INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Int. Agrophys., 2019, 33, 277-283
doi: 10.31545/intagr/110773

Hydrophysical properties of ombrotrophic peat under drained peatlands

*Ahmad Kurnain**

Department of Soil Science, Faculty of Agriculture, Lambung Mangkurat University
Banjarbaru 70714, South Kalimantan, Indonesia

Received June 23, 2018; accepted December 11, 2018

Abstract. Understanding the processes that control the retention and flow of water in peat soils is critical to the effective management of such soils from both agricultural and ecological perspectives. The water retention properties of peats collected from rubber-cultivated, oil palm-cultivated, and abandoned (uncultivated) areas in the vicinity of Kanamit Barat Village, Pulang Pisau District, Province of Central Kalimantan were characterized using the van Genuchten equation. Based on the parameters of α indicating a change in the water content as water potential changes and n indicating the rate of decreasing water content as water potential becomes more negative, the more decomposed peats in the rubber cultivated peatland lost their water relatively slowly at small negative pressure heads, while less decomposed peats in the oil palm-cultivated and abandoned peatlands lost their water more quickly. This reflects difference of pore-size distribution among different land uses of peatlands. The total volume of water retained by the unsaturated layers in the rubber-cultivated peatland was lower than that in the oil palm-cultivated and abandoned areas. Also, the residual water content was higher in the rubber-cultivated peatland compared to the oil palm-cultivated and abandoned areas. This implies that the proportion of the maximum volume of water being removed decreases as a result of agricultural activities in peatlands. This evidence shows that the moisture state of peat soil is greatly influenced by the degree of peat decomposition and water table fluctuation.

Keywords: drainage, moisture retention, residual porosity, tropical peatland

INTRODUCTION

Peatland is a mega-terrestrial ecosystem containing massive amounts of carbon (C). Peatlands cover only 3% (4,000,000 km^2) of the land area of the world, but 550 Gton of carbon is stored in peat worldwide (Parish *et al*., 2008). In Indonesia it is currently estimated that peatland covers an area of approximately 14.9 million hectares (IAARD, 2012). Many people are currently linking the issue of the emissions of greenhouse gases (GHG) with a loss of C from peatlands. In their natural condition when peatlands remain wet, their immense carbon storage capacity remains intact. Peatland is naturally waterlogged resulting in an anoxic and water-saturated condition that may inhibit peat oxidation, and consequently the carbon stored in peatlands remains stabilized in peat layers.

Problems then arise when the natural peatlands are drained for various purposes such as agriculture, forestry, deforestation, peat extraction, and infrastructure development. The use of peatlands for various purposes is hindered by the hydrological constraint that they are always wet and stagnant throughout the year, making affordable utilization difficult and also hampering accessibility. Therefore, the natural peatland must be reclaimed through the construction of drainage systems (Alan Tan and Ritzema, 2003; Kurnain *et al*., 2001). Problems then occur when the natural peatlands are cleared and drained resulting in an oxic and water-unsaturated peat layer. Changes in the moisture condition of the peat layers will in turn result in increasing peat compaction and oxidation and these factors contribute to subsidence and greenhouse gas emission in developed peatlands.

The processes controlling the retention and flow of water in peat soils need to be understood and are critical to the effective management of such soils from both agricultural and ecological perspectives. In contrast to mineral soils, much less is known about the unsaturated soil hydraulic properties of peat soils, especially water retention and hydraulic conductivity. This is, in part, due to the unique nature of the physical and hydraulic properties of peat soils, such as volume changes during dewatering. The water retention characteristics of mineral soils have been modelled quite intensively, and several models have been

---

*Corresponding author e-mail: akurnain@ulm.ac.id presented in the last 25 years (Brooks and Corey, 1964; van Genuchten, 1980). Some of these models could also be calibrated for peat soils, and therefore some of them will be investigated here. Most of the water retention models for mineral soils allow for analytical solutions of the hydraulic conductivity or permeability function. Unfortunately, these analytical models contain curve shape parameters that were originally determined for large sets of mineral soil samples (Mualem, 1976). Consequently, they should not be used for peat soils without refitting the shape.

Many agrohydrological designs require measurements of the hydrophysical properties of unsaturated soils. These properties are related to the ability of a soil to retain or release water and its dissolved substances. For example, they affect the available water in the soil root zone, and recharge to or capillary rise from the groundwater table, among many other processes in the unsaturated or vadose zone between the soil surface and the groundwater table. The hydrophysical properties are also critical components of mathematical models for studying or predicting site-specific water and solute transport processes in the subsurface. The present study aimed at investigating the characteristics of the water retention of peats that were collected from land used in three different ways, namely rubber-cultivated, oil palm-cultivated, and abandoned areas. Peat water retention was characterized using the equation of van Genuchten, and related to some of its physical properties.

MATERIALS AND METHODS

The present study was conducted through laboratory and fieinld measurement. The field measurements took place in the vicinity of Kanamit Barat Village, Pulang Pisau District, Province of Central Kalimantan. The area is a part of the ex-mega rice project in the peatland of Central Kalimantan. There are three peatland covers for field measurement, including land that was cultivated for rubber for ten years, oil palm for four years, and land that had been abandoned for five years at the time of sampling. The distribution of the field measurement was presented in Table 1.

Peat soils taxonomically classified as Histosols (Andriesse, 1988; Soil Survey Staff, 1999) were collected on acrotelm, intermediate and catotelm layers. The classification of these layers have been described elsewhere (Morris *et al*., 2011; Reeve *et al*., 2000; Schuldt *et al*., 2013; Kurnain and Hayati, 2016). Their depths depended on the position of the water table at the study sites. An acrotelm layer is located permanently above the water table during the year, and a catotelm layer is always water-saturated due to its position below the water table. An intermediate layer that is located between the acrotelm and catotelm layers is temporarily water-saturated especially during the rainy season. Before sample collection at each point, the water table was measured using a PVC pipe that was inserted into the surface and the depth of the water from the soil surface was recorded as the water table depth.

Table 1. Study sites of field measurement and peat sampling on 30-31 January 2016 in Kanamit Barat, Pulang Pisau, Central Kalimantan

Land use	Point	Water table (cm)	Layer*	Type of sample
		K1		
	S:02°52’311”	80	acrotelm	disturbed and core
	E:114°06’06”		intermediate	disturbed and core
			catotelm	disturbed
		K2		
Rubber cultivated	S:02°52’277”	70	acrotelm	disturbed and core
	E:114°06’05”		intermediate	disturbed and core
			catotelm	disturbed
		K3		
	S:02°52’280”	70	acrotelm	disturbed and core
	E:114°06’04”		intermediate	disturbed and core
			catotelm	disturbed
		B1		
	S:02°52’219”	40	acrotelm	disturbed and core
	E:114°05’52”		intermediate	disturbed and core
			catotelm	disturbed
		B2		
Abandoned area	S:02°52’201”	40	acrotelm	disturbed and core
	114°05’48”		intermediate	disturbed and core
			catotelm	disturbed
		B3		
	S:02°52’191”	50	acrotelm	disturbed and core
	E:114°05’48”		intermediate	disturbed and core
			catotelm	disturbed
		S1		
	S:02°52’185”	40	acrotelm	disturbed and core
	E:114°05’44”		intermediate	disturbed and core
			catotelm	disturbed
		S2		
Oil palm cultivated	S:02°52’201”	40	acrotelm	disturbed and core
	E:114°05’46”		intermediate	disturbed and core
			catotelm	disturbed
		S3		
	S:02°52’223”	70	acrotelm	disturbed and core
	E:114°05’46”		intermediate	disturbed and core
			catotelm	disturbed

* Acrotelm is the upper layer of peat that was above the water table during the study; catotelm is the bottom layer of peat that is permanently below the water table; and intermediate layer represent the condition between the acrotelm and catotelm layers. K1, K2, K3, B1, B2, B3, S1, S2, S3 – code of sample.

The materials used for these laboratory measurements consisted of two types of peat samples, those were the disturbed and undisturbed (core) samples. The disturbed sample was taken using a metal soil auger. The soil auger was incorporated into the soil by gently rotating the auger at any depth of the auger bit. In accordance with the depth of the groundwater level at any point, the soil samples collected weighed approximately 300 g and consisted of layers of acrotelm, intermediate, and catotelm respectively. The sample was divided partly into a fresh sample and an air-dried sample. The undisturbed sample was collected using a core sampling unit. Before sampling, the peat soil was excavated above the first depth to be sampled and a flat smooth horizontal surface was made. The area of the flat surface should be sufficient to take two core samples, one for measuring bulk density and the other for moisture retention. The driving head was placed on top of the sampling cylinder and the cylinder was driven into the soil with steady blows of the heavy small hammer on the driving head. The cylinder was driven down to about 2 cm below the real height of the cylinder. The driving head was gently removed. The soil around the sampling cylinder was excavated by a strong sharp knife, allowing sufficient soil below the lower rim for trimming the soil up to the rim. The soil was trimmed up to the rim on both sides so that the soil inside the cylinder was exactly the same volume as the cylinder. Finally, both sides of the cylinder were covered with lids, thus avoiding damage and moisture loss.

The variables measured in the laboratory (Table 2) were bulk density, fibre content, the optical density ratio (E4/E6), effective and total porosity, and water retention at various pressure heads. The soil bulk density is defined as the ratio of the mass of a given sample to its bulk volume, which includes soil particles and pore spaces in the sample. The fibre content is a physical property of peat soils often used to characterize the degree of peat decomposition (Malterer *et al*., 1992; Blackford and Chambers, 1993; Kurnain, 2005). The lower the fibre content, the higher the degree of peat decomposition, and vice versa. The extraction of humic substances from the peat material can also be used to assess the degree of peat decomposition (Kumada, 1987; Sapek and Sapek, 1987; Blackford and Chambers, 1993; Kurnain, 2005). Humic acids produced by the decomposition of the peat materials will result in a brown colour of the humic filtrates. Kumada (1987) reported that the increase in the intensity of the brown colour is proportional to the formation of humic substances. Therefore, the measurement of the optical density of the humic filtrate may be used to assess the degree of peat decomposition. The optical density was usually presented as the ratio of the optical density (E4/E6), the ratio of the absorbance at a lower wavelength (465 or 400) and the absorbance at a higher wavelength (665 or 600) (Kononova, 1966; Kumada, 1987; Sapek and Sapek, 1987; Blackford and Chambers, 1993; Kurnain, 2005). The procedures used to determine all of the hydrophysical parameters will refer to standard methods found elsewhere (Kurnain *et al*., 2006; Guber *et al*., 2010; Gallage *et al*., 2013). Table 2 summarizes the methods used for measuring or calculating selected soil parameters.

The hydrological characteristics of soils, such as water retention and the rate of water movement, depend, to a large degree on the total porosity and pore-size distribution of the material (Kutilek and Novak, 1998). The soil water potential – moisture characteristics allow for the calculation of effective pore size distribution. Water retention curves make it possible to determine the amount of closely bound water at a soil water potential of –1500 kPa, which is an indicator of the presence of micropores in the soil (Walczak *et al*., 2006). The volume of mesopores may be calculated as the difference between water content at –10 kPa and –1500 kPa. The mesopore content of the soil corresponds to the content of water available for plants and the water content ~~at~~ from -10 to -33 kPa and from -33 to -1500 kPa represents easily available and insufficiently available water respectively. The water content between saturation and at –10 kPa indicates the presence of macropores. In macropores, a rapid gravitational efflux of water takes place, which is called soil aeration capacity. Water capacity between –10 kPa and –1500 kPa may be described as potentially useful retention, but below –1500 kPa water is unavailable for plants (Okruszko, 1993). The water retention was characterized using the retention function given below:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha h)^n\right]^{1-1/n}} ,$$

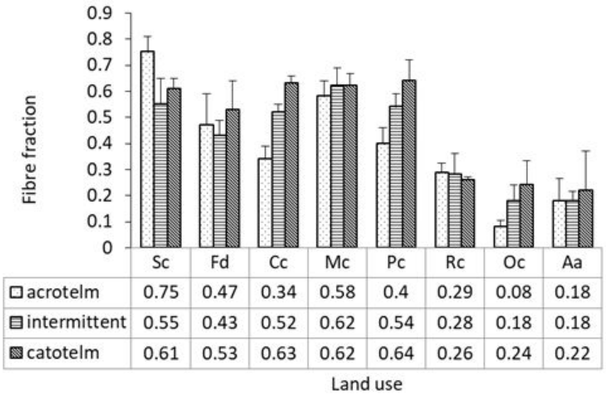
where $\theta(h)$ is the measured volumetric water content ($cm^3\ cm^{-3}$) at the suction h (cm, assumed to be positive for increasing suction). The parameters θ_r and θ_s are residual and saturated water contents, respectively ($cm^3\ cm^{-3}$); α (> 0, in cm^{-1}) is related to the inverse of the air entry suction, and n (> 1) is a measure of the pore-size distribution (van Genuchten, 1980).

Table 2. Types of soil samples required for laboratory analysis

Soil parameter	Methods of laboratory analysis	Types of soil sample		
		Disturbed		Core
		fresh	air-dried	
Bulk density	Gravimetric – oven dried	–	–	+
Fibre content	Volumetric (Linn *et al*., 1974)	+	–	–
Optical density ratio (E4/E6)	Spectrophotometer UV-Vis (Kurnain, 2005)	–	+ Ø = 0.5 mm	–
Total porosity	(1) Nimmo (2004) and (2) $\phi = 1 - \rho_b / \rho_p$	+ (2)	–	+ (1)
Water retention	At 0,1, 2, 5, and 10 kPa with hanging column At 34 and 100 kPa with pressure plate	+	–	–

RESULTS AND DISCUSSION

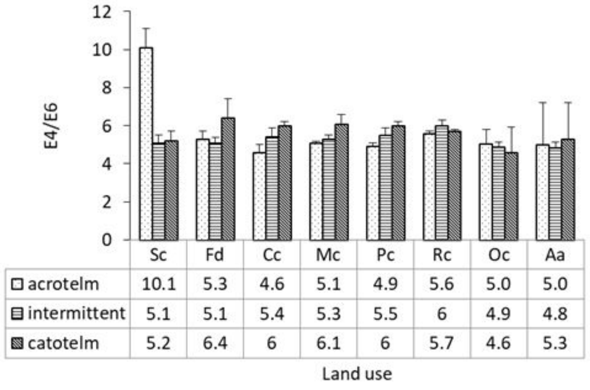
Peat decomposition may take place chemically through an oxidation process, and physically through changes in the size of the peat materials. Considering how peat materials change due to physical and chemical processes, the degree of peat decomposition was determined by measurement of the fibre content of the peat materials and the optical density of the humic substances. Figure 1 shows the fibre contents of the peat material from rubber-cultivated, oil palm-cultivated, and abandoned areas of the ombrotrophic peatland in Kanamit Barat Village. Based on the criteria of the fibre content mentioned in Linn *et al*. (1974) and Kurnain (2005), all peat materials from three types of land use were classified as sapric peat that is highly decomposed. However, the degree of peat decomposition in the unsaturated zones (acrotelm and intermediate layers) was higher than it was in the saturated zone (catotelm layer). This is due to the peat decomposition being partly inhibited by water-filled pore spaces (Saidy, 2002).



	Sc	Fd	Cc	Mc	Pc	Rc	Oc	Aa
□ acrotelm	0.75	0.47	0.34	0.58	0.4	0.29	0.08	0.18
⊟ intermittent	0.55	0.43	0.52	0.62	0.54	0.28	0.18	0.18
▨ catotelm	0.61	0.53	0.63	0.62	0.64	0.26	0.24	0.22

Fig. 1. Fibre content of peat materials collected at three peat layers in three different land uses of peatland.

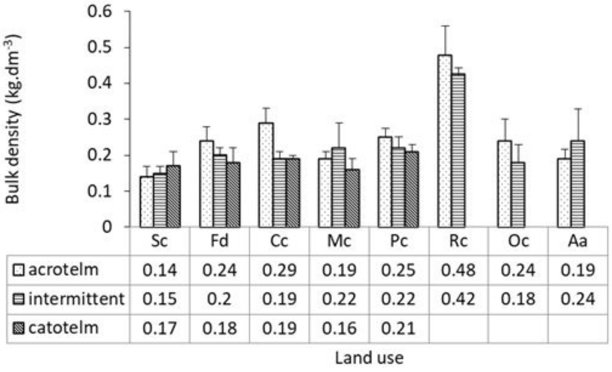
This is also implied by the measurement of the optical density ratio of humic substances (Fig. 2). Peat material in the upper layer of developed peatland is more decomposed than in the lower layer. This difference can be attributed to a lowering of the water table due to drainage in the peatland used for agriculture. The declining water table resulted in peat material in the upper layer receiving an air flow more freely (more aerobic) than the lower layer, so that the oxidation process took place more intensively (Saidy, 2002; Kurnain, 2005).



	Sc	Fd	Cc	Mc	Pc	Rc	Oc	Aa
□ acrotelm	10.1	5.3	4.6	5.1	4.9	5.6	5.0	5.0
⊟ intermittent	5.1	5.1	5.4	5.3	5.5	6	4.9	4.8
▨ catotelm	5.2	6.4	6	6.1	6	5.7	4.6	5.3

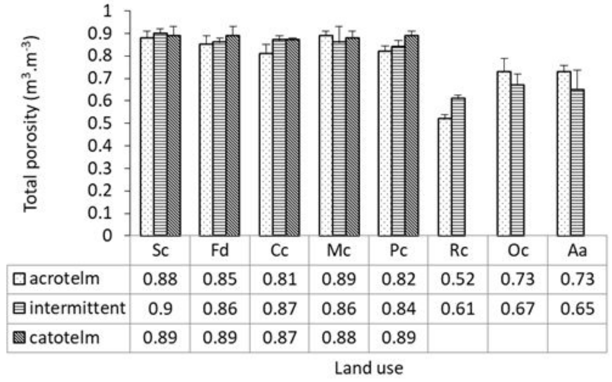
Fig. 2. Optical density ratio of humic substances of peat materials collected at three peat layers in three different land uses of peatland.

The physical properties of peat soils, which are often compared to those of mineral soils, are mainly bulk density and porosity. Both physical properties significantly affect the water characteristics of peat soils. As peat materials become more decomposed when natural peatlands are drained, both bulk density and porosity changed accordingly (Kurnain *et al*., 2006). Figure 3 shows the bulk density of peat soils collected in the unsaturated zone of drained peatlands. Compared to the selectively logged peat forest of the upper River Sebangau, Central Kalimantan, as shown by Kurnain (2005), the bulk density values obtained were significantly higher. The peat bulk density of the rubber-cultivated peatland was higher than that of the oil palm-cultivated and abandoned areas. This is the case because rubber cultivation requires a more compacted peatland surface for supporting the growth of rubber trees.



	Sc	Fd	Cc	Mc	Pc	Rc	Oc	Aa
□ acrotelm	0.14	0.24	0.29	0.19	0.25	0.48	0.24	0.19
⊟ intermittent	0.15	0.2	0.19	0.22	0.22	0.42	0.18	0.24
▨ catotelm	0.17	0.18	0.19	0.16	0.21			

Fig. 3. Bulk density of peat samples collected at three peat layers in three different land uses of peatland.



	Sc	Fd	Cc	Mc	Pc	Rc	Oc	Aa
□ acrotelm	0.88	0.85	0.81	0.89	0.82	0.52	0.73	0.73
⊟ intermittent	0.9	0.86	0.87	0.86	0.84	0.61	0.67	0.65
▨ catotelm	0.89	0.89	0.87	0.88	0.89			

Fig. 4. Total porosity of peat materials collected at the unsaturated zone in three different land uses of peatland.

Figure 4 shows the total porosity of peat soils collected in the unsaturated zone of the drained peatlands. The total porosity of the peat soil may be calculated from particle density or it can also be compared with the volume of the moisture content at a water potential of 0 kPa (Kurnain *et al*., 2006). In this report, the total porosity of peat soil was determined by the second measurement. The average total porosity varied from a low of 54% in the acrotelm layer of the rubber-cultivated peatland to a high of 83% in the intermediate layer of oil palm-cultivated peatland. This range is lower than the range reported by Kurnain (2005) for developed peatland in Central Kalimantan. However, the range of total porosity is consistent with the findings of Kurnain (2005) when taking into account the effect of peat bulk density on the total porosity. The compaction of the soil structure will reduce the pore volume, and change the configuration of the pores in the soil (Richard *et al*., 2001; Dexter, 2004; Tarawally *et al*., 2004). The total porosity values showed the same results as the bulk density values since they are inversely related to one another. The positions that had the highest porosity also had the lowest bulk density and *vice versa*. The ability of peat to retain water is determined by the water potential and the degree of peat decomposition (Matthew *et al*., 2000). Water potential is associated in the field with the groundwater levels relative to baseline observations. The characterization of moisture contents at a head of water potential of 0, –1, –2, –5, –10, –34, and –100 kPa using the van Genuchten equation (van Genuchten, 1980) was conducted in order to understand the effect of water table fluctuation on water retention. The water retention curves of peats which were collected in rubber-cultivated (Fig. 5a), oil palm-cultivated (Fig. 5b), and abandoned peatlands (Fig. 5c) were matched to the van Genuchten equation. Figure 5 may be interpreted as showing the equilibrium water content distribution above a water table where the pressure head is zero and the soil fully saturated. The plots in Figure 5 show that the more decomposed peats in the rubber cultivated peatland lose their water relatively slowly at small negative pressure heads, while the less decomposed peats in the oil palm-cultivated and abandoned peatlands lose their water more quickly. This reflects the difference in pore-size distribution among the different land uses of peatlands. The majority of pores in the less decomposed peats have larger diameters and thus drain at a relatively small negative pressure or operationally, in relatively shallow water tables. This phenomenon may also be applied to acrotelm and intermediate peat layers that are in different decomposition states.

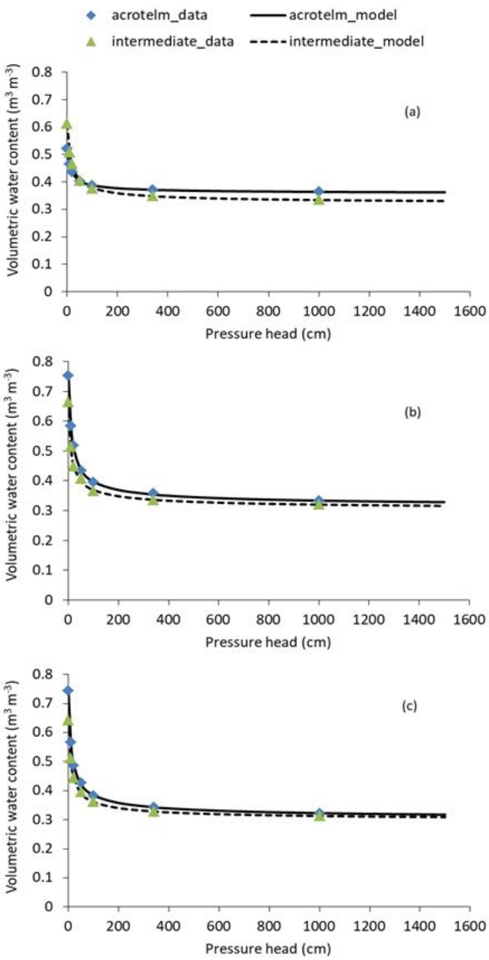


Fig. 5. Water retention curves of unsaturated peat layers in rubber-cultivated (a), oil palm-cultivated (b) and abandoned (c) peatlands. The solid and dashed lines are the van Genuchten fittings resulting in parameters as in Table 3.

The parameters of the equation for each type of land use and peat layer are shown in Table 3. The following parameters can be derived from this equation, those are the volumetric water content at saturated (θ_s), residual volumetric water content (θ_r), parameter α indicating water loss due to a lowering water table (Hodnett and Tomasella, 2002), and parameter *n* indicating the intensity of changes in water content due to the decreasing level of the water table (Tomasella *et al*., 2000; Hodnett and Tomasella. 2002). The total volume of water retained by unsaturated layers in the rubber-cultivated peatland was lower than that in the oil palm-cultivated and abandoned peatlands. Otherwise, the residual water content was higher in the rubber-cultivated peatland as compared to the oil palm-cultivated and abandoned peatlands. This implies that the proportion of the maximum volume of water being removed decreases as a result of agricultural activities in the peatlands. This evidence shows that the moisture state of the peat soil was greatly influenced by the degree of peat decomposition and water table fluctuation.

Table 3. Parameters of the van Genuchten equation of water retention on unsaturated peat layers in three types of peatland uses

Land use	Water retention parameters				
	θ_s	θ_r	α	n	r^2
Rubber cultivated:					
Acrotelm layer	0.52 (0.03)	0.34 (0.02)	θ0.16 (0.02)	1.58 (0.08)	0.999
Intermediate layer	0.61 (0.02)	0.34 (0.02)	0.15 (0.02)	1.64 (0.08)	0.999
Oil palm cultivated:					
Acrotelm layer	0.73 (0.03)	0.31 (0.01)	0.21 (0.01)	1.54 (0.00)	0.999
Intermediate layer	0.67 (0.02)	0.31 (0.02)	0.23 ((0.03)	1.53 (0.04)	0.998
Abandoned area:					
Acrotelm layer	0.73 (0.04)	0.30 (0.01)	0.22 (0.01)	1.53 (0.02)	0.999
Intermediate layer	0.65 (0.05)	0.29 (0.02)	0.21 (0.02)	1.53 (0.03)	0.999

Parameter α varied between 0.15- 0.23. According to the aforementioned Hodnett and Tomasella (2002) the higher value of parameter α resulted in a higher degree of moisture loss as a result of the decreasing level of the water table. Otherwise, the lower value of α indicated a lower level of moisture loss. Based on the value of α, the unsaturated peat layer in the oil palm-cultivated peatland will lose water at a higher rate than in the rubber-cultivated peatland. This result can be explained by what was revealed by Assouline *et al*. (1997) and van Dijck and van Asch (2002) that the water retention curve will be flat in the case of compression as the proportion of macro pores decreases and vice versa; the proportion of micropores increases. The n parameter values tend to be lower in the compacted peat layer. Parameter n indicates the intensity of changes in moisture content due to changes in water potential (pressure head) (Tomasella *et al*. 2000; Hodnett and Tomasella. 2002). If the value n is greater in the unsaturated layer of the abandoned area, the decrease in moisture content progresses rapidly due to the lowering level of the water table. This means that the peat soil with a lower degree of decomposition will lose moisture more rapidly during the early period of decline in the water table.

Water retention curves of peats collected in rubber-cultivated, oil palm-cultivated, and abandoned peatlands were matched to the van Genuchten equation. The curves show that the more decomposed peats in the rubber-cultivated peatlands lose their water relatively slowly at low negative pressure heads, while the less decomposed peats in the oil palm-cultivated and abandoned peatlands lose their water more quickly. This reflects the differences in the pore-size distribution among different land uses of peatlands. This phenomenon may also be applied to acrotelm and intermediate peat layers that are in different decomposed states. The total volume of water retained by unsaturated layers in the rubber-cultivated peatland was lower than that in the oil palm-cultivated and abandoned peatlands. Otherwise, the residual water content was higher in the rubber-cultivated peatland compared to the oil palm-cultivated and abandoned peatlands. This implies that the proportion of the maximum volume of water being removed decreases as a result of the agricultural activities in the peatlands. This evidence shows that the moisture state of the peat soil was greatly influenced by the degree of peat decomposition and water table fluctuation. Based on parameters α and n, the unsaturated peat layers in the oil palm-cultivated peatland will be lose water at a higher rate than in the rubber cultivated peatland during the early period of decline in the water table. This result may be explained by the fact that the water retention curve will be flat in the case of compression as the proportion of macropores decreases and *vice versa*, the proportion of micropores increases.

The present study has resulted in important findings in relation to the implementation of ecohydrological approaches toward the sustainable management of peatlands. The results show that the hydrophysical properties of peat materials were varied with different land uses and consequently, a different degree of peat decomposition. More decomposed peats will result in more compacted peat and this will subsequently result in a higher bulk density, lower total and effective porosities and an otherwise higher residual porosity. Changes in the hydrophysical properties due to land use changes have evidently influenced hydraulic characteristics including water retention and hydraulic conductivity. This finding is of some importance for implementing ecohydrological approaches toward the sustainable management of peatlands.

CONCLUSIONS

1. The hydrophysical properties of peat materials varied with different land use. There is a relationship between both the bulk density and the total porosity of peat materials with the progress of peat decomposition.
2. The characteristics of the water retention of unsaturated peat layers varied with different land use. The unsaturated peat layer of the oil palm-cultivated land evidently lost water at a higher rate than the rubber-cultivated area.

AKNOWLEDGEMENTS

The author thanks to Dr. Afiah Hayati for field works collecting peat samples in the study site. This work was partially supported by 2016 APCE-UNESCO Program.

Conflict of interest: The authors declare that they have no conflict of interest.

Compliance with ethical requirements: This study does not contain any experiment involving human or animal subjects.

REFERENCES

Alan Tan K.C. and Ritzema H.P., 2003. Sustainable Development development in Peat peat land of Sarawak – Water Management management Approachapproach. Int. Conf. on Hydrology and Water Resources in Asia Pacific Region, March 13-15, Kyoto, Japan

Andriesse J.P., 1988. Nature and management of tropical peat soils. FAO Soil Bulletin, 59. Food and Agricultural Organization of the United Nations, Rome.

Assouline S., Tavares-Filho J., and Tessier D., 1997. Effect of compaction on soil physical and hydraulic properties: Experimental results and modeling. Soil Sci. Soc. Am. J. 61, 390-398. https://doi.org/10.2136/sssaj1997.03615995006100020005x

Blackford J.J. and Chambers F.M., 1993. Determining the degree of peat decomposition for peat-based palaeoclimatic studies. Int. Peat J., 5, 7-24.

Brooks R.H. and Corey A.T., 1964. Hydraulic properties of porous media. Hydrology Paper No. 3, Colorado State Univ., Ft. Collins, CO.

Dexter A.R., 2004. Soil physical quality: Part III. Unsaturated hydraulic conductivity and general conclusion about S-theory. Geoderma, 120, 227-239. https://doi.org/10.1016/j.geoderma.2003.09.006

Gallage C., Kodikara J., and Uchimura T., 2013. Laboratory measurement of hydraulic conductivity functions of two unsaturated sandy soils during drying and wetting processes. Soils and Foundations. 53(3), 417-430. https://doi.org/10.1016/j.sandf.2013.04.004

Guber A.M., Tuller F.S.J., Martinez P., Iassonov M.A., and Martin, 2010. The through porosity of soils as the control of hydraulic conductivity. 19th World Congress of Soil Science. Soil Solutions for a Changing World. Brisbane. Australia. (published on DVD).

Hodnett M.G. and Tomasella J., 2002. Marked differences between van Genuchten soil water-retention parameters for temperate and tropical soils: A new water-retention pedo-transfer functions developed for tropical soils. Geoderma, 108, 155-180. https://doi.org/10.1016/S0016-7061(02)00105-2

IAARD**, 2012.** Basisdata sumberdaya lahan pertanian pada skala tinjau (1:250.000) (in English: Database of agricultural land resources on a scale of 1:250.000). Indonesia Agency for Agricultural Research dan Development, Ministry of Agriculture, Bogor.

Kononova M.M., 1966. Soil Organic Matter, its Nature, its Role in Soil Formation and Soil Fertility. Edisi ke 2Second Edition. Pergamon Press, London. 544 halamanp.

Kumada K., 1987. Chemistry of Soil Organic Matter. Japan Sci. Soc. Press, Tokyo. 241 halamanp.

Kurnain A., Notohadikusumo T., Radjagukguk B., and Hastuti S., 2001. Peat soil properties related to degree of decomposition under different land use systems. Int. Peat J., 11, 67-77.

Kurnain A., 2005. Dampak Kegiatan kegiatan Pertanian pertanian dan Kebakaran kebakaran Atas atas Watak watak Gambut gambut Ombrogen ombrogen (in English: Impact of Agricultural agricultural Activities activities and Forest forest Fires fires on Characteristics characteristics of Ombrotrophic ombrotrophic Peatpeat). PhD Thesis. Graduate school of Agricultural Faculty. Gadjah Mada University. 315 p.

Kurnain A. and Hayati A., 2016. Characteristics of water retention of ombrotrophic peats under different land uses. Full Paper Proceeding ETAR-2016, 3, 271-280.

Kurnain A., Radjagukguk B., and Notohadikusumo T., 2006. Impact of development and cultivation on hydro-physical properties of tropical peat soils. Tropics, 15(4), 383-389. https://doi.org/10.3759/tropics.15.383

Kutilek M. and Novak V., 1998. Exchange of water in the soil-plant-atmosphere system. Int. Agrophys., 12, 28-33.

Linn W.C., Mickinzi W.E., and Grossman R.B., 1974. Field laboratory test for characterization of histosols. Dalamin: A.R. Aandahl. S.W. Boul. D.E. Hill. H.H. Bailey. M. Stelly. and R.C. Dinaues (eds.). Histosols: Their Characteristics. Classification. and Use. Soil Sci. Soc. Am. Spec. Publ., 6, 11-12.

Malterer T.J., Verry E.S., and Erjavec J., 1992. Fibre content and degree of decomposition in peats: a review of national methods. Soil Sci. Soc. Am. J., 56, 1200-1211. https://doi.org/10.2136/sssaj1992.03615995005600040033x

Matthew G.L., Roelet N.T., and N.T. Comer. 2000. Parametrization of peatland hydraulic properties for the Canadian land surface scheme. Atmosphere-Ocean, 38(1), 141-160. https://doi.org/10.1080/07055900.2000.9649643

Morris P.J., Waddington J.M., Benscoter B.W. and Turetsky M.R., 2011. Conceptual frameworks in peatland ecohydrology: looking beyond the two-layered (acrotelm-catotelm) model. Ecohydrology, 4, 1-11. https://doi.org/10.1002/eco.191

Mualem Y., 1976. A new model predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res., 12, 513-522. https://doi.org/10.1029/WR012i003p00513

Nimmo J.R., 2004. porosity and pore pore size size distribution. In: Encyclopaedia of Soils in the Environment (Ed. D.Hillel). Volume 3, 295-303. https://doi.org/10.1016/B0-12-348530-4/00404-5

Okruszko J., 1993. Transformation of fen-peat under the impact of drainage. Zesz. Probl. Post. Nauk Roln., 406, 3-74.

Parish F., 2002. Peatlands. biodiversity and climate change in SE Asia: an An overview. Makalah disajikan padaPaper presented on Workshop on Prevention and Control of Fire in Peatlands. 19-21 March 2002. Kuala Lumpur. Malaysia. 11 halamanp.

Reeve A.S., Siegel D.I., and Glaser P.H., 2000. Simulating vertical flow in large peatlands. Journal of Hydrology, 227, 207-2017. https://doi.org/10.1016/S0022-1694(99)00183-3

Richard G.I., Cousin J.F., Sillon Bruand A., and Guérif J., 2001. Effect of compaction on the porosity of a silty soil: Influence on unsaturated hydraulic properties. Eur. J. Soil Sci., 52, 49-58. https://doi.org/10.1046/j.1365-2389.2001.00357.x

Saidy A.R., 2002. Carbon and nitrogen mineralisation in tropical peats: role of peat properties and management practices. M. Agr. Sc Thesis. The University of Adelaide. Glen Osmond, SA, Australia pp. 144 p.

Sapek B. and Sapek A., 1987. Changes in the properties of humus substances and the sorption complex in reclaimed peat soils. International Peat Journal 2: 99-117.

Schuldt R.J., Brovkin V., Kleinen T., and Winderlich J., 2013. Modelling Holocene carbon accumulation and methane emissions of boreal wetlands - an Earth system model approach. Biogeosciences, 10, 1659-1674. https://doi.org/10.5194/bg-10-1659-2013

Soil Survey Staff**, 1999.** Soil Taxonomy: a Basic System of Soil Classification for Making and Interpreting Soil Surveys, the Second Edition. United States Department of Agriculture, Washington DC. 886 p.

Tarawally M.A., Medina H., Frometa M.E., and Itza C.A., 2004. Field compaction at different soil-water status: effects on pore size distribution and soil water characteristics of a Rhodic Ferralsol in Western Cuba. Soil and Tillage Research, 76, 95-103. https://doi.org/10.1016/j.still.2003.09.003

Tomasella J., Hodnett M.G., and Rossato L., 2000. Pedotransfer function for the estimation of soil water retention in Brazilian soils. Soil Sci. Soc. Am. J., 64, 327-338. https://doi.org/10.2136/sssaj2000.641327x

Van Dijck S.J.E. and van Asch, Th.W.J. 2002. Compaction of loamy soils due to tractor traffic in vineyards and orchards and its effect on infiltration in southern France. Soil Till. Res., 63, 141-153. https://doi.org/10.1016/S0167-1987(01)00237-9

van Genuchten. M.Th., 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J., 44, 892-898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

Walczak R.T., Moreno F., Slawinski C., Fernandez E., and Arrue J.L., 2006. Modeling of soil water retention curve using soil solid phase parameters. J. Hydrol., 329, 527-533. https://doi.org/10.1016/j.jhydrol.2006.03.005