Jurnal Manajemen Hutan Tropika, *31*(3), 250–260, September 2025
EISSN: 2089-2063
DOI: 10.7226/jtfm.31.3.250

Scientific Article
ISSN: 2087-0469

Hydrological Responses to Rainfall Across Varying Canopy Densities in a Tropical Peat Swamp Forest

Marryanna Lion[1*], Azian Mohti[1], Hyrul Izwan Mohd Husin[1], Mohd Azahari Faidi[1], Mohd Afizzul Misman[1], Muhamad Nazhif Ismail[2], Mohamad Danial Md Sabri[1]

[1]Forest Research Institute Malaysia, Kepong Selangor, Malaysia 52109
[2]University Malaysia Kelantan, Kampus Jeli, Jeli, Kelantan, Malaysia 17600

Received February 7, 2024/Accepted June 5, 2025

Abstract

Peat swamp forests play a vital role in carbon storage, water regulation, and biodiversity conservation. This study about the hydrological behaviour of three compartments in the Resak Tambahan Forest Reserve with different forest canopy densities categorized as degraded forest and good forest based. Groundwater levels (GWL) and rainfall data were collected and analyzed from April 2023 to June 2024 to evaluate the impact of forest conditions on water retention and hydrological stability. The results show distinct patterns in GWL fluctuations across forest types, with high forest cover density consistently maintaining higher water retention during wet months due to its dense vegetation. A moderate relationship exists between rainfall and GWL variability in all compartments of a healthy forest, with 51% to 65% of the variation in GWL attributed to rainfall amounts. In degraded forest areas, about 52% to 54% of the variation in GWL can also be linked to rainfall effects. Regression analysis revealed a stronger correlation between rainfall and GWL in forests with high canopy density compared to low- and medium-canopy-density forests, suggesting that intact canopy structures enhance predictability in hydrological responses. Conversely, low and medium canopy density forests displayed erratic fluctuations and weaker correlations, highlighting the impact of forest degradation on groundwater dynamics. These findings emphasize the importance of forest canopy density in regulating water cycles and highlight the need for restoration initiatives aimed at improving forest resilience through hydrological studies in degraded peat swamp forests.

Keywords: *water, temperature, peat, tree density, evapotranspiration*

**Correspondence author, email*: *marryanna@frim.gov.my*

Introduction

Peat swamp forests represent a unique component of Malaysia's tropical rainforest ecosystem, characterized by distinct hydrological and ecological features. The peat swamp forest is extremely important for its role in carbon storage and climate regulation at both the local and global levels (Jauhiainen et al., 2008). Groundwater levels (GWL) and rainfall play a critical role in maintaining the health of forest ecosystems. These factors are essential for supporting the growth of trees and vegetation, which in turn enhances soil moisture retention. GWL provides a crucial water source for trees, especially during dry periods. A stable GWL ensures that trees have access to water, which is essential for their growth and survival. In a flip, forests play a crucial role in the water cycle by intercepting rainfall, facilitating infiltration, and promoting groundwater recharge. This process helps maintain GWL and supports the overall health of the ecosystem (Calle, 2024). Research indicates that denser canopies can significantly reduce evaporation rates, leading to higher levels of groundwater. Dense canopy also reduces the amount of sunlight reaching the forest floor, which in turn reduces the rate of evapotranspiration (Ishikura et al., 2019). Conversely, areas with lower canopy density tend to experience increased evapotranspiration and diminished GWLs (Wösten et al., 2008; Ishikura et al., 2019). Dense canopies promote better water retention in the soil by lessening the impact of rainfall on the soil surface, thereby helping to sustain higher GWLs. In contrast, sparse canopies are associated with greater surface runoff and reduced groundwater recharge (Ishikura et al., 2019). Moreover, regular rainfall is crucial for maintaining GWLs, enabling forests to flourish and play a role in ecological balance. While the general principle is valid, peatlands and peat swamp forests possess a unique hydrological balance. Some studies, for example, Limpens et al. (2014), show that adding more trees in these areas can increase moisture loss through evaporation and transpiration. For example, experiments have found that a small to moderate increase in tree density on bogs can lower the water table. This happens mainly because the trees use more water through evaporation and transpiration; however, it was concluded that the relationship between the number of trees (tree density) and water loss from the peatland is not always straightforward or proportional.

The Resak Tambahan Forest Reserve, located in Pahang, Malaysia, is part of the Southeast Pahang Peat Swamp Forest (SEPPSF). It provides sources and catchments for many of its water supplies and is irreplaceable biologically diverse (Yule,

EISSN: 2089-2063 ISSN: 2087-0469
DOI: 10.7226/jtfm.31.3.250

2010). The forest is characterized by its peat swamp ecosystem, which plays a crucial role in water retention and groundwater recharge (Nur Shuhada et al., 2025).

While the SEPPSF has been the subject of numerous scientific studies, the Resak Tambahan Forest Reserve has received comparatively little attention. This lack of research is particularly concerning when considering the critical relationship between water levels and canopy densities in this reserve, especially in light of the various challenges that this ecosystem faces.

Deforestation, primarily driven by agricultural expansion, urban development, and the conversion of land for palm oil plantations, poses considerable risks to forest integrity in many regions. Furthermore, drainage practices implemented for land development can significantly disrupt the hydrological dynamics of an area, impacting both GWLs and surface water availability (Miettinen et al., 2016). Given these pressing issues, it is essential to study the fluctuations in GWL across various forest canopy densities. Understanding the connections between these factors will offer valuable insights into the resilience of the ecosystem and guide conservation strategies aimed at reducing the negative impacts of human activity on the forest reserve (Hooijer et al., 2012). In this regard, the study aims to evaluate GWL fluctuations across different canopy densities in the Resak Tambahan Peat Swamp Forest.

The limited dedicated research on Resak Tambahan Forest Reserve, particularly in comparison to other components of the SEPPSF complex, stems from a confluence of factors. Existing literature predominantly features only brief insights rather than comprehensive, longitudinal analyses. Furthermore, research efforts within the SEPPSF complex have historically adopted a broader focus, often examining overarching characteristics of peat swamp forests across various densities rather than conducting in-depth, site-specific investigations of Resak Tambahan Forest Reserve. These factors, coupled with inherent logistical challenges associated with fieldwork in peat swamp environments, have collectively contributed to a significant knowledge deficit regarding Resak Tambahan Forest Reserve. Consequently, this study is uniquely positioned to address this critical gap, providing much-needed empirical data to enhance our understanding of Resak Tambahan Forest Reserve's unique ecological dynamics within the broader SEPPSF complex.

Methods

Study area The Resak Tambahan Forest Reserve is situated within the Southeast Pahang Peat Swamp Forest (SEPPSF) in Malaysia (Figure 1). This forest reserve is organized into several compartments, which serve as the fundamental units for all forest management activities. The extensive Permanent Forest Reserve (PRF) area is segmented into smaller, more manageable compartments. Each compartment is assigned a unique number, making it a permanent geographical unit that can be easily identified in the field. The SEPPSF is a forested belt along the east coast of Pahang state, bounded by the Pahang River to the north and the Rompin River to the south. The SEPPSF has a total area of roughly 200,000 ha, but only 126,361 ha are within the Permanent Reserve Forests (PRFs) (Jamil et al., 2021). Pekan FR is the largest of the four forest reserves, covering an area of about 50,000 ha (Ismail et al., 2011). This research focused on three compartments: Compartments 9, 25, and 28 in Resak Tambahan Forest Reserve. These compartments were categorized based on forest canopy density (FCD), with low- to medium-density representing degraded forests (DF) and high-density representing good forests (GF) in each compartment. The bulk density of peat soil across high (representing GF), medium, and low (representing DF) density forest did not show any significant variation, with values of 0.13 ± 0.02 g cm^{-3}, 0.14 ± 0.03 g cm^{-3}, and 0.13 ± 0.03 g cm^{-3}, respectively (p-value < 0.05). The carbon stock calculation indicate the average soil carbon content at a depth of 50 cm in the Resak Tambahan peat swamp forest was as follows: 330.37 ± 61.02 C t ha^{-1} for high-density forest, 328.50 ± 64.70 C t ha^{-1} for medium-density forest, and 326.46 ± 48.79 C t ha^{-1} for low-density forest (Nur Shuhada et al., 2025).

Forest canopy density classification The FCD map was carefully created using a high-resolution Sentinel-2 image sourced from the Sentinel Hub website, selected for its low cloud coverage. The clearest image, captured on August 13, 2022, was chosen due to its lack of clouds and shadows obscuring the SEPPSF. This image underwent a series of pre-processing steps, including atmospheric correction and cloud masking, followed by detailed processing to generate a comprehensive FCD map (Rikimaru et al., 2002; Azizi et al., 2008). To enhance the interpretation of the FCD map, the resulting density values were categorized into three distinct strata: low, medium, and high (Figure 2). The low stratum is defined by FCD values ranging from 0 to 4.5, indicating areas with sparse canopy cover and limited vegetation. The medium stratum encompasses values between 4.5 and 6.5, suggesting a moderate level of canopy density with a variety of tree sizes. In contrast, the high stratum includes values exceeding 6.5, representing areas expected to possess superior forest quality, characterized by larger trees and greater ground biomass/carbon storage. An analysis of forest stratification in the Resak and Resak Tambahan Forest Reserve, based on the FCD assessment, revealed that approximately 46.4%, or 4,942.95 ha, of the total forest area was classified as high strata. The remaining 53.6% was divided between the low and medium strata, with the low stratum covering a significantly larger area than the medium stratum. Specifically, the low stratum accounted for 29.2% of the total area within SEPPSF, equating to 3,116.98 ha, while the medium stratum encompassed 24.4%, or 2,602.24 ha, of the total area.

In conducting the hydrology assessment, we employed a stratified approach for site selection. The high stratum was designated as good forest (GF) to represent areas with healthy, well-preserved forest ecosystems characterized by robust biodiversity and effective water management capabilities. In contrast, the medium and low strata were categorized as degraded forest (DF), identified as indicators of degraded forest environments, where factors such as reduced vegetation cover, soil erosion, and diminished biodiversity are prevalent. This stratification allows for a

Jurnal Manajemen Hutan Tropika, *31*(3), 250–260, September 2025
EISSN: 2089-2063
DOI: 10.7226/jtfm.31.3.250

Scientific Article
ISSN: 2087-0469

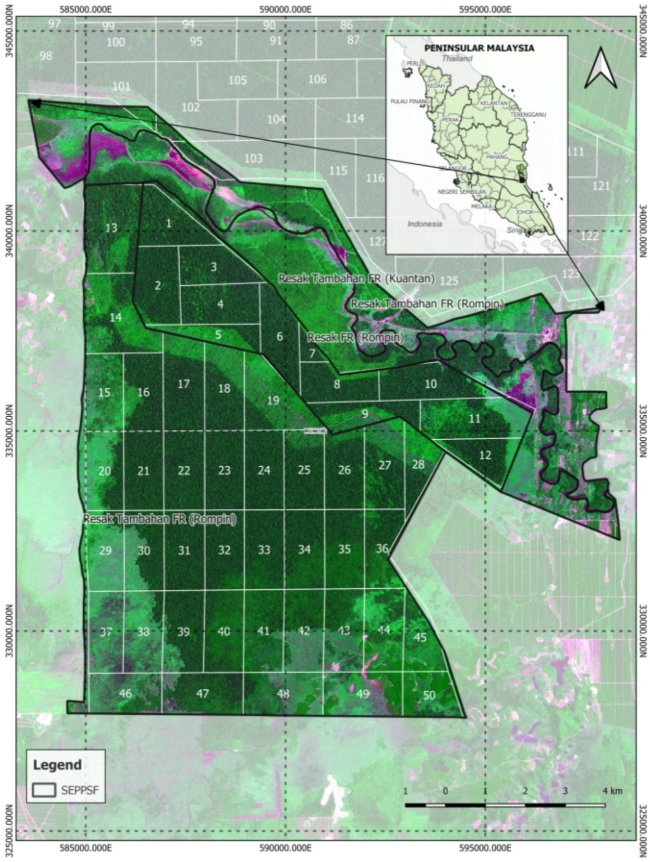

Figure 1 Resak and Resak Tambahan Forest Reserve in the Southeast Pahang Peat Swamp Forest (SEPPSF). The number refers to the unique identifier assigned to a specific, defined unit of forest land that allows forest managers to easily identify and differentiate it from other areas within the larger forest.

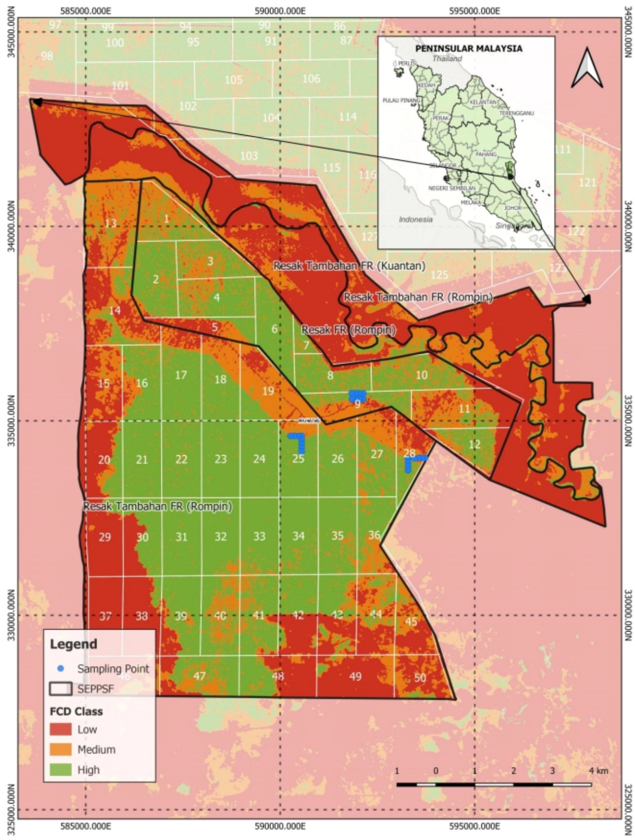

Figure 2 Map of Resak Tambahan Forest Reserve highlighting the forest canopy density class of high, medium, and low. The number refers to the unique identifier assigned to a specific, defined unit of forest land that allows forest managers to easily identify and differentiate it from other areas within the larger forest.

comprehensive evaluation of the hydrological dynamics across varying forest conditions, ultimately contributing to more informed conservation strategies.

Data collection

Groundwater levels Before establishing GWL monitoring stations, we conducted a thorough peat digging process at each selected site, using a specialized auger designed for soil investigations (Roundtable on Sustainable Palm Oil Manual, n.d.; Nyoman et al., 2005). This step was essential for accurately assessing the depth of the peat layer in each location, as variations in peat depth can significantly impact groundwater dynamics. Once we determined the precise peat depth, we carefully inserted a sturdy perforated PVC pipe into the underlying mineral layer, which served as the GWL monitoring station. The PVC casing was strategically buried 30 cm into the mineral soil to ensure both stability and protection from environmental factors, while leaving 50 cm above ground to act as a reference point for measurements and ensure accessibility. After the installation of the monitoring stations, we systematically monitored the GWL across all designated compartments within the forest. This result was achieved using a combination of barometric sensors and diver sensors, which were positioned based on a comprehensive forest stratification analysis utilizing FCD. Measurements were meticulously recorded daily in centimeters (cm) at 15-minute intervals, enabling precise tracking of groundwater fluctuations over time and providing valuable data for our research and analysis.

Rainfall data Monthly rainfall data was collected to examine the relationship between groundwater response and seasonal rainfall patterns, using a high-precision automatic tipping bucket rain gauge (Noguchi et al., 2016; Marryanna et al., 2017). Rainfall measurements were recorded in millimeters to facilitate a comprehensive assessment of precipitation over time. For this study, we utilized a 5 mm tipping bucket mechanism, which allows for accurate measurement of rainfall in event-based and incremental amounts. The rain gauge recorded data at 15-minute interval. A rain gauge was installed in an open area near the village, at the edge of the forest boundary, to ensure the security of the equipment. This location is adequate for representing the rainfall data for the study area, as there are no high topographical features within

Jurnal Manajemen Hutan Tropika, *31*(3), 250–260, September 2025
EISSN: 2089-2063
DOI: 10.7226/jtfm.31.3.250
Scientific Article
ISSN: 2087-0469

the region that would obstruct the collection of rainfall measurements within the radius of 10 km.

Data analysis Correlation and regression analysis were used to analyze GWL in relation to rainfall patterns to identify the water retention capacity and hydrological stability of each forest type (Pratama et al., 2019). We use correlation analysis to measure how changes in rainfall impact GWLs. The relationship's strength and direction are indicated by a value between -1 and 1. Additionally, we use a scatter plot with a linear trendline to show the association between GWLs and rainfall data. Rainfall was set as the independent variable and GWL as the dependent variable. A regression equation of the linear trendline showing the positive and negative trends of the relationship.

Results

Rainfall pattern From April 2023 to May 2024, the Resak Tambahan Forest Reserve exhibited notable monthly rainfall variability, shaped by Malaysia's monsoon cycles and broader climatic phenomena. The maximum rainfall recorded in 2023 was 703 mm in December, while the highest amount in 2024 at 923 mm, was observed in January. Figure 3 illustrates the seasonal distribution, with reduced rainfall during mid-year months, followed by gradual increases from June to August and declines in September and October. A sharp rise was observed in December and January, succeeded by a steep reduction in February and consistently low rainfall levels averaging less than 150 mm per month from March to May. The average monthly rainfall over the entire study period was 220 mm.

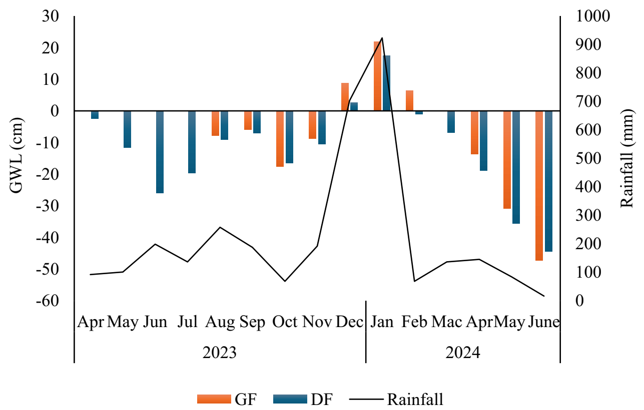

Figure 3 Monthly groundwater levels with rainfall patterns at Compartment 9 (April 2023 –June 2024).

GWL distribution across the forest compartments The GWL in Compartment 9, which spans from April 2023 to June 2024 for DF and from August 2023 to May 2024 for GF, displays unique hydrological patterns in relation to FCD (Figure 3). During the monsoon period (December 2023 January 2024), both forest types experienced elevated GWL, with GF showing superior water retention (8.75 cm in December) compared to DF (2.72 cm). However, this pattern reverses during periods of dry conditions attributed to the Northwest monsoon in June 2024, where GF records lower levels (-47.31 cm) than DF (-44.49 cm), attributed to increased evapotranspiration through its fuller canopy structure.

In Compartment 25, GWL from April 2023 to June 2024 demonstrates the dynamics between FCD (Figure 4). The DF area experiences its highest GWL in January 2024 (48.56 cm) and lowest in June 2024 (-6.97 cm), while GF follows a similar pattern with peaks at 47.68 cm and troughs at -7.9 cm during the same periods. A notable transition occurs in DF from May 2023 (17.07 cm) to June 2023 (-9.90 cm), followed by a recovery to 6.07 cm in July 2023.

In compartment 28, the GWL patterns from April 2023 to June 2024 present unexpected relationships between forest condition and water retention (Figure 5). The DF area reaches its maximum GWL in March 2024 (52.59 cm) and minimum in August 2023 (-29.88 cm), while GF peaks lower at 36.24 cm (January 2024) and drops further to -52.03 cm (July 2023). GF experiences more dramatic fluctuations, demonstrated by sharp declines from March to April 2024 (2.12 cm to -8.75 cm) and May to June 2024 (-25.4 cm to -33.02 cm). In contrast, DF shows more gradual transitions, such as the modest increase from December 2023 (16.05 cm) to January 2024 (20.75 cm).

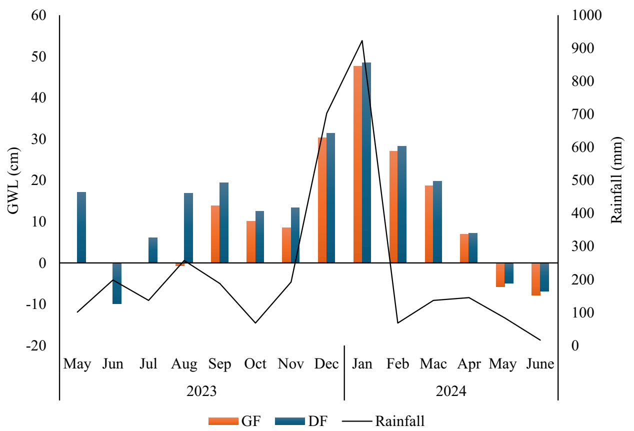

Figure 4 Monthly groundwater levels (GWL) with rainfall patterns at Compartment 25 (May 2023–June 2024).

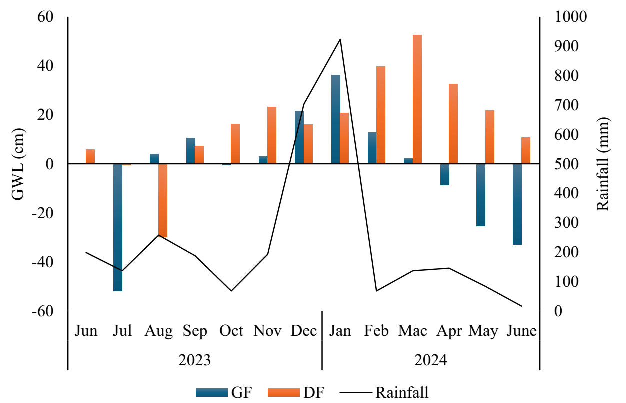

Figure 5 Monthly groundwater levels (GWL) with rainfall patterns at Compartment 28 (Jun 2023 –June 2024).

Rainfall–groundwater relationships Regression analysis revealed significant differences in rainfall–GWL relationships across forest types and compartments (Table 1). Higher R^2 values indicate stronger predictive capacity of rainfall on GWL; *p*-values assess statistical significance. In Compartment 9, both GF and DF showed significant negative coefficients. GF's stronger negative relationship suggests that increased rainfall is associated with a short-term decline in GWL, potentially due to canopy interception and delayed recharge. DF also displayed a significant negative trend, though less pronounced. Compartment 25 showed stronger rainfall–GWL coupling than compartment 9. GF exhibited a robust correlation (r = 0.807, R^2 = 0.651), with rainfall accounting for approximately 65% of GWL variability. DF also showed a positive correlation (r = 0.737, R^2 = 0.543), though with less predictive power. These findings align with prior observations in tropical forests (Abdullahi et al., 2015), where GF areas exhibit more predictable hydrological responses due to continuous canopy cover and higher infiltration capacity. Compartment 28 revealed the most pronounced divergence. GF showed a significant positive correlation (r = 0.769, R^2 = 0.592), indicating that rainfall explains 59% of GWL variation. Conversely, DF exhibited negligible correlation (r = 0.078, R^2 = 0.006), suggesting that factors other than rainfall such as subsurface flow, soil compaction, or anthropogenic disturbance may be driving GWL variability. Despite its low correlation, DF recorded higher maximum GWL values than GF. This paradox implies that while DF can accumulate water, its retention and regulation mechanisms are compromised. The concept of effective accumulated rainfall, which integrates the temporal distribution and intensity of rainfall events, may help explain such variability (Jan et al., 2007).

The association between rainfall and GWL across the FCD at Resak Tambahan Forest Reserve The relationship between rainfall and GWL as depicted in Figure 6 indicates how well the independent variable (rainfall) explains the variability in the dependent variable (GWL). A higher R^2 value indicates a stronger relationship between the independent and dependent variables. In this context, the R^2 values suggest that rainfall has a significant impact on the GWL in peat swamp forests, although other factors also play a role. Given that rainfall can account for about 45–51% of the variability in GWLs in Compartment 9, it highlights the critical role of precipitation in maintaining the hydrological balance of these ecosystems. The coefficient of determination for GF determined that about 51.14% of the variability in GWL can be explained by the changes in rainfall. This means that just over half of the changes in GWL can be attributed to the amount of rainfall. Meanwhile in DF, about 45.37% of the variability in GWL can be explained by changes in rainfall. The slope of 0.0472 in GF indicates the change in GWL for each unit change in rainfall. Here, for every 1 mm increase in rainfall, GWL rises by 0.0472 cm. This positive slope suggests that increased rainfall leads to higher GWL, which is expected in peat swamp forests where rainfall significantly influences water levels. In the event of no rainfall, it is predicted that the GWL will be at -20.582 cm. In the DF area, for every 1 mm increase in rainfall, the GWL rises by 0.041 cm. Like the first plot, this positive relationship indicates that rainfall positively affects GWL, albeit slightly less so than in the first plot. The predicted baseline level of GWL without rainfall influences is around -21.693 cm, similar to the GF area. The remaining 48.86 to 54.63% variability in GWL is due to other factors not captured by the model (e.g., soil properties, vegetation, water table depth, etc.).

The variability of rainfall influences on the GWL at the GF and DF in Compartment 25 is depicted in Figure 7. The coefficient of determination suggests that this area pose a slightly tighter relationship between rainfall and GWL at about 52 to 60% compared to Compartment 9. This implies that rainfall is a stronger predictor for GWL. In the ecological context of peat swamp forests, having an R^2 around 0.5–0.6 suggests that rainfall is a significant but not exclusive driver of GWLs. A unit (mm) increase in rainfall raises the GWL by about 0.0444 cm (GF) and 0.0441 cm (DF). The model predicted that in the event of no rainfall, the area will still hold about 2.2893 cm in GF and 4.051 cm in DF. In GF of the Compartment 28 (Figure 8a), a higher slope (0.0581) indicates that for each 1 mm increase in rainfall, GWL increases by about 0.0581 cm. This is a steeper response than those in the previous four models. However, the R^2 of 0.44 means only 44% of the variance in GWL is explained by rainfall. Although the influence per unit of rainfall is stronger (as the slope suggests), the overall model fit is a bit lower, perhaps because other local factors add noise. Meanwhile, in the DF area (Figure 8b), the negative slope indicates a very weak, almost negligible relationship where increasing rainfall slightly *decreases* GWL, but the value is so close to zero that it can be considered statistically irrelevant. An R^2 of 0.0048 (less than 0.5% of the variance explained) tells us that rainfall, in this particular dataset, does virtually nothing to account for the variability in the GWL. This area may need further investigation to determine the underlying factors of such feedback. The first four models (Figure 6 and Figure 7) consistently suggest that as rainfall increases, the GWL in the peat swamp forest rises, an expected ecological outcome. Their slopes are quite similar (about 0.041 to 0.047), and together they capture between 45% and 60% of GWL

Table 1 Summary of analysis for rainfall and groundwater level data from good and degraded forest

	Good forest			Degraded forest		
	Compt. 9	Compt. 25	Compt. 28	Compt. 9	Compt. 25	Compt. 28
Multiple R	0.715	0.807	0.769	0.719	0.737	0.078
R square	0.511	0.651	0.592	0.517	0.543	0.006
Significance F	0.020	0.005	0.006	0.004	0.004	0.810
Coefficient of predictor (intercept)	-7.790	-0.790	-52.030	-2.470	17.070	5.750
p-value	0.0023	0.6951	0.0037	0.0001	0.3163	0.0417

Jurnal Manajemen Hutan Tropika, *31*(3), 250–260, September 2025
EISSN: 2089-2063
DOI: 10.7226/jtfm.31.3.250

ISSN: 2087-0469

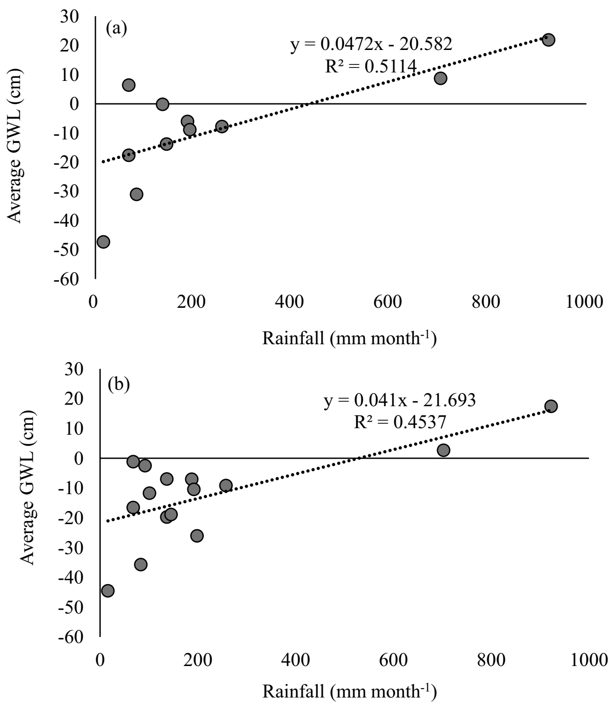

Figure 6 The association between monthly rainfall and average monthly groundwater at (a) good forest and (b) degraded forest in Compartment 9 of Resak Tambahan Forest Reserve (*the number of observation were not same because to delayed installation at the GF due to flood*).

variation. In Figure 8, the GF area has a steeper slope (0.0581), meaning each additional millimeter of rainfall is linked with a larger increase in GWL compared to the previous models. However, its R^2 is lower at 44%, suggesting that, although the rainfall effect per unit is stronger, there is more unexplained variability (perhaps due to a different microenvironment or more noise in the data). A micro-habitat where groundwater is regulated by processes other than direct rainfall input may be among the possible factors. The comparison across these models highlights the inherent complexity of peat swamp ecosystems. While a broad positive relationship with rainfall is evident in many cases, there can be pockets or conditions within the forest where this relationship breaks down.

Discussion

Attributing heavy December-January rainfall at Resak Tambahan Peat Swamp Forest to seasonal monsoon, not La Niña The La Niña phenomenon is generally known to intensify rainfall patterns across Southeast Asia, which could explain the extreme spikes in precipitation observed during December and January (Cai et al., 2015). This weather pattern typically leads to heavier rainfall events, affecting agricultural productivity and water supply in the region. However, there was no evidence of La Niña occurrences recorded in Malaysia during the years 2023 and 2024. Consequently, the significant increase in rainfall observed in December and January at the Resak Tambahan Peat Swamp

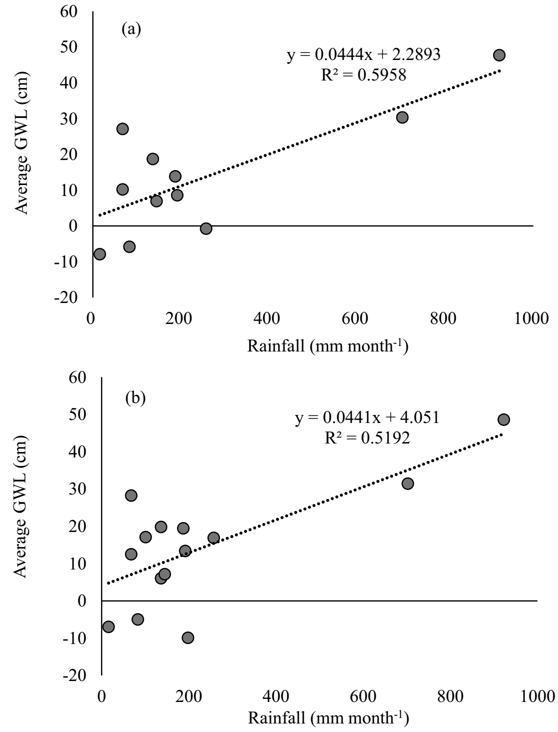

Figure 7 The association between monthly rainfall and groundwater at (a) good forest and (b) degraded forest in Compartment 25 of Resak Tambahan Forest Reserve (*the number of observation were not same due to flood*).

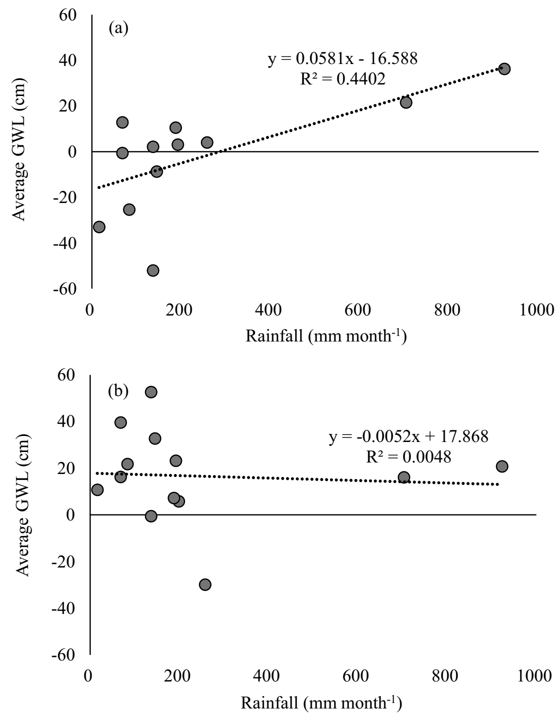

Figure 7 The association between monthly rainfall and groundwater at (a) good forest and (b) degraded forest in Compartment 28 of Resak Tambahan Forest Reserve (*the number of observation were not same due to flood*).

Forest area can be attributed solely to seasonal variations inherent to the region's climate, rather than any influence from the La Niña phenomenon. These seasonal fluctuations are part of the natural climatic cycle experienced annually in Southeast Asia, which can lead to dramatic changes in weather patterns, including heavy downpours during the monsoon season. Malaysia's climate is defined by the two main monsoons and monsoon transition periods: the Northeast Monsoon (which lasts from November to March and is associated with heavy rainfall) and the Southwest Monsoon (from May to September, typically bringing drier weather). The Resak Tambahan Peat Swamp Forest experiences between 10 and 27 rainy days during the southeast monsoon. This area receives rain almost every day during the peak period of the southeast monsoon in December and January, totaling 27 days. In contrast, the number of rainy days decreases to between 11 and 14 during the northwest monsoon, resulting in less overall rainfall. According to Tangang et al. (2017), the characteristics of Malaysia's monsoon, where the Northeast Monsoon significantly contributes to peak rainfall in December and January, align with the rainfall pattern observed in this study.

The balance of canopy effects: Groundwater regulation and water loss in two forest types The denser vegetation and healthier canopy of GF contribute to more stable groundwater regulation throughout most months, while DF's compromised forest structure results in more erratic fluctuations. During dry spells, increased canopy coverage can lead to higher evapotranspiration rates, which intensifies water loss (Hirano et al., 2007). This is because evapotranspiration is often limited by soil water availability, and increased canopy coverage can shift the dominant factors from soil water to energy-related factors (Chen et al., 2022). This contrast highlights how forest condition directly influences groundwater dynamics, with GF's enhanced vegetation cover and soil quality providing better resilience during adverse conditions, while DF's degraded state makes it more vulnerable to seasonal variations. The rapid decline in the GWL indicates poor water retention capacity and normally characterizes areas with reduced vegetation cover and disrupted soil structure. Where there is insufficient vegetation and root density, water absorption and retention are reduced (Taufik et al., 2020). However, in areas with less vegetation, the evaporation from the soil surface is suspected to be high, and therefore evapotranspiration increased (Zhu et al., 2022). GF in compartment 25 exhibits more moderate fluctuations, suggesting better hydrological stability due to its intact canopy structure. The role of canopy density and topography in water retention processes is consistent and emphasizes their influence on peatland hydrology (Dommain et al., 2011).

Counterintuitive rainfall-groundwater dynamics in forested compartments The relationship between rainfall and GWL in peat swamp forests at Resak Tambahan Forest Reserve reflects the complex hydrological dynamics driven by canopy density, peat depth, and spatial heterogeneity. Overall, the regression models show a broadly positive association between rainfall and GWL, especially in areas with intact canopy cover. These results are consistent with previous studies highlighting rainfall as a primary driver of water table fluctuations in tropical peatlands (Wösten et al., 2008; Abdullahi et al., 2015). In compartments dominated by GF, rainfall consistently emerges as a significant predictor of GWL, with moderate to strong model fits. This reinforces the notion that undisturbed canopy and vegetation structures enhance infiltration and reduce surface runoff, allowing for more direct recharge of the peat water table. The slopes of these models suggest a predictable and measurable rise in GWL in response to rainfall, underscoring the hydrological efficiency of healthy peat swamp systems.

The monsoon season (December 2023–January 2024) brings elevated GWL in both forest types at Compartment 28, though the similarities in their responses suggest that local geological factors might play a more significant role than vegetation coverage in this compartment's groundwater dynamics. This is expected, since these environments are complex and subject to multiple interacting influences. This reinforces the idea that rainfall is important in maintaining hydrological conditions crucial for peat accumulation and ecosystem sustainability.

Rainfall is the predominant driver of groundwater variations across all compartments, with GF consistently exhibiting stronger correlations between rainfall and GWL. Notably, R^2 values in GF compartments range from 0.511 in Compartment 9 to 0.651 in Compartment 25, reflecting the beneficial role of intact canopies. In contrast, DF, particularly in Compartment 28, shows a near-negligible correlation (with an R^2 of just 0.006), suggesting that factors like altered drainage patterns and compromised root systems significantly influence soil water dynamics in these degraded landscapes (Page et al., 2006; Anggat et al., 2024). The effective accumulation and distribution of rainfall are crucial for GWL recovery. For instance, GF recorded a GWL of -47.31 cm in June 2024 compared to -44.49 cm in DF. This highlights that while dense canopies in GF support long-term moisture retention, they also risk accelerated water loss during prolonged droughts (Chen et al., 2022). Seasonal rainfall from the Northeast Monsoon plays a vital role in recharging groundwater, yet extreme events, whether droughts or intense downpours, exacerbate water stress in DF and challenge the water retention capacity of GF.

A moderate relationship exists between rainfall and GWL variability in all compartments of a healthy forest, with 51% to 65% of the variation in GWL attributed to rainfall amounts. In degraded forest areas, about 52% to 54% of the variation in GWL can also be linked to rainfall effects. However, a counterintuitive negative relationship between rainfall and GWL has been observed. The finding suggests several potential factors contributing to the negative correlation. This consistent pattern indicates that both DF and GF respond similarly to changes in precipitation, though the comparable R^2 values also suggest that additional environmental factors, such as temperature and soil moisture, significantly influence groundwater dynamics. In this area, a significant portion of the rainfall may rapidly run off the surface rather than infiltrating the soil to recharge groundwater. Furthermore, increased rainfall could lead to heightened evapotranspiration, which might deplete and indirectly lower GWL. Additionally, the underlying geology, not accounted for in this study, may hinder rainfall infiltration. The specific vegetation, soil type, and topography of each compartment could also play a role in how rainfall impacts GWL. The stark contrast appears in the last model (Figure 8b), where the slope is nearly zero and actually negative with an insignificant R^2 value. This model tells us that in that particular dataset or location, rainfall does not explain the variation in GWL at all. Such a finding could be due to local factors (e.g., soil heterogeneity, micro-topography, or interactions with other variables like canopy cover).

This result suggests that in the area or under the conditions corresponding to DF, other environmental or micro-site factors dominate over rainfall, or else the relationship is too noisy to detect. As for the negative weak relationship between rainfall and GWL in DF at Compartment 28, several potential causes suggested are dominance of other environmental factors (canopy structure, soil type, microtopography, or even anthropogenic disturbances), spatial heterogeneity (variable soil conditions and topographic differences), nonlinear or threshold effects (below a certain amount of rainfall, there is little to no change in groundwater, but once a threshold is passed, the effect becomes pronounced), saturation (if the GWL in DF area was already near saturation for most of the measurement period, additional rainfall would have little impact) and recession effects (if the system was in recession (drying out), then a given amount of rainfall might not be enough to cause a significant measurable change).

This implies that even with little to no rainfall, the GWL is above the reference marker or above the ground surface. This could reflect differences in site characteristics, as Compartment 25 has a deeper peat layer (4.43 to 4.82 m), located slightly far from the canal and forest road, with the presence of inundated water most of the time. This is something interesting to be further investigated with long-term monitoring. However, the extremely low R^2 value in DF Compartment 28 indicates that rainfall is a poor predictor of GWL in this compartment, suggesting that other factors likely influence GWL fluctuations. While rainfall serves as a statistically significant predictor of GWL in most compartments except for GF Compartment 25 and DF Compartment 25, the direction of this relationship can vary. In the healthy forest, the statistically significant negative coefficients for compartments 9 and 28 suggest that increases in rainfall are associated with decreases in GWL. The variation in GWL responses between compartments may be due to differences in soil and vegetation characteristics (Page et al., 2006). The concept of effective accumulated rainfall, which considers both current and past rainfall events, has been shown to correlate strongly with GWL increments, emphasizing the importance of rainfall intensity and distribution (Jan et al., 2007).

The findings indicate that GWLs in both forest types exhibit only a short-lived recovery following rainfall events. This observation raises concerns regarding the vulnerability of degraded forests, which struggle to maintain moisture over extended periods. The erratic water levels characteristic of these degraded environments render them particularly prone to extreme weather events like prolonged dry periods and floods. This susceptibility stems from the diminished canopy cover and root systems, which play vital roles in buffering against climatic extremes and sustaining local hydrology (Hrachowitz et al., 2021). From a management perspective, it suggests that conservation strategies must account for spatial variability, recognizing that protecting or restoring canopy and controlling hydrological inputs might need to be tailored to local conditions. These findings underline the critical importance of hydrological restoration and sustainable forest management. Practices such as rewetting, reforestation, and the implementation of water-blocking structures have been effective in enhancing ecosystem resilience and reducing carbon losses in tropical peatlands (Jauhiainen et al., 2008). Overall, preserving and restoring intact forest canopies is vital for stabilizing hydrological processes and mitigating the impacts of climate variability in these sensitive ecosystems.

The structure of peat swamp forests, characterized by raised hummocks and depressions, supports effective water storage by allowing water to collect in these depressions, which helps maintain soil moisture during dry periods (Dommain et al., 2011). Canopy cover can enhance water retention by intercepting rainfall, which reduces surface runoff and increases soil moisture during wet periods. This benefit is particularly evident in agroforestry systems where canopy cover influences soil water isotopic composition and dynamics (Hasselquist et al., 2018). This finding suggests that in areas such as Compartments 25 and 28, rainfall plays a role in increasing GWLs. The reduced vegetation in these degraded zones may result in lower rates of evapo-transpiration, allowing more water to reach the groundwater table. Furthermore, the degradation might have modified the soil structure, enhancing its capacity for water infiltration.

The analyses reveal distinct hydrological behaviors between degraded forests (DF) and healthy forests (GF) in the Resak Tambahan Forest Reserve. GF consistently demonstrates superior water retention during wet seasons, highlighting the stabilizing influence of dense vegetation and intact canopy structures. This enhanced water retention promotes groundwater recharge by reducing surface runoff and increasing infiltration, a finding that aligns with previous research (e.g., Hirano et al., 2007). Conversely, during periods of extreme dryness, GF is more vulnerable to higher evapotranspiration rates, leading to sharper declines in GWL compared to DF.

One of the most notable contrasts is observed in Compartment 28, where GF shows a stronger per-unit rainfall response but a lower overall model fit, implying that other local environmental factors may be interacting with rainfall inputs. In contrast, DF in this same compartment displays a near absence of correlation between rainfall and GWL. The negligible slope and extremely low coefficient of determination indicate that rainfall does not explain GWL variation at this site. Several plausible explanations exist for this anomaly.

First, spatial heterogeneity may be significant in this compartment, with localized variations in peat depth, compaction, and subsurface hydrological connectivity. Second, canopy degradation may have altered evapo-transpiration regimes or reduced interception capacity, both of which affect how rainfall is translated into subsurface storage. Third, the presence of recession effects or near-saturation conditions could diminish the apparent impact of rainfall. If GWLs remain consistently high, additional rainfall may not produce measurable changes, especially over short timescales. In tropical peatlands, especially under high water table conditions, additional rainfall may have little effect on water table depth due to saturation and limited storage capacity (Aper et al., 2022). Finally, anthropogenic disturbances such as drainage infrastructure or proximity to roads and canals may further complicate hydrological processes, decoupling rainfall from its expected influence on GWL.

Compartment-specific monitoring and adaptive management The differing behaviors observed in various compartments underscore the heterogeneous nature of forest ecosystems. Monitoring these specific compartments relies on localized data rather than broad averages. In compartments where the model is robust, indicated by a high R^2 value and significant predictors, continuous monitoring can facilitate the early detection of deterioration. Implementing a feedback loop through adaptive management allows interventions to be adjusted based on timely data from these particular compartments. A sudden change in a predictor within a sensitive compartment can prompt proactive measures. These insights emphasize that effective forest management cannot rely solely on generalized guidelines; each forest compartment tells its own unique story. The interplay between a predictor potentially representing a critical stressor or a beneficial factor and forest health illustrates that nature operates along gradients and thresholds. Forest managers are tasked with the dual responsibility of safeguarding the delicate balance in nearly pristine areas while revitalizing or re-engineering the complex interactions in degraded zones.

Conclusion

This study evaluates the fluctuations in GWLs across different canopy densities in the Resak Tambahan peat swamp forest. The findings indicate that healthy peat swamp forests (GF) play a crucial role in retaining water and recharging groundwater, particularly during wet seasons, due to their dense canopies. However, during dry periods, these forests tend to lose significant amounts of water through evaporation and transpiration. In contrast, DFs exhibit a weaker connection between rainfall and GWLs, suggesting that factors such as changes in drainage and compromised root systems are more influential in their water management. The results emphasize the importance of intact forest canopies for maintaining consistent water levels. The varying responses observed in different parts of the forest reflect the complexity of these ecosystems. Therefore, effective forest management requires local monitoring and adaptive strategies tailored to the specific needs of each forest area. This approach is vital for preserving ecological balance and enhancing resilience to climate change.

Acknowledgement

This study was co-funded by the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) of the Federal Republic of Germany and the European Union through Sustainable Use of Peatland and Haze Mitigation in ASEAN (SUPA/ASEAN REPEAT) Component 1, implemented by GIZ. We would like to acknowledge the contribution of the Pahang State Government through its dedicated agencies, which are the Pahang Forestry Department and the Pahang Biodiversity Council, for granting us permission to conduct research and providing a study area for this study.

References

Abdullahi, M., Gasim, M., & Juahir, H. (2015). Determination of groundwater level sased on rainfall distribution: Using integrated modeling techniques in Terengganu, Malaysia. *Journal of Geology & Geosciences*, *4*(1), Article 187. https://doi.org/10.4172/2329-6755.1000187

Apers, S., De Lannoy, G. J. M., Baird, A. J., Cobb, A. R., Dargie, G. C., del Aguila Pasquel, J., Gruber, A., Hastie, A., Hidayat, H., Hirano, T., Hoyt, A. M., Jovani-Sancho, A. J., Katimon, A., Kurnain, A., Koster, R. D., Lampela, M., Mahanama, S. P. P., Melling, L., Page, S. E., ..., & Bechtold, M. (2022). Tropical peatland hydrology simulated with a global land surface model. *Journal of Advances in Modeling Earth Systems, 14*(2), Article e2021MS002784. https://doi.org/10.1029/2021MS002784

Anggat, F. U., Soh-Fong, L., Yau-Seng, M., Nur Azima, B., Nagamitsu, M., Faustina, S., & Lulie, M. (2024). Long-term rainfall and water table influence on groundwater nutrient dynamics from an oil palm plantation. *Water Science*, *38*(1), 569–586. https://doi.org/10.1080/23570008.2024.2417514

Azizi, Z., Najafi, A, & Sohrabi, H. (2008). Forest canopy density estimating using satellite images. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *37*, 1127–1130. https://doi.org/10.13140/2.1.2953.6967

Cai, W., Wang, G., Santoso, A., McPhaden, M. J., Wu, L., Jin, F. -F., Timmermann, A., Collins, M., Vecchi, G., Lengaigne, M., England, M. H., Dommenget, D., Takahashi, K., & Guilyardi, E. (2015). Increased frequency of extreme La Niña events under greenhouse warming. *Nature Climate Change*, *5*(2), 132–137. https://doi.org/10.1038/nclimate2492

Calle, J. (2024). Exploring forest hydrology: The crucial role of forests in water cycle dynamics. *Hydrology: Current Research*, *15*, Article 542. https://doi.org/10.37421/2157-7587.2024.15.542

Chen, Q. -W., Liu, M. -J., Lyu, J., Li, G., Otsuki, K., Yamanaka, N., & Du, S. (2022). Characterization of dominant factors on evapotranspiration with seasonal soil water changes in two adjacent forests in the semiarid Loess Plateau. *Journal of Hydrology*, *613*, Article 128427. https://doi.org/10.1016/j.jhydrol.2022.128427

Dommain, R., Couwenberg, J., & Joosten, H. (2011).

Development and carbon sequestration of tropical peat domes in south-east Asia: Links to post-glacial sea-level changes and Holocene climate variability. *Quaternary Science Reviews*, *30*(78), 999–1010. https://doi.org/10.1016/j.quascirev.2011.01.018

Hasselquist, N. J., Benegas, L., Roupsard, O., Malmer, A., & Ilstedt, U. (2018). Canopy cover effects on local soil water dynamics in a tropical agroforestry system: Evaporation drives soil water isotopic enrichment. *Hydrological Processes*, *32*(8), 994–1004. https://doi.org/10.1002/hyp.11482

Hirano, T., Segah, H., Harada, T., Limin, S., June, T., Hirata, R., & Osaki, M. (2007). Carbon dioxide balance of a tropical peat swamp forest in Kalimantan, Indonesia. *Global Change Biology*, *13*(2), 412–425. https://doi.org/10.1111/j.1365-2486.2006.01301.x

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

Hrachowitz, M., Stockinger, M., Coenders-Gerrits, M., van der Ent, R., Bogena, H., Lücke, A., & Stumpp, C. (2021). Reduction of vegetation-accessible water storage capacity after deforestation affects catchment travel time distributions and increases young water fractions in a headwater catchment. *Hydrology and Earth System Sciences*, *25*(9), 4887–4915. https://doi.org/10.5194/hess-25-4887-2021

Ishikura, K., Hirata, R., Hirano, T., Okimoto, Y., Wong, G. X., Melling, L., Aeries, E. B., Kiew, F., Lo, K. S., Musin, K. K., Waili, J. W., & Ishii, Y. (2019). Carbon dioxide and methane emissions from peat soil in an undrained tropical peat swamp forest. *Ecosystems*, *22*, 1852–1868. https://doi.org/10.1007/s10021-019-00376-8

Ismail, P., Nizam, M. S., Latiff, A., Faridah Hanum, I., & Shamsudin, I. (2011). Phenology of *Gonystylus bancanus* in Pahang, Peninsular Malaysia. *Journal of Tropical Forest Science*, *23*(2), 143–151.

Jamil, R. A., Mohd Yasin, M. H., Tahir, R., Akeng, G., Ismail, M. S., & Modingin, D. (2021). Pahang as an integral part of Central Forest Spine (CFS) in Peninsular Malaysia. Retrieved from https://www.forestry.gov.my/images/pengumuman/2022/MFC/MFC2022/paperwork/KK13.pdf

Jan, C. -D., Chen, T. -H., & Lo, W. -C. (2007). Effect of rainfall intensity and distribution on groundwater level fluctuations. *Journal of Hydrology*, *332*(34), 348–360. https://doi.org/10.1016/j.jhydrol.2006.07.010

Jauhiainen, J., Limin, S., Silvennoinen, H., & Vasander, H. (2008). Carbon dioxide and methane fluxes in drained tropical peat before and after hydrological restoration. *Ecology*, *89*(12), 3503–3514. https://doi.org/10.1890/07-2038.1

Limpens, J., Holmgren, M., Jacobs, C. M. J., van der Zee, S. E. A. T. M., Karofeld, E., & Berendse, F. (2014). How does tree density affect water loss of peatlands? A mesocosm experiment. *PLoS ONE*, *9*(3), Article e91748. https://doi.org/10.1371/journal.pone.0091748

Marryanna, L., Kosugi, Y., Itoh, M., Noguchi, S., Takanashi, S., Katsuyama, M., Tani, M., & Siti Aisah, S. (2017). Temporal variation in stable isotopes in precipitation related with rainfall pattern in a tropical rainforest in peninsular Malaysia. *Journal of Tropical Forest Science*, *29*(3), 349–362. https://doi.org/10.26525/jtfs2017.29.3.349362

Miettinen, J., Shi, C., & Liew, S. C. (2016). Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. *Global Ecology and Conservation*, *6*, 67–78. https://doi.org/10.1016/j.gecco.2016.02.004

Noguchi, S., Kosugi, Y., Takanashi, S., Tani, M., Niiyama, K., Siti Aisah, S., & Marryanna, L. (2016). Long term variation in soil moisture in the Pasoh Forest Reserve, a lowland tropical rain forest in Malaysia. *Journal of Tropical Forest Science*, *28*, 324–333.

Nur Shuhada, M. T., Azian, M., Hyrul Izwan, M. H., Muhamad Afizzul, M., & Nurul Mayzaitul Azwa, J. (2025). The assessment of peat physico-chemical properties and carbon stocks in Resak Tambahan Peat Swamp Forest, Pahang. *Malaysian Journal of Soil Science*, *29*, 1–11.

Nyoman, I. N. S., Alue, D., Roh, S. B. W., Lili, M., Irwansyah, R. L., Ferry, H., & Iwan, T. C. W. (2005). *A guide to the blocking of canal and ditches in conjunction with the community.* Bogor: Wetland International Indonesia Programme.

Page, S. E., Rieley, J. O., & Wüst, R. (2006). Chapter 7 Lowland tropical peatlands of Southeast Asia. *Developments in Earth Surface Processes*, *9*, 145–172. https://doi.org/10.1016/s0928-2025(06)09007-9

Pratama, H., Sutikno, S., & Yusa, M. (2019). Modeling of groundwater level fluctuation in the tropical peatland area of Riau, Indonesia. *IOP Conference Series: Materials Science and Engineering*, *796*(1), Article 012037. https://doi.org/10.1088/1757-899X/796/1/012037

Roundtable on Sustainable Palm Oil Manual. (n.d.). *Manual amalan pengurusan terbaik (BMP) Pekebun kecil RSPO untuk penanaman sawit sedia ada di tanah gambut*.

Rikimaru, A., Roy, P. S., & Miyatake, S. (2002). Tropical forest cover density mapping. *Tropical Ecology*, *43*(1), 39–47.

Taufik, M., Minasny, B., McBratney, A. B., van Dam, J. C., Jones, P. D., & van Lanen, H. A. J. (2020). Human-induced changes in Indonesian peatlands increase drought severity. *Environmental Research Letters*, *15*, Article 084013.

Tangang, F., Chung, J. X., Juneng, L., Supari, Salimun, E., Ngai, S. T., Jamaluddin, A. F., Mohd, M. S. F., Cruz, F., Narisma, G., Santisirisomboon, J., Ngo-Duc, T., Van Tan, P., Singhruck, P., Gunawan, D., Aldrian, E., Sopaheluwakan, A., Grigory, N., Remedio, A. R. C., & Sein, D. V. (2020). Projected future changes in rainfall in Southeast Asia based on CORDEX–SEA multi-model simulations. *Climate Dynamics*, *55*(56), 1247–1267. https://doi.org/10.1007/s00382-020-05322-2

Warren, M., Frolking, S., Dai, Z., & Kurnianto, S. (2017). Impacts of land use, restoration, and climate change on tropical peat carbon stocks in the twenty-first century: Implications for climate mitigation. *Mitigation and Adaptation Strategies for Global Change, 22*(6), 1041–1061. https://doi.org/10.1007/s11027-016-9712-1

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

Yule, C. M. (2008). Loss of biodiversity and ecosystem functioning in Indo-Malayan peat swamp forests. *Biodiversity and Conservation*, *19*(2), 393–409. https://doi.org/10.1007/s10531-008-9510-5

Zhu, G., Yong, L., Zhao, X., Liu, Y., Zhang, Z., Xu, Y., Sun, Z., Sang, L., & Wang, L. (2022). Evaporation, infiltration and storage of soil water in different vegetation zones in the Qilian Mountains: A stable isotope perspective. *Hydrology and Earth System Sciences*, *26*, 3771–3784. https://doi.org/10.5194/hess-26-3771-2022