SLJoAS Sri Lankan Journal of Applied Sciences

Review Article

A Review- Comparison of Methods of Soil Water Content Estimation

S.S. Garusingha[a], Y.N.S. Wijewardana[b*] and D.T. Udagedara[a]
[a]Department of Applied Earth Sciences, Uva Wellassa University, Badulla, Sri Lanka
[b]Department of Engineering Technology, Uva Wellassa University, Badulla, Sri Lanka

*** Corresponding author email address**: senani@uwu.ac.lk

(Received 21st April 2023; Accepted 11th August 2023)

Abstract:

Soil water content (SWC) is one of the foremost ecological factors affecting the natural ecosystem. It is the principal constituent of plant protoplasm and vital to soil formation. Therefore, continuous monitoring of SWC is essential. Furthermore, information on the SWC measurements is important to various fields like hydrology, agriculture, environmental studies, etc. In past decades, researchers have employed different methods to measure the SWC in laboratories and *in-situ* conditions. Therefore, a large body of knowledge is available on the theory and applications of the methods of SWC measurements. This study aims to critically evaluate the several SWC measurement techniques such as Gravimetric, Time domain reflectometry (TDR), Frequency domain reflectometry (FDR), Ground penetrating radar (GPR), Neutron scattering, Tensiometry and Gamma-ray attenuation method including both advantages and disadvantages, and physical principles based on the past research findings. This study will be useful to develop new techniques to estimate the SWC and to introduce modifications for existing methods.

Keywords: Soil water content (SWC), Gravimetric method, Time domain reflectometry (TDR), Frequency domain reflectometry (FDR), Neutron Scattering, Ground penetrating radar (GPR).

1. Introduction

Soil water content (SWC) is the measure of the amount of water held in a unit volume or mass of soil and is the foremost ecological factor affecting the ecosystem. It can exist in three different forms capillary, gravitational and hygroscopic water. Measurements of SWC have an important impact on many fundamental biophysical [1] and chemical process. This is essential to plant growth, soil formation, and the organization of the natural ecosystem and biodiversity. Furthermore, SWC can be used as an indicator for the prediction of natural disasters, such as drought and flooding [2]. There are several mechanical properties of the soil, such as consistency, compatibility, swelling, and density. It is necessary to estimate SWC since these properties depend on it for a variety of applications, from large-scale calibration of global-scale climate models to field monitoring in agricultural systems [3].

There are several methods which are available to measure the SWC. These methods can be divided into two groups; (i) direct and (ii) indirect method. The direct method which is cheap and simple includes gravimetric method and indirect methods include Time Domain Reflectometry (TDR), Tensiometry, Ground Penetrating Radar (GPR), Neutron scattering method etc. There are some drawbacks of direct methods such as destructive, time-consuming, labor-intensive and costs. Indirect methods are simple and easy to be implemented for continuous operations. Hence, the applications of indirect methods for measuring SWC is popular among the soil scientist to cover large area and to have repeat measurement.

The TDR method is non-destructive and far easier indirect method than the gravimetric method. Topp et al. reported first application of TDR to SWC measurements [4]. It is used in stationary laboratories and field experiments in which changes in time and depth of SWC in the soil profile [5]. TDR equipment determines the SWC by performing dielectric measurement through the probes [6]. Frequency domain reflectometry (FDR) is similar to TDR [7] because both methods are based on dielectric techniques.

The tensiometry method is a non-destructive indirect method. The tensiometer is the equipment that is used in this method. It is made comprised of a manometer and a porous ceramic cup that are all connected by a tube and filled with water. The tension reading on the tensiometer is related to SWC by the water retention relationship. This is very useful as continuous reading equipment for estimating SWC in specific location though this will work only up to 1 atm.

The neutron scattering method is an indirect method for estimating SWC. In this method, the source neutrons that reach the soil are moderated and thermalized in interactions with hydrogen. The detector signal is further related to the amount of water in the soil [8].

The GPR is another method that is used to measure topsoil moisture content. This is the most promising, non-destructive geophysical method that uses high-frequency electromagnetic waves to detect material properties inside the medium [9]–[11]. The gamma ray attenuation method is the non-destructive indirect method used to measure SWC. This technique measures the changes in saturated density and from this density change, the SWC is determined. The objective of this review article is to compare the different SWC estimation methods using past research findings with including working principle, advantages and disadvantages. The details of this review article are useful to select the suitable SWC measurement method for a particular research, to estimate SWC and to introduce modifications for existing methods.

2. Research methodology

Scientific databases such as Google Scholar and Science Direct were searched using keywords of gravimetric method, tensiometry method, use of groundwater penetrating radar methods, neutron scattering method and other relevant keywords for different SWC methods. There were 98 articles randomly selected at the beginning as shown in Table 1. Then those articles were categorized based on the relevant keywords. Among those article, the number of 58 articles were selected after refining for do the review as shown in Table 2. Then, the available methods were compared based on their principle, major specifications, measured parameters, cost effectiveness, response time and depth of measurement.

Table 1. The number of initial articles according to the relevant keywords.

Keyword	Number of articles
Gravimetric method	8
TDR method	24
FDR method	10
Neutron scattering method	17
Tensiometric method	8
GPR method	21
Gamma ray attenuation method	10
Total	98

Table 2. The number of articles after refining the initial searching.

Keyword	Number of articles
Gravimetric method	3
TDR method	12
FDR method	5
Neutron scattering method	14
Tensiometric method	5
GPR method	17
Gamma ray attenuation method	2
Total	58

3. SWC measurement methods

3.1. Gravimetric method

The gravimetric method is the widely used, accurate method for SWC estimation. In this method, a wet soil sample is dried at 105 ºC in the oven for overnight. The constant dry mass is measured and calculate the SWC using the Eq. 3.1. Excessive oxidation may occur at 105 ºC and some organic matters can remove from the sample. The wet and dry mass of the soil sample is measured before and after oven drying, respectively. Mass of the water exist in the soil sample can be determined from the mass difference between wet and oven dry soil sample [12]. Furthermore, it can expressed as a percentage of the dry soil mass [13]. SWC can be calculated as follows;

$$\% SWC = \frac{W_{wet}(g) - W_{dry}(g)}{W_{dry}(g)} \quad \text{Eq 3.1}$$

W_{wet} = Mass of wet soil

W_{dry} = Mass of dry soil

This is a destructive, labor-intensive, and time-consuming method [2]. Furthermore, it is independent on salinity and soil type but estimation of SWC in a heterogeneous soil profile is difficult [13].

3.2. Time domain reflectometry method

The TDR method is an indirect method for non-destructive and continuous measurements of SWC. The working principal of TDR is, it applies a voltage signal to transmission line inserted into the soil. The signal of voltage requires time to travel from source to the end of the transmission line and back again. The propagation velocity is determined using travel time along a TDR probe and known length of the probe. Propagation velocity can be calculated as equation Eq. 3.2.1:

$$v=2l/t \quad \text{Eq. 3.2.1}$$

Where;

v = Propagation velocity

l = Length of the probe

t = Travel time.

The dielectric constant (K) is determined from the velocity of electromagnetic waves. The K of pure water is 80 as compared to other constituents of the soil [14]. Table 3 shows K of various constitutes of the soil.

Table 3. Dielectric constants of soil constituents and major textures of soils [15].

Material	Dielectric constant (*K*)
Air	1
Water	80 at 20 ^{0}C
Ice	3 at -5 ^{0}C
Sandstone	9 -11
Dry loam	3.5
Dry sand	2.5

TDR method determines the apparent dielectric constant (*Ka*) of the soil according to Eq. (3.2.2) [3] and this *Ka* of soil is dependent on the volume fractions of the other soil constituents and their respective dielectric constants [16].

$$Ka = (ct/2l)^2 \quad \text{Eq. 3.2.2}$$

Where;

c = Velocity of light in free space (3 x 10^8 ms^{-1})

l = Length (m)

t = Travel time (s)

The empirical relationship between *Ka* and volumetric water content (θ) is proposed by [17] as in the Eq: 3.2.3: [3]

$$\theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} Ka - 5.5 \times 10^{-4} Ka^2 + 4.3 \times 10^{-6} Ka^3 \quad \text{Eq. 3.2.3}$$

The relationship between the *Ka* and θ is not entirely linear, although it is nearly so over much of the range of SWC encountered in the field [18]. Fig.1 shows the schematic diagram of SWC measurements using TDR.

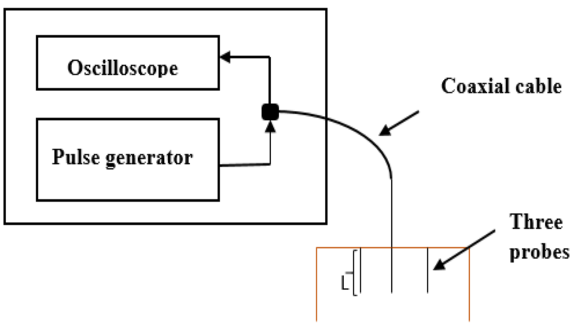

Fig. 1. Schematic diagram representing SWC measurements using TDR after [3].

The TDR can measure SWC on-site without testing the SWC of the physical sample in the laboratory [19]. This method has investigated by various researchers in different soil textures and the equipment is conveniently usable for determining SWC [6]. This method is independent from the soil texture, temperature, and Organic materials [3]. When TDR is used to measure SWC, the un-insulated conductors are inserted in the medium being tested. The conductors are normally placed at the end of the coaxial cable and they referred as a "probe''. These probes are comprised with two or three rods which made from stainless steel. Most of the time, three-rod probes are used to measure SWC because, it nears to coaxial condition easily [20]. The SWC response of two-rod probes and three-rod probes were compared by [21]. As a result, many studies examining the attributes of these TDR probes conducted a desk study comparing in detail the Sampling volume of balanced two and three-rod probes [22]. SWC can be measured by using hand probe and portable TDR equipment has shown by [23]. Rods installed horizontally can be used to measure water content near the soil surface but rods installed vertically cannot be used to measure water content near the soil surface [24].
TDR 100 has given good results in clay loam and loamy soils and overestimated the SWC in sandy soils according to the research done by [25]. The SWC measurements were evaluated by [26] at a clay loam location in Switzerland, over the period of two years using three low-cost sensors and one high-accuracy and high-cost TDR sensor. Most of the time, TDR is used to measure the SWC of mineral soils. However, TDR method has been used to determine the water content of organic growing media by [18].

The advantages of this method are high temporal resolution, the rapidity of acquisition and repeatability of measurements. Moreover, TDR includes its small measurement volume, ease of use and its ability to be automated and multiplexed compared to gravimetric methods [27]. However high initial cost, loss of reflection in highly saline soil and the accurate measurements with TDR require proper calibration and it involves establishing a relationship between the time delay of the electromagnetic pulses and the corresponding SWC and the calibration curves for TDR used to measure SWC can be varied across different soil types due to the inherent variations of soil properties. Furthermore, TDR is often more suitable for shallow SWC measurements, typically within the first 20cm of the soil profile.

3.3. Frequency Domain Reflectometry (FDR) method

The FDR method is similar to the TDR method, however, FDR method provides continuous measurement of SWC, which is based on changes in the frequency of signals due to the dielectric properties of the soil [28]. In here the tested sensor is mainly composed of a pair of circular metal rings which are formed into a capacitor and the soil act as a dielectric material. The tuning circuit contains a capacitor and an oscillator with 100 MHz sinusoid signal scanning [29]. When the capacitor is coupled to an oscillator, forming an electrical circuit, changes in the SWC is indicated by changes in the frequency of the circuit [30]. Then the SWC is calculated using the resonance frequency value. The relationship between the frequency of oscillation and SWC is inverse [31].The polarization between the measured *K* of the soil constituents and the sensor capacitance is directly proportional.
FDR probes must be calibrated for the type of soil they will be buried in and should be careful installation is necessary to

avoid air gaps [7]. FDR has a faster response time and better resolution than TDR. Moreover, certain FDR devices may be less expensive than TDR devices since they utilize low frequency standard circuitry [7].

3.4. Neutron scattering method

This method is appropriate for measurements that involve estimating soil moisture in the upper 1000 to 2000 mm of soil [32]. The SWC in expansive soils has been measured using this method by [33]. The neutron scattering method of measuring SWC is based on the principle of neutron thermalisation [32]. Thermalisation is the process of reducing fast neutrons to slow [16]. This process is relevant because it influences the number of slow neutrons that return to the detector after interacting with the soil. These neutrons are thermalized or slowed down by collisions with the nuclei of hydrogen atoms present in water molecules in the soil. The propagation of thermalized neutrons is related to SWC [3].

Several instruments are available to use in this method, such as neutron moisture meter, neutron-scattering moisture meter, neutron probe, neutron depth probe and neutron meter [34]. This is not hampered by environmental factors such as barometric pressure and temperature but salinity and degree of water binding to the soil are slightly affected. The total SWC can be measured using this instrument if it is properly calibrated with gravimetric sampling [2]. The SWC in a swelling clay soil was measured by [35] using a neutron moisture meter. The gauge and the probe are the two major parts of the neutron moisture meter. The probe has a slow neutron detector and a fast neutron source, which commonly creates fast neutrons by mixing beryllium and alpha particles from the radioactive emitter. The actual SWC measurements is made by lowering a probe consisting of the source and a detector to the required depth in appropriate access hole in the field [35]. The neutron probe assumes the overall SWC of a volume of soil by measuring the extent of thermalisation of a diffuse cloud of neutrons and thereby has the potential to determine the overall SWC equally well in both cracked and uncracked soils [30]. Schematic diagram of neutron gauge has shown in Fig. 2 [36].

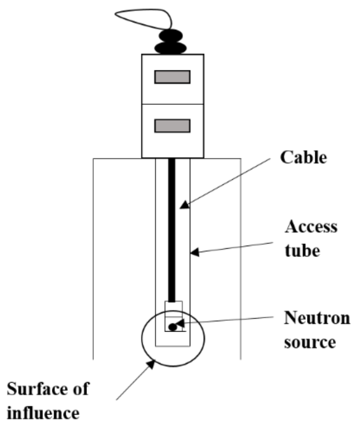

Fig. 2. Schematic diagram of neutron gauge after [36].

The accuracy of this method depends on the derivation of the regression whereby neutron counts can be converted to SWC [36]. The detector measures the neutron cloud's density. This was confirmed in swelling/shrinking clay soils by [37].

The main advantage of this method is the measurement procedure is relatively easy and straightforward [2]. When the instrument is properly calibrated, it provides higher accuracy of better than $\pm$ 0.02 in volumetric water content [2], [16]. Furthermore, this method is nondestructive, fast and repeated measurements can be performed at exact same location [36]. However, instrument is very expensive, it requires extensive soil specific calibration [3]. Manufacturers provides a calibration curve with each neutron probe, but it is probably useful only for SWC measurements in homogeneous sands and gravels [16]. Radiation hazard can be happen. The application of this method is lesser than past years due to that radiation hazards.

3.5. Tensiometry method

The tensiometry method is an indirect method for estimating SWC. This method estimates the soil water matric potential. The tensiometer is very useful as continuous reading instrument in this method. This is the only equipment that can make a direct measurement of soil suction. The tension reading on the tensiometer is related to SWC.

This is made with a porous ceramic cup, connected through a tube to a manometer with all parts filled with water. Different shape and size of the ceramic cups are available [7]. The ceramic cup is placed in the soil, where information, regarding soil water is desired. This instrument measures the moisture potential based on the suction force exerted on water by soil [13]. The working principle of the tensiometer is as follows: a porous vessel is buried in the soil to the depth at which SWC is to be measured; it is connected by means of copper tubing to a manometer. When the system is sealed and filled with water, thus forming a continuous column between the porous vessel and manometer. This water communicates with the SWC through the pores in the vessel and any change in capillary tension in the soil is accompanied by a flow of water through the pores until the tension inside equals the capillary tension in the soil surrounding the cup [38]. The magnitude of this tension is measured by the manometer. It is commonly expressed in units of bars. A thermally insulated tensiometer to investigate the movement of water under frozen soils was developed by [39].

The advantages of this method including: inexpensive, less-destructive, and easy to install. Operate satisfactorily only in the saturated range is disadvantage. Furthermore, it has slow response time and intimate contact with soil around the ceramic cup is required for consistent reading [7]. Moreover, it needs different calibration for different soil types and it works in the range from saturation to 0.8 bar.

3.6. Ground Penetrating Radar (GPR) method

The GPR method is an efficient electromagnetic wave based method [40] which has been successfully used as non-destructive tool to estimate SWC. It has made significant progress over the past 25 years in estimating SWC [41]. GPR measurements are based on the transmission and reflection of an electromagnetic wave in the soil [42]. This is also the dielectric method as TDR and FDR methods.

The GPR system consists of a transmitting antenna, receiving antenna, control unit and display unit. Transmitting antenna emits pulses of electromagnetic radiation into the subsurface and the receiving antenna then receives echo signals as a function of time. These received signals thus contain useful information as a result of high frequency electromagnetic waves propagation within the media of different *K* [10]. The schematic diagram of the GPR antenna and travel path of ground wave, air wave and reflected wave shows in Fig.3 [43]

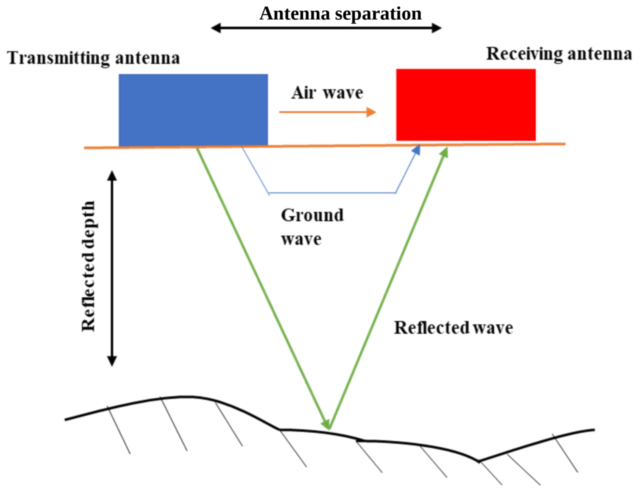

Fig. 3. Schematic diagram showing the GPR antenna and travel path of ground wave, air wave and reflected energy modified from [43].

In modern days, SWC measurement can be performed by using ground-coupled, air-launched, and borehole GPR antenna systems [9], [10]. In the ground-coupled GPR antenna system, antennas are placed on the investigated surface to maximize energy coupling into the subsurface [44] and the surface GPR measurements, fixed separation between transmitting and receiving antenna is essential [45], [46]. Air-launched antennas are elevated 0.3-1.0 m above the ground for pavement studies [47].

Earlier researchers have conducted so many researches to estimate SWC using different GPR method such as ground wave, borehole, reflected wave, surface reflections, full waveform inversion, average envelope amplitude and frequency shift method [10]. The borehole GPR methods are carried out in three different kind of modes, such as, reflection, cross-hole, and surface to borehole. In the reflection mode, transmitting and receiving antennas are placed in same borehole. Trnasmitting and receiving antennas are placed in different boreholes in cross-hole mode. In the surface to borehole mode, one borehole antenna is placed on the surface and other one is lowered into borehole. The borehole GPR system both transmitting and receiving antennas were placed in same borehole and they were recorded reflection data along the length of borehole by [48]. Furthermore, the borehole GPR method was used by [49] to measure the temporal and spatial variability of SWC under uniform wetting and drying conditions and the capacity of ground wave GPR method has been examined by [50] to predict water content in this zone.

The direct ground wave GPR technique is well-suited for monitoring SWC in shallow root zone environments [51]. The full-waveform inverse modelling procedure was applied to identify surface soil moisture from proximal GPR, in irrigated areas in southern Tunisia by [52]. Furthermore, the SWC was determined of the unsaturated zone in sandy deposits via measurements from the surface at two test sites in the Netherlands by using GPR method by [53] and the SWC determination was used by [41] using a digital GPR. The GPR Trans-ZOP (Transillumination Zero Offset Profile) method was used to measure SWC in raised beds by [45].

Most researchers have used GPR method as very common non-destructive method, and it facilitate to acquire precise and repeat data for large covering area with very short period of time.

3.7. Gamma ray attenuation method

The gamma ray attenuation method is a radioactive method that can be used to measure SWC which is restricted to a soil depth of 2.5cm or less with high resolution [3]. There is a presumption that the diffusion and absorption of gamma rays are correlated with the density of the matter in its path, gravity being constant irrespective of the SWC [30]. The instrument consists a source that emits gamma rays encircled by a collimator, detector and scalar [13].

This method permits exploration of the profile by sample movement of measuring device inside the tube and the main disadvantage of this method is that different types of soils give the same calibration curve [2]. Moreover this method is a non-destructive in situ method having response time of approximately less than 1 min which measures the SWC.

4. Discussion

The reviewed literature indicates researchers have employed various SWC measurement methods like gravimetric, TDR, FDR, GPR, neutron scattering, tensiometry and gamma ray attenuation method. The choice of the SWC measurement method is dependent on the applications, cost, and the resource availability. Furthermore, while choosing a method one should consider such as accuracy, repeatability, calibration requirements, and ease of use [16]. Gravimetric method is the precise method compare to other methods. As it is direct and destructive method, that will not help to have repeat measurement. The gravimetric method can be apply for any depth size where we can take soil sample. The dielectric methods including TDR, FDR, GPR and tensiometry methods do not provide direct SWC

measurements data. They need different calibration curves for different soils.
The GPR is not typically used to obtain a specific range of values from saturation. Direct ground wave can be used to measure the SWC in the soil and further different GPR transmitting method will help to investigate the soil moisture profile. The suitability of each indirect methods based on several factors such as the accuracy, response time, management and durability of the instrument [7]. Table 4 shows the comparisons of various SWC measurement techniques based on their principle, major specifications, measured parameter, response time, cost effectiveness, and depth of measurement and Table 5 shows the general specifications of the several soil moisture techniques.

The TDR is an economical [34] non-destructive indirect method. The TDR equipment are portable therefore can be carried easily to the field. Most of the researcher have employed both methods to measure SWC in various soil type and they have compared which data they have taken. The SWC measurements were taken from TDR and gravimetric method by [54] and it shows a 1:1 relation between both methods. We measured the SWC in topsoil using TDR and gravimetric method in Uva Wellassa University (UWU) premises (N 60 58’ 52.53708, E 810 4’ 30.26964) [55]. In here, TDR-100 portable instrument was used to measure field moisture content. The TDR-100 and field measurements are shown in Fig. 4a and 4b respectively. Fig. 5 shows that 1:1 relationship for measured SWC using the TDR and gravimetric method in the UWU selected 5-survey lines.

Furthermore, SWC measurements data was taken by [19] using TDR and the gravimetric methods for agricultural clay and marine clay soil and it has been shown, the significant discrepancy in SWC value as the quantity of water increase for agricultural and marine clay samples.
In here, agricultural clay provides more accurate moisture content reading compared to marine clay using both methods. The accuracy of TDR is higher than FDR [30].

The GPR method is an efficient electromagnetic wave-based method [41] which has been successfully used as non-destructive tool to estimate SWC. Furthermore, it covers the large area but it is sensitive to unwanted signals caused by different geological factors [30].

The accuracy of GPR used to measure SWC can vary based on GPR antenna configuration and soil condition. Only the frequency shift method can reclaim information of SWC directly from GPR data [10]. The borehole GPR method can obtain distribution of SWC at greater depth with higher resolution than the ground and air coupled GPRs [10]. Earlier Researches have done several experiments using TDR and GPR to measure SWC and compare these two methods respectively.
The SWC has been measured by [9] using TDR and borehole GPR method in well-drained sandy loam soil profile and the off-ground inverse modelling techniques and the ground wave GPR methods were used to estimate the shallow SWC at the field scale by [56].

Earlier researches have used different SWC measurement methods to measure the SWC in different types of soil. The summary of these research in the SWC measurement techniques which is applied to determine SWC in various soil types have illustrated in Table 6.

(a)

(b)

Fig. 4. Measurement of volumetric water content in the field using the (a) TDR-100 and (b) reading of TDR data.

Table 4. The Comparison of various SWC measurement techniques.

Method	Principle	Major specification	Measured parameter	Cost effectiveness	Response time	Depth of measurement
Gravimetric technique	Evaporation	105 ^{0}C	Gravimetric SWC	Economical	24 hours	Any depth
TDR	Dielectric constant	Operating frequency up to 1 GHz	Volumetric water content	Economical	28s [2]	1m
FDR	Dielectric constant	Operating frequency 10-150 MHz	Volumetric water content	Expensive [30]	Instantaneous	1m
Neutron scattering	Neutron scattering	Mean energy 5 Mev fast neutron is the input	Volumetric water content	Expensive	1-2 min	$\geq$3m
Tensiometry method	Suction or negative tension created	0-1 atm	Volumetric water content	Economical	2-3 hours	15cm–60cm [3]
Gamma ray attenuation	Diffusion and absorption	Not reported	Volumetric water content	Expensive [30]	Instantaneous	Upper soil layer (up to 1-2cm) [30]
GPR	Dielectric constant	Generally 1 MHz and 1 GHz [3]	Volumetric water content	Economical	Not reported	It can be vary due to GPR frequency and antenna configuration

Table 5. General specifications of the several soil moisture techniques.

Parameter	Gravimetric method	TDR method	FDR method	Neutron scattering
Accuracy	$\pm$0.01g of samples of around 100g	$\pm$0.01 to $\pm$0.02%Ø	$\pm$0.025% Ø	$\pm$0.001 to $\pm$0.002% Ø
Installation	Field soil samples and lab application	Permanently or temporarily burying is possible	PVC access tube is required	Permanently or temporarily burying is possible
Repeatability	Not applicable	$\pm$0.2 to $\pm$0.3% Ø	$\pm$0.3 to $\pm$0.4% Ø	$\pm$0.01 to $\pm$0.03% Ø
Sensitivity	$\pm$1.5 ^{0}C	$\pm$1 to $\pm$3% Ø	$\pm$1 to $\pm$3% Ø	$\pm$0.011 to $\pm$4% Ø
Data logging	Possible	Possible	Possible	Not possible
reference	[3]	[3]	[3]	[3]

Table 6: Summary of some research in SWC measurement techniques to determine SWC in various soil types.

Year	Author	Technique	Remarks
2008	Bittelli et al. **[1]**	TDR and Gravimetric method	SWC is determined in conductive soils under three different depths using gravimetric, corrected TDR and non-corrected TDR.
1997	Wyseure et al. **[57]**	TDR	They have shown that for saline soils the effects of conductivity and frequency on the travel time cannot be neglected and that, as a result, TDR systematically overestimates the water content in saline soils.
1987	Jarvis & leeds-harrison **[37]**	Neutron probe	Comparison of results obtained for bulk soil and for small clods have been shown that calibrating the neutron probe using small diameter cores may lead to serious under estimates of changes in SWC in swelling/shrinkling clay soils.
2008	Huang & Fityus, 2008) **[58]**		They have measured SWC in expansive soils and they have shown development of cracks in soils lead to nonlinear relationship between volumetric water content and neutron count.
2019	Zhou et al., **[59]**	GPR	High frequency GPR antenna system have used to measure shallow SWC in loamy sand, clay, and silty loam.

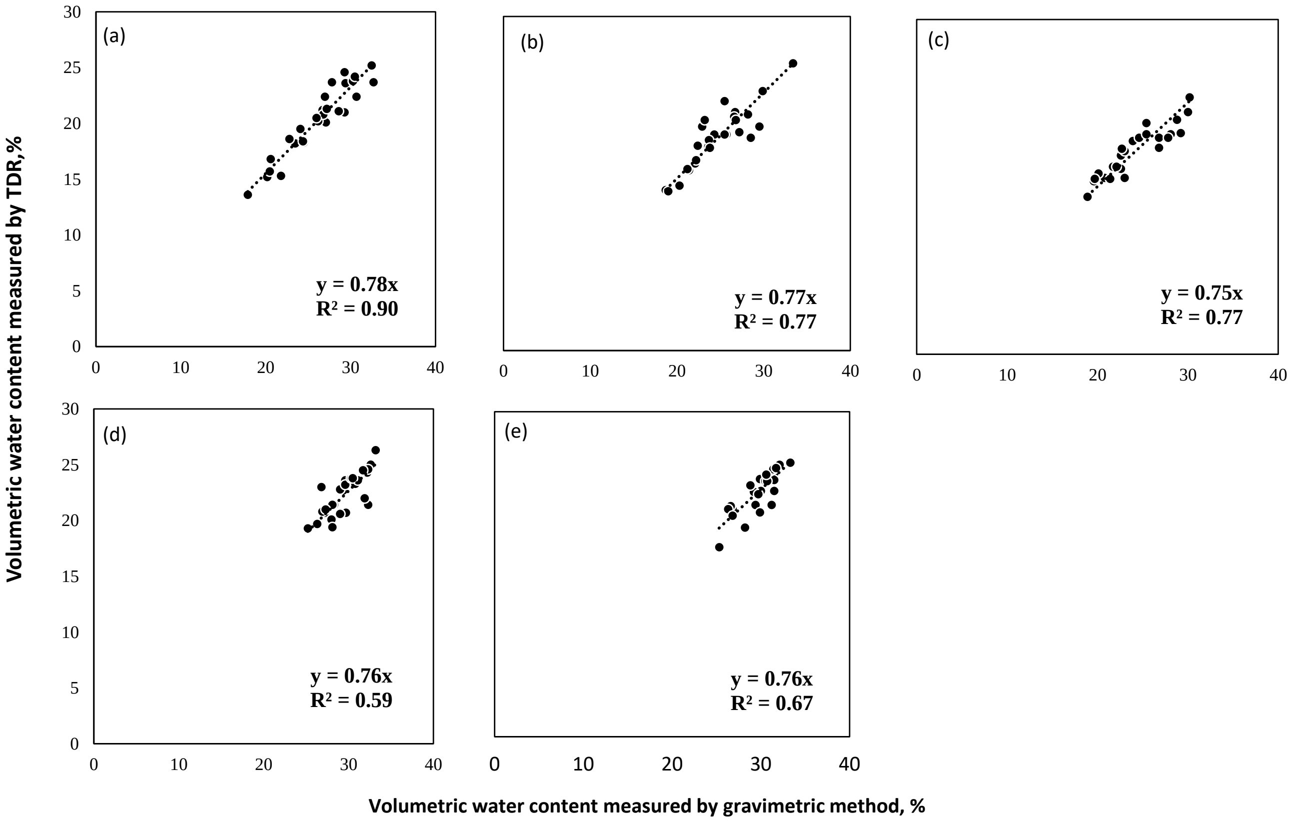

Fig.5. The comparison of measured volumetric soil water content from TDR (θ_{TDR}), and gravimetric method (θg) for survey lines, (a) L1, (b) L2, (c) L3, (d) L4 and (e) L5

5. Conclusion

We reviewed SWC estimation methods such as gravimetric, TDR, FDR, GPR, neutron scattering, tensiometry and gamma ray attenuation methods based on working principle, advantages and disadvantages of each methods in this paper. Although understanding of the principles of each SWC estimation method is the best way to certify that it is not used in a situation where another method might relevant better outcomes, each has characteristics that make it especially useful for specific uses, and each also has drawbacks that would make it unacceptable for use in some situations or under certain constraints. The selection of a suitable method depend on soil properties, application, and accuracy. The gravimetric method is the most accurate and standard method for SWC determination because it gives direct measurement data as well as it can be applied for the depth of soil profile where we can get a soil sample. Generally, the good relationship between TDR and GPR method confirms that available TDR calibrations between SWC and dielectric constant, such as Topp's equation. Furthermore, GPR is the promising technique for accurate SWC Measurements over large areas due to the rapid data acquisition. Future research should focus on developing new techniques or modifying the available methods to overcome the main disadvantage of requirements to measure the SWC.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] M. Bittelli, "Measuring soil water content: A review," *Horttechnology*, vol. 21, no. 3, pp. 293–300, 2011, doi: 10.21273/horttech.21.3.293.

[2] P. K. Sharma, D. Kumar, H. S. Srivastava, and P. Patel, "Assessment of Different Methods for Soil Moisture Estimation : A Review," *J. Remote Sens. GIS*, vol. 9, no. 1, pp. 57–73, 2018.

[3] S. U. Susha Lekshmi, D. N. Singh, and M. Shojaei Baghini, "A critical review of soil moisture measurement," *Meas. J. Int. Meas. Confed.*, vol. 54, pp. 92–105, 2014, doi: 10.1016/j.measurement.2014.04.007.

[4] S. B. Jones, J. M. Wraith, and D. Or, "Time domain reflectometry measurement principles and applications," *Hydrol. Process.*, vol. 16, no. 1, pp. 141–153, 2002, doi: 10.1002/hyp.513.

[5] B. Usowicz and J. Kossowski, "Distribution of soil water content in cultivated fields based on the measurements by gravimetric and reflectometric methods," *Zesz. Probl. Postep. Nauk Rol. - Pol. Akad. Nauk*, vol. 436, pp. 157–165, 1996.

[6] C. Tanriverdi, H. Degirmenci, E. Gonen, and S. Boyaci, "a Comparison of the Gravimetric and Tdr Methods in Terms of Determining the Soil Water Content of the Corn Plant," no. August, 2019.

[7] R. Muñoz-Carpena, "Field Devices For Monitoring Soil Water Content," *Edis*, vol. 2004, no. 8, 1969, doi: 10.32473/edis-ae266-2004.

[8] S. Balaghi, N. Ghal-Eh, A. Mohammadi, and H. R. Vega-Carrillo, "A neutron scattering soil moisture measurement system with a linear response," *Appl. Radiat. Isot.*, vol. 142, pp. 167–172, 2018, doi: 10.1016/j.apradiso.2018.10.002.

[9] L. W. Galagedara, G. W. Parkin, J. D. Redman, P. Von Bertoldi, and A. L. Endres, "Field studies of the GPR ground wave method for estimating soil water content during irrigation and drainage," *J. Hydrol.*, vol. 301, no. 1–4, pp. 182–197, 2005, doi: 10.1016/j.jhydrol.2004.06.031.

[10] X. Liu, J. Chen, X. Cui, Q. Liu, X. Cao, and X. Chen, "Measurement of soil water content using ground-penetrating radar: a review of current methods," *Int. J. Digit. Earth*, vol. 12, no. 1, pp. 95–118, 2019, doi: 10.1080/17538947.2017.1412520.

[11] N. S. Wijewardana, L. W. Galagedara, and M. I. M. Mowjood, "GprMax2D Modeling to Identify Contaminated Areas in Groundwater with Landfill Leachate," vol. 12, no. January, pp. 16–22, 2012.

[12] A. Shukla *et al.*, "Soil Moisture Estimation using Gravimetric Technique and FDR Probe Technique : A Comparative Analysis," pp. 89–92, 2014.

[13] T. J. Schmugge, T. J. Jackson, and H. L. McKim, "Survey of methods for soil moisture determination.," vol. 16, no. 6, pp. 961–979, 1979.

[14] M. Bittelli, F. Salvatorelli, and P. R. Pisa, "Correction of TDR-based soil water content measurements in conductive soils," *Geoderma*, vol. 143, no. 1–2, pp. 133–142, 2008, doi: 10.1016/j.geoderma.2007.10.022.

[15] K. Noborio, "Measurement of soil water content and electrical conductivity by time domain reflectometry: A review," *Comput. Electron. Agric.*, vol. 31, no. 3, pp. 213–237, 2001, doi: 10.1016/S0168-1699(00)00184-8.

[16] J. M. Baker, "Measurement of soil water content," *Remote Sens. Rev.*, vol. 5, no. 1, pp. 263–279, 1990, doi: 10.1080/02757259009532134.

[17] G. C. Topp, J. L. Davis, and A. P. Annan, "Electromagnetic determination of soil water content: Measurements in coaxial transmission lines," *Water Resour. Res.*, vol. 16, no. 3, pp. 574–582, 1980, doi: 10.1029/WR016i003p00574.

[18] T. Anisko, D. S. NeSmith, and O. M. Lindstrom, "Time-domain reflectometry for measuring water content of organic growing media in containers," *HortScience*, vol. 29, no. 12, pp. 1511–1513, 1994, doi: 10.21273/hortsci.29.12.1511.

[19] N. H. H. Abdullah *et al.*, "Determination of soil water content using time domain reflectometer (TDR) for clayey soil," *AIP Conf. Proc.*, vol. 2020, no. October 2018, 2018, doi: 10.1063/1.5062642.

[20] C. H. Benson and P. J. Bosscher, "Time-domain reflectometry (TDR) in geotechnics: a review," *ASTM Spec. Tech. Publ.*, no. 1350, pp. 113–136, 1999, doi: 10.1520/stp13313s.

[21] S. Dasberg and J. W. Hopmans, "Time Domain Reflectometry Calibration for Uniformly and

Nonuniformly Wetted Sandy and Clayey Loam Soils," *Soil Sci. Soc. Am. J.*, vol. 56, no. 5, pp. 1341–1345, 1992, doi: 10.2136/sssaj1992.03615995005600050002x.

[22] D. A. Robinson, S. B. Jones, J. M. Wraith, D. Or, and S. P. Friedman, "A Review of Advances in Dielectric and Electrical Conductivity Measurement in Soils Using Time Domain Reflectometry," *Vadose Zo. J.*, vol. 2, no. 4, pp. 444–475, 2003, doi: 10.2113/2.4.444.

[23] G. C. Topp, J. L. Davis, W. G. Bailey and W. D. Zebchuk, " The measurement of Soil water content using a portable TDR hand probe," Can. J. Soil Sci. 64: 313-321.

[24] G. . TOOP and P. A. Ferre, "Measuring Water Content in Soil Using Tdr:A STATE-OF-THE-ART IN 1998 G.C.," 1998.

[25] V. Zupanc, G. Adam, and M. Pintar, "Comparison of laboratory TDR soil water measurements," *Acta Agric. Slov.*, vol. 2, no. let 85, pp. 359–374, 2005.

[26] H. Mittelbach, I. Lehner, and S. I. Seneviratne, "Comparison of four soil moisture sensor types under field conditions in Switzerland," *J. Hydrol.*, vol. 430–431, pp. 39–49, 2012, doi: 10.1016/j.jhydrol.2012.01.041.

[27] D. Serrarens, J. L. MacIntyre, J. W. Hopmans, and L. H. Bassoi, "Calibração de sondas TDR de níveis múltiplos de profundidade, para umidade do solo," *Sci. Agric.*, vol. 57, no. 2, pp. 349–354, 2000, doi: 10.1590/S0103-90162000000200024.

[28] A. Robock, K. Y. Vinnikov, G. Srinivasan, J. K. Entin, S. E. Hollinger, N. A. Speransakaya, S. Liu, and A. Namkhai, 2000: The Global Soil Moisture Data Bank. Bull. Amer. Meteror. Soc., 81, 1281-1300, https:// doi.org/10.1175/1520-0477(2000)081<1281: TGSMDB>2.3.CO:2.

[29] Y. Linmao *et al.*, "FDR Soil Moisture Sensor for Environmental Testing and Evaluation," *Phys. Procedia*, vol. 25, pp. 1523–1527, 2012, doi: 10.1016/j.phpro.2012.03.271.

[30] P. Dobriyal, A. Qureshi, R. Badola, and S. A. Hussain, "A review of the methods available for estimating soil moisture and its implications for water resource management," *J. Hydrol.*, vol. 458–459, pp. 110–117, 2012, doi: 10.1016/j.jhydrol.2012.06.021.

[31] J. Guadalupe Ramos Hernández, J. Gracia-Sánchez, T. Patricia Rodríguez-Martínez, and J. Adalberto Zuñiga-Morales, "Correlation between TDR and FDR Soil Moisture Measurements at Different Scales to Establish Water Availability at the South of the Yucatan Peninsula," *Soil Moisture*, 2019, doi: 10.5772/intechopen.81477.

[32] J. Kodikara, P. Rajeev, D. Chan, and C. Gallage, "Soil moisture monitoring at the field scale using neutron probe," *Can. Geotech. J.*, vol. 51, no. 4, pp. 332–345, 2014, doi: 10.1139/cgj-2012-0113.

[33] S. Fityus, T. Wells, and W. Huang, "Water content measurement in expansive soils using the neutron probe," *Geotech. Test. J.*, vol. 34, no. 3, 2011, doi: 10.1520/GTJ102828.

[34] D. S. Chanasyk and M. A. Naeth, "Field measurement of soil moisture using neutron probes," *Can. J. Soil Sci.*, vol. 76, no. 3, pp. 317–323, 1996, doi: 10.4141/cjss96-038.

[35] N. S. Jayawardane, W. S. Meyer and H. D. Burrs, "Moisture measurement in a swelling clay soil Using Neutron Moisture Meters," Soil research., 22, 109-117, 1984, doi: org/10.1071/SR9840109.

[36] J. Li, D. W. Smith, S. G. Fityus, and D. Sheng, "Numerical Analysis of Neutron Moisture Probe Measurements," *Int. J. Geomech.*, vol. 3, no. 1, pp. 11–20, 2003, doi: 10.1061/(asce)1532-3641(2003)3:1(11).

[37] N. J. Jarvis and P. B. Leeds-harrison, "Some problems associated with the use of the neutron probe in swelling/shrinkling clay soils," *J. Soil Sci.*, vol. 38, no. 1, pp. 149–156, 1987, doi: 10.1111/j.1365-2389.1987.tb02132.x.

[38] E. F. Wallihan, "Use of Tensiometers for Soil Moisture Measurement in Ecological Research Author (s): Ellis F . Wallhan Published by : Wiley Stable URL : http://www.jstor.org/stable/1930393 Accessed : 25-06-2016 09 : 23 UTC Your use of the JSTOR archive indicates your a," *Ecol. Vol. 20, No. 3 (Jul., 1939)*, vol. 20, no. 3, pp. 403–412, 2016, [Online]. Available: http://www.jstor.org/stable/1930393.

[39] Y. Iwata and T. Hirota, "Development of Tensiometer for Monitoring Soil-Water Dynamics in a Freezing and Snow Covered Environment," *Journal of Agricultural Meteorology*, vol. 60, no. 5. pp. 1065–1068, 2005, doi: 10.2480/agrmet.1065.

[40] Z. Leng and I. L. Al-Qadi, "An innovative method for measuring pavement dielectric constant using the extended CMP method with two air-coupled GPR systems," *NDT E Int.*, vol. 66, pp. 90–98,

2014, doi: 10.1016/j.ndteint.2014.05.002.

[41] H. Marcak, S. Tomecka-Suchoń, R. Czarny, P. Pysz, A. Akinsunmade, and T. Kril, "GPR ground-wave parameters changes due to variation of soil moisture," *E3S Web Conf.*, vol. 66, pp. 0–7, 2018, doi: 10.1051/e3sconf/20186601003.

[42] A. Chanzy, A. Tarussov, F. Bonn, and A. Judge, "Soil Water Content Determination Using a Digital Ground-Penetrating Radar," *Soil Sci. Soc. Am. J.*, vol. 60, no. 5, pp. 1318–1326, 1996, doi: 10.2136/sssaj1996.03615995006000050005x.

[43] I. A. Lunt, S. S. Hubbard, and Y. Rubin, "Soil moisture content estimation using ground-penetrating radar reflection data," *J. Hydrol.*, vol. 307, no. 1–4, pp. 254–269, 2005, doi: 10.1016/j.jhydrol.2004.10.014.

[44] N. Diamanti and A. P. Annan, "Air-launched and ground-coupled GPR data," *2017 11th Eur. Conf. Antennas Propagation, EUCAP 2017*, pp. 1694–1698, 2017, doi: 10.23919/EuCAP.2017.7928409.

[45] Y. G. N. S. Wijewardana and L. W. Galagedara, "Estimation of spatio-temporal variability of soil water content in agricultural fields with ground penetrating radar," *J. Hydrol.*, vol. 391, no. 1–2, pp. 24–33, 2010, doi: 10.1016/j.jhydrol.2010.06.036.

[46] H. Vereecken, J. A. Huisman, Y. Pachepsky, C. Montzka, J. Vanderkruk, H. Bogena, L. Weihermuller, M. Herbst, G. Martinez, and J. Vanderborght, "On the spatio-temporal dynamics of soil moisture at the field scale," *J. Hydrol.*, vol. 516, pp. 76–96, 2014, doi: 10.1016/j.jhydrol.2013.11.061.

[47] D. Huston and D. Busuioc, Radar technology: Radio frequency, interferometric, millimeter wave and terahertz sensors for assessing and monitoring civil infrastructures, vol. 1. Woodhead Publishing Limited, 2014.

[48] S. Nelliat, B. B. Babu, P. C. Jha, and Y. V Sivaram, "mapping the extension of old working at a Pb-Zn Mine in Rajasthan , India," no. Rare, pp. 512–517, 2016.

[49] L. W. Galagedara, G. W. Parkin, and J. D. Redman, "An analysis of the ground-penetrating radar direct ground wave method for soil water content measurement," *Hydrol. Process.*, vol. 17, no. 18, pp. 3615–3628, 2003, doi: 10.1002/hyp.1351.

[50] K. Grote, S. Hubbard, and Y. Rubin, "Field-scale estimation of volumetric water content using ground-penetrating radar ground wave techniques," *Water Resour. Res.*, vol. 39, no. 11, pp. 1–14, 2003, doi: 10.1029/2003WR002045.

[51] C. Ferrara, P. M. Barone, C. M. Steelman, E. Pettinelli, and A. L. Endres, "Monitoring Shallow Soil Water Content Under Natural Field Conditions Using the Early-Time GPR Signal Technique," *Vadose Zo. J.*, vol. 12, no. 4, p. vzj2012.0202, 2013, doi: 10.2136/vzj2012.0202.

[52] S. Lambot, E. Slob, D. Chavarro, M. Lubczynski, and H. Vereecken, "Measuring soil surface water content in irrigated areas of southern Tunisia using Full-waveform inversion of proximal GPR data," *Near Surf. Geophys.*, vol. 6, no. 6, pp. 403–410, 2008, doi: 10.3997/1873-0604.2008028.

[53] R. A. Van Overmeeren, S. V. Sariowan, and J. C. Gehrels, "Ground penetrating radar for determining volumetric soil water content; results of comparative measurements at two test sites," *J. Hydrol.*, vol. 197, no. 1–4, pp. 316–338, 1997, doi: 10.1016/S0022-1694(96)03244-1.

[54] O. H. Jacobsen and P. Schjønning, "Field evaluation of time domain reflectometry for soil water measurements," *J. Hydrol.*, vol. 151, no. 2–4, pp. 159–172, 1993, doi: 10.1016/0022-1694(93)90234-Z.

[55] S. S. Garusingha, Y. N. S. Wijewardana, D. T. Udagedara,"Comparison of Topsoil water content by time domain reflectometry and gravimetric method [abstract]. In: Proceedings of the postgraduate Institute of science research congress, Sri Lanka; 2022 Oct 28-30; University of Peradeniya:RESCON; 2022. Abstract no 120.

[56] L. Weihermüller, J. A. Huisman, S. Lambot, M. Herbst, and H. Vereecken, "Mapping the spatial variation of soil water content at the field scale with different ground penetrating radar techniques," *J. Hydrol.*, vol. 340, no. 3–4, pp. 205–216, 2007, doi: 10.1016/j.jhydrol.2007.04.013.

[57] G. C. L. Wyseure, M. A. Mojid, and M. A. Malik, "Measurement of volumetric water content by TDR in saline soils," *Eur. J. Soil Sci.*, vol. 48, no. 2, pp. 347–354, 1997, doi: 10.1111/j.1365-2389.1997.tb00555.x.

[58] W. Huang and S. Fityus, "Numerical study of neutron probe measurement of water content in expansive soils," *12th Int. Conf. Comput. Methods Adv. Geomech. 2008*, vol. 2, pp. 1420–1427, 2008.

[59] L. Zhou, D. Yu, Z. Wang, and X. Wang, “Soil water content estimation using high-frequency ground penetrating radar,” *Water (Switzerland)*, vol. 11, no. 5, pp. 1–16, 2019, doi: 10.3390/w11051036.