JOURNAL OF DEGRADED AND MINING LANDS MANAGEMENT
Volume 11, Number 3 (April 2024):5717-5725, doi:10.15243/jdmlm.2024.113.5717
ISSN: 2339-076X (p); 2502-2458 (e), www.jdmlm.ub.ac.id

Research Article

Hydrological function of rewetted peatlands linked to saturated hydraulic conductivity in Kubu Raya, West Kalimantan, Indonesia

Rabbirl Yarham Mahardika[1,5*], Suria Darma Tarigan[1,2], Dwi Putro Tejo Baskoro[1,2], Vinni Lovita[3], Adibtya Asyhari[5,6], Adi Gangga[5,6], Arif Fatoni[4], Kristoporus Jepri[4], Adzan Pandu Ravelle[4]

[1] Graduate School, Department of Soil Science and Land Resource, IPB University, Bogor, Indonesia
[2] Soil and Water Conservation Division, IPB University, Bogor, Indonesia
[3] Department of Soil Science, UPN "Veteran" Yogyakarta, Indonesia
[4] Department of Soil Science, Tanjungpura University, Pontianak, Indonesia
[5] Yayasan Konservasi Alam Nusantara, Jakarta, Indonesia
[6] The Nature Conservancy, Virginia, United States of America

[*]corresponding author: rabbirlyarhammahardika@apps.ipb.ac.id

Article history:
Received 9 December 2023
Revised 26 January 2024
Accepted 18 February 2024

Keywords:
hydraulic conductivity
hydrological degradation
peat physical properties
rewetting

Abstract

The hydrological function of peatlands, one of which is acting as a medium for storing and releasing water, undergoes alteration due to degradation. Saturated hydraulic conductivity (*K*s) is a pivotal parameter for comprehending the hydraulic properties of peatlands. *K*s plays a crucial role in the transmission and release of water influenced by other peat properties. This research examined the impact of *K*s and selected peat properties, namely bulk density and available water content, to depict the hydrological function in rewetted peatlands. The study sites are rubber plantation (RB), oil palm plantation (OP), and drained secondary forest (SF). Results revealed a significantly higher *K*s in OP (106.7 cm hr^{-1}) compared to RB (19.56 cm hr^{-1}) and DSF (15.1 cm hr^{-1}). The hydrological function at all study sites was categorized as high, with minor degradation in OP and moderate degradation in RB and SF. Nonetheless, these findings necessitate fundamental interpretation and adjustment. The outcomes of this study can be utilized to prioritize rewetting efforts in the study sites, emphasizing the importance of prioritizing immature peat (fibric) with high *K*s.

To cite this article: Mahardika, R.Y., Tarigan, S.D., Baskoro, D.P.T., Lovita, V., Asyhari, A., Gangga, A., Fatoni, A., Jepri, K. and Ravelle, A.P. 2024. Hydrological function of rewetted peatlands linked to saturated hydraulic conductivity in Kubu Raya, West Kalimantan, Indonesia. Journal of Degraded and Mining Lands Management 11(3):5717-5725, doi:10.15243/jdmlm.2024.113.5717.

Introduction

The global importance of peatlands as providers of diverse ecosystem services, from carbon storage to water regulation, is well documented (Jaenicke et al., 2008; Page et al., 2011; Joosten et al., 2012; Murdiyarso et al., 2019a; Menberu et al., 2021). Peatlands face a multitude of threats stemming from inadequate management practices, the ever-increasing demands of a burgeoning population, and the intensifying impacts of climate change (Joosten et al., 2012). Analyzing their physical and hydraulic properties can provide invaluable insights into the consequences of land-use changes and drainage regimes (Schwärzel et al., 2002; Anshari et al., 2010; Kechavarzi et al., 2010).

Land use change and artificial drainage disrupt the natural hydrological functions and water storage (Rieley, 2007; Evers et al., 2017), which is linked to the risk of fire and water scarcity during the dry season (Merten et al., 2016; Taufik et al., 2017) and the flooding (Hooijer et al., 2015; Wells et al., 2016). In addition, several peat physical properties are affected by this process, including total porosity (Tonks et al., 2017; Gusmayanti et al., 2019), water holding capacity (Iiyama et al., 2012; Kurnain, 2019), and saturated hydraulic conductivity or *Ks* (Iiyama et al., 2012; Gabriel et al., 2018; Murdiyarso et al., 2019b). *Ks* is the most important parameter in studying the hydraulic properties of peatlands (Morris et al., 2022; Fewster et al., 2023), and it has a significant impact on the transmission and storage of water in peat soils (Lennartz and Liu, 2019).

In response to the escalating degradation of tropical peatlands in Indonesia, the government has initiated a restoration effort employing the rewetting program. However, the implementation of this program poses challenges due to various factors, including the intricate variability of environmental factors and peat properties. Knowledge concerning tropical peatland restoration remains at an early stage (Jaenicke et al., 2010). Assessing the effectiveness of the rewetting in reinstating the hydrological functions of peatland is a crucial aspect.

Previous studies on the impact of rewetting on peatlands in Indonesia have focused on the groundwater table (GWT) and CO_2 emissions (Ritzema et al., 2014; Sutikno et al., 2019; Putra et al., 2022; Urzainki et al., 2023). However, there is a paucity of research on the impact of this process on other peatland hydrological functions, including the ability of peat to store and transport water. Additionally, the limitations of previous studies in quantifying *Ks* in tropical peatlands have led to limitations in knowledge of the water flow mechanism within this ecosystem (Dommain et al., 2010; Kurnianto et al., 2018). Therefore, this study aimed to fill this knowledge gap and provide further insights into the role of *Ks* and several peat hydro-physical properties in affecting the hydrological function of tropical peatlands. The results are expected to make an important contribution to the management and conservation of this ecosystem.

Materials and Methods

Time and study site

This study was conducted from January to April 2023 for field measurements and June 2023 for laboratory analyses. Study sites were three land uses of rewetted peatlands i.e. oil palm plantations (OP) at 0°10'35"S, 109°22'38"E; rubber plantation (RB) at 0º10’37”S, 109º22’35”E; and drained secondary forest (SF) at 0°5'24"N, 109°25'3"E in Kubu Raya Regency, West Kalimantan (Figure 1). The BRGM (Badan Restorasi Gambut dan Mangrove; Peat and Mangrove Restoration Agency) is working to restore peatlands in all sites. This restoration is being carried out through rewetting with canal blocking. Peat properties analyses were conducted at the Soil and Water Conservation Laboratory of IPB University, Bogor, Indonesia.

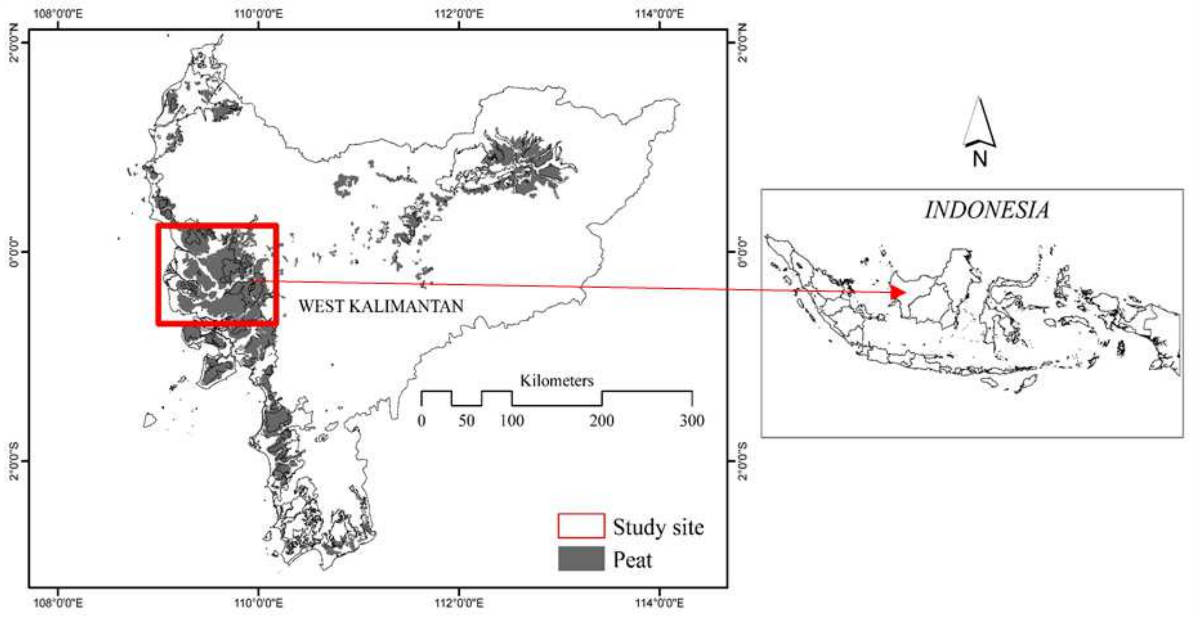

Figure 1. Study site (base map: Semi-detail peatland map 1:50,000 ICALRRD/BBSDLP 2019).

Materials and tools

The field equipment used for measurements includes the Eijkelkamp peat auger, Kubiēna box, and various field tools. A peat auger was employed for disturbed soil sampling for on-site peat properties analysis and the installation of a piezo hole. Kubiēna box was utilized for collecting intact soil samples for laboratory analyses. The Kubiēna box is 10 cm x 5 cm x 5 cm for length, width, and depth (modified from Anwar et al., 2001). The box is constructed using galvanized material with a diameter of 0.8 mm. Note that the box has a larger volume than some other peat soil sampling equipment, such as ring samplers or Eijkelkamp augers. This tool is also able to preserve the mass and volume of peat from external disturbances due to the vertical sampling process. Piezometers were constructed using 2-inch (5.08 cm) diameter PVC pipes with a length of 200 cm. The piezos were inserted to a depth of 180 cm, with 20 cm remaining above the soil surface.

Data collection and analyses

*K*s data were collected in five plots. Five plots were established at 10 m intervals along a 40 m transect. For OP and RB, the transect was aligned with planting rows and extended 20-30 m far from drainage channels. Soil samples for peat properties were taken from three plots. The following soil properties were measured: peat decomposition rate (DR), bulk density (BD), total porosity (PG), and available water content – represented by water potential at pF 4.2 to pF 2.54 matrix suction – (AWC).

Daily precipitation data were collected from the Indonesian Meteorological, Climatological, and Geophysical Agency (data downloaded at: https://dataonline.bmkg.go.id/home). A graphical time series of daily precipitation was obtained using HEC-HMS 4.11 (HEC, DA, USA). DR was measured directly in the field, while BD and PG were measured in the laboratory.

DR analysis was conducted using the Von Post humification scale (Table 1). BD and PG were determined using gravimetric methods at 105°C using UNB 400 dry oven (Memmert GmbH, DE). AWC was determined using a 1600F1 5 Bar Plate Extractor (Soilmoisture, CA, USA). DR analysis was conducted at every 50 cm depth interval of the peat profile until the mineral substratum was reached. BD, PG and AWC were collected between depths of 0-50 cm using a Kubiēna box.

Table 1. Von Post method for measuring peat decomposition rate*.

Symbol	Description
H1	Completely undecomposed peat, which, when squeezed, releases almost clear water. Plant remains easily identifiable. No amorphous material is present.
H2	Almost entirely undecomposed peat, which, when squeezed, releases clear or yellowish water. Plant remains still easily identifiable. No amorphous material is present.
H3	Very slightly decomposed peat which, when squeezed, releases muddy brown water, but from which no peat passes between the fingers. Plant remains still identifiable, and no amorphous material is present.
H4	Slightly decomposed peat, which, when squeezed, releases very muddy brown water. No peat is passed between the fingers, but plant remains are slightly pasty and have lost some of their identifiable features.
H5	Moderately decomposed peat, which, when squeezed, releases very muddy water with a very small amount of amorphous granular peat escaping between the fingers. The structure of the plant remains is quite indistinct, although it is still possible to recognize certain features. The residue is very pasty.
H6	Moderately highly decomposed peat with a very indistinct plant structure. When squeezed, about one-third of the peat escapes between the fingers. The residue is very pasty but shows the plant structure more distinctly than before squeezing.
H7	Highly decomposed peat. Contains a lot of amorphous material with very faintly recognizable plant structure. When squeezed, about one-half of the peat escapes between the fingers. The water, if any is released, is very dark and almost pasty.
H8	Very highly decomposed peat with a large quantity of amorphous material and very indistinct plant structure. When squeezed, about two-thirds of the peat escapes between the fingers. A small quantity of pasty water may be released. The plant material remaining in hand consists of residues such as roots and fibers that resist decomposition.
H9	Practically fully decomposed peat in which there is hardly any recognizable plant structure. When squeezed, it is a fairly uniform paste.
H10	Completely decomposed peat with no discernible plant structure. When squeezed, all the wet peat escapes between the fingers.

*) This method was devised by Lennart von Post during his work on the 1926 Soil Survey of Sweden to measure the degree of decomposition of dead plant matter such as *Sphagnum* moss. Using parameters such as fiber integrity, color and viscosity of exudate, and presence of colloidal particles, it creates a descriptive framework across a wide range of organic soils and assigns a numerical value from H1 (undecomposed) to H10 (colloidal). The USDA/FAO compressed von Post's 10 steps into three levels (fibric, hemic, and sapric), thereby reducing its diagnostic usefulness at the field scale.

*K*s data was measured using the auger-hole method (Oosterbaan and Nijland, 1994), as described in equation 1 (eq1). The measurements *K*s and GWT were obtained directly from the piezometer (Figure 2). Peatland hydrological function was assessed using a modeling scheme comparing values of multiple peat physical properties, i.e., *K*s, AWC, and BD (Lennartz and Liu, 2019). This model classifies peatland hydrology based on their ability to store and release water.

$Ks = C\,(H_0 - H_t)/t$ ... (eq1)

when $D > \frac{1}{2} D_2$, then $C = \frac{4000\ r/h'}{(20+D2/r)(2-h'/D2)}$ ... (eq2)

when $D = 0$, then $C = \frac{3600\ r/h'}{(10+D2/r)(2-h'/D2)}$ ... (eq3)

when $0 < D < \frac{1}{2} D_2$, then

$C = \frac{4000\ r/h'}{(20+D2/r)(2-h'/D2)}$, $h' = 0{,}5\,(H_0+H_n)-D_1$ ... (eq4)

where:

*K*s	:	saturated hydraulic conductivity (cm hr^{-1})
C	:	coefficient permeability
T	:	elapsed time (s)
H_t	:	GWT depth from reference at time t (cm)
H_0	:	GWT depth at time zero (cm)
D	:	distance impermeable layer to piezo bottom (cm)
D_1	:	GWT depth below reference (cm)
D_2	:	distance of piezo bottom to GWT (cm)
R	:	hole radius (cm)
h'	:	average GWT within the hole (cm), $h' > D_2/5$
H_n	:	GWT inside the hole after pumping (cm)

All data were analyzed using descriptive statistics. The statistical significance of the differences between sites was assessed with one-way ANOVA with a significance level of 95%. The statistical analyses were obtained using SPSS Statistics 25 (IBM, NY, USA).

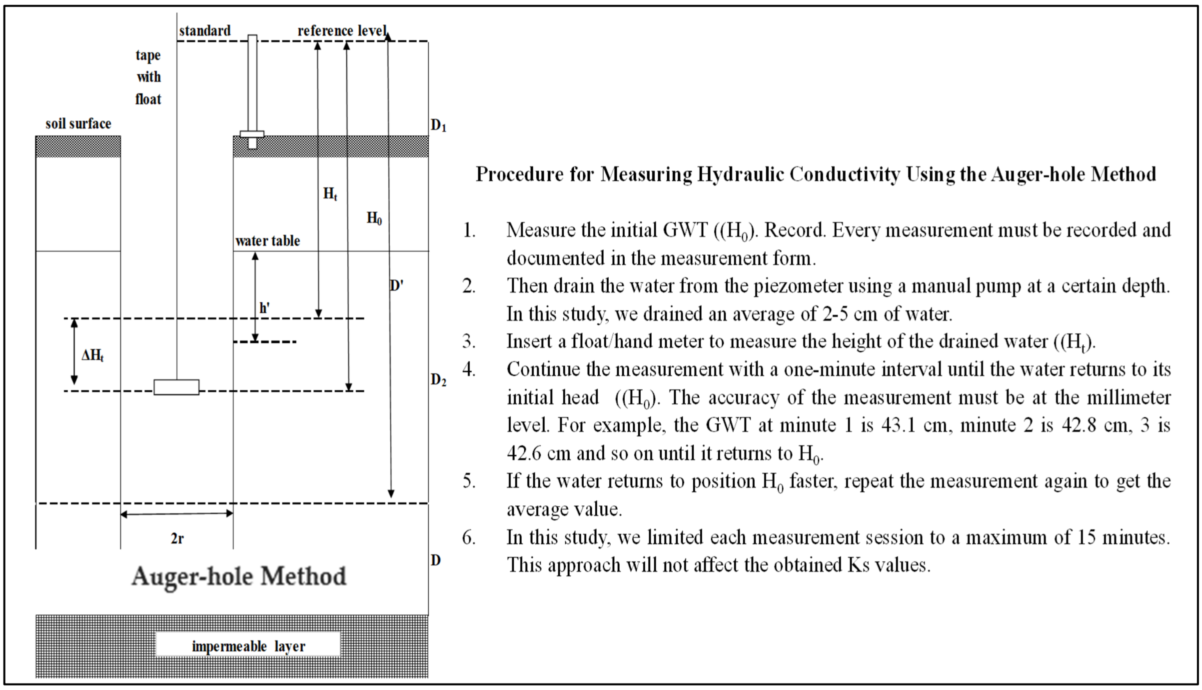

Figure 2. Auger-hole method.

Results

Peat properties

The 50 cm profile is predominantly composed of sapric (mature peat) in RB and SF, while fibric (immature peat) in OP. These contrasting DR levels significantly influence other peat properties (Table 2). The mean of BD and PG in OP is significantly lower than the mean BD value in RB and SF (p=0 for BD and p=0.001 for PG). AWC across all sites is not significantly different, with a p-value of 0.789.

Ks, GWT, and precipitation

*K*s exhibited significant spatial variability across the study sites. Measurements indicated a clear disparity in *K*s values. The average *K*s values in RB, OP, and SF were cm hr^{-1} 19.56 (min 8.34, max 43.13, n=30), 106.7 cm hr^{-1} (min 57.21, max 155.93, n=30), and 15.13 ± 5.96 cm hr^{-1} (min 1.77, max 29.26 n=30), respectively. The results indicate that *K*s values vary over the land uses. The result of the ANOVA test indicates that *K*s were significantly different in all sites (p=0), and OP was the highest. GWT was observed to vary at all study sites. According to the prevailing regulations on GWT management in Indonesia, the water level must be maintained at no more than 0.4 m. These regulations apply to cultivated peatlands such as RB and OP in this study. The average GWT for RB was 57.9 (min 33.1, max 75.5, n=30), OP 27.9 (min 15.3, max 38.3, n=30), and SF 31.9 (min 19.8, max 45.9, n=30). Daily precipitation is shown in Figure 3.

Discussion

The influences of peat properties on Ks values

The *Ks* values in this study are relatively similar to some previous research findings in tropical peatlands

(Sayok et al., 2007; Wösten et al., 2008; Baird et al., 2017). The observed variations in *Ks* values are closely linked to peat properties, particularly the DR, BD, and PG.

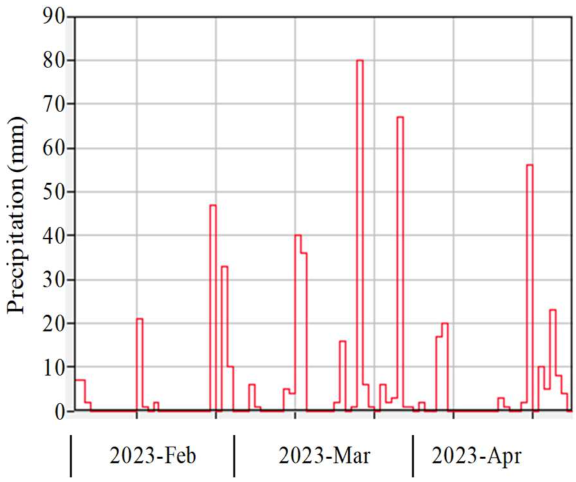

Figure 3. Daily precipitation from Feb-Mar 2023.

Previous research has established a strong negative correlation between DR and *Ks*, implying that lower DR corresponds to higher *Ks* values (Wösten et al., 2008; Kurnianto et al., 2018). A higher degree of peat decomposition rate is associated with a lower content of coarse fiber fractions and increases bulk density (Kurnain, 2019). This, in turn, eliminates the macropores that are responsible for the movement of water through peat deposits (Wallor et al., 2018; Liu and Lennartz, 2019). This is consistent with the findings of studies that have shown that the *Ks* value is much lower in sapric peat than in fibric peat (Table 2). Furthermore, previous research indicates that the heterogeneity of *Ks* is influenced by various complex biogeochemical processes, such as the occurrence of biogenic gas ebullition in peat pores linked to the formation of local aquitards (Reeve et al., 2013; Kaczmarek et al., 2023), inhibiting soil permeability, and the development of secondary pores (Liu et al., 2016; Liu and Lennartz, 2019; Glaser et al., 2020) that extend the flow path of water and/or disrupt the continuity of the peat soils.

Table 2. *K*s and peat properties in soil profile 0-50cm (average, standard deviation, N = number of samples).

Site	Decomposition rate	*Ks* (cm hr^{-1})*	Bulk density (g cm^{-3})*	Total porosity (%)*	Available water content (cm^3 cm^{-3})*
OP	H4-H5, fibric	106.7 ±26.6^a (n=30)	0.087 ±0.004^a (n=3)	91.942 ±0.419^a (n=3)	0.330 ±0.019^a (n=3)
RB	H7-H9, sapric	19.56 ±7.94^b (n=30)	0.148 ±0.006^b (n=3)	86.587 ±0.162^b (n=3)	0.320 ±0.060^a (n=3)
SF	H8-H9, sapric	15.13 ±5.96^b (n=30)	0.146 ±0.013^b (n=3)	90.185 ±1.172^b (n=3)	0.352 ±0.050^a (n=3)

Notes: OP = oil palm plantation, RB = rubber plantation, and SF = drained secondary forest. *results accompanied by different notations indicate a significant difference at a 95% confidence level.

Hydrological function of peatland to study sites

This study employed the hydrological function classification model by Lennartz and Liu (2019) as it utilizes a combination of the common and easily measurable peat properties, accompanied by relevant justification in categorizing peat hydrological classes. The conceptual models constructed serve as valuable tools for depicting interactions and aiding in the comprehension of potentialities and threats (Suter, 1999; King and Hobbs, 2006). Additionally, it assists in identifying conservation intervention methods to support ecosystem recovery (McDonald et al., 2016).

The model presented in Figure 4 indicates that all study sites exhibit a high hydrological function. Based on this classification, peatlands at the study sites are capable of providing maximum environmental services in their role of storing and releasing water. Furthermore, based on the level of hydrological degradation, the OP is classified as experiencing minor degradation, while the RB and SF exhibit moderate degradation.

This result can be interpreted from two perspectives. First, it shows that the rewetting process affects the hydrological function of peatlands in study sites. This is evidenced by the *K*s at all sites being no lower than 1 cm hr^{-1}. Where peatlands with very low *K*s values, which range from 0.01 to 1 cm hr^{-1}, are limited in the hydrological services because they act as a hydraulic barrier, which hampers restoration efforts (Lennartz and Liu, 2019).

Considering that the model was constructed using non-tropical peat properties that are almost certainly different from the general properties of tropical peat, these results cannot be directly applied and require an advanced interpretation. For example, *Ks* values for sapric peat in some studies have been shown to be lower than those for fibric peat (this study, Wösten et al., 2008; Kurnianto et al., 2018). Sapric peat is generally found in peat landscapes that have undergone long-term oxidation due to the decomposition of peat materials in the layer above the GWT, such as in intensive agricultural/plantation areas. However, other studies have reported that sapric peat is also found in the layers of primary peat forest peat (Nusantara et al., 2020) and that GWT in certain seasons can reach 0.6 m in undrained peat landscapes (Könönen et al., 2015). This can certainly have an impact on soil hydrological properties.

Secondly, these findings do not directly assert that oil palm plantations represent the optimal land use for addressing peatland hydrological function, compared to other uses, including secondary forests. Furthermore, there are several aspects that warrant discussion. We suspect that in oil palm plantations (OP), there is a loss of mature (sapric) peat materials, leaving behind more immature (fibric) peat. This mechanism occurs in several stages, either through a single process of oxidative decomposition, compaction, and shrinkage or through loss due to subsidence processes that occur simultaneously, as described in previous reports (Hooijer et al., 2012; Sinclair et al., 2019). In addition, this model does not account for the impact of soil subsidence and the associated loss of water storage on AWC (Lennartz and Liu, 2019).

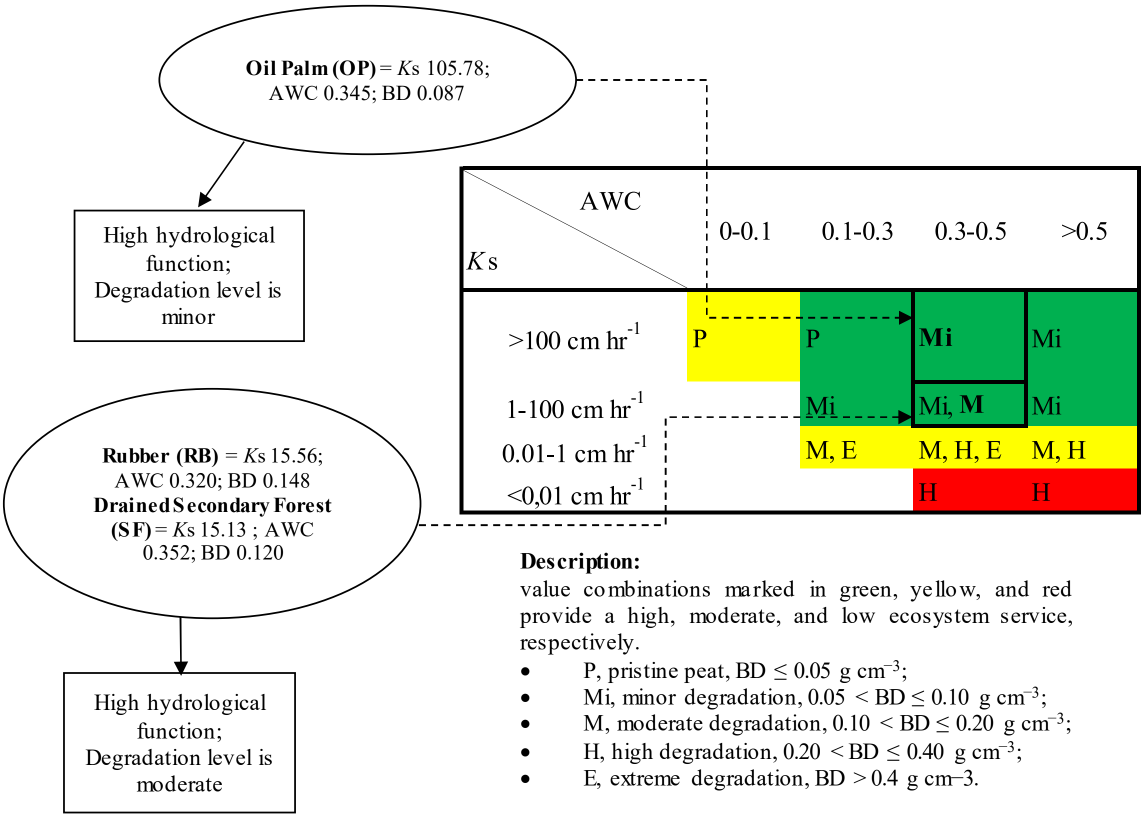

Figure 4. Hydrological function in study sites using Lennartz and Liu (2019) modelling scheme.

Furthermore, in this model, the BD value was used as a proxy, which tends to be inconsistent with the general characteristics of BD in tropical peatlands in Indonesia. Even in undisturbed peatlands, the average BD is 0.13 g cm^{-3} (Könönen et al., 2015). Drained peatlands, subjected to anthropogenic alterations, typically display higher BD values compared to their pristine counterparts, such as undisturbed peat swamp forests (Lampela et al., 2014; Wakhid et al., 2017; Sazawa et al., 2018).

Regarding the hydrological function, it has the potential to offer insights into hydrological degradation at study sites. However, the use of a database limited to non-tropical peat renders this model imperfect in analysis, especially when applied to tropical peat, as in this study. This model represents a step towards understanding the dynamics of peatland hydrological degradation in a simplified method using a combination of soil properties. As a long-term effort, collecting more data on the hydraulic properties of tropical peat, especially *K*s, will be essential to enhance the accuracy of the model. Regarding the rewetting process carried out in the study sites, it is possible that this process, which has not yet reached a decade, has a positive impact on maintaining the hydrological function of peatland. However, future strategies are still needed to restore peatland in order to achieve a balance between increased productivity and peatland sustainability.

Future strategy for peatland rewetting in study sites

Rewetting, defined as the enhanced elevation of GWT using canal blocks, can contribute to the restoration of the natural hydrological conditions in degraded peatlands. However, the primary focus of the rewetting process should be directed towards peatlands with high *K*s and immature peat. A previous study showed that canal blocks are most effective in peatlands with high hydraulic conductivity, lowered GWT, and reduced carbon loss (Urzainki et al., 2022). For instance, low *K*s in sapric peat at RB and SF, while high *K*s in fibric peat at OP. Hence, when canal blocking is implemented for rewetting purposes, the GWT rises or becomes shallower, consequently suppressing the potential for water loss. Fibric peat, characterized by immature peat, exhibits a coarse fiber structure and a higher organic fiber content. This facilitates water loss. Therefore, rewetting this type of peatland can reduce the potential for water loss, considering its inherent ability to store water.

Restoring the drained peatlands through rewetting is often considered essential for promoting the natural regeneration of peatland vegetation (Jaenicke et al., 2011). A review of 94 replanting pilots and studies conducted on degraded peatlands between 1988 and 2019 has been reported (Smith et al., 2022). The results suggest that rewetting significantly reduces the survival rates of peat forest seedlings despite not affecting their half-life or relative growth rates. This is attributed to the adaptation of native peat swamp forest species to waterlogged conditions. However, other reports have shown that reducing GWT contributes to the recovery of woody vegetation, highlighting the need for effective rewetting efforts (Giesen et al., 2023). Understanding *K*s is essential for effective peatland management, particularly in balancing conservation needs with agricultural practices (Giesen and Sari, 2018).

The interdependence between peat properties and processes within it also provides crucial insights into the overall dynamics of this ecosystem. For instance, distinctive hydrological conditions and specific peat characteristics are essential in supporting peat pedogenesis processes and vegetation succession (Page and Baird, 2016).

Strategies in rewetting efforts have the potential to restore their natural hydrological functions, reduce water loss, and support the long-term sustainability of these vital ecosystems. Prioritizing peatlands with properties as described in the study for rewetting does not mean that other peatlands with different properties do not require restoration. This is a challenge in the rewetting process, requiring careful planning and specific considerations related to peat properties and environment. Ongoing research can pave the way for successful peatland restoration and the preservation of their diverse hydrological and carbon services.

Conclusion

In this study, the hydrological functions of rewetted peatlands were generally high, with minor to moderate levels of degradation. However, further adjustments and interpretations of the models used are needed. These efforts still require more practical plans to improve the effectiveness of rewetting in maintaining these hydrological functions, especially by considering inherent peat properties such as hydraulic conductivity. In addition, this study found a significant difference in *K*s between peatlands with different degrees of decomposition. Fibric peats have higher *K*s than sapric peats.

Acknowledgments

This work was supported by Yayasan Konservasi Alam Nusantara from Bezos Earth Fund under The Nature Conservancy's Applied Science to Catalyze Natural Climate Solutions Project and prototyping Project.

References

Anshari, G.Z., Afifudin, M., Nuriman, M., Gusmayanti, M., Arianie, L., Susana, R., Nusantara, R.W., Sugardjito, J. and Rafiastanto, A. 2010. Drainage and land use impacts on changes in selected peat properties and peat degradation in West Kalimantan Province, Indonesia. *Biogeosciences* 7:3403-3419, doi:10.5194/bg-7-3403-2010.

Anwar, S., Kosaki, T. and Yonebayashi, K. 2001. Impregnation of peat soils using polyethylene glycol 4000 for the preparation of thin sections. *Soil Science and Plant Nutrition* 47(1):79-86, doi:10.1080/00380768.2001.10408370.

Baird, A.J., Low, R., Young, D., Swindles, G.T., Lopez, O.R. and Page, S.E. 2017. High permeability explains the vulnerability of the carbon stored in drained tropical peatlands. *Geophysical Research Letters* 44:1333-1339, doi:10.1002/2016GL072245.

Dommain, R., Couwenberg, J. and Joosten, H. 2010. Hydrological self-regulation of domed peatlands in South-East Asia and consequences for conservation and restoration. *Mires and Peat* 6:1-17.

Evers, S., Yule, C.M., Padfield, R., O'Reilly, P. and Varkkey, H. 2017. Keep wetlands wet: The myth of sustainable development of tropical peatlands - implications for policies and management. *Global Change Biology* 23(2):534-549, doi:10.1111/gcb.13422.

Fewster, R.E., Morris, P.J., Swindles, G.T., Baird, A.J., Turner, T.E. and Ivanovic, R.F. 2023. Controls on saturated hydraulic conductivity in a degrading permafrost peatland complex. *Water Resource Research* 59:e2023WR035398, doi:10.1029/2023WR035398.

Gabriel, M., Toader, C., Faul, F., Roßkopf, N., Grundling, P., van Huyssteen, C., Grundling, A.T. and Zeitz, J. 2018. Physical and hydrological properties of peat as proxies for degradation of South African peatlands: implications for conservation and restoration. *Mires and Peat* 21:1-21, doi:10.19189/MaP.2018.OMB.336.

Giesen, W. and Sari, E.N.N. 2018. *Tropical Peatland Restoration Report: The Indonesian Case*. Berbak Green Prosperity Partnership Kemitraan Kesejahteraan Hijau (Kehijau Berbak). Millennium Challenge Account – Indonesia Euroconsult Mott MacDonald.

Giesen, W.B.J.T., Persch, S., Urzainqui, I., Wardwell, D., Chatellier, J.L., Wang, Y-H.O., Mahardhitama, P., Nurzirwan, R.Y., Laurén, A. and Giesen, P.T. 2023. Roles of fire history and rewetting in peatland restoration and vegetation recovery on the Merang peat dome, South Sumatra, Indonesia. *Mires and Peat* 29:21-25, doi:10.19189/MaP.2023.OMB.Sc.2096288.

Glaser, P.H., Rhoades, J. and Reeve, A.S. 2020. The hydraulic conductivity of peat with respect to scaling, botanical composition, and greenhouse gas transport: Mini-aquifer tests from the Red Lake peatland, Minnesota. *Journal of Hydrology* 596:125686, doi:10.1016/j.jhydrol.2020.125686.

Gusmayanti, E., Anshari, G.Z., Pramulya, M. and Ruliyansyah, A. 2019. CO_2 fluxes from drained tropical peatland used for oil palm plantation in relation to peat characteristics and crop age after planting. *Biodiversitas* 20(6):1650-1657, doi:10.13057/ biodiv/d200622.

Hooijer, A., Page, S., Jauhiainen, J., Lee, W.A., Lu, X.X., Idris, A. and Anshari, G.Z. 2012. Subsidence and carbon loss in drained tropical peatlands. *Biogeoscience* 9(3):1053-1071, doi:10.5194/bg-9-1053-2012.

Hooijer, A., Vernimmen, R., Visser, M. and Mawdsley, N. 2015. Flooding projections from elevation and subsidence models for oil palm plantations in the Rajang Delta peatlands, Deltares report (p. 76).

Iiyama, I., Osawa, K. and Nagai, T. 2012. A seasonal behavior of surface soil moisture condition in a reclaimed tropical peatland. *Soil Science and Plant Nutrition* 58(5):543-552, doi:10.1080/00380768.2012.723222.

Jaenicke, J., Englhart, S. and Siegert, F. 2011. Monitoring the effect of restoration measures in Indonesian peatlands by radar satellite imagery. *Journal of Environmental Management* 92:630-638, doi:10.1016/j.jenvman.2010.09.029.

Jaenicke, J., Rieley, J.O., Mott, C., Kimann, P. and Siegert, F. 2008. Determination of the amount of carbon stored in Indonesian peatlands. *Geoderma* 147(3-4):151-158, doi:10.1016/j.geoderma.2008.08.008.

Jaenicke, J., Wösten, H., Budiman, A. and Siegert, F. 2010. Planning hydrological restoration of peatlands in Indonesia to mitigate carbon dioxide emissions. *Mitigation and Adaption Strategies for Global Change* 15:223-239, doi:10.1007/s11027-010-9214-5.

Joosten, H., Tapio-Biström, M-L. and Tol, S. 2012. *Peatlands: Guidance For Climate Change Mitigation Through Conservation, Rehabilitation and Sustainable Use* (2nd ed). Mitigation of Climate Change in Agriculture Series 5. Rome: Food and Agriculture Organization of the United Nations.

Kaczmarek, L., Grodzka-Łukaszewska, M., Sinicyn, G., Grygoruk, M., Jastrzebska, M. and Szatyłowicz, J. 2023. Hydraulic Conductivity Tests in the Triaxial Stress State: Is Peat an Aquitard or an Aquifer? *Water* 15:1064, doi:10.3390/w1506106.

Kechavarzi, C., Dawson, Q. and Leeds-Harrison, P. 2010. Physical properties of low-lying agricultural peat soils in England. *Geoderma* 154:196-202, doi:10.1016/j.geoderma.2009.08.018.

King, E.G. and Hobbs, R.J. 2006. Identifying Linkages among Conceptual Models of Ecosystem Degradation and Restoration: Towards an Integrative Framework. *Restoration Ecology* 14:369-378, doi:10.1111/j.1526-100X.2006.00145.x.

Könönen, M., Jauhiainen, J., Laiho, R., Kusin, K. and Vasander, H. 2015. Physical and chemical properties of tropical peat under stabilised land uses. *Mires and Peat* 16(8):1-13.

Kurnain, A. 2019. Hydrophysical properties of ombrotrophic peat under drained peatlands. *International Agrophysics* 33:277-283, doi:10.31545/intagr/110773.

Kurnianto, S., Selker, J., Kauffman, J.B., Murdiyarso, D. and Peterson, J.T. 2018. The influence of land-cover changes on the variability of saturated hydraulic conductivity in tropical peatlands. *Mitigation and Adaption Strategy for Global Change* 24:535-555, doi:10.1007/s11027-018-9802-3.

Lampela, M., Jauhiainen, J. and Vasander, H. 2014. Surface peat structure and chemistry in a tropical peat swamp forest. *International Journal of Plant-Soil Relationship* 382:329-347, doi:10.1007/s11104-014-2187-5.

Lennartz, B. and Liu, H. 2019. Hydraulic functions of peat soils and ecosystem service. *Frontiers of Environmental Sciences* 7:92, doi:10.3389/fenvs.2019.00092.

Liu, H. and Lennartz, B. 2019. Hydraulic properties of peat soils along a bulk density gradient—A meta study. *Hydrological Processes* 33:101-114, doi:10.1002/hyp.13314.

Liu, H., Janssen, M. and Lennartz, B. 2016. Changes in flow and transport patterns in fen peat following soil degradation. *Euro. Journal of Soil Science* 67(6):763-772, doi:10.1111/ejss.12380.

McDonald, T., Gann, G.D., Jonson, J. and Dixon, K.W. 2016. International standards for the practice of ecological restoration - including principles and key concepts. Society for Ecological Restoration, Washington, D.C.

Menberu, M.W., Marttila, H., Ronkanen, A.K., Haghighi, A.T. and Kløve B. 2021. Hydraulic and physical properties of managed and intact peatlands: Application of the van Genuchten-Mualem models to peat soils. *Water Resources Research* 57:e2020WR028624, doi:10.1029/2020WR028624.

Merten, J., Röll, A., Guillaume, T., Meijide, A., Tarigan, S., Agusta, H., Dislich, C., Dittrich, C., Faust, H., Gunawan, D., Hein, J., Hendrayanto, Knohl, A., Kuzyakov, Y., Wiegand, K. and Hölscher, D. 2016. Water scarcity and oil palm expansion: social views and environmental processes. *Ecology and Society* 21(2):5, doi:10.5751/ES-08214-210205.

Morris, P.J., Davies, M.L., Baird, A.J., Balliston, N., Bourgault, M.-A., Clymo, R.S., Fewster, R.E., Furukawa, A.K., Holden, J., Kessel, E., Ketcheson, S.J., Kløve, B., Larocque, M., Marttila, H.,….Wilkinson, S.L. 2022. Saturated hydraulic conductivity in northern peats inferred from other measurements. *Water Resources Research* 58:e2022WR033181, doi:10.1029/2022WR033181.

Murdiyarso, D., Lilleskov, E. and Kolkam R. 2019a. Tropical peatlands under siege: the need for evidence-based policies and strategies. *Mitigation and Adaption Strategy for Global Change* 24:493-505, doi:10.1007/s11027-019-9844-1.

Murdiyarso, D., Saragi-Sasmito, M.F. and Rustini, A. 2019b. Greenhouse gas emissions in restored secondary tropical peat swamp forests. *Mitigation and Adaption Strategy for Global Change* 24:507-520, doi:10.1007/s11027-017-9776-6.

Nusantara, R.W., Sudarmadji, S., Djohan, T.S. and Haryono, E. 2020. Impact of land-use change on soil carbon dynamics in tropical peatland, West Kalimantan Indonesia. *Indonesian Journal of Geography* 52:61-68, doi:10.22146/ijg.48451.

Oosterband, R.J. and Nijland, H.J. 1994. Determining the saturated hydraulic conductivity. Chapter 12. In: Ritzema, H.P. (ed.), *Drainage Principles and Applications*. International Institute for Land Reclamation and Improvement (ILRI), Publication 16, second revised edition, 1994, Wageningen, The Netherlands. ISBN 9070754339.

Page, S.E., Rieley, J.O. and Banks, C.J. 2011. Global and regional importance of the tropical peatland carbon pool. *Global Change Biology* 17:798-818, doi:10.1111/j.1365-2486.2010.02279.x.

Page, S.E. and Baird, A.J. 2016. Peatlands and global change: Response and resilience. *Annual Review of Environment and Resources* 41:35-57, doi:10.1146/annurev-environ-110615-085520.

Putra, S.S., Baird, A.J. and Holden, J. 2022. Modelling the performance of bunds and ditch dams in the hydrological restoration of tropical peatlands. *Hydrological Processes* 36:e14470, doi:10.1002/hyp.14470.

Reeve, A.S., Glaser, P.H. and Rosenberry, D.O. 2013. Seasonal changes in peatland surface elevation recorded with GPS stations in the Red Lake Peatlands, northern Minnesota, USA. *Journal of Geophysical Research: Biogeosciences* 118, doi:10.1002/2013JG002404.

Rieley, J.O. 2007. Tropical peatland – the amazing dual ecosystem: coexistence and mutual benefit. *Proceedings of the International Symposium and Workshop on Tropical Peatland*. Gadjah Mada University, pp. 1-14.

Ritzema, H., Limin, S., Kusin, K., Jauhiainen, J. and Wösten, H. 2014. Canal blocking strategies for hydrological restoration of degraded tropical peatlands in Central Kalimantan, Indonesia. *Catena* 114:11-20, doi:10.1016/j.catena.2013.10.009.

Sayok, A.K., Nik, A.R., Melling, L., Samad, R.A. and Efransjah, E. 2007. Some characteristics of peat in Loagan Bunut National Park, Sarawak, Malaysia. In: Rieley, J.O., Banks, C.J. and Ragjagukguk, B (eds), *Proceedings of the International Symposium and Workshop in Tropical Peatland*, Yogyakarta, 95-100.

Sazawa, K., Wakimoto, T., Fukushima, M., Yustiawati, Y., Syawal, M.S., Hata, N., Taguchi, S., Tanaka, S., Tanaka, D. and Kuramitz H. 2018. Impact of peat fire on the soil and export of dissolved organic carbon in tropical peat soil, Central Kalimantan, Indonesia. *ACS Earth and Space Chemistry* 2:692-701, doi:10.1021/acsearthspacech em.8b00018.

Schwärzel, K., Renger, M., Sauerbrey, R. and Wessolek, G. 2002. Soil physical characteristics of peat soils. *Journal of Plant Nutrition and Soil Science* 165(4):479-486, doi:10.1002/1522-2624(200208)165:4<479::AID-JPLN479>3.0.CO;2-8.

Sinclair, A.L., Graham, L.L.B., Putra, E.I., Saharjo, B.H., Applegate, G., Grover, S.P. and Cochrane, M.A. 2019. Effects of distance from canal and degradation history on peat bulk density in a degraded tropical peatland. *Science of The Total Environment* 699:134199, doi:10.1016/j.scitotenv.2019.134199.

Smith, S.W., Rahman, N.E.B., Harrison, M.E., Shiodera, S., Giesen, W., Lampela, M., Wardle, D.A., Chong, K.Y., Randi, A.,… Lee, J.S.H. 2022. Tree species that 'live slow, die older' enhance tropical peat swamp restoration: Evidence from a systematic review. *Journal of Applied Ecology* 59:1950-1966, doi:10.1111/1365-2664.14232.

Suter, G.W. 1999. Developing conceptual models for complex ecological risk assessments. *Human and Ecological Risk Assessment: An International Journal* 5:375-396, doi:10.1080/10807039991289491.

Sutikno, S., Nasrul, B., Gunawan, H., Jayadi, R., Rinaldi, Saputra, E. and Yamamoto, K. 2019. The effectiveness of canal blocking for hydrological restoration in tropical peatland *MATEC Web Conference* 276:06003, doi:10.1051/matecconf/201927606003.

Taufik, M., Torfs, P.J.J.F., Uijlenhoet, R., Jones, P.D., Murdiyarso, D. and Van Lanen, H.A.J. 2017. Amplification of wildfire area burnt by hydrological drought in the humid tropics. *Nature Climate Change* 7(6):428- 431, doi:10.1038/nclim ate3280.

Tonks, A.J., Aplin, P., Beriro, D.J., Cooper, H., Evers, S., Vane, C.H. and Sjögersten, S. 2017. Impacts of conversion of tropical peat swamp forest to oil palm plantation on peat organic chemistry, physical properties and carbon stocks. *Geoderma* 289:6-45, doi:10.1016/j.geoderma.2016.11.018.

Urzainki, I., Palviainen, M., Hökkä, H., Persch, S., Chatellier, J., Wang, O., Mahardhitama, P., Yudhista, R. and Laurén, A. 2023. A process-based model for quantifying the effects of canal blocking on water table and CO_2 emissions in tropical peatlands. *Biogeosciences* 20:2099-2116, doi:10.5194/bg-20-2099-2023.

Wakhid, N., Hirano, T., Okimoto, Y., Nurzakiah, S. and Nursyamsi, D. 2017. Soil carbon dioxide emissions from a rubber plantation on tropical peat. *Science of The Total Environment* 581-582:857-865, doi:10.1016/j.scitotenv.2017.01.035.

Wallor, E., Rosskopf, N. and Zeitz, J. 2018. Hydraulic properties of drained and cultivated fen soils, part I - Horizon-based evaluation of van Genuchten parameters considering the state of moorsh-forming process. *Geoderma* 313(1):69-81, doi10.1016/j.geoderma.2017.10.026.

Wells, J.A., Wilson, K.A., Abram, N.K., Nunn, M., Gaveau, D.L.A., Runting, R.K., Tarniati, N., Mengersen, K.L. and Meijaard, E. 2016. Rising floodwaters: mapping impacts and perceptions of flooding in Indonesian Borneo. *Environmental Research Letters* 11(6):064016, doi:10.1088/1748-9326/11/6/064016.

Wösten, J.H.M., Clymans, E., Page, S.E., Rieley, J.O. and Limin, S.H. 2008. Peat - water inter-relationships in a tropical peatland ecosystem in Southeast Asia. *Catena* 73(2):212-224, doi:10.1016/j.catena.2007.07.010.