

Calibration of Time Domain Reflectometry for Water Content in Peat Soil

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Since peat soil differs from mineral soil in several respects, mineral-soil calibration functions for time domain reflectometry (TDR) are not necessarily applicable. This paper evaluates a number of calibration functions, both empirical polynomial and theoretical mixing models, on the basis of laboratory measurements on undisturbed *Sphagnum* peat samples. Deviations between different samples within this study indicate dissimilarities in dielectric properties between peats with different degrees of humification. Connections to physical properties such as amount of bound water and structural orientation are likely to exist. There is, however, a lack of methods to measure and quantify parameters expressing these properties. Therefore, until further studies on physical properties are accomplished, empirical or semi-empirical calibration curves are preferred. The best fit was obtained by an empirical, third order polynomial model. This model also gave a better fit than the mixing models when data were grouped into humification classes. However, all models reproduced pooled data with an r^2 better than 0.93.

Introduction

Peatlands are an important feature of the northern boreal landscape and their hydrology is of substantial importance for both local and regional water balances as well as for runoff generation. However, the water storage and wetness variation in the unsaturated zone over the seasons are poorly investigated. The use of time domain re-

flectometry (TDR) to measure peat water content has been explored in a few studies (e.g., K. Roth *et al.* 1990; Pepin *et al.* 1992; C.H. Roth *et al.* 1992; Myllys and Simojoki 1996; Lapen *et al.* 2000) but there is yet no consensus as to the calibration procedures needed. Maybe because of this, field measurements of water content in peat soils are uncommon and soil water characteristics of peat soils are rarely presented.

Peat soil differs from mineral soil by its lower bulk density, higher porosity and higher soil dielectric number. It also has a relatively high specific surface area. The high porosity causes a much larger water-content range (typically 5-95% by volume) as compared to mineral soils. There are thus reasons to investigate if calibration functions developed and used for mineral soils are applicable also for peat soils. This paper presents an evaluation of calibration functions, both empirical polynomial and theoretical mixing models, on the basis of measurements on undisturbed *Sphagnum* peat samples in laboratory.

Dielectric Models

The TDR method makes use of the large difference in dielectric number (K_a) between free, liquid water and other soil constituents. The dielectric number is the real part of the relative complex dielectric constant, or permittivity, and is also referred to as the apparent dielectric constant. Measurements of water content using TDR have developed rapidly over the past two decades. Ease of use and the idea that calibration for individual soils was not needed contributed to the development. The empirical calibration function presented by Topp *et al.* (1980) was for a long time regarded as universal. The function is a third-order relationship between the dielectric number obtained from the TDR reading and water content of the soil layer measured

$$\theta = a + b K_a + c K_a^2 + d K_a^3 \quad (1)$$

where θ is the water content by volume. Topp *et al.* (1980) gave the values $a = -5.3 \cdot 10^{-2}$, $b = 2.92 \cdot 10^{-2}$, $c = -5.5 \cdot 10^{-4}$, and $d = -4.3 \cdot 10^{-6}$. Several authors have presented elaborations of the Topp formula (e.g. Dasberg and Hopmans 1992; Ponzovsky *et al.* 1999; Yu *et al.* 1999). Discrepancies have been noted at low and high water contents. Especially for organic soils and clays this was identified as a problem.

A different approach, using a dielectric mixing-model, was suggested by K. Roth *et al.* (1990). Here, the composite dielectric number can be calculated if the dielectric numbers and volume fractions of the constituents (the phases), as well as their geometrical configuration, are known

$$K_a^\alpha = \theta K_w^\alpha + (1-\eta) K_{\text{sol}}^\alpha + (\eta-\theta) K_{\text{air}}^\alpha \quad (2)$$

and the water content by volume is given by

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$$\theta = \frac{K_{\alpha}^{\alpha} - (1-\eta)K_{\text{sol}}^{\alpha} - \eta K_{\text{air}}^{\alpha}}{K_w^{\alpha} - K_{\text{air}}^{\alpha}} \quad (3)$$

where η is porosity, α is a parameter expressing the geometry of the soil in relation to the electric field, and K_{α} , K_w , K_{sol} , K_{air} are the dielectric numbers of the bulk soil, the liquid water, the solid (here organic matter) and gaseous soil phases, respectively, at ambient temperature. The geometry parameter, α , varies between 1, for a soil with constituent layers parallel to the electric field, and -1 , for a soil with constituent layers perpendicular to the field generated by the probe, with $\alpha = 0.5$ for an isotropic soil (K. Roth *et al.* 1990). Theoretical reasoning, arguing that soils are isotropic, *i.e.*, $\alpha = 0.5$, has been put forward, *e.g.*, by Birchak *et al.* (1974). K. Roth *et al.* (1990) demonstrated that using an α value of 0.46 gives good results for a range of investigated soils. Weitz *et al.* (1997) investigated humid tropical soils with porosities in the order of 70% and reported good agreement using $\alpha = 0.47$. Other findings, *e.g.* Dirksen and Dasberg (1993); Ponizovsky *et al.* (1999), indicate that α varies between soils, thus calling for calibration of measurements.

Varying dielectric properties of water may also explain differences in α . The water molecules adsorbed on particle surfaces are less mobile and this 'bound water' is often considered as having a dielectric number similar to ice, *i.e.* 3.2. As water molecules are situated more distant from the surface the dielectric properties are more and more similar to free, bulk water. Four-phase mixing models, distinguishing between free and bound water, have also been presented (Dobson *et al.* 1985). Yu *et al.* (1999) suggested that for organic soils, because of their high surface area, associated with high fractions of bound water, a four-phase mixing model should be used

$$K_{\alpha}^{\alpha} = (\theta - \theta_{bw})K_w^{\alpha} + \theta_{bw}K_{bw}^{\alpha} + (1-\eta)K_{\text{sol}}^{\alpha} + (\eta - \theta)K_{\text{air}}^{\alpha} \quad (4)$$

where K_{bw} is the dielectric number of the bound water and θ_{bw} is the fraction of bound water. The solution with respect to water content is then

$$\theta = \frac{K_{\alpha}^{\alpha} - (1-\eta)K_{\text{sol}}^{\alpha} - \eta K_{\text{air}}^{\alpha} + \theta_{bw}(K_w^{\alpha} - K_{bw}^{\alpha})}{K_w^{\alpha} - K_{\text{air}}^{\alpha}} \quad (5)$$

Note that different values of the geometry parameter result, depending on whether data are fitted to a three- or a four-phase mixing model. Weitz *et al.* (1997), *e.g.*, reported an α -value of 0.6 for the best fit to the four-phase model, Dobson *et al.* (1985) used an average value of 0.65, and Dirksen and Dasberg (1993) found values ranging from 0.39 to 0.81 for seven clay soils, in contrast to the suggested three-phase α -value of 0.5.

Ponizovsky *et al.* (1999) presented a further elaboration of the four-phase model in their assumption of a piecewise constant distribution of the soil water dielectric

number and found this model to be superior in a comparison with the models described above. Their study covered seven soil types, ranging from clay to sand in texture. In practise, however, since data on bound water are difficult to obtain, the use of four-phase mixing models has so far resulted in calibration functions with three parameters; α , K_{bw} and θ_{bw} .

In the theoretical four-phase Maxwell-De Loor mixing model, no empirical geometry parameter is introduced but the problem of assessing properties for bound water is unchanged. Dirksen and Dasberg (1993) recommended the use of the Maxwell-De Loor model because it avoids having to handle the unpredictable behaviour of the geometry parameter. Bohl and Roth (1994) concluded that there is some uncertainty about the physical relevance of the Maxwell-De Loor model at high water contents. Weitz *et al.* (1997) tested the model and supported a general use of mixing models but recommended the use of the three-phase mixing model for their particular data.

Empirical polynomial models dominate in published TDR calibrations for organic soils. Already Topp *et al.* (1980) investigated a disturbed organic soil (bulk density 0.422 g/cm^3) reaching just above 50% by volume in water content. Later C.H. Roth *et al.* (1992) presented a calibration function for seven soil samples with organic matter content ranging from 10.5 to 54.8% C, extending Eq. (1) to water contents close to 80% by volume with $a = 2.33 \cdot 10^{-2}$, $b = 2.85 \cdot 10^{-2}$, $c = -4.31 \cdot 10^{-4}$, and $d = 3.04 \cdot 10^{-6}$. (Note that the proper calibration constants are given in a corrigendum by C.H. Roth *et al.* (1993).) However, in undrained and poorly decomposed *Sphagnum* peat, soil water content regularly extends above 90% by volume. Pepin *et al.* (1992) evaluated 163 samples of undisturbed peat taken from 5 to 50 cm depth with porosities ranging from 83 to 95%. They found that a second-order equation performed well, claiming a standard deviation of 3.4% in the range 21 to 95% by volume. In the context of Eq. (1), their parameters were $a = 0.85 \cdot 10^{-1}$, $b = 1.92 \cdot 10^{-2}$, $c = -0.95 \cdot 10^{-4}$, and $d = 0$. Myllys and Simojoki (1996) suggested a third-order equation with $a = -8.30 \cdot 10^{-2}$, $b = 4.32 \cdot 10^{-2}$, $c = -8.53 \cdot 10^{-4}$, and $d = 5.99 \cdot 10^{-6}$ for 24 samples of cultivated *Sphagnum* peat, taken from 5 to 25 cm depth. Toikka and Hallikainen (1989) took a practical view of the problem and suggested a linear relationship between dielectric number and water content in the range 50 to 80% by volume.

The generality of mixing models (Eq. (3)) has also motivated application of them to peat soils. K. Roth *et al.* (1990) included a peat (Typic Sphagnofibrist) soil core in the wide range of soils in their study. Bohl and Roth (1994) included several organic soil samples in an evaluation of dielectric mixing models. They found that the four-phase mixing model (Eq. (5)) and the Maxwell-De Loor model described the $\theta(K_a)$ -relation well when θ_{bw} was allowed to be optimised, whereas the three-phase model application (Eq. (3)) with $\alpha = 0.5$ was less successful. Schaap *et al.* (1997) made a study over several organic forest floor soils and concluded that it should be possible to use a relationship similar to Eq. (3) with $\alpha = 0.5$, but that the amount of bound water has to be considered, which would give different values of K_w . To our

knowledge, no attempt has so far been made to test any dielectric mixing-model on a poorly decomposed *Sphagnum* peat.

When performing seasonal measurements in peat with high water contents, temperature corrections have to be considered as the dielectric number of water changes considerably with temperature. Between 0 and 30 °C, K_w decreases from 88 to 76 (e.g. Weast 1980). Polynomial functions, like Eq. (1), are determined at a certain temperature. In order to account for temperature dependence, additional multi-temperature calibrations are thus needed. Composite mixing models, that are physically based, allow for temperature corrections if K_w is made a function of temperature, although Pepin *et al.* (1995) found some deviations from theory in the net effect of temperature for $K_a(\theta)$ relations.

Methods

Site Description

The calibration was carried out using undisturbed samples from the bog Stormossen at 60°07'N, 17°05'E, in central Sweden, 50 km north of Uppsala. The bog is representative of undisturbed, open bogs in the southern part of the boreal zone and was used as a site of the climate processes land-surface experiment NOPEX (Halldin *et al.* 1999; Kellner and Halldin 2002).

Bog hollows are dominated by *Sphagnum* species of the *Cuspidata* section (*S. balticum*, *S. tenellum*) and *Eriophorum vaginatum* dominates the cover of vascular plants. Ridges and hummocks are covered by denser *Sphagnum* species (*S. fuscum*, *S. rubellum*) and the shrub layer is dominated by low *Calluna vulgaris* and *Empetrum nigrum*.

TDR Calibration

Sampling of peat for the TDR calibration took place in summer 1998. Eight samples were cut out from the bog surface layer; four of the samples were taken from hummocks and four from hollows. The specially designed stainless steel box-samplers also operated as containers to keep the samples undisturbed during transport and laboratory examination. The samples were 45 cm long and 20 cm wide in order to be sufficiently large for insertion of the 40-cm long three-rod TDR probes (Dynamax Inc.). The sampling depth was 40-45 cm for the hummock samples and 30-40 cm for the hollow samples. The samples were put in plastic jars in which the water level could be regulated. Low-tension pF-curves could be established in three hummock samples and two hollow samples by inserting TDR probes and small tensiometers at average depths of 5, 15 and 25 cm below peat surface. Three of the samples (one hollow and two hummock samples) were then cut in 10-cm thick segments and a TDR probe was inserted in each segment. Cutting was done carefully with a saw-toothed knife, following marks to get the right thickness. The segments were totally

immersed in water and the depth from the water surface down to the segment was measured in a grid net of 20 points to get the thickness of the segment. The dielectric number was measured in the samples while they were saturated and later as they were air-dried at ambient indoor temperature. Water content was simultaneously measured by collecting drained water from the saturated samples and by weighing the unsaturated samples. After 7-10 days, the TDR probes were removed and the samples cut in pieces and oven dried at a temperature of 70°C, in order to determine bulk density. Before drying the samples, their states of humification were determined using the von Post scale (von Post and Granlund 1926) as described by Clymo (1983). The degree of humification is thus given in classes (H1-H10) where H1 is unhumified and H10 is totally humified. Porosity of each sample was calculated using solid organic matter density 1.4 g/cm³ (Eggelsmann *et al.* 1993).

The TDR probes were connected to a Tektronix 1502C TDR, controlled by a Campbell data logger. Trace curves were stored and trace length was later interpreted with software that identified start and end of the probe by an algorithm based on a method by Heimovaara and Bouten (1990). This algorithm identifies the start of the probe trace as the coincidence of the trajectories of the trace before and after the probe connection. An offset value was thereafter subtracted from the measured value to obtain the length of the probe trace, excluding the probe handle. It was noted that the water content influenced the starting point of the probe traces. Empirically found offset values, proportional to the trace length, *i.e.*, the water content, were thus used.

The effect of sample size and volume around the TDR probes on the dielectric number measurements was studied in a water-filled rectangular tub where a vertical probe was moved from the centre towards the rim. The dielectric number started to be significantly different when the distance between probe and rim became less than 3 cm. At 2.5-cm distance K_a had decreased 1 unit, from 78.5 to 77.5. The given values of the measurements were therefore interpreted as representing mean values of the soil within 2.5 cm from the probes. This is in agreement with the results of Weitz *et al.* (1997).

The uncertainty in the calibration depends partly on the uncertainty in the gravimetric estimations (sample weight and volume) and partly on the uncertainty in the estimation of K_a . Probable error of bulk density was estimated to 3% by error-propagation analysis from uncertainty of laboratory scales and in the volume determination. The standard error of the dielectric number was estimated, by identifying the start and end of the probe trace under steady state conditions, to typically 0.1 in the drier samples and 0.4 in the wettest samples. The standard error grows with increasing K_a , since K_a is proportional to the square of the trace length.

Eqs. (1), (3) and (5) were applied to the transformation from measured dielectric number to water content and the results were compared with measurements. For Eq. (1) the parameter values suggested by Topp *et al.* (1980), Pepin *et al.* (1992) and C.H. Roth *et al.* (1992) were used. For Eq. (3) the parameter value $\alpha = 0.5$ was used.

In addition, a multiple regression analysis of the data was performed to relate θ to K_a . The selected values of dielectric numbers for mixing model analysis were: $K_{sol} = 5.0$, $K_{air} = 1.0$, $K_{bw} = 3.2$, $K_w = 79.2-79.6$ (22-23°C). The coefficient of determination, r^2 , and the standard error were used to describe goodness of fit. In order to test the influence of structure, the samples were grouped into classes by their degree of humification. The analysis was done for each of the classes and for the pooled data of all samples. Measured θ values from each class were compared with calculated values for each regression function. The residuals of the classes were compared to reveal possible differences between the classes (t-test, $p < 0.1$). The distributions of K_a values in each class and of the pooled data were checked with χ^2 test.

Results

Peat Characteristics

The total porosity was similar in all samples, from 95% in the deepest layers to 97% in the surface layer (Table 1). The degree of humification was within H2-H3 in the top layers. The humification increased with depth to H4 at 30-40 cm depth. In all samples, there were strings of dark humic matter following the root structure of the vascular plants. The hollow samples showed clusters of more decomposed material with humification H7 around tufts of grass roots. The bulk density (and thus the porosity) varied with the degree of humification (Fig. 1) but the scatter was too large to find a relationship by regression.

The water holding characteristics at 5 cm depth of hummocks agreed well with results by Hayward and Clymo (1982) for *Sphagnum capillifolium* (Fig. 2). In two of the hummock samples, the layer 10-15 cm depth could hold less water than sur-

Table 1 – Physical characteristics and their standard deviation in the investigated samples.

Sample	Level (cm)	Dry bulk density (g cm ⁻³) (± SD)	Porosity	Degree of humification (von Post)
Hummock #1	0-10	0.0363 ± 0.0021	0.974 ± 0.002	H3
	10-20	0.0426 ± 0.0024	0.970 ± 0.003	H3
	20-30	0.0572 ± 0.0031	0.959 ± 0.004	H3
	30-40	0.0483 ± 0.0027	0.965 ± 0.003	H4
Hummock #2	0-10	0.0372 ± 0.0023	0.973 ± 0.003	H2
	10-20	0.0291 ± 0.0019	0.979 ± 0.002	H2
	20-30	0.0410 ± 0.0024	0.971 ± 0.003	H3
	30-40	0.0542 ± 0.0032	0.961 ± 0.004	H4
Hollow #1	0-10	0.0399 ± 0.0023	0.972 ± 0.003	H2
	10-20	0.0546 ± 0.0031	0.961 ± 0.004	H4
	20-30	0.0662 ± 0.0039	0.953 ± 0.004	H3

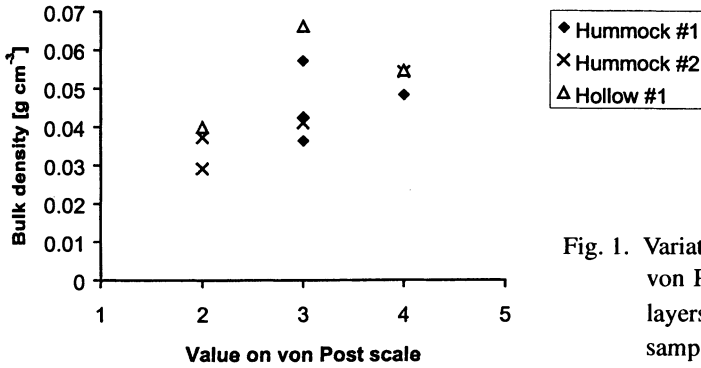


Fig. 1. Variation of bulk density with von Post number in different layers of three surface peat samples.

rounding layers, whereas in the third profile there was a stronger water holding capacity at this level. This third profile (Hummock #1 in Fig. 1) was also found to have a higher degree of humification than the other humification-examined profile (Hummock #2). The hollow 5-10 cm samples could generally retain water better than the hummock samples and differed largely from the hollow species (*S. papillosum*) characteristics found by Hayward and Clymo (1982) but agreed fairly well with the results of Päivänen (1973) for *Sphagnum* Spp. samples. The surface level of the hollow samples dropped on average 2 cm when the water table was lowered 25 cm. With an original sample height of 40 cm this means a compression of 5%. However, the surface levels in the hummock samples did not change notably. The possible effects of the compression on the pF curve were omitted.

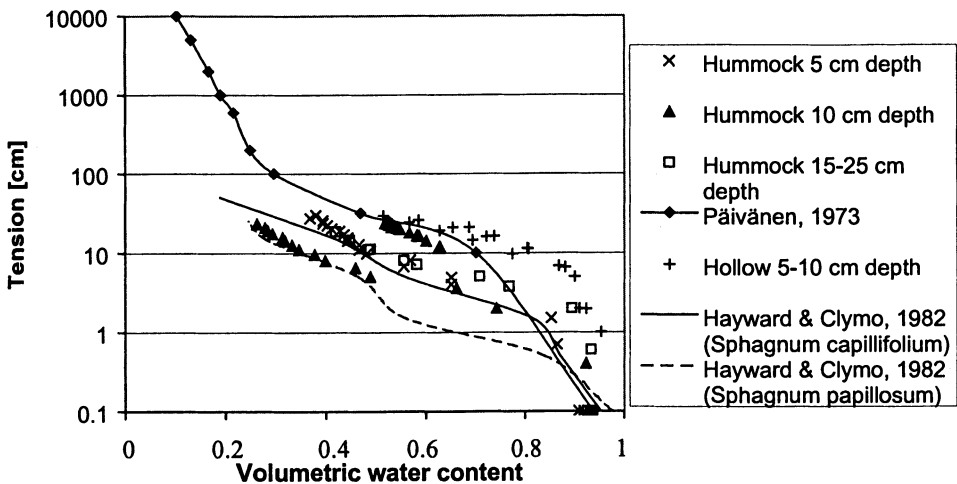


Fig. 2. Water holding characteristics for laboratory peat samples. All data are established during a drying sequence starting with completely saturated samples.

Water Content in Peat Soil by TDR

Table 2 – Parameters (\pm standard error) for the third-order equation $\theta = a + bK_a + cK_a^2 + dK_a^3$ by regression analysis.

Parameter	Pooled data	Degree of humification (von Post)		
		H2	H3	H4
<i>a</i>	$3.9 (\pm 1.3) \cdot 10^{-2}$	$6.1 (\pm 1.4) \cdot 10^{-2}$	$5.9 (\pm 1.8) \cdot 10^{-2}$	$4.4 (\pm 6.0) \cdot 10^{-2}$
<i>b</i>	$3.17 (\pm 0.2) \cdot 10^{-2}$	$2.9 (\pm 0.2) \cdot 10^{-2}$	$2.8 (\pm 0.2) \cdot 10^{-2}$	$3.4 (\pm 0.5) \cdot 10^{-2}$
<i>c</i>	$-4.5 (\pm 0.5) \cdot 10^{-4}$	$-4.5 (\pm 0.7) \cdot 10^{-4}$	$-3.2 (\pm 0.6) \cdot 10^{-4}$	$-5.1 (\pm 1.4) \cdot 10^{-4}$
<i>d</i>	$2.6 (\pm 0.4) \cdot 10^{-6}$	$3.0 (\pm 0.6) \cdot 10^{-6}$	$1.4 (\pm 0.5) \cdot 10^{-6}$	$3.0 (\pm 1.0) \cdot 10^{-6}$
Number of data points	190	56	98	36
<i>R</i> ²	0.968	0.989	0.976	0.948
Standard Error of θ estimate	0.04	0.03	0.04	0.04

TDR-Calibration

The χ^2 test showed the H2 class to be lognormally distributed, whereas neither normal nor lognormal distributions were rejected for any other class. The H2 class values were logarithmically transformed before analysis. The other classes and the pooled data were analysed without transformation.

The less decomposed samples yielded larger values of K_a at the same water content. Especially samples within the H2 class differed from the others in this respect. The H2 class differed also significantly from the other classes in the comparison of the third order functions derived for the relationships $K_a(\theta)$ (Table 2; Fig. 3). No clear difference between the hollow and hummock samples was found.

The dielectric three-phase mixing-model was, with its single parameter α , less effective in distinguishing between the humification classes. Despite that α was significantly different between classes, varying from 0.28 for H4 to 0.38 for H2, the differences between calibration functions were within one standard error of the estimation. The pooled data resulted in an α -value of 0.34. Introducing a four-phase model, using the bound-water content, θ_{bw} , as a free parameter, improved the fit to the data in all classes (Table 3, Fig. 3). However, the resulting θ_{bw} was negative in the best fit to the H2 class. When α was set constant, the bound-water content attained in the regression increased with degree of humification. When θ_{bw} was held constant, the α value decreased with increased degree of humification whereas a higher fixed value of θ_{bw} caused α to increase (Table 4).

The second-order function suggested by Pepin *et al.* (1992) and the third-order function found by C.H. Roth *et al.* (1992) generally underestimated the water content (Fig. 4). Using $\alpha = 0.5$ in the three-phase dielectric mixing model also generally rendered too low values of wetness. The function presented by Topp *et al.* (1980)

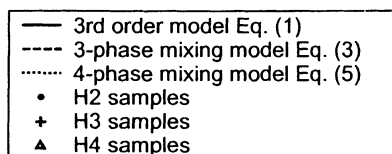
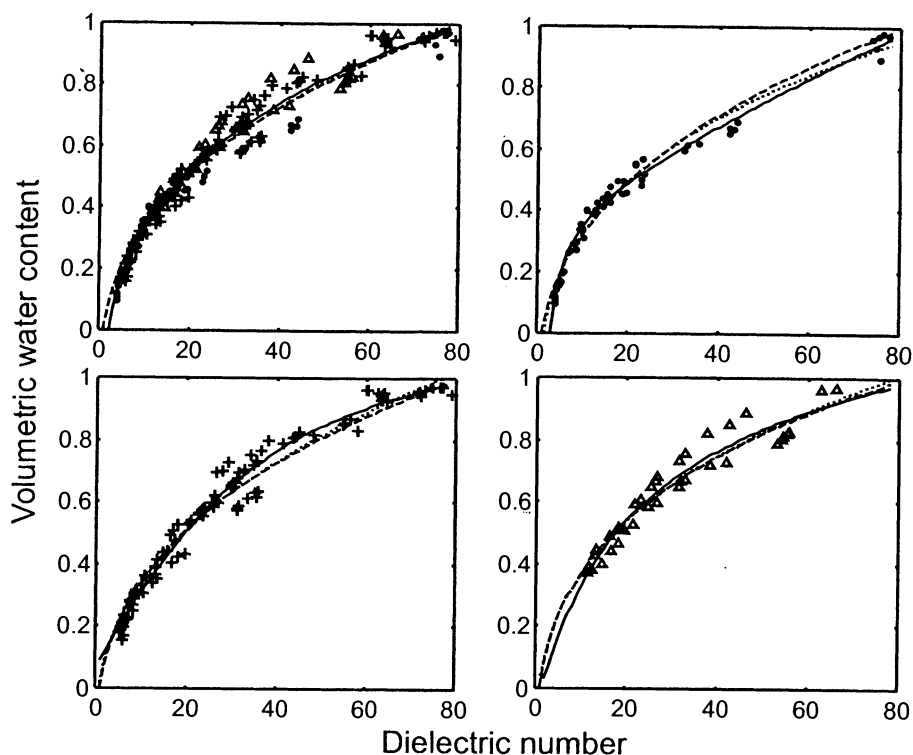


Fig. 3. Regression curves of three models (Eqs. (1), (3) and (5)), fitted to different groups of peat samples, divided according to their degree of humification (H2-H4 on von Post scale).

deviated significantly from the sample populations and the other functions describing organic soils. Among the three different classes of humification the H2 data fitted best to all of these functions (Table 5).

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Table 3 – Estimated values of the parameters α (Eqs. (3),(5)) and θ_{bw} (Eq. (5)) by regression.

Degree of humification (von Post)	Equation	α	Parameters		Standard error of θ estimate
			θ_{bw}	r^2	
H2	Eq. 2	0.38	–	0.976	0.037
	Eq. 3	0.29	-0.048	0.982	0.034
H3	Eq. 2	0.33	–	0.968	0.044
	Eq. 3	0.39	0.026	0.970	0.043
H4	Eq. 2	0.28	–	0.929	0.046
	Eq. 3	0.31	0.016	0.946	0.046
Pooled data	Eq. 2	0.34	–	0.966	0.045
	Eq. 3	0.35	0.0061	0.967	0.045

Table 4 – Estimated values of the parameters α and θ_{bw} (Eq. (3)) by regression with fixed value (given in italics) on one of the parameters.

Degree of humification (von Post)	α	Parameters		Standard error of θ estimate
		θ_{bw}	r^2	
H2	<i>0.50</i>	0.042	0.967	0.046
	0.49	<i>0.050</i>	0.966	0.046
	0.611	<i>0.10</i>	0.944	0.059
H3	<i>0.50</i>	0.069	0.965	0.046
	0.44	<i>0.050</i>	0.969	0.044
	0.55	<i>0.10</i>	0.958	0.050
H4	<i>0.50</i>	0.093	0.930	0.050
	0.38	<i>0.050</i>	0.943	0.046
	0.49	<i>0.10</i>	0.929	0.050
Pooled data	<i>0.50</i>	0.067	0.959	0.049
	0.44	<i>0.050</i>	0.963	0.047
	0.56	<i>0.10</i>	0.951	0.054

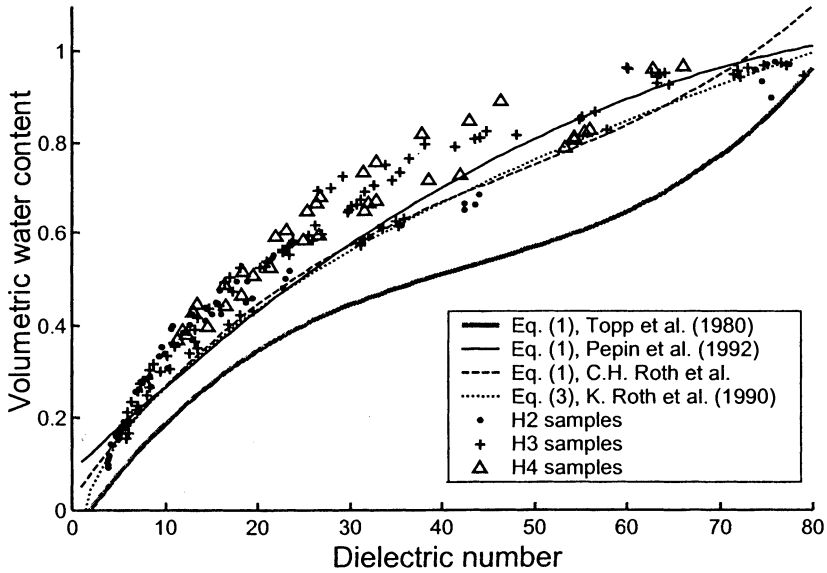


Fig. 4. Relationship between the apparent dielectric number and the volumetric water content in *Sphagnum* peat samples with different degree of humification (on the von Post scale). Plotted are also calibration functions by other authors.

Table 5 – Goodness of fit parameters correlation (r^2) and standard error (SE) in the relations between measured water contents and calculated water content for four suggested functions.

Degree of humification (von Post)	Parameter	Function			
		Polynomial models			Dielectric mixing model
		Topp <i>et al.</i> (1980)	Pepin <i>et al.</i> (1992)	C.H. Roth <i>et al.</i> (1992)	K. Roth <i>et al.</i> (1990)
H2	R^2	0.970	0.946	0.970	0.961
	SE	0.14	0.07	0.06	0.07
H3	R^2	0.935	0.961	0.965	0.940
	SE	0.19	0.07	0.08	0.08
H4	R^2	0.936	0.920	0.923	0.907
	SE	0.23	0.10	0.10	0.10
Pooled data	R^2	0.937	0.948	0.959	0.937
	SE	0.18	0.07	0.08	0.08

Discussion

The peat water characteristic relations found in this study (Fig. 2) suggest that the main parameters for water retention capacity are depth of the layer and its degree of humification although *Sphagnum* species composition also influences in the surface layers.

The higher retention capacity of the hollow 5-10 cm depth samples probably depends on a higher decomposition activity close to the water table. The wetness around the fluctuating water table makes it a favourable environment for decomposition, thereby increasing both degree of humification and bulk density. As the humified peat will have more fine humus particles, it can hold more water at moderate tensions. The results also suggest that the hollow layers have a weaker structure, which will get more compacted when the support decreases as the water table is lowered. The compressed peat then also gets a higher water retention capacity. Weiss *et al.* (1998) found that bulk density, peat type (*Sphagnum*, *Carex* or ligneous) and a distinction between the surface and deeper layers were, in order, the most significant variables explaining parameters for a modified van Genuchten (1980) pedotransfer function. These results indicate that a separation of *Sphagnum* species or the level in relation to water table would improve such an estimation of parameter values.

The third-order polynomial with its four adjustable parameters was naturally easier to fit individually to different groups of data than the one- (Eq. (3)) or two-parameter (Eq. (5)) mixing models. However, the scatter was large and the degree of humification is crudely described (with von Post scale) and probably not the exclusive factor to consider. Hence, the use of separate H2-, H3-, and H4-functions keeps being an open question. We would therefore rather use the pooled data functions, although the maximal scatter range was as large as $\pm 10\%$. There were small differences in the pooled data regressions of the third-order function and the mixing models. If the theoretical ground for the mixing models holds, they would be preferable to use in field measurements as they allow adjustment of parameter values by the physical properties of the peat and for change in K_w with temperature.

The values of α , ranging from 0.28 to 0.38 in this study, suggest that the investigated peat is more organised in vertical structures than the soils investigated by K. Roth *et al.* (1990). Comparing with the relationship reported by Pepin *et al.* (1992), it seems from the shape of the curve that an α -value about 0.5 would result, had they used the mixing model (Eq. (3)). Lapen *et al.* (2000) made a TDR-calibration for a study on bog and fen peat and used a model with linear relationship between θ and $K_a^{0.5}$, which is close to the relation found by Pepin *et al.* (1992). There are also indications (Table 3; Fig. 3) that low humification degree is associated with high α -value. Connecting to the theory behind the three-phase mixing model, this suggests that the peat is gradually reorganised from more or less isotropic conditions towards a more vertically arranged structure. This is hard to accept on physical ground as the peat normally changes from a fibrous to a more amorphous structure during decom-

position. On the other hand, highly decomposed root tufts of primarily *Eriophorum* plants were more common in the decomposed layers (H3 and H4). The presence of these humus accumulations may give an effect of discontinuity along the probes that resembles a vertical soil structure. The occurrence of these discontinuities may also explain the large scatter in the $K_a(\theta)$ relation among the H3 and H4 samples. Applying a calibrated function in this occasionally heterogeneous and anisotropic medium may hence be questionable as well as applying it to both horizontally and vertically inserted probes.

The relative amount of bound water affects the relation between water content and K_a and the resultant K_a becomes smaller for soils with large specific area (Yu *et al.* 1999). For peat, the amount of bound water is likely to increase with degree of humification, as the amount of small humus particles, and thereby the specific area of the peat, increases. The results also indicate larger amount of bound water in the more decomposed samples at the same assigned α -value. However, to confirm a hypothesis stating that the dielectric number depends on the structural organisation and amount of bound water, these two entities must be quantifiable and measurable. The von Post method is not strictly objective and does not give a quantitative measure of the proportion of humic substances. On the other hand, there is presently no other reliable and readily used method to determine the proportion of humic matter (Eggelsmann *et al.* 1993) although bulk density can possibly be used as it is related to the degree of humification (*e.g.* Boelter 1969; Päivänen 1973; Eggelsmann *et al.* 1993) and should have an effect on the water holding capacity. In this study the connection between the $K_a(\theta)$ relation and bulk density was fairly weak, though.

There is a significant difference between the $K_a(\theta)$ relations found in this study and earlier findings by other authors. Studying a similar peat, Pepin *et al.* (1992) spotted a divergence in $K_a(\theta)$ between two different sizes (5 and 3 cm wide, respectively) of their two-wire probes. The larger probes needed a larger sample thickness and underestimated the K_a value because of insufficient sample volume round the probes. The deviation found in their data resembled the deviation between this study and their accurate, small probes. The three-wire probes we used in this study were also wide (6 cm), which increases the risk of insufficient sample volume round the probes. On the other hand, the use of three-wire probe concentrates the electric field distribution considerably compared to the use of two-wire probes (Zegelin *et al.* 1989) and calls for a smaller sample thickness. The large scatter between different samples in this study indicates that variation in physical properties may be a cause to differences to other author's results. A problem of laboratory setting is also that the distribution of water content could be uneven in the samples. No measurements of changes in volume were made during calibration, but peat is further a non-rigid material and drying of samples can cause shrinkage. The largest problem herein concerns the representation of measurements as the volume of the sample itself has changed. However, the effects of increases in bulk density and fraction of bound water on the TDR signal would probably be small. Shrinkage of up to a third of the vol-

ume in a soil with 5% organic matter will cause a change of 3% in porosity. Using Eq. (3), this will only change the water content reading with 0.4%. The effect of the increased fraction of bound water is difficult to estimate. However, extrapolating a sensitivity analysis presented by Yu *et al.* (1999), if a more appropriate specific area of 600 m²/g is used, a two-fold increase of solid matter will not change the reading of water content more than 1%.

Conclusions

The peat hydraulic characteristics conformed to results found by other authors. In the surface layer, with living mosses, the moss species composition is important, but in lower layers, the degree of humification and bulk density seem to be dominating factors. The samples in this study generally had lower K_a values than earlier published functions for the same θ values. There were also large dissimilarities in the $K_a(\theta)$ relation between different samples. Amount of bound water and structural orientation are likely to affect the $K_a(\theta)$ relation. Useful parameters expressing these entities could be humification, combined with bulk density, structure and orientation. However, there is a lack of methods to measure and quantify these properties. Further studies on physical properties of peat soil are thus needed in order to use theoretically deduced functions properly. Therefore, for the time being, empirical or semi-empirical calibration curves are preferred. The empirical polynomial model appeared to be easier to fit to humification-classified groups of data than the mixing models. However the two types almost equivalently reproduced pooled data. A four-phase mixing model did not give better fit to the data than a three-phase model when physically reasonable values of bound water were applied. The ability to include physically based temperature adjustments gives an advantage for the mixing models over the polynomial, for field measurements with substantial temperature fluctuations.

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References

- Birchak, J.R., Gardner, C.G., Hipp, J.E., and Victor, J.M. (1974) High dielectric constant microwave probes for sensing soil moisture, *Proc. IEEE*, Vol. 62, pp. 93-98.
- Boelter, D.H. (1969) Physical properties of peat as related to degree of decomposition, *Soil Sci. Soc. of America J.*, Vol. 33, pp. 606-609.
- Bohl, H., and Roth, K. (1994) Evaluation of dielectric mixing models to describe the $\theta(\epsilon)$ -relation, In: Symposium on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications, Spec. Publ. SP19-94, Bur. of Mines, U.S. Dep. of Interior, Washington D.C., pp. 309-319.
- Clymo, R.S. (1983) Peat, In: Gore, A.J.P. (Ed.), *Ecosystems of the World 4A Mires: Swamp, Bog, Fen and Moor*, Elsevier Scientific Publishing Company, Amsterdam, pp. 159-224.
- Dasberg, S., and Hopmans, J.W. (1992) Time-domain reflectometry calibration for uniformly and nonuniformly wetted sandy and clayey loam soils, *Soil Sci. Soc. of America J.*, Vol. 56, pp.1341-1345.
- Dirksen, C., and Dasberg, S. (1993) Improved calibration of time-domain reflectometry soil-water content measurements, *Soil Sci. Soc. of America J.*, Vol. 57, pp.660-667.
- Dobson, M.C., Ulaby, F.T., Hallikainen, M.T., and El-Rayes, M.A. (1985) Microwave dielectric behavior of wet soil. II: Dielectric mixing models, *IEEE Trans. Geosci. Remote Sens.*, GE-23(1), pp.35-46.
- Eggelsmann, R., Heathwaite, A.L., Grosse-Brauckmann, G., Küster, E., Naucke, W., Schuch, M., and Schweickle, V. (1993) Physical Processes and Properties of Mires, In: Heathwaite, A.L. and Göttlich, K.H., *Mires: Process, Exploitation and Conservation*, John Wiley and Sons, Chichester, UK, pp. 171-262.
- van Genuchten, M.T. (1980) A closed form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Sci. Soc. of America J.*, Vol. 44, pp. 892-898.
- Halldin, S., Gryning, S.-E., Gottschalk, L., Jochum, A., Lundin, L.-C., and Van de Griend, A.A. (1999) Energy, water and carbon exchange in a boreal forest landscape – NOPEX experiences, *Agri. and Forest Met.*, Vol. 98-99, pp. 5-29.
- Hayward, P.M., and Clymo, R.S. (1982) Profiles of water content and pore size in Sphagnum and peat, and their relation to peat bog ecology, *Proc. of the Royal Soc. of London, Series B*, Vol. 215, pp. 299-325.
- Heimovaara, T.J., and Bouten, W. (1990) A computer-controlled 36-Channel Time Domain Reflectometry System for Monitoring Soil Water Contents, *Wat. Resour. Res.*, Vol. 26, pp. 2311-2316.
- Kellner, E., and Halldin, S. (2001) Water budget and surface-layer water storage in a Sphagnum bog in central Sweden, *Hydrol. Proc.*, in press.
- Lapen, D.R., Price, J.S., and Gilbert, R. (2000) Soil water storage dynamics in peatlands with shallow water tables, *Can. J. of Soil Sci.*, Vol. 80, pp.43-52.
- Myllys, M., and Simojoki, A. (1996) Calibration of time domain reflectometry (TDR) for soil moisture measurements in cultivated peat soils, *Suo*, Vol. 47, pp. 1-6.
- Päivänen, J. (1973) Hydraulic conductivity and water retention in peat soils, *Acta For. Fenn.*, Vol. 129, pp.1-70.
- Pepin, S., Livingston, N.J., and Hook, W.R. (1995) Temperature-dependent measurement errors in time-domain reflectometry determinations of soil-water, *Soil Sci. Soc. of America J.*, Vol. 59, pp. 38-43.

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- Pepin, S., Plamondon, A.P., and Stein, J. (1992) Peat water-content measurement using time domain reflectometry, *Can. J. of Forest Res.*, Vol. 22, pp. 534-540.
- Ponizovsky, A.A., Chudinova, S.M., and Pachepsky, Y.A. (1999) Performance of TDR calibration models as affected by soil texture, *J. of Hydrol.*, Vol. 218, pp. 35-43.
- von Post, L., and Granlund, E. (1926) Södra Sveriges torvtillgångar (in Swedish), *Sveriges Geologiska Undersökning, Årsbok 1925, Ser. C 335*, pp. 1-127.
- Roth, C.H., Malicki, M.A., and Plagge, R. (1992) Empirical evaluation of the relationship between soil dielectric constant and volumetric water content as the basis for calibrating soil moisture measurements by TDR, *J. of Soil Sci.*, Vol. 43, pp. 1-13.
- Roth, C.H., Malicki, M.A., and Plagge, R. (1993) Corrigenda, *J. of Soil Sci.*, Vol. 44, pp. 749.
- Roth, K., Schulin, R., Flühler, H., and Attinger, W. (1990) Calibration of time domain reflectometry for water content measurement using a composite dielectric approach, *Wat. Resour. Res.*, Vol. 26, pp. 2267-2273.
- Schaap, M.G., de Lange, L., and Heimovaara, T.J. (1997) TDR calibration of organic forest floor media, *Soil Tech.*, Vol. 11, pp. 205-217.
- Toikka, M.V., and Hallikainen, M. (1989) A practical electrical instrument for in situ measurement of peat properties, In: Dodd, V.A. and Grace, P.M., *Land and water use, Agricultural engineering: Proceedings of the Eleventh International Congress on Agricultural Engineering*, Dublin, 4-8 September 1989, Balkema, Rotterdam, pp. 804. pp. 101-105.
- Topp, G.C., Davis, J.L., and Annan, A.P. (1980) Electromagnetic determination of soil water content: measurements in coaxial transmission lines, *Wat. Resour. Res.*, Vol. 16, pp. 574-582.
- Weast, R.C. (Ed.) (1980) *CRC Handbook of chemistry and physics: a ready-reference book of chemical and physical data*, Ed. 60, CRC Press, Cleveland, Ohio.
- Weiss, R., Alm, J., Laiho, R., and Laine, J. (1998) Modeling moisture retention in peat soils, *Soil Sci. Soc. of America J.*, Vol. 62, pp. 305-313.
- Weitz, A.M., Grauel, W.T., Keller, M., and Veldkamp, E. (1997) Calibration of time domain reflectometry technique using undisturbed soil samples from humid tropical soils of volcanic origin, *Wat. Resour. Res.*, Vol. 33, pp. 1241-1249.
- Yu, C., Warrick, A.W., and Conklin, M.H. (1999) Derived functions of time domain reflectometry for soil moisture measurement, *Wat. Res. Res.*, Vol. 35, pp. 1789-1796.
- Zegelin, S.J., White, I., and Jenkins, D.R. (1989) Improved field probes for soil water content and electrical conductivity measurement using time domain reflectometry, *Wat. Resour. Res.*, Vol 25, pp. 2367-2376.

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