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Variability of Hydro-Physical Properties in Drained Peat Soil (A Case Study of Perigi Village Ogan Komering Ilir South Sumatra Indonesia)

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Abstract. Peatlands have a hydrological function to provide water, control floods, weather conditions and control chemical and biological processes in the soil. Furthermore, it also plays an important role in the wetland development process. For this reason, peatland management must be careful so as not to disrupt the function of the peat ecosystem. One of the most important hydrological parameters which is an indicator of peatland damage is the soil hydraulic conductivity value (Ks), bulk density and porosity. The research aims to determine the diversity of soil hydraulic conductivity values in peatlands reclaimed for agriculture. Soil sampling was carried out in the peatlands of Perigi Village, included in the Sugihan-Saleh KHG (Peat Hydrological Area). The Ks measurement method in the laboratory uses the constant head method. The research results showed that the vertical permeability coefficient (kv) was 50.21-52.63 cm/hour and the horizontal permeability coefficient (kh) was 113.2 cm/hour. Spatial variations do not show significant differences where the Ks value relative to the distance to the drainage channel shows the same inhibiting value between 50.21-52.63 cm/hour. Soil porosity values range between 92.10-95.34% and soil bulk weights range from 0.12-0.23 gr/cm^3. This condition shows that horizontal water movement is very fast and this causes a rapid decrease in the water level if the land is opened up by building channels. Therefore, assessing damage to peat land also determines the number of land drainage networks that have been built. To control the groundwater level so that it does not fall quickly and in accordance with the compliance figure of 40 cm, the construction of canal blocking is absolutely necessary in the drainage system in agricultural and plantation areas

Key words: peat soil; hydraulic conductivity; water table; drainage

INTRODUCTION

Background

Peatlands occupy 3% of the earth's surface, which can store 21% of the world's carbon and 10% of freshwater [1]. The limitations of dry land for agriculture and plantations make peatlands cleared using land drainage techniques to dispose of its water. Of the total peat area, 15% has been drained [2]. So far, Indonesia has the largest peat area in the tropical zone, estimated at 21 million ha, representing 70% of the peat area in Southeast Asia and 50% of the world's tropical peatlands [3]. Indonesia's peatlands are concentrated in three large islands, namely Sumatra (35%), Kalimantan (32%), Papua (30%), and other islands (3%) with a total area of 21 million ha [4]. According to [5], peatlands in Indonesia are spread from lowland areas to highland areas.

On the other hand, peatland ecosystems are vital in the hydrological system because they can absorb water up to 13 times their weight. The ability of peat in each cubic meter can store around 850 liters of water so each hectare of peat can store the largest water of 88.60 million liters. Peat areas also very large carbon reserves, both above and below the surface [6]. Peatland degradation has a major impact on the local environment (in situ) and the surrounding environment (ex-situ). Flooding in the downstream of the watershed is one of the impacts of peat ecosystem damage. Peatlands in Indonesia have not been managed properly because of the low understanding of the swamp ecosystem characteristics. Wood logging and transporting activities as well as peat swamp land opening for agriculture and plantations are carried out by creating drainage channels to set the groundwater level. This can decrease the groundwater level and change the swamp ecosystem and physical characteristics of the peatland. The decrease in the peat water level can compress the peat surface, with indications of aerobic processes in the upper layer of the water level [7]; So that one of the indicators of land degradation is the decrease in soil permeability and increase in soil bulk density.

The physical characteristics of the soil are the key determinants of the land quality and environment. Good physical land characteristics will provide good environmental quality too. The physical characteristics of the soil are taken as the first consideration in determining a land for agriculture purpose [8]. Meanwhile, according to [9], the physical characteristics of the soil are a very important component in providing facilities for plant growth and affect soil fertility which will ultimately support its growth, even more important than the chemical and biological characteristics of the soil. The physical characteristic of peat soil is part of the soil morphology which plays an important role in providing facilities for plant growth [10]. The physical characteristics of the soil will also determine the soil ability to store water in peatlands. So, if the physical characteristics of the soil are well maintained, the hydrological function of peatlands can be properly maintained too [11].

Related to this condition, research is needed to determine the soil physical characteristics that are closely related to the hydrological function of peat. Some important parameters are the value of the soil bulk density; total pore space, and soil permeability. This data is very important, especially in the preparation of the water management system design and the operation of water level controlling on the land.

Purposes

This study aims to identify the diversity of soil physical characteristics that are closely related to the ability of peatlands as hydrological functions on cleared peatlands. Peatland restoration efforts will also be presented for the purpose of hydrological function restoration of peatlands.

METHODOLOGY

Place and Time

The research was conducted in the peatland of Perigi Village as part of Sungai Sugihan-Sungai Saleh land area (KHG). This peatland was opened in 2010 for rice field production. However, due to the biophysical limiting factors of the land and the high-water table conditions, this land has not been optimally managed by farmers. The research location area can be seen in Figure 1.

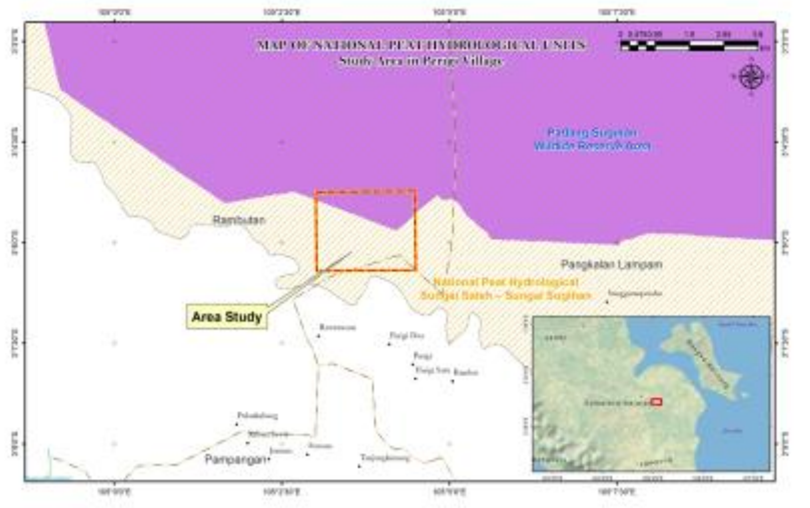

Figure 1. Research area in Perigi Village, OKI Regency, South Sumatra

Tools and Materials

The research was conducted in the field and in the laboratory. The tools and materials needed were soil survey equipment such as peat drills, meters, sample rings and stationery. The tools and materials needed in the laboratory were permeameters, water reservoirs, ovens, and scales.

Method

Field research used a survey method in a representative area about 10-hectare pilot plot. Sampling of intact soil for soil physical properties analysis was carried out using the grid method with one point representing 1 hectare of soil. The parameters of soil physical characteristic and methods used in the laboratory can be seen in the following table.

Table 1. Observation parameter

Observation Variable	Method
Bulk density	Cilinder
Porosity	Equation of BI/BJ
Saturated hydraulic conductivity	Constant head
Ground water level	Monitored well

To identify the effect of distance on drainage channels, a transect was also made to take soil samples perpendicular to the channel. The sampling distance is 20 m.

RESULTS AND DISCUSSION

General Description

Perigi Village is located in Pangkalan Lampam Sub-District. This area is covered by a peatland included in the cultivation and conservation area. Agriculture activity on peatlands has many major limiting factors, namely the condition of inundation in the rainy season, (Figure 2), in the dry season, the water level drops very quickly because the land area is not equipped yet with water level control buildings (Figure 3). Peatlands are also known as lands with low fertility levels. Therefore, burning is also an alternative to make the soil more fertile quickly. This farming model is often used by farmers. This model is a rice planting technique by spreading it on burned land. In the field, farming is started in mid-August and there are farmers who have begun burning the land (Figure 3). The burning process leaves ash that can quickly provide nutrients and increase soil pH. Furthermore, rice planting is carried out by spreading or digging. This farming pattern is known as *sonor* system.

Figure 2. Condition of flooded land in the rainy season (January-May 2024)

Figure 3. Condition of land that is no longer flooded in August 2024.

*Sonor/*swidden agriculture technique is still a cheap alternative for farmers for land clearing (Figure 4). Farmers burn to clear land. When land is often burned, it will change its physical characteristic. Especially the value of soil hydraulic conductivity. Ash from burning in the surface layer (0-20) cm will infiltrate into the layer below and fill the soil pore space. This condition causes the land to have an increase in soil bulk density and a decrease in the value of soil hydraulic conductivity. Therefore, the value of soil hydraulic conductivity is used as a land indicator of degradation or it is still in good condition. However, in a short-term perspective, it will have a positive impact on supporting plant growth areas.

Figure 4. Farmers start land clearing for *sonor*/swidden farming

In order for the community to gradually leave the *sonor*/swidden farming pattern, the selection of commodities and planting techniques must be tested. The mounding land elevation model is a suitable technique for farmers to cultivate annual crops or fruits on peatlands (Figure 4). Meanwhile, rice cultivation is carried out by utilizing the land below it (Figure 5). Rice cultivation with a transplanting system can be socialized to farmers so that they are convinced that this cultivation technique can produce higher productivity. However, there must be government efforts to help with land-clearing equipment, land-clearing slashers, and tractors.

Figure 4. Adaptation patterns of plant cultivation in peat wetlands, with raised soil hilling techniques, coffee cultivation trials

Figure 5. Rice cultivation model without tillage, transplanting system

Level of Variability in Soil Physical Characteristic in Drained Peat Area

The land survey was conducted in the dry season, namely August-September. Observations of groundwater levels at various peat depths did not show significant differences where the groundwater level was in the range of 45-47 cm below the ground surface (Figure 6). However, shallow peat showed a relatively deeper groundwater level, and all valuesshowed numbers that had exceeded the critical compliance limit of 40 cm. During this period, there was no rainfall so that there was a decrease in the groundwater level, and the water level control structure in the channel was not functioning yet (there was no canal bulkhead).

The impact of the groundwater levels decreasing due to the land drainage process will also increase the decomposition process of organic materials. It can gradually change the level of peat maturity and increase the value of the soil bulk density. Table 2. Shows the values of several parameters of soil physical characteristic. Soil sampling was carried out in a transect perpendicular to the channel. The soil bulk density value ranged from 0.09-0.12 gr/cm^3, very low, and the average porosity value was still very high at 86.76%. It did not show soil samples high diversity rate in area near the channel to the middle of the channel.

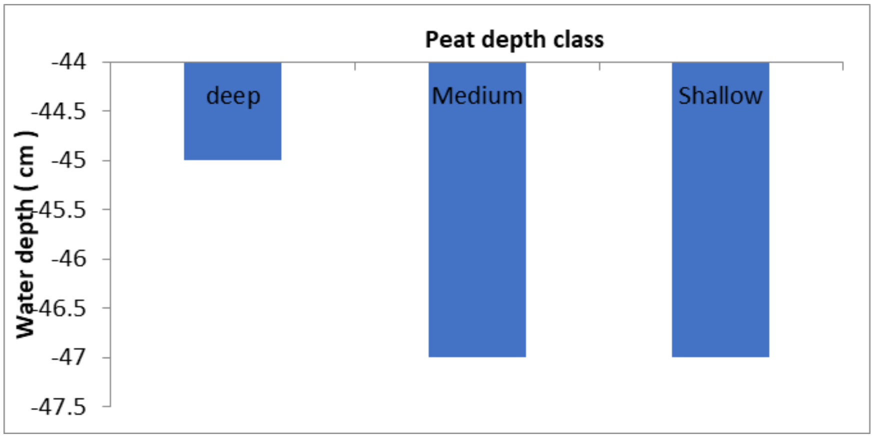

Figure 6. Groundwater level in various peatland thickness class

Furthermore, random soil sampling was taken at a peat depth of 1.5 - 2m and the results showed that the values were not significantly different from the data in Table 1. The average soil bulk density value was 0.13 gr/cm^3 and the soil porosity value was 95.12%. This condition was in line with the research results by [12] in Central Kalimantan peatlands which showed that the peat soil porosity value ranged from 85.5-86.5%, and the soil bulk density value was in the range of 0.11 - 0.16 gr/cm^3, the average porosity value in Norway is 88-89% [13]. [14] added that the level of peat maturity also affects the soil bulk density value. In fibric maturity conditions, the soil bulk density value was in the range of 0.18-0.27 gr/cm^3. This means that soil maturity would affect the density level of peat soil. Low soil bulk density values are followed by high porosity values. An increase in porosity values indicates that peat soil has a high-water storage capacity [15]. Research by [16] on peatlands in Pontianak showed that porosity figures were in the range of 85.5-95.5%.

The low soil BD value is caused by the soil on peatlands from organic materials. [17] stated that the low soil BD is caused by the relatively high organic material content (average >3.0%). High organic material content causes the soil more porous and lower BD value. Table 2 shows the soil bulk density value on land with medium peat depth (1.5-2.0 m) with a Hemic maturity level. The average soil bulk density is 0.11 gr/cm^3 and the maximum is 0.21 gr/cm^3. The variation of BD value is related to the organic material content and the time of agriculture land cultivation. The highest level was obtained at a BD value of 0.21 gr/cm^3, the land has been opened 3 years ago and on land that has not been cultivated even though a channel has been built, the BD value was still in the range of 0.11-0.12 gr/cm^3. The land area that is cultivated for plant cultivation is a fruit plant cultivation model with a limited drainage pattern and plants are planted on raised land (mounding). In general, the opening of the area three years ago did not show any real changes in physical characteristics. The value of the soil bulk density and total pore space between the opened land (P) and that which has not been planted (K) did not show any real difference.

Table 2. Value of soil bulk weight and total pore space in Perigi Village peatlands

Sample number	Soil Bulk Weight (gr/cm^3)	Total Pore Space (%)
P1	0.09	88.13
P2	0.17	78.18
P3	0.12	84.71
P4	0.12	85.57
P5	0.10	87.03

P6	0.12	85.34
T1	0.09	88.87
T2	0.08	90.13
T3	0.07	91.08
T4	0.11	86.13
T5	0.09	89.15
T6	0.11	86.79
Average	0.11	86.76

The porosity level in the study area (Table 3) was relatively high, ranging from 86-88%. Based on these results, it can be concluded that the soil in this study can be classified as porous ([18]; [19]). This condition indicated that the land had a very large water storage capacity. Measuring soil porosity is an important aspect of analyzing the physical characteristics of peat soil in oil palm plantations. Soil porosity is a very relevant indicator because it is related to the soil's ability to store water, gas exchange, and the development and health of the plant root system [18]. High porosity in peat soil allows for a large enough pore space to store water, oxygen, and nutrients needed by oil palm plants. In addition, high porosity also contributes to good air circulation in the soil, helping gas exchange which is important for biological activity and the balance of soil microorganisms [20].

Table 3. Soil physical characteristic data, bulk density, and total porosity values in peatlands cleared for agricultural purpose

Code	Bulk Density gr/cm^3	Total Porosity (%)	
P1	0.11	86.11	
P2	0.11	86.13	
P3	0.12	84.50	
P4	0.12	85.11	
P5	0.14	83.03	
P6	0.14	82.51	
P7	0.14	81.90	
P8	0.15	81.46	
P9	0.21	73.59	
P10	0.12	85.22	
P11	0.10	88.09	
Average	0.10	87.05	
Control 1	0.10	85.25	
Control 2	0.12	83.84	
Average	0.11	86.11	

The physical characteristics of the soil that are very important in land drainage planning for agricultural cultivation on peatlands are permeability level. The permeability level of peat soil in the study area ranges from 23.6-38.7 cm/hour with very fast criteria (Table 4). This condition was in line with the research results of [16] where the assessment of peat soil permeability in Pontianak was 20.5-30.5 cm/hour. This condition showed that the movement of water in peatlands is very fast especially horizontal movement so the loss of water to the channel is very fast.

Table 4. The soil permeability in Perigi Peat Land

Sample	Permeability (cm/hour)	Criteria
P1	31.57	very fast
P2	37.47	very fast
P3	38.76	very fast
P4	34.91	very fast
P5	32.60	very fast
P6	27.21	very fast
L1	22.59	very fast
L2	37.47	very fast
L3	27.21	very fast
L4	33.62	very fast
L5	32.34	very fast
L6	38.76	very fast
Average	32.88	very fast

Changes in permeability occur when peat soil is in the decomposition process and the level of maturity changes. Land cultivation and agricultural food business activities can accelerate the soil compaction process (increasing bulk density) and impact on the decreasing permeability. Research by [21] stated that on pineapple land in Kuburaya Regency, Kalimantan, the permeability value was 11.3 cm/hour (rather fast). It should be in the range of 30-50 cm/hour on peat soil. Peat soil permeability is also greatly influenced by the level of soil maturity. Research by [22] showed that peat soil with hemic maturity has a permeability value of 2.97×10-5 m/s- 6.01×10-5 m/s, and for the fibric maturity level, the permeability value is between 7.05×10-5 m/s - 8.31×10-5 m/s.

Meanwhile, the peat in the well study area has an average permeability value of 32.88 cm/hour or equivalent to 9.13 ×10-5 m/s. In terms of criteria, the flow rate can be classified as very fast so the peat is not degraded yet. The rate of fluid flow in the soil is also influenced by the level of maturity. Fibric peat soil has a higher permeability than hemic peat soil because the porosity of fibric peat soil is higher than hemic peat soil. Therefore, the ability to release fluid in fibric peat soil is higher than in hemic peat soil. High fluid flow in the soil can affect the water conditioning system, especially in the distance between channels and channel dimensions.

Research by [23] showed that the permeability value using the direct measurement method on the cleared land for oil palm plantations had a lower value by using the laboratory measurement method, which was 106.7 cm hr-1 compared to land planted with rubber plants, which was 19.56 cm hr-1 and secondary forests of 15.1 cm hr-1. The dynamics of the permeability value are greatly influenced by the characteristics of other physical soil characteristic such as the soil bulk density and total porosity. The permeability value is also used as a parameter of the hydraulic function in determining whether peatlands are degraded or not. Peat can be categorized as severe land if the soil hydraulic conductivity value is less than 0.01 cm/hour, and the moderate category if the permeability value is between 1-100 cm/hour. Very good peat condition is shown by its hydraulic permeability value of >100 cm/hour [24]. Therefore, based on the soil permeability figure of 32.88 cm/hour and soil bulk density of 0.1 gr/cm^3, it meets the criteria for moderately degraded peatland.

Relative Groundwater Level Status to Drainage Channels

At the time the channel is functioned as suppletion (put some water in it), then the water will decrease as it gets further away from the channel. Conversely, if the water in the channel is empty, the closer it to the channel, the lower the groundwater level will be. Figure 3 shows the profile of the groundwater level relative to the drainage channel. The water level tends to decrease if it further away from the channel. The groundwater level at the initial 10 m point is at a depth of 40-45 cm and then decreases further. In the 6th observation, at a distance of 120 m, the groundwater level is at a position of 50-60 cm below the ground surface. This means that if the water level in the channel is at 40 cm below the ground surface (assuming a ground surface of 0 cm), then at a point 120 m from the channel the groundwater level has exceeded the critical limit of -60 cm. The compliance level met the government regulations namely -40 cm below the ground surface (PP 57. 2016). This indicated that in September, the land area must be water-retained in the channel. This condition can be the basis that the spillway structure must be installed lower than 40 cm from the level of the embankment or bulkhead.

On the other hand, the water conditions in the channel have decreased (drainage flow pattern). It occurs during the condition in the dry season and there is no rain (supplement). Then, the groundwater level is deeper when it is close to the drainage channel. This is caused by the higher movement of groundwater, resulting in a reduction in peat soil water content due to drying, which reduced groundwater retention power, the manufacture of drainage channels greatly affects the reduction of peat groundwater levels [25]. In line with the research of Putra and [26] the rapid decline in ground water level in the dry season causes dry land surface and flammable land. In this period, the groundwater level tends to decrease until the land drainage limit reaches -1.5 m (base of the channel).

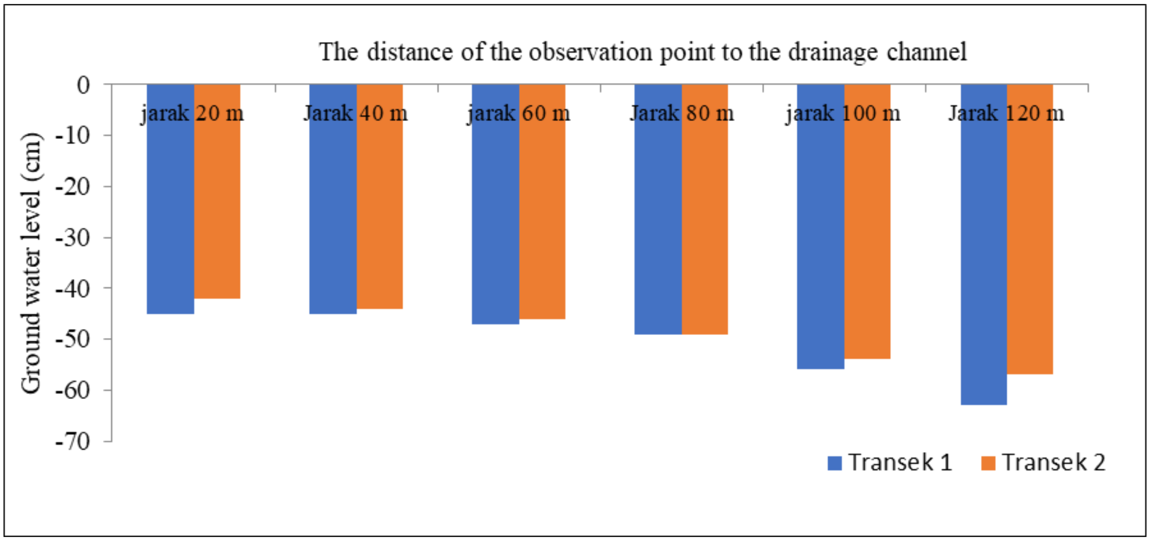

Figure 7. Changes in the depth of relative ground water to the channel

The peat water level at the research location (natural forest peat) was 500-600% (Table 3). This condition very much met with the original characteristic of peat soil which has porous properties to store large amounts of water. The relationship between the depth of the groundwater table and the groundwater content shows a positive relationship where an increase in the groundwater table will be followed by an increase in the groundwater content. However, diversity occurs because the movement of groundwater to the surface is also greatly influenced by the maturity of the peat, the content of organic matter, and other physical parameters of the soil.

Table 3. Earth water dynamics and water content in the plant's root zone (20 cm).

Sample number	Water Table (cm)	Water Content (%)
P1	-42	519.64
P2	-46	497.20
P3	-40	603.17
P4	-49	553.93
P5	-54	668.66
P6	-57	558.91

T1	-49	455.84
T2	-45	593.68
T3	-41	683.14
T4	-47	601.38
T5	-56	482.75
T6	-63	575.02
Average	-49.08	566.11

However, in general, observations in the dry season in September 2024 showed that the water content on the surface (root zone 0-20) showed a high number and was relatively safe from fire hazards. This was caused by the upper biomass and still maintained so that the surface soil moisture was still good. The relationship between groundwater level and soil moisture showed a positive effect where the increase in groundwater level would be followed by an increase in groundwater content. According to [27], a decrease in the depth of the peat groundwater level from 40-50 cm, 60-70 cm, and 80-90 cm can reduce the field water content of peat soil. Too deep groundwater level decreasing will affect the distribution of soil moisture in the entire peat soil profile and release of a number of groundwater volumes from the layers above it [28].

In line with the research results of [29], the water content of peat soil can be influenced by the depth of the groundwater table. The field water content value reached the highest figure as many as 801.82% with a groundwater table depth of 15 cm, while the lowest field water content was 437.43% with a groundwater table depth of 49 cm. This shows that the pattern of the relationship between groundwater table depth and field water content is opposite because the shallower the groundwater table depth, the higher the field water content, and vice versa. This condition was in line with [30], stating that water content can be influenced by the depth of the groundwater table, the shallower the groundwater table, the higher the water content. [31], also added that the depth of the deep peat groundwater table can significantly reduce the water content of the peat. Peat fires can still occur at a water level of 119% as the critical water level for peat fires ([32]; [33]). The critical level of peatland fires at groundwater content is 110-120% dry basis [34]. [35] added that the critical water content in peat soil materials generally ranges from 272-275%. Peat land with a water content less than this critical water content can be classified as an irreversible drying characteristic.

Strategies efforts to restore their natural hydrological functions,

Peatlands have a hydrological function as a medium for storing and releasing water. Peat soil can store 0.8-0.9 m^3/m^3 of water [36]. The land area in the Perigi area has a porosity figure of 85%, meaning that 85 mm of water can be stored from 100 mm of rainwater that falls or from 1 m^3 of peat soil it has a water storage of 0.85 m^3. Added by [37] the water content of peat soil that has not been decomposed was 500% - 1000% weight, while decomposed peat was 200% - 600% weight. This is the reason why peat soil is called a very large water storage medium. Its ability to store water in an area will affect the conditions of air humidity and temperature. Good air temperatures in peatland will be cooler than those that have been degraded. This ability to store large amounts of water can influence regional and even global climate [38].

The physical characteristics of peat soil have a very low buffer effect against fluctuations in water flow in response to rainfall. The "spongy" nature of tropical forests in peat forests also acts as a water reservoir for downstream areas. As long as the saturation limit has not been exceeded, the peat forest is still a water reservoir area with a very large capacity. However, if saturation has been exceeded, fluctuations in surface flow, in response to rainfall, will occur very directly [39].

Another soil physical parameter is the saturated hydraulic conductivity (Ks) value as an important parameter for understanding the hydraulic properties of peatlands. Ks greatly affects the horizontal movement of water to the nearest water body or drainage channel. Therefore, for land drainage planning, the Ks parameter must be available. The study area has a very fast Ks value of 50-60 cm/hour. This figure is classified as moderately degraded peatland, so it is time to improve water management and water level control.

Too deep and wide drainage channels can decrease the depth of the groundwater table and peat becoming dry. Low groundwater tables can indicate peat damage. The depth of the groundwater table is an important factor in assessing peat damage and the success of peatland restoration. The level of damage to the peat ecosystem in cultivation and protection functions can be determined by measuring the depth of the groundwater table [40]. Based on [41], peat ecosystems with cultivation functions are damaged if the depth of the groundwater table is more than 0.4 (zero point four) meters below the peat surface at the point of compliance.

Peat ecosystem restoration efforts by [42] stated that canal blocking was useful for increasing groundwater levels. Research conducted by [43] also stated that canal blocking can maintain groundwater levels up to a distance of 400 m from the channel towards the upstream and 1 m perpendicular to the channel. The same thing was also revealed in the research of [44], stating that canal blocking can affect the depth of the groundwater level at a distance of 444 m and 476 m from the channel towards the land. However, research by [11] canal blocking functions effectively for filling up to a distance of 150 m, so the ideal distance between channels is 250-300 m.

To restore the hydrological function of peat, the Indonesian government has implemented a peat restoration program through the Regulation of the Minister of Environment and Forestry No. 2024. One of the programs is an effort to rewet peat. Rewetting peat is needed to restore peat moisture as close as possible to its natural condition. For this reason, drainage channels must be equipped with water structures (blocking canals). Wetting can gradually restore some of the physical characteristic of the soil related to the hydrological function of peat. Research by [45] showed that land with canal blocks provides higher water content and total pore space values, and a lower B Bulk Weight than land without canal blocks. Land without canal blocks allows more lost water and peat soil decreases its water content. Meanwhile, land with canal blocks is an effort to retain as much water in the canal (rewetting) so that land wetting occurs.

The results of [46] study on rewetted peat swamps showed a better hydrological buffer function against rainfall events compared to drained swamps. The depth at groundwater interacts with incoming rainfall, peat in rewetted swamps had a higher specific yield, so groundwater rise more slowly compared to the response in drained swamps. A 20-year rewetting period is sufficient to form a new layer of organic matter with most of the macropores providing storage capacity. Additional research results of [47] showed that rewetting of peatlands causes a significant increase in groundwater levels of 60 mm compared to controls. Long-term rewetting has the potential to create favorable conditions for the accumulation of new peat, so it able to change the response of the water surface. For this reason, rewetting peatlands by canal blocks building is the right program to continue.

With rewetting, the peatland area will gradually be overgrown with natural trees. [48] research in Southeast Asia showed that as many as 57 native tree species grow on rewetted peat. So that there will be regrowth of natural forests. For this reason, gradual rewetting is the best effort. This activity also has an impact on reducing carbon emissions. It is expected that the peatland area will experience natural vegetation growth, so that peat vegetation, forests, and canals will be created which will form a new nature-based ecosystem balance.

CONCLUSION

The conclusions and recommendations that can be concluded in this study results are mentioned below:

- The study area has a moderate to deep peat depth class with a hemic to sapric maturity level
- Several physical characteristics of soil such as porosity and soil bulk density were still relatively good, the soil's ability to store water was in the range of 0-85 m^3/m^3 and the permeability level was in the range of 35-60 cm/hour so it can be classified as moderately degraded peatland.
- The depth of groundwater is still below 100 cm, but there is a rapid downward trend transition from the rainy season to the dry season. This condition requires water retention in channels with a blocking canal model.
- Monitoring the effect of wetting on the changes in soil physical properties and changes in natural plants is needed to ensure that the rewetting program is the best effort in restoring peatlands that have been degraded by fires

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