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Helsinki 1996

ISSN 0039-5471
Suo 47 (1): 1–6

Calibration of time domain reflectometry (TDR) for soil moisture measurements in cultivated peat soils

TDR-mittausten kalibrointi viljeltyjen turvemaiden kosteuden mittaamiseen

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Time domain reflectometry (TDR) is a relatively new technique for measuring soil water content. It is based on measuring the apparent dielectric number (K_a) of the soil from the propagation velocity of an electromagnetic pulse travelling in the soil. Soil water content is then calculated from the apparent dielectric number. In this study, an empirical relationship between the apparent dielectric number and the volumetric water content was established for cultivated peat soils in the laboratory. A third-degree polynomial described the relationship with a coefficient of determination of 0.980 and a standard deviation of 0.027 m^3 m^{-3}. The relationship can be used to measure water content in typical cultivated *Sphagnum* and *Carex* peat soils in the range usually prevailing in the field, i.e. 0.3–0.8 m^3 m^{-3}.

Key words: dielectric number, water content

INTRODUCTION

Time domain reflectometry (TDR) is a relatively new method for measuring volumetric soil water content. It is a rapid and accurate tool for *in situ* soil moisture measurements, and allows real time moisture readings with minimal soil disturbance. Such a method is essential for all branches of soil science and hydrology studies, where large numbers of measurements are required to characterize the water content and its rapid changes in a heterogeneous soil.

The theoretical basis of TDR was developed by Fellner-Feldegg (1969), and Topp et al. (1980) introduced TDR to soil science. The technique is based on measuring the apparent dielectric number (K_a) of the soil, which in turn is determined from the propagation velocity of an electromagnetic pulse travelling in the soil. The velocity of the pulse is decreased in higher dielectric materials. Soil can be considered as a three-component mixture of air, solids and water, where the dielectric number of air equals 1, that of mineral and organic solid matter 3–5, and that of free water 80 (at 20°C) (Handbook of Chemistry and Physics 1987). As free water has a much higher dielectric number than mineral and organic solid matter, the pulse velocity (and thus K_a) is mainly determined by the water content of the soil.

In the TDR measurement, parallel metallic wave guides of known length (L) are embedded in the soil. TDR measures the travel time (Δt) of a high frequency (1MHz–1GHz) voltage pulse, as it travels to the end of the wave guides and reflects back. The apparent dielectric number of the soil (K_a) can then be calculated:

$$K_a = (c\Delta t/2L)^2, \qquad (1)$$

where c is the velocity of light in free space ($c = 3 \times 10^8$ m s^{-1}). K_a is determined by the mean velocity of the pulse and represents the average water content of the soil.

In this paper, "dielectric number" refers to the real component of the dielectric number only. The imaginary component of the dielectric number is related to the electrical conductivity of the soil and can be used to study soil salinity (Dalton & van Genuchten 1986).

Topp et al. (1980) showed that for many soil materials a general empirical relationship exists between the apparent dielectric number (K_a) and the volumetric soil water content (θ_v). They established a relationship with water contents ranging from 0.033 to 0.55 m^3 m^{-3}. The relationship was described by a third-degree polynomial:

$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} K_a - 5.5 \times 10^{-4} K_a^2 + 4.3 \times 10^{-6} K_a^3 \quad (2)$$

Topp et al. (1980) found that the relationship between K_a and θ_v was relatively independent of soil texture, bulk density, temperature, and electrical conductivity. Their results indicated that θ_v could be accurately estimated from K_a by using an empirically determined calibration curve.

However, even in their original paper, Topp el al. (1980) stated that organic soils may have different dielectric properties, and therefore a different relationship between K_a and θ_v. Henkelrath et al. (1991), Roth et al. (1992) and Jacobsen & Schjønning (1993) further reported that calibration for different soil types increases the accuracy of the relationship. This concerns especially fine textured soils and organic soils, possibly due to their large surface area and large volume of bound water around the particles.

Few calibration equations between K_a and θ_v have been published for soils with high organic matter content, low bulk density and high water content. This is especially the case for cultivated peat soils. This study establishes an empirical relationship between the apparent dielectric number (K_a) and volumetric soil water content (θ_v) on cultivated *Carex* peat and *Sphagnum* peat soils in Finland.

MATERIAL AND METHODS

Sample preparation

The relationship between the apparent dielectric number (K_a) and volumetric soil water content (θ_v) of cultivated peat soils was determined empirically in the laboratory in undisturbed soil samples. A total of 48 undisturbed samples from two locations were collected for analyses. Half of the samples were moderately decomposed *Carex* peat, and the other half were well decomposed *Sphagnum* peat (Table 1). These soils were selected for this study as they represent typical peat soils in agricultural production in Finland.

The samples were taken in metal-edged plastic cylinders of 15 cm inner diameter and a height of 20 cm. The sampling depth was from 5 to 25 cm. The cylinders were pushed vertically into the soil, and excavated with the soil inside. The soil columns were then taken into the laboratory and subjected to 12 different moisture conditions, ranging approximately from wilting point to saturation. The moisture conditions were created by suction, pressure or by drying at room temperature. The moisture was not necessarily evenly distributed in the sample. This, however, did not affect TDR (Topp et al. 1982) nor gravimetric moisture measurements in this study.

Table 1. Physical and chemical properties of the peat samples used for calibration.

Taulukko 1. Kalibrointiin käytettyjen turvenäytteiden fysikaalisia ja kemiallisia ominaisuuksia.

peat type *turvelaji*	bulk density *tiheys* Mg m^{-3}	porosity *huokoisuus* m^3 m^{-3}	ash content *tuhkapitoisuus* %DM	pH$_{(CaCl_2)}$
Sphagnum	0.4	0.77	48	5.1
Carex	0.3	0.75	37	5.0

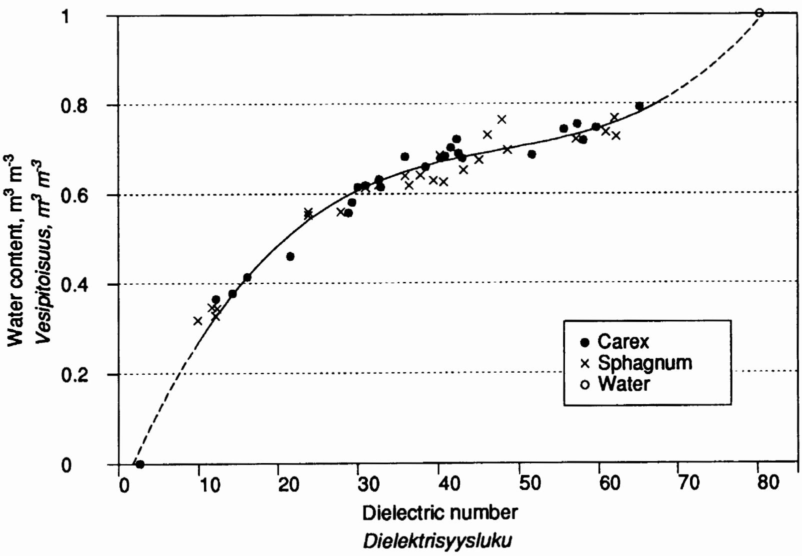

Fig. 1. Relationship between the apparent dielectric number (K_a) and the volumetric water content (θ_v) in cultivated peat soils. $\theta_v = -7.33 \times 10^{-2} + 4.17 \times 10^{-2} K_a - 8.01 \times 10^{-4} K_a^2 + 5.56 \times 10^{-6} K_a^3$.

Kuva 1. Dielektrisyysluvun (K_a) *ja maan kosteuden* (θ_v) *välinen suhde viljellyissä turvemaissa.*

There were two columns of both soils in each moisture condition. In addition, two extra disturbed samples were taken from a *Carex* peat soil. These samples were oven dried and then pressed into plastic cylinders.

TDR measurements

After letting the soil column reach the desired moisture condition the K_a value was measured with TDR using "TRASE-system I", model 6050X1, Soilmoisture Equipment Corporation (Santa Barbara, CA, USA). The measurement was carried out at room temperature (20°C). A TDR probe with two parallel wave guides, 15 cm in physical length, 6 mm in diameter and 50 mm apart, was installed vertically into the soil, and the K_a value of the soil was recorded. According to Baker and Lascano (1989) the effective cross sectional area measured by the probe was approximately 20 mm × 65 mm. The K_a value of each column is the average of two separate measurements. The K_a values of the two oven-dried samples were also measured.

The electrical length (L) of the TDR probe differs from the physical length (Heimovaara 1993). The electrical length was determined by measuring the travel time (Δt) of the pulse in demineralized water at known temperature and substituting the correct value for K_a (Eq.1).

Gravimetric measurements

Water content of the soil column was determined gravimetrically after the TDR measurements. The upper 15 cm of the soil column (the measured part) was cut from the rest of the column and water outflow was minimized. The mass and volume of the cut sample were measured, and the soil was removed from the cylinder for oven drying. A drying temperature of 65°C was chosen to prevent thermal decomposition of the organic matter. The samples were kept in the oven until they reached constant mass, after which the dry mass was determined at room temperature. Volumetric water content was calculated using the gravimetric water content and the volume of the moist soil.

Standard procedures were used to determine relevant physical properties of the peats used in the study. Peat type was determined visually. Bulk density was calculated from the volume of the soil at saturation and the dry mass. Total porosity was estimated from the water content of the soil at saturation. Ash content was determined by combusting the organic material in an oven at 800°C and soil pH was measured in 0.01 M $CaCl_2$.

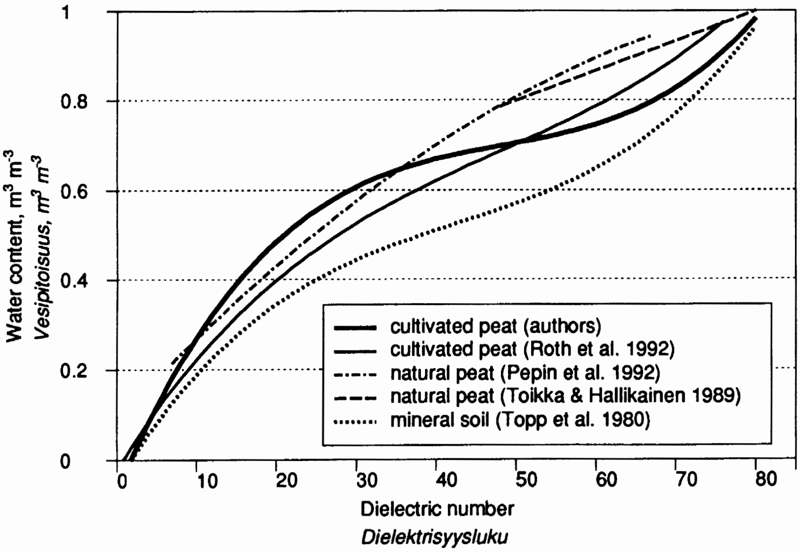

Fig. 2. Comparison of TDR calibration curves for peat soils.

Kuva 2. Turvemaiden TDR-kalibraatiokäyrien vertailu.

Statistics

Polynomials were fitted to the data values of K_a and θ_v by the least squares method. The fitting was done to both peat types separately and then to the pooled data. A SAS polynomial model was used for fitting (SAS Institute Inc. 1991).

RESULTS AND DISCUSSION

A third-degree polynomial equation between the volumetric water content (θ_v) and the apparent dielectric number (K_a) was suitable for calibration. Third-degree polynomials have been used in most calibrations made for various soil types (Topp et. al 1980, Roth et al. 1992, Jacobsen & Schjønning 1993).

The polynomials for *Sphagnum* peat and for *Carex* peat were so similar that the data were pooled and a single polynomial was used to describe the entire data set (Table 2). The coefficient of determination (R^2) of the polynomial was 0.980, and the standard deviation 0.027 m^3 m^{-3}. The best-fit third-degree polynomial equation for θ_v and K_a was

$$\theta_v = -7.33 \times 10^{-2} + 4.17 \times 10^{-2} K_a - 8.01 \times 10^{-4} K_a^2 + 5.56 \times 10^{-6} K_a^3 \quad (3)$$

The K_a value of deionized water was included in the data, and the curve was drawn up to the θ_v value 1.0 m^3 m^{-3} (Figure 1). However, the water content range from approximately 0.8 to 1.0 m^3 m^{-3} does not represent true situation as the volumetric water content of a soil cannot be higher than the total porosity, unless the soil structure is destroyed. Also the dry end of the curve is uncertain, as there were no sam-

Table 2. Parameter estimates ± standard errors of the estimates for the calibration curve $\theta_v = a + bK_a + cK_a^2 + dK_a^3$. The goodness of curve fit is indicated by the coefficient of determination (R^2) and standard deviation (s.d.).

Taulukko 2. Kalibraatioyhtälön $\theta_v = a + bK_a + cK_a^2 + dK_a^3$ parametrien estimaatit ± estimoitujen parametrien keskivirheet. Selitysaste (R^2) ja keskihajonta (s.d.) kuvaavat yhtälön sopivuutta aineistoon.

peat type *turvelaji*	a × 10^{-2}	b × 10^{-2}	c × 10^{-4}	d × 10^{-6}	R^2	s.d.
pooled *yhdistetty*	−7.33 ± 1.9	4.17 ± 0.19	−8.01 ± 0.53	5.56 ± 0.44	0.980	0.027
Sphagnum	−8.30 ± 2.3	4.32 ± 0.25	−8.53 ± 0.72	5.99 ± 0.59	0.984	0.030
Carex	−9.86 ± 1.9	4.28 ± 0.19	−8.08 ± 0.54	5.52 ± 0.44	0.990	0.023

ples with θ_v values between 0 and 0.3 $m^3 m^{-3}$. However, the volumetric water content range of the soil samples covered the area that is most representative of practical field conditions, i.e. from wilting point to saturation.

K_a of water varies with temperature, and therefore the relationship between θ_v and K_a is also temperature dependent. The effects of temperature changes were not studied in this context, but Ledieu et al. (1986) and Halbertsma et al. (1995) proposed temperature correction formulas for TDR measurements.

Our empirical calibration curve for cultivated peat soils differs from curves published for mineral soils and for some other peat soils (Figure 2). The difference between mineral soils and organic soils is well known (Topp et al. 1980, Roth et al. 1990, Henkelrath et al. 1991, Roth et al. 1992). Organic matter has a large surface area, and therefore a lot of bound water around the particles. A few layers of water molecules around the soil particles are thought to have a restricted rotational freedom, which results in a lower dielectric number of this bound water than that of bulk water. At the same water content, the K_a of organic soils would therefore be lower than that of coarse textured mineral soils. Roth et al. (1992) observed that bulk density also explains the differences between mineral and organic soils.

Observations by Topp et al. (1980) support the hypothesis of bound water. They observed little measurable change in K_a until θ_v was greater than 0.10 $m^3 m^{-3}$, and concluded that the first few layers of water molecules around the soil particles have a dielectric number near that of ice (i.e. $K_a \approx 3$). The empirical curve of Topp et al. (1980) indicated a K_a value of 2.5 for dry organic soil. Toikka & Hallikainen (1989) reported a K_a value of 3.0 and Roth et al. (1990) a K_a value of 5.0 for dry peat. The K_a value of 2.8 for the oven dried peat measured in this study falls within these limits.

Our calibration relationship is more curved than that of Roth et al. (1992) which was also established for cultivated peat soils (Figure 2). Ours gives lower water contents in wet soils and higher ones in dry soils. However, six peat soils out of seven studied by Roth et al. (1992) had a lower organic matter content than the soils in our study, which may explain the difference between these two curves.

For natural peat soils, both a linear equation reported by Toikka and Hallikainen (1989), and a second-degree equation by Pepin et al. (1992) indicate considerably higher water contents in wet soils than does our equation. Toikka and Hallikainen (1989) restricted their calibration to water contents over 0.80 $m^3 m^{-3}$, whereas Pepin et al. (1992) expanded their calibration to include water contents from 0.21 to 0.95 $m^3 m^{-3}$.

The empirical relationship between θ_v and K_a is the most widely used approach to relate the electrical properties of a soil to its water content. However, other approaches have been developed. Ledieu et al. (1986) and Henkelrath et al. (1991) determined the volumetric soil water content directly from the pulse velocity, using a linear relationship between Δt and θ_v. Roth et al. (1990) used a dielectric mixing model by which the volumetric water content was obtained from the dielectric numbers and volume fractions of the soil components i.e. soil, water and air (Tinga et al. 1973). Dirksen & Dasberg (1993) added a fourth component to the model, i.e. tightly bound water. However, the theoretical background to bound water still remains incomplete, thus justifying empirical approaches.

CONCLUSIONS

This study demonstrated that time domain reflectometry is a reliable method for measuring water content of cultivated peat soils. The empirical relationship between K_a and θ_v established in this study can be used to calibrate TDR measurements for cultivated *Sphagnum* and *Carex* peat soils in the water content range usually prevailing in the field, i.e. 0.3–0.8 $m^3 m^{-3}$.

ACKNOWLEDGEMENTS

The authors are grateful to Ms. Marja-Liisa Westerlund for her assistance with the experimental procedures.

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TIIVISTELMÄ:

TDR-mittausten kalibrointi viljeltyjen turvemaiden kosteuden mittaamiseen

TDR (time domain reflectometry) on suhteellisen uusi maan kosteuden mittausmenetelmä. Se perustuu maan näennäisen dielektrisyysluvun (K_a) määrittämiseen maassa kulkevan sähkömagneettisen pulssin etenemisnopeuden perusteella. Maan kosteus voidaan laskea K_a:n avulla. Tässä tutkimuksessa määritettiin empiirinen yhtälö viljellyistä turvemaista mitatun näennäisen dielektrisyysluvun ja maan kosteuden välille. Mittaukset tehtiin laboratoriossa. Aineistoon sovitetun kolmannen asteen polynomifunktion selitysaste oli 0.980 ja keskihajonta 0.027 m^3 m^{-3}. Tätä funktiota voidaan käyttää viljellyillä sara- ja rahkaturvemailla maan kosteuden ollessa pelto-oloille tyypillinen 0.3–0.8 m^3 m^{-3}.

Received 10.11.1995, accepted 18.1.1996