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Models for moisture estimation in different horizons of yellow argisol using TDR

Modelos para estimativa da umidade em diferentes horizontes de argissolo amarelo com uso da TDR

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Abstract

The determination of soil moisture is very important because it is the property with the most influence on the dielectric constant of the medium. Time-domain reflectometry (TDR) is an indirect technique used to estimate the water content of the soil (θ) based on its dielectric constant (Ka). Like any other technique, it has advantages and disadvantages. Among the major disadvantages is the need for calibration, which requires consideration of the soil characteristics. This study aimed to perform the calibration of a TDR100 device to estimate the volumetric water content of four horizons of a Yellow Argisol. Calibration was performed under laboratory conditions using disturbed soil samples contained in PVC columns. The three rods of the handcrafted probes were vertically installed in the soil columns. Weight measurements with digital scales and daily readings of the dielectric constant with the TDR device were taken. For all soil horizons evaluated, the best fits between the dielectric constant and the volumetric water content were related to the cubic polynomial model. The Ledieu model overestimated by approximately 68 % the volumetric water content in the A and AB horizons, and underestimating by 69 % in Bt2, in relation to volumetric water content obtained by gravimetry. The underestimation by linear, Topp, Roth, and Malicki models ranged from 50 % to 85 % for all horizons.

Key words: Apparent dielectric constant. Soil water content. TDR calibration.

Resumo

A reflectometria no domínio do tempo (Time Domain Reflectometry, TDR) é uma técnica indireta usada para estimar o conteúdo de água do solo (θ) em função da constante dielétrica (Ka). As vantagens do uso desta técnica são, no entanto, requer calibração específica para cada tipo de solo. Neste estudo objetivou-se realizar a calibração de modelos para estimar a umidade volumétrica de quatro horizontes de um Argissolo Amarelo com uso da TDR. A calibração foi realizada em condições de laboratório utilizando amostras deformadas do solo em estudo, acondicionadas em colunas de PVC. As sondas fabricadas artesanalmente com três hastes foram instaladas verticalmente nas colunas de solo. Foram realizadas pesagens com balança de precisão e leituras diárias da constante dielétrica com o equipamento TDR. Os modelos polinomial cúbico e linear foram os que apresentaram melhor ajuste aos dados de umidade observados. Os modelos de Topp et al. (1980), Ledieu et al. (1986), Malicki et al. (1996) e Roth et al. (1990) superestimaram em aproximadamente 15% as médias de umidade nos horizontes A e AB e subestimam em aproximadamente 18% no Bt2. No horizonte Bt1 todos os modelos foram semelhantes entre si.

Palavras-chave: Constante dielétrica aparente. Conteúdo de água no solo. Calibração de TDR.

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Introduction

The precise monitoring of soil water content is an important action for studies on soil water dynamics, and the planning and rational management of water in agricultural activities. Various methods are available to determine soil water content. Among them, the time-domain reflectometry (TDR) technique stands out. TDR was introduced in the late 1960s by Feellner-Feldegg (1969) to measure the complex dielectric permittivity of liquids (GOMIDE, 1998). In the early 1980s, TDR was used to determine soil physical properties and it was observed that the dielectric constant was closely associated with the water content and, to a lesser extent, with soil density and composition (PEREIRA et al., 2006).

The operating principle of the TDR to measure soil moisture is based on the travel time of one electromagnetic pulse along the rod of the probe inserted into the soil, which depends on the soil dielectric constant, with reference to the weighted mean of the dielectric constants of the fractions of the soil components, i.e., of its liquid, solid and gaseous phases. However, because the dielectric constant is 1 for air, approximately 80 for water and varies from 3−7 for the solid material (mineral and organic), a small variation in the volumetric soil water content causes a considerable variation in its dielectric constant (SANTOS et al., 2009).

Through the experimental relation between the TDR measured dielectric constant and the gravimetry measured volumetric soil water content, the TDR technique can be used to determine soil moisture. It is a technique with many advantages, such as the non-utilization of radioactive material, thus, it is a safe device and it also allows the accurate measurement of soil moisture, at any depth, without limitations regarding the superficial measurements. Additionally, it can be used to determine multiple measurements at the same site, without destroying the soil sample, and has an automated system for data collection (SOUZA; MATSURA, 2002).

The disadvantages of the TDR include the high cost and the need for calibration (TOMMASELLI; BACCHI, 2001; CICHOTA, 2003), which is necessary to obtain the correct value of the volumetric water content for the various soil types. This is considered a disadvantage because there is currently no calibration method considered as standard, despite the various methods found in the literature (PEREIRA et al., 2006). Furthermore, it is important to consider the particular properties of each soil to ensure an accurate and reliable calibration (VILLWOCK et al., 2004).

The assumption of the empirical calibration models is that the association between the apparent dielectric constant and the soil water content depends only on the latter (TOMMASELLI; BACCHI, 2001). As the volumetric water content increases in the soil, the apparent dielectric constant also increases, which consolidates the use of the model presented by Topp et al. (1980). These authors claimed that the characteristics of the environment and the soil, such as density, salt contents and temperature, do not affect the moisture measurement with the TDR, thus, not requiring calibration for the various soil types.

However, some authors have observed that the equation proposed by Topp et al. (1980) has a good fit for coarse-textured soils but not for fine-textured soils (ROTH et al., 1990; PONIZOVSKY et al., 1999). This may occur due to the increase in the specific surface of the soil with the increment in clay content, which causes the influence of the adsorbed layer of water to be significant (ROTH et al., 1990).

The studies conducted by Coelho et al. (2006) in tropical soils evidenced that it is not possible to generalize the calibration model. In addition, Kaiser et al. (2010), working with Brazilian soils, identified the ineffectiveness of the proposed general models, which demonstrates the need for specific models for each soil.

The absence of a robust and exact model, with a physical basis, promoted the appearance of numerous empirical calibration models for the TDR (ROBINSON et al., 2005). However, despite decades of use and development of the technique, it is still not possible to ignore the effect of the characteristics of the material on the measurements taken (CERNY, 2009).

Given the above, this study aimed to determine the calibration curves for various horizons of Yellow Argisol using handcrafted TDR probes.

Material and Methods

Disturbed soil samples were collected from four depths in a soil profile located at the Gaviao Farm, in the municipality of Inhambupe, BA, Brazil, which is located in the zonal range of low latitude, a fundamental factor that gives it the tropical character. The samples were collected from soil horizons A (0−0.17 m), B (0.17−0.50 m), Bt1 (0.50−0.80 m), and Bt2 (0.80−1.20 m).

Table 1 presents the soil physical attributes, which were determined according to methods recommended in the literature (RICHARDS; FIREMAN, 1943; FLINT; FLINT, 2002; GEE; OR, 2002; GROSSMAN; REINSCH, 2002). The physical analyses were conducted at the Laboratory of Soil Physics, of the Federal University of Reconcavo of Bahia.

Table 1. Physical attributes of different horizons of the evaluated Yellow Argisol.

Horiz.	Depth	TS	Silt	Clay	Porosity			Volumetric water content	
					Macro	Micro	D_s	-10 kPa	-1500 kPa
	(m)	g kg^{-1}			m^3 m^{-3}		kg dm^{-3}	m^3 m^{-3}	
A	0-0.17	665	68	267	0.1000	0.2336	1.51	0.248	0.128
AB	0.17-0.50	521	66	413	0.1381	0.2721	1.42	0.258	0.165
Bt1	0.50-0.80	490	71	439	0.2107	0.2781	1.25	0.257	0.154
Bt2	0.80-1.20	446	85	469	0.2575	0.2927	1.12	0.240	0.148

TS = total sand; D_s = soil density.

The disturbed samples were crushed to break up clods, air-dried, passed through sieves with 0.005-m mesh and then put in PVC columns with a height of 0.20 m and 0.144 m diameter. The known volume of the container was used to calculate the mass of dry soil necessary to reach the soil density determined for each horizon. The soil was homogeneously distributed throughout the columns. The bottom of each column was sealed with two layers of fine-mesh screen to avoid soil loss, and the columns were subjected to saturation for 48 h. All the material involved in the process, i.e., the air-dried soil, PVC columns and fine-mesh screen, were initially weighed. Three PVC columns containing the soil of each horizon were used, totaling 12 columns. After saturation, a TDR probe, which was previously weighed, was inserted in the center of each soil column.

The handcrafted TDR probes had three stainless steel rods of 0.003 m diameter, 0.13 m length and 0.022 m spacing, isolated by polyester resin, with 1.0-m long RG58 coaxial cables (50 Ω). Additionally, the construction of the three-rod probes required the following materials: resin catalyst, electric welding machine, tin alloy Sn 63/37, 1% phosphoric acid and wire stripping pliers.

The weight recordings of the set, composed of pipe, probe, soil and screen, started after saturation. Immediately after the initial weighing, the probes of the TDR100 device were connected to determine the soil water content corresponding to that weight. At the beginning of the calibration, this procedure was performed at short time intervals because the water losses through percolation were high. As the volume of percolated water decreased and there were no large variations in weight and the dielectric constant (Ka), the samples were oven-dried at 30 ºC for approximately 4 h. Weight recordings and readings of the soil water content were performed after the soil samples reached ambient temperature.

Volumetric water contents were determined simultaneously to each reading of the TDR device, according to Equation 1:

$$\theta v = \left(\frac{WS - DS}{DS - CPS} \right) \times d_s \qquad (1)$$

where: θv = volumetric water content of the soil (m^3 m^{-3}); WS = weight of wet soil + CPS (kg); DS = weight of dry soil + CPS (kg); CPS = weight of PVC column + weight of probe + weight of two fine-mesh screens (kg); and d_s = soil bulk density (kg dm^3).

After determination of the apparent soil water contents obtained with the TDR probes, the dielectric constant (Ka) was estimated using Equation 2 (LEDIEU et al., 1986).

$$\theta_v = 0.1138\sqrt{Ka - 0.1758} \quad (2)$$

where: θv = volumetric water content in the soil (m^3 m^{-3}); and Ka = dielectric constant of the soil.

These data were associated with the values of **θv**, determined through Equation 1, thus generating the calibration equations of the TDR probes, through the fit of five calibration models of TDR probes including the cubic polynomial function (Equation 3) and the model of Topp et al. (1980) (Equation 4) as follows:

$$\theta_v = a + bKa + cKa^2 + dKa^3 \qquad (3)$$

$$\theta_v = -5.3\times10^{-2} + 2.92\times10^{-2}Ka - 5.5\times10^{-4}Ka^2 + 4.3\times10^{-6}Ka^3 \qquad (4)$$

where: θv is the volumetric water content in the soil (m^3 m^{-3}) and Ka is the dielectric constant of the soil, dimensionless. The empirical model developed by Topp et al. (1980) does not contemplate attributes of soils with a high degree of weathering, such as those found in regions of tropical climate; the linear function (Equation 5):

$$\theta_v = aKa + b \qquad (5)$$

and the model of Malicki et al. (1996) (Equation 6), as follows, relating water content and Ka with the inclusion of soil bulk density, which was tested in organic soils and sands:

$$\theta_v = \frac{\sqrt{Ka} - 0.819 - 0.168d_s - 0.159d_s^2}{7.17 + 1.18d_s} \qquad (6)$$

and finally, the model of Roth et al. (1990) (Equation 7) , as follows:

$$\theta_v = \frac{Ka^\alpha - (1-\varepsilon)Ka_s^a - (\varepsilon Ka_a^\alpha)}{(Ka_w^\alpha - Ka_a^\alpha)} \qquad (7)$$

where: ε corresponds to soil total porosity (m^3 m^{-3}); α is a parameter that takes into account the effects of the geometric arrangement of the soil matrix; and Ka_s, Ka_a and Ka_w are, respectively, the dielectric constants of the soil matrix, air and water. The values of Ka_s, Ka_a and Ka_w were 5, 1 and 77 (COELHO et al., 2006), respectively, for all calculations. The initial value of α was 0.5, according to some authors (TOPP et al., 1980; LEDIEU et al., 1986; ROTH et al., 1990; MALICKI et al., 1996).

The results of volumetric water content measured and estimated by the calibration models of the TDR probes were compared through simple linear regression, namely y = ax, in which the angular coefficient close to 1.0 with high R^2 indicates a higher accuracy of the fitted model. The evaluation of the model also used the statistical indicators MEA (mean of errors) and RMSE (root mean square error), calculation of the model's efficiency (Ef) according to Nash and Sutcliffe (1970), and the parameter "d", which is the Willmott's index of agreement that determines the accuracy of the method and indicates the degree of distance between estimated and observed values. Ef and d indices varies from 0, for no agreement, to 1, for perfect agreement (ANDRADE JÚNIOR et al., 2003). These indices were obtained by the following equations:

$$MEA = \frac{1}{n}\sum_{i=1}^{n}\left(O_i - E_i\right)^2 \tag{8}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(O_i - E_i\right)^2} \tag{9}$$

$$Ef = \left[\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2 - \sum_{i=1}^{n}\left(O_i - E_i\right)^2\right] / \sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2 \tag{10}$$

$$d = 1 - \left[\sum_{i=1}^{n}\left(E_i - O_i\right)^2 / \sum_{i=1}^{n}\left(\left|E_i - \bar{O}\right| + \left|O_i + \bar{O}\right|\right)^2\right] \tag{11}$$

where n = number of data; O_i = observed value; E_i = estimated value; $\bar{O}$ = mean of the estimated value; and *Ef* = efficiency of the model.

Tukey's test ($p<0.05$) was applied to compare the means of water contents obtained for the various models and soil horizons.

Results and Discussion

The observed values of volumetric water content (θv, $m^3\ m^{-3}$) as a function of the apparent dielectric constant (Ka), for the various depths and horizons evaluated, as well as the cubic polynomial and linear curves fitted to the observed data, and the curves referring to the models of Topp et al. (1980), Ledieu et al. (1986), Roth et al. (1990) and Malicki et al. (1996), are presented in Figure 1. The curves referring to the analyzed models were vastly dissimilar for the all depths studied. The dispersion around the fitted curves may have occurred because of the non-uniform characteristics of the soil, such as density and porosity, for the various depths evaluated. Soil density varied from 1.12−1.51 kg dm^{-3} for the various depths. This variation is because once air-dried, the studied soil was uniformly deposited in the containers (PVC pipes).

In general, the fitted curves are not coincident at the various depths, thus, demonstrating the need for calibration of the device in each soil, specifically defining the curve that best fits a particular soil (Figure 1).

All calibration curves for the cubic polynomial model showed R^2 determination coefficients ≥ 0.986 (Table 2). The discrepancies between the curves of the models linear, Topp et al. (1980), Ledieu et al. (1986), Roth et al. (1990) and Malicki et al. (1996), in relation to the linear and polynomial models, are possibly due to the differences between the soils used in each of the studies.

The cubic polynomial models fitted to the values of $\boldsymbol{\theta}\mathbf{v}$ = f(Ka) are presented in Table 2. According to the R^2 determination coefficient, there was a good fit for all depths. The fits of the cubic models indicated that more than 98.6% of the variations in volumetric water content can be explained by the variations in the dielectric constant for all depths studied. The magnitude of R^2 was the same found by Silva and Gervásio (1999) and by Tommaselli and Bacchi (2001) for Brazilian soils.

Figure 1. Relationships between the volumetric water content and apparent dielectric constant of the soil, at the horizons/depths of the evaluated Yellow Argisol, according to the cubic polynomial,linear, Topp et al. (1980), Ledieu et al. (1986), Roth et al. (1990), and Malicki et al. (1996) models.

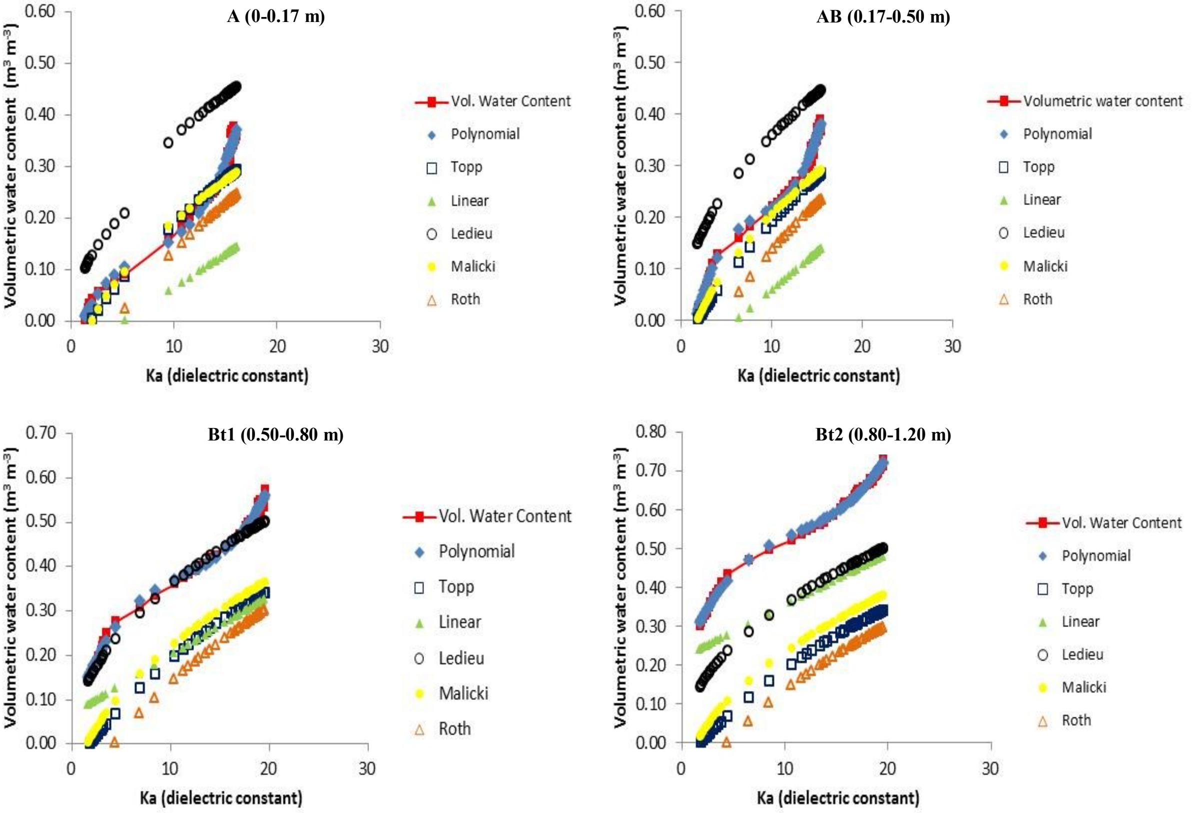
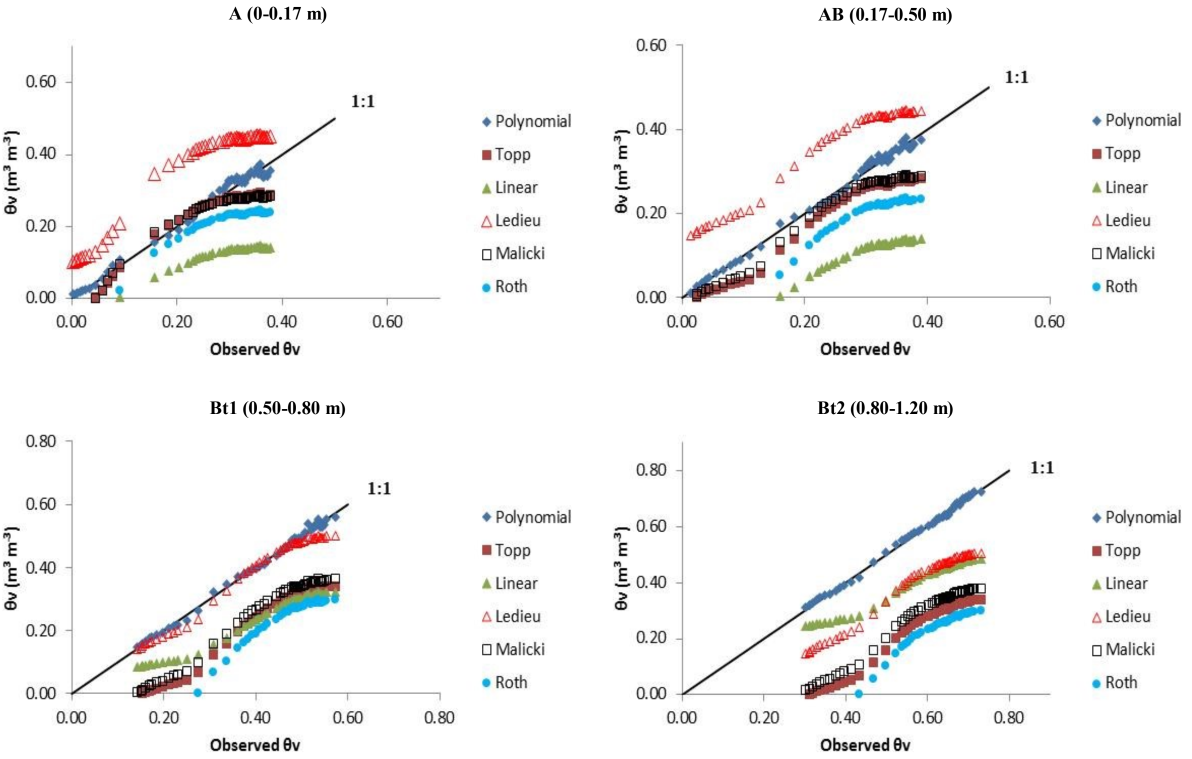


Table 2. Fit of the cubic polynomial model to the data of volumetric water content (θ), as a function of the dielectric constant (Ka), for the different horizons of the evaluated Yellow Argisol.

Horizon	Polynomial model	R²
A	$\theta = 0.00024194Ka^3 - 0.00553779Ka^2 + 0.05264493Ka - 0.05449018$	0.986
AB	$\theta = 0.00037600Ka^3 - 0.00992070Ka^2 + 0.09657990Ka - 0.13509846$	0.993
Bt1	$\theta = 0.00015511Ka^3 - 0.00519934Ka^2 + 0.06842402Ka + 0.04572936$	0.996
Bt2	$\theta = 0.0001382294Ka^3 - 0.0046660475Ka^2 + 0.0645445040Ka + 0.2083978151$	0.997

The observed values of volumetric water content (θ, $m^3\ m^{-3}$**)** as a function of the water content estimated by the cubic polynomial, linear, Topp et al. (1980), Ledieu et al. (1986), Roth et al. (1990) and Malicki et al. (1996) models at the different depths of the soil horizons (0−0.17, 0.17−0.50, 0.50−0.80 and 0.80−1.20 m) are presented in Figure 2. The linear, Topp et al. (1980), Ledieu et al. (1986), Roth et al. (1990), and Malicki et al. (1996) models were ineffective, because they overestimated and or underestimated the water contents as the dielectric constant increased, as previously observed by other authors (SILVA; GERVASIO, 1999; TOMER et al., 1999; TOMASELLI; BACCHI, 2001).

Figure 2. Soil volumetric water content gravimetrically determined in relation to those determined by the polynomial cubic, Topp et al. (1980), linear, Ledieu et al. (1986), Malicki et al. (1996), and Roth et al. (1990) models, for the different horizons/depths of the evaluated Yellow Argisol.



A (0-0.17 m)

AB (0.17-0.50 m)

Bt1 (0.50-0.80 m)

Bt2 (0.80-1.20 m)

For all soil horizons evaluated, the best fits between the dielectric constant and the volumetric water content were related to the cubic polynomial model (Figure 2). The Ledieu et al. (1986) model overestimated the volumetric water content for A and AB horizons, underestimated for Bt2, and was effective for Bt1. The linear, Topp et al. (1980), Roth et al. (1990), and Malicki et al. (1996) models systematically underestimated the volumetric water content for all horizons. In general, the volumetric water content data simulated with the equations of linear, Topp et al. (1980), Ledieu et al. (1986), Roth et al. (1990), and Malicki et al. (1996) models do not show a good agreement with the volumetric water content obtained by gravimetry (Figure 2).

Studies conducted in soils with various textures demonstrated that the association between the dielectric constant and soil moisture best fits exponential models (COELHO et al., 2001) or polynomial models (TOMMASELLI; BACHI, 2001).

The evaluation of the calibration equations for the various depths in relation to the six models evaluated, based on RMSE, MEA, d and Ef of the model, is presented in Table 3. In general, the model with d and Ef values equal or close to one (1.00) was the cubic polynomial for all evaluated depths, which indicates good performance. For the other models that showed low Ef values, it can be justified by the empirical nature, which does not consider the physical properties and the dielectric components of the soil, considering the fixed coefficients.

Table 3. Determination of the statistical indicators for the evaluated models at the different horizons of the evaluated Yellow Argisol.

Model	Soil horizons							
	A				AB			
	RMSE	**MEA**	**d**	**Ef**	**RMSE**	**MEA**	**d**	**Ef**
Polynomial	0.0142	0.0002	0.9993	0.9865	0.0093	0.0001	0.9997	0.9939
Linear	0.1661	0.0276	0.8159	0.3000	0.1839	0.0338	0.7654	0.2644
Topp	0.0440	0.0019	0.9927	0.8785	0.0594	0.0035	0.9860	0.7954
Ledieu	0.1261	0.0159	0.9638	0.4644	0.1110	0.0123	0.9710	0.5271
Malicki	0.0476	0.0023	0.9914	0.8596	0.0518	0.0027	0.9897	0.8360
Roth	0.0957	0.0092	0.9591	0.6014	0.1138	0.0129	0.9384	0.5172
	Depth (m)							
	Bt1				**Bt2**			
	RMSE	**MEA**	**d**	**Ef**	**RMSE**	**MEA**	**d**	**Ef**
Polynomial	0.0083	0.0001	0.9999	0.9961	0.0070	0.0000	1.0000	0.9972
Linear	0.1762	0.0310	0.9334	0.3337	0.1802	0.0325	0.9666	0.3208
Topp	0.1789	0.0320	0.9324	0.3535	0.3396	0.1153	0.8351	0.1302
Ledieu	0.0258	0.0007	0.9991	0.9635	0.1792	0.0321	0.9673	0.3500
Malicki	0.1557	0.0243	0.9520	0.4196	0.3022	0.0914	0.8801	0.1595
Roth	0.2341	0.0548	0.8680	0.2416	0.3947	0.1558	0.7498	0.0999

RMSE: root mean square error; MEA: mean of errors; “d”: Willmott’s index of agreement; Ef: efficiency of the model.

The use of the TDR technique to determine the volumetric water content of the soil is very promising in soil science. Despite its simple use, in the laboratory or in the field, in any direction of the soil profile and in real time, this technique can be used to monitor soil water content for irrigation management with different systems. However, accurate water content determination requires calibration curves, which must be estimated so that the differences between devices and types of soils can be minimized and corrected.

In the use of this method, it is important to have a better distribution of the water content between field capacity and soil saturation. The soil accommodated in containers must also be in agreement with the soil density in the area where the water content will be monitored (SANTOS et al., 2012).

In Table 4, water content means followed by the same uppercase letter in the rows in the A and AB horizons were statistically similar for the cubic polynomial, Topp et al. (1980), Roth et al. (1990), and Malicki et al. (1996) models and the observed volumetric water content, which differed from the linear and Ledieu et al. (1986) models. With exception of the Ledieu et al. (1986) model for Bt1, the other models were significantly different from cubic polynomial and observed volumetric water content, in Bt1 and Bt2 horizons. These differences may be associated with the soil physical attributes.

Table 4. Comparison of means of water content in the different horizons of the evaluated Yellow Argisol.

	Models						
Horiz.	**Polynomial**	**Topp**	**Linear**	**Ledieu**	**Malicki**	**Roth**	θ_{vol} **(cm³cm⁻³)**
A	0.2466 a A	0.2477 a A	0.1231 a B	0.3681 a C	0.2454 a A	0.2184 a A	0.2466 a A
AB	0.2520 a A	0.2017 a A	0.1134 a B	0.3601 a C	0.2107 a A	0.2036 a A	0.2519 a A
Bt1	0.4077 b A	0.2388 a B	0.2383 b B	0.3908 b A	0.2530 a B	0.2439 a B	0.4076 b A
Bt2	0.5676 b A	0.2329 a B	0.3940 b C	0.3895 b C	0.2659 a B	0.2408 a B	0.5676 b A

Means followed by the same letter, uppercase in the row and lowercase in the column, do not differ by Tukey test ($p<0.05$).

Based in Table 4, the Ledieu et al. (1986) model overestimated by approximately 68 % the volumetric water content in the A and AB horizons, and underestimating by 69 % in Bt2, in relation to volumetric water content obtained by gravimetry. The underestimation by linear, Topp et al. (1980), Roth et al. (1990), and Malicki et al. (1996) models ranged from 50 % to 85 % for all horizons.

Hence, it is possible to claim the need for calibration of the soils, corroborating with Villwock et al. (2004), who assert that calibration is required, particularly, when working with Latosols, due to certain particularities, such as high contents of Fe and clay, because the calibration provided by the manufacturer does not consider these particularities.

Among the models tested for the estimation of soil water content as a function of the dielectric constant, the data simulated by the cubic polynomial and linear models showed the highest agreement with the data determined through gravimetry. These results demonstrate that the use of empirical models, with fixed coefficients, can be subject to inaccuracies in the estimates of water content or apparent dielectric constant.

Conclusions

For all soil horizons evaluated, the best fits between the dielectric constant and the volumetric water content were related to the cubic polynomial model.

The Ledieu model overestimated by approximately 68 % the volumetric water content in the A and AB horizons, and underestimating by 69 % in Bt2, in relation to volumetric water content obtained by gravimetry.

The underestimation by linear, Topp, Roth, and Malicki models ranged from 50 % to 85 % for all horizons.

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