Performance Assessment and Calibration of Low-cost Moisture Sensors at Multiple Oxisol Depths

Avaliação de Desempenho e Calibração de Sensores de Umidade de Baixo Custo em Múltiplas Profundidades de Latossolos

Evaluación del rendimiento y calibración de sensores de humedad de bajo costo a múltiples profundidades de Oxisol

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Abstract
Monitoring of soil moisture is a key component in irrigation management and can be carried out with the aid of low-cost electromagnetic sensors. This study aimed to develop calibration equations for the HFM2030 sensor at different depths (0-20; 20-40; 40-60; 60-80; 100 cm) of Oxisols and to assess the accuracy levels of calibration equations used in the continuous monitoring of soil moisture. Reference values of soil moisture content were measured by a standard gravimetric method, converted to volumetric moisture, and then compared with sensor readings to develop calibration equations. The fit of the regression function was evaluated based on the determination coefficient (R^2). The results indicated that the calibration equations were linear at different soil depths. Calibrating the HFM2030 sensor improved the estimate of volumetric water content by 31.21%, 23.46%, 24.93%, 31.93%, and 41.18% in the 0-20, 20-40, 40-60, 60-80 and 80-100 cm layers, respectively. Here, it is demonstrated that the correct calibration of HFM2030 should precede the installation and use of these sensors in the field. The results of this study represent another step toward the development of criteria aiming for greater precision in the use of sensors in irrigation management. The calibration equations developed in this study can be applicable and useful for farmers and researchers working with HFM2030 sensors in similar soil conditions in other regions of Brazil and globally.
Keywords: Calibration function; Electromagnetic sensors; HFM2030 sensor; Soil moisture content; Volumetric water content.

Resumo
O monitoramento da umidade do solo é um componente fundamental no manejo da irrigação e pode ser realizado com o auxílio de sensores eletromagnéticos de baixo custo. Este estudo teve como objetivo desenvolver equações de calibração para o sensor HFM2030 em diferentes profundidades (0-20; 20-40; 40-60; 60-80; 100 cm) de Latossolos e avaliar os níveis de precisão das equações de calibração utilizadas no monitoramento contínuo de umidade do solo. Os valores de referência do teor de umidade do solo foram medidos por um método gravimétrico padrão, convertidos em umidade volumétrica e, em seguida, comparados com as leituras do sensor para desenvolver equações de calibração. O ajuste da função de regressão foi avaliado com base no coeficiente de determinação (R^2). Os resultados indicaram que as equações de calibração foram lineares em diferentes profundidades do solo. A calibração do sensor HFM2030 melhorou a estimativa do teor volumétrico de água em 31,21%, 23,46%, 24,93%, 31,93% e 41,18% nas camadas de 0-20, 20-40, 40-60, 60-80 e 80-100 cm, respectivamente. Aqui, fica demonstrado que a correta calibração do HFM2030 deve anteceder a instalação e uso desses sensores em campo. Os resultados deste estudo representam mais um passo para o desenvolvimento de critérios visando maior precisão no uso de sensores no manejo da irrigação. As equações de calibração desenvolvidas neste estudo podem ser aplicáveis e úteis para agricultores e pesquisadores que trabalham com sensores HFM2030 em condições de solo semelhantes em outras regiões do Brasil e no mundo.
Palavras-chave: Função de calibração; Sensores eletromagnéticos; Sensor HFM2030; Teor de umidade do solo; Conteúdo volumétrico de água.

Resumen
El control de la humedad del suelo es un componente clave en la gestión del riego y se puede llevar a cabo con la ayuda de sensores electromagnéticos de bajo costo. Este estudio tuvo como objetivo desarrollar ecuaciones de calibración para el sensor HFM2030 a diferentes profundidades (0-20; 20-40; 40-60; 60-80; 100 cm) de Oxisoles y evaluar los niveles de precisión de las ecuaciones de calibración utilizadas en el monitoreo continuo. de la humedad del suelo. Los valores de referencia del contenido de humedad del suelo se midieron mediante un método gravimétrico estándar, se convirtieron en humedad volumétrica y luego se compararon con las lecturas del sensor para desarrollar ecuaciones de calibración. El ajuste de la función de regresión se evaluó con base en el coeficiente de determinación (R^2). Los resultados indicaron que las ecuaciones de calibración eran lineales a diferentes profundidades del suelo. La calibración del sensor HFM2030 mejoró la estimación del contenido volumétrico de agua en 31,21%, 23,46%, 24,93%, 31,93% y 41,18% en las capas de 0-20, 20-40, 40-60, 60-80 y 80-100 cm, respectivamente. Aquí, se demuestra que la correcta calibración del HFM2030 debe preceder a la instalación y uso de estos sensores en el campo. Los resultados de este estudio representan un paso más hacia el desarrollo de criterios que apuntan a una mayor precisión en el uso de sensores en la gestión del riego. Las ecuaciones de calibración desarrolladas en este estudio pueden ser aplicables y útiles para agricultores e investigadores que trabajan con sensores HFM2030 en condiciones de suelo similares en otras regiones de Brasil y a nivel mundial.
Palabras clave: Función de calibración; Sensores electromagnéticos; Sensor HFM2030; Contenido de humedad del suelo; Contenido volumétrico de agua.

1. Introduction

Agriculture is the sector with the largest freshwater consumption worldwide (Chen et al., 2018). Therefore, monitoring of soil water content is developing rapidly for different types of soil-plant systems (Vera et al., 2019). This is associated with the fact that soil water content influences the rate of soil water infiltration, runoff, and evapotranspiration, influencing the availability of water for plants (Woodward et al., 2001; Azizan et al., 2019).

Monitoring soil moisture is one of the best and simplest ways to accurately plan water management; for example, irrigation interval, wetting depth, root extraction depth, and wetting adequacy (Hanson et al., 2000; Hedley et al., 2010; Peters et al., 2013). The upper and lower limits of soil moisture are known as field capacity (FC) and permanent wilting point (PWP), respectively. In FC, the soil retains sufficient amounts of water and air to provide optimal plant growth. Thus, FC corresponds to the amount of moisture in the soil after the latter has been completely moistened and drained freely. On the other hand, PWP corresponds to the amount of moisture in soil at which plants begin to wither and are unable to recover with subsequent watering.

Readily-available soil moisture is critical for plant growth and development and depends on physical properties of the soil and meteorological conditions of the local environment (Nagahage et al., 2019). However, the readily-available moisture content varies across soil profiles due to differences in transpiration and moisture loss, even in controlled environments

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(Kramer and Boyer, 1995).

Several techniques are used to estimate soil water content (SWC), such as the destructive gravimetric method, electromagnetic sensors, tensiometers, heat pulses, and optical fiber hygrometers, in addition to remote sensing (Zazueta and Xin, 1994; Sui, 2017). Among them, time-domain reflectometry (TDR), time-domain transmission (TDT), and capacitance sensors are the most commonly used to estimate soil moisture levels using electromagnetic techniques (Bogena et al., 2017; Vaz et al., 2013).

TDR and TDT sensors are accurate; however, their applicability on large scales is limited owing to their high cost (Nagahage et al., 2019). On the other hand, lower-cost sensors such as HFM2030 Ltd. have been developed and are commercially available for field water management. This sensor uses the principle of high-frequency soil impedance (HFSI) as an electromagnetic measure to determine volumetric moisture, thereby providing real-time moisture data (Falker, 2018).

Although they have a lower cost, soil water measuring devices such as HFM2030 perform with the same accuracy throughout multiple depths of soil. Currently, there are no calibration equations for HFM2030 sensors at different depths in the soil. Calibration procedures are necessary because the accuracy of measurement performed by these sensors can be affected by factors such as soil temperature and electrical conductivity (EC), the type and content of clay, salinity, and soil porosity (Bittelli, 2011; Evett et al., 2012).

Several studies have reported the importance of estimating soil moisture for monitoring and management of irrigation. Dobryal et al. (2012) stated that soil moisture is important for nutrient cycling and is a prerequisite for metabolic activities and primary production by plants. Studies have indicated that reduction in available soil moisture restricts transpiration and photosynthesis of plants, with consequent impacts on water, energy, and biogeochemical cycles (Moradkhani, 2008; Ni-Meister, 2008; Seneviratne et al., 2010). Other studies have indicated that plants have greater difficulty in extracting water (Wang et al., 2012). Additionally, prolonged water stress has been reported to negatively affect crop rooting, with prolonged exposure of roots to drought conditions, causing anatomical changes to roots (Norte and Nobel, 1991).

These situations demand methodologies and tools to guide decision making in irrigation management, aiming at greater efficiency in the use of fresh water in agricultural production. Thus, some studies have focused on the calibration of low-cost sensors used to measure water content in the field, aiming to develop low-cost automated irrigation systems, while others have considered the effects of the physical and chemical properties of soil on the performance of soil moisture sensors (Cardenas-Lailhacar et al., 2015; Fares et al., 2016; Ferrarezi et al., 2015).

Thus, this study aimed to develop a calibration function for the low-cost sensor HFM2030 based on a comparison of sensor readings with the standard gravimetric method at different depths of an Oxisol.

2. Materials and Methods

2.1 Specifications of HFM2030 sensor

HFM2030 is a soil moisture sensor employing an electromagnetic principle that has the capacity to measure a volume of 15 cm in radius and 20 cm in depth. This sensor estimates the volumetric humidity (m^{-3} m^{-3}), with output reading in percentages (%), from the emission of electromagnetic waves, using a technology termed HFSI. The HFM2030 sensor is an intermediate technology between capacitive and TDR sensors, having a better cost-benefit ratio in relation to such sensors (Falker Ltd, 2018).

The active area of the HFM2030 sensors was designed to be completely buried in the soil under analysis and is connected to a datalogger (Figure 1) for data transmission. This sensor can operate at temperatures from 0°C to 50°C, are easy to install, and can be deployed in all irrigation systems, providing continuous measurements of soil moisture content.

Additionally, HFM2030 sensors are wireless-compatible, which facilitates communication via the Internet, in addition to ensuring remote access.

Figure 1. Illustration of a datalogger and HFM2030 sensor.

Source: Authors (2022).

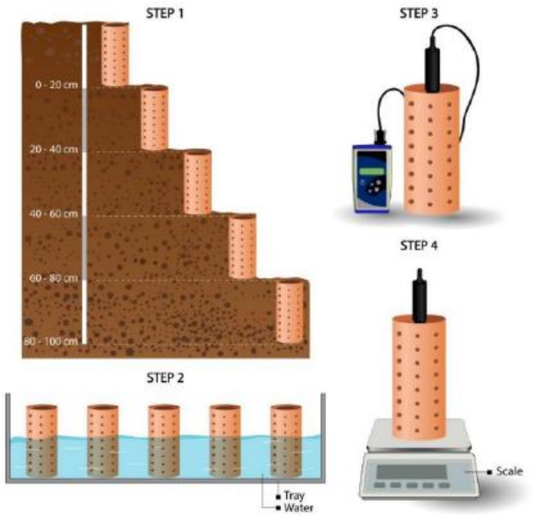
2.2 Procedures in Soil Sampling

Undisturbed soil samples were collected from three trenches (50 × 50 cm and 1 m deep) from Oxisols. Samples were taken at depths of 0–20, 20–40, 40–60, 60–80, and 80–100 cm, and then collected in cylindrical PVC tubes 10 cm in diameter and 30 cm in height. The cylinders were previously drilled with holes that allowed the escape of water, but not soil loss (Gava et al., 2016). Three replicates were collected at each depth, totaling 15 samples.

The soil was saturated at the sampling site to facilitate the complete immersion of the PVC tubes and the removal of samples without causing their disaggregation. For sampling, one end of the PVC tubes was inserted into the face of the previously opened soil profile. This was done with the aid of a 5 kg mallet and the positioning of rubber plates on top of the tubes, enabling the removal of undisturbed samples. Each end of the tubes was protected with a plastic wrap to facilitate transport from the field to the laboratory.

In the laboratory, the PVC tubes containing soil were saturated again by means of gradual elevation, with a water depth equivalent to 2/3 of the height of the samples for 24 h. After this, the samples were drained for 48 h until the FC was reached at a water depth of 5 cm. This procedure was adapted from the standard gravimetric method for undisturbed samples (Figure 2) and was performed with the samples completely sealed with plastic film to prevent water loss by evaporation.

Figure 2. Diagram showing the workflow for calibration of HFM2030 sensors.



Step 1: collection of undisturbed soil samples at depths of 0–20, 20–40, 40–60, 60–80 and 80–100 cm. **Step 2**: undisturbed soil samples saturated by gradual elevation of water depth for 24 hours. **Step 3**: insertion of the HFM2030 sensor into each tube containing soil, followed by daily measurements carried out three times throughout the day (8 AM, 1 PM and 6 PM). **Step 4**: weighing of soil samples, immediately after measurement using HFM2030 sensors in order to obtain actual gravimetric moisture measurements. Source: Authors (2022).

2.3 Measurement, Calibration and Validation

After saturating the soil samples in the laboratory, an HFM2030 sensor was inserted into each sample, which was then transported to a room with constant temperature and humidity conditions of 20°C and 50%, respectively. Probe readings were recorded daily, three times a day (8:00 AM, 1:00 PM, and 6:00 PM). After recording the moisture readings, the PVC tubes containing soil samples were weighed to obtain the real gravimetric moisture (θ_g), according to Equation 1. It was possible to estimate the volumetric moisture of soil samples on a dry basis (θ_v), according to Equation 2. After evaluating the moisture content, estimates of soil sample density were obtained (Equation 3), and the samples were dried for 72 h.

$$\theta_g = M_w - M_s / M_s * 100 \quad (1)$$

where θ_g represents gravimetric moisture, M_u is the mass of water, M_s is the dry mass of soil (g), and 100 is the conversion factor (dimensionless).

$$\theta_v = \theta_g * ds \quad (2)$$

where θ_v represents the volumetric moisture (cm^{-3} cm^{-3}), θ_g is the gravimetric moisture (%), and ds is the soil density (g cm^{-3}).

$$ds = M_s / Vs \quad (3)$$

where ds represents the soil density (g cm^{-3}), M_s is the dry mass of soil (g), and Vs is the soil volume in the PVC tubes (cm^{-3}).

Undisturbed soil samples were taken at the same depths sampled with the PVC tubes; for this, a 5.1 cm diameter soil sampler was used. Soil water retention was measured using the method described by Wang and Benson (2004), and the data were fitted to Van Genuchten's (1980) soil water retention model, as per Equation 4.

$$\theta = (\theta_s - \theta_r)\,[1 + (\alpha h)^n]^{-m} + \theta r \qquad (4)$$

where θ_s represents the saturation moisture, θr is the residual moisture at -1500 kPa, h is the pressure applied, and α, n, and m are adjustment parameters. This equation assumes the restriction m = 1-1/n.

The water content based on weight (gravimetric method) was plotted against readings of the HFM2030 sensors in order to obtain calibration equations for different soil depths. The fit of the regression functions was evaluated based on the determination coefficient (R^2). The consideration of R^2 was aimed at avoiding overfitting effects (Bello, et al 2019).

2.4 Statistical analysis

Calibration equations and Pearson's correlation coefficient were tested using R software, version 4.0.3 (R Core Team, 2020). The performance of the equations before and after calibration was evaluated based on the estimation of the standard error (SEE), calculated according to Equation 5, proposed by Allen (1986). The performance analysis of each method was based on the parameters of the simple linear regression equation (a and b), the coefficient of determination (R^2), agreement index (d) (Willmott, et al. (1985), (Equation 6); and performance index (c), obtained by multiplying the correlation coefficient (r) by d, Camargo and Sentelha (1997).

$$SEE = [(\sum(\theta_v - \theta_{SF})^2/n\text{-}1)]^{0.5} \qquad (5)$$

where SEE represents the estimate of standard error (m^3 m^{-3}), θ_v is the volumetric moisture estimated by the standard gravimetric method (m^3 m^{-3}), θ_{SF} is the estimate of volumetric moisture obtained by HFM2030 (m^3 m^{-3}), and n represents the number of observations.

$$d = [\textstyle\sum^n_{i=1}(Pi - Oi^2)] \,/\, \textstyle\sum^n_{i=1} [(\,|\theta_{SF\,-\,\bar{O}}|\,) + (\,|\theta_{v\,-\,\bar{O}}|\,)]^2 \qquad (6)$$

Where d represents the agreement or fit index, Pi is reference evapotranspiration obtained by the method considered, mm day^{-1}, Oi is reference evapotranspiration obtained by the standard method, mm day^{-1}, θ_{SF} is the estimate of volumetric moisture obtained by the HFM2030 (m^3 m^{-3}), θ_v is the estimate of volumetric moisture estimated by the standard gravimetric method (m^3 m^{-3}), and Ō represents the average of moisture content obtained by the standard gravimetric method (m^3 m^{-3}).

3. Results and Discussion

3.1 Physical and hydric properties of soil

The physical and hydric properties of the soil, as well as characteristics of the PVC tubes, are listed in Table 1. Higher clay contents were found in the 40-60 cm layer, representing 77.5% of the soil fraction at these depths. In a previous study, the clay in this soil was described as having low activity and was dominated by kaolinite and gibbsite, in addition to the iron oxides goethite and hematite (Muggler, Buurman and Van Doesburg, 2007). Soil density ranged from 1.08 to 1.26 g cm^{-3}, with higher densities in the upper layers and a reduction in densities as soil depth increased. The microporosity in the layers below 40 cm was 10.6% higher, while in the layers 0-20 and 20-40 cm it was 12.8% higher. In contrast, macroporosity was higher in the 0-20 and 20-40 cm layers than in the other layers.

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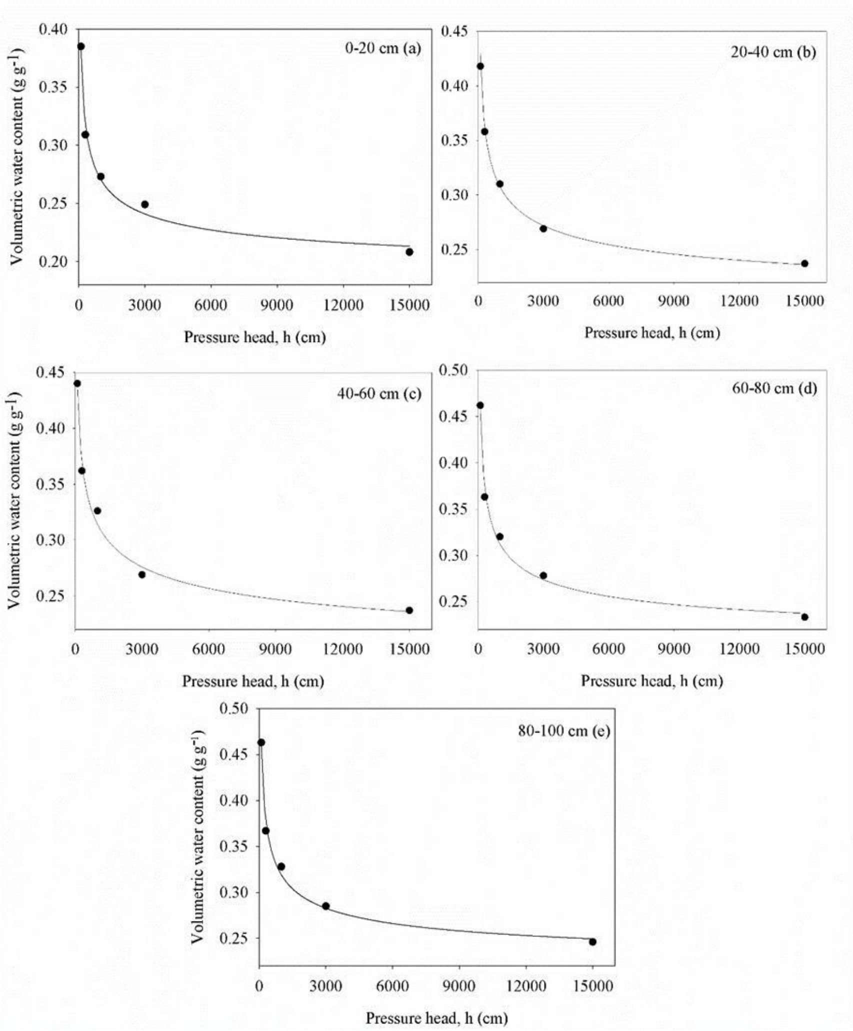
Table 1. Physical and hydric properties of soil at different depths and characteristics of PVC tubes.

Depth (cm)	Sand Total (%)	Silt (%)	Clay (%)	Mi (m^{-3} m^{-3})	Ma (m^{-3} m^{-3})	H (cm)	D (cm)	Ms (kg)	Ds (g cm^{-3})
0-20	32.2	10.4	57.4	0.42	0.07	27.83	10.5	3.01	1.25
20-40	17.6	11.2	71.2	0.41	0.11	27.57	10.5	3.00	1.26
40-60	12.6	9.9	77.5	0.47	0.04	27.00	10.5	2.82	1.21
60-80	13.9	8,7	77.4	0.47	0.04	24.97	10.5	2.53	1.16
80-100	14.3	9.5	76.2	0.47	0.03	25.30	10.5	2.38	1.08

Mi = microporosity, Ma = macroporosity, H = soil height inside the PVC tubes, D = soil diameter inside the PVC tubes, Ms = dry mass of soil, and Ds = soil density. Source: Authors (2022).

The water retention capacity of each soil layer is presented in Figure 3, and the optimal adjustment parameters for each curve are shown in Table 2. These results suggested that soil water retention increased at greater depths, stabilizing from 60 cm.

Figure 3. Water retention curves for different soil layers.



Source: Authors (2022).

There was an increase in water saturation as the depth in the soil profile increased from 0.523 g g^{-1} (20-40 cm) to 1.205 and 1.198 g g^{-1} in 60-80 and 80-100 cm strata, respectively (Table 2). These results can be explained by differences in the distribution of pore sizes along the soil profile, which demonstrated the predominance of macropores in superficial layers and the predominance of micropores in subsurface layers. With a smaller diameter, micropores have a greater capacity to resist water loss compared to macropores, so that water retention under low pressure values increases as the soil depth increases.

The α parameter represents the suction required to initiate the release of moisture and the speed at which moisture is released as the suction increases (Ankenbauer and Loheide, 2017), as shown in Table 2. Thus, the high values of α indicate rapid changes in water content, while low values indicate a slight change in water content as the pressure becomes more negative. The observation of higher values for α at 0-20, 40-60, 60-80 and 80-100 cm indicates that these layers have more stable particle structures, probably associated with higher levels of organic matter (layers 0–20) and clay (other layers). On the other hand, the lower value of α corresponding to the 20-40 cm layer indicates that this depth would require greater pressure (> -10 kPa) to clean pores with diameters between 0.15 and 0.03 mm (Lima et al., 2014). With this, it is possible to infer that there exists some restriction in the 20-40 cm layer in the analyzed soil profile.

Table 2. Estimates of water retention curve parameters at different soil depths, according to the Van Genuchten model.

Depth (cm)	θr	θs	α	n	R^2
0-20	0,17414	0,98229	0,58499	1,33391	0,989
20-40	0,17463	0,52315	0,02996	1,28382	0,999
40-60	0,15587	0,95097	0,61498	1,25136	0,990
60-80	0,18619	1,20583	0,52250	1,33387	0,992
80-100	0,20559	1,19896	0,49028	1,35031	0,991

θr = water gravimetric content (g g^{-1}) at a matrix potential of -1500 kPa, θs is the gravimetric water content in the saturated sample (g g^{-1}), α and n are the adjustment parameters of the model, and R^2 is the determination coefficient. Source: Authors (2022).

Knowing the physical and hydric properties of soil is essential for monitoring soil water, especially when irrigation management is carried out through the use of sensors, because aspects such as density, clay content, porosity, and salinity directly influence the storage and retention of water in soil (Lukanu and Savage 2006). Therefore, it is reasonable to state that the readings provided by the sensors may vary depending on the soil conditions. This is due to the relative permittivity (~ 3-5) and the air content in soil pores (~ 1) is much lower than the water content (~80), where the relative permittivity is highly dependent on the content of soil moisture (Parvin and Degré, 2016). Thus, our results suggested that calibration of sensors for monitoring water in irrigation management should also consider different soil depths and not just the different types of soil, as has generally been done in other studies.

3.2 Measurement of soil water content by the gravimetric method and from sensors

Table 3 shows the variation between the first and last readings of soil moisture measured by the direct method (on a gravimetric basis), as well as soil moisture estimates provided by sensors in the different soil layers. The gravimetric content was converted to the volumetric water content. The standard deviation (SD) of volumetric water content ranged between 0.03 and 0.08, considering all soil depths. This showed that variability in soil water loss during the period evaluated was low for all depths. The range of volumetric soil water content, measured by the direct method at the beginning of the measurements in the 0–20 cm layer was 0.47 m^3 m^{-3}, while in the 80–100 cm layer it was 0.51 m^3 m^{-3}. This confirmed the efficiency of the methodology used to promote a uniform distribution of water in the soil core during the wetting process.

Table 3. Direct (gravimetric) and indirect (HFM2030 sensors) measurements of soil water at different soil depths.

Depth	Gravimetric measurement		HFM2030 sensors	
	(θv, $m^3\ m^{-3}$)	SD[a]	(θv, $m^3\ m^{-3}$)	SD[a]
0-20 cm	0.47–0.34	0.03	0.34–0.21	0.04
20-40 cm	0.50–0.37	0.03	0.40–0.25	0.04
40-60 cm	0.54–0.39	0.04	0.47–0.22	0.08
60-80 cm	0.52–0.37	0.04	0.36–0.24	0.03
80-100 cm	0.51–0.34	0.05	0.34–0.17	0.05

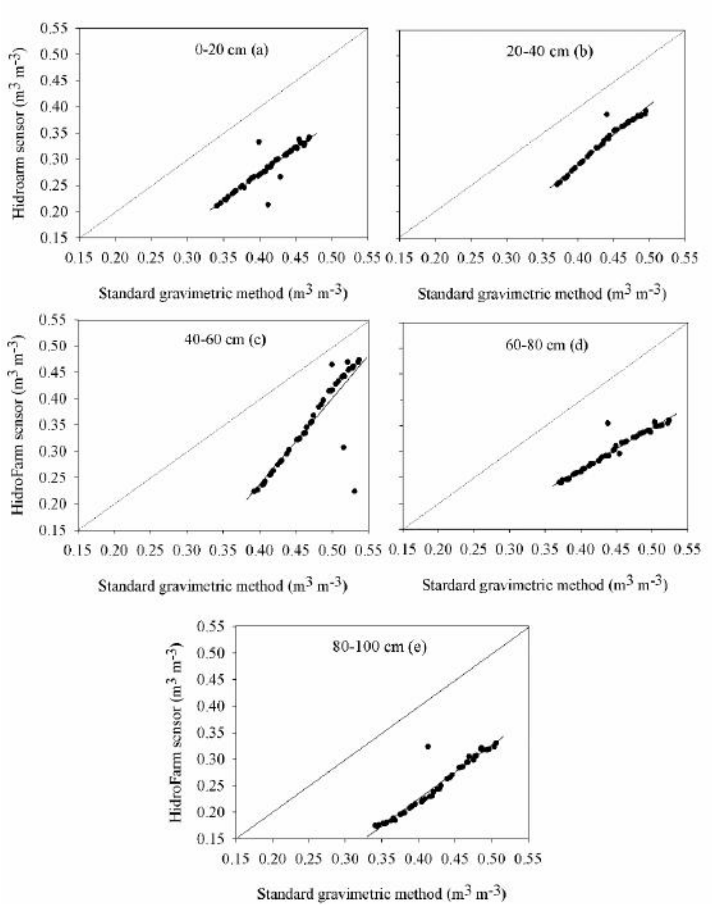
[a] SD = mean standard deviation of all readings at the different soil depths. Source: Authors (2022).

The consideration of soil structure in the calibration of soil moisture sensors represents an advance in the present study. Soil samples were obtained without disturbing aspects such as density and structure, thus corresponding to the natural conditions of the soil. Additionally, the orifices in the PVC tubes used to collect the soil samples were uniform in terms of size and spacing. This ensured that water loss in the soil samples and sensor reading radius measurements were carried out uniformly, providing accurate estimates of the moisture content in the samples. In this context, Bello et al. (2019) adopted similar procedures in the calibration of capacitance probes, obtaining satisfactory calibration results in terms of high coefficients of determination (R^2) for different types of soil. A study by Bello et al. (2019) demonstrated the importance of capacitance probe calibration for each location when calibration equations were applied in irrigation management. These results show the importance of considering soil texture in the calibration of capacitance probes, corroborating the results of the present study in which the adjustments resulted in different calibration equations for each depth of the soil profile.

3.3 Calibration of soil moisture sensors

Relationships involving volumetric soil water content determinations obtained by the standard gravimetric method and by sensor readings were plotted to obtain the calibration equations (Figure 4). Data were also subjected to Pearson's correlation test ($p \leq 0.05$). Statistically significant correlations were verified at all depths of the soil profile. Despite the significance of correlation and the high value of such correlation coefficients, the HFM2030 sensors underestimated the soil water content by 31.21, 23.46, 24.93, 31.93, and 41.18% in the 0-20, 20-40, 40-60, 60-80 and 80-100 cm layers, respectively. These results corroborate the findings of Bello et al. (2019). These authors reported that capacitance sensors also underestimated the volumetric water content of clayey soil types and attributed this to the delay of sensors in responding to changes in the soil volumetric water content.

Figure 4. Relation between the real volumetric moisture of soil obtained based on the standard gravimetric method, and volumetric moisture measured by HFM2030 sensors.



Source: Authors (2022).

The calibration equations for each soil depth are presented in Table 4. These equations were used to adjust the sensor readings at each depth of the soil profile.

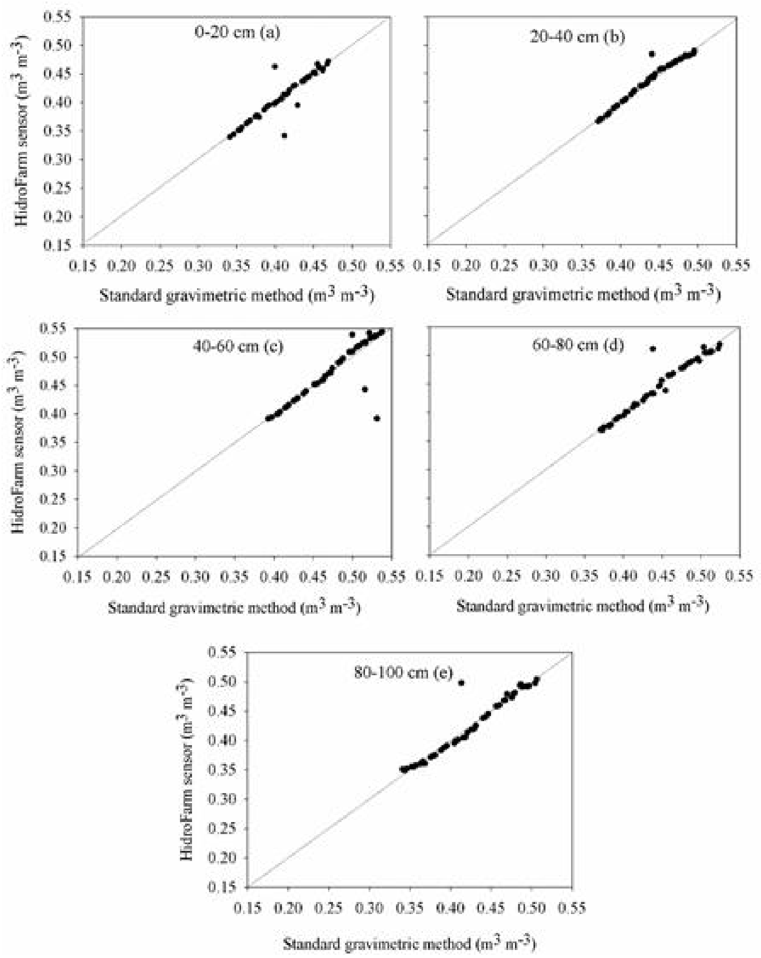
Table 4. Adjustment equations estimated based on the relationship between the real volumetric moisture, obtained based on the standard gravimetric method, and the volumetric moisture measured by HFM2030 sensors.

Soil depth (cm)	Classification	Equations	r^2	*p* value
0 – 20	Linear	θv real = (θv sonda + 0,1243) / 0,9880	0,86	$2,2e^{-16}$
20 – 40	Linear	θv real = (θv sonda + 0,1661 / 1,1440	0,96	$2,2e^{-16}$
40 – 60	Linear	θv real = (θv sonda + 0,4183) / 1,6386	0,75	$1,29e^{-16}$
60 – 80	Linear	θv real = (θv sonda + 0,0555) / 0,8022	0,94	$2,2e^{-16}$
80 – 100	Linear	θv real = (θv sonda + 0,1806) / 1,0138	0,94	$2,2e^{-16}$

Source: Authors (2022).

The relationship between estimates of real volumetric moisture, obtained based on the standard gravimetric method, and the volumetric moisture measured by the sensor after adjustments are shown in Figure 5.

Figure 5. Relationship between the estimate of real volumetric moisture, obtained based on the standard gravimetric method, and the volumetric moisture measured by the sensor after adjustments



Source: Authors (2022).

After adjustments, estimates of soil moisture obtained from HFM2030 sensors revealed a linear distribution with low dispersion over the 1:1 line at all soil depths. This indicates that soil moisture estimates using HFM2030 and corrected by calibration equations are highly correlated with the standard gravimetric method.

The results obtained in this study confirmed the particularity and importance of calibrating HFM2030 sensors for each location where they will be used to assist in irrigation management or monitoring of moisture along soil profiles after irrigation. The results obtained in this study provide greater accuracy because the calibration equations developed based on data obtained in the laboratory usually perform better than those developed from data collected in the field (Kinzli et al., 2012). This is supported by strict control in ensuring that moisture loss of the soil samples was equal during experiments, as already shown. Here, in addition, temperature and humidity control were maintained while conducting experiments in the laboratory. Corroborating the results obtained in this study, Gabriel et al. (2010) described greater pertinence in adopting calibration equations developed from data collected in the laboratory, with the aim of reducing errors in estimates of soil water content in the field. In accord with this, the results of Kinzli et al. (2012) revealed greater errors in calibration equations obtained from field data, attributing such results to greater difficulty in ensuring homogeneous conditions in the field.

3.4 Adjustment validation of soil moisture sensors

Data analysis for validating sensor readings before and after adjustment is presented in Table 5. Because the main purpose of this study was to develop calibration equations for estimating moisture along soil profiles, specific statistical parameters were employed to validate such adjustments made using the equations. This was aimed at optimizing the estimation of volumetric water content as measured by sensors. According to Willmott et al. (1985), the precision of a method can be measured by the agreement index “d”; in this case, the closer to 1 the values of this parameter are, the better the agreement between the measured and predicted values. Camargo and Sentelha (1997) reported that the performance of a method can be measured by the performance index “c,” which is obtained by multiplying the agreement index “d” by the precision index “r”; in this case, higher values of “c” represent greater adjustment. Therefore, this study considered the best alternative to the one with the highest value of "c,” the lowest EEP and with "d" close to 1.

The values of the equation parameters (*a* and *b*), determination coefficient (r^2) and correlation (r), estimation of the standard error (SEP), agreement index (d), confidence or performance index (c), as well as moisture average (θm), before and after adjustments, are presented in Table 5.

The results obtained before adjustment demonstrated that HFM2030 sensors underestimated the soil moisture at all soil depths. Thus, based on performance indices, moisture readings from different depths were classified as “Bad” (c = 0.41–0.50) at 0–20 cm, and as “Poor” (c ≤ 0.40), at other depths. This highlights the poor reliability of sensor moisture estimates without specific adjustments.

After adjustments, there was an improvement in the parameters of the calibration equations, particularly in terms of average moisture, equating moisture estimated by the sensor with soil moisture estimates obtained from the standard gravimetric method. Good agreement was observed between the actual volumetric water content and the content estimated by the sensors after calibration, which was associated with a high level of agreement (d) in all soil layers.

The highest agreement index (d) corresponded to the 20-40 cm layer, with 0.99, while the lowest index corresponded to the 40-60 cm layer at 0.92. The values of performance index “c,” after adjustment, ranged from 0.80 to 0.97 for the 20-40 and 40-60 cm layers, respectively. With this, these values could be classified as "very good" (c = 0.76-0.85) in the 20-40 cm layer and "Excellent" (c > 0.85) at the other depths, according to the classification described by Camargo and Sentelha (1997).

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Table 5. Regression parameters and average humidity (θm m^3 m^{-3}) measured by HFM2030 sensors, without calibration, compared to the standard gravimetric method Regression parameters (a and b), determination coefficient (r2), estimation of standard error (EES), correlation coefficient (r), agreement index (d), confidence or performance index (c), and classification (Classi).

Soil depth		a	b	r^2	SEE	r	d*	c**	Classi**	θ_m
0 – 20 cm										
Not adjusted	θ_v									0.41
	θ_{SF}	0.988	-0.124	0.8545	0.132	0.92	0.395	0.338	Poor	0.29
Adjusted	θ_v									0.41
	θ_{SF}	1.000	$-1.48e^{-5}$	0.8545	0.015	0.92	0.960	0.887	Excellent	0.41
20 – 40 cm										
Not adjusted	θ_v									0.44
	θ_{SF}	1.144	-0.166	0.9616	0.104	0.98	0.492	0.482	Bad	0.34
Adjusted	θ_v									0.44
	θ_{SF}	1.000	$1.91e^{-5}$	0.9616	0.008	0.98	0.990	0.971	Excellent	0.44
40 – 60 cm										
Not adjusted	θ_v									0.48
	θ_{SF}	1.639	0.418	0.7522	0.127	0.87	0.507	0.440	Bad	0.36
Adjusted	θ_v									0.48
	θ_{SF}	1.000	$2.47e^{-5}$	0.7522	0.026	0.87	0.928	0.805	Very god	0.48
60 – 80 cm										
Not adjusted	θ_v									0.45
	θ_{SF}	0.802	-0.056	0.9382	0.146	0.97	0.425	0.412	Bad	0.31
Adjusted	θ_v									0.45
	θ_{SF}	1.000	$1.93e^{-5}$	0.9382	0.012	0.97	0.984	0.953	Excellent	0.45
80 – 100 cm										
Not adjusted	θ_v									0.43
	θ_{SF}	1.014	-0.181	0.9297	0.177	0.96	0.400	0.386	Poor	0.25
Adjusted	θ_v									0.43
	θ_{SF}	1.000	$2.80e^{-5}$	0.9297	0.014	0.96	0.982	0.946	Excellent	0.43

*Willmott, et al. (1985); **Camargo & Sentelha (1997). Source: Authors (2022).

This study demonstrated that the calibration equations had contrasting adjustments between different soil layers, highlighting the need to calibrate HFM2030 sensors for each specific situation. Therefore, the correct calibration of HFM2030 sensors must precede their use in the field in order to reduce errors in estimating soil moisture. Additionally, the HFM2030 sensor costs US$150.04, which is considerably lower than the cost of sensors such as TDR, with an average cost of US$2,295.00. Thus, it is crucial to explore sensor responses and the overall reliability of their reading from comparisons based on reference methods, as this can demonstrate the relevance of soil and the need for specific sensor calibration in capturing sorption and desorption of moisture. This is even more relevant when irrigation schedules are based on real-time soil moisture data obtained from sensors configured *in situ* (Hajdu et al., 2019).

There is a limitation in obtaining a wide range of volumetric water content determinations in soil profiles during the calibration process (Geesing et al., 2004), similar to the results obtained in the present study. This was achieved by rigorous monitoring of soil weight loss. This weight loss was converted to volumetric water content, which helped to bypass limitations inherent to field conditions. In this sense, it is pertinent to emphasize that the calibration of soil moisture sensors under controlled conditions in the laboratory represents an advance in the reliability of these sensors (Fares et al., 2004; Polyakov et al., 2005).

4. Conclusion

The HFM2030 sensor underestimated the volumetric soil water content at all soil depths prior to adjustment. Calibrating the equations for the HFM2030 readings was efficient in adjusting soil moisture values in relation to the standard gravimetric method at different depths of Oxisols. After the adjustment, the data measured by HFM2030 were linearly positioned on a 1:1 line, providing adjustments classified as good and excellent. However, considering that the study was carried out under a highly controlled condition, future studies are necessary for the implementation of generalist criteria, this is because the different soil layers may have different soil compaction, and what more important, different salinity, that may interfere in sensor reading. It is necessary to calibrate HFM2030 sensors for each specific installation site, as the individual properties of each soil layer influence the efficiency of the sensor.

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