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Research Paper

Peatland Hydrology Analysis Using Rainfall and Water Table Level Approaches in the Riau Peat Hydrological Unit for the 2018-2020 Period

Raden Putra[1*], Jessica Adelheid[1], Deni Okta L.[2], Lesi Mareta[2]

[1] *Department of Environmental Engineering, Institut Teknologi Sumatera, South Lampung, 35365, Indonesia*
[2] *Department of Atmospheric and Planetary Science, Institut Teknologi Sumatera, South Lampung, 35365, Indonesia*
***Corresponding author e-mail**: raden.putra@tl.itera.ac.id

Abstract
Peat ecosystems are the world's largest carbon sink and are important in climate change mitigation and global environmental balance. However, tropical peat ecosystems, particularly in Riau Province, face serious threats due to anthropogenic activities such as land clearing, drainage, and plantation conversion. These activities are exacerbated by climate change, which causes a decrease in rainfall and increases the risk of peat fires. This study aims to analyze the relationship between rainfall and peat water level in the Riau Peat Hydrology Unit (PHU) during the period from October 2018 to December 2020. The main data used are daily rainfall and peat water level data from 39 SIPALAGA stations owned by the Peat and Mangrove Restoration Agency (BRGM). Spatial data on peatland distribution and regional administrative boundaries were used to support the hydrological zone-based analysis. Statistical methods applied included correlation and coefficient of determination tests to evaluate the relationship between rainfall and peat water level. Daily data were accumulated monthly, and peat hydrological zones were identified based on the distribution of peatlands from the Ministry of Environment and Forestry (MoEF) Indonesia. The results showed that a decrease in rainfall significantly decreased peat water levels, with strong correlations in most hydrological zones. In addition, areas with intense drainage activities experienced a major shift from naturally flooded to drought-prone conditions, increasing the risk of fires. In contrast, significant rainfall only temporarily restores peat hydrological conditions. Spatially, some hydrological zones show different peat water table dynamics, depending on the intensity of rainfall and the level of anthropogenic disturbance. These findings make an important contribution to peat fire risk mitigation strategies and sustainable peat ecosystem management. By integrating temporal and spatial data, this research offers a comprehensive approach to support area-based peat protection policymaking, particularly in the face of climate change impacts and human activities.

Keywords
Peatland, Rain Intensity, Peat Water Level, Peat Hydrology Region, Peat Fire

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1. INTRODUCTION

Peat ecosystems are unique and play a crucial role in maintaining the global environmental balance. As the largest carbon sink, peatlands store up to 550 gigatons of carbon, equivalent to 42% of global organic carbon in soils (Dargie et al., 2017; Joosten and Clarke, 2002; Page and Hooijer, 2016). Globally, peatlands are distributed across the northern hemisphere, such as Canada, Russia, and Scandinavia, as well as tropical regions in Southeast Asia, Africa, and South America. Southeast Asia has the largest tropical peatland area, with Indonesia being home to approximately 14.9 million hectares or 47% of the world's total tropical peatland area (Miettinen et al., 2017; Wahyunto et al., 2004). The presence of peat in Indonesia, particularly in Riau Province, significantly contributes to ecological and socioeconomic functions. However, threats to the sustainability of this ecosystem are increasing due to human activities and climate change (Jefferson et al., 2020; Purnomo et al., 2017; Purnomo et al., 2024; Rossita et al., 2021)

Riau Province is one of the regions with the highest cases of peat fires in Indonesia. These fires have been a concern since the 1990s, with major incidents in 1997, 2015, and 2019 causing transboundary haze and significant economic and ecological losses (Gaveau et al., 2014; Hayasaka, 2023; Irfan et al., 2024; Miettinen et al., 2017). Peatland fires in Riau release massive carbon emissions, exacerbating global climate change. Moreover, peatland degradation due to land conversion for agriculture and plantations increases the

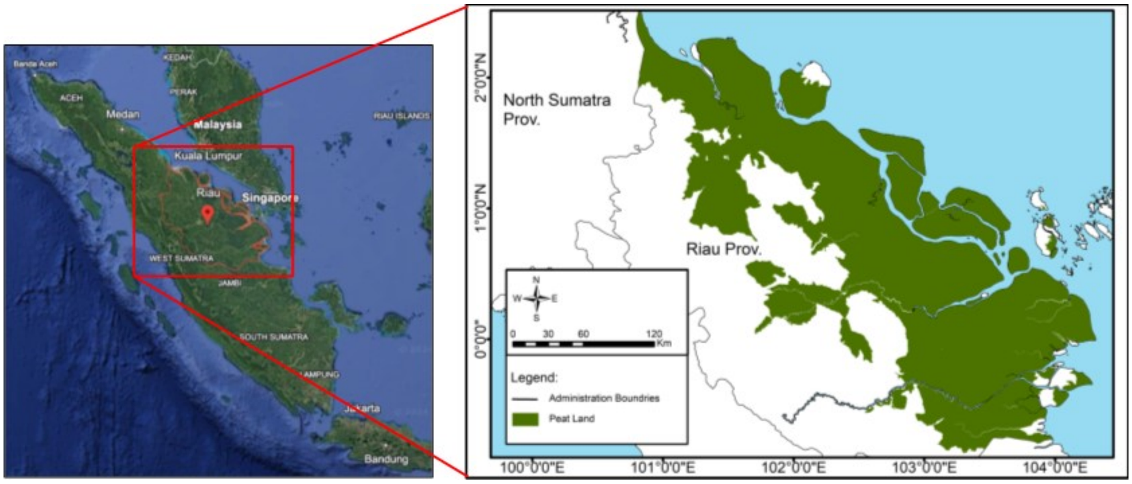

Figure 1. Research Location

land's vulnerability to fire (Tacconi, 2016; Tacconi et al., 2007).

Peatland fires are triggered by both anthropogenic and natural factors. Anthropogenic factors include land clearing using fire techniques, lowering of the peat water table due to drainage, and expansion of oil palm and acacia plantations (Carlson et al., 2013; Hergoualc'h et al., 2018). Meanwhile, natural factors, such as prolonged dry seasons and El Nino, exacerbate these conditions by reducing peatland moisture, making it susceptible to fire (Field et al., 2009; Lestari et al., 2018; McPhaden, 2004). This combination of factors underscores the complexity of peat ecosystem management, particularly in tropical regions such as Riau (Hergoualc'h et al., 2018).

Peat ecosystems are naturally waterlogged throughout the year, a condition essential for maintaining carbon stability and preventing the oxidation of organic matter (Bertrand et al., 2021). However, anthropogenic activities, such as the construction of drainage channels, result in a decrease in the peat water table, increasing the risk of fire (Wosten et al., 2008). Additionally, rainfall is one of the key factors influencing peat water table dynamics. A decrease in rainfall intensity or extreme drought can dry out the peat surface, increasing the likelihood of fire (Bonell and Bruijnzeel, 2005; Ohkubo et al., 2021; Wosten et al., 2006).

Most previous studies on peatland degradation in Southeast Asia have focused on land-use impacts and fire risk (Dohong et al., 2017; Rossita et al., 2023), while fewer studies have examined the direct hydrological response of peatlands to rainfall fluctuations in different Peat Hydrological Unit (PHU) (Cahyono et al., 2022; Jaenicke et al., 2010). This study addresses this gap by providing a quantitative analysis of the rainfall-PWT relationship across different Peat Hydrological Regions in Riau, offering insights into spatial hydrological variations and ecosystem stability.

This study aims to analyze the relationship between rainfall and peat water levels across different PHUs in Riau, considering spatial variations in hydrological response. Furthermore, it evaluates whether the peatland hydrology in Riau remains natural-where peatlands remain waterlogged year-round-or has shifted toward a degraded state, where rainfall alone may no longer be sufficient to sustain peat saturation due to drainage and other disturbances. By investigating the hydrological stability of Riau's peat ecosystems, this study contributes to the scientific understanding of tropical peatland hydrology and provides essential data for peatland conservation and sustainable water management. The findings are expected to support peatland restoration policies and contribute to climate change mitigation efforts by preserving the carbon storage function of peatlands.

2. EXPERIMENTAL SECTION

2.1 Research Location

The study area is situated in Riau Province, home to the largest peat ecosystem in Sumatra, which holds significant ecological and economic importance. The peat ecosystems in Riau span a vast area, predominantly distributed along the province's eastern and central coastal regions. As one of the largest carbon sinks, peat ecosystems in Riau play a crucial role in regulating the hydrological cycle and preserving biodiversity. However, the region faces significant challenges due to land use changes, particularly the expansion of oil palm and acacia plantations, which have led to extensive peat degradation. Riau has also experienced widespread peat fires, particularly during the dry season, resulting in severe environmental damage and posing health and social risks due to transboundary haze. The maps presented in Figure 1 illustrate the spatial distribution of peatlands in Riau, providing essential context for understanding the region's hydrological characteristics and fire susceptibility.

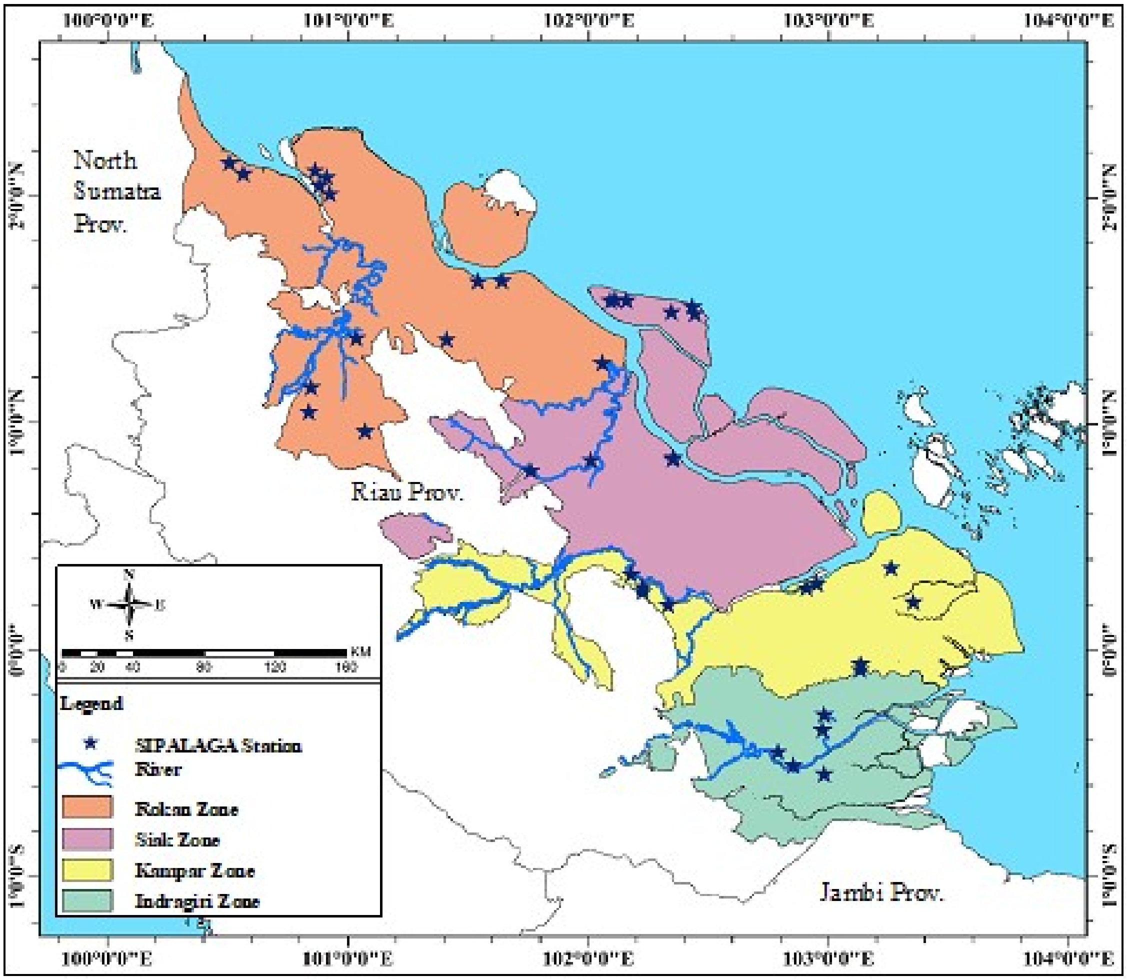

Figure 2. The Location of SIPALAGA Station in Riau Peat Ecosystem

2.2 Data Collections

This study utilizes multiple datasets to analyze the impact of rainfall on peat water levels within the PHU of Riau Province. The primary data sources include rainfall measurements and peat water level records obtained from 39 monitoring stations operated under the Peatland Monitoring Information System (SIPALAGA), managed by the Peat and Mangrove Restoration Agency (BRGM). These datasets comprise daily records spanning from October 2018 to December 2020, offering comprehensive insights into the temporal dynamics of rainfall and peat water levels across the study area. Additionally, this study incorporates spatial data on peatland distribution from the Ministry of Environment and Forestry (2017) to map the extent of peat ecosystems and delineate the study area. This dataset provides critical information on the extent, depth, and physical characteristics of peatlands in Riau, serving as a fundamental reference for spatial analysis. To further enhance the study, administrative boundary data was obtained from the Geospatial Information Agency (BIG) via InaGeoportal, ensuring that the analysis aligns with official administrative divisions. This alignment facilitates the integration of research findings into spatial planning frameworks and local government policies. By combining temporal and spatial datasets, this study enables a comprehensive evaluation of the relationship between rainfall and peat water levels, offering valuable insights into the hydrological dynamics of peat ecosystems within the PHU of Riau Province.

2.3 Calculation and Analysis

The research methodology involved multiple phases, beginning with the identification and classification of peat hydrological zones in Riau Province. These zones were delineated based on spatial data on peatland distribution obtained from the Ministry of Environment and Forestry (2017). This classification served as the foundation for analyzing peat hydrology dynamics within distinct ecological settings. To ensure the reliability of the statistical analysis, it was essential to assess whether the rainfall and peat water level data followed a normal distribution, as this influences the selection of appropriate statistical methods.

A normality test was conducted using the Kolmogorov-

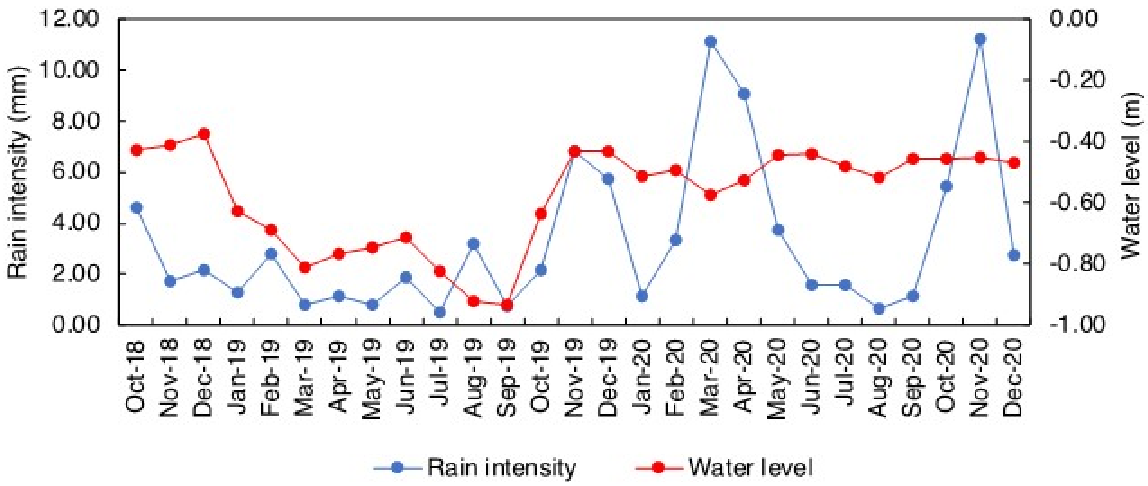

Figure 3. Temporal Variation of Rainfall Intensity and PWL in the Rokan Zone (October 2018-December 2020)

Smirnov (K-S) test to determine whether the data conformed to a normal distribution. The K-S test compares the empirical cumulative distribution function (ECDF) of the sample data with the expected normal distribution, as calculated using Equation 1.

$$D = \sup |F_n(X) - F(X)| \tag{1}$$

Where: D is the Kolmogorov-Smirnov statistic; $F_n(X)$ is the empirical cumulative distribution function (ECDF) of the sample; and $F(X)$ is the cumulative distribution function (CDF) of a normal distribution. If the p-value obtained from the test was greater than 0.05, the data was considered normally distributed. Only datasets meeting the normality assumption were used for further statistical analysis to ensure the validity of the results.

To evaluate the relationship between rainfall and peat water levels, Pearson's product-moment correlation coefficient (r) was applied, as described in Equation 2.

$$r = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 \sum(Y_i - \bar{Y})^2}} \tag{2}$$

Where: X_i and Y_i represent individual data points of monthly rainfall (mm) and peat water levels (m); $\bar{X}$ and $\bar{Y}$ denote the mean values of rainfall and peat water levels; and r ranges from -1 to 1 indicating the strength and direction of the correlation.

To assess the extent to which rainfall influences peat water levels, the coefficient of determination (R^2) was calculated, as shown in Equation 3.

$$R^2 = r^2 \tag{3}$$

Where: R^2 represents the proportion of variance in peat water levels explained by rainfall variability. A higher R^2 value suggests a stronger influence of rainfall on peat hydrology.

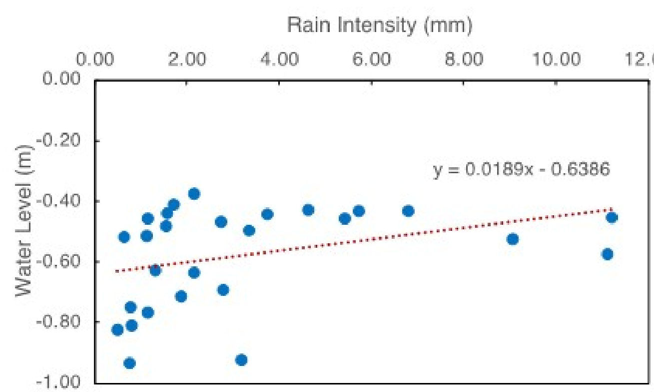

Figure 4. Correlation Between Rain Intensity and PWL in the Rokan Zone

This study adopted a zone-based approach, where the analysis was conducted separately for each peat hydrological zone to capture localized variations in peat water dynamics. This method enables a more precise evaluation of the relationship between rainfall and peat water levels across different ecological and geographical settings. Additionally, the findings contribute to a better understanding of area-specific peatland hydrology, supporting more effective peatland water management strategies (Bertrand et al., 2021; Wosten et al., 2008). By integrating spatial and temporal datasets, performing rigorous statistical tests, and applying a hydrological zonation approach, this research provides a comprehensive assessment of rainfall-driven peat hydrology variations in Riau's PHU.

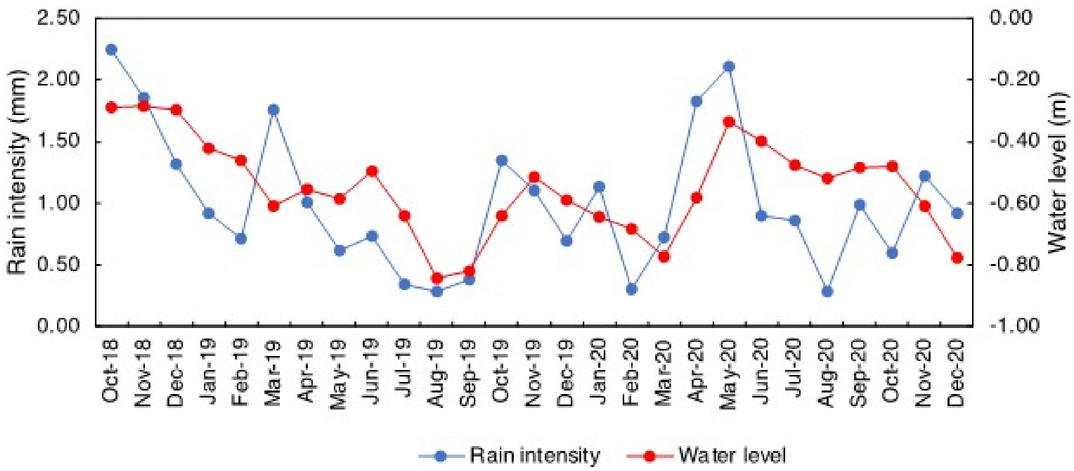

Figure 5. Temporal Variation of Rainfall Intensity and PWL in the Siak Zone (October 2018-December 2020)

3. RESULT AND DISCUSSION

Peat ecosystems in Riau Province have diverse characteristics, which can generally be grouped into four main hydrological zones: Rokan Zone, Siak Zone, Kampar Zone, and Indragiri Zone. The division of these zones is based on the depth and maturity characteristics of the peat, represented through the PHU Each zone plays an important role in maintaining hydrological balance, with peat depths varying from shallow to very deep, and maturity levels affecting water storage capacity and carbon stability. To support this research, SIPALAGA monitoring stations, which are strategically distributed across each hydrological zone, were used as the main data collection points. The spatial distribution of peat ecosystems, zonal boundaries, and SIPALAGA station locations is presented in Figure 2, providing a geographic reference for the study area and sampling framework.

3.1 Rokan Zone

The Rokan Zone is one of the most important areas of the peat ecosystem in Riau Province. The hydrological characteristics of this zone are influenced by variable annual rainfall, which contributes to fluctuations in peat water level (PWL). Understanding the relationship between rainfall and PWL in this region is critical to identifying potential droughts that could increase the risk of forest and land fires. Figure 3 presents an analysis of the relationship between rainfall and PWL in the Rokan Zone.

At the beginning of the period (October 2018 - February 2019), the decrease in rainfall from around 4.00 mm to below 2.00 mm had a significant impact on the PWL decline to -0.60 m, suggesting a direct link between reduced rainfall inputs and shrinking peatland wetness. The drastic increase in rainfall in November 2019, which reached over 6.00 mm, contributed to the recovery of PWL to -0.40 m, reflecting the capacity of peatlands to store water during high rainfall. However, fluctuations in rainfall during 2020 were not always followed by significant changes in PWL, indicating that additional factors such as drainage and physical characteristics of peatlands influence their hydrological dynamics. These results confirm that managing peatland hydrology, especially through intensive monitoring and implementing strategies such as canal blocking, is crucial for maintaining PWL stability to reduce the potential for forest and land fires, especially in the dry season.

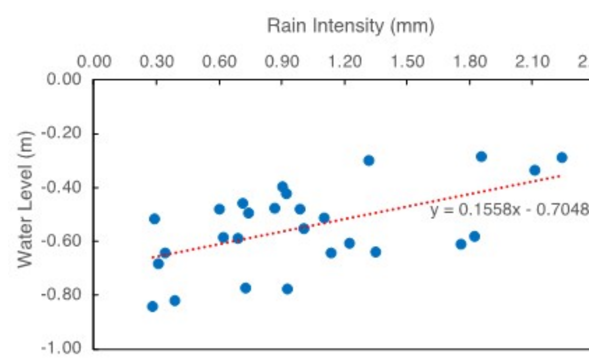

Figure 6. Correlation Between Rain Intensity and PWL in the Siak Zone

In the Rokan Zone, the normality test results indicate that both rainfall and peat PWL data are normally distributed. Furthermore, as illustrated in Figure 4, the relationship between rainfall and PWL presents a weak positive correlation, with a correlation coefficient (r) of 0.35 and a coefficient of determination (R^2) of 12.27%. This indicates that an increase in rainfall only contributes to fluctuations in PWL. The weakness of this correlation suggests that other factors, such as geomorphological conditions or anthropogenic activities, may have a greater influence on PWL dynamics. This finding aligns with research by Irfan et al. (2020) and Irfan et al. (2021), which suggests that water management is key to maintaining the hydrological stability of tropical peatlands.

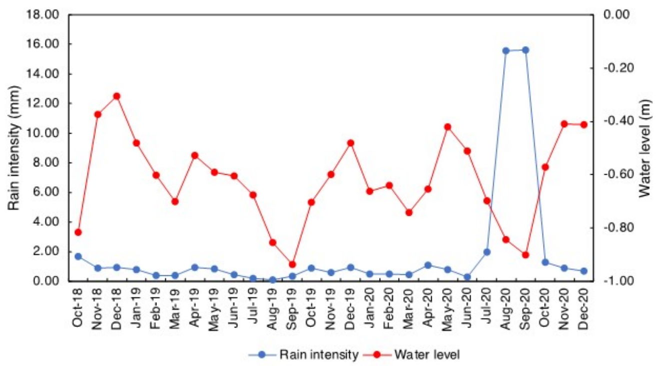

Figure 7. Temporal Variation of Rainfall Intensity and PWL in the Kampar Zone (October 2018–December 2020)

3.2 Siak Zone

The Siak Zone is known as one of the peat areas that demonstrates a strong relationship between rainfall and peat water level (PWL). Hydrological conditions in this area are highly influenced by rainfall patterns, which play a critical role in maintaining the wetness and ecological stability of the peat layer. A detailed overview of the temporal dynamics of rainfall and PWL in this zone is presented in Figure 5, which illustrates monthly fluctuations over two years. Both rainfall intensity and peat water levels exhibit synchronized variations over time, with notable declines during dry months and increases during periods of higher precipitation. This pattern highlights the responsiveness of peat hydrology in the Siak Zone to climatic variability, reinforcing the importance of rainfall as a controlling factor in peatland water balance.

The Siak Zone indicates the dynamic relationship between rainfall intensity and peat water level from October 2018 to December 2020. The graph reflects that fluctuating rainfall patterns have a direct impact on changes in peat water levels, albeit with a certain time lag. During periods of high rainfall, such as March 2020 and May 2020, the peat water level experienced a significant increase, indicating that this zone is still quite responsive to hydrological inputs. In contrast, during periods of low rainfall, such as in July 2019 and September 2020, the peat water table decreased to -0.80 m. This indicates that peat areas in the Siak Zone are highly drained, potentially increasing the risk of ecosystem degradation if not managed properly. The response of water levels to rainfall intensity emphasizes the importance of ecosystem-based hydrological management to support the sustainability of this zone.

The normality test results for rainfall and peat water level (PWL) data in the Siak Zone indicate that the data are normally distributed, thereby allowing the use of parametric statistical methods. The correlation analysis reveals that the Siak Zone demonstrates a stronger relationship between rainfall and PWL, with a correlation coefficient (r) of 0.56, indicating a moderate positive correlation, and a coefficient of determination (R^2) of 30.91%. This means that approximately 31% of the variation in PWL can be explained by changes in rainfall. The pattern of this relationship is illustrated in Figure 6, which presents a scatter plot showing the positive linear correlation between rain intensity and PWL in the Siak Zone. The regression line further highlights the increasing trend of water levels with greater rainfall input. This finding suggests that rainfall exerts a considerable influence on PWL fluctuations, making the Siak Zone potentially more vulnerable to drought conditions in periods of reduced rainfall. This finding supports the study of Page and Hooijer (2016), which confirms the importance of rainfall as a major factor in maintaining peatland wetness to minimize the risk of forest and land fires.

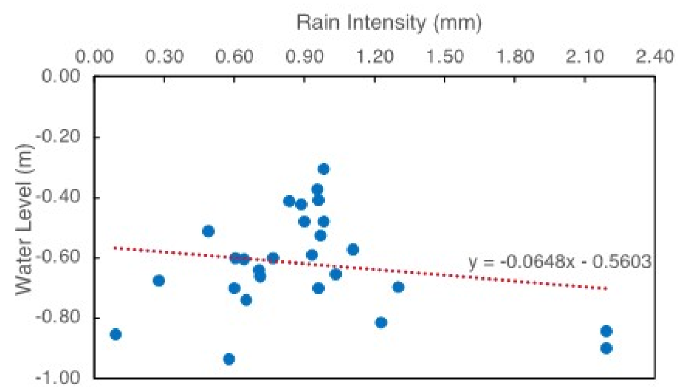

Figure 8. Correlation Between Rain Intensity and PWL in the Kampar Zone

3.3 Kampar Zone

The Kampar zone has different hydrological characteristics compared to other zones. The relationship between rainfall and PWL in this zone tends to be more complex, with significant influence from external factors such as drainage and anthropogenic activities. This study aims to explore these dynamics by presenting graphs and tables analyzing the relationship between rainfall and PWL in the Kampar Zone.

Figure 7 in Kampar Zone presents the dynamics of rainfall intensity and peat water level over the period October 2018 to December 2020, reflecting the significant relationship between water input from rainfall and the hydrological response of peatlands. Rainfall appears relatively low and stable throughout the observation period, with significant increases only in some months, such as June 2020. Peat water levels experienced more extreme fluctuations, with decreases of up to -1.00 m in dry months such as July 2019 and August 2020. These declines signal a high risk of peatland drying during the dry season, which could increase

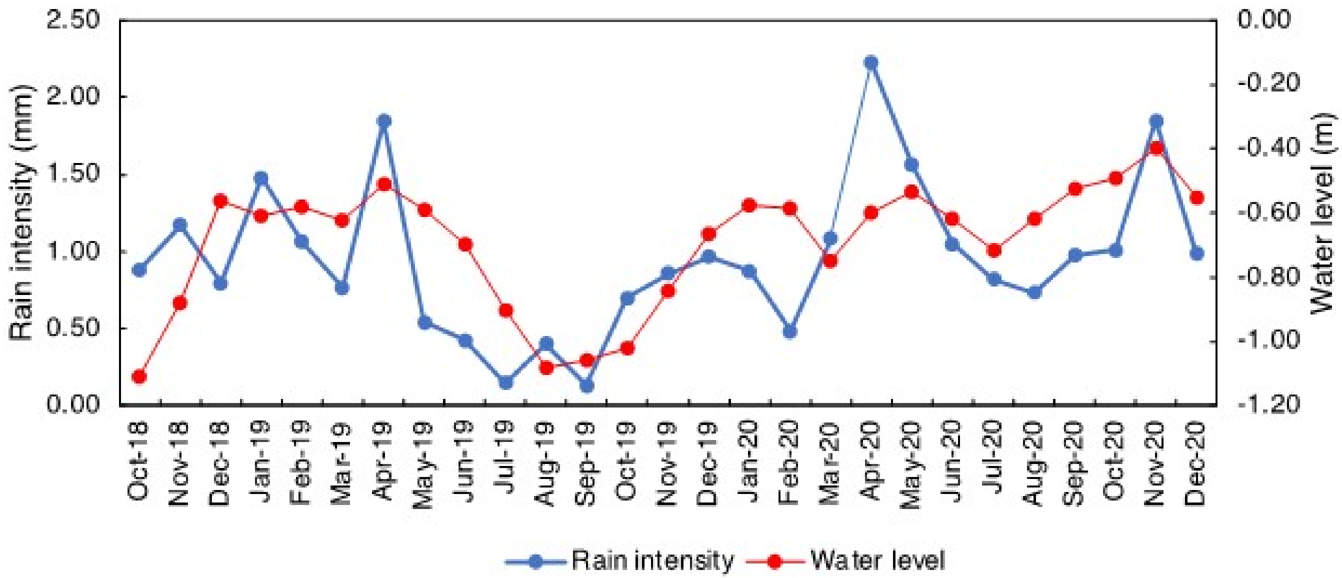

Figure 9. Temporal Variation of Rainfall Intensity and PWL in the Indragiri Zone (October 2018–December 2020)

vulnerability to environmental degradation and peat fires. However, the rapid rise in water levels during periods of high rainfall demonstrates the capacity of peatlands to absorb water. These results confirm the importance of data-driven hydrological management to maintain water balance in Kampar Zone peatlands, reduce the risk of ecosystem damage, and ensure its sustainability.

The normality test for the temporal data in the Kampar Zone indicates that rainfall data are not normally distributed, while peat water level (PWL) data are normally distributed. To allow for correlation analysis, a data transformation was applied to the rainfall dataset to meet the normality assumption. Following this adjustment, the analysis revealed a very weak negative correlation between rainfall and PWL, with a correlation coefficient (r) of -0.18 and a coefficient of determination (R^2) of only 3.20%. The characteristic of this relationship is illustrated in Figure 8, which presents a scatter plot of rainfall intensity versus PWL in the Kampar Zone. The linear regression line shows a slight downward trend, suggesting that increased rainfall does not necessarily lead to higher peat water levels. This weak association may be attributed to other influencing factors, such as the low permeability of peat soils or anthropogenic disturbances, particularly from drainage infrastructure. The study by Dommain et al. (2014) mentioned that non-optimal peatland drainage management can cause anomalous relationships between rainfall inputs and peat wetness conditions.

3.4 Indragiri Zone

The Indragiri Zone is one of the peat areas that has a moderate relationship between rainfall and PWL. The hydrological conditions in this area indicate that rainfall plays an important role in maintaining peatland wetness, although other factors also influence PWL fluctuations. Figure 9-10 presents the results of the analysis of the relationship between rainfall and PWL in the Indragiri Zone, as a basis for hydrological management in the area.

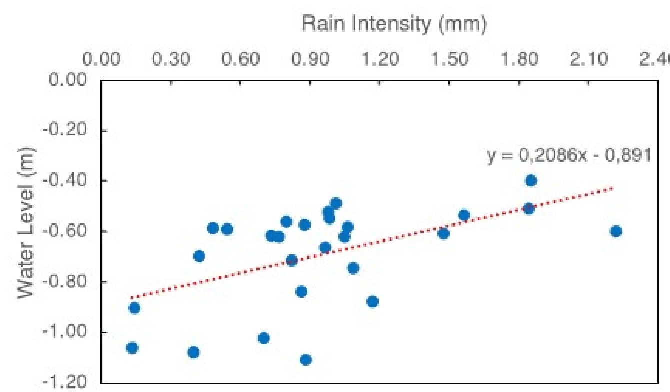

Figure 10. Correlation Between Rain Intensity and PWL in the Indragiri Zone

The fluctuation pattern in the graph demonstrates that the peat water level (red line) tends to follow the trend of rainfall intensity (blue line), although there is a certain time lag. During the rainy season, especially in months with high rainfall such as April 2019 and April 2020, the peat water table rises to near saturation. In contrast, during dry season periods such as July 2019 and July 2020, low rainfall caused a significant decrease in the peat water level, reaching a low point of around -1.00 m. This phenomenon shows that the hydrological dynamics of peat are strongly influenced by rainfall intensity. However, high rainfall does not always guarantee a full recovery of peat water levels, especially in zones with disturbed drainage or intensive human activities. Significant declines during the dry season indicate the vulnerability of the Indragiri zone to drought and potential peat fires, especially during periods of below-average rainfall. This analysis emphasizes the importance of adaptive management of peat hydrology to reduce the risk of environmental damage in the region.

The hydrological characteristics of natural peat ecosystems are defined by their ability to remain saturated throughout the year, independent of seasonal rainfall variations (Dommain et al., 2014; Miettinen et al., 2012). This stability is attributed to the low permeability of peat soils, which enables them to store large volumes of water, maintaining a high PWL and preventing the oxidation of organic matter (Wosten et al., 2008). However, the findings of this study suggest that peat hydrology in Riau's PHUs has deviated from this natural condition, with noticeable variations in PWL responses to rainfall inputs across different zones.

The results of the Pearson's product-moment correlation analysis reveal that the Siak and Indragiri Zones exhibit moderate positive correlations between rainfall and PWL ($r = 0.56$; $R^2 = 30.91\%$ and $r = 0.53$; $R^2 = 27.96\%$), indicating that rainfall still plays a significant role in maintaining peat water balance in these areas. Although not entirely independent of rainfall, these zones retain some degree of hydrological resilience, making them less vulnerable to prolonged droughts if properly managed (Cahyono et al., 2022; Rossita et al., 2023).

In contrast, the Rokan and Kampar Zones display weak to very weak correlations ($r = 0.35$; $R^2 = 12.27\%$ and $r = -0.18$; $R^2 = 3.20\%$), suggesting a diminished natural hydrological function where external factors, such as peat drainage networks, land-use changes, and subsurface water flow disruptions, play a more dominant role in PWL fluctuations (Miettinen et al., 2012; Taufik et al., 2023). The particularly low correlation in the Kampar Zone suggests severe hydrological degradation, where increased rainfall does not necessarily lead to a rise in PWL, reinforcing concerns that peat subsidence, groundwater depletion, or artificial drainage structures have altered the natural hydrological response of peatlands (Cahyono et al., 2022).

These findings align with studies conducted in drained peatlands in Malaysia and Indonesia, which have demonstrated a progressive loss of hydrological resilience, making peat water levels increasingly dependent on rainfall inputs (Ngau et al., 2022; Rossita et al., 2023). This study confirms a similar pattern in Riau, particularly in Rokan and Kampar, where advanced peatland degradation has heightened vulnerability to seasonal droughts and fire risks.

4. CONCLUSIONS

Natural peatlands are hydrologically self-sustaining, remaining water-saturated year-round due to their high-water retention capacity and low permeability. However, this study confirms that peatland hydrology in Riau has deviated from this natural condition, with varying levels of rainfall dependency across different PHUs, indicating progressive ecosystem degradation. The Pearson's correlation analysis shows that Siak and Indragiri retain moderate hydrological resilience, where rainfall still contributes to peat water levels. In contrast, Rokan and Kampar exhibit weak to very weak correlations, suggesting that drainage networks, land-use changes, and groundwater depletion have significantly altered their hydrology, making these zones more susceptible to droughts and fire risks. To address these disparities, Siak and Indragiri should be prioritized for fire mitigation, with sustainable water management and controlled land use, while Rokan and Kampar require urgent hydrological restoration, including rewetting programs and canal blocking to recover their water retention capacity. These findings emphasize the need for strong government intervention, integrating data-driven conservation policies, peatland restoration programs, and climate resilience strategies to safeguard peatlands as carbon sinks, biodiversity reserves, and regulators of local hydrology.

5. ACKNOWLEDGEMENT

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REFERENCES

Bertrand, G., A. Ponçot, B. Pohl, A. Lhosmot, M. Steinmann, A. Johannet, S. Pinel, H. Caldirak, G. Artigue, P. Binet, C. Bertrand, L. Collin, G. Magnon, D. Gilbert, F. Laggoun-Deffarge, and M. L. Toussaint (2021). Statistical Hydrology for Evaluating Peatland Water Table Sensitivity to Simple Environmental Variables and Climate Changes: Application to the Mid-Latitude/Altitude Frasne Peatland (Jura Mountains, France). *Science of The Total Environment*, **754**; 141931

Bonell, M. and L. A. Bruijnzeel, editors (2005). *Forests, Water and People in the Humid Tropics: Past, Present and Future Hydrological Research for Integrated Land and Water Management.* International Hydrology Series. Cambridge University Press, Cambridge, UK

Cahyono, B. K., T. Aditya, and Istarno (2022). The Determination of Priority Areas for the Restoration of Degraded Tropical Peatland Using Hydrological, Topographical, and Remote Sensing Approaches. *Land*, **11**(7); 1094

Carlson, K. M., L. M. Curran, G. P. Asner, A. M. Pittman, S. N. Trigg, and J. M. Adeney (2013). Carbon Emissions from Forest Conversion by Kalimantan Oil Palm Plantations. *Nature Climate Change*, **3**(3); 283–287

Dargie, G. C., S. L. Lewis, I. T. Lawson, E. T. A. Mitchard, S. E. Page, Y. E. Bocko, and S. A. Ifo (2017). Age, Extent and Carbon Storage of the Central Congo Basin Peatland Complex. *Nature*, **542**(7639); 86–90

Dohong, A., A. A. Aziz, and P. Dargusch (2017). A Review of the Drivers of Tropical Peatland Degradation in South-East Asia. *Land Use Policy*, **69**; 349–360

Dommain, R., J. Couwenberg, P. H. Glaser, H. Joosten, and I. N. N. Suryadiputra (2014). Carbon Storage and Release in Indonesian Peatlands since the Last Deglaciation. *Quaternary Science Reviews*, **97**; 1–32

Field, R. D., G. R. van der Werf, and S. S. P. Shen (2009). Human Amplification of Drought-Induced Biomass Burning in Indonesia since 1960. *Nature Geoscience*, **2**(3); 185–188

Gaveau, D. L. A., M. A. Salim, K. Hergoualc'h, B. Locatelli, S. Sloan, M. Wooster, M. E. Marlier, E. Molidena, H. Yaen, R. DeFries, L. Verchot, D. Murdiyarso, R. Nasi, P. Holmgren, and D. Sheil (2014). Major Atmospheric Emissions from Peat Fires in Southeast Asia during Non-Drought Years: Evidence from the 2013 Sumatran Fires. *Scientific Reports*, **4**; 6112

Hayasaka, H. (2023). Peatland Fire Weather Conditions in Sumatra, Indonesia. *Climate*, **11**(5); 92

Hergoualc'h, K., R. Carmenta, S. Atmadja, C. Martius, D. Murdiyarso, and H. Purnomo (2018). *Managing Peatlands in Indonesia: Challenges and Opportunities for Local and Global Communities*. Center for International Forestry Research (CIFOR)

Irfan, M., E. Koriyanti, K. Saleh, Hadi, S. Safrina, Awaludin, A. Sulaiman, H. Akhsan, Suhadi, R. A. Suwignyo, E. Choi, and I. Iskandar (2024). Dynamics of Peatland Fires in South Sumatra in 2019: Role of Groundwater Levels. *Land*, **13**(3); 373

Irfan, M., O. C. Setya, F. Virgo, Sutopo, M. Ariani, A. Sulaiman, and I. Iskandar (2020). Is There a Correlation between Rainfall and Soil Moisture on Peatlands in South Sumatra? In *Journal of Physics: Conference Series*, volume 1572. page 012053

Irfan, M., F. Virgo, M. Y. N. Khakim, M. Ariani, A. Sulaiman, and I. Iskandar (2021). The Dynamics of Rainfall and Temperature on Peatland in South Sumatra during the 2019 Extreme Dry Season. In *Journal of Physics: Conference Series*, volume 1940. page 012059

Jaenicke, J., H. Wosten, A. Budiman, and F. Siegert (2010). Planning Hydrological Restoration of Peatlands in Indonesia to Mitigate Carbon Dioxide Emissions. *Mitigation and Adaptation Strategies for Global Change*, **15**(3); 223–239

Jefferson, U., R. Carmenta, W. Daeli, and J. Phelps (2020). Characterising Policy Responses to Complex Socio-Ecological Problems: 60 Fire Management Interventions in Indonesian Peatlands. *Global Environmental Change*, **60**; 102027

Joosten, H. and D. Clarke (2002). *Wise Use of Mires and Peatlands: Background and Principles Including a Framework for Decision-Making*. International Mire Conservation Group and International Peat Society, Jyväskylä, Finland

Lestari, D. O., S. Sabaruddin, I. Iskandar, and E. Sutriyono (2018). Respective Influences of Indian Ocean Dipole and El Niño-Southern Oscillation on Indonesian Precipitation. *Journal of Mathematical and Fundamental Sciences*, **50**(3); 257–272

McPhaden, M. J. (2004). Evolution of the 2002/03 El Niño. *Bulletin of the American Meteorological Society*, **85**(5); 677–695

Miettinen, J., A. Hooijer, J. Wang, C. Shi, and S. C. Liew (2012). Peatland Degradation and Conversion Sequences and Interrelations in Sumatra. *Regional Environmental Change*, **12**(4); 729–737

Miettinen, J., C. Shi, and S. C. Liew (2017). Fire Distribution in Peninsular Malaysia, Sumatra and Borneo in 2015 with Special Emphasis on Peatland Fires. *Environmental Management*, **60**(4); 747–757

Ministry of Environment and Forestry (2017). *Ministry of Environment and Forestry (MoEF 2017)*

Ngau, L. D., S. S. Fong, K. L. Khoon, E. Rumpang, H. Vasander, J. Jauhiainen, K. Yrjälä, and H. Silvennoinen (2022). Mapping Peat Soil Moisture under Oil Palm Plantation and Tropical Forest in Sarawak. *Mires and Peat*, **28**; 1–17

Ohkubo, S., T. Hirano, and K. Kusin (2021). Influence of Fire and Drainage on Evapotranspiration in a Degraded Peat Swamp Forest in Central Kalimantan, Indonesia. *Journal of Hydrology*, **603**; 126906

Page, S. E. and A. Hooijer (2016). In the Line of Fire: The Peatlands of Southeast Asia. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371**(1696); 20150176

Purnomo, H., D. Puspitaloka, B. Okarda, A. Andrianto, N. Qomar, S. Sutikno, A. Muhammad, I. Basuki, A. Jalil, Yesi, P. Prasetyo, Tarsono, Zulkardi, S. D. Kusumadewi, H. Komarudin, A. Dermawan, and M. A. Brady (2024). Community-Based Fire Prevention and Peatland Restoration in Indonesia: A Participatory Action Research Approach. *Environmental Development*, **50**; 100971

Purnomo, H., B. Shantiko, S. Sitorus, H. Gunawan, R. Achdiawan, H. Kartodihardjo, and A. A. Dewayani (2017). Fire Economy and Actor Network of Forest and Land Fires in Indonesia. *Forest Policy and Economics*, **78**; 21–31

Rossita, A., R. Boer, L. Hein, D. R. Nurrochmat, and A. Riqqi (2023). Peatland Fire Regime across Riau Peat Hydrological Unit, Indonesia. *Forest and Society*, **7**(1); 76–94

Rossita, A., D. R. Nurrochmat, R. Boer, L. Hein, and A. Riqqi (2021). Assessing the Monetary Value of Ecosystem Services Provided by Gaung–Batang Tuaka Peat Hydrological Unit (KHG), Riau Province. *Heliyon*, **7**(10); e08208

Tacconi, L. (2016). Preventing Fires and Haze in Southeast

Asia. *Nature Climate Change*, **6**(7); 640–643

Tacconi, L., P. F. Moore, and D. Kaimowitz (2007). Fires in Tropical Forests—What Is Really the Problem? Lessons from Indonesia. *Mitigation and Adaptation Strategies for Global Change*, **12**(1); 55–66

Taufik, M., M. Haikal, M. T. Widyastuti, C. Arif, and I. P. Santikayasa (2023). The Impact of Rewetting Peatland on Fire Hazard in Riau, Indonesia. *Sustainability*, **15**(3); 2169

Wahyunto, S. Ritung, Suparto, and H. Subagjo (2004). *Map of Peatland Distribution Area and Carbon Content in Kalimantan.* Wetlands International Indonesia Programme

Wosten, J. H. M., E. Clymans, S. E. Page, J. O. Rieley, and S. H. Limin (2008). Peat–Water Interrelationships in a Tropical Peatland Ecosystem in Southeast Asia. *Catena*, **73**(2); 212–224

Wosten, J. H. M., J. Van Den Berg, P. Van Eijk, G. J. M. Gevers, W. B. J. T. Giesen, A. Hooijer, A. Idris, P. H. Leenman, D. S. Rais, C. Siderius, M. J. Silvius, N. Suryadiputra, and I. T. Wibisono (2006). Interrelationships between Hydrology and Ecology in Fire Degraded Tropical Peat Swamp Forests. *International Journal of Water Resources Development*, **22**(1); 157–174

