Hydro-physical properties of agriculturally used peatlands in Liang Anggang Protected Forest, South Kalimantan, Indonesia

A G Salim, B H Narendra, Y Lisnawati, H H Rachmat
Forest Research and Development Center, Ministry of Environment and Forestry, Jl.Gunung Batu No. 20 Bogor, 16610, Indonesia

*Corresponding author: budihadin@yahoo.co.id

Abstract. The utilization of peatlands as agricultural areas that do not pay attention to proper water management will result in peatland degradation. To restore the degraded peatlands, it is necessary to explore the peat’s hydrological and physical characteristics. Therefore this study investigates the hydro-physical peat characteristics in the peatlands that have been converted into agricultural use. The research was carried out in the Liang Anggang Protected Forest area, specifically in the area converted to agricultural land. Undisturbed peat samples were collected in both intensive and un-intensive agricultural sites. Peat characteristics were analysed in the laboratory include bulk density, particle density, porosity, total soil water content, and hydraulic conductivity variables. The result shows that peat characteristics in the intensive agricultural land significantly indicate higher bulk density and particle density with the values 0.30 g/cm$^3$ and 0.91 g/cm$^3$, respectively. Still, significantly lower values are found in porosity (66.87%), total soil water content (226.95%), and hydraulic conductivity (0.0025 cm/s). Degraded peatland restoration that functions as a protected forest must be carried out through rewetting activities and maintaining the water table depth. On the other side, the peatland whose function is designated as an agricultural area, wetland farming systems should be applied using adaptive crop species.

1. Introduction

Peat is a unique organic deposit because it can absorb up to 95% water and the solid material content of 5-10% [1]. This uniqueness is supported by the physical characteristics of peat in regulating water systems, which are influenced by the bulk density value. Although the bulk density of tropical Indonesian peat is naturally very low (0.013-0.3 g/cm$^3$) than mineral soils, its carbon content is quite high, reaching 62% of its mass [2, 3]. With a thickness of up to 20 m [4], tropical peat becomes the largest terrestrial carbon deposit [2]. Damage to peat ecosystems globally due to human activities has been increasingly widespread. The damage usually begins with drainage and will be followed by mineralization, subsidence, and changes in hydrological properties due to increased bulk density and reduced macropores [5]. Peatlands' hydrology is strongly influenced by peat characteristics, vegetation cover, and climate factors [6].

Peat soils are rich in organic matter, and due to the decrease in water level in peat, it causes oxidation of organic matter [7]. This often happens on peatlands so that it turns peatlands from a carbon sink into a carbon source due to high carbon dioxide (CO$_2$) emissions [8, 9] and usually causes
nutrient losses [10]. Managing water on peatlands is vital because it affects the rate of oxidation, subsidence, and soil consolidation. Maintain the peat conditions that are always wet will minimize the entry of oxygen into the peat so that the oxidation process is hampered [11].

Climate change affects the water cycle with increasing extreme events such as drought or high rainfall. These extreme conditions affect the amount of water that can be stored on the peat surface. Peat surface moisture is the main controller of biological interactions that influence climate change and interactions with the atmosphere [12]. This makes peatland ecosystems need to be protected. The peatland typology in South Kalimantan is characterized by average shallow peat with the potential for acid sulfate. One of the peat protection areas is located in Banjarbaru City, South Kalimantan Province known as Liang Anggang Protected Forest. Although this area is functioned as biodiversity protection and regulates the surrounding water system, its condition has been heavily degraded. The land cover is dominated by secondary forests, shrubs, and agricultural land. About half of this protected forest area has been occupied by the community utilized as agricultural land by practicing intensive drainage. This land-use conversion will affect the hydrological function of peatlands and need to be assessed as a basis for handling action and future planning management.

The physical properties associated with water on agricultural peat must be quantified to evaluate hydrological behavior on peat, such as soil water content, groundwater level dynamics, and evapotranspiration. At the same level of decomposition, different land uses will cause different hydro-physical peat characteristics [13]. The hydraulic properties are characterized by high porosity and a wide range of properties as in bulk density. The properties are important in influencing water table depth, especially during the dry season, and affecting fire hazards. But unfortunately, like most peatlands in Indonesia, the agricultural peat properties have not been explored much, and there is currently no available pedotransfer function that easily predicts their value [14, 15]. Based on this situation, this study aims to investigate the hydro-physical peat characteristics in the peatlands that have been converted into agricultural use. This information is useful as a consideration in restoring the peatlands and reducing the danger of land fires.

2. Materials and Methods

2.1. Study area
This research was carried out in February 2020 at block I of Liang Anggang protected peat forest area. This area covers approximately 960 ha and the position (3°23′55″S, 114°43′08″E) is 15 km from the center of Banjarbaru City, South Kalimantan Province as shown in figure 1. The area has an altitude range of 7-20 m above sea level. Based on the Banjarbaru Climatology Station, annual rainfall in the region is 2516 mm/year with 212 rainy days and an average temperature of 26.8 °C. Agricultural land in this protected forest area can be distinguished based on the intensification level of land management.

The intensities of agricultural management were distinguished by the length or period of land occupation, and land management pattern by farmers. Based on preliminary field interviews, there are two groups of agricultural practices in Liang Anggang. The first group is intensive farming, which was started about seven years ago and initiated with the cultivation of vegetables, palawija, or empon-empon herbs. In this group, the farmers routinely add ash and fertilizer at the beginning of planting time, and based on field observation, the degree of peat decomposition was categorized as mature peat (sapric). In the second group, the agricultural land was opened about three years ago and was not cultivated intensively. The decomposition level was dominated by hemic level and a small proportion by sapric.
2.2. Field data collection

The hydro-physical characteristics of peat soils were measured based on samples taken from two groups of agricultural land in the protected forest areas. The first group is intensive agriculture, and the second group is un-intensive agriculture. To determine valid and representative hydraulic physical soil properties in the laboratory, it is necessary to take undisturbed peat samples [16]. Each agricultural group was represented by three separate locations, and six peat samples were collected in each location. Therefore, each group of agricultural was represented by 18 samples. Samples were taken very carefully using the 5cm diameter of stainless steel cores/cylinders. Both ends of the core were sealed with plugs and waterproof tapes for transport to the laboratory [6].

2.3. Laboratory and statistical analysis

Bulk density ($\rho_b$) was determined by analysing replicate samples following International Standard ISO 11272: 1998 using the core method [17]. The bulk density was calculated based on the dry mass and the sample volume [18]. Particle density ($\rho_p$) was measured using the fluid pycnometer method based on ISO 17892-3: 2004 [17, 19]. The values were calculated based on the liquid volume difference filled in the pycnometer with and without the sample being present [20]. The total pore volume (porosity, $\phi$) of a sample was calculated based on the bulk density ($\rho_b$) and particle density ($\rho_p$) values obtained for each sample using the equation (1) [6].

$$\phi = \left[1 - \left(\frac{\rho_b}{\rho_p}\right)\right] \times 100\%$$  \hspace{1cm} (1)

The total soil water content was measured based on the total mass of the water that fills up the soil in the sampling core up to the saturated condition reached [21]. Saturated Hydraulic Conductivity ($K_s$) of the cylindrical samples was determined by the constant head permeameter method. The value was calculated from the downward water flow through the peat sample using Darcy’s law [16]. The volume of water collected within a certain period was recorded. The $K_s$ was calculated for each sample placed under constant water head by the equation (2) [22, 23]:

$$K_s = \frac{(V \cdot L)}{(S \cdot t \cdot H)}$$  \hspace{1cm} (2)

where $V$ is the water volume passing through the core (cm$^3$), $L$ is the length of the core (cm), $S$ is the section of the core (cm$^2$), $t$ is the time (s), and $H$ is the height of the hydraulic gradient (cm).

Statistical Analysis System (SAS) 9.0 was used for all statistical data analysis. The first procedure was performing the normality tests using Shapiro-Wilk in SAS Univariate procedure for all datasets. A normally distributed dataset was then used to assess the differences in peat hydro-physical properties. The student’s t-test was run to determine if there was a significant difference between the means of
two groups of variables using the SAS t-test procedure. The correlations between two peat hydro-
physical variables were assessed using the SAS CORR procedure [24, 25]. The critical value used in
all statistical procedures was at $\alpha = 0.05$.

3. Results and Discussion
The mean values of hydro-physical characteristics, including the significance value of the t-test are
given in table 1.

| Agricultural Groups | Bulk density (g/cm$^3$) | Particle Density (g/cm$^3$) | Porosity % | Total soil water content % | Hydraulic conductivity (cm/s) |
|---------------------|-------------------------|-----------------------------|------------|-----------------------------|-------------------------------|
| Intensive (n=18)    | 0.30±0.03               | 0.91±0.09                   | 66.87±3.12 | 226.95±20.43                | 0.0025±0.0007                 |
| Un-intensive (n=18) | 0.22±0.02               | 0.71±0.04                   | 69.76±2.02 | 307.13±22.41                | 0.0076±0.0006                 |

$\text{p-value of T-test}$ & < 0.001 & < 0.001 & 0.033 & < 0.001 & < 0.001

Intensive peat agricultural land, on average, shows a 50% higher bulk density than the un-intensive
agriculture area. The bulk density’s mean on the un-intensive is equivalent to those measured for
abandoned agricultural peatland in Jabiren (0.23 g/cm$^3$) [26] and Tumbang Nusa (0.24 g/cm$^3$) [27]
both in Central Kalimantan Province. Individual sample analysis reveals that the overall bulk density
values are range from 0.18 to 0.35 g/cm$^3$. This range shows the agreement with the range from [19] for
low-lying agricultural peat soils (0.09 to 0.44 g/cm$^3$). A trend that shows increasing in BD due to
intensive agriculture, which accelerates the decomposition and degradation of the peatlands. The
maximum value in this study (0.35 g/cm$^3$) is similar to the bulk density value in the Fenlands of
Norfolk agricultural peatland. The farmers manage the peat under intensive arable and horticultural
farming primarily grows vegetables on a commercial scale [17]. Although this value is still lower than
the highest BD in the degraded tropical peatland in Indonesia and several other countries that is equal
to 0.57 g/cm$^3$ [2], the lowest value in this study (0.18 g/cm$^3$) is far above the lowest BD in natural
tropical peatland (0.013 g/cm$^3$). This indicates that the level of peat degradation in Liang Anggang
protected forest is quite high even though in the un-intensive agriculture area. T-test confirmed that
BD value will increase in line with the intensity of the agriculture pattern. This is consistent with the
previous results study of [28], which states that intensively managed peatlands such as agricultural and
plantation lands tend to have a higher bulk density value than natural peatland forests or peatlands
covered by shrubs or swamp shrubs. Amorphous peat tends to have a higher bulk density starting at
1.2 g/cm$^3$ and can weigh up to 500% water content, whereas in fibrous peat, the moisture content
reaches 3000%, with the bulk density about half of the amorphous peat [29].

Table 2. Correlation analysis between peat hydro-physical variables

| Variable            | Bulk Density | Particle density | Porosity | Total soil water content | Hydraulic conductivity |
|---------------------|--------------|------------------|----------|--------------------------|------------------------|
| Bulk density        | -            | 0.98             | - 0.82  | - 0.98                   | - 0.98                 |
| Particle density    | -            | -                | -0.70    | - 0.94                   | - 0.96                 |
| Porosity            | -            | -                | -        | 0.86                     | 0.83                   |
| Total soil water content | -        | -                | -        | -                       | 0.99                   |
| Hydraulic conductivity | -         | -                | -        | -                       | -                      |
There was also a significant increase in the particle density variable which was in line with the intensity of the farming pattern. The correlation analysis showed in table 2 indicates that the particle density has a high positive correlation with the bulk density. However, the increment of particle density was not as high as in the bulk density variable. Regarding peat has a compressible characteristic, the depreciation variable also depended on peat decomposition level [17].

The maximum particle density value observed in this study (0.97 g/cm³) is lower than [17] study result on agricultural peatland, which shows the range of particle density from 1.24 to 1.57 g/cm³, and result of [19] with the range from 1.10 to 1.57 g/cm³. The porosity variable, calculated based on the bulk density and particle density, shows a significant decrease in the intensive agricultural group. This is also confirmed by the highly negative correlation between the porosity and either the bulk density or particle density. Drained peatlands to expand agricultural land have increased the occurrence of peat decomposition. They have led to peat physical characteristics changes due to the soil structure degradation and loss of structural pore in peat. This condition also decreases the water storage capacity because peat decomposition will be followed by a reduction of macropore number [19, 30]. As shown in table 2, the water content in intensive agricultural land is significantly lower and has a high positive correlation with porosity.

The fiber content of peat will influence the characteristics of peat. Fibrous peat contains more than 20% fiber content, and its decomposition level is low. In contrast, amorphous peat has less fiber content because it has been decomposed and has low water holding capacity. Photomicrographs of coarse peat particles show that the pore space between particles can hold water when fully saturated [31]. Adequate water content in the peat, especially on the surface area, is very important because it plays a major role in controlling physical and biogeochemical processes, greenhouse gas emissions, and the relationship between the biosphere and the atmosphere [12]. In drained peat, the microbial activity also plays a significant role in accelerating the peat material decomposition. The pore and coarse material of the peat are reduced, accompanied by an increase in bulk density which results in changes in water content [15].

Hydrological dynamics that occur in peat must also be supported by adequate soil hydraulic properties that can describe more on the condition of wetlands. Hydraulic conductivity indicates the capacity of the soil to pass the water. In pristine conditions, peat is a porous material and has good permeability and drainage. There are variations in the range of peat permeability values from one location to another due to differences in soil fabric of peat, physical and structural arrangement of peat particle [32]. Table 2 indicated that intensive agricultural activities carried out by the community at the research location clearly showed lower hydraulic conductivity values compared to non-intensive agriculture. The value is three times lower and positively correlated to the porosity and total water content values. Peat hydrological conditions depend on the type of vegetation, land use, water management, and climate conditions [5]. Peat hydraulic conductivity is influenced by the size, shape, fabric, and packing of the particles [29]. A significant decrease in hydraulic conductivity has been commonly observed on disturbed peat. The value is in line with the level of peat degradation and decomposition, higher bulk density, and lower porosity. In fully decomposed peat, the hydraulic conductivity value can be eleven times lower than fibrous peat, even though the bulk density value is only three times greater [19, 33]. Under natural conditions, the water table depth (WTD) on the peat should be near the surface, with the peat moisture being in equilibrium [14]. The decrease in hydraulic conductivity needs to be controlled because it affects the water flow process and the amount of water stored in the peat. Controlling should be carried out by adjusting the water level as the main factor determining peat decomposition and reducing the risk of hydrological drought and associated land fire.

The existence of well-preserved peat ecosystems and being important for biodiversity, carbon sequestration, and storage also play a role in maintaining water characteristics. Changes in water systems often result in the loss of certain plant species on peatlands that cannot adapt. Efforts to rehabilitate the degraded peatlands are usually carried out by blocking canals. If successful, these efforts can significantly reduce peatland fluctuations, increase water reserves, and minimize further degradation. However, not all conditions can be returned to normal, depending on the severity of
degradation [5]. Peatlands used as agricultural land in the long term have experienced changes in characteristics due to drainage and fertilization actions. Restoration of protected forest areas through rewetting activities is recommended to minimize carbon and nutrient losses from peat. Peatlands that meet agricultural land requirements should be managed by implementing wetland farming systems using adaptive crop species.

4. Conclusions
Intensive agriculture in the peatland was practiced by lowering the water table depth using drainage canals, soil tillage, and adding fertilizer and ash. All the practices lead to an increase in peat decomposition rate and further encourage the loss of structural pores and degrade soil structure. This study showed that different intensities of agricultural management in the peat area caused distinctive physical and hydraulic characteristics. Intensive agricultural management on peat areas would result in higher bulk density and particle density values but lower porosity values, total soil water content, and hydraulic conductivity variables. Degradation of the peat's physical and hydraulic characteristics causes a decrease in peat function to preserve, hold, and flow the water, thus increasing the vulnerability to hydrological drought and associated fire hazards. Peatland restoration functioned as a protected forest must be carried out through rewetting activities and maintaining the water table depth using canal blocking. On the peatland whose function is designated as an agricultural area, wetland farming systems should be applied using adaptive crop species and minimizing the tillage to control peat decomposition.

Acknowledgements
The authors gratefully acknowledge the support and funding from a collaboration between the Forest Research and Development Center and the Forestry Services of South Kalimantan Province. We thank the staff of the Forestry Services of South Kalimantan Province for assistance during fieldwork. Furthermore, we are grateful to Iskandar for his help in the laboratory. The authors declare that the main contributor in this article is BHN.

References
[1] Warburtona J, Holden J and Mills A J 2004 Earth-Sci. Rev. 67 139
[2] Rudiyanto, Minasny B, Setiawan B I, Arif C, Saptomo S K and Chadirin Y 2016 Geoderma 272 20
[3] Rudiyanto, Setiawan B I, Arif C, Saptomo S K, Gunawan A, Kuswarman, Sungkono and Indriyanto H 2015 Procedia Environ. Sci. 24 152
[4] Page S E, Rieley J O and Banks C J 2011 Glob. Chang. Biol. 17 798
[5] Menberu M W, Tahvanainen T, Marttila H, Irannezhad M, Ronkanen A K, Penttinen J and Kløve B 2016 Water Resour. Res. 52 3742
[6] Scarlett S J and Price J S 2019 Ecol. Eng. 139 105575
[7] Giesen W and Sari E N N 2018 Tropical Peatland Restoration Report: The Indonesian Case (Jakarta: Millennium Challenge Account Indonesia) p 82
[8] Wösten J H M, Clymans E, Page S E, Rieley J O and Limin S H 2008 Catena 73 212
[9] Frank S, Tiemeyer B, Bechtold M, Lücke A and Bol R 2017 Sci. Total Environ. 574 1243
[10] Holden J 2005 Philos. Trans. R. Soc. 363 2891
[11] Vos J A, Bakel P J T, Hoving I E and Smidt R A 2010 Agric. Water Manag. 97 1887
[12] Nijp J J, Metselaar K, Limpens J, Teutschbein C, Peichl M, Nilsson M B, Berendse F and Zee S E A T M 2017 Sci. Total Environ. 580 1389
[13] Gnatowski T, Szatyłowicz J, Brandyk T and Kecchavarzi C 2010 Geoderma 154 188
[14] Dettmannau U, Bechtold M, Viohl T, Piayda A, Sokolowsky Land Tiemeyer B 2019 J. Hydrol. 575 933
[15] Taufik M, Veldhuizen A A, Wösten J H M and Lanen H A J 2019 Geoderma 347 160
[16] Kruse J, Lennartz B and Leinweber P 2008 Wetlands 28 527
[17] Dawson Q, Kechavarzi C, Leeds-Harrison P B and Burton R G O 2010 Geoderma 154 181
[18] Arrouays D, Saby N P A, Boukri H, Jolivet C, Ratié C, Schrumpf M, Merbold L, Gielen B, Gogo S, Delpierre N, Vincent G, Klumpp K and Loustau D 2018 Int. Agrophys. 32 633
[19] Kechavarzi C, Dawson Q and Leeds-Harrison P B 2010 Geoderma 154 196
[20] IMANOR (Institut Marocain de Normalisation) 2019 Determination of particle density (Rabat: Laboratory testing of soil) p 12
[21] Ma Y, Qub L, Wang W, Yang X and Lei T 2016 Geoderma 271 42
[22] Michel J C and Kerloch E 2017 Sci. Hortic. 217 28
[23] Grover S P P and Baldock J A 2013 J. Hydrol. 479 130
[24] Steel R G D and Torrie J H 1997 Principles and procedures of statistics: a biometrical approach (New York: McGraw-Hill) p 633
[25] SAS Institute 2004 SAS/STAT 9.1 User’s Guide (North Caroline: SAS Institute) p 4884
[26] Wakhid N, Hirano T, Okimoto Y, Nurzakah S and Nursyamsi D 2017 Sci. Total Environ. 581–582 857
[27] Itoh M, Okimoto Y, Hirano T and Kusin K 2017 Sci. Total Environ. 609 906
[28] Suratman, Widiatmaka, Pramudya B, Purwanto M Y J, Agus F 2019 Jurnal Tanah dan Iklim 43 97
[29] Bell F G 2000 Engineering properties of soil and rock (Oxford: Blackwell Science)
[30] Rezanezhad F, Price J S, Quinton W L, Lennartz B, Milojevic T, Cappellen P V 2016 Chem. Geol. 429 75
[31] Wong L S, Hashim R and Ali F H 2009 J. Appl. Sci. 9 3207
[32] Edil TB 2003 Proc. the 2nd Int. conf. in soft soil engineering and technology (Putrajaya: Universiti Putra Malaysia) pp 3-26
[33] Hogan J M, Kamp G V D, Barbour S L and Schmidt R 2006 Hydrol. Process. 20 3635