



Laboratory Calibration of Capacitance-Based Soil Moisture Sensor to Monitor Subsurface Soil Moisture Movement in Laterite Soil

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/IJPSS/2021/v33i1730558

Editor(s):

(1) Dr. Sangita Sahni, Dholi, Dr. Rajendra Prasad Central Agricultural University, India.

Reviewers:

(1) Manuel Filipe Pereira da Cunha Martins Costa, University of Minho, Portugal.

(2) Sofyan A Taya, Islamic university of Gaza, Palestine.

Complete Peer review History: <https://www.sdiarticle4.com/review-history/71185>

Original Research Article

Received 24 May 2021
Accepted 27 July 2021
Published 03 August 2021

ABSTRACT

Subsurface soil moisture movement in the unsaturated zone plays a critical role in the replenishment of groundwater table. This comprehension can be vital for the terrain with lateritic soil followed by the charnockite bedrock system. The conventional techniques to determine the subsurface soil moisture and its movement is cumbersome owing to high cost, large scale time consumption, field drudgery and greater possibility of manual errors. Among many other modern technologies for the measurement of volumetric water content, capacitance-based moisture sensors are capable and less expensive, thus, making them highly suitable for the research scholars worldwide. The study involves the use of TEROS 12 moisture sensors. The capacitance-based sensor TEROS 12, equipped with advanced soil moisture technique curtails the constraints in the conventional technique of soil moisture assessment and can provide precise measurements if suitably calibrated for the site specific soils. The study involves a soil specific calibration of TEROS 12 moisture sensor which was performed for the laterite soil to incorporate the sensor with the automated soil moisture monitoring system. The reliability of the sensor TEROS 12 was assessed by comparing its moisture measurements with that of the gravimetric method. The

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calibration was performed for three TEROS 12 moisture sensors in order to monitor the interflow at three varying soil depths in the vadose zone. The R^2 values obtained from the calibration of sensors at depths of 0-0.4 m, and 0.8-1.2 m were 0.996, 0.994 and 0.992 respectively. Further, during validation it was found that the new measurements coordinated with the gravimetric measurements to a greater extent and increased the preciseness as compared to that of uncalibrated values of moisture contents, thereby establishing TEROS 12 capacitance-based sensor as a reliable and cost effective moisture sensor.

Keywords: Calibration; capacitance-based sensor; TEROS 12; interflow; soil moisture movement.

1. INTRODUCTION

Analysis of soil water movement plays a vital role in understanding various hydrological processes and their efficient simulation through hydrological models. However, there is only limited knowledge available regarding soil moisture movement in the subsurface soil strata as it is influenced by a number of forces and heterogeneous characteristics of the substrata [1,2]. Thus, real-time monitoring of soil moisture movement in the vadose zone is highly essential to interpret the groundwater recharge and preferential flow characteristics of the soil [3]. Direct measurement and thereby the characterization of vadose zone is quite challenging as it needs to carry out the investigations deeper than one or two meters below the soil surface. Additionally, direct measurements involve invasive methods of collecting soil samples in order to carry out laboratory examinations. Thus, direct measurements cannot be convenient and reliable owing to the rapidity in spatial and temporal variation of soil moisture movement [4].

Among the various methods used for monitoring the soil moisture movement, optical sensors, sensors using the electromagnetic technique namely, Time Domain Reflectometer TDR and Frequency Domain Reflectometer FDR (Capacitance-Based Sensor) are used, being convenient in handling and for the acquisition of real time data. Electric permittivity and magnetic permeability μ are the basic physical parameters describing electromagnetic properties of a medium [5]. An optical sensor is a device in which light interacts with the substance to be detected (measurand) and converts light affected by the measurand substance into electrical signal which gives information about the analyte [6]. Interaction between light and matter is of high significance to a wide variety of interesting applications [7]. Since optical fiber utilizes light rays instead of electrical signals, it is less affected by weather changes [8]. Time Domain

Reflectometer (TDR) is an electronic device that works on the principle of radar based on transmitting signals into the medium and collecting reflected signals [9]. TDR determines dielectric constant and consequently permittivity and water content (direct related) of the medium, which is soil, via wave propagation transmitted by two parallel embedded metal probes with the utmost accuracy [9,10]. Although, Time Domain Reflectometer (TDR) is precise but, it has limited wide scale applicability due to the cost of investment and discrepancy of data in high saline soils [11,12]. Conversely, capacitance-based sensors are cheaper as compared to the former and utilize high frequency to withstand the variations due to salinity and temperature [13]. The output of capacitive moisture sensors depends on the complex relative permittivity ϵ^* of the soil (dielectric medium) [14]. However, capacitance-based sensor needs to be calibrated specifically for the soil under the study for very precise results [15]. TEROS12 moisture sensor by the METER Group, Inc. USA, is a commercially available moisture sensor that assures consistency, robust construction, a large volume influence of 1010 ml, and data reliability at a cost which is affordable. The capacitance-based soil moisture sensor TEROS 12 has been already company calibrated for mineral soils and soilless media [16]. However, the sensor has not been calibrated for its accuracy in the laterite terrain at different soil profiles with varying soil aggregation and texture. Hence, the present study was carried out (i) to examine the accuracy and reliability of TEROS 12 capacitance-based moisture sensor using the conventional gravimetric and core sampling methods, (ii) to develop a calibration function for the site specific soil, (iii) to validate the calibrated sensor results, (iv) to integrate the calibrated moisture sensor to a data acquisition system.

2. MATERIALS AND METHODS

TEROS 12 capacitance-based soil moisture sensor as illustrated in Fig. 1 is a METER Group

product. It has three needles. Soil moisture is measured in between needle 1 and needle 2. The sensor measures electrical conductivity (EC) between needle 2 and needle 3. A thermistor is embedded to measure the temperature. It measures the dielectric permittivity or the ability of medium (soil) to get polarized by creating an electromagnetic field.

An oscillating wave of 70 MHz is supplied by the sensor to the sensor needles, which gets charged depending upon the dielectric property of medium. The charge time taken by the needles is recorded by the TEROS 12 microprocessor and provides the output in the form of a raw value based on the substrate dielectric property. The raw value is converted to volumetric water content (VWC) by a calibration equation specific to the substrate. The configuration for the TEROS 12 moisture sensors and its data collection was done by the ZL6 data logger (Fig1-b, c). ZL6 logger is a plug-n-play data logger for field research endeavours. A weather resistant enclosure houses the data logger thereby making the device compatible for long term outdoor operations. The collected data from the logger was transmitted to the ZENTRA cloud web service via cellular communication which was furnished in the ZENTRA Utility software. ZENTRA Utility was used to set all the configuration parameters required for the logger and real time sensor measurements were performed at the study site. The calibration was carried out for a lateritic terrain to monitor subsurface soil moisture movement. To analyse the soil moisture movement and its characteristics using TEROS 12 a trench of dimension 1.5 m x 0.6 m x 1.6 m (length x width x height) was dug in the experimental site. Three different soil profile depths i.e. 0-0.4 m, 0.4-0.8 m and 0.8-1.2 m were selected to determine the variation in volumetric water content with soil depth. Calibration was carried out for three TEROS 12 sensors separately for the three soil profile depths following the phases as explained below.

2.1 Field Data Acquisition and Analysis

Soil samples from the trench were collected (Fig 2.a) from the study site to determine the major index properties i.e. bulk density, specific gravity and type of the soil at three different profile depths from the trench face. Adequate care was taken while extracting the soil core samples so as to prevent excessive invasion of soil from the trench face. Subsequently, field data acquisition

was carried out in two phases. The first phase involved installation of TEROS 12 capacitance-based soil moisture sensors along with ZL6 data logger at the study site (Fig 2. b & c). The three TEROS 12 moisture sensors were marked as 1, 2 and 3 as per the sequence of their insertion at different soil depths. The tines of the moisture sensors were carefully inserted in all the three soil profile depths in the study site. The insertion was carried out carefully particularly, at 2nd and 3rd soil depths (0.4-0.8 m and 0.8-1.2 m). Proper care was taken to avoid the bending or breakage of the sensor tines, considering the presence of lateritic clay clods and compact soil, usually occurring at greater soil depths. The stereo plug connector of the moisture sensors were connected to sensor input ports inside the ZL6 data logger. A TEROS 12 sensor comes with a standard 5 m cable. The excess cable was secured during this experiment as it needs to be protected against the damage caused by rodents and other animals (Fig 2.d). Data logger was configured through ZENTRA Utility interface. Subsequently, the sensor configuration was done by providing a measurement interval of fifteen minutes and the sensor type information was supplied to the respective ports. Desired preferences for the volumetric water content, temperature and electrical conductivity measurements were set through the ZENTRA Utility interface. Subsequently, the sensor readings were scanned for all three soil depths at different time to obtain the real time soil moisture data.

The second phase of field data acquisition was for the gravimetric moisture content analysis. Soil samples from the three profile depths of 0-0.4 m, 0.4-0.8 m and 0.8-1.2 m were collected carefully from the vicinity of the TEROS 12 sensors creating the least / no disturbance to the moisture sensors and depicting the representative sample in the volume of influence of moisture sensor at the same time.

The samples were taken after noting down the sensor readings so as to ensure no discrepancy in the sensor data. The collected soil samples were kept in oven at a temperature of 105^oC for 24 hours after removing their lids. Mandatory calculations and comparisons were done among the results obtained from both phases of field data acquisition.

2.2 Sensor to Sensor Variability Analysis

Sensor to sensor variability analysis was performed for different soil moisture contents. A

calibration container of size 0.295 m x 0.225 m x 0.12 m (L x W x H) was used to perform the analysis. This was done by inserting two TEROS12 moisture sensors at different points in the calibration container for the same volumetric water content. Adequate caution was taken to prevent insertion of one sensor in the holes created by the other sensor. The coefficient of variation between the sensors was calculated at each varying moisture contents for the soil sample taken from a depth of 0-0.4 m from the trench face.

2.3 Soil Sample Preparation and Calibration of Sensor

Following the comparative analysis of the soil moisture obtained from the capacitance- based moisture sensor TEROS 12 and that from the gravimetric method, soil sample from the first profile depth of 0-0.4 m was taken. The calibration procedure preferred was “Method A” for soil specific calibration of METER soil moisture sensors. It is a method recommended by the METER group for higher accuracy and is based on weighing the entire sample of calibration. The collected soil sample from the study site was air-dried for 24 hours (Fig 3.a). The air dried sample was run through a sieve of 0.002 m size after breaking the larger clods. A plastic container was used as a calibration container (Fig 3.b). The container was packed with the soil to match field bulk density, of 0-0.4 m soil profile depth. This was done using the dry density value which was calculated through the core sample analysis in the laboratory. Subsequently, the air dried soil was packed upto a height of eight meter in the plastic container in

such a way, that it matched the field bulk density of soil. The procedure was carried out gradually by adding the soil in layers and also by compacting it after every layer so as to minimize the voids. TEROS 12 moisture sensor was inserted vertically directly into the soil filled in the container, avoiding any air gaps between the sensor tines and the soil. Raw moisture data from the sensor was collected and noted down. Soil sample of about 0.015 Kg was collected in the moisture can for gravimetric moisture content determination. Water was added in the dry soil to about ten percent of the total soil volume to raise the volumetric water content by ten percent (Fig.3.c). The soil was thoroughly mixed by overturning, until the mixture became homogeneous. The soil sample was filled again into the plastic calibration container in layers and with each layer light compaction was done to minimize the voids. Raw value of raised volumetric water content was recorded by the TEROS 12 sensor. At this point sensor to sensor variation was also determined using sensor 2 (Fig.3.d).

The above procedure was repeated to yield five calibration points. The calibration of sensor 1 was opted for the soil profile depth of 0-0.4 m. Similarly, sensor 2 and sensor 3 were calibrated for soil profile depths of 0.4-0.8 m and 0.8-1.2 m respectively. Proper care was taken to maintain the same bulk density of the sample throughout the calibration process, by packing the soil sample in the calibration container to the same height while raising the volumetric water content. The whole procedure was carried out at room temperature. Raw data from the sensor obtained via ZENTRA Utility was then tabulated.

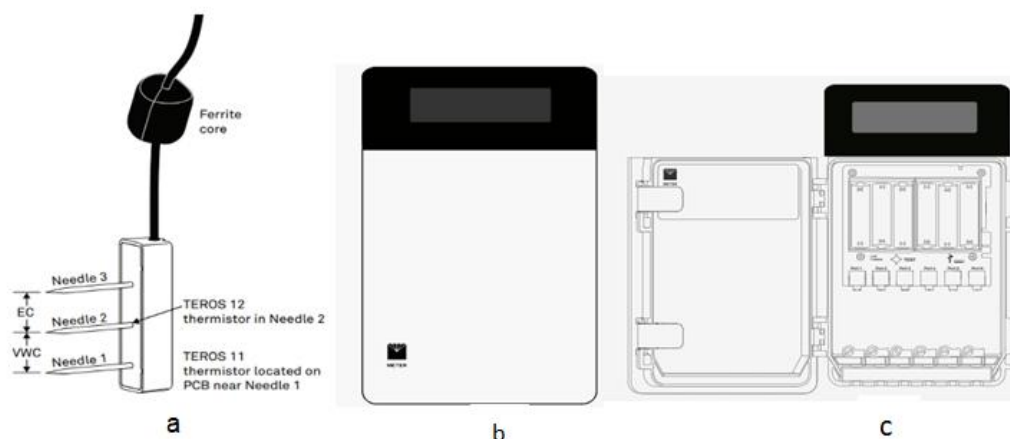


Fig. 1. a) TEROS 12 Sensor, b) Exterior of TEROS 12 Sensor, c) Interior of Sensor

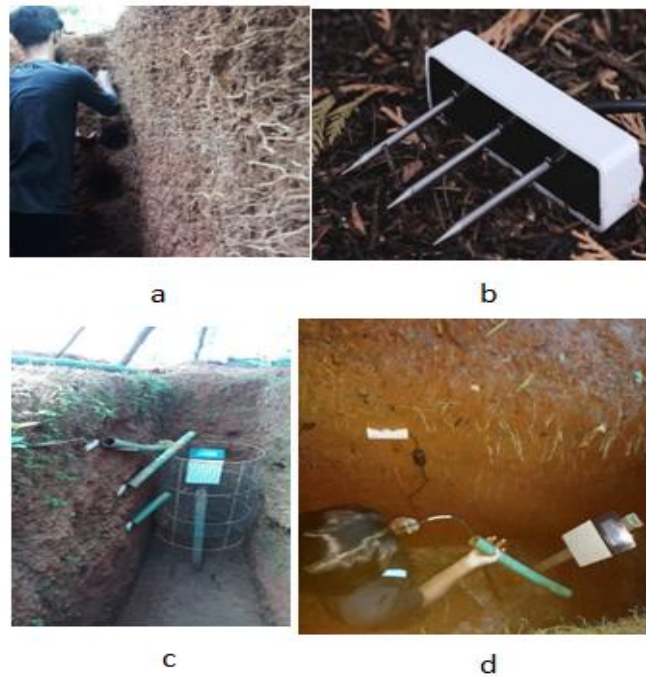


Fig. 2. a) Core cutter Sampling , b) TEROS 12 Sensor, c) Installation of TEROS 12 Sensor in the trench, d) Prevention from the rodent damage

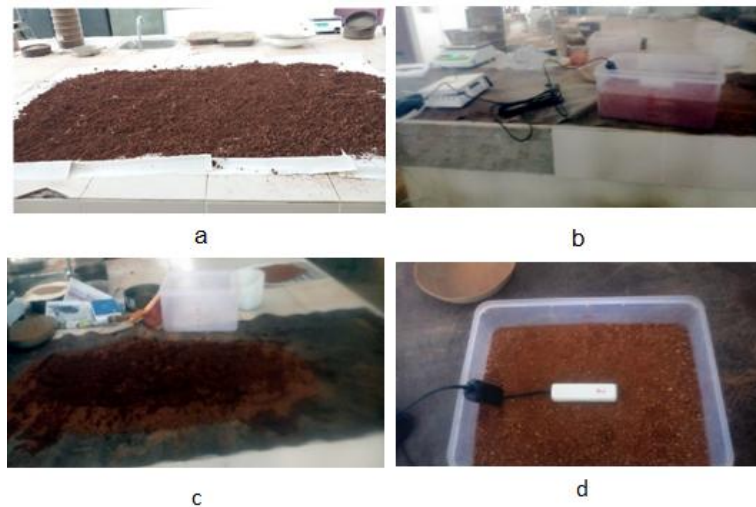


Fig. 3.a) Air drying of site specific soil , b) Addition of water to raise VWC of soil, c) Compaction of soil in plastic container to attain field BD, d) Insertion of TEROS 12 sensor

2.4 Integration of TEROS 12 moisture sensor with ZENTRA Cloud Software

Once the calibration functions were determined for all the three soil moisture sensors specific for the respective soil profile depths, it can be applied to the METER sensor data. In the

present study the calibration function was applied using ZENTRA Cloud software. Coefficients of new calibration function were added along with ancillary data obtained from field analysis. Once the coefficients for new calibration function were fed in the ZENTRA Cloud validation was carried out.

2.5 Validation of the Generated Calibration Function

The developed calibration function was validated by determining volumetric water contents in the site specific soil samples. The first soil profile depth of 0-0.4 m at the study site represented sandy loam type of soil and the other two depths contain loamy sand. The calibration procedure as prescribed in TEROS 12 user manual resulted in calculated coefficients which were put in the calibration equation via ZENTRA cloud software. The validation was performed for all the three soil profile depths with varying moisture content soil samples: oven dried, air dried, samples with volumetric water contents of 20%, 30% and 40%.

3. RESULTS AND DISCUSSIONS

The major soil index properties were identified. Bulk density was calculated using the core cutter method following equation 1. Specific gravity was calculated using pycnometer test and equation 2. Sieve analysis provided the grain size distribution of the soil. The textural classification was carried out by opting USDA textural classification triangle.

$$\rho = \frac{M_s}{V} \quad (1)$$

Where, ρ is soil bulk density, M_s is the mass of oven dry soil and V is bulk volume of the soil.

$$G = \frac{M_2 - M_1}{(M_2 - M_3) - (M_3 - M_4)} \quad (2)$$

Where, G is the specific gravity of soil, M_1 is mass of empty Pycnometer, M_2 is mass of the Pycnometer with dry soil, M_3 is mass of the Pycnometer and soil and water, M_4 is mass of Pycnometer filled with water only. The site specific soil index properties have been depicted in Table 1. The results which were determined by the capacitance-based soil moisture sensor TEROS 12 involved volumetric water content, soil temperature and electrical conductivity. The measurements were stored in ZL6 data logger.

The retrieval of data was done through ZENTRA Utility interface software. The gravimetric water content measurements were carried out for all the three profile depths. The collection of soil samples for laboratory analysis was done exactly at the same time for which the TEROS 12 moisture sensor data were analysed. The volumetric water content, θ (m^3 / m^3) of the site specific soil was obtained using equation 3 where, W_g (kg/kg , %) is the gravimetric water content of the sample, ρ_d (kg/m^3) and ρ_w (kg/m^3) are the dry bulk density of the soil and density of water respectively.

$$\theta = W_g \frac{\rho_d}{\rho_w} \quad (3)$$

The spatially varying data obtained from gravimetric analysis and TEROS 12 moisture sensors were then compared. Subsequently, it was revealed that the values predicted by TEROS 12 sensors were not precise (Table2).

3.1 Results of Gravimetric Analysis and Moisture Sensor for the Three Soil Profile Depths

The gravimetric analysis and volumetric water content determination through TEROS 12 moisture sensor was carried out in the lateritic terrain simultaneously. The textural classification of the site specific soil revealed sandy loam soil type at first profile depth and loamy sand at the other two profile depths. The comparison between the moisture contents obtained from gravimetric analysis and TEROS 12 moisture sensors depicted that TEROS 12 moisture sensor recorded a variation of (-5%) at a depth of 0-0.4 m, (-12%) variation at 0.4-0.8 m depth and (+3%) variation at 0.8-1.2 m depth.

3.2. Results of Sensor to Sensor Variability Analysis

The Sensor to sensor variability analysis was carried out prior to the calibration for the predetermined soil moisture content sample. It

Table 1. Index properties of the site specific soil

Soil index properties of the site specific soil			
Depth	Bulk Density (kg/m^3)	Specific Gravity	Type of Soil
0-0.4 m	1230	2.42	Sandy Loam
0.4-0.8 m	1110	2.49	Loamy Sand
0.8-1.2 m	1260	2.54	Loamy sand

Table 2. Comparison of TEROS 12 moisture sensor readings to gravimetric measurements

S.No.	Before calibration					
	TEROS 12 Measurements			Gravimetric Measurements		
	Volumetric Water Content (%)			Volumetric Water Content (%)		
	0-0.4 m	0.4-0.8 m	0.8-1.2 m	0-0.4 m	0.4-0.8 m	0.8-1.2 m
1	40.3	41.3	34.6	42.4	47.3	33.52

was performed only for the soil depth of 0-0.4 m. Samples at different moisture contents (air dry, 10%, 20%, 30%, 40%) were used to test sensor to sensor variability.

The values of Coefficient of Variation as shown in Table 3 depicted no significant sensor to sensor variability. Thus, calibration of one sensor was only required for a particular depth and type of soil with specific bulk density.

3.3 Calibration of TEROS 12 Capacitance-Based Moisture Sensor for Site Specific Laterite Soil

The comparison between the moisture measurements taken by gravimetric analysis and TEROS 12 moisture sensor depicted variations. Thus, in order to obtain precise measurements sensor calibration was performed using Calibration A method used for the TEROS 12 moisture sensor by the METER group. The calibration resulted in an equation with calculated coefficients for all the three soil depths of the trench separately. Fig. 4, Fig. 5 and Fig. 6 depicts the calibration curves (CC) for all the three soil depths in the trench. Calibrated coefficients were obtained through the calibration equations 4, 5, and 6 for the three respective soil profile depths of 0-0.4 m, 0.4-0.8 m and 0.8-1.2 m. In equations 4, 5, and 6 the x values represent raw moisture data and the y values represent actual VWC values in m^3 / m^3 . Subsequently, the calibrated coefficients were fed through ZENTRA cloud to determine the calibrated and site specific precise values of Volumetric water content of the soil.

$$y = 9.610e^{-10}x^3 - 7.362e^{-6}x^2 + 1.892e^{-2}x - 1.596 \dots \dots (4)$$

$$y = 1.891e^{-9}x^3 - 1.457e^{-5}x^2 + 3.734e^{-2}x - 3.145 \dots \dots (5)$$

$$y = 1.164e^{-9}x^3 - 8.902e^{-6}x^2 + 2.274e^{-2}x - 1.905 \dots \dots (6)$$

The values of coefficient of determination i.e. R^2 obtained for the moisture sensors were 9.964,

9.941 and 9.922 for the depths 0-0.4 m, 0.4-0.8 m and 0.8-1.2 m respectively.

3.4 Insertion of Calibrated Function for TEROS 12 Sensor through ZENTRA Cloud

The calibrated coefficients obtained from equations 4, 5 and 6 were fed in the polynomial equations through ZENTRA cloud to obtain calibrated values of volumetric water content.

3.5. Data Validation with the Conventional Gravimetric Method

Validation of the developed calibrated function was done by measuring the site specific moisture contents. This was done by installing the TEROS 12 moisture sensors in the experiment site along with the ZL6 data logger. All the three sensors were installed carefully in the trench face at depths of 0-0.4 m, 0.4-0.8 m and 0.8-1.2 m. Proper caution was taken while connecting the moisture sensors to the data logger, such that sensor 1 which was calibrated for first soil depth (sandy loam soil, BD=1.23) was connected to the first port in the data logger and successively for the other two soil depths (loamy sand, BD=1.11, BD= 1.26 respectively) sensor 2 and Sensor 3 were connected to the second and third ports in the data logger. The calibrated volumetric water content was obtained directly from ZENTRA cloud. The soil samples for gravimetric moisture content analysis were collected in a set of three from all the three soil depths. Three soil samples from each depth were taken so as to obtain a representative sample from the volume of influence of TEROS 12 moisture sensor for a better comparison and thus validation of sensor. The comparative results represented a significant reduction in the variation between the results obtained through capacitance-based moisture sensor and gravimetric moisture content analysis. The Root Mean Square Error (RMSE) was calculated for soil moisture contents derived by different calibrated functions. The RMSE values for the three depths were 0.13, 0.16 and 0.20 respectively. The percentage variation in the

Table 3. Coefficient of Variation among the three sensors at various pre-determined soil moisture contents

M.C	Sensor 1	Sensor 2	Sensor3	Mean	SD	CV (%)
Air Dry	1974.5	1960.5	1980.9	1972.0	10.4	0.5
10%	2083.1	2059.1	2071.3	2071.1	12.0	0.6
20%	2255.3	2246.2	2255.6	2252.3	5.3	0.2
30%	2660.3	2659.2	2640.8	2653.4	11.0	0.4
40%	2924.1	2930.6	2945.2	2933.3	10.8	0.3

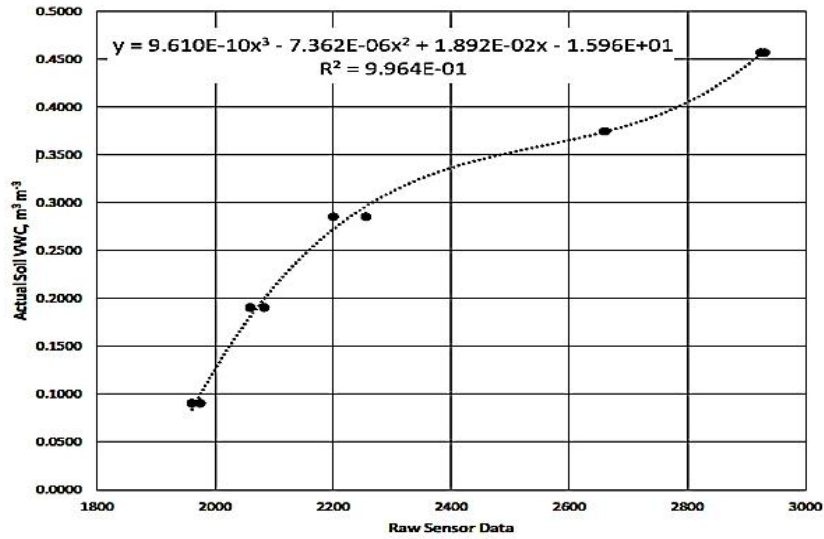


Fig. 4. Calibration curve for sensor 1 (for soil profile at 0-0.4 m)

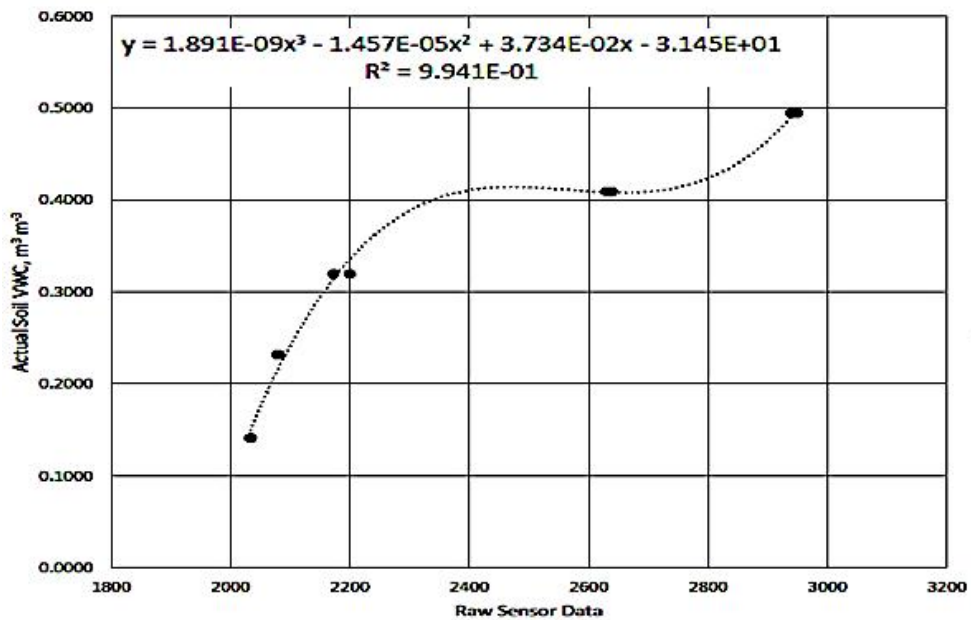


Fig. 5. Calibration curve for sensor 2 (for soil profile at 0.4-0.8 m)

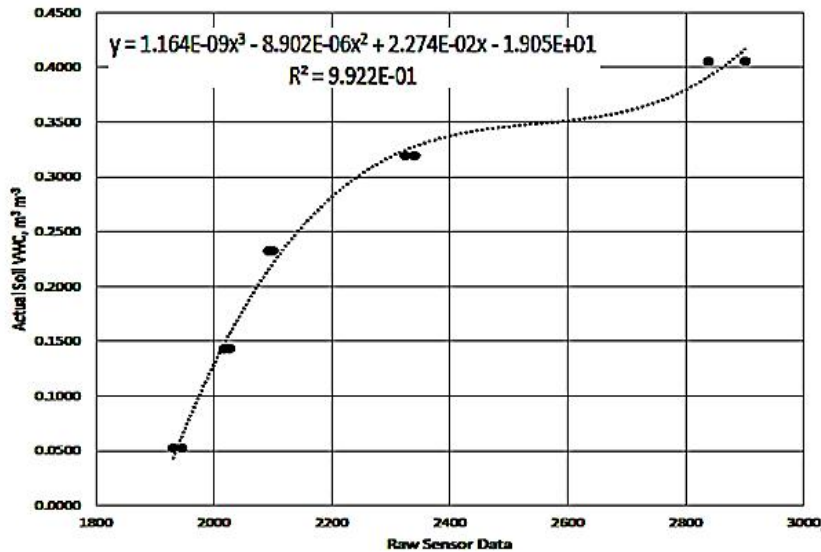


Fig. 6. Calibration curve for sensor 3 (for soil profile at 0.8-1.2 m)

volumetric water content for the depths 0-0.4 m, 0.4-0.8 m and 0.8-1.2 m were reduced after calibration to (+1.7%), (+3.9%) and (-1.8%) respectively. Thus, the data prediction by the capacitance-based TEROS 12 moisture sensor was improved.

4. CONCLUSIONS

The study involved evaluation of the accuracy and reliability of TEROS 12 capacitance-based sensor under field conditions. The study also established the reliability of calibration method A provided by the sensor company. The main purpose of installing the moisture sensor was to study the high spatial and temporal variation of lateral flow of water in the laterite soil. The TEROS 12 sensor is not sensitive to variation in soil texture and EC because it runs at a high measurement frequency which was identified during the study. Therefore, its generic calibration equation should result in reasonable absolute accuracy according to the METER group (Pullman). But, the site chosen for the study had unusual decrease in bulk density and greater porosity at a soil depth of 0.4-0.8 m as compared to the depths of 0-0.4 m and 0.8-1.2 m. Moreover the site represented a lateritic terrain. Thus, a reliability check was essential before completely relying on the sensor measurements. The developed soil specific calibration equation for the site specific soil performed satisfactorily during the sensor validation procedure for the determination of

volumetric water content of soil in the field. Hence, TEROS 12 sensor can be used successfully to determine the VWC of mineral soils with appropriate calibration. The sensor is highly suitable for the experiments involving greater temporal variation for long duration. Additionally, the results suggest that the accuracy of sensor greatly depends upon the bulk density and texture of soil.

However, while working at varying soil depths or profile (on the trench face) with TEROS 12 sensors it is essential to create least disturbance at the experimental site before and after installing the sensors. It is also important to investigate the effect of varying bulk densities of the soil profile on the sensor measurements. The results depicted a positive error at the first two depths of the soil profile suggesting higher porosity as the calibration will be too wet at the dry end due to the filling up of pore with air. This positive error was highest for the second depth. The third depth noticed negative error which suggested lower porosity as the calibration will be too dry at the wet end due to the filling of pore spaces with water. Further studies should be undertaken to include the effects of soil mineralogy, and organic matter content on the sensor measurements and its calibration.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our

area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

ACKNOWLEDGEMENTS

I would like to present my foremost thanks to my supervisor Dr.Sathian K.K, *Dean of the Institution, Professor and Head*, Dept. of SWCE, Tavanur, Kerala for providing his valuable guidance. I am grateful to Kerala Agricultural University for the required funding to acquire the advanced capacitance based sensors and data logger in order to accomplish this study. I would like to present my thanks to Mr. Adarsh S.S for his sincere help during laboratory tests for the calibration of TEROS 12 sensors.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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