Thermal diffusivity of the peat soil surface layer

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Summary

The paper presents the results of thermal diffusivity estimation in peat soil using two methods: amplitude equation and non-steady state single probe technique. The performed study showed that the water content did not significantly influence on the soil thermal diffusivity. Application of the two different methods for the volumetric soil water content ranging from 50 to 70 % gave comparable results of thermal diffusivity for the peat soil surface layer.

Key index words: thermal diffusivity, peat soil and amplitude equation

Introduction

Solution of the heat transfer equation requires formulation of initial and boundary conditions and also soil thermal properties. The volumetric heat capacity (C_v) and apparent thermal conductivity (λ) should be assessed as the basic thermal parameters. The thermal diffusivity coefficient as the quotient between λ and C_v is defined. The volumetric heat capacity and thermal conductivity coefficient as the functions of the water content and the physical properties of the mineral soils are well reported in the literature by De Vries (1963), Jury *et al.* (1991) and Hubrechts (1998). These studies indicated relatively poor recognition of thermal properties of peat soils. Therefore, the main objective of this paper is to determine thermal diffusivity of the peat soil surface layer using two different methods. The first method is based on the temperature distributions measured at two different depths in the soil surface layer. The second method combines field measurements of the thermal conductivity using non-steady state single probe technique (NSSP) and the volumetric heat capacity calculated from the empirical formula.

Methods

The heat transfer equation for one-dimensional isotropic soil as described by Fourier law can be solved analytically with boundary conditions representing the sinusoidal changes of temperature on the soil surface and the average temperatures at lower boundary. The mathematical description of the soil temperature distribution as a function of depth and time can be written in the following form (Horton *et al.*, 1983):

$$T(z,t) = T_{avg} + A \cdot \exp\left(-z\sqrt{\omega/2K_T}\right)\sin\left(\omega t - z\sqrt{\omega/2K_T}\right) \quad (1)$$

where T_{avg} is the average soil temperature, A is the amplitude of the surface temperature wave and ω is the radial frequency equal to 2π divided by the period P, K_T is the apparent thermal diffusivity coefficient (m^2 s^{-1}). The measurements of the soil temperature distributions at two depths enables to calculate the thermal diffusivity explicitly from equation (1) which can be expressed as the amplitude equation (Evett, 2002):

$$K_T = \frac{\omega}{2}\left[(z_1 - z_2)/\ln(A_1/A_2)\right] \quad (2)$$

where A_1 is the amplitude at depth z_1, A_2 is the amplitude at depth z_2.

Thermal diffusivity (K_T) also is calculated as a quotient between measured value of thermal conductivity (λ) and value of volumetric heat capacity (C_v). Parameter λ can be measured using non - steady state single probe method. In this method, an electrical wire (probe) is inserted in the soil. A steady current is supplied to the probe and the temperature rise of the heat element is measured by a thermocouple and recorded during a short heating time period (approximately 100 s). The temperature T of the probe during heating is related to the time t according to the analytical solution for an infinite line heat source (Jackson and Taylor, 1986):

$$T - T_0 = (Q/4\pi\lambda)\cdot\ln(t + t') + d \quad (3)$$

where T_0 is the initial temperature in °C; Q is the energy input per unit length of heater per unit time in W m^{-1}, λ is the thermal conductivity of the material surrounding the line source in W m^{-1} $°C^{-1}$; t is a time correction used to account for the finite dimensions of the heat source and the contact resistance between the heat source and the medium outside the source and d is a constant. Assuming that during heating the relation between temperature of heat element T and ln(t) is linear the thermal conductivity can be expressed in the following form (Huksefluks, 2003):

$$\lambda = (Q/4\pi\Delta T)\cdot\ln(t_2/t_1) \quad (4)$$

For determination the volumetric heat capacity (C_v) can be determined using simple relation adopted from Romanov (1968) and implemented by Weiss *et al.* (2006):

$$C_v = C_m \rho + C_w \rho_w \theta \qquad (5)$$

where C_m is the specific heat of organic material equal 1.7 (J g^{-1} °C^{-1}), ρ is the soil bulk density (g cm^{-3}), C_w is the specific heat of water 4.2 (J g^{-1} °C^{-1}), ρ_w is the water density (g cm^{-3}), θ is the soil water content (cm^3 cm^{-3}).

Materials

The investigations were conducted at experimental station, located at Kwatera 17 of the Kuwasy drainage subirrigation system in the middle part of the Biebrza River Valley for the period from 15.04 to 19.07.2005 are reported in this study. The temperature distributions were measured in peat soil with hourly interval at two depths, 5 and 10 cm below the soil surface. The moisture regime of the soil was characterised by volumetric water content measured at 10 cm depth below surface with daily interval using TDR method with calibration equation proposed by Oleszczuk *et al.* (1998). The precipitation sums at each day of the investigated period were recorded using automatic raingauge. The soil temperature data were used for calculation of the daily amplitudes. Those values were then applied in eq. 2 for determination of thermal diffusivities for each day of the analysed period. Additionally on 8.09.2007 the preliminary values of thermal conductivity for the peat surface layer (0-15 cm) at the same field were measured along transect (52 measurements with 1m spacing) using non-steady single probe method. The gravimetric moisture content and bulk density values of considered soil were determined together with λ measurements. The volumetric heat capacities were determined using eq. 5. Then the K_T values were calculated as a quotient between λ and C_v values.

Results and discussion

The measured daily values of the peat soil moisture content and the sums of precipitation are shown in Fig. 1. The soil at the beginning of the analysed period was nearly saturated and volumetric soil moisture content was equal to 80.4%. During the next days the soil water content at 10 cm was gradually decreasing and at the end of the analysed period was approximately equal to 35%. The recorded rainfall was not able to stop the soil drying. Precipitation events were mainly influencing the values of the temperature amplitudes at the depth 5 and 10 cm (Fig. 1). From the data plotted in Fig. 1 it can be concluded that vegetation period in 2005 can be assumed as relatively dry. Therefore the analysed period allowed the study of the influence of the soil moisture content on thermal properties. The temperature amplitudes presented in Fig. 1 were used in (eq. 2) in order to calculate the thermal diffusivity coefficients for the days without the precipitation.

Relationship between the soil thermal diffusivity and its volumetric moisture content is presented in Fig. 2. The data presented in this figure showed that the soil water content changed of about 45% whereas the soil thermal diffusivity was ranging from 2.69 to 4.59 cm^2 h^{-1}. These data suggest that the water content in the surface peat layer did not significantly influence its thermal diffusivity. The performed calculations and analysis showed that values of the thermal diffusivity of organic soils are much lower in comparison with those of mineral soils (Fig. 2).

The second applied method was based on the field measurements of thermal conductivity (NSSP) and calculation of C_v value for peat surface layer along the transect. The average value of λ from each measuring point was equal to 0.317 (W m^{-1} °C^{-1}) and standard deviation was equal to 0.089 (W m^{-1} °C^{-1}). The average determined volumetric heat capacity value was 2.96 10^6 with standard deviation equal to 2.41 10^5 (J m^3 °C^{-1}). The thermal diffusivity values were

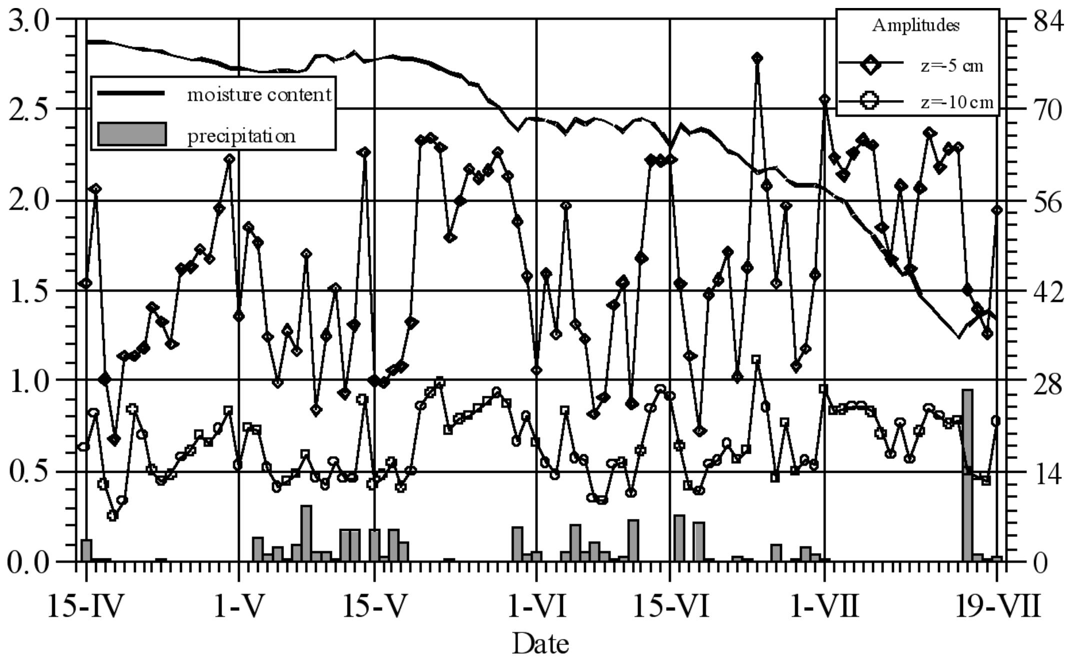

Figure 1. The measured values of volumetric moisture content in peat-moorsh soil as well as the values of soil temperature amplitudes and precipitation at Kwatera 17 of Kuwasy drainage subirrigation system for the period from 25 April to 19 July 2005.

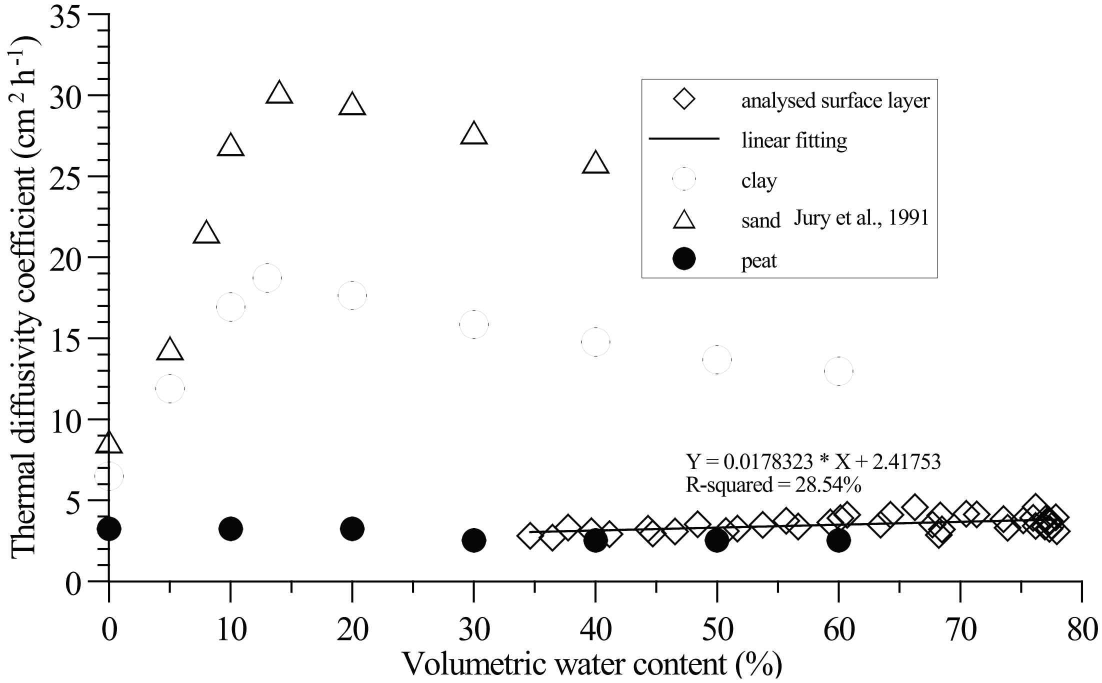

Figure 2. Soil thermal diffusivity data as function of the volumetric moisture content for different soil types.

calculated from estimated λ and C_v values. The K_T for each transect point determined from combined method (NSSP + C_v) are presented in Fig 3. From this figure it can be seen that K_T values ranging from 1.85 to 6.50 $cm^2\,h^{-1}$ whereas the corresponding soil moisture content values were ranging from 49.29 to 67.84%. The data presented in the Fig. 2 indicates that thermal diffusivities determined from amplitude equation were not significantly correlated to corresponding soil water contents. Therefore this data set was divided into five independent soil moisture classes (Table 1). Each class was characterised by average value of moisture content and by basic statistics for thermal diffusivity. Additionally in Table 1 the K_T values approximated from combined method were also presented. From the data presented in Table 1 it can be seen that the application of the two different methods for the same water content range from 50 to 70 % leads to the similar results. The calculated thermal diffusivity data using the first method showed slightly lower values for volumetric water content below 40% in comparison with combined method.

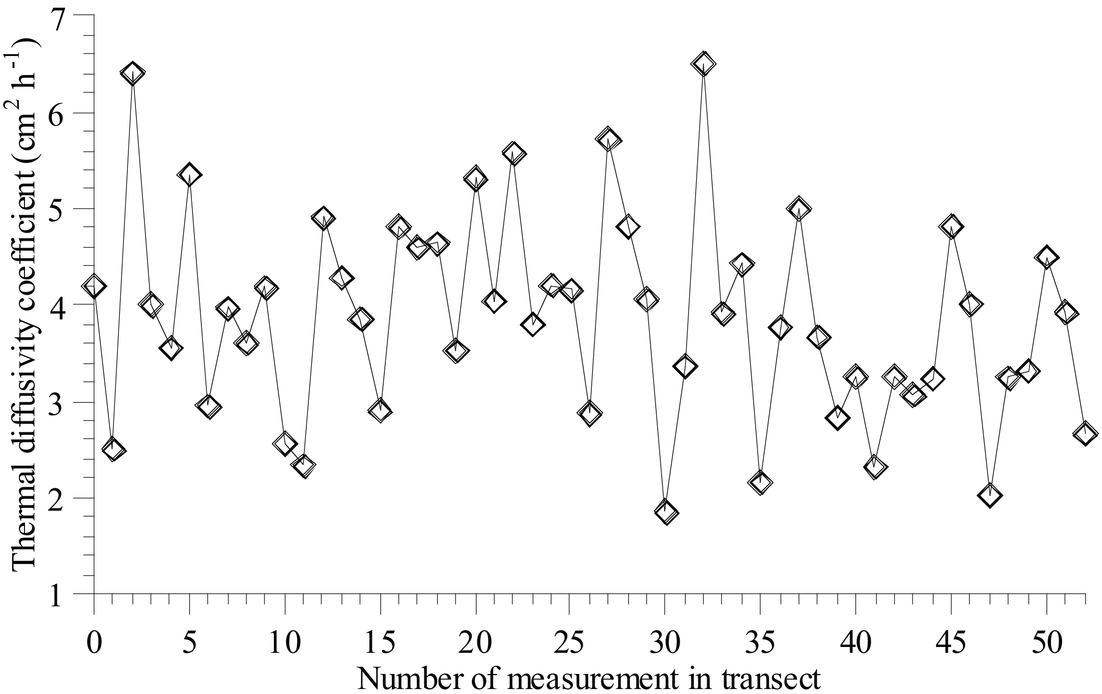

Figure 3. Thermal diffusivity calculated for each point of transect at 8.09.2007.

Table 1. Thermal diffusivity calculated for each point of transect at 8.09.2007.

Methods	Class of moisture content (%)	θ_{avg}* (%)	Thermal diffusivity ($cm^2\ h^{-1}$)				
			average	median	minimum	maximum	std#
Amplitude equation	>70	75.75	3.715	3.753	3.097	4.588	0.396
	60÷70	65.29	3.751	3.899	2.851	4.567	0.533
	50÷60	54.64	3.427	3.428	3.090	3.725	0.236
	40÷50	45.02	3.132	3.065	2.900	3.514	0.252
	<40	37.11	2.973	2.943	2.690	3.315	0.282
NSSP+C_v¶	49.28÷67.85	59.79	3.864	3.914	1.856	6.503	1.060

*- class average water content, #- standard deviation, ¶- combined method

Conclusions

The obtained results indicate that the thermal diffusivity of the studied peat layer can be approximated by application of the amplitude equation. The analysis of the performed calculation showed that the soil water content did not significantly influence on the soil thermal diffusivity of the surface peat layer. Application of the two different methods, for the volumetric soil water content ranging from 50 to 70%, leads to the comparable results of K_T values in average for analysed peat soil.

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