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CALIBRATION AND ACCURACY OF TWO ELECTROMAGNETIC METHODS OF SOIL MOISTURE MEASUREMENT IN OXISOL

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1 ABSTRACT

Accurately measuring soil moisture is an important technological challenge. Sensors development and validation for agricultural applications is a relevant research theme. Electromagnetic techniques have been shown to be useful for soil moisture measurement. However, these techniques typically benefit from calibration. In this context, the aim of this study was to calibrate and evaluate the accuracy and precision of the soil moisture measured by two devices with different electromagnetic principles: Frequency Domain Reflectometry (FDR) e High Frequency Soil Impedance (HFSI) in the laboratory with in oxisol. The probes used were Diviner 2000 and Hidrofarm HFM 1010. Soil moisture was measured using both FDR and HFSI probes. A large variation in soil moisture values occurred during the experiment, as it varied from 0.489 m^3 m^{-3} to 0.077 m^3 m^{-3}. Both electromagnetic methods showed good correlation compared to the standard method (gravimetric). HFSI probe overestimated the soil moisture values when compared to the gravimetric method, while FDR underestimated the values.

Keywords: capacitance probes, HFSI sensor, FDR sensor, high frequency soil impedance.

SILVA, A. L. B. O.; PIRES, R. C. M.; OHASHI, A. Y. P.; PAVÃO, G. C.; BLAIN, G. C. CALIBRAÇÃO E PRECISÃO DE DOIS MÉTODOS ELETROMAGNÉTICOS DE MEDIÇÃO DE UMIDADE DO SOLO EM OXISOL

2 RESUMO

Medir a umidade do solo com precisão é um importante desafio. O desenvolvimento e validação de sensores para aplicações agrícolas é um tema de pesquisa relevante. As técnicas eletromagnéticas demonstraram ser úteis para a medição da umidade do solo. No entanto, essas técnicas geralmente se beneficiam da calibração. Nesse contexto, o objetivo deste estudo foi

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calibrar e avaliar a exatidão e precisão da umidade do solo, medida por dois dispositivos com diferentes princípios eletromagnéticos: Reflectometria no Domínio da Frequência (FDR) e Impedância do Solo de Alta Frequência (HFSI) em laboratório em latossolo. As sondas utilizadas foram Diviner 2000 e Hydrofarm HFM 1010. A umidade do solo foi medida usando as sondas FDR e HFSI. Houve uma grande variação nos valores de umidade do solo durante o experimento, de 0,489 m^3 m^{-3} a 0,077 m^3 m^{-3}. Ambos os métodos eletromagnéticos mostraram boa correlação em comparação com o método padrão (gravimétrico). A sonda HFSI superestimou os valores de umidade do solo quando comparada ao método gravimétrico, enquanto a FDR subestimou os valores.

Palavras-chave: sondas de capacitância, sensor HFSI, sensor FDR, impedância do solo em alta frequência.

3 INTRODUCTION

Water and soil are essential resources for agriculture. The water availability is critical for plant growth and development. Whether they are for human, industrial or agricultural purposes, water resources are scarce and there is an increase of water use (FAO, 2013). Water resources management has become an important issue for society and agribusiness since it is directly related to the productivity and quality of the productive chain. Therefore, it is necessary to plan the efficient use of water to promote the development of methodologies and techniques that make it possible to estimate more accurately the water content in the soil, thus obtaining better crop results. (Evett et al., 2012). The SWC estimation is an important tool for crop management to minimize losses of water and nutrients by leaching in the soil profile and consequently to promote environmental sustainability (Soto et al., 2014). Thus, the use of SWC estimation methods to improve water use efficiency and reduce energy consumption is relevant for modern agriculture (Paraskevas et al., 2012; Haberland et al., 2015). Nowadays, there are several methods to estimate SWC, classified as either direct or indirect methods (Chávez & Varble, 2011).

The gravimetric is a direct measure of soil moisture and it is considered the standard method, in which soil samples are taken to the laboratory to measure their wet and dry mass. Thus, it is a laborious technique that does not allow sampling and measuring at the same place (Paraskevas et al., 2012). Gravimetry is used for calibration of indirect methods, in which SWC can be monitored continuously in the same site and decreases soil disturbance. The most widespread indirect methods are based on soil dielectric constant, neutron moderation, electrical resistivity and thermal conductivity (Paraskevas et al, 2012). Among the indirect methods based on the dielectric constant of the soil, the main techniques are Reflectometry in Frequency Domain (FDR), Time Domain Reflectometry (TDR) and Time Domain Transmissivity (TDT).

The capacitance probes and their sensors consist of a pair of electrodes or conductive metal plates, which are arranged in parallel, with insulating material separating the plates, thus forming a capacitor. The capacitance increases with increasing number of free water molecules and with dipoles responding to the electric field created by the capacitor. The Sentek® Diviner 2000 probe stands out among the other FDR sensors because it allows the reading of soil moisture at different depths, does not use radioactive source, monitors several points for the portable characteristic, among other factors

(Haberland et al., 2015). Another equipment that uses electromagnetic principle for indirect SWC measurements by reading the high frequency soil impedance (HFSI) was developed by Falker, which is denominated Hidrofarm (HF-1100)®[1]. It is considered an economical and interesting alternative and allows reading the soil water content, with average values of the soil surface layer (0 m) up to 0.2 m Depth (Hidrofarm, 2012; Gomes et al., 2013).

The HFSI probe is a device developed recently, therefore, requires more information about calibration and performance in different soils. Thus, performing laboratory calibration with the soil of the location where the sensors will be used can improve their accuracy. (Souza et al., 2013). In addition, the adoption of more rigorous index indices may improve the calibration data adjustments of both FDR and HFSI probes.

Some parameters must be taken into account to choose the best method to be used, because there are limitations of application related to labor, costs, accuracy and precision of the measured values. The main limitation reported in the literature is related to moisture measurement in soils with high organic matter, higher presence of clay minerals and high salinity (Ghazouani et al., 2015). Measurements in those cases may be imprecise and overestimate soil water content or, in some cases, underestimate (Evett et al., 2012). Thus, in order to improve the accuracy and precision of the values obtained with electromagnetic techniques, the sensors must be calibrated with the soil where they are installed, either in the field or in the laboratory (Souza et al., 2013). In fact, there are several studies about FDR sensors calibrations for different soils (Evett et al., 2012).

Some indexes for determining differences or measurement errors, which were not widely used for the determination of accuracy and precision of models, are currently being used along with traditionally indexes such as and/or coefficient of determination, as well as root mean square error (RMSE). In this context, Willmott (1981) developed indexes that allow modeling based on the difference between estimated and measured values, called the Willmott's D index. This same author and collaborators, in other studies, discuss about the various estimates of the mean error of the measurements and suggest modifications to the calculation of the D index, making it more rigorous, as known as the modified D index (Willmott et al., 1985).

The present aimed study was to calibrate and evaluate the accuracy and precision of SWC values measured by two devices based on electromagnetic principles (FDR and HFSI) in laboratory with clay rich soil.

4 MATERIAL AND METHODS

The experiment was carried out using five plastic pots, with 0.34 x 0.35m (height x diameter) and 20 L of volume. The pots were filled with soil, classified as Oxisol, with a clay content ranging from 400 to 510 g kg^{-1} to up to 0.8 m depth (Table 1). The soil was collected from the soil surface up to 0.2 m depth. After sampling, the soil was placed in the air for drying and after that it was sieved (2-mm mesh) to remove the coarser material.

Table 1. Granulometric composition, soil and solids density and soil porosity of the experimental area at different depths.

[1] References to trademarks do not correspond to endorsement by the authors.

Depth (m)	Granulometry ($g\ kg^{-1}$)				Soil bulk density ($kg\ m^{-3}$)		Porosity ($m^3\ m^{-3}$)
	Coarse sand	Thin sand	Silt	Clay	Soil	Solids	
0.2	300	110	190	400	1560	2300	0.68
0.3	270	110	190	430	1470	2300	0.64
0.4	250	110	180	460	1490	2300	0.65
0.6	190	90	230	490	1280	2220	0.58
0.8	210	90	190	510	1200	2250	0.53

The evaluation period lasted 105 days until the stabilization of the measurements and 24 readings were performed on all equipment during the entire period. The pots filling was done in layers around 0.05 m each to accommodate the soil and allowing simulating the soil density in the field. Thus, during filling, pots were weighed to ensure the density reached around 1450 kg m^{-3} on average, with a standard deviation of ± 0.05. A layer of 0.025 m of gravel was used at the bottom of each pot and it was covered with a permeable blanket aiming to improve drainage and avoid soil loss.

The access tubes for the FDR probe were allocated in the center of each pot simultaneously to the soil filling. Each access tube had a depth of 0.2 m, thus allowing the soil moisture to be read from the pot surface up to 0.1 m (FDR 0.1 m) and from 0.1 to 0.2 m (FDR 0.2 m). The HFSI probe length was 0.2 m, which provided mean values of SWC from the soil surface up to 0.2 m depth. The HFSI probes were installed at 0.07 m from the FRD prove and 0.07 m from the pot wall. The sensors calibration by the gravimetric method started with saturation of the pots with tap water. The pots were immersed and kept for 48 h in a tank with water, with the water reaching the upper edge of the pots, ensuring that the entire soil was saturated. Immediately after the saturation phase, the pots were removed from the tank and kept at rest for approximately 12 h to allow the drainage of water excess.

The mass variation to obtain soil moisture by gravimetry was performed by weighing all the pots, through a weighing machine, with a maximum capacity of 50 kg and accuracy of 0.01 kg. Soil density was used to convert moisture based on dry mass to moisture based on volume and thus enable the comparison and adjustment of the sensor’s values to the standard method. The probes readings were performed after the end of the drainage phase and after that the pot mass variation were performed about two to three times a day in the initial period. The interval between readings was increased as the variation of SWC values decreased.

Indices like Willmott’s Index were estimated in order to verify the accuracy and precision of the data obtained in the sensors in relation to the standard method (gravimetric). According to Wilks (2006), the accuracy is the degree of agreement between the estimated values and the observed values, whereas, precision is the degree of agreement of the values observed in the same dataset.

There are several indexes that allow to verifying the accuracy and precision between observed and estimated data, such as the coefficient of determination (R^2), mean error (ME), mean absolute error (MAE) and root mean square error (RMSE) the last two as described by the following equations (1 and 2) :

$$\mathrm{MAE} = \mathrm{N}^{-1} \sum_{i=1}^{N} (o_i - e_i)^2 \quad (1)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (o_i - e_i)^2}{N}} \quad (2)$$

Willmott (1981) noted that the correlation coefficient (r) as well as the coefficient of determination (R^2) did not allow verifying the presence of systematic errors in the estimation of models, since these coefficients represent the dispersion of the data compared to the regression obtained from these same data. Thus, it may not be related to the amplitude of the differences between estimated and observed values. Given these characteristics, Willmott (1981) stated that the coefficients of determination and regression are not recommended as methods for verification of an estimator model. Because of this, he developed the Willmott D index (Do), considered as a sensitive index to verify systematic errors present in a model or set of data, as described by the following equation (3):

$$\mathrm{Do} = 1 - \left[\frac{\sum(e_i - o_i)^2}{\sum(|e_i - o| + |o_i - o|)^2}\right] \quad (3)$$

Where:
Do - original concordance index d;
o - observed data;
e - estimated data.

The Do index, according to Willmott (1981) is widely used in model validation (Gonçalves et al., 2008). However, Willmott et al. (1985) pointed out that the use of the quadratic function in the Do index can lead to higher values even when the estimator model does not perform well. Therefore, these authors proposed a change in the Do index, denominating it the modified index of agreement (Dm), described as:

$$\mathrm{Dm} = 1 - \left[\frac{\sum(e_i - o_i)}{\sum(|e_i - o| + |o_i - o|)}\right] \quad (4)$$

Where:
Dm - modified index of agreement (Dm);
o - observed data;
e - estimated data.

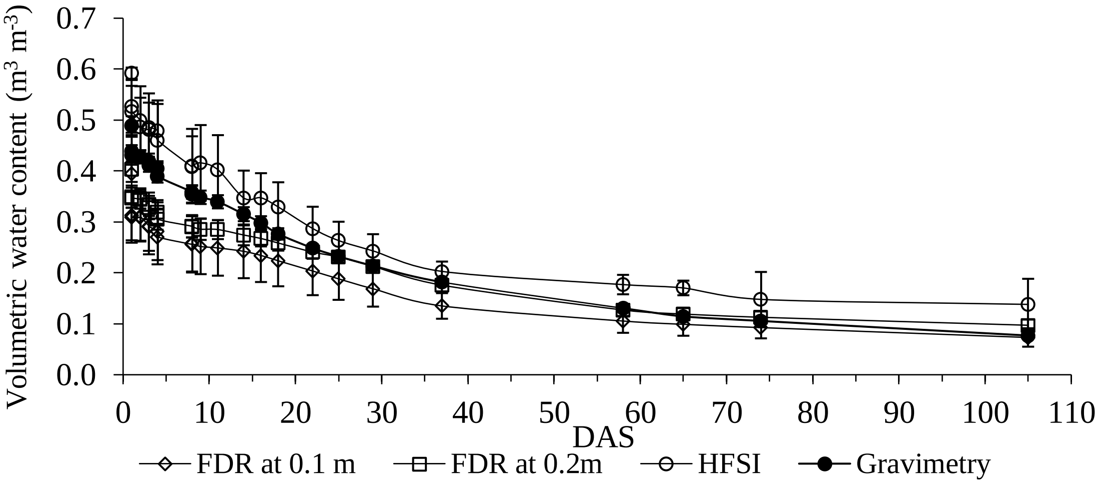
According to Legates and McCabe (1999), the Dm index has the advantage do not be influence by the power of two on errors (ei-oi), which, makes it more rigorous, since the values of Dm tend to be lower than Do. In both cases Do and Dm, the estimated values can vary from 0 to 1, and values close to the unit indicate good adjustment (Camparotto et al., 2013).

5 RESULTS AND DISCUSSIONS

The SWC values obtained by the three methods: FDR, HFSI and gravimetric are presented in Figure 1. The gravimetric method reached a soil moisture content of 0.489 $m^3 m^{-3}$, approximately 12 hours after the beginning of the saturation process. After 105 days of saturation (DAS) the soil moisture value was 0.077 $m^3 m^{-3}$, and the end of the dry soil experiment was determined (Figure 1). Thus, according to the standard method the standard method was 0.412 $m^3 m^{-3}$ in the period evaluated.

The FDR method at soil depths of 0.0 - 0.1 and 0.1 - 0.2 m obtained SWC values of 0.395 and 0.404 $m^3 m^{-3}$, respectively, 12 hours after the beginning of saturation. After 105 DAS the soil moisture were 0.073 and 0.097 $m^3 m^{-3}$ for the two depths, respectively. There was a variation of 0.322 and 0.307 $m^3 m^{-3}$ for the 0.0-0.1 and 0.1-0.2 m depths, respectively. The highest soil moisture variation was 0.454 $m^3 m^{-3}$, which was observed using the HFSI method (Figure 1); the values varied from 0.592 $m^3 m^{-3}$ 12 hours after saturation to 0.138 $m^3 m^{-3}$ after 105 DAS.

Figure 1. Volumetric water content values obtained during the experimental period: gravimetric (layer 0 to 0.2m), FDR (layers from 0.0 to 0.1 and 0.1 to 0.2 m.) and HFSI (layer from 0 to 0.2 m) in Oxisol.



The values presented with FDR sensors close to those observed in the standard method (gravimetry); for both 0.0 to 0.1 m and 0.1 to 0.2 m depths (Figure 2A and 2B) with a coefficient of determination (R^2) of 0.98. Although this coefficient is high, it is important to note that the distance of dashed line (1: 1) and the curve expressed for the values of sensor in Figures 2A and 2B. The FDR sensors underestimated the values in both sampled layers. The 0.0 to 0.1 m depth, particularly, presented moisture values below the 1:1 line, with a difference up to 0.126 m^3 m^{-3} (-28.8%) as it was observed in the period with higher SWC, reducing to 0.016 m^3 m^{-3} (-13.5%) at the end of the experiment in the Period when the soil was drier, at approximately 100 DAS (Figure 1).

The values obtained by the FDR probe in the 0.1 to 0.2 m depth using the 1:1 line was also underestimated compared to gravimetry (Figure 2B). However, the differences in values in the two soil depths were lower in the measurements at 0.1-0.2 m when compared to the 0.0-0.1 m, where the highest difference was 0.089 m^3 m^{-3} (-20.3%) in the region of higher humidity, reducing to 0.018 m^3 m^{-3} (-6.5%) in the medium moisture region (Figure 2B).

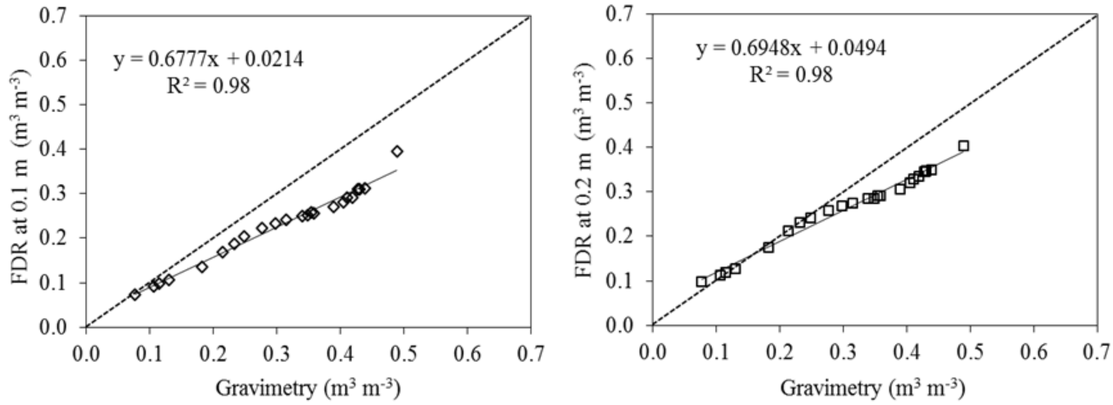
The difference in the SWC values observed with FDR in the depths of 0.0-0.1 m and 0.1-0.2 m could be attributed to the influence of water loss by evaporation occurring at the soil surface in the soil. Thus, at or near the surface (0.0-0.1m), the SWC estimated with the FDR sensor was more distant from those determined by (gravimetry) at any time during the experimental period (Figure 1). However, it is to point out that sensors, which could work with thinner soil layers (0.1 m against 0.2), provide more accurate information related to SWC dynamics.

Despite the variation observed in this study, high coefficients of determination were achieved with FDR (R^2 = 0.98) for the two layers evaluated (Figures 2A and 2B). These values were higher than those reported by Geesing et al. (2004), which obtained R^2 = 0.78 in the calibration of FDR probes in two soil types distinct from that of the present study.

When performing calibration with FDR probe in a soil with similar texture to that of the present study, Jabro et al. (2005) obtained a high coefficient of determination (R^2 = 0.96). Thus, it is possible to observe that soil texture may influence the dispersion related to linear regression line of the estimates. This fact corroborates other studies that associate the soil structure and granulometry with the differences observed between the SWC obtained in the equipment calibrations and those estimated by the manufacturer's equation, which demonstrates the importance of the calibration for each type of soil (Souza et al., 2013).

The FDR sensors presented better results when measuring in the intermediate and lower SWC range considering the 1:1 line in the two analyzed depths (Figures 1, 2A and 2B). In this aspect, Gabriel et al. (2010) and Paraskevas et al. (2012) also noted that SWC values were similar to the standard with lower SWC values. In addition, they observed larger variation when SWC increased.

Figure 2. Soil water content (SWC; $m^3\ m^{-3}$) correlation obtained for the FDR sensors in 0.0 to 0.1 m (A) and 0.1 and in 0.2 m (B) soil layers compared to the gravimetric method. Dashed line corresponds to a 1:1 line (x = y).

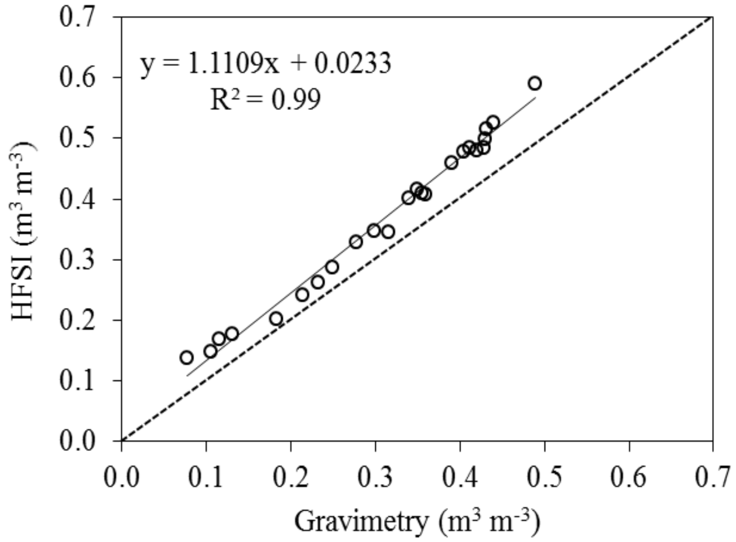


The results estimated by HFSI sensor, however, overestimated the SWC values, when compared to gravimetry (Figure 3) Compare to with 1:1 line it is possible to observe that there was variation of the soil moisture obtained in the HFSI sensors when collate to the standard method (gravimetric) throughout the experimental period. On the first day after saturation, the HFSI sensors presented a value of 0.103 $m^3\ m^{-3}$, that is, 21.06% higher than the gravimetric method. During the intermediate phase of the evaluations (58 DAS), this difference between the measurements of the two methods reduced to 0.021 $m^3\ m^{-3}$ (1.54%). When the soil was dry, at 105 DAS, the moisture variation observed at the HFSI sensor increased by 0.061 $m^3\ m^{-3}$ (79.4%). However, even though this variation occurred, the HFSI data adjustment line remained close to the 1:1 line during most the experimental period.

The coefficient of determination for the HFSI sensor was higher than that obtained for the FDR in the two evaluated layers. However, even with high 0,99 R^2, these sensors slightly overestimated the soil water content compared to the standard method. Taking into account that HFSI sensor, which estimates the average soil moisture of the entire assessed layer (0.0 to 0.2 m), may have been attenuated by the HFSI sensor, which explains the higher value of R^2, as opposed that noted on the FDR, where the higher variation in SWC values observed in the upper layer (0 to 0.1) . Moreover, during the process of soil drying by evaporation, the pot bottom (0.1-0.2 m layer) tended to remain wetter than the surface, which possibly influenced the average values obtained by the sensor.

Gomes et al. 2013 performed the HFSI calibration in the field and obtained a correlation coefficient of 0.72. These authors justified that the lower coefficient value may be related to the sensor shape, which does not always allow a perfect contact of the sensor with soil, especially in the layer close to the soil surface. In fact, in the present study, it was observed that the HFSI sensors do require attention during the measurements in order to keep the contact between the sensor and adjacent soil, especially with high SWC.

Figure 3. Soil water content (SWC; m3 m-3) correlation obtained during HFSI sensors calibration in the 0.0-0.2 m soil depth compared to gravimetric method. Dashed line corresponds to 1:1 line (x=y).



The accuracy between SWC values estimated by the sensors and obtained in the gravimetry is presented in Table 2. The absolute mean error achieved in the HFSI and FDR sensors did not differ much from the gravimetry method. The largest error obtained between the values was 0.08 m^3 m^{-3} for the FDR sensor at a depth of 0.0-0.1 m. The HFSI sensor had the largest mean error 0.07 m^3 m^{-3}. The smallest error observed was 0.05 m^3 m^{-3} at the 0.1-0.2 m depth of the FDR sensor. According to the Willmott D indexes, original and modified (Do and Dm), both the HFSI sensor and the 0.1-0.2 m FDR sensor showed the same indices values of 0.92 and 0.72 respectively for Do and Dm. Regarding the FDR sensor at 0.1 m, the Do and Dm indexes were 0.83 and 0.59, respectively (Table 2).

Mean absolute error and root mean square error rates were similar among the sensors, with the FDR at 0.1-0.2 m presenting the lowest value (Table 2). Although these values were above compared to those obtained by Varble & Chavez (2011), they could be considered acceptable values.

The Do index (original D) presented values close to the unit, 0.92 for HFSI and FDR at 0.1-0.2 m, while the FDR sensor at 0.0-0.1 m showed a slightly lower value, 0.83. As it was previously mentioned, the lowest values of concordance and accuracy for the FDR sensor at 0.0-0.1m can be related to the influence of soil surface direct evaporation, and such difference could only be observed by applying Willmott's agreement indexes as they increased the rigor and improved the understanding of the values variation observed when using the sensors.

This accuracy became more evident when we analyzed the values of the Dm (modified) index that is even more rigorous. In fact, it is possible to observe that the indexes values decreased as the accuracy of the test increased. Thus, the value of Do (0.92) obtained in the 0.1-0.2 m FDR and HFSI probes decreased to 0.72 when using Dm. The 0.0-0.1 m FDR sensor, consequently, showed the lowest values in all calculated indices herein. However, few sensor calibration studies have used these Willmott indexes. Varble & Chavez (2011) used only the original Do and obtained values close to those found in this study for the calibration of FDR probes.

Table 2. Indexes of accuracy for the calibration of the FDR and HFSI sensors compared to the values obtained by the standard gravimetric method.

Type of probe	MAE	RMSE	Do	Dm
HFSI	0.07	0.08	0.92	0.72
FDR at 0.1m	0.08	0.06	0.83	0.59
FDR at 0.2m	0.05	0.06	0.92	0.72

(MAE: absolute mean error; RMSE: Root mean square error; Do: Original Willmott Index D; Dm: modified Willmott Index D.

6 CONCLUSIONS

- The FDR and HFSI sensors presented calibration with high values of coefficient of determination with to the gravimetric method in laboratory condition.
- The dispersion of the soil water content estimates, obtained through the sensors used in this study, was shown to be directly proportional to the soil water content.
- Willmott’s test added important information to data analysis by better evaluating sensors for accuracy of their measurements.
- The two electromagnetic methods had different behaviors compared to the gravimetric. The FDR underestimated the soil water content values, while the HFSI overestimated it, especially when close to soil saturation. Thus, the FDR method was more suitable in the soil drying phase.

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