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Calibration of TDR for moisture determination in peat deposits**

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A b s t r a c t. Determination of soil water content using the Time Domain Reflectometry (TDR) method is recently considered modern and widely used. The practical application of TDR requires its calibration *ie* determination of the relationship between the dielectric constant and the volumetric moisture content of the soil. The paper presents the development of calibration equations for the range of different peat types (willow peat, sedge-moss, reed and sedge-reed) from the Biebrza river valley. Undisturbed soil samples were used in the calibration procedure. The volumetric moisture content and the dielectric constant were measured simultaneously during the calibration. The study showed that bulk density substantially affects the relation between the dielectric constant and moisture content in peat soils. The empirical calibration equation accounting for bulk density values ranging from 0.08 to 0.25 g cm^{-3} was found.

K e y w o r d s: peat soils, TDR, calibration, bulk density

INTRODUCTION

Soil water content and the availability of water for plants are fundamentally important to land activities, especially those involving agriculture, forestry, hydrology and engineering. Knowledge of soil water content over extensive areas is necessary in crop yield optimization and flood control. Recently, the time domain-reflectometry method (TDR) is being used increasingly for measuring the moisture content of soils (Nissen *et al*., 2003). The measurement is nondestructive, the data can be obtained accurately over very small horizontal or vertical distances. The determination of soil water content using the TDR method requires the knowledge of the relationship between the apparent dielectric constant (K_a) and the volumetric moisture content of the soil (θ). The first more general calibration results were published by Topp *et al*. (1980). They found a third order polynomial relationship between (K_a) and (θ) as the form of calibration equation to be valid for mineral soils ranging from sandy loam to heavy clay soils, where soil water content values practically do not exceed 55%. Topp *et al*. (1980) also established a calibration equation ($K_a(\theta)$) for organic soils. However, that equation does not apply to natural or cultivated peat soils, where the water content can be as high as 95%. Stein and Kane (1983), after a preliminary verification of the equation, indicated an overestimation of the water content values close to the saturation for organic soils with bulk density values around 0.55 g cm^{-3}. They indicated also that the value of K_a above 47 resulted in the calculated moisture content values higher than 100%. A number of empirical relationships between the dielectric constant and soil water content for mineral soils were established later (Ledieu *et al*., 1986; Nadler *et al*., 1991; Dasberg and Hopmans, 1992; Roth *et al*., 1992; Jacobsen and Schjonning, 1993), but only a few for organic and peat soils. The calibration equations for organic soils published in the literature together with a 'universal' equation, proposed by Topp *et al*. (1980) and widely used for mineral soils, are presented in Table 1 and plotted in Fig. 1. The majority of the equations presented are in the form of the third order polynomial:

$$\theta_v = \left(\mathrm{A} + \mathrm{B}K_a + \mathrm{C}K_a^2 + \mathrm{D}K_a^3\right)10^{-4}, \qquad (1)$$

and some formulas are proposed in the form of the square-root relationship:

$$\theta_v = \mathrm{A} + \mathrm{B}\sqrt{K_a}, \qquad (2)$$

where: θ_v – soil moisture content (cm^3 cm^{-3}); K_a – dielectric constant ; A, B, C, D – constants of the models.

As mentioned above, the equations are in the form of relationships between the dielectric constant and moisture content only, and they do not include other properties of the

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T a b l e 1. Empirical equations for organic soils, organic materials and the 'universal' calibration equation for mineral soils

Authors	Type of soil	Bulk density ($g\ cm^{-3}$)	Range of water content (%)	Type of model*	Constants of empirical equations			
					A	B	C	D
Topp *et al*. (1980)	Mineral soil	1.3-1.4	10-50	a	-530.0	292.0	-5.5	0.043
Topp *et al.* (1980)	Organic soil	0.422	3-55.1	a	-252.0	415.0	-14.4	0.22
Pepin *et al*. (1992)	*Sphagnum* peat	0.064-0.248	20-95	a	850.0	192.0	-0.95	0.0
Roth *et al*. (1992)	Fibric Histosol, Cambic Arenosol	0.2-0.77	0-80	a	-233.0	285.0	-4.3	0.03
Myllys and Simojoki (1996)	*Sphagnum* and *Carex* peat	0.1-0.4	30-95	a	-733.0	417.0	-8.01	0.056
Oleszczuk *et al.* (1998)	Alder peat	0.19	24-88	a	-27.6	247.7	-3.15	0.02
Beckwith and Baird (2001)	*Sphagnum cuspidatum* peat	-	65-94	a	-4028.9	645.91	-12.06	0.079
Herkelrath *et al.* (1991)	Typic Haplorthod	-	10-80	b	-0.051	0.127		
Schaap *et al*. (1996)	Organic forest floor media	0.09-0.26	0-80	b	-0.119	0.136		
Caron *et al*. (2002)	Organic growing media	-	0-95	b	-0.1672	0.1357		

*a – polynomial model Eq. (1); b – square-root model Eq. (2).

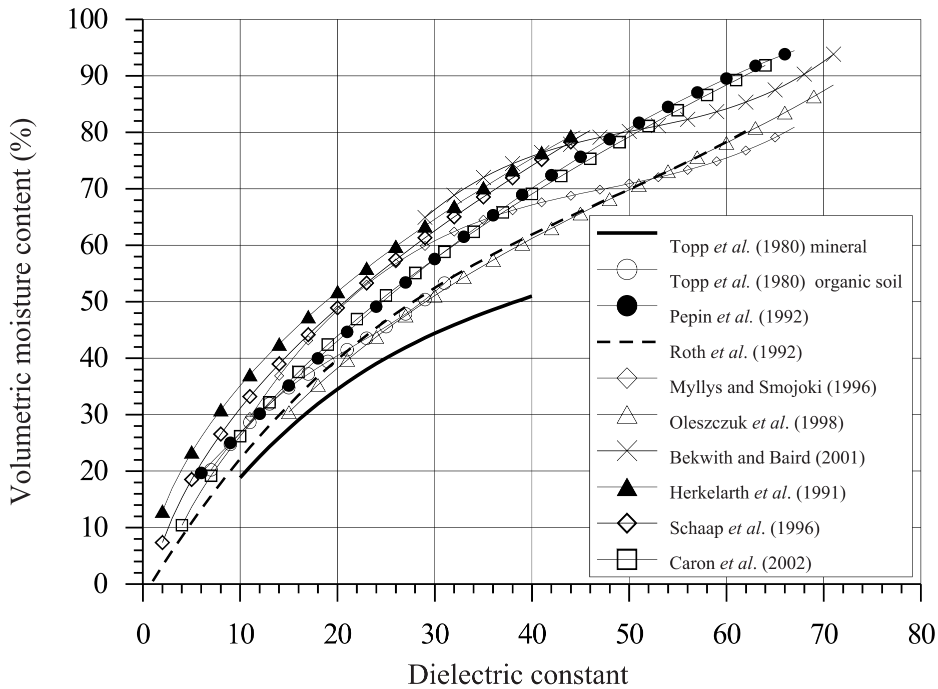

Fig. 1. Calibration curves for organic soils and organic materials based on the published data.

soil matrix, such as bulk density or porosity. Analysis of the shape of the calibration curves for organic soils, presented in Fig. 1, indicates that for the whole range of K_a values similar differences in moisture content are observed. For example, comparison of the calibration curves obtained by Pepin *et al*. (1992) with Myllys and Simojoki (1996) shows a difference in the volumetric moisture content of about 15% for K_a value equal to 60. The respective $K_a(\theta)$ relationships for organic soils are significantly different from the "universal" function developed for mineral soils. The measured values of the dielectric constants of organic soils at each selected moisture content level are lower than for similar moisture levels in mineral soils. According to Roth *et al*. (1992), bulk density is a physical parameter influencing the soil moisture content of organic soils. Jacobsen and Schjonning (1995) suggested that a few layers of water molecules around the soil particles are thought to have a restricted rotational freedom, which will result in a lower dielectric number of bound water than that of bulk water. In peat soils, organic matter is the main contributor to the specific surface area, which determines the amount of bound water. This difference can be caused by the effect of bulk density *ie* at the same water content, a lower bulk density value results in a lower dielectric number. These differences in volumetric moisture water content gradually decrease for lower values of the dielectric constant.

The aim of this study was to determine the contribution of bulk density to the function that relates the dielectric constant to moisture content for different types of peat.

MATERIALS AND METHODS

Peat soil deposits located in the Biebrza river valley are considered in this study. The measurements were performed for 8 soil layers from 5 soil profiles. The characteristics of sampling points together with the basic soil properties are presented in Table 2. It can be seen from the data presented in this table that the peat deposits under consideration represent: different peat types (willow peat, sedge-moss, reed and sedge-reed), different degree of decomposition (ranging from H_1 to H_7), bulk density (ranging from 0.081 to 0.232 g cm^{-3}) and saturated moisture content (ranging from 83.4 to 93.8%). Analysis of the properties shows that the peat types investigated represent the full range of peat deposits appearing in the Biebrza river valley (alder, herbaceous and moss). Undisturbed soil samples were collected into plastic rings of an inner diameter of 8.7 and of 8.2 cm in height from every measuring point. The samples were taken in three replications from each layer. The springtime was chosen for sample collection, because during that time the organic soils were almost saturated and fully expanded. In the laboratory the samples were equipped with Easy Test TDR probes. Each probe consisted of two parallel wave-guides that were 6 cm long, 0.5 mm in diameter and 5 mm apart, and it was inserted horizontally into the soil. The TDR LOM/mpts meter (Malicki and Skierucha, 1989; Malicki, 1993) was used in the calibration procedure. After the installation of TDR probes, the peat samples were placed in the laboratory and allowed to dry at room temperature (about 20°C). Changes of the sample weight, as well as of the dielectric constant values, were measured simultaneously during the drying process. The measurements were conducted until the soil moisture changes were negligible. Then the samples were dried in an oven at a temperature of 105°C in order to determine their final dry weight values which were used to calculate the volumetric water content and also to determine the bulk density of each sample.

T a b l e 2. Physical properties of considered peat deposits from the Biebrza river valley

Soil profile	Depth (cm)	Peat type	Degree of decomposition (von Post' scale)	Bulk density (g cm^{-3})	Saturated moisture content (% vol.)
Biebrza 29	50-60	Willow	H_7	0.174	88.9
Toczyłowo	60-70	Sedge-moss	H_2	0.095	83.4
JWE 5	70-80	Reed	$H_{4.5}$	0.129	90.2
Otoczne 4	40-50	Sedge-reed	H_7	0.166	88.0
	70-80	Reed	H_6	0.134	90.9
Czarnawieś 2	5-15	Sedge-moss	H_4	0.232	87.0
	50-60	"	H_1-H_2	0.083	85.5
	60-70	"	H_1-H_2	0.085	93.8

RESULTS AND DISCUSSION

The measured data relating the values of the volumetric moisture content with the dielectric constant for different types of peat from the Biebrza river valley are plotted in Fig. 2. From this figure it can be seen that the relationship between the volumetric moisture content and the dielectric constant depends on the peat type which can be characterized by different bulk density values. This can be illustrated by the assumption of volumetric moisture content equal to 70%, which results in the following values of dielectric constant: 46, 52, 55 and 50-60 for willow, reed, sedge-reed, sedge-moss peat, respectively.

The following relationship was fitted to the presented measurement data for each of the 24 soil samples considered:

$$\sqrt{K_a} = a + b\,\theta_v, \tag{3}$$

where: $\sqrt{K_a}$ – refractive index, a – intercept, b – slope, θ_v – moisture content (cm^3 cm^{-3}).

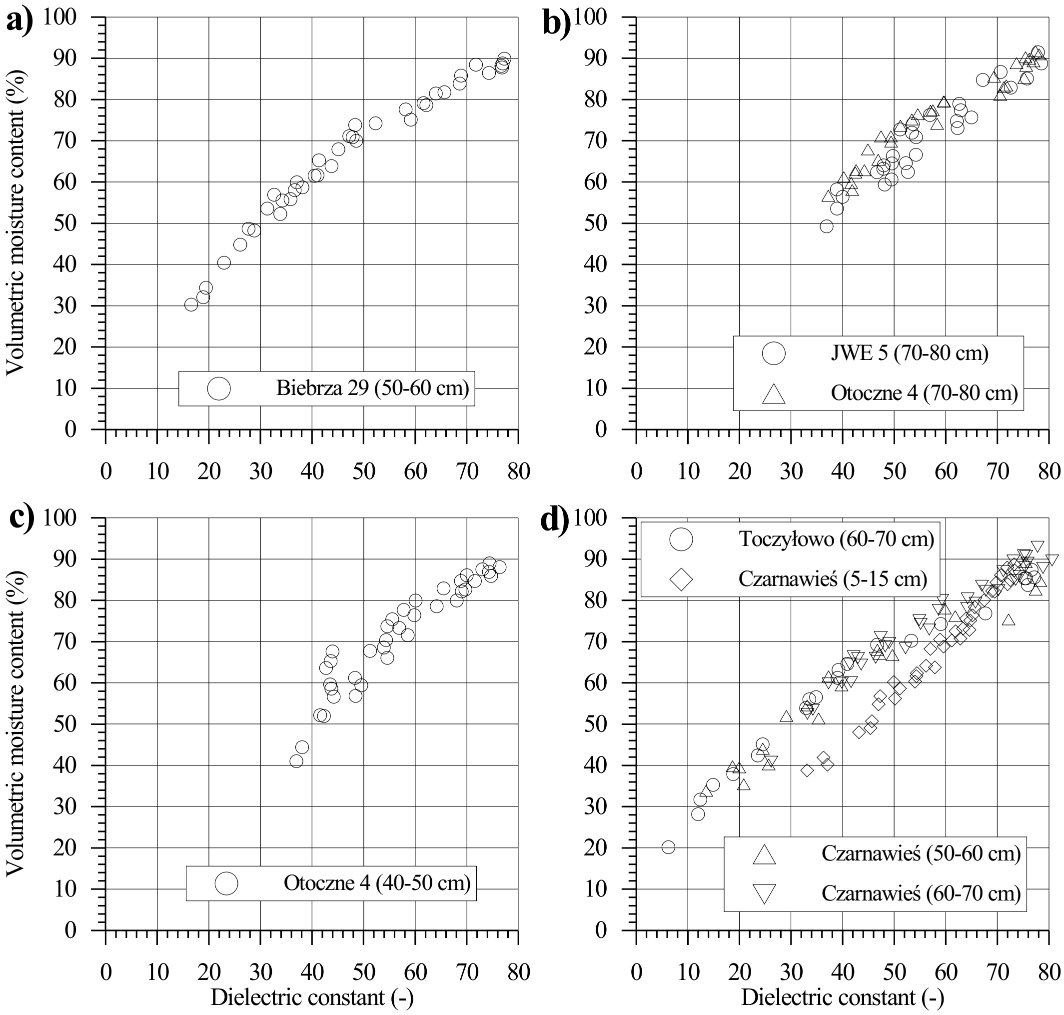

Fig. 2. Measured data for different types of peat from the Biebrza valley: a) willow, b) reed, c) sedge-reed and d) sedge-moss.

Such a type of relationship was applied because in non-magnetic media the value of square root of the dielectric constant is the measure of the absolute value of the refraction coefficient of magnetic wave (Malicki, 1993). Analyses of the determination coefficient for the linear Eq. (3), which was fitted to measured data for each soil sample considered, show relatively high values ranging from 87.6 to 99.9%. Then the approach proposed by Malicki *et al.* (1996) was used in order to find the influence of the peat bulk density on the fitted parameters required in Eq. (3) - intercepts *a* and slopes *b*. The following respective regression equations relating these parameters with bulk density were found:

$$a \quad 18.6619 \; {}^{2}_{b} \quad 13.8513 \; {}_{b} \quad 0.383943, \qquad (4)$$

$$b \quad 25.8003 \; {}^{2}_{b} \quad 32.0302 \; {}_{b} \quad 11.5445 \qquad (5)$$

where: ρ_b is soil bulk density (g cm^{-3}).

The values of intercepts *a* and slopes *b*, plotted against the corresponding bulk density values ρ_b, are shown in Fig. 3, and the respective regression relationships are also presented. It can be seen that the relationship between parameter *a* and bulk density ρ_b shows increasing values of *a* with increasing ρ_b, and the relationship between parameter *b* and bulk density ρ_b shows decreasing values of *b* with increasing ρ_b. The relationship between parameter *b* and ρ_b has opposite direction in comparison with the corresponding relationship presented by Malicki *et al.* (1996). It can be attributed to the differences in the ranges of ρ_b values which, for the Biebrza peat deposits, vary from 0.08 g cm^{-3} to 0.25 g cm^{-3}, while the data presented by Malicki *et al.* (1996) covered soils with bulk density from 0.2 to 1.8 g cm^{-3}. Moreover, the data for the Biebrza peat deposits resulted from measurements on undisturbed soil samples collected from the field, while the data of Malicki *et al.* (1996) were measured on disturbed soil samples previously sieved and packed to assumed value of ρ_b.

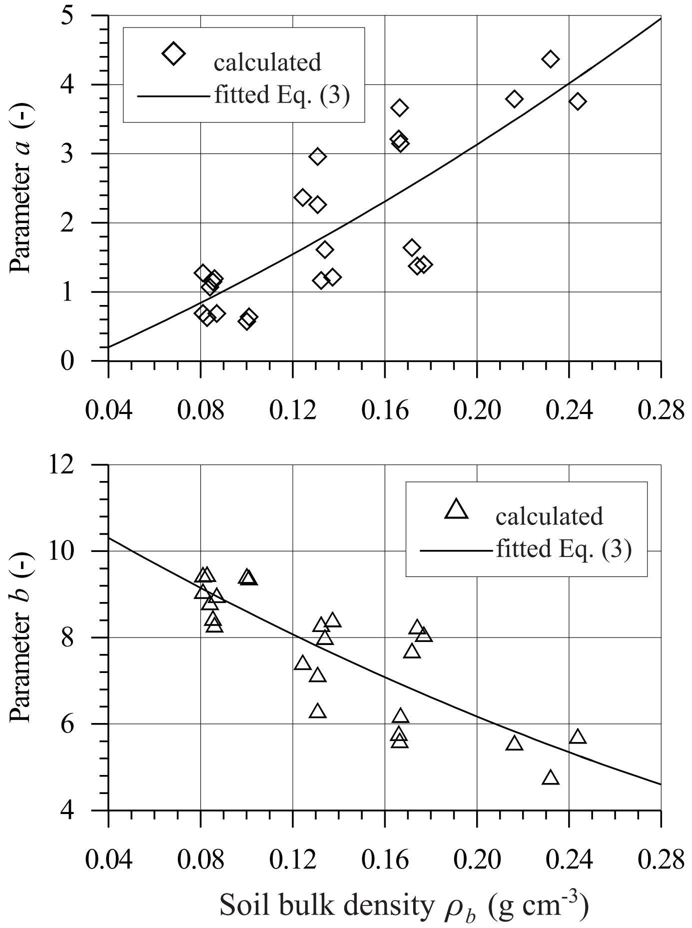

Fig. 3. Relationships between parameters required in Eq. (3) and soil bulk density.

Equations (4) and (5), describing parameters a and b as a functions of ρ_b, were combined with Eq. (3) and the resulting equation has the form of:

$$\sqrt{K_a} = 18.6619\rho_b^2 + 13.8513\rho_\mathrm{b} - 0.383943 + \left(25.80003\rho_b^2 - 32.0302\rho_\mathrm{b} + 11.5445\right)\theta_v. \quad (6)$$

Transformation of Eq. (6) with regard to (θ_v) yields:

$$\theta_v = \frac{\sqrt{K_a} = 18.6619\rho_b^2 + 13.8513\rho_\mathrm{b} + 0.383943}{\left(25.8003\rho_b^2 - 32.0302\rho_\mathrm{b} + 11.5445\right)} \quad (7)$$

where: θ_v – moisture content (cm^3 cm^{-3}), ρ_b – soil bulk density (g cm^{-3}).

Comparisons between measured and calculated (from Eq. (7)) values of volumetric moisture content are presented in Fig. 4. The value of the determination coefficient (R^2) for

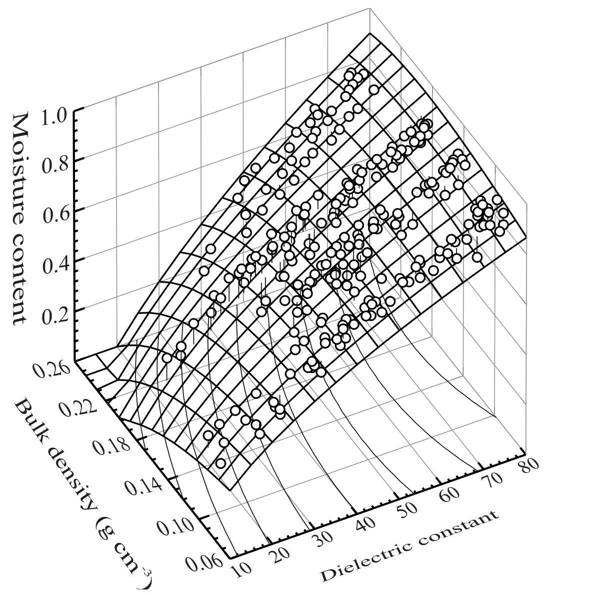

Fig. 4. Measured and calculated (Eq. (7)) volumetric soil moisture content values as a function of soil bulk density and dielectric constant.

the relationship obtained is equal to 99.7%. The data presented show that bulk density significantly influences the dielectric constant values for volumetric soil moisture content values lower than 70%. Increasing values of soil bulk density lead to higher values of the dielectric constant for given moisture content values.

The value of R^2 is very high, which, however, is not enough to accept this equation from the statistical point of view. Therefore, the analysis of residuals was performed. The residuals are a function of measurement numbers, and their normal probability distribution is plotted in Fig. 5. From the data presented in this figure, no trend or normal probability distribution of residual values can be seen. In order to examine whether the residuals had a normal distribution, the Shapiro-Wilk test was applied. As a result of the examination, the empirical value of the Shapiro-Wilk statistics (W_a) equal to 0.986 was determined and it was higher than the critical value of W=0.975. The critical value of W, assuming a confidence level of 0.05, was calculated using the procedure described by Zieliński (1999).

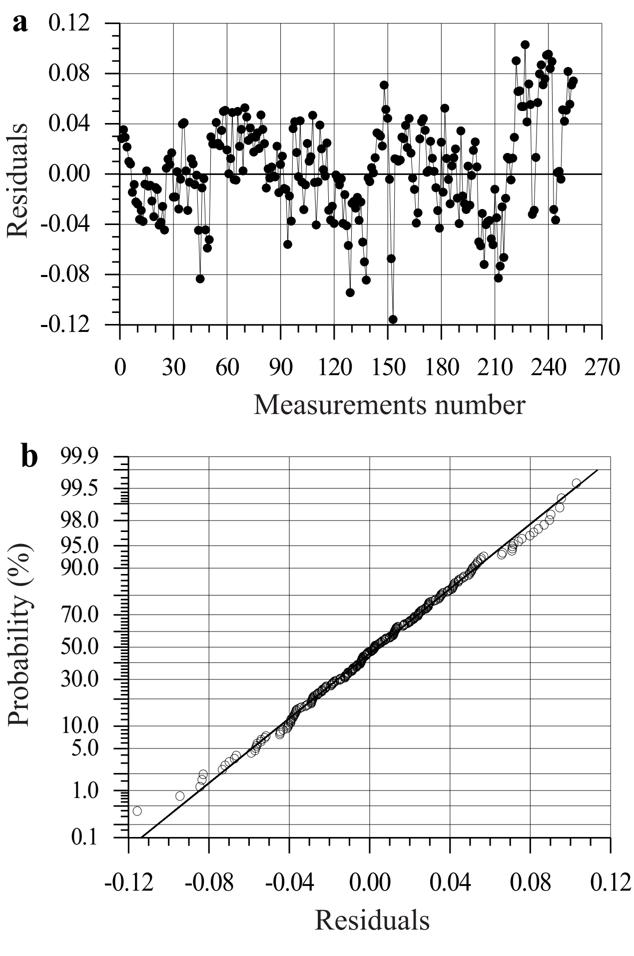

Fig. 5. Residuals plotted as a function of the number of measurements (a) and their normal probability distribution (b).

CONCLUSIONS

The results obtained from the presented research led to the following conclusions:

1. The measurements performed on undisturbed peat samples from the Biebrza river valley showed that bulk density of peat soils substantially affects the relation between the dielectric constant and the moisture content.

2. The relationship between the dielectric constant and moisture content in peat deposits can be represented by a square-root Eq. (3) and it was proven that the values of intercept *a* and slope *b* in this equation are strongly dependent on bulk density.

3. The proposed calibration Eq. (7), relating the moisture content with the dielectric constant and bulk density for TDR moisture measurements in peat deposits from the Biebrza river valley, is statistically significant and can be applied for peat soils with bulk density values ranging from 0.08 to 0.25 g cm^{-3}. The peat bulk density significantly influences the dielectric constant values for the volumetric soil moisture content lower than 70%. Increasing values of soil bulk density lead to higher values of the dielectric constant for a given moisture content.

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