagnetic properties of the soil water media. The overall performances of the time domain reflectometry are summarized in Table 2.

Frequency Domain Reflectometry: A Frequency Domain Reflectometry (FDR) approach to the measurement of soil water content is also known as radio frequency (RF) capacitance techniques (Figure 3). This technique measures soil capacitance. A pair of electrodes is inserted into the soil. The soil acts as the dielectric completing a capacitance circuit, which is part of a feedback loop of a high-frequency transistor oscillator. As high-frequency

Fig. 3: FD probes: a) Capacitance (plates imbibed in a silicon board); b) Capacitance (rods); and c) FDR (rings)

radio waves (about 150 Mhz) are pulsed through the capacitance circuitry, a natural resonant frequency is established which is dependent on the soil capacitance. The soil capacitance is related to the dielectric constant by the geometry of the electric field established around the electrodes. This is also a dielectric method developed for measuring the dielectric constant of the soil water media and, through calibration. The electrical capacitance of a capacitor that uses the soil as a dielectric depends on the soil water content. When connecting this capacitor with 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 FDR sensors. Probes usually consist of two or more electrodes that are inserted into the soil. On the ring configuration, the probe is introduced into an access tube installed in the field. Thus, when an electrical field is applied, the soil around the electrodes (or around the tube) forms the dielectric of the capacitor that completes the oscillating circuit. The use of an access tube allows for multiple sensors to take measurements at different depths.

The FDR is similar to TDR but estimates soil moisture content through measuring changes in the frequency of a signal as a result of soil dielectric properties [41]. An electrical circuit using a capacitor and an oscillator measures changes in the resonant frequency and indicates variations in soil moisture content. The signal reflected by soil combines with the generated signal to form a standing wave with amplitude that is a measure of the soil-water content. In the case of capacitance-type sensors, such as that used by Grooves and Rose [85], the charge time of a capacitor is used to determine the soil-water content. The moisture is calculated by considering the dielectric constant of the soil. The dielectric constant of any material is defined as the capacity to transmit the electromagnetic pulses or waves. The dielectric constant of water is much higher than the soil. Two electrodes are embedded in the soil and soil acts as a dielectric medium. The electrodes are given voltage supply, due to the presence of water the dielectric of soil changes. Because of which the frequency oscillations occur, at a certain point resonance occurs and the resonance frequency value is used to calculate the water content in the soil. The more the water, the smaller will be the resonant frequency.

Profile-probe versions using FDR and capacitance methods are now commercially available [86-88]. The manufacturer's calibration of the probe is for sand and yields generally very high volumetric soil water percentages than other soils. Calibration of the probe for soils other than sands is therefore required for use in an irrigation scheduling program. Bulk density differences in soils (i.e., with depth) will also require separate calibrations. Properly calibrated and with careful access to tube installation, the probe's accuracy can be good. Many of the advantages of the neutron probe system are available with this system including rapid, repeatable measurements at the same locations and depths. The probe comes with either an analog, color-coded (for three different soil types: sand, loam and clay) dial gauge, or a digital readout. Both give readings on a scale from 0% to 100%. High readings reflect higher soil water content and vice versa. Probe readings near 100% (blue range) represent saturated conditions. Readings near 85% to 90% (dark green range) are near field capacity. Readings in the 50% to 70% (light green) range indicate adequate soil water. Readings in the 30% to 50% (orange range) represent the onset of water stress and readings below 30% (red range) represent conditions approaching a wilting point.

Many of the soil moisture sensing technologies measure volumetric soil water content indirectly by using dielectric properties, electrical resistance, amount of hydrogen, or the reflectance properties of the soil, all of which are influenced, by varying degrees, by the amount of water in the soil. The soil dielectric property [which is the basis for FDR and TDR-based sensors [48, 89-91] measurements can be influenced by environmental factors other than water content [19]. It has been shown that the soil temperature variation can affect soil dielectric properties [83, 92], which may influence the performance of TDR or FDR-type sensors. Thus, investigating the effect(s) of soil temperature on sensor performance is critical to identify sensor performance-influencing factors and their magnitudes, which can be used to enhance sensor design, engineering, circuits, etc. and guide in terms of a sensor's operational limits under certain conditions. Furthermore, since different soil moisture sensors have different engineering designs, circuits and technology that handle soil temperature and/or soil thermal conductivity vs. dielectric properties and volumetric soil water content relationships differently, different soil moisture sensors may be influenced differently in measuring the volumetric soil water content of the same soil medium.

A very limited number of studies investigated the soil temperature effect(s) on different soil properties that, in turn, influence sensor response to changes in volumetric soil water content through field and laboratory research and modeling [93-96]. Pepin *et al*. [83] investigated the TDR measurement errors of the apparent dielectric constant of distilled water and different soils (sand, loam and peat) associated with soil temperature variations. In all cases, they found that the apparent dielectric constant decreased with increasing temperatures. The temperature dependence of the dielectric constant of water in a soil matrix was lower than that of bulk water, which was more pronounced for fine-textured and organic soils than for loamy soil. They also observed that with higher volumetric soil water content in the same soil, the temperature effect on the dielectric constant was more pronounced. In examining the interactions between soil surface area, volumetric soil water content and soil temperature, Wraith and Or [92] found that finer soils and/or soils with lower volumetric soil water content favored an increase in bulk dielectric constant with increasing temperature and that coarse-textured soils and/or soils with high volumetric soil water content favored a decrease in bulk dielectric constant under the same temperature conditions. This observation can be explained through the competing effects of temperature on the bulk dielectric constant of soil-water. The dielectric constant of bulk soil-water decreases with increased soil temperature, while that of bound water is presumed to increase with temperature.

The aforementioned sensor performance studies indicate that the same soil moisture sensor can perform differently in different soil-water environments, which require calibration for local soil conditions to establish and/or enhance the accuracy of volumetric soil water content measurements. Also, because soil moisture sensors are evolving rapidly with newer sensors or the same type of sensors that have improved or different engineering features continually being released to the market, scientific evaluations of sensors in different soil types are justified to provide information to the users that can be useful in practical applications. Even if most of the sensors can be categorized as TDR- or FDR-type sensors, the engineering design, circuitry and other manufacturing features can change significantly from one sensor to another even under the same category. For example, two FDR-type sensors that are made by different manufacturers may perform differently and the known performance of one FDR-type sensor may not apply to another FDR type sensor that was designed and manufactured by a different company. This alone is an important justification to continue to evaluate soil moisture sensors under different soil conditions. Also, a single study may not be able to investigate all soil moisture sensors that are available in the market in all soil types. Thus, a collection of numerous studies that investigate and quantify the performance of various types of sensors in different soil textures can provide a unique database and information that can collectively form a rich source that can provide invaluable guidance and information to the users in practical applications. Furthermore, research projects that evaluate the performance of the same sensor with different installation angle or orientation in the soil are rare. Finally, the effect of soil temperature on different soil moisture sensors' response can be considerably or significantly different for different soil, which justifies the need for investigating the response of different soil moisture sensors to soil temperature.

Advantages and Disadvantages: The main advantage of this method is that it is nondestructive, but in comparison with TDR, it can provide less accurate results due to sensitivity to soil characteristics (e.g., salinity and temperature) and also has a limited scale of use [41]. However, FDR is a more accurate method as compared to

Table 3: Summary of evaluation criteria for frequency domain reflectometry soil moisture measurements

SN	Evaluation parameters	Performance of the technique
1	Principles used and methodology	It is a dielectric method obtaining moisture content by observing response at different frequencies. The probe is introduced into the soil after applying the electric field to give reading due to the capacitance effect.
2	Logging capacity	Yes
3	Installation method	Permanently buried *in-situ*
4	Soil type not recommended	None
5	Affected by salinity	Minimal
6	Field maintenance	No
7	Accuracy	±0.001 ft^3ft^{-3}
8	Safety hazard	No
9	Advantages	High accuracy, volumetric water content and salinity.
10	Disadvantage	Highly influenced by adjacent moisture/voids.

TDR under optimum growing conditions of the plants. The design of the probe is flexible and robust. It is an inexpensive method compared to other methods. It is quite easy to interface the FDR soil moisture sensor with a microcontroller. On the other hand, installation requires extensive care. The presence of air gaps also affects the accuracy of the readings. The overall performances of the frequency domain reflectometry are summarized in Table 3.

Tensiometric Methods

Tensiometer Techniques: Tensiometer readings may be used as indicators of soil water and the need for irrigation. When instruments installed at shallower depths of the root zone reach a certain reading, they can be used to determine when to start irrigating, based on soil texture and crop type. Similarly, instruments at deeper depths of the root zone may be used to indicate when adequate water has been applied. Careful installation and maintenance of tensiometers are required for reliable results. The ceramic tip must be in intimate and complete contact with the soil. This is done by auguring a pilot hole out to the proper depth, making a soil water slurry mix with the soil removed and re-introducing this into the hole. Finally, the tensiometer tip is pushed into this slurry. Soil is banked up around the tube at the soil surface to prevent water from standing around the tube itself. A few hours to a few days are required for the tensiometer to come to equilibrium with the surrounding soil. The tensiometer should be pumped with a hand vacuum pump to remove air bubbles. All available tensiometric instruments have a porous material in contact with the soil, through which water can move. Thereby, water is drawn out of the porous medium in dry soil and from the soil into the medium in wet soil. It is worth noticing, that in general, they do not need a soil specific calibration, however, in most cases, they have to be permanently installed in the field, or a sufficiently long time must be allowed for equilibration between the device and the soil before making a reading.

Tensiometers are devices that measure the tension or the energy with which water is held by the soil and are comprised of water-filled plastic tubes with hollow ceramic tips attached on one end and a vacuum gauge and airtight seal on the other. The vacuum generates tension inside the tube. A vacuum gauge connected with the tube measures the value of the tension. More water in the soil less will be the tension and vice versa. So, the reading of the gauge gives the idea that how much water is present inside the soil. These tubes are installed into the soil at the depth at which the soil moisture measurement is required. At this depth, water in the tensiometer eventually comes to pressure equilibrium with the surrounding soil through the ceramic tip. When the soil dries, soil water is pulled out through the tip into the soil, creating tension or vacuum in the tube. As the soil is rewetted, the tension in the tube is reduced, causing water to reenter the tip, reducing the vacuum. Tensiometers are available commercially in many different types of configurations and are inexpensive, non-destructive and easy to install and operate satisfactorily in the saturated range. If properly maintained, they can operate in the field for long periods. Another important advantage of using a tensiometer is that they can allow measurement of the water table elevation and/or soil water tension when a positive or negative gauge is installed. However, they are only able to provide direct measurements of the soil water suction, allowing an indirect estimation of soil moisture content. Furthermore, tensiometers are fragile and require care during their installation and maintenance in the field [97]. Automated measurements are possible but at a high cost and they are not electronically stable.

Tensiometers are the devices used to sense the water tension inside the soil (Figure 4). They provide useful information for planning irrigation and managing soil moisture levels to the best advantage to maintain healthy landscape plants. The principle of tensiometer is the measurement of soil tension that is, the force that is required by the plants to acquire water from the soil. When the glass tube is put into the soil at the root level, the water is allowed to move out through the permeable ceramic tip. The water will move out only when the soil is not saturated i.e. the water content in the soil is not highest. When the water present in the tube goes down into the soil, a vacuum is generated inside the tube. Most commercially available tensiometers use a vacuum gauge to read the tension created and have a scale from 0 to 100 centi-bars (one bar or 100 centi-bars of pressure or tension is equal to 14.7 psi). The practical operating range is from 0 to 75 centi-bars. If the water column is intact, a zero reading indicates saturated soil conditions. Readings of around 10 centi-bars (cb) correspond to field capacity for coarse-textured soils, while readings of around 30 cb can approximate field capacity for some finer-textured soils. The upper limit of 75 cb corresponds to as much as 90% depletion of total available water for the coarse-textured soils but is only about 30% depletion for silt loam, clay loams and other fine-textured soils. This limits the practical use of tensiometers to coarse-textured soils or too high-frequency irrigation where soil water content is maintained high. 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 concerning 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.

The tensiometer should be installed to one-half of the effective root depth. The porous tip must be in good contact with the adjacent soil. Field experiences with tensiometers have been mixed. When properly installed and maintained, tensiometers are reliable. Unsatisfactory results are usually caused by inadequate maintenance. Sandy soils, which are best suited for tensiometers, have low levels of plant-available water. In coarse, sandy soils the water content may decrease from field capacity to less than 20 percent of the plant-available water within three days. At this depletion rate, tension can exceed 80 cb within three days, breaking the water column (tension). The soil may then appear dry and the crop may show visible signs of stress. Because tension was broken and the tensiometer is no longer functioning correctly, however, the gauge shows a low tension (high soil moisture). Thus the irrigator concludes that the tensiometer is unreliable. Tensiometers should be read every day (sometimes twice a day in very sandy soils) until you obtain a feel for how fast the soil dries after rainfall or irrigation. Whenever tension is broken, the tensiometer must be serviced. This includes refilling the instrument with boiled water and checking it with the vacuum pump. Adding a little food coloring to the boiled water makes it easier to see whether water is still present in the tensiometer. Air bubbles in the water column tend to collect at the top of the barrel and appear clear compared to the colored water. The water column should always be free of air bubbles and water should always be stored in the reservoir. It may be necessary to add water to the reservoir during the season even if tension is not broken.

Soil water tension, soil water suction, or soil water potential are all terms describing the energy status of soil water. Soil water potential is a measure of the amount of energy with which water is held in the soil. A soil-water characteristic or water release curve shows the relation between soil water content and soil water tension. Soil water tension is related to water potential. This also is not water content but the potential of the soil to provide water to plants. As the soil dries and soil water tension increases, the water potential decreases. As the soil water content increases due to additions from rainfall or irrigation, the soil-water tension decreases and soil water potential increases. The tensiometer allows us to monitor these fluctuations in soil water potential. The tensiometer reading is accurate as long as air does not enter the tube—the system must remain hydraulic. Unlike water, air readily expands and contracts as pressure changes and air in the tensiometer tube causes inaccurate measurements. Even if the instrument does not have any leaks, air dissolved in the water will accumulate during normal operation. This air must be removed periodically by refilling the tensiometer with water to restore reliable operation.

Advantages and Disadvantages: It provides direct and continuous readings. No power supply is required. Variable-length tensiometers are available to take any

Table 4: Summary of evaluation criteria for tensiometer soil moisture measurements

SN	Evaluation parameters	Performance of the technique
1	Principles used and methodology	Depends on the suction produced by water into a sealed tube coming into equilibrium with the soil solution through a porous medium. The tip of the ceramic cup is placed into the soil. Water is drawn outside to form equilibrium suction is created inside the tube. Depending on the amount of suction produced moisture content is indicated.
2	Logging capacity	Only when using transducers
3	Installation method	Permanently inserted into the augured hole
4	Soil type not recommended	Sandy or coarse soils
5	Affected by salinity	No
6	Field maintenance	Yes
7	Accuracy	±0.01 bar
8	Safety hazard	No
9	Advantages	Instantaneous approximate soil moisture content.
10	Disadvantage	High maintenance, tension breaks, freezing temperatures.

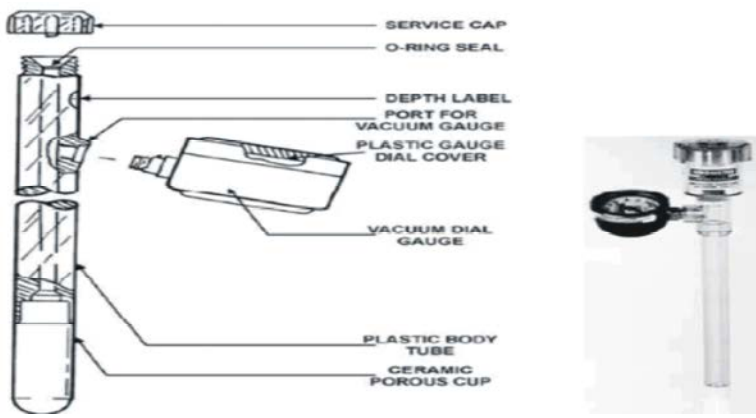

Fig. 4: Tensiometer

variable depth moisture measurement. Minimal skill is required to read the reading of gauge. It is an inexpensive system. However, the response time is relatively slow. Careful handling of equipment is required. It requires frequent maintenance. The overall performances of the tensiometer are summarized in Table 4.

Resistive Sensor (Gypsum): One type of electrical resistance block, the gypsum block, has been in use since the 1940s. Porous blocks of gypsum are used in one of the most common dielectric constant techniques employed for measuring soil moisture content in the field (Figure 5). The gypsum block is cylindrical or rectangular. The electrodes are embedded into the block. The dry gypsum block is inserted into the soil. A small voltage is provided to the electrodes. The electric resistance between the electrodes measures the tension of the soil. If water is present in the soil, it is absorbed by gypsum block and comes in equilibrium with soil water. Hence, the resistance between the electrodes will decrease and vice versa and gives information about the water content of the soil. A gypsum block sensor constitutes an electrochemical cell with a saturated solution of calcium sulfate as the electrolyte. The device consists of a porous block made of gypsum or fiberglass containing two electrodes linked to a wire lead. When the device is buried into the soil surface, water will enter or exit the block until the matric potential of the block and the soil are the same. Then, the electrical conductivity of the block to the matric potential for any particular soil is calculated using a calibration curve. Its ability to absorb water and to come into equilibrium with the medium makes it a convenient soil moisture sensor. The resistance between the block-embedded electrodes is determined by applying a small AC voltage (to prevent block polarization) using a Wheatstone bridge. Since changes to the soil electrical conductivity would affect readings, gypsum is used as a buffer against soil salinity changes (up to a certain level). The inherent problem is that the block dissolves and degrades over time (especially in saline soils) losing its calibration properties. It is recommended that the block pore size distribution matches the soil texture being used. The readings are temperature dependent (up to 3% change/°C) and field measured resistance should be corrected for differences between calibration and field temperatures.

Fig. 4: Gypsum block

Table 5: Summary of evaluation criteria for gypsum block soil moisture measurements

SN	Evaluation parameters	Performance of the technique
1	Principles used and methodology	The electrical conductivity of a porous medium in contact with the soil. The electrical resistance between electrodes embedded in a porous medium (block) is proportional to its water content, which is related to the soil water matric potential of the surrounding soil. Electrical resistance reduces as the soil, hence the block, dries.
2	Logging capacity	Yes
3	Installation method	Permanently inserted into the augured hole
4	Soil type not recommended	Sandy or coarse soils, avoid swelling soils
5	Affected by salinity	>6 ds/m
6	Field maintenance	No
7	Accuracy	±0.01bar
8	Safety hazard	No
9	Advantages	Measurement of soil moisture in the same location in the field over an extended period.
10	Disadvantage	Each block requires individual calibration. Calibration changes with time. Provides inaccurate measurements. Life of device limited

Electrical resistance blocks consist of two electrodes enclosed in a block of porous material. The block is often made of gypsum, although fiberglass or nylon is sometimes used. Electrical resistance blocks are often referred to as gypsum blocks and sometimes just moisture blocks. The electrodes are connected to insulated lead wires that extend upward to the soil surface. Resistance blocks work on the principle that water conducts electricity. When properly installed, the water suction of the porous block is in equilibrium with the soil-water suction of the surrounding soil. As the soil moisture changes, the water content of the porous block also changes. The electrical resistance between the two electrodes increases as the water content of the porous block decreases. The block's resistance can be related to the water content of the soil by a calibration curve. To make a soil water reading, the lead wires are connected to a resistance meter containing a voltage source. Because of the pore size of the material used in most electrical resistance blocks, particularly those made of gypsum, the water content and thus the electrical resistance of the block does not change dramatically at suctions less than 0.5 bar (50 cb). Therefore, resistance blocks are best suited for use in fine-textured soils such as silts and clays that retain at least 50 percent of their plant available water at suctions greater than 0.5 bar. Electrical resistance blocks are not reliable for determining when to irrigate sandy soils where over 50 percent of the plant-available water is usually depleted at suctions less than 0.5 bar.

Blocks are installed in the soil similar to the procedure for tensiometers, ensuring intimate contact with the surrounding soil and are allowed to come to water tension equilibrium with the surrounding soil. Gypsum blocks require little maintenance and can be left in the soil under freezing conditions. Being made of gypsum, the blocks will slowly dissolve, requiring replacement. The rate of dissolution is dependent upon soil pH and soil water conditions. As discussed above, gypsum blocks are best suited for use in finer-textured soils. They are not sensitive to changes in soil water tension from 0 to 100 cb. High soil salinity affects the electrical resistivity of the soil solution, although the gypsum buffers this effect to a certain degree. Like tensiometers, electrical resistance blocks should be soaked overnight before they are installed in the field. A soil probe should be used to make a hole to the desired installation depth. The hole should be slightly larger than the moisture block so the block slips in easily. After placing the resistance block in the hole, backfill the hole with a thick soil slurry using soil from the installation depth. Since fine-textured soils do not dry as rapidly as sandy soils, resistance blocks do not need to be read as frequently as tensiometers. Normally, three to four readings per week are adequate. The electrical resistance of soil-water is affected by substances dissolved in the water. The exchange of water between the soil and the block throughout the irrigation season may gradually alter the electrical resistance of the block and eventually alter the calibration. This is not a serious problem in North Carolina soils unless highly saline water is used for irrigation. Since electrical resistance blocks are inexpensive, however, new calibrated blocks should be installed at the beginning of each growing season.

A meter is used to read the electrical resistance of moisture blocks installed in the ground. The blocks come in a variety of configurations but generally incorporate two electrodes embedded in a gypsum material. The block may be entirely gypsum or covered with a porous material such as sand, fiberglass, or ceramic. Meters are portable and are intended for use in reading a large number of blocks throughout one or more fields. Since the blocks are porous, water moves in and out of the block in equilibrium with the soil moisture. Meter resistance readings change as moisture in the block changes which, in turn, is an indication of changes in the amount of water in the soil. The manufacturer usually provides calibration to convert meter readings to soil tension. Proper installation is important for reliable readings. Good soil contact with the block is essential. Follow manufacturer's and Extension Service guidelines for installation and use of the blocks and meter. Resistance methods are suitable for most soils and the readings cover most of the soil moisture ranges of concern to irrigation management. The blocks tend to deteriorate over time and it may be best to use them for only one season. Problems may occur with highly acid or highly saline soils.

Advantages and Disadvantages: The main advantage of this technique is that it is a low-cost solution, allowing the measurement of soil moisture content in the same location in the field over extended periods, although this is limited by the dissolution and degradation of the block [41]. Nonetheless, the key disadvantage of this technique is that it requires individual calibration of the porous blocks for each location and for each measurement interval, which limits the gypsum block life span [46]. The accuracy of this method is affected by both salt and temperature [41]. The overall performances of the gypsum block are summarized in Table 5.

CONCLUSION

There are several ways to monitor soil water, with varying costs and accuracy. Although it is common for growers to estimate soil moisture by feel, appearance, or time between irrigation events, soil moisture can be more accurately and effectively monitored using a variety of commercially available soil moisture monitoring systems. The effectiveness of the monitoring system is dependent on proper placement and installation. The sensors or sampling should be in locations that represent the overall field, garden, or landscape. Avoid placing sensors where there are variations due to shade, nearby structures, or at the top of a hill or bottom of a depression. Since there is significant variation across fields, it is recommended that several sensor locations be used for large fields. Consider soil type, plant distribution and irrigation when placing the sensors or sampling. Several methods are available for monitoring soil moisture. Each has advantages and disadvantages, but when installed and calibrated properly, they all can be effective tools measuring soil water content. Knowing the soil moisture content will enable us to manage irrigation effectively based on plant moisture needs, soil water storage capacity and root zone depth and characteristics. Timely and adequate but not excessive irrigation promotes water conservation and profitability.

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