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Calibration of two capacitive soil moisture sensors in Ultisol

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Abstract
The objectives of this study were to perform the calibration and determine the calibration equations of two ECH_2O soil moisture sensors, for an Ultisol, collected in the Municipality of Pesqueira-PE located in Brazilian semi-arid region. The study was carried out in 5-liter plastic containers in a protected environment at the Federal Rural University of Pernambuco, Recife-PE, where soil moisture was daily monitored for 51 days from saturation moisture to natural drying. The authors verified that the ECH_2O sensors showed an exponential response to the variation of soil moisture, obtaining $R^2>0.97$. RMSE values ranged from 0.065 to 0.012 $m^3\ m^{-3}$ for the 5TE sensor and from 0.045 to 0.011 $m^3\ m^{-3}$ for the EC-5 sensor. The researchers concluded that the calibration equations obtained were more accurate than the factory equations for that type of soil.

Keywords: capacitance; water content soil probe, 5TE, EC-5.

Calibración de dos sensores capacitivos de humedad en un Ultisol

Resumen
Los objetivos de este estudio fueron realizar la calibración y determinar las ecuaciones de calibración de dos sensores de humedad de suelo ECH_2O para un suelo Ultisol colectado en el Municipio de Pesqueira-PE, localizado en el Semiárido Brasileño. El estudio se llevó a cabo en baldes plásticos de 5 litros implementados en ambiente protegido en la Universidad Federal Rural de Pernambuco, Recife-PE, donde se realizó el monitoreo diario de la humedad del suelo durante 51 días, desde la humedad de saturación hasta el secado natural. Los autores verificaron que los sensores ECH_2O presentaron una respuesta exponencial a la variación de humedad de suelo obteniendo $R^2>0,97$. Valores de RMSE variaron de 0,065 a 0,012 $m^3\ m^{-3}$ para el sensor 5TE y de 0,045 a 0,011 $m^3\ m^{-3}$ para el EC-5. Los investigadores concluyeron que las ecuaciones de calibración obtenidas fueron más precisas que las ecuaciones de fábrica para ese tipo de suelo.

Palabras clave: capacitancia; sonda de humedad del suelo, 5TE, EC-5.

1. Introduction

One of the biggest problems at present is the lack of water, as this resource is becoming increasingly scarce. Likewise, the lack of water for several uses forces the search for alternatives that can contribute to its adequate management. Agriculture is a production sectors that consumes around 70% of the water in the world [1]. Most of this water is used in irrigated crops, and its improper use is causing great economic losses for farmers.

For this reason, monitoring the soil water content is a fundamental technique for various economic activities in agriculture [2]. The control of soil moisture helps farmers to take proper and responsible management of this resource since it allows decisions to be made as to when and how much to irrigate, optimizing the production of their crops, reducing water losses due to runoff and percolation, thus reducing the environmental impacts [3].

There are direct and indirect methods that allow determining the water content in the soil [4,2]. Among the

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direct methods is the gravimetric method, used as a standard method. One of the disadvantages of this method is that, in addition to requiring 24 hours to obtain the results, it is a destructive method, so it cannot be used to take soil moisture measurements in the same site [5,6].

At present, indirect methods are gaining a great deal of space in agriculture, most of these are based on electromagnetic techniques to estimate the water content in the soil in situ, in real time and with acceptable accuracy. Indirect methods are not destructive, which is a great advantage since soil moisture can be estimated in the same place [7-9]. Among the methods for indirectly determining soil moisture, radiometric tests (Neutron Probe), Frequency Domain Reflectometry (FDR), Time Domain Reflectometry (TDR) can be cited [10].

ECH_2Os are among the sensors that measure soil moisture content based on capacitance. This group of sensors measure the apparent dielectric permittivity of the surrounding environment, generally working with a frequency of 70 MHz [11], and include the 5TE and EC-5 models. The 5TE sensor (length = 10.9 cm, width = 3.4 cm, depth = 1.0 cm), in addition to measuring the volumetric soil moisture, it measures temperature and electrical conductivity using capacitance technology [12]. EC-5 is a small sensor (length = 8.9 cm, width = 1.8 cm, depth = 0.7 cm), suitable for use in greenhouses [6], and measures the volumetric soil moisture of the means where it is used, using capacitance [13]. These types of sensors are pre-calibrated at the factory to be used in a wide range of soils, mostly by farmers using the factory calibration equation [14]. However, due to the physical, chemical and biological properties of each soil, it is necessary to perform a specific calibration [15].

The specific calibration of this type of sensor allows reliable volumetric soil moisture data to be obtained [16]. An alternative for calibration is to perform it in representative soils of each sector so that the results of the calibration equations can be extrapolated to soils whose physical and chemical characteristics are similar. This will allow farmers to achieve maximum sensor performance [17] in addition to obtaining soil moisture content readings with greater precision and accuracy.

Due to the need to obtain calibration equations for specific soils, the objective of this work was to perform the calibration of two ECH_2O sensors, 5TE and EC-5 models, for a sandy-textured soil of the Brazilian semi-arid region under controlled conditions and determine a calibration curve for each sensor.

2. Materials and methods

Soil samples were collected in the municipality of Pesqueira, located in the Brazilian semi-arid region, with the following geographical coordinates: 07º 15’ 18’’ S and 35º 52’ 40’’ W, at average altitude of 550 m. The climate of this site was classified as hot semi-arid, BSh, according to Köppen’s climate classification. According to Molinier et al. (1994), this region has an average temperature of 27 °C, relative humidity of 73% and annual precipitation of 670 mm, with highest levels of rainfall in the period from March to April. The present study was carried out in a greenhouse of the Federal Rural University of Pernambuco, in Northeast Brazil.

The soil used in this study was classified as *Planossolo Háplico Sálico Sódico Hipereutrófico* using the Brazilian Soil Classification System [18], corresponding to an Ultisol according to the U.S. Soil Taxonomy. The soil used has a sandy texture, with the following textural composition: 789 g kg^{-1} of sand, 160.5 g kg^{-1} of silt and 50.5g kg^{-1} of clay. Disturbed and undisturbed soil samples were collected at 40 cm depth. The undisturbed soil samples were collected using an Uhland soil sampler in 100-cm^3 steel cylinders (5 cm in diameter by 5 cm in height) and used to determine soil density. Disturbed samples were air dried, pounded to break up clods and sieved through a 4.75-mm mesh. Five 5-L plastic buckets, previously perforated at the base, received one layer of gravel (∅ = 2 cm), covered by a nonwoven textile, and a usable volume of 4.66 L was left, being subsequently filled with soil.

The amount of air-dried soil used in each container in order to maintain soil density (1.43 g cm^{-3}) was 7024 g. Buckets with soil were saturated by capillarity and placed on a bench to allow drainage of excess water and to reach field capacity.

Subsequently, two capacitive sensors, 5TE and EC-5 models from Decagon Devices, were placed in each bucket, which had been previously weighed, installed vertically 0.05 m below the surface, 0.05 m away from the bucket wall and equidistant from each other. Daily weightings and readings of soil moisture were measured at 8:00 a.m. The capacitive sensors estimated the volumetric soil moisture in m^3 m^{-3}, and the readings were taken using a portable data logger for 51 days, when the mass of the set (bucket, gravel, nonwoven textile and soil) became constant.

The volumetric soil moisture was calculated based on the gravimetric soil moisture using Eq. (1):

$$\theta = U \, x \, Ds \tag{1}$$

Where θ is the volumetric soil moisture expressed in m^3 m^{-3}, U is the gravimetric soil moisture expressed in g g^{-1} and Ds is the soil density expressed in g cm^{-3}.

For the linear regression analysis, the volumetric soil moisture measured, Y (m^3 m^{-3}), and estimated by the sensors, X (m^3 m^{-3}), were related. The following statistical indices were used to compare the volumetric soil moisture data measured and estimated by the sensors: coefficient of determination (R^2), root mean squared error (RMSE), calculated by the Eq. (2) defined in the reference [19], and the Willmott’s index of agreement, expressed through Eq. (3) determined by [20]:

$$\mathrm{RMSE}=\sqrt{\left[\frac{\sum_{i=1}^{n}(P_i-O_i)^2}{n}\right]} \tag{2}$$

$$d=1-\left[\frac{\sum_{i=1}^{n}(P_i-O_i)^2}{\sum_{i=1}^{n}\left(|P_i-\bar{O}|+|O_i-\bar{O}|\right)^2}\right] \tag{3}$$

Table 1.
Performance classification according to the value of the "c" coefficient.

Value of "c"	Performance
> 0.85	Excellent
0.76 a 0.85	Very Good
0.66 a 0.75	Good
0.61 a 0.65	Moderate
0.51 a 0.60	Tolerable
0.41 a 0.50	Bad
≤ 0.40	Lousy

Source: [21]

Where n is the number of observations, Oi and Pi are the observed and estimated values, respectively (i = 1, 2,... n), $\overline{O}$ and $\overline{P}$ are the averages of the observed and estimated values, respectively.

The Willmott's index varies between 0 and 1; a value of 1 indicates a perfect match between the measured and estimated values, while 0 indicates no agreement at all between those values [5].

To determine the performance of the proposed methods, the performance index (c) was used according to Eq. (4), proposed by [21].

$$c = \mathrm{r\ x\ d} \tag{4}$$

Where R is the correlation coefficient and d the agreement index. For the interpretation of the coefficient of performance values (Table 1), the classification proposed by [21] was used.

3. Results and discussion

The drying curve shown in Fig. 1 was generated from the measured volumetric soil moisture data generated based on soil density and the calibrated values of volumetric soil moisture obtained from the data estimated by the 5TE and EC-5 sensors.

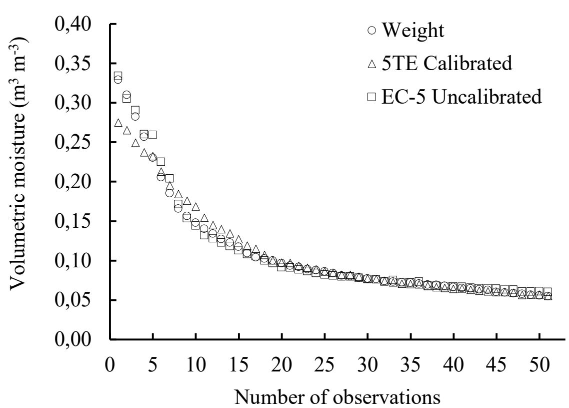

Figure 1. Soil drying curve according to volumetric soil moisture values obtained by gravimetry based on soil density and volumetric soil moisture values obtained using the calibration equations for each sensor during the observation period.
Source: The Authors.

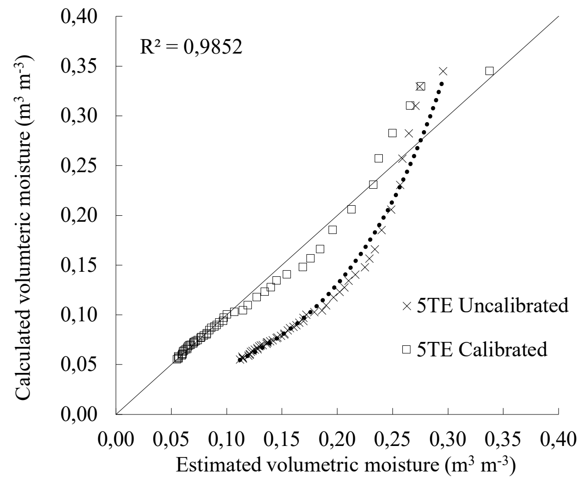

Figure 2. Volumetric soil moisture estimated by the 5TE sensor before and after calibration and its correlation with the calculated volumetric soil moisture.
Source: The Authors.

As shown in Fig. 1, the volumetric soil moisture values corrected with the calibration equation of each sensor are close to those calculated, but the soil moisture values of the 5TE sensor are closer to the curve determined by gravimetry. In the range from 0.33 to 0.08, the EC-5 sensor lost sensitivity, estimating soil moisture readings different from those calculated by gravimetry.

The calibration equation (5) for the 5TE sensor was obtained by measuring the ratio between the average volumetric soil moisture calculated for the five buckets based on soil density and the average volumetric soil moisture after calibration, as shown in Fig. 2.

$$\theta = 0.0181e^{9.8851\theta_{5TE}} \tag{5}$$

Where θ corresponds to the actual volumetric soil moisture expressed in $m^3\ m^{-3}$ and θ_{5TE} is the volumetric soil moisture given by the 5TE sensor according to the factory calibration.

The statistical model that fitted best was the exponential, obtaining a coefficient of determination (R^2) of 0.985.

The volumetric soil moisture values obtained with the 5TE sensor with the factory calibration overestimated the volumetric soil moisture values calculated within the moisture range from 0.11 to 0.26 $m^3\ m^{-3}$ (values located below the 1:1 line). Note that the volumetric soil moisture calculated for these values varied from 0.06 to 0.23 $m^3\ m^{-3}$ (Fig. 2), indicating that there is a need to calibrate the sensor for this type of soil. As mentioned above, the minimum moisture value estimated by the sensor was 0.11 $m^3\ m^{-3}$, which means that, in order to determine the water content in the soil at field capacity, the sensor would not be useful since the value for this soil according to the soil water characteristic curve was 0.096 $m^3\ m^{-3}$; however, when calibrating the sensor, the field capacity value falls within the soil moisture range.

From 0.26 m^3 m^{-3} of moisture, the sensor underestimated the calculated volumetric soil moisture values, where it is clearly noted that the sensor reduced the sensitivity to detect the soil moisture values within that range.

After calibration of the 5TE sensor, it can be seen that the soil moisture values are close to the 1:1 line. However, there was an overestimation in lower intensity within the soil moisture ranges from 0.11 to 0.15 and from 0.20 to 0.23 m^3 m^{-3}, whereas in the range from 0.16 to 0.19 m^3 m^{-3} there was overestimation with greater intensity.

From 0.24 m^3 m^{-3} of moisture, there was dispersion in the values, which shows that for soil moisture greater than this value the 5TE sensor does not work properly, despite being calibrated, showing an underestimation error of 0.0372.

Evaluating the performance of the 5TE sensor in the estimation of the volumetric soil moisture, [22] concluded that for clay-textured soils the sensor requires calibration, showing an estimation error of ± 0.025 m^3 m^{-3}, confirming the results of this study.

On the other hand, the calibration equation (6) of the EC-5 sensor was obtained in the same way as that of 5TE.

$$\theta = 0.0345e^{6.7043\theta_{EC\text{-}5}} \quad (6)$$

The EC-5 sensor showed an exponential response to the variation of soil moisture, as seen in Fig. 3, with a coefficient of determination of 0.991. Studies conducted by [8] corroborate the results for the coefficient of determination of this study.

For the EC-5 sensor, the soil moisture range estimated by it varied from 0.08 to 0.33 m^3 m^{-3} while the calculated volumetric soil moisture range varied from 0.06 to 0.33 m^3 m^{-3} (Fig. 3).

The volumetric soil moisture values determined by means of the factory calibration of the EC-5 sensor were overestimated compared to the calculated volumetric soil moisture values (located below the 1:1 line).

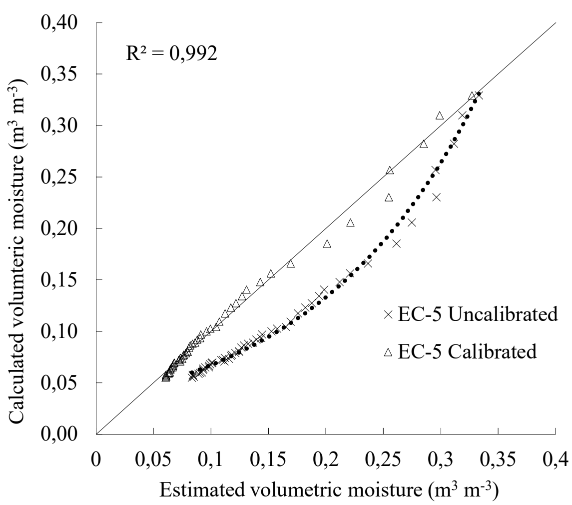

Figure 3. Volumetric soil moisture estimated by the EC-5 sensor before and after calibration and its correlation with the calculated volumetric soil moisture.
Source: The Authors.

Table 2.
Statistical indexes for sensors before and after calibration.

Parameter	5TE		EC-5	
	Factory calibrated	Calibrated	Factory calibrated	Calibrated
RMSE	0,065	0,012	0,045	0,011
Willmott (d)	0,791	0,991	0,914	0,995
Performance (c)	0,785	0,984	0,910	0,991

Source: The Authors.

After calibration of the EC-5 sensor, the soil moisture values approached the 1:1 line, thus the soil moisture values of the ranges from 0.06 to 0.17 and from 0.25 to 0.33 m^3 m^{-3} approached the 1:1 line; however, the soil moisture values that are within the range from 0.20 to 0.25 m^3 m^{-3} were overestimated compared to the calculated soil moisture values, with an estimation error of 0.012.

On the other hand, Table 2 shows that for the 5TE sensor there is a significant difference between the accuracy of the volumetric soil moisture readings before and after calibration, with RMSE values of 0.065 and 0.012 cm^3 cm^{-3}, respectively, varying in the sensor precision scale from poor to moderate according to the classification presented by [23].

Table 2 shows that for the same sensor the values of performance coefficient (c) before and after calibration were 0.785 and 0.984, respectively, varying from very good (factory calibration) to excellent (laboratory calibration) according to the classification of [21]. Likewise, the indices of agreement varied from 0.791 to 0.991 before and after calibration, showing greater accuracy between the volumetric soil moisture values measured and estimated by the 5TE sensor.

Studies carried out by [22] obtained a coefficient of performance of 0.99 after calibration for a soil of sandy clay texture, evaluating a 5TE sensor in the estimation of soil moisture, corroborating the results obtained in the present study, which leads to the conclusion that the calibration applied to this sensor improved soil moisture readings using the calibration equation.

On the other hand, the RMSE for the EC-5 sensor decreased from 0.045 to 0.011 (Table 2). According to the classification of [23], the accuracy of this sensor is classified as moderate and was maintained before and after calibration. Likewise, according to the classification proposed by [21], for the EC-5 sensor the model used was classified as excellent before and after laboratory calibration.

As can be seen, soil moisture can be estimated with reliability after the specific calibration of the EC-5 sensor since it had a fairly high coefficient of determination, corresponding to 0.99.

4. Conclusions

In this study, two calibration equations were determined for the 5TE and EC-5 sensors in a sandy soil that can replace the factory equations, increasing the accuracy of soil moisture readings, contributing to the efficient management of irrigation water and thus contributing to the sustainability of agriculture.

The correlation between the volumetric soil moisture values corrected with the calibration equations obtained and those of the volumetric soil moisture obtained by the standard method was significant, with determination coefficients of 0.98 and 0.99 for the 5TE and EC-5 sensors, respectively.

The RMSE values for the 5TE sensor before and after calibration varied from 0.065 to 0.012 m^3 m^{-3}, respectively, as occurred with the EC-5 sensor, which had a low RMSE value (0.011), showing that these types of sensor promoted better estimation of volumetric soil moisture after being calibrated.

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