

Water Retention and Saturation Degree of Peat Soil in Sebangau Catchment Area, Central Kalimantan

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ABSTRACT

Water is an essential factor in forming, utilization, management, and sustainability of peat soil. This study was to obtain characteristics of water retention and porosity of peat soil. Peat samples were taken from the Natural Laboratory of Peat Forest, Central Kalimantan at shallow, medium, and deep peat at 0-50cm (surface) and 50-100 cm (subsurface), while laboratory analyses carried out at Soil Laboratory, Universitas Gajahmada. The result shows that volumetric moisture content at the surface lower than subsurface, except for deep peat. The total pore for the surface was 84.67-86.98%, while subsurface layers were 83.53-86.93%. For surface layer, saturated degree (S) medium peat higher than shallow and deep peat, while for shallow subsurface peat higher than medium and deep peat. S value all pF levels of surface for medium and deep peat higher than the subsurface. Bulk density for surface was $0.094\text{g}\cdot\text{cm}^{-3}$ ($\rho_{b(\text{wet})}$) and $0.22\text{g}\cdot\text{cm}^{-3}$ ($\rho_{b(\text{dry})}$) for shallow peat while medium peat are $0.084\text{--}0.087\text{g}\cdot\text{cm}^{-3}$ ($\rho_{b(\text{wet})}$) and $0.18\text{--}0.20\text{g}\cdot\text{cm}^{-3}$ ($\rho_{b(\text{dry})}$), deep peat $0.064\text{--}0.090\text{g}\cdot\text{cm}^{-3}$ ($\rho_{b(\text{wet})}$) and $0.11\text{--}0.16\text{g}\cdot\text{cm}^{-3}$ ($\rho_{b(\text{dry})}$). For subsurface, bulk density of medium peat are $0.094\text{--}0.107\text{g}\cdot\text{cm}^{-3}$ ($\rho_{b(\text{wet})}$) and $0.16\text{--}0.20\text{g}\cdot\text{cm}^{-3}$ ($\rho_{b(\text{dry})}$), deep peat are $0.067\text{--}0.090\text{g}\cdot\text{cm}^{-3}$ ($\rho_{b(\text{wet})}$) and $0.10\text{--}0.17\text{g}\cdot\text{cm}^{-3}$ ($\rho_{b(\text{dry})}$). The particle density of surface and subsurface for shallow peat higher than medium and deep peat, with values $0.67\text{--}0.77\text{g}\cdot\text{cm}^{-3}$, $0.61\text{--}0.66\text{g}\cdot\text{cm}^{-3}$, and $0.53\text{--}0.63\text{g}\cdot\text{cm}^{-3}$ for shallow, medium, and deep peat, respectively. Total pores for the surface layer decrease with increasing dry bulk density ($R = 0.624$) and particle density ($R = 0.375$). This fact seems to confirm a directly proportional relationship between parameters bulk and particle density with total pores.

Keywords: Moisture content of soil, peat land, saturation degree, soil porosity

INTRODUCTION

Water plays an essential role in forming, cultivation, utilization management, and sustainability of peat soil. Integrated water management is the key to restoring tropical peatland (Ritzema 1998; Sutikno *et al.* 2020), in which diverse and contrasting requirements of the various types of land use need to be balanced. Water management to maintain levels optimal for distant land uses is crucial to achieving the wise use of tropical peatlands (Wösten and Ritzema 2001). Peatland was forming by the accumulation of organic material over a long time. The permanent waterlogging covered land surface caused the accumulation rate of organic material faster than their decomposition.

Most tropical peat is located at low altitudes where rain forest vegetation grows on a thick mass

of mater there has accumulated over a thousand years to form deposits that are up to 20 m thick (Anderson 1983; Radjagukguk 1995; Page *et al.* 2006; Lampela *et al.* 2016). In the last two decades, some of the utilization and cultivated policy of tropical peatland, especially for peatland in Central Kalimantan, has been related to the water management aspect. Then, this policy caused many aspects of the peatland ecosystem have been damage, water release out of inland toward the area was accelerated, so while dry season, more layers of peat soil was extreme drying.

Therefore, to understand peatland's water release behavior, peat soil's water-holding capacity be understood as necessary. That is considered a macro scale for peatland water characteristics, and it depends on and is related to the water suction capacity of peat soil material. Moisture content was retained in peat soil material at various pressure levels, It could be explained by the suction capacity of peat soil material, and one of the determination

was moisture contents measurement at some pF value level (soil moisture tension). It is defined as the logarithm of the absolute value of soil matric potential (Lal and Shukla 2004), which describes the work required to transfer reversibly and isothermally an infinitesimal amount of soil solution from a reservoir to the point of interest in the soil. That work to water transfer is considered as a force of water movement in the soil. In other words, the force that works is what causes the movement of water in the soil, commonly named water potential (ψ), and this water potential can be described as the value of pF curve. The peat matrix's capacity to retain and contain water depends on its several physical properties, particularly related to porosity availability. The water movement and moisture contents in the soil can be considered a function of gravimetrically and isothermally and influenced by several factors of soil properties, like structure, porosity, and another. (Weiss *et al.* 1998 and Walczak *et al.* 2002).

For the uncultivated area (natural condition) in the peatland field, the water movement has a crucial role in sustainability for its natural function. So, understanding peat soil's water tension characteristics is fundamental to get its wise management in the future. Water management, based on an understanding of peatland hydrology, is considered a prerequisite for the wise use of tropical peatland ecosystems (Muhammad and Rieley 2002; Rieley and Page 2005; Wösten *et al.* 2008). For this reason, a study was conducted in the intact tropical peatland Sebangau Catchment area, Central Kalimantan. This research aimed to determine the characteristics of water retention and saturation degree of peat soils from a different depth of peat.

MATERIAL AND METHODS

Study Site

The study was conducted in the Natural Laboratory of Peat Forest, Sebangau catchment areas, Central Kalimantan Province, as showed in Figure 1. Peat samples were taken from as many as 13 point locations, consist of namely shallow peat (SP = 100 cm) as many 1 locations; medium peat MP (100 - 200 cm) as many 2 locations; and deep peat DP (> 200 cm) as many 10 locations. At each sampling point, an undisturbed peat sample was taken using peat borers and a disturbed peat sample using ring samples with a diameter size 5.1/5.0 cm and 5.1 cm high. Peat samples were taken from peat layer of 0-50 cm dan 50 - 100 cm respectively, and that coded as SP L-1 (shallow peat 0-50 cm), SP L-

2 (shallow peat 50-100 cm), MP L-1 (medium peat 0-50 cm), MP L-2 (medium peat 50-100 cm), DP L-1 (deep peat 0-50 cm), and DP L-2 (deep peat 50-100 cm).

Determination of water retention was carried out the initiated method by Richards and Fireman (1943) and Richards (1947). Water retention measured at pressure 0.01 atm (pF 1.0); 0.1 atm (pF 2.0); 0.33 atm (pF 2.54); and 15 atm (pF 4.2).

Besides, saturated peat samples were prepared to measure moisture content or equivalent to the pressure at pF 0, bulk density determined by gravimetrically before undisturbed oven sample, namely wet or saturated bulk density, ρ_b (wet) and after oven undisturbed peat sample at 105 C during 24 hours, namely dry bulk density, ρ_b (dry) (Blake and Hartge 1986). Particle density (ρ_s) was measured using liquid pycnometers with water as filling liquid and water bath (Heiskanen 1992 and Redding *et al.* 2005), and the porosity is calculated from bulk density and particle density value (Hillel 1982).

Analytical Procedures for Water Retention

Peat samples to be analyzed are undisturbed in the ring sample. Pushed out the soil in the ring used to stick on one end, cut and taken a 1 cm thick from the other end, and then separated into four parts. Put each part of peat samples on the ceramic plate of pF 1.0; pF 2.0; and pF 2.54, except peat sample for pF 4.2 determination, was air-dried and sieved (2 mm mesh) and put on the ceramic plate also. Peat samples on the ceramic plate were saturated for 48 hours. Peat samples on a ceramic plate to determine pF 1.0, pF 2.0, and pF 2,54 were placed into pressure plate apparatuses, while pF 4.2 placed into pressure membrane apparatus. Tightly closed the pans (pressure plate apparatus and pressure membrane apparatus) and switch on the compressor to provide pressure according to specified pF. Take out the peat samples from pans after given pressure for 48 hours and then measure moisture content gravimetrically.

In this study, that meant of water retention is the amount of water that is retained in the peat matrix when it is being pressured or suction at a certain level (van Genuchten 1980; Walczak *et al.* 2002; Rajkai *et al.* 2004; Badv and Faridfard 2005; Kanzari *et al.* 2012; Jayakody *et al.* 2014; and Madi *et al.* 2018). The purpose of water retention measurement is to obtain a water retention curve, which can be obtained using various methods, such as that developed by van Genuchten 1980; Weiss 1998; Walczak *et al.* 2002; Rajkai *et al.* 2004; Badv and Faridfard 2005; Seki 2007; and Madi *et al.* 2018.

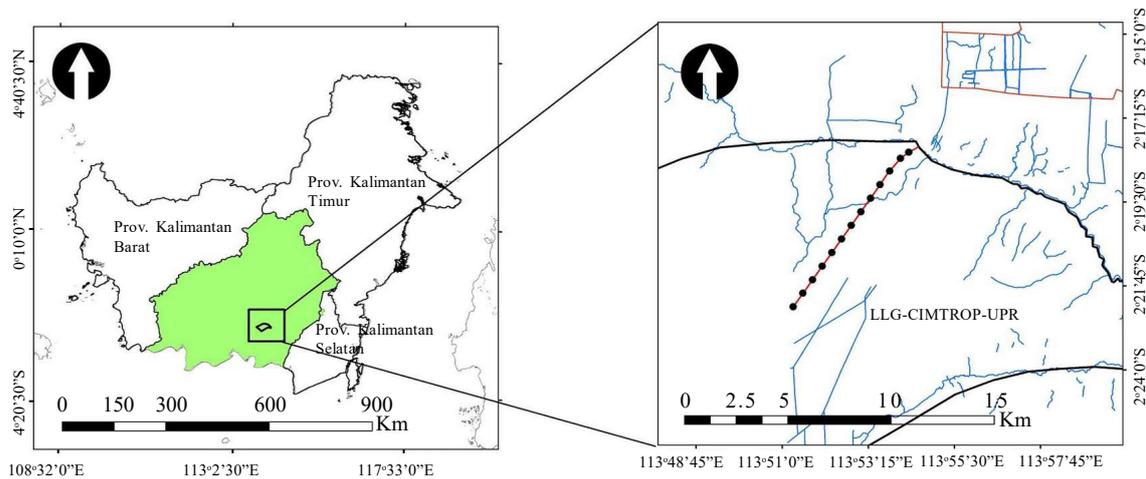


Figure 1. Location of research sites. ◻ : Areal LLG_CIMTROP-UPR, ● : Observation plot

For this study, water retention curves were obtained using the method developed by van Genuchten (1980). In order to follow the procedure for making water retention curves or pF curve, according to van Genuchten (1980), three kinds of moisture content values are needed at each pF value, namely as follows:

Measured Value of Water Retention

Moisture contents were obtained directly from measured in the laboratory, defined as gravimetric moisture content, and converted to volumetric moisture contents value (cm cm⁻³) named as the measured value (Eq 1).

Calculated Value of Water Retention

The calculated value of moisture content was determined, followed van Genuchten equation:

$$\theta_v = \theta_s + \frac{\theta_s - \theta_r}{(1 + (\alpha \psi)^n)^m} \dots\dots\dots (1)$$

where:

- = Volumetric moisture contents
- θ_s = saturated moisture contents
- θ_r = residual moisture contents
- ψ = potential matric (h = cm water column)
- α, n, m = empirical parameters by van Genuchten

The van Genuchten parameters, including the empirical parameters, were used in the SWRC fit program. This program can be executed directly from a web page (<http://purl.org/net/swrc> and Seki 2007). with the assumption that the value of m parameter is 1-1/n; soil moisture unit in cm cm³; matric potential unit in cm (water column); the manual value of

saturated soil moisture was fixed value at 0.900; the initial value of residual soil moisture was fixed value at 0.010; with positive value regression direction and fixed minimum value at 0.010 (Mualem 1976). After all of the van Genuchten parameters were obtained, the above equation's volumetric moisture contents can be calculated in the worksheet excel file using the excel solver function.

Estimated Value of Water Retention

In the worksheet excel file, the calculated value of volumetric moisture contents is shown in the regression line to get a regression with R² value optimal (nearly value of 1). According to the equation getting in a worksheet, Excel can make an estimated value of volumetric moisture contents for more pF ranges.

Bulk Density (ρ_b) and Particle Density (ρ_s)

Bulk Density (ρ_b)

Bulk density was determined by gravimetric methods, mentioned in two different peat sample conditions, namely wet or saturation condition, symbolized as ρ_b (wet) and dry condition symbolized as ρ_b (dry) with a unit in g cm³. Both bulk density values will be used to calculate the total pores (ϕ) and porosity (η) values. The wet or saturated bulk density is the weight value of the wet peat sample (before oven), calculated by following equation 1a:

$$\rho_b(wet) = WV \dots\dots\dots (2a)$$

Where :

$$\rho_b(wet) = \text{wet or saturated bulk density (g cm}^{-3}\text{)}$$

W = weight of wet peat sample before oven (g)
 V = volume of peat sample, considered to the volume of ring sample (cm³)

$$\rho^b(dry) = \frac{W}{V} \dots\dots\dots (2b)$$

Where :

$\rho^b(dry)$ = dry bulk density (g cm⁻³)

W = weight of wet peat sample after oven at temperature 105 °C (g) during 24 h.

V = volume of peat sample, considered to the volume of ring sample (cm³)

Particle Density (ρ_s)

Particle density (s) was measured using liquid pycnometers with water as filling liquid and water bath (Heiskanen 1992 and Redding *et al.* 2005), calculated following equation:

$$\rho_s = \frac{[100 \times (B - A)]}{(100 + \theta) \times (V_{w2} - V_{w1} - V_{w3})} \dots\dots (3)$$

where:

ρ_s = Particle density (g cm³)

B = weight of pycnometer whit containing peat sample which 2 mm sieve pass (g)

A = weight of pycnometer (g)

θ = moistures content of peat sample (%)

$$V_{w1} = \frac{[C - B]}{\rho_{w1}} \dots\dots\dots(3a)$$

where:

V_{w1} = water volume for water-specific density (g.cm³) at a pycnometer temperature after filled by water and peat sample (cm³).

C = weight of pycnometer containing peat sample and water (g)

B = weight of pycnometer containing peat sample (g)

ρ_{w1} = Specific density of water at a temperature in pycnometer after filled by water (g cm⁻³).

$$V_{w2} = \frac{[D - A]}{\rho_{w2}} \dots\dots\dots(3b)$$

where:

V_{w2} = water volume for water-specific density (g cm⁻³) at a pycnometer temperature was filled by certain water only.

D = weight of pycnometer was filled by certain water only (g)

A = weight of pycnometer (g)

ρ_{w2} = Specific water density at a temperature in pycnometer after filled by water only (g.cm³).

$$V_{w3} = \frac{[\theta(B - A)]}{[(100 + \theta) \times \rho_{w3}]} \dots\dots\dots(3c)$$

where:

V_{w3} = volume of water for water-specific density (g.cm³) at temperature 60 °C.

B = weight of pycnometer containing peat sample (g)

A = weight of pycnometer (g)

θ = moistures content of peat sample (%)

ρ_{w3} = Specific density of water at temperature 60 °C (g cm³).

Porosity

Porosity value was determined as total pore (mentioned in % value) and porosity, calculated by the following equation (Ninmo 2004) :

$$\Phi = (1 - (\rho_{b(wet)} / \rho_s)) \times 100\% \dots\dots\dots (4)$$

where :

Φ = pore total (%)

$\rho_{b(wet)}$ = saturated bulk density, mentioned in g cm⁻³ (see equation 2a);

ρ_s = specific density or particle density (g cm⁻³) (see equation 3)

Moisture Volumetric

Moisture volumetric calculated by following equation (Wiess *et al.* 1998) :

$$\theta_v = \theta_m \times \frac{\rho_{b(dry)}}{\rho_w} \dots\dots\dots (5)$$

where :

θ_v = moisture volumetric (% v)

θ_m = moisture gravimetric (% w = g g⁻¹)

$$\theta_m = \frac{m_w}{m_{sd}} : \dots\dots\dots (5a)$$

where :

m_w = mass of water (water loss after the oven, at T = 105 °C during 24 h)

m_{sd} = mass of dry soil (after oven at T = 105 °C during 24 h)

$\rho_{b(dry)}$ = dry bulk density mentioned in g cm⁻³

ρ_w = water particle density (g cm⁻³)

Pores Saturation

Saturated degree, namely as water retention, calculated using the following equation (Walker *et al.* 1931):

$$S = (\theta / \eta)100 \dots\dots\dots (6)$$

where :

- S = saturated degree (% v)
- θ = moisture volumetric (% v) at each certain pF value
- η = porosity (%)

RESULTS AND DISCUSSION

Water Retention

Measured Value

Table 1 shows that volumetric moisture content (θ_w) at the surface layer (0-50 cm) is always lower than subsurface layer (50-100 cm), except from deep peat categories, where for the level of pF 1, pF 2, and pF 2,54, the θ_w at a surface layer higher than a subsurface layer. Moisture contents for deep peat sample, at the surface layer, were 29.36%, 17.59%, and 13.37%, respectively for the level of pF 1, pF 2, and pF 2.54, lower than the subsurface layer, which each has 36.77%, 18.90% and 14.51 % moisture contents respectively. The results because water movement in the surface layer is more dynamic than in the subsurface layer (Kutilek and Novak 1998). However, almost all of them, shallow peat moisture contents at the same pF value, are commonly higher than medium peat and deep peat. As mentioned above, that on the shallow peat, there might have more micropores, while the medium peat and peat were more macropores (Nimno 2004).

As mentioned previously, shallow peat in this study is located at about 1 km from the Sebangau river's edge, just behind and even including the levee area. The accumulation rate of peat material in

shallow peat zones runs very slowly and even for the current decade as if deemed to have stopped. Pedogenesis dynamics on these zones are not significantly accelerated to the peat material accumulation. Regarding this study's focus, the important thing that concerns the influence of the peat layer's proximity with the mineral layer below and the presence of sedimentary minerals in the peat matrix to water-retaining capacity. On the other hand, for medium peat and deep peat sample, they have been taken from around and including peat dome area, it is estimated to have a more porous physical structure than shallow peat. It is thought to be the reason why its ability to retain water is lower than shallow peat.

Calculated Value

Data of measured value used to obtain the calculated value of volumetric moisture contents after divided 100 (convert from percent volumetric value). Furthermore, I entered these data as input data on the SWRC software program (version 3) and then computed them to obtain the van genuchten empirical parameters. The computation result is shown in Table 2.

Based on data shown in Table 2, doing calculation volumetric moisture contents value (θ) by input data to van Genuchten equation (eq.1). In equation number 1 before, a water potential parameter (pF value) is converted to a high value of centimeters (cm) of the water column, in its equation symbolled (Ψ). For example, after input data of these the parameters (α , n, and m) to equation (1), is $\theta = 1 + (\alpha \Psi)^n)^m$, the value of (θ) for curve 1 (SP L-1) at pF 0, pF 1 and pF 2 are 0.798; 0.747; and 0.250 respectively. This computation is mentioned as θ value before solved because that changes after the excel solver function have been done. Furthermore, using the solver function in the worksheet excel program to obtain

Table 1. The measured value of moisture contents (θ_v in % v).

pF level	SP				MP				DP			
	0-50 cm		50-100 cm		0-50 cm		50-100 cm		0-50 cm		50-100 cm	
	V	%	V	%	v	%	v	%	v	%	v	%
0	0.798	79.83	0.816	81.62	0.857	85.68	0.827	82.73	0.823	82.26	0.817	81.72
1	0.789	78.88	0.803	80.33	0.832	83.23	0.807	80.69	0.804	80.36	0.808	80.77
2	0.253	25.32	0.309	30.86	0.346	34.55	0.276	27.64	0.326	32.59	0.299	29.89
2.54	0.207	20.72	0.269	26.89	0.325	32.45	0.256	25.64	0.294	29.37	0.275	27.51
4.2	0.189	18.92	0.224	22.43	0.092	9.18	0.082	8.23	0.066	6.55	0.061	6.14

Table 2. Van Genuchten parameters value (empirical parameter by SWRC program version 3).

Curve/sample	Van Genuchten parameters value				
	θ_r	α	n	θ_s	m
1/SP L-1	0.195	0.0312	3.0282	0.799	0.6698
2/SP L-2	0.240	0.0346	2.6417	0.820	0.6215
3/MP L-1	0.092	0.0529	1.5356	0.879	0.3488
4/MP L-2	0.110	0.0452	1.8137	0.847	0.4486
5/DP L-1	0.065	0.0504	1.5392	0.846	0.3503
6/DP L-2	0.075	0.0467	1.6346	0.842	0.3882

the θ value after solved. The value of θ (before and after solved) computation by excel solver function is shown in Table 3.

The value of θ after solved was obtained by following completely and appropriately the procedures in excel solver dialog, were filled the cell target dialog with the value of van Genuchten parameter (α , n , and θ_r), which will be changed to fitting water retention curve. One of its procedures is optimizing the squared difference at the minimum value and different (diff.) value, which is mentioned as distinct (θ) between a measured value and calculated value before it is solved. Based on the calculating result in the excel solver procedure, an estimated value of (θ) can be obtained at more points of pF ranges. The estimated value makes fitting water retention (pF) curve, as shown in Figures 2 and 3. In this paper, as many as six curves could be made. Naming curve 1, curve 2, and so on until curve 6 is actually the name for the sample code tested, namely curve 1 for SP L-1, curve 2 for SP L-2, curve 3 for MP L-1, curve 4 for MP L-2, curve 5 for DP L-1 and finally curve 6 for DP L-2. This water retention curve is a curve form after fitting has been used the SWRC program and excel solver function.

According to Figure 2, volumetric moisture contents' changes follow the same pattern for all peat sample categories, but the SP has a more apparent pattern than MP and DP. For the SP sample, the estimated value of volumetric moisture content is more approach to the measured value, while for

the MP and DP sample categories, it has weak proximity to the measured value. The decreasing volumetric moisture content following an increasing pF value for SP more confirm the curve pF pictures by many other types of research, particularly with the water retention study in mineral soil (Rajkai *et al.* 2004; and Vernay *et al.* 2016). The SP can represent the peat soil in hemic decomposition stages, which is more penetrated by fine mineral material (Widjaya-Adhi 1992). The MP and DP, which have lowes stages of decomposition, mentioned fabric material, which is undoubtedly formed by more large fraction material than the SP sample. Perhaps this case is because the pattern of water retention changes is difficult to define, where proximity estimated value line with measured value is more weakness than SP categories.

Volumetric moisture content tends to decrease when the water potential is increasing. That most significant change happened between pF 1 to pF 2 and pF 2.54 to pF 4.2, but almost unchanged between pF 0 to pF 1 and pF 2 to pF 2.5. However, it is related to the pores size distribution of the peat matrix. The same trend happened for volumetric moisture contents at the surface layer (0-50 cm) and subsurface layer (50-100 cm). In general, water retention curves' appearance is similar to the other studies (Walczak *et al.* 2002; Campos *et al.* 2011; Indahyani *et al.* 2017; and Madi *et al.* 2018). Volumetric moisture contents slowly decreased at low pF value (pF 0 to pF 1) and high pF value (pF 2.54 to pF 4.2), but its rapid decrease from pF 1 to

Table 3. Calculated value of θ (before and after solved) computation by excel solver function

pF value	Curve 1		Curve 2		Curve 3		Curve 4		Curve 5		Curve 6	
	Before	After										
0	79.85	79.90	81.77	81.99	74.40	86.90	79.21	84.44	71.60	83.65	74.60	83.60
1	74.70	78.78	73.36	80.04	55.20	78.24	59.36	77.97	52.68	75.37	54.94	76.03
2	24.96	25.38	30.69	31.13	32.07	41.40	27.70	31.21	29.53	39.11	28.46	35.80
2.54	20.08	19.93	25.12	24.80	23.45	24.30	18.59	17.56	20.83	21.77	19.26	19.02
4.2	19.50	19.65	24.00	24.27	11.28	12.45	11.35	13.41	8.57	9.56	8.64	10.27

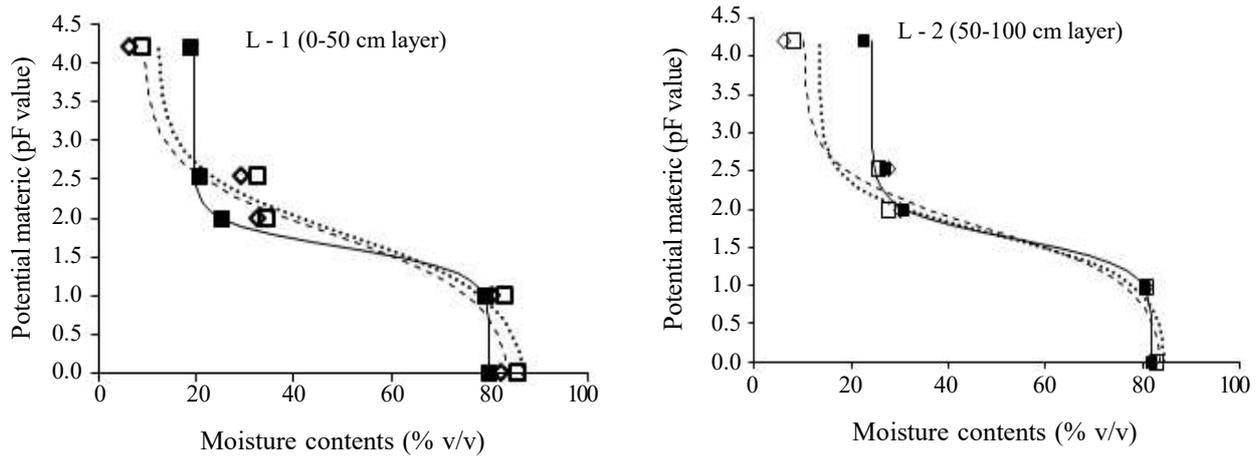


Figure 2. Water retention curve for surface layer peat sample. ■ : SP measured, □ : MP measured, ◇ : DP measured, — : SP estimated, : MP estimated, - - - : DP estimated.

pF 2. The hydrological characteristics of soils, such as water retention and the water movement rate, depend primarily on the material’s total porosity and pore-size distribution (Kutilek and Novak 1998). The soil water potential-moisture characteristics allow the calculation of effective pore size distribution.

Water retention curves make it possible to determine the amount of strongly bound water (pF higher than 4.2), which indicates the presence of micropores in soil. The volume of mesopores can be calculated as a difference between water content at pF 2 and 4.2. The soil’s mesopore content corresponds to the water content available for plants, and the water content at pF 2.0 - 2.7 and 2.7 - 4.2 represents readily available and poorly available water, respectively. The water content between saturation and pF 2 indicates the presence of macropores. In macropores, a rapid gravitational efflux of water takes place. It is called soil aeration capacity. Water capacity between pF 2.0 and 4.2 is potentially good retention, but water is unavailable for plants at the up of pF 4.2 (Okruzsko 1993).

The peat matrix’s volumetric moisture matrix has the same trend for three-peat thickness categories; were shallow peat, medium peat, and deep peat. Shallow peat moisture levels always appear to be higher than medium peat and deep peat, and this occurs both for the top surface peat layer (0-50 cm) and for the subsurface peat layer (50-100 cm). The results may be related to soil mineral materials’ solubility in the peat matrix, which is supported by a peat layer that coincides with the mineral layer in the ground. Essential on some of the peat characteristic studied in the tropical peatland of Sabangau catchment area, the mineral soil material under the peat layer is generally in the form of clay mineral material with a fraction size of <2

µm or amorphous fraction of peat material, which varies of 0.04 to 0.11 g.cm³ (Könönen *et al.* 2015), and its solubility can fill the peat matrix pore space. The existence of the clay fraction in the peat matrix determines the structure of the pore space, where micropores dominate the more fine fractions (<2 µm), including clay minerals, the pores space in the peat matrix.

For all peat thickness categories and separate peat layer, the volumetric moisture content as a measured value at pF 4,2 is remaining about 20 % volume of pore space (except SP L-2, which have $q = 22.30$ %v); while at the pF 0 is maximum about 85.86 % by volume (Table 2 and 3). The first phenomena show that when there is a driving force to release water from the peat matrix equal (pF 4.2), less than 20% of the pore space volume still filled water. The two phenomena show that when the power of water release from the peat matrix is equal to pressure nearly pF 0 (in a flooded field) or saturated, a maximum of 86% of the volume of the pore space is filled by water, or about 14 % volume of pore space is filled by air as a void pore.

For the first phenomena, explained at pF e” 4.2, the plant’s root can not take that water, so it is often referred to as the permanent wilting point. Based on the soil pore function, the pore filled with water at that pF d” 4,2 level has namely pored for available water, where accorded water release from the soil matrix naturally. The value of about 20 % pore volume still containing water for this study was lower than the percent volume value of water at the same pF level for mineral soil. For the second phenomenon, a maximum of 86% of the pore volume contains water, even though it is a saturated condition (in a flooded field). In other words, there is always an empty pore, filled with air or vacuum. Van

Genuchten and Wierenga (1976) have grouped pores into “2 regions”, namely “mobile region” and “immobile region.” For the pores, including the “mobile region” group, water and soil solutions are relatively more accessible, but the “immobile region” is relatively more complex. The water and soil solution movement occur only through the diffusion mechanism, and the potential water that works is the osmotic potential.

Porosity and Volumetric Moisture Content

The total pore for surface layer is 84.67%; 86.40% (average); and 86.98% (average) for SP, MP and DP categories respectively. The total pores' value for the subsurface layer is 83.53%, 84.56% (average), and 86.93% (average) for SP, MP, and DP categories. The data shows that most of the volume of soil is pore space. Furthermore, not all pore spaces can be filled with water, and the maximum volume of the pore that can be filled by water is called saturated volume or known as volumetric moisture content. The value of volumetric moisture contents calculated following equation 5 above, and its result calculated in Table 1.

Additionally, in the van Genuchten Models, several volumetric moisture content parameters were used, namely saturated moisture contents (θ_s) and residual moisture contents (θ_r). The saturated moisture contents (θ_s) which are equivalent to porosity ($\eta = V_v/V$; where V_v = void volume \cong total pore (ϕ); and V is the volume of soil sample), and the residual moisture contents (θ_r) is the residual water content, defined as the water content for which the gradient $d\theta/dh$ becomes zero. In addition, the term pore saturation degree is also known. Based on available data, and that may be calculated, some porosity parameters are obtained, as shown in Table 4.

The data presented in Table 4 illustrates the characteristics of peat soils' porosity, which are only data on a laboratory scale, which cannot necessarily explain the field's actual situation. However, the data obtained is still within the range of normal values commonly found by researchers. The value of pores total (ϕ) are ranges from 0.84 (83.53%) to 0.87 (86.98%) and the porosity (η) are ranges from 0.83 (83.45%) to 0.87 (86.90%). According to Radforh *et al.* (1977) in Letts *et al.* (2000), the average value of peat porosity ranges from 0.81 to 0.95, greater in fibric peat than in sapric peat. Porosity from deep peat (DP) area is greater than shallow (SP) and medium-deep (MP). As mentioned in the text data shown in Table 6 interpretation, the peat

decomposition stages' level is fibric, determined based on measured bulk density data. The surface layer and subsurface layer's difference porosity is not significant, less than 1 value or 2 in percent.

The solid fraction volume (less than 20%) in the ranges from 13.11% to 16.56% means less than one-third of the peat matrix in the form of solids material. For fibric peat, almost organic material is a significant fraction, so the matrix structure and arrangement are porous and easily disturbed. One of the parameters related to porosity behavior reported in table 4 is pores value (e), ranging from 5.04 to 6.63. The value obtained is slightly lower than the (e) value reported by Johari *et al.* (2016) for peat soil from Parit Nipah Darat. The value of pores (e) or often mentioned as a void ratio, is defined as a (volumetric) ratio of the volume of void space (fluid and air together) (V_v) and volume of solids (V_s). The value of the void ratio depends on soils' volumetric changes (the void ratio of loose soils is higher than that of dense soils).

Saturated Degree (S)

V_v 's value ranges from 83.53% to 86.98%, highest for deep peat compared to shallow and medium peat. The deep peat material, which has fibric stages decomposition, might consist of high organic material, with a large fraction, so pores structure formed is dominated by macropores and mesopores (Ninmo 2004; Rezanezhad *et al.* 2009; Rezanezhad *et al.* 2010). The pores' void space can be broken down into two-phase volumes, i.e., saturation phase and the unsaturation phase (volume of air). For a sample of DP L-1 and DP L-2, it has a void volume (V_v) value of about 86.93% and 86.96%, respectively, was consist of saturation pores (S) portion and air pores portion (V_a). The value of (S), from DP L-1, for example, has (S) value about 94.57%; 92.39%; 37.47%; 33.77%; and 7.53% at different of water potential (pF value) are pF 0; pF 1; pF 2; pF 2.54 and pF 4.2, respectively.

Table 5 show that for almost all pF level in the surface layer (L-1), the value of S for MP tends to higher than SP and DP, except for pF 4.20, the SP (22.35%) has higher than MP (10.63%) and DP (7.53%). For the subsurface layer (L-2), the value of S for SP tends to higher than MP and DP, except for pF 0, the MP has higher than SP and DP. Another phenomenon found was that the S value for all pF levels in the surface layer (L-1) for MP and DP categories tended to be higher than the S Value for the subsurface layer (L-2). Unlike what happened for SP, the S value for the subsurface layer (L-2) tended to be higher than for the surface layer (L-

Table 4. Data resume related to porosity parameters.

Peat sample	Porosity parameters				Pores value
	Total pore	porosity	Void pore	Soil solid volume	
Sample Code	Layer (cm)	$\phi = (1 - (\rho_b/\rho_w)) \times 100\%$; (Anovitz and Cole 2015)	$\eta = (V_v/V) \times 100\%$; (Anovitz and Cole 2015)	$(V_s = \%)$ or $(V_d = \%)$ $V_s = (V - \eta)$	$e = (V_v/V_s)$ (e)
SP	L-1 (0-50) L-2 (50-100)	84.67 83.53	84.59 83.45	84.67 83.53	5.49 5.04
MP	L-1 (0-50) L-2 (50-100)	86.40 84.56	86.32 84.48	86.40 84.56	6.31 5.44
DP	L-1 (0-50) L-2 (50-100)	86.98 86.93	86.90 86.85	86.98 86.93	6.63 6.61

1). Based on these data, it can be concluded that the S value tends to decrease with the deeper peat layer. It is related to the movement of water in a saturated atmosphere, both vertically and horizontally on peat soils, which according to Beckwith *et al.* (2003a) in Rezanezhad *et al.* (2012), the K value (saturated hydraulic conductivity) generally decreases downward into the peat layer.

The saturated degree is the proportion of volumetric moisture contents on porosity. The saturated degree at the surface layer is not significantly different from the subsurface layer for all peat thickness categories. The changes of saturated degree have the same pattern with volumetric moisture content changes in its relation with the porosity characteristic, e.g., size, distribution, structure, and interconnection or continuously (Quinton *et al.* 2008; Quinton *et al.* 2009; Rezanezhad *et al.* 2010). The most likely main factor that affected the saturated degree appearance is the type of material texture forming the peat matrix (Rezanezhad *et al.* 2012 and 2016).

The relation between bulk and particle density with porosity

The parameters of bulk density, particle density, and porosity are presented in Table 6.

Bulk Density

The value of $\rho_{b(wet)}$ for shallow peat samples is 0.094 g.cm⁻³, lower than 0.22 g.cm⁻³ of $\rho_{b(dry)}$, and that trend was followed by its for medium peat and deep peat categories. For the surface layer, values bulk density of medium peat are ranges of 0.084 – 0.087 g.cm⁻³ ($\rho_{b(wet)}$) and 0.18 – 0.20 g.cm⁻³ ($\rho_{b(dry)}$). While for deep peat are ranges 0.064 – 0.090 g.cm⁻³ ($\rho_{b(wet)}$) and 0.11 – 0.16 g.cm⁻³ ($\rho_{b(dry)}$). For the subsurface layer, values bulk density for sample of medium peat are ranges of 0.094 – 0.107 g.cm⁻³ ($\rho_{b(wet)}$) and 0.16 – 0.20 g.cm⁻³ ($\rho_{b(dry)}$). While for deep peat are ranges of 0.067 – 0.090 g.cm⁻³ ($\rho_{b(wet)}$) and 0.10 – 0.17 g.cm⁻³ ($\rho_{b(dry)}$). The dry bulk density always higher than in wet conditions. That is related to the phenomena of water release from the peat matrix, followed by the shrinking of peat volume and contents of the fine fraction of the peat matrix and porosity (Boelter 1965). When peat materials are dried, their volume is reduced considerably caused by shrinkage events. Therefore, bulk density must be calculated based on the wet bulk volume to represent field conditions. If bulk densities are measured using a reduced volume, they will be too high, and volumetric water contents calculated with these values will also be too high. Some reports show bulk density and water contents (oven- dry weight

Table 5. Saturated degree (%) of peat sample at some pF level.

Level of pF value	Shallow Peat		Medium Peat		Deep Peat	
	L-1	L-2	L-1	L-2	L-1	L-2
	(0-50 cm)	(50-100 cm)	(0-50 cm)	(50-100 cm)	(0-50 cm)	(50-100 cm)
pF 0	94.28	97.71	99.17	97.84	94.57	94.01
pF 1	93.16	96.17	96.33	95.42	92.39	92.91
pF 2	29.90	36.94	39.99	32.69	37.47	34.38
pF 2.54	24.47	32.19	37.56	30.32	33.77	31.65
pF 4.20	22.35	26.85	10.63	9.73	7.53	7.06

basis) that result in volumetric water contents well over 100 percent (Boelter 1965).

Peat material from deep peat (DP) area, commonly have dry bulk density were lowes than 0.15 g.cm^{-3} , except for DP-6 ($\rho_{b(dry)} = 0.16 \text{ g cm}^{-3}$). That is considered as fabric categories of decomposition degree. Peat material from shallow peat (SP) and medium peat (DP) area were have dry bulk density 0.22 g cm^{-3} (SP-1); 0.18 g cm^{-3} (MP-1) and 0.20 g cm^{-3} (MP-2), respectively. That is considered hemic categories of decomposition level (Widjaya-Adhi 1992), and their structures of peat matrix structures are not dominated by the fine or coarse fraction.

Particle Density

Based on data shown in Table 6, the value of particle density (ρ_s) in the surface layer (L-1) and subsurface layer (L-2) for SP categories consistently higher than the MP and DP categories, where the SP categories have values 0.67 g cm^3 and 0.77 g.cm^3 ; for the MP categories has values range from 0.61 g cm^3 to 0.66 g cm^3 ; and for the DP categories has values range from 0.53 g cm^3 to 0.63 g cm^3 . The occurrence of this fact in the shallow peat area

(SP) is thought to cause by the strong influence of the presence of mineral fractions that can infiltrate the structure of the peat matrix so that the fine-sized soil fraction (mineral and organic) has a more significant proportion than medium peat (MP) and deep peat (DP) area. The mineral fraction that can infiltrate the peat matrix in the SP area comes from minerals carried by the flood swings of the Sabangau river, where the SP area is right on the Sabangau river edge. It is also due to the mineral ground's influence under the peat layer, which is $<100 \text{ cm}$ from the ground surface.

Relation of bulk density, particle density, and porosity shown in Figure 3. The bulk density parameter used to determine its relationship with the total pores is dry bulk density, because this parameter is not used in calculating the total pore value directly. In contrast, the wet bulk density parameter is used directly in calculating the total pore parameter value, so of course, the pattern of the relationship can be predictable in advance. The purpose of knowing the relationship between these two parameters is to determine the trend of changes in total pore value when there is a change in peat volume, which in this case is represented by the dry bulk density parameter.

Table 6. Bulk density ($\rho_b = \text{g cm}^{-3}$), particle density ($\rho_s = \text{g cm}^{-3}$) and total pore ($\phi = \%$).

Sample code	Surface layer (L-1 = 0-50 cm)				Subsurface layer (L-2 = 50-100 cm)			
	$\rho_{b(wet)}$	$\rho_{b(dry)}$	ρ_s	ϕ	$\rho_{b(wet)}$	$\rho_{b(dry)}$	ρ_s	ϕ
SP-1	0.094	0.22	0.67	84.67	0.127	0.26	0.77	83.53
MP-1	0.087	0.18	0.64	86.47	0.107	0.20	0.66	83.71
MP-2	0.084	0.20	0.61	86.32	0.094	0.16	0.64	85.41
DP-1	0.087	0.14	0.61	85.84	0.087	0.16	0.59	85.34
DP-2	0.080	0.14	0.59	86.41	0.090	0.17	0.60	84.84
DP-3	0.070	0.13	0.63	88.87	0.087	0.16	0.59	85.17
DP-4	0.070	0.16	0.59	87.99	0.080	0.17	0.56	85.72
DP-5	0.067	0.13	0.56	88.06	0.077	0.12	0.57	86.42
DP-6	0.074	0.13	0.58	87.23	0.087	0.14	0.59	85.24
DP-7	0.064	0.12	0.57	88.92	0.074	0.13	0.57	87.06
DP-8	0.074	0.12	0.53	85.83	0.080	0.10	0.57	90.83
DP-9	0.074	0.13	0.57	87.02	0.067	0.11	0.54	86.94
DP-10	0.090	0.11	0.55	83.61	0.074	0.12	0.54	86.37

Figure 3 showing that total pores value (f) for surface layer (L-1= 0-50 cm) and subsurface layer (L-2= 50-100 cm) tends to decrease when increasing the dry bulk density and particle density, however that has low coefficient value ($R= 0.624$ for $r_{b(dry)}$ and $R= 0.375$ for r_s). This fact seems to confirm a directly proportional relationship between parameters bulk and particle density with total pores, even though the bulk density parameter used is dry bulk density, which is not used directly in calculating the total pore parameter.

Porosity describes as volume space filled by water or air in the peat matrix. It depends on the structure of the fraction in the peat matrix formation. Bulk density is a parameter that describes the undisturbed solid mass structure of the peat matrix, and inside there is pores space.

The compressibility of peat is controlled by its physical properties, including its pores' structure and arrangement (Kennedy and Price 2005). Therefore, the particle density parameter describes the amount of solid mass in the peat matrix volume, and inside there is without pore space. In other words, the mass of solids per unit volume of solids (Weindorf and Wittie 2003). The porosity of soil depends on several factors, including (1) packing density, (2) the breadth of the particle size distribution, (3) the shape of particles, and (4) cementing (Ninmo 2004). Although these two parameters describe the same object, namely the mass solids of the peat matrix, the difference between there agree and the amount of pore space mentioned pore total (% v), consequently, a comparison that parameters are in line (Figure 4). The peat surface layer has a regression coefficient

(R) that is 0.814 higher than the subsurface layer ($R = 0.594$). For subsurface, the low of $R (< 0,75)$ indicates that an increase of solid mass volume does not always follow an increase in the amount of solid mass.

Its inconsistency might be related to the physically dynamic of peat material nearly ground surface (under peat layer deposit), particularly its porosity behavior, e.g., pore structure and its arrangement. Peat material near the ground surface has both elastic and plastic properties that enable it to expand and contract readily with wetting and drying (Boelter 1965). Porosity is often conceptually partitioned into two components, most commonly called textural and structural porosity. The textural component is the value the porosity would have if the particles' arrangement were random, as described above, for granular material without cementing. The textural porosity might be about 0.3 in a granular medium (Ninmo 2004). The structural component represents nonrandom structural influences, including macropores, and is arithmetically defined as the difference between the textural porosity and the total porosity. A research conclusion that the physical properties (bulk density, total porosity, water retention, differential water capacity) of peat depend to no small extent on the relation between their organic and mineral parts (Boelter 1965, Schwärzel *et al.* 2002, Schwärzel *et al.* 2006 and Walczak *et al.* 2002).

CONCLUSIONS

The relation of bulk and particle density with porosity was a weak tendency, although the porosity

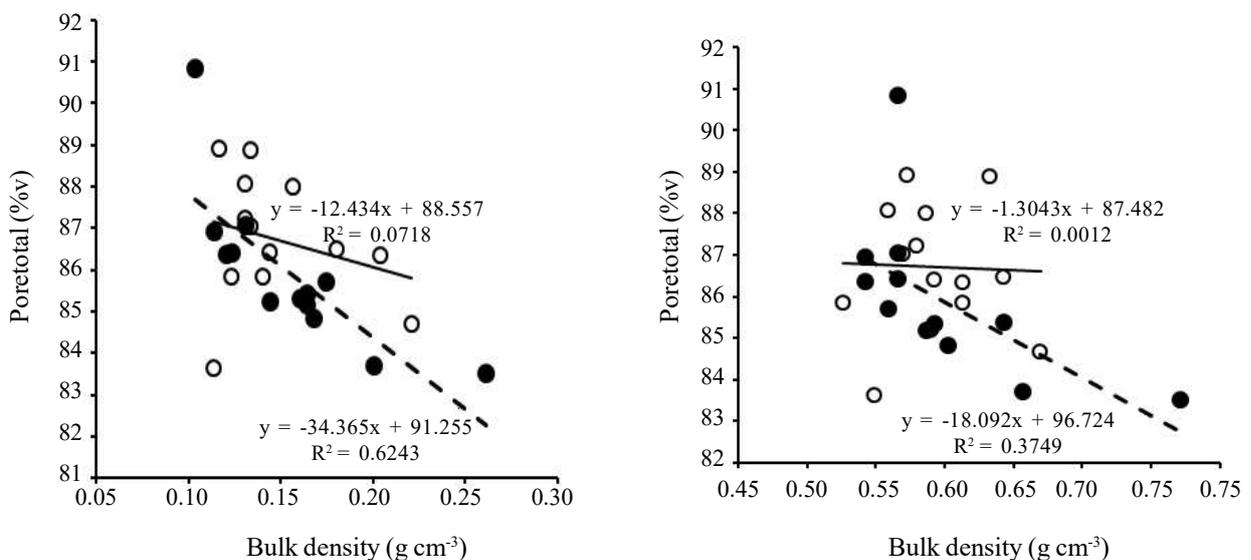


Figure 3. Relation bulk density ($r_{b(wet)}$) dan particle density (r_s) with total pores (f). ● : 50-100 cm layer, ○ : 0-50 cm layer.

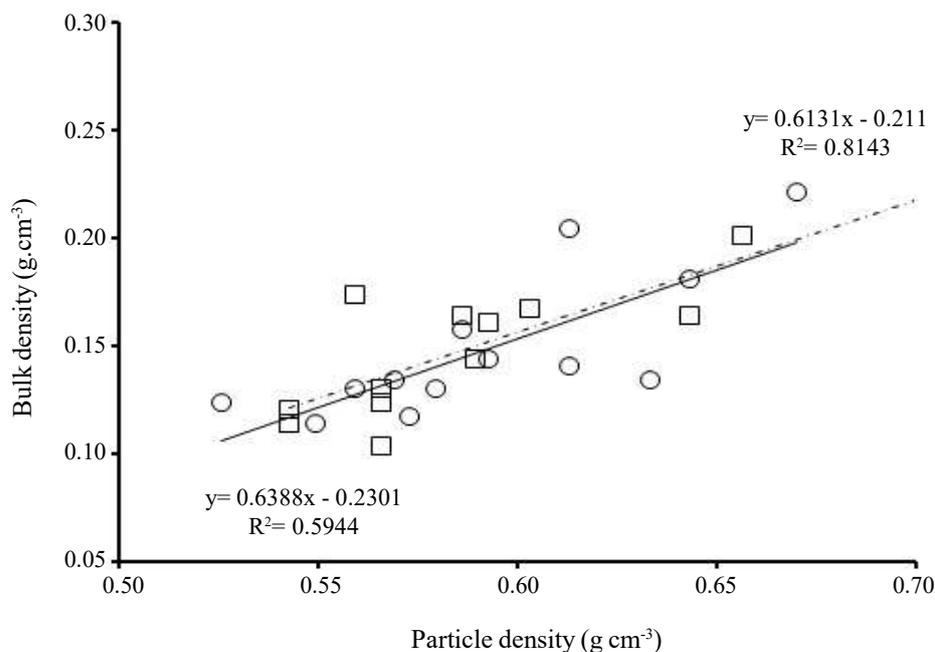


Figure 4. Relation bulk density and particle density. ● : 0-50 cm layer, □ : 50-100 cm layer.

trend to decrease while increasing the bulk and particle density has a low coefficient ($R=0.624$ for BD and $R=0.375$ for PD). The compressibility of peat is controlled by its physical properties, including its pores' structure and arrangement.

The peat matrix's volumetric moisture matrix has the same trend for three-peat thickness categories; were shallow peat, medium peat, and deep peat. Shallow peat moisture levels always appear to be higher than medium peat and deep peat, and this occurs both for the top surface peat layer (0-50 cm) and for the subsurface peat layer (50-100 cm). It may be related to soil mineral materials' solubility in the peat matrix, which is supported by the peat layer's presence that coincides with the mineral layer in the ground.

For all peat thickness categories and separate peat layer, the moisture content at pF 4.2 is less than 20% by volume, and at pF 0 is a maximum of 86% by volume. The first phenomenon shows that when there is a driving force to release water from the peat matrix equal to a pressure of 15 atm, less than 20% of the volume of the peat matrix still filled water. The two phenomena show that when the power of water release from the peat matrix is equal to a pressure of nearly 0 atm (in a flooded field) or saturated, a maximum of 86% of the peat matrix volume is filled by water.

The saturated degree of shallow peat at the level $pF \geq 1$ ($pF 1 - pF 4.2$) consistently high compared to the medium peat and deep peat, both at the surface layer (0-50 cm) and subsurface layer (50-100 cm). While at pF 0, it is always lower than

that of medium peat and deep peat. For all peat thickness categories, the saturated degree at the surface is not significantly different from the subsurface layer.

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