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Precipitation and Water Table Dynamics in Peat Swamp Catchment in Sarawak, Malaysia

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ABSTRACT

Globally, peatland covers 3% of the land area, with significant concentrations in tropical regions. In Malaysia, Sarawak alone accounts for 70% (1.6 Mha) of the country's peatland. Tropical peatland is characterized by waterlogged conditions that promote the accumulation of organic matter (peat) from decaying plant material. These conditions strongly influence vegetation, species composition, peat type, and carbon release, making them crucial for climate change mitigation. The hydrology of tropical peatland is primarily influenced by the fluctuation of the water table (WT) depth in its catchment. This study analyzes five years (2011-2015) of field measurements on WT and precipitation (PT) dynamics, observing their trends. PT was found to significantly regulate monthly WT at the study site ($p < 0.01$), showing a positive correlation. However, PT exhibited a downward trend over the study period, although not significantly for all sites. Similarly, WT at MA, MC, and MD did not show significant trends, likely due to ENSO events from 2011 to 2015. In contrast, MB experienced a significant decrease in WT, possibly caused by a nearby river acting as a drain and accelerating WT lowering.

Keywords: Tropical peatland, water table, precipitation, trend analysis, hydrology.

1. INTRODUCTION

Globally, peatland covers 3% of the total land area [1]. Large areas of peatland are found in the tropics. South-East Asia contains 11% of global peatland and is mainly distributed among Indonesia and Malaysia. In Malaysia, about 70% (1.6 Mha) of the country's peatland is located in the state of Sarawak [2]. Tropical peatland is characterized by its waterlogged conditions, which promote the accumulation of organic matter (peat) derived from dead and decaying plant material. Such hydrological conditions strongly influence the vegetation structure, species composition, peat type and vice versa [2]. Furthermore, the hydrological condition of tropical peatland is one of the most important factors controlling carbon release, which, in turn, helps climate change mitigation efforts [3-5]. Therefore, with the onset of global warming and climate change, there have been concerns in the scientific community that peatland could switch its role from carbon sink to carbon source.

The focus then turns into studying the hydrology of this unique ecosystem. The major mode of peatland hydrology is governed by the fluctuation of its catchment's water table (WT) depth. According to Page et al., tropical peatland is typically ombrotrophic, i.e. their main water source and nutrient input are via precipitation (PT) [6]. Therefore, its WT varies according to residuals (storage change) between PT as input, while water is discharged from the ecosystem via

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evapotranspiration and groundwater flow. While the study of WT fluctuations of tropical peat swamp forests has been gaining interest [7-9], most of our knowledge of peatland hydrology is based on studies undertaken in temperate peatlands [10-13].

Li et al. used climate models and predicted decreases in rainfall and evaporative fraction over the Southeast Asia region, implying a deeper WT depth and increased surface dryness during the dry season south of the equator [14]. Therefore, there is an urgent need to investigate the trend in WT depth. One commonly used test for trend analysis for hydrological data is the Mann-Kendall (MK) test. The MK test is a non-parametric statistical test used to detect trends in time series data [15]. It is widely employed in various fields, including environmental science and hydrology [16-21]. The MK test compares the ranks of the data points over time. If the ranks of the data points are monotonically increasing or decreasing, then the test will find a significant trend. The test is also able to detect trends that are not linear, such as quadratic or exponential trends. The MK test is robust against outliers and does not require a normal distribution assumption, making it suitable for analyzing time series data with irregular patterns. However, continuous long-term measurement and trend analysis, especially for WT and PT dynamics for tropical peatland, is limited. Therefore, this study aims to elucidate the PT and WT dynamics for a peat swamp catchment in Sarawak, Malaysia.

2. MATERIAL AND METHODS

2.1 Site Information

The study was conducted in Maludam National Park in Sarawak, Malaysia. It's the largest peat dome in Malaysia [22]. The total park area is 432 km2 [23]. According to Melling et al., peat depth in the park can reach up to 10 m, with peat surface elevation for the study sites estimated to be between 5-12 m above mean sea level (Figure 1) [24].

Characterized by the equatorial climate, the study sites have consistently high temperatures, high humidity, and abundant PT throughout the year. It has two monsoon seasons and two shorter inter-monsoon seasons. The northeast monsoon is more noticeable due to a sudden increase in rainfall amounts, which usually occurs from October to February [25]. Between May and August, the site experiences a comparatively dry period due to the Southwest monsoon. However, the climate in Sarawak, in general, is relatively stable with rain events throughout the year [16]. Based on the study by Wong et al., 17 years (1998–2014) of annual PT was found to be at 3182 ± 494 mm (mean ± 1 standard deviation (SD)), measured at Lingga rainfall station about 12 km away from the study site [26]. The same study also found the mean annual air temperature for the same period to be at 26.5 ± 0.2 °C.

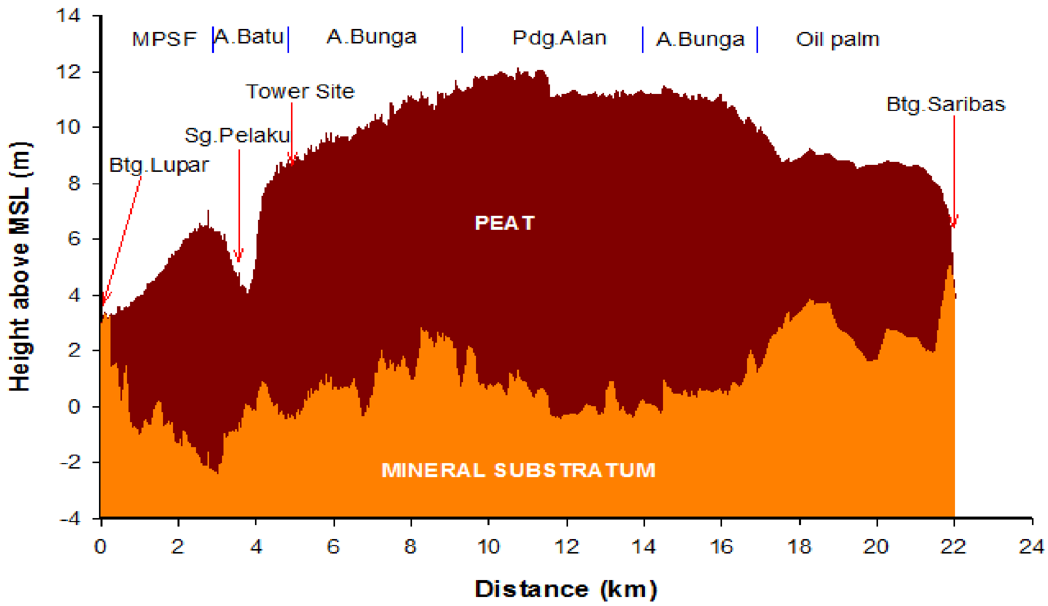

Figure 1: Peat dome and cross-section of Maludam National Park.

There are four (4) forest types in Maludam National Park, namely mixed peat swamp forest (MPS), Alan Batu (ABt), Alan Bunga (ABg), and Padang Alan (PA) (Figure 2).

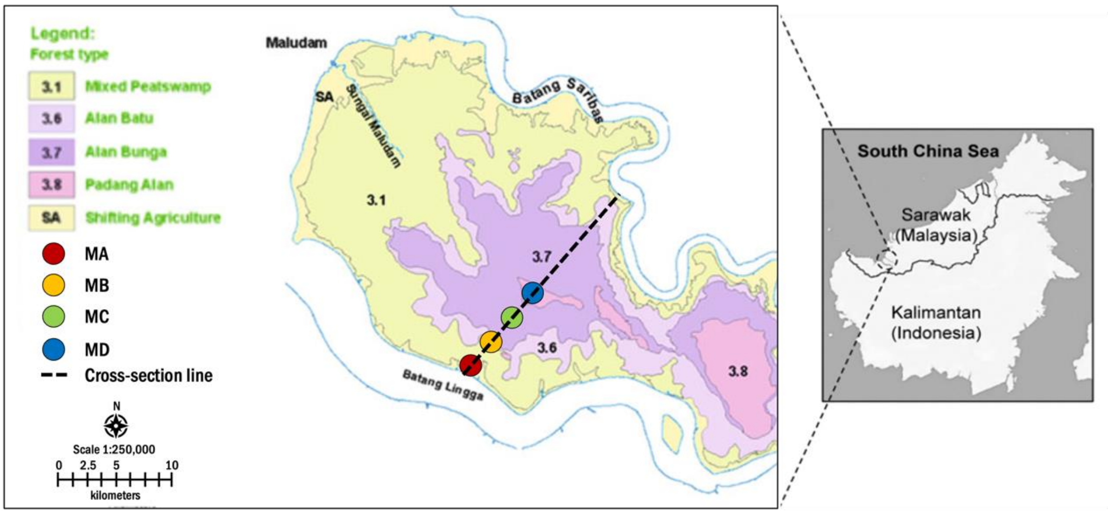

Figure 2: Study sites in Maludam National Park.

2.2 Data Collection

Four (4) plots have been set up to monitor the WT depth continuously for each of the forest types. Each forest type has one plot, namely MA (1°25'51.41"N, 111° 7'52.06"E) for MPS, MB (1°27'12.51"N, 111° 8'57.26"E) for ABt, MC (1°27'47.89"N, 111° 9'28.64"E) for ABg, and MD (1°28'53.82"N, 111°10'25.18"E) for PA. At each plot, two (2) piezometers were installed, and a water level logger (HOBO U20; ONSET HOBO Water Level Logger) was deployed at each piezometer, with an additional one (1) deployed to measure barometric pressure. The loggers were set to log data continuously every 30 minutes. WT data is then processed using the HOBOware Pro Version 3.7.10. Monthly PT data have been collected using a rain gauge since January 2011. PT data is also recorded using a tipping bucket TE525; Campbell Sci.), where a 40-meter Eddy Covariance Flux tower was erected at the MB site. For MA, MB and MC sites, precipitation was also measured using a rain gauge at the respective sites. However, there was no precipitation data available for the MD site due to its inaccessibility. Therefore, the rainfall for MD site was represented by the nearest rain gauge to the site, which is data collected from the MC. The distance between MC and MD sites is about 1.2 km.

2.3 Site Information

Monthly data for each site were used for analysis. Monthly WT is defined as the arithmetic mean of WT recorded by the water level logger for a month [27]. Gaps in monthly WT data (due to equipment malfunction or corrupted data files and data that has been screened for outliers) were filled using in-situ measurements of WT, which are also recorded every month during fieldwork at the sites. Monthly PT is defined as the sum of rain events for each month. Since PT variations among sites were few for the missing months, missing monthly PT data were filled using the arithmetic mean of other monitoring points where data are available [28]. For the MD site, since PT data was not available, we used the PT data from MC site to represent the MD site as it was the closest (about 1.2km) to MD site. Hypothesis testing using Analysis of Variance (ANOVA) was done to investigate whether the sites share the same water table precipitation distributions. Regression analysis was conducted on the dataset for each site to estimate the relationships between PT, and WT [29], and the MK test was conducted to analyze WT and PT trends for the study period. The MK test is a reliable nonparametric test for evaluating trends [30]. The test assumes the null hypothesis H_0 as there is no trend i.e., the data is independent and randomly ordered, while the alternative hypothesis H_1 indicates that there is a trend. The MK S statistics were calculated as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(T_j - T_i) \tag{1}$$

$$Sign(T_j - T_i) = \begin{cases} 1 \; if \; T_j - T_i > 0 \\ 0 \; if \; T_j - T_i = 0 \\ -1 \; if \; T_j - T_i < 0 \end{cases} \tag{2}$$

where T_j and T_i are the monthly values months j and i, $j > i$, respectively. For $n < 10$, $|S|$ is compared directly to the theoretical distribution of S derived by MK test. For this purpose, the two-tailed test is used. If $|S|$ is equal or greater than a specified value $S_{\frac{\alpha}{2}}$, where $S_{\frac{\alpha}{2}}$ is the smallest S that has a probability less than $\frac{\alpha}{2}$ to appear in case of no trend, H_0 is rejected in favour if H_1. Positive S indicates an upward trend, while negative S indicates a downward trend. For $n > 10$, S is approximately normally distributed with the mean and variance as follows:

$$E(S) = 0 \tag{3}$$

The variance (σ^2) for the -statistic is given by the following equation:

$$\sigma^2 = \frac{n(n-1)(2n+5) - \sum t_i(i)(i-1)(2i+5)}{18} \tag{4}$$

Where t_i is the number of ties to extent i. The summation term in the numerator is used if the data series contains tied values. For standard test statistics Z_s, the computation is done as follows:

$$Z_s = \begin{cases} \dfrac{S-1}{\sigma} \; for \; S > 0 \\ 0 \; for \; S = 0 \\ \dfrac{S+1}{\sigma} \; for \; S < 0 \end{cases} \tag{5}$$

3. RESULTS AND DISCUSSION

3.1 Water Table Dynamics

The mean annual PT for MA, MB, and MC were 2737 ± 551, 2686 ± 536, and 2527 ± 496 mm, respectively (Table 1). As mentioned in the previous section, the PT for MD site is represented by the PT collected at MC site. Figure 3 shows the monthly average WT, and the sum monthly total of PT for the study sites from Jan 2011 to Dec 2015. The mean monthly WT for all sites from 2011 to 2015 were – 13.5 ± 14.3, -8.7 ± 10.0, -1.3 ± 10.5, and 0.4 ± 17.3 cm for MA, MB, MC, and MD, respectively (Table 1).

Table 1: Mean water table, and precipitation from 2011 – 2015 (mean ± SD).

	MA	MB	MC	MD
Water table (cm)	-13.5 ± 14.3	-8.7 ± 10.0	-1.3 ± 10.5	0.4 ± 17.3
Min water table (cm)	-47	-39.9	-27.2	-48.3
Max water table (cm)	9.9	11.8	20.2	25.1
Precipitation (mm yr^{-1})	2737 ± 551	2686 ± 536	2527 ± 496	2527 ± 496

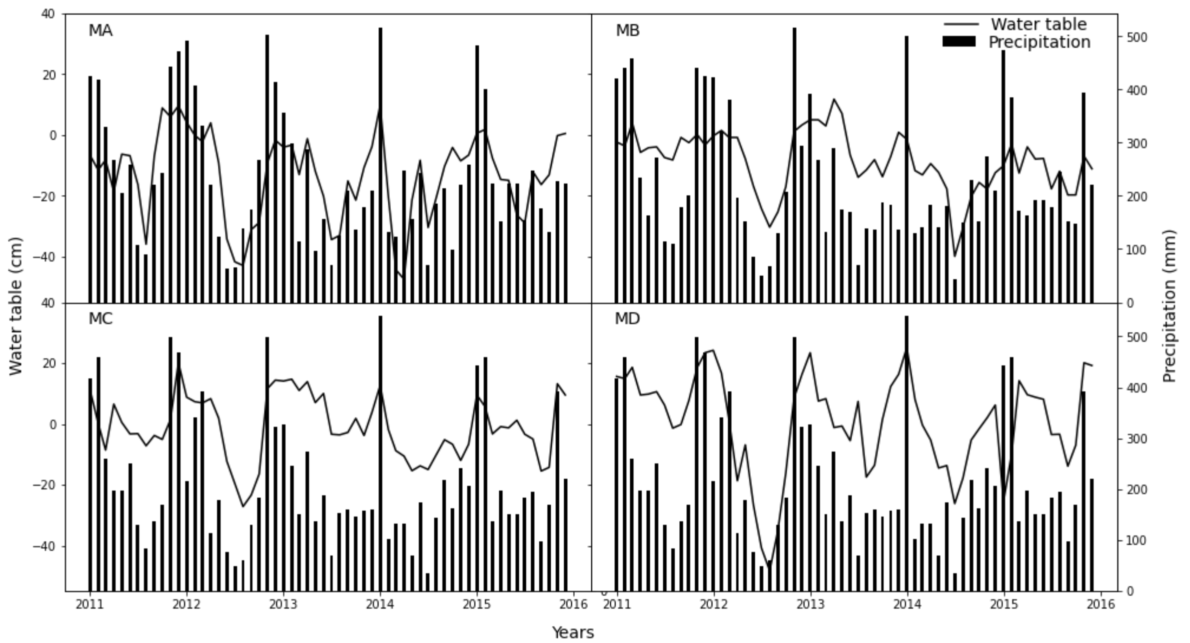

Figure 3: Seasonal variations in water table and precipitation in MA, MB, MC, and MD sites from 2011 to 2015.

A negative value indicates that the WT is below the ground surface. The ANOVA revealed that the water table mean for MA does not share the same distribution with the MB, MC, and MD sites. The same can also be concluded between the mean water table at MB and the mean water table at MC and MD. However, the ANOVA test showed that MC and MD shared the same distribution. From the results, the WT was observed to increase as we moved from the edge of the peat dome towards the centre. This was explained by Ritzema & Wösten [31], wherein the periphery peat surface topography is steeper compared to the flatter topography in the centre of the peat dome and, therefore deeper WT than the centre. This description is similar to Maludam National Park, as shown by the cross-section study that was conducted there (Figure 1). As shown in Figure 1, the elevation of the periphery of Maludam National Park for the study site was about 3 m above mean sea level (m.s.l.). As we move towards the centre of the peat dome, the elevation peaks at about 12 m above m.s.l. In addition, this characteristic could explain why MC and MD sites share the same WT distribution, as both are located closer to the centre of the peat dome, where the topography is relatively flat.

The mean WT observed in the MA site was comparable to the observation reported by Hirano et al., for an undisturbed peat swamp forest (-14.0 ± 8.0) and a drained burnt ex-peat swamp forest with re-growing vegetation (-13.0 ± 10.0) in Kalimantan, Indonesia [32]. For MB, MC, and MD, the WT was higher than that observed by Hirano et al. [32]. In comparison, the WT of the sites in this study was within the range (less than 0.3m above and below peat surface) observed by Hooijer in the Jamoreng catchment, which is located north of Sibu, Sarawak [33]. For precipitation, the ANOVA test concluded that they share the same distribution across the study site.

Monthly values were ensemble averaged for each site for each month of 5 years from January 2011 to December 2015 to investigate seasonal variation (Figure 4). The trends for all the sites showed that the lowest monthly WT was generally recorded in July and August, which coincided with the period for the lowest PT.

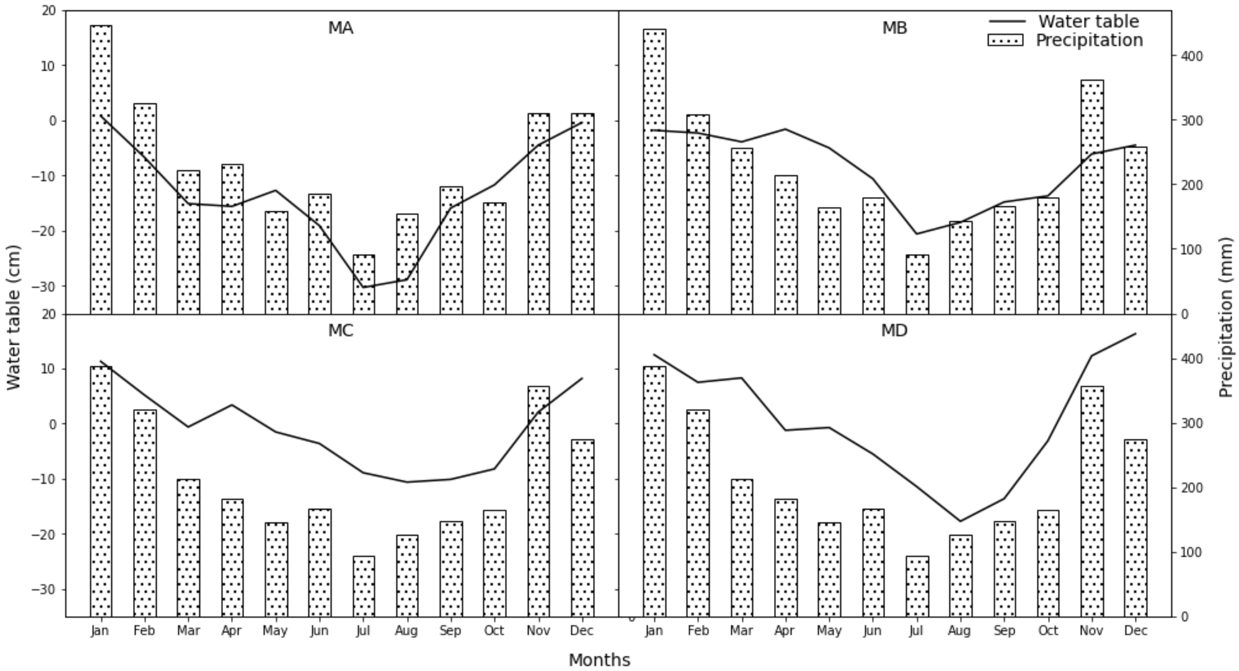

Figure 4: Ensemble averaged monthly water table and precipitation in MA, MB, MC, and MD sites from 2011 to 2015.

This period is generally the driest period of the year in that region. This is consistent with what was reported by Nusantara et al. in West Kalimantan, Indonesia, where low WT was recorded in the month of August in their study of land use change of peatlands [34]. In addition, the observations also agree with the results from Hirano et al., which showed that the lowest PT was recorded on average between August and September for tropical peat swamp forests in Kalimantan, Indonesia [35]. For this study, the highest WT for the sites is generally recorded from November to February, coinciding with the period with the highest PT. Regression analysis for

PT and WT for the all the sites showed that they are all significantly ($p < 0.01$) and positively correlated. The R^2 for each site were 0.4103, 0.3026, 0.3855, and 0.2671 for MA, MB, MC, and MD, respectively (Figure 5).

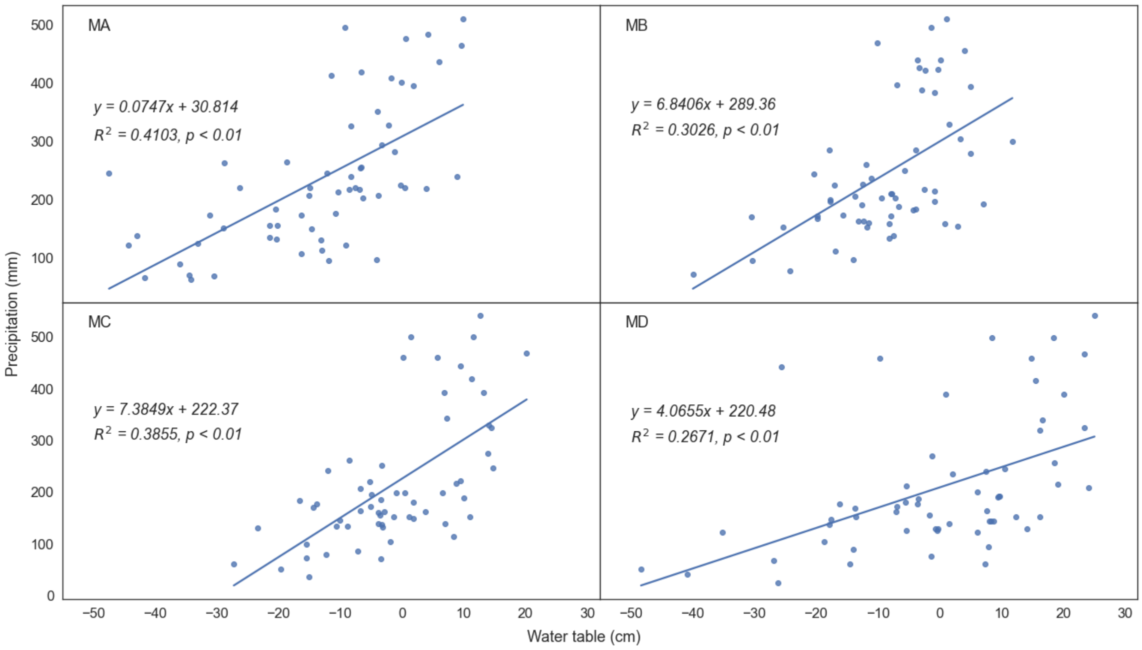

Figure 5: Regression analysis of water table and precipitation in MA, MB, MC, and MD sites for the period of 2011 - 2015.

3.2 Trend Analysis of Monthly Water Table

Trend analysis on the monthly WT during the study period showed that, in general, there was a decreasing trend for all the sites indicated by the negative Z value between -1.45 and -3.10. However, MA, MC, and MD were determined to be insignificant, as shown by a p-value greater than 0.01 (Table 2). Initial investigation suggests that this downward trend could be the effect of ENSO events during the study period. At the beginning of 2011, the La Nina event was recorded. It continued until April 2012 [36]. Towards the end of the study period, an El Nino event was recorded from October 2014 to December 2015. For MB, which showed a significant (Z = -3.10, p < 0.01) decreasing trend in the monthly WT, in addition to the ENSO events, this could be attributed to the presence of a river, namely, Sg. Pelaku down-slope of the site (Figure 1) may act as a drain and result in an accelerated lowering of the WT compared to the rest of the sites. Examination of the monthly PT trend showed a downward trend (negative Z between -0.81 to -1.16) for the available stations but was not significant ($p > 0.01$) for all the sites during the study period. As shown in the previous section, the WT is strongly correlated to PT. Therefore, as the MK test has suggested, albeit not significant for all the study sites, the decrease in the WT during the study period can be explained by the decrease in PT.

Table 2: Mann-Kendall test results, *Z*, for Maludam National Park's water table and precipitation for 2011-2015.

Parameter	Site	*Z*	*p*-value	Trend
Water table	MA	-0.83	0.407	No trend
	MB	-3.10	0.002	Decreasing
	MC	-1.22	0.221	No trend
	MD	-1.45	0.148	No trend
Precipitation	MA	-1.16	0.246	No trend
	MB	-0.81	0.418	No trend
	MC	-0.81	0.418	No trend

4. CONCLUSION

With the onset of global warming and climate change, it is important to analyze the long-term WT and PT dynamics of tropical peat swamp catchments as they have an important role in climate change mitigation efforts. Therefore, an analysis of PT and WT dynamics from 2011 to 2015 was conducted. Based on the analysis conducted in this study, it can be concluded that:

1. Seasonal PT and WT analysis showed that low PT between July and August led to low WT during the year while high PT between November and February yielded the highest WT.
2. Precipitation was identified as a significant factor that regulates monthly WT for this study site ($p < 0.01$) with a positive correlation. Therefore, changes in PT will influence the WT fluctuations in peatland.
3. Trend analysis during the study period showed that PT had a downward trend but was not a significant trend for all sites. As a result, the same was also true for WT at MA, MC, and MD. The downward trend could be attributed to ENSO events during the study period. In addition, for MB, we concluded that it has exhibited a significant decrease in WT trend. From the survey that had been conducted, we attributed this trend to the presence of a river downslope of the site, which may act as a drain and possibly has accelerated WT lowering.

Research into long-term WT and PT dynamics of tropical peat swamp catchments are still needed to better understand tropical peatland hydrology. Other micrometeorological and soil factors that drive the hydrological processes of tropical peat swamp catchments should be examined in future studies of the location.

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