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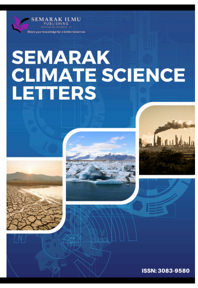

The Effects of Landslides on River Sedimentation and Water Quality: Insights from the Batang Penar River, Malaysia

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ABSTRACT

Landslides pose a significant environmental threat in tropical forested catchments, as they can severely impact water quality and increase sedimentation in downstream rivers. This study evaluates the effects of landslides that occurred on December 18, 2021, in the Berembun Forest on the water quality of the Batang Penar River. Precipitation data and water quality parameters for 2021-2022 were recorded by the Department of Irrigation and Drainage (DID) at 15-minute intervals and by the Department of Environment (DOE) at two-month intervals. The analysis focused on changes in Total Suspended Solids (TSS), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Ammoniacal Nitrogen (AN), as well as their correlations with rainfall. Statistical methods, including T-tests, simple regression, and Pearson's correlation coefficient, were employed to assess the landslide impacts. The results indicated a significant increase in TSS (66.833 to 132.28 mg/L, $p = 0.0143$) following the landslides, while variations in BOD (1.23 to 0.92 mg/L, $p = 0.1767$), COD (10.63 to 10.00 mg/L, $p = 0.4640$), and AN (0.10 to 0.03 mg/L, $p = 0.0912$) were not statistically significant. Contrary, correlation between rainfall and water quality parameters show no statistically significant difference, suggesting no enhanced sedimentation. Notable spatial and temporal variations in water quality were also observed across sampling stations. The findings highlight the impact of land use that shade the pollutions from landslides on water quality especially parameter TSS, underscoring the importance of implementing effective land use planning, with supplementing landslide prevention and post-event rehabilitation strategies to mitigate sedimentation and safeguard water resources.

1. Introduction

A landslide is defined as the movement of a mass of rocks, debris, earth, or soil down a slope (USGS, n.d.). This phenomenon occurs when the surface material of a slope becomes unstable, increasing the likelihood of sliding. Several factors determine the stability of slope surface materials, including slope inclination, soil mechanical properties, and the distribution of vegetation roots [1].

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These factors influence the shear strength and shear stress within the materials; slope instability arises when shear stress exceeds shear strength [2]. For instance, on a steep slope with a high gradient, the surface material experiences significant downward forces due to gravity, resulting in increased shear stress within the slope materials.

In addition to these stability factors, rainfall is a primary trigger for landslides [3]. Climate change leads to increased rainfall volume and intensity, resulting in higher antecedent and event water inputs into the soil [4]. This excess moisture can elevate soil water content to critical levels, ultimately triggering landslides. Antecedent water from previous rainfall events contributes to the overall moisture content, while new rainfall adds to this amount [5]. When the combined antecedent and event water exceed the soil's drainage capacity, and the rate of rainwater input surpasses the drainage rate, the soil reaches its critical water content level, significantly increasing the likelihood of landslides. Hence, these would increase the risks of landslides at higher altitudes and pose threats to the downstream community.

Landslides cause significant changes to the landscape of slopes and downstream areas, resulting in the accumulation of debris, soil, and rocks at the base of the slope. This process often leads to the formation of landslide-dammed lakes and reduces surface soil depth, increasing erosion, particularly in areas where vegetation has been removed. These topographical changes can alter how rainfall interacts with the slope and affect water flow, which, as noted by study [6], influences water chemistry through interactions with sliding surfaces and landslide deposits, although the study focused on mineral content rather than total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), and ammoniacal nitrogen (AN) levels.

Landslides can result in fatalities and property loss along the flow path and downstream of the slope [7]. Additionally, landslides modify the topography of both the slope and downstream landscapes, altering surface and underground water flow paths and quality, while also destroying vegetation cover and disrupting natural habitats for both terrestrial and aquatic ecosystems [8]; [9]. There are approximately US $1 billion in economic losses estimated due to landslides in Malaysia from 1973 to 2007 [7]. Between 1993 and 2011, 28 major landslides were reported in Malaysia, up to two occurring annually.

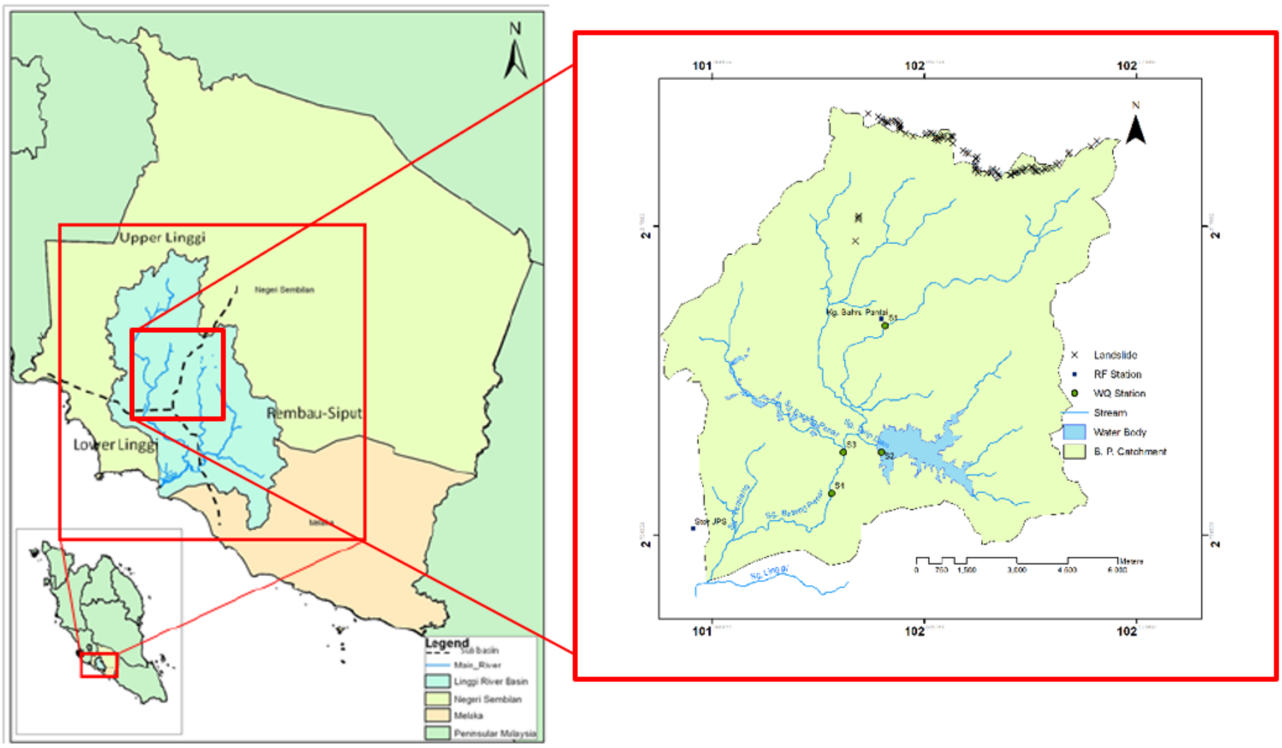
In addition to landslides, rainfall, its amount and intensity affects the chemical and physical properties of stream water. Rainfall contributes to surface runoff, which transports dust, chemical pollutants, and eroded materials into rivers, while groundwater carries dissolved compounds and pollutants from the soil. The flow rate and discharge of the river impact its chemical composition, including dissolved oxygen and oxygen demand. Study [10] found that precipitation correlates positively with TSS, ammonium ions, phosphates, total phosphorus, and chemical oxygen demand, while correlating negatively with dissolved oxygen in the lower Mekong River. However, further research is needed to explore the correlation between precipitation and water quality, considering the effects of landslides.

The forest ecosystem potentially purifies the rainwater it receives and improves the water quality of surface runoff [11]. The deforestation due to landslides upstream of Batang Penar River may reduce the purification effects in the catchment area while enhance sedimentation. However, the impacts of the December 18, 2021, landslide on water quality in the Batang Penar River remain undefined. Clarifying the impacts can provide critical insights for managing water resources in vulnerable catchment areas. In addition, identifying the impacts of landslides on water quality will support ecosystem conservation efforts by illustrating the relationship between landslides and aquatic health, while also addressing the economic implications of landslides in Malaysia [12]. Finally, studying how altered rainfall patterns influence landslide risks [13] and water quality can contribute to climate adaptation strategies. Therefore, this study was designed to analyse the water quality parameters and to examine the correlation between precipitation and water quality parameters both before and after landslide events.

2. Methodology

2.1 Study Area

The study focuses on the Batang Penar River, which drains the Batang Penar River Water Catchment area, covering 123.05 km². This area was selected due to the landslides that occurred on December 18, 2021, resulting in more than 83 landslide scars within the catchment. The Batang Penar River is situated in the Linggi River Basin, which spans 1,297.69 km², in the northern region of Pantai, Seremban, Negeri Sembilan (Figure 1).



(a) (b)

Fig. 1. (a) Mapping of the Batang Penar Catchment within the Linggi River Basin and (b) the Batang Penar River in its water catchment, highlighting several locations of landslides that occurred on December 18, 2021
*The locations of multiple landslides were marked during the site visit on June 22, 2023

According to the Climatic Research Unit (n.d.), the mean temperatures in Pantai were 27.27 °C in 2021 and 27.38 °C in 2022. Total rainfall recorded in Pantai was 2,692.9 mm in 2021 and 2,422.7 mm in 2022. Additionally, the vapor pressure was 29.94 hPa in 2021 and 29.76 hPa in 2022. The study area has an average elevation of 109 m, with a minimum of 64 m and a maximum of 329 m. Several water bodies are present in the catchment, including the Trip Dam and various ponds along the tributaries of the Batang Penar River in the west-central part of the catchment, as shown in Figure 1. According to the Department of Statistics [14], Pantai had a population of 2,783 in 2020, with a population density of 27.88 per km².

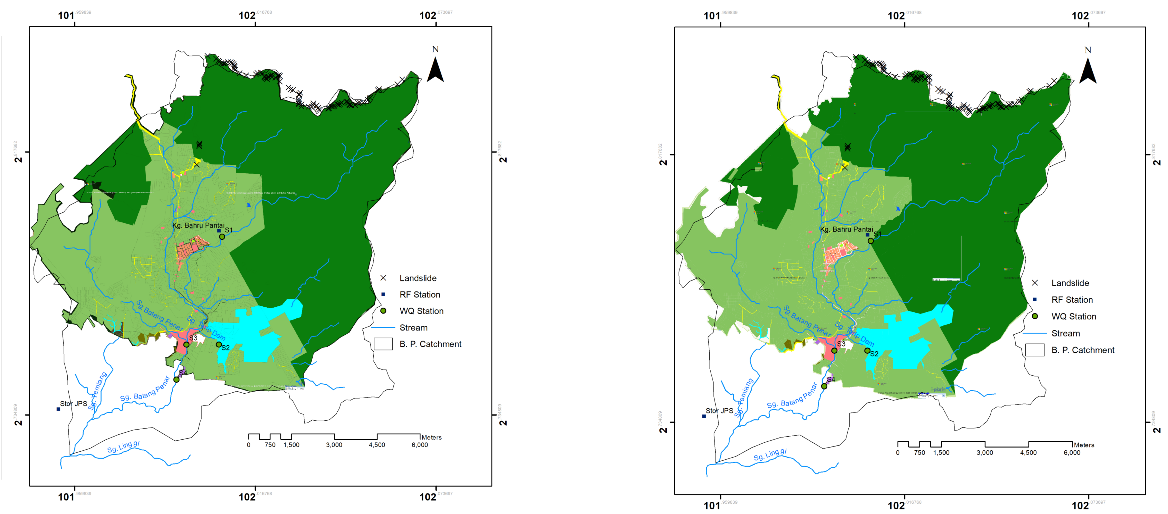
In December of 2021 and 2022, two major landslides occurred respectively in Batang Penar, Negeri Sembilan, and Batang Kali, Selangor. Abnor [15] reported that the landslide in Batang Penar severed the route from Genting Peras to Kuala Klawang and destroyed the Jeram Toi Eco Park in the

Jeram Toi Recreation Forest in Jelebu. The Batang Kali landslide was particularly devastating, resulting in 31 fatalities and marking it as the second-worst disaster in Malaysia in terms of mortality [16]. The December 18, 2021, landslide in Batang Penar caused significant issues, including disrupted road connectivity, particularly the road linking Genting Peras to Kuala Klawang. The recreational and tourism industry was adversely affected by the destruction of the Jeram Toi Eco Rimba Park. Furthermore, the landslide poses potential risks to the water treatment plant supplying water to Pantai and surrounding areas, with concerns over sediment and nutrient pollution.

Overall, land use and land cover in the Pantai district remained similar between 2021 and 2022, with notable changes near Kg. Bahru Pantai station (S1), where 127.85 ha of agricultural land was designated as forest land. There were also minor conversions of 16.61 ha from agricultural land to transportation routes. The land use and land cover in the Pantai district include forests, agriculture, water dams, transportation routes, residential areas, community institutions, industrial zones, and open land. The types of land use and their respective areas are detailed in Table 1, corresponding to Figure 2.

Table 1
Colours and total area of land use land cover of Pantai district in 2021 and 2022

Land use land cover	Colour	Area (Ha)		Changes
		2021	2022	
Forest	Dark green	5068.50	5196.35	(+) 127.85
Agriculture	Light green	4069.22	3944.15	(-) 152.07
Water dam	Light blue	376.78	376.79	
Transportation route	Yellow	63.53	80.14	(+) 16.61
Residential area	Peach	31.73	31.73	
Community institution	Pink	61.13	61.13	
Industry	Purple	6.47	6.47	
Open land	Greenish brown	12.88	11.89	
Others	-	18.10	18.10	



(a) (b)

Fig. 2. (a) Mapping of land use land cover in Pantai district in 2021 and (b) 2022 (DTCP, 2023)

2.2 Data Acquisition

Data on precipitation and river water quality parameters were required for the year before and after the landslide event on December 18, 2021. Consequently, the selected dataset spans from January 1, 2021, to December 31, 2022 (Table 2).

Table 2
Summary of data acquisition

Data	Station	Duration	Frequency	Sources
Water quality	Kg. Bahru Pantai	2021-2022	2-monthly	DOE
	Empangan Terip	2021-2022	2-monthly	DOE
	Jambatan Jab. Haiwan Pantai	2021-2022	2-monthly	DOE
	Jambatan Jln. K. Kelawang	2021-2022	2-monthly	DOE
Rainfall	Kg. Bahru Pantai	2021-2022	15-minute	DID
LULC	Pantai	2021-2022	Annual	DTCP

LULC: land use land cover; DOE: Department of Environment; DID: Department of Drainage; DTCP: Department of Town and Country Planning

The water quality parameters data was collected at four water quality stations along the Batang Penar River while the precipitation data were collected at a rainfall station in Kampung Bahru Pantai. The location of each station is shown in the map in Figure 3, while the summary of the data acquisition is shown. All water quality stations measured four water quality parameters, the total suspended solid (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), and ammoniacal nitrogen (AN). All of these parameters are measured by DOE to determine the water quality and class of the Batang Penar River. The land use land cover data was downloaded from the iPlan: Town plan website operated by the Federal Department of Town and Country Planning, Malaysia. The area downloaded covers the whole Pantai district, which occupies catchments of the water quality stations along the Batang Penar River. The data duration was set parallel to the analysis of one year before and after landslides, which include the land use land cover in 2021 and 2022.

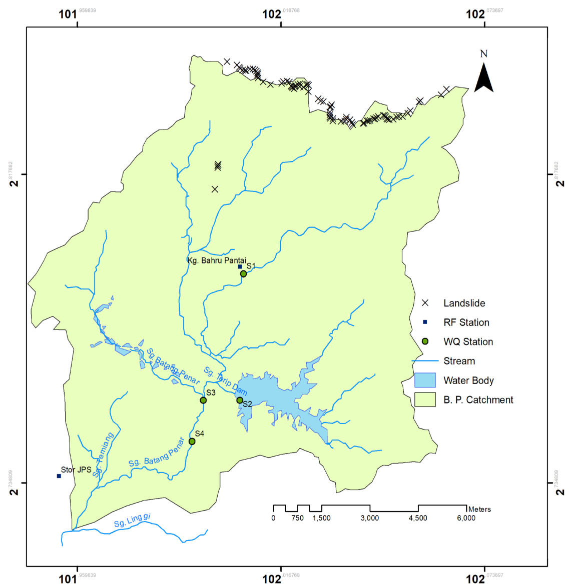


Fig. 3. Location of rainfall and water quality stations in Batang Penar River Water Catchment

The catchment boundary of Batang Penar Catchment is delineated based on the Digital Elevation Model acquired from Earth Explorer, USGS, dated on September 23, 2014. The coverage of Batang Penar Catchment covers two scenes along the same latitude, with coordination of (N 2°, E 102°) and (N 2°, E 101°). The scenes were combined and brightness adjusted by using ERDAS IMAGINE 2015. After the combination, the catchment boundary was drawn in ArcMap 10.8 by using the combined raster image of the DEM. Lastly, the shape files of the streamflow and the catchment boundary were overlapped to produce the map of the Batang Penar Catchment. After that, a contour map of the catchment was produced by using the DEM and vector file of the basin boundary. The contour map was further used to delineate the catchment boundary of each water quality station along the Batang Penar River. After that, the drainage length from the upper stream to each water quality station was measured by geometry calculation.

2.3 Data Analysis

The changes in water quality parameters before and after rainfall events were illustrated in a time series line chart created using Microsoft Excel 2019, plotting the water quality parameters against time. Due to the bi-monthly interval for the water quality data collection, the trend only displays data for February, April, June, August, October, and December in 2021 and 2022. The water quality data were classified according to water quality classes, ranging from Class I to IV, by Department of Environment [17].

The correlation between precipitation and water quality parameters was analyzed twice: once for the period before the landslide events and once for the period after. This was accomplished by calculating the Pearson Product Moment Coefficient of Correlation. In this case, all the parameters were assumed to be linearly correlated with similar variability, while no outliers were presented. A T-test was conducted at a 95% confidence interval to determine the difference of each correlation coefficient from zero in the populations. Rainfall and intensity values were based on total rainfall recorded in the 24 hours preceding the water quality measurements. Following this, Microsoft Excel was used to construct a linear regression model between precipitation and water quality parameters to calculate the slope of the regression line ($\hat{\beta}_1$). Both the coefficient of correlation and the slope of the regression line were validated and compared for correlations before and after the landslide event.

2.4 Missing Data Estimation

Due to missing rainfall data from May to August 2021 at the Kg. Bahru Pantai station, a simple linear regression model was developed to correlate rainfall data between Kg. Bahru Pantai and the nearest rainfall station, Kg. Tanjung Limau. A simple linear regression model was selected for estimation due to the absence of several station data for other estimation methods discussed in the study [18]. A single station was selected among the four nearest stations from Kg. Bahru Pantai station is the only one presented with complete rainfall data for the years 2021 and 2022, particularly the period of missing data. The period of rainfall data for model construction covers January to April 2021 and September 2021 to December 2022. The resulting regression equation is:

$$\hat{Y} = 0.5007X + 4.7272 \quad (1)$$

where Y represent rainfall in Kg. Bahru Pantai station and X represent rainfall in Kg. Tanjung Limau. The adjusted model's R2 value of 0.2068 indicates 20.68% of the variance in rainfall of Kg. Bahru

Pantai is explained by rainfall of Kg. Tanjung Limau. The slope coefficient $\beta 1 = 0.5007$ ($p < 0.001$) and intercept $\beta 0 = 4.7272$ ($p < 0.001$) indicate the rainfall in station Kg. Bahru Pantai is generally higher than rainfall in Kg. Tanjung Limau. The rainy day was assumed to be the same between the correlated stations. Hence, the estimated rainfall value with the input of zero value (no rain event) will be maintained as zero. This model was used to estimate the missing rainfall data at Kg. Bahru Pantai, facilitating further analysis of annual rainfall parameters and the correlation between precipitation and water quality parameters.

3. Results

3.1 Land Use Land Cover

The Batang Penar Catchment was delineated into four smaller catchments corresponding to each water quality station (Figure 5). In 2021, the S1 watershed comprised both forest and agricultural land, with forest cover in the upper stream region and agricultural fields in the lower stream. By 2022, the lower stream region had been designated as forest land, resulting in a forested area surrounding the Batang Penar River upstream of S1. Multiple landslide scars were observed along the northern edge of the S1 catchment.

The Batang Penar River subsequently drains into the S3 catchment after S1. The S3 catchment includes a forested upper stream region, agricultural fields in the middle and lower regions, residential areas, transportation routes, community institutions, and some open land along its southern edge. Landslides also occurred in the northern edge and upper stream of the S3 catchment. After S3, the river flows into the S4 catchment, which has a slightly larger area than S3 due to its proximity. The S4 catchment encompasses community institutions on the northern edge, agricultural land, and an industrial area on the southern edge. Conversely, the S2 catchment, which is free from landslide occurrences, consists of a forest area in the northern region, a dam in the middle, and agricultural fields in the southern region. Water from the S2 catchment flows into the S3 and S4 catchments via the Terip Dam River, eventually reaching the Batang Penar River.

The variation in land use within each catchment can significantly influence measured water quality. Areas dominated by agriculture and urban development typically exhibit lower water quality compared to those primarily consisting of forested regions [19]; [20]. Additionally, water quality tends to be lower in plains than in upstream areas due to increased pollution from urban runoff and discharges from industrial and agricultural land [21]; [9]. Consequently, the S1 and S2 catchments exhibited lower pollution levels in the Batang Penar River compared to the S3 and S4 stations. Furthermore, the absence of landslide scars in the S2 catchment suggests that it may be less affected by landslide-related impacts on stream water quality.

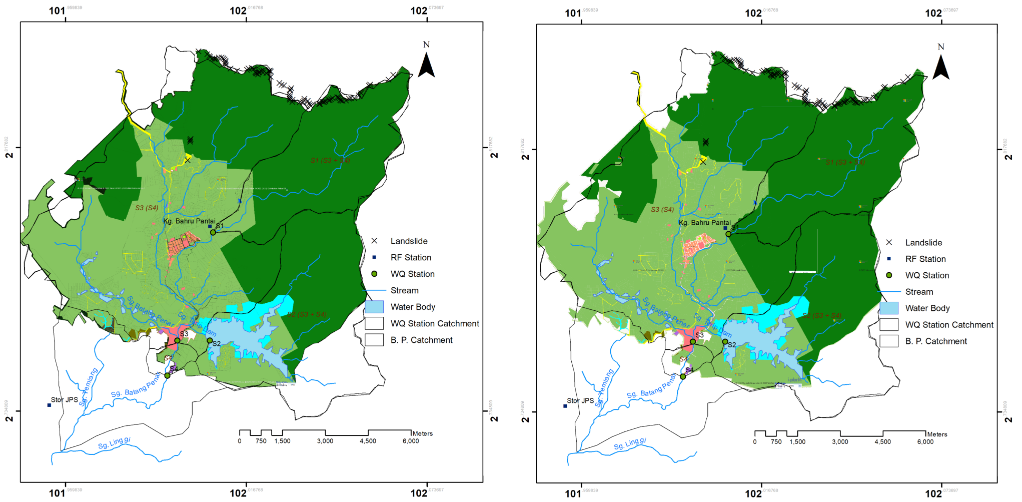


Fig. 5. (a) Land Use and Land Cover in the Watersheds of Each Water Quality Station in 2021 (left) and (b) 2022 (colour coding: green for forest, light green for agriculture, light blue for dam, yellow for transportation route, peach for residential area, pink for community institution, purple for industrial area, greenish brown for open land)

3.2 Drainage Length and Catchment Area per Water Quality Station

The average drainage length of the Batang Penar River before reaching the S1 station is 8.50 km, passing through both forested and agricultural land. The stream channel before reaching the S2 station measures 1.70 km, with an additional 3.03 km representing the longest length of Terip Dam Lake, resulting in an average drainage length of 4.73 km. The average drainage lengths of the Batang Penar River before reaching the S3 and S4 stations are 12.35 km and 13.66 km, respectively. In summary, the ascending order of drainage length before the stations is as follows: S2, S1, S3, and S4 (Table 3), with S4 exhibiting the longest stream flow and encompassing the largest watershed area, which includes the other three catchment areas.

Table 3
Land use land cover and average drainage length before arriving water quality station

ID	WQ Station	LULC	Average drainage length (km)
S1	Kg. Bahru Pantai	Forest, Agriculture	8.50
S2	Empangan Terip	Dam, Forest, Agriculture	1.70
S3	Jambatan Jab. Haiwan Pantai	Residential, Agriculture, Community Institution, Open land	12.35
S4	Jambatan Jln. K. Kelawang	Agriculture, Community Institution, Industry	13.66

The S1, S2, S3, and S4 catchments are situated in the northeast, southeast, and western regions of the middle and lower sections of the Batang Penar Catchment (Figure 6). Among these, the S4 station has the largest catchment area at 106.36 km², followed by S3 at 104.93 km², and S2 at 26.87 km². The S1 station has the smallest catchment area at 19.24 km². Additionally, the total drainage length in the S4 catchment is the longest at 51.65 km, followed by S3 at 50.29 km, S2 at 11.33 km, and the shortest in S1 at 10.31 km (Table 4). The variation in catchment area and total drainage length for each water quality station may contribute to the spatial differences in water quality levels observed in the Batang Penar River. This variation is further influenced by land use, land cover, and the types of pollution present at each site.

Table 4
Catchment area and total drainage length before arriving at water quality station

ID	WQ Station	Catchment ID	Catchment Area (km^2)	Total drainage length (km)
S1	Kg. Bahru Pantai	S1	19.24	10.31
S2	Empangan Terip	S2	26.87	11.33
S3	Jambatan Jab. Haiwan Pantai	S1-3	104.93	50.29
S4	Jambatan Jln. K. Kelawang	S1-4	106.36	51.65

On the other hand, the delineation of the catchments for each water quality station indicates that the S2 catchment is independent of the effects of landslides (Figure 6). Consequently, subsequent analyses of water quality levels and the correlations between water quality and rainfall parameters, both before and after the landslide events, excluded the data recorded at the S2 station.

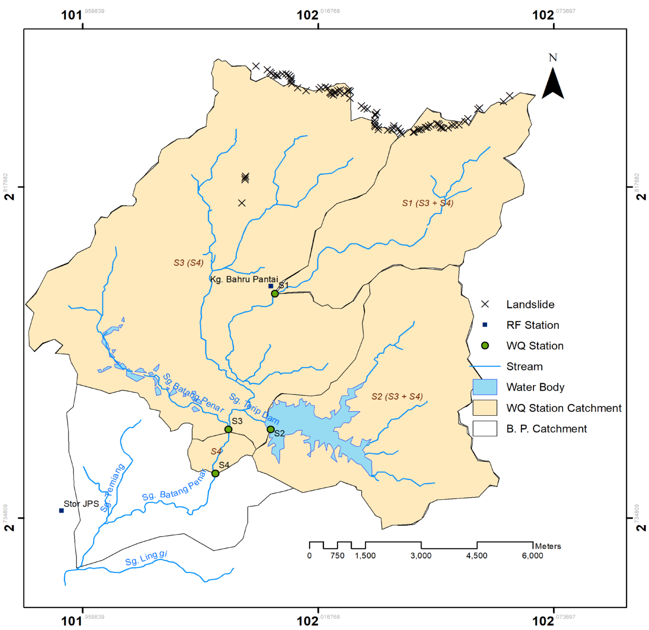


Fig. 6. Catchment for each water quality station. S1 and S2 catchment is sub-catchment to S3 and S4 catchment, while S3 catchment is sub-catchment to S4 catchment

3.3 Summary of Rainfall Data

In 2021, there were an estimated 198 rainy days, with an average daily rainfall of 12.20 mm. Based on the calculated standard error, the mean daily rainfall ranged from 9.88 mm to 14.52 mm at a 95% confidence level. The maximum daily rainfall of 151.5 mm was recorded on December 18, 2021, which triggered the landslides in the Batang Penar Catchment. In 2022, a total of 205 rainy days were recorded, with an average daily rainfall of 13.81 mm. The mean rainfall for 2022 ranged from 11.67 mm to 15.95 mm at a 95% confidence level, with a maximum daily rainfall of 71 mm—about half of the maximum recorded in 2021. Overall, the number of rainy days and total rainfall were higher in 2022, with 205 days and 2832.6 mm, compared to 198 days and 2415.61 mm in 2021. A summary of the statistical properties of daily rainfall recorded at the Kg. Bahru Pantai rainfall station is provided in Table 5.

Table 5
Statistical properties of the processed daily rainfall data in Kg. Bahru Pantai on 2021 and 2022

Year	n	Mean (mm year^{-1})	Std. Error	Std. Dev.	Variance	Min (mm)	Max (mm)	Total (mm)
2021	198	12.20	1.16	16.35	267.46	0.5	151.5*	2415.6
2022	205	13.81	1.07	15.31	234.54	0.5	71	2832.6

**Maximum rainfall amount of 151.5 mm per day recorded on Dec 18, 2021*

3.3.1 Trend of Rainfall (2021-2022)

The rainfall patterns in 2021 and 2022 exhibit two distinct undulations: one from January to July and another from July to December (Figure 7). These undulation patterns are influenced by the Southwest monsoon from May to September and the Northeast monsoon from November to March [22]. In 2021, the peak monthly rainfall was recorded in March (208.45 mm) and November (392 mm) for the first and second undulations, respectively. In 2022, the peaks occurred in April (238 mm) and October (427 mm) for the first and second undulations, respectively. The variation in peak rainfall between the two years can be attributed to the higher rainfall brought in by the South China Sea during the early to mid-phase of the Northeast monsoon.

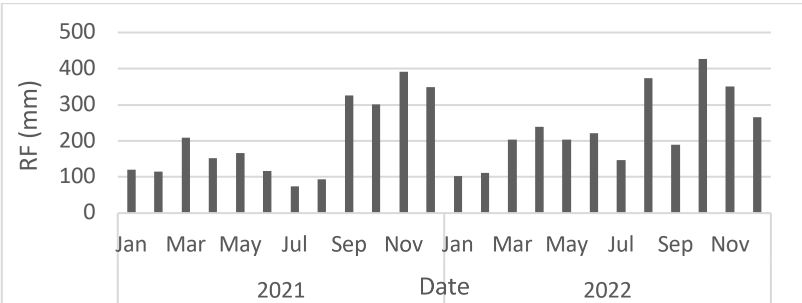


Fig. 7. Trend of rainfall in Kg. Bahru Pantai on 2021 and 2022

In 2021, the recorded rainfall within 24 hours prior to the water quality sampling dates showed no rainfall on June 12, June 13, and August 10. In 2022, similar zero-rainfall observations were noted on February 13, April 11, June 15, August 11 and 12, and October 10 and 13 (Figure 8). This resulted in 3 out of 11 sampling dates (27.27%) in 2021 and 7 out of 12 sampling dates (58.33%) in 2022 having no rainfall before water quality measurements. The highest rainfall was recorded on December 9, 2022 (66 mm), followed by April 8, 2021 (21 mm), and June 14 and December 12, which received 16 mm and 12.5 mm, respectively. Other sampling dates recorded less than 10 mm or no rainfall. The occurrence of rainfall events may contribute to the variability of water quality in the Batang Penar River. According to study Ling *et al.,* [23] the water quality index in Batang Baram improved as the concentration of dissolved oxygen increased following rain events. However, their study also found that total suspended solids in the river were affected by soil erosion after these rain events.

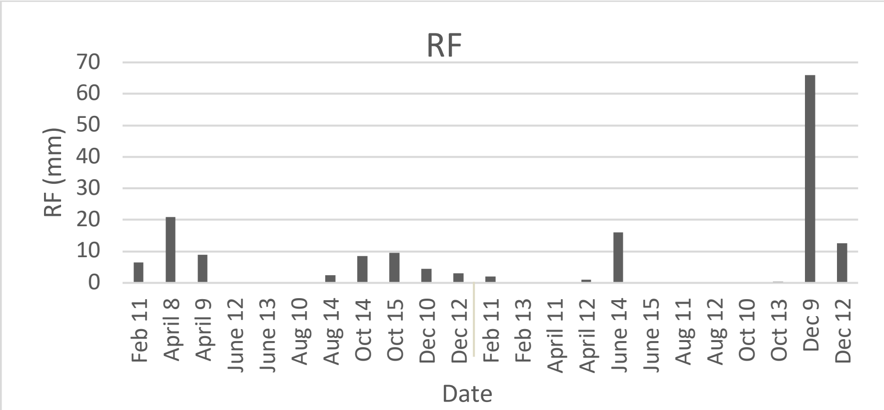


Fig. 8. Rainfall in 24 hours recorded before water quality sampling in Batang Penar River on 2021 and 2022

3.4 Summary of Water Quality Data

The statistical properties of the water quality parameter between the years 2021 and 2022 highlight the temporal variation of water quality in Batang Penar River between the years (Table 6). There are 4 water quality stations along the Batang Penar River, each contributing 6 samplings annually, giving a total of 24 samplings for each water quality parameter per year. Due to the small number of samples, the standard error of the mean is high for the data. For example, the TSS mean is 15.98 mg/L for 2021 and 18.65 mg/L for 2022. Based on the standard error of the TSS mean, it is 95% confident to state that the population mean of TSS in Batang Penar River falls within the range from 18.54 to 82.46 mg/L and from 62.26 to 136.86 mg/L for 2021 and 2022 respectively. Although the standard error and deviation of the sampling data are high, the data was accepted in this study as it is the only data available that can be acquired from DOE.

Table 6
Mean of water quality parameters of each station in Batang Penar River on 2021 and 2022

Station	Station no.	N	Year	Mean (mg/L)			
				TSS	BOD	COD	AN
Kg. Bahru Pantai	S1	6	2021	9.67	0.92	7.33	0.043
		6	2022	63.50	0.83	6.33	0.010
		12	-	36.58	0.88	6.83	0.026
Empangan Terip	S2	6	2021	1.50	0.67	6.33	0.015
		6	2022	1.42	0.67	4.67	0.011
		12	-	1.46	0.67	5.50	0.013
Jambatan	S3	6	2021	109.33	1.00	11.83	0.020
Jab. Haiwan Pantai		6	2022	153.17	0.67	9.67	0.036
		12	-	131.25	0.83	10.75	0.028
Jambatan	S4	6	2021	81.50	2.33	17.00	0.327
Jln. K. Kelawang		6	2022	180.17	1.50	19.33	0.080
		12	-	130.83	1.92	18.17	0.203
All	-	24	2021	50.5	1.23	10.63	0.100
		24	2022	99.56	0.92	10.00	0.030

Based on the water quality data acquired, samplings in 2021 measured a higher mean for BOD (1.23 mg/L), COD (10.63 mg/L), and AN (0.10 mg/L) as compared to 2022 (0.92, 10.00, 0.03 mg/L), while sampling in 2022 measured a higher mean for TSS (99.56 mg/L) as compared to 2021 (50.5 mg/L). This indicates that the recorded level of BOD, COD, and AN is higher while the recorded TSS level is lower in 2021 as compared to 2022. Hence, this may indicate that nutrient pollution will be higher during 2021 while sedimentation will be higher in 2022.

In comparing the mean of water quality parameters from 2021 to 2022 for each station, the mean TSS level for each station is higher in 2022 as compared to 2021, except for the S2 station recorded with lower value in 2022 (Table 6). This may result from the additional sediment supply from the landslide scars that were generated on December 18, 2021, which did not influence the Terip Dam. The means of BOD level of all stations show a dropping except for the S2 station which recorded with a constant mean from 2021 to 2022. The means of COD level decreased from 2021 to 2022 for all stations, except the S4 station which recorded an increment. Lastly, the means of AN level of all stations decreased from 2021 to 2022 except for the S3 station which shows an increment.

As compared to the mean of water quality parameters between stations, the S4 station recorded the highest means value for BOD, COD, and AN, which indicates the highest level of pollution for organic matter, chemicals and ammonia respectively as compared to other stations. This is similar to the findings in Pinang River [19] in which water quality was dropped in the lower stream due to the higher pollution from the urban, industrial, and agricultural areas. The S2 station recorded the lowest mean values for TSS, BOD, COD, and AN, which indicates that the water quality is the highest as compared to the other stations. This may be due to the minimum pollutant supplies in the protected catchment of Terip Dam, where the S2 station was measured.

3.5 Trend of Water Quality (2021-2022)
3.5.1 Total Suspended Solids (TSS)

The trend of water quality over time shows some spatial and temporal variation between stations and throughout the timeline. As shown in Figure 9, the TSS level recorded in Terip Dam (S2) stays constant in Class I, ranging from 0.5 to 5 mg/L. In addition, the TSS level was recorded in Jambatan Jab. Haiwan Pantai (S3) and Jambatan Jln. K. Kelawang (S4) show a similar trend throughout the study period, varied from Class II to V, with most of the TSS value recorded in S4 higher than that in S3. The TSS level recorded in Kg. Bahru Pantai (S1) shows a lower level as compared to S3 and S4, varied from Class I to III, except during October 2022, while showing a higher level as compared to S2 most of the time.

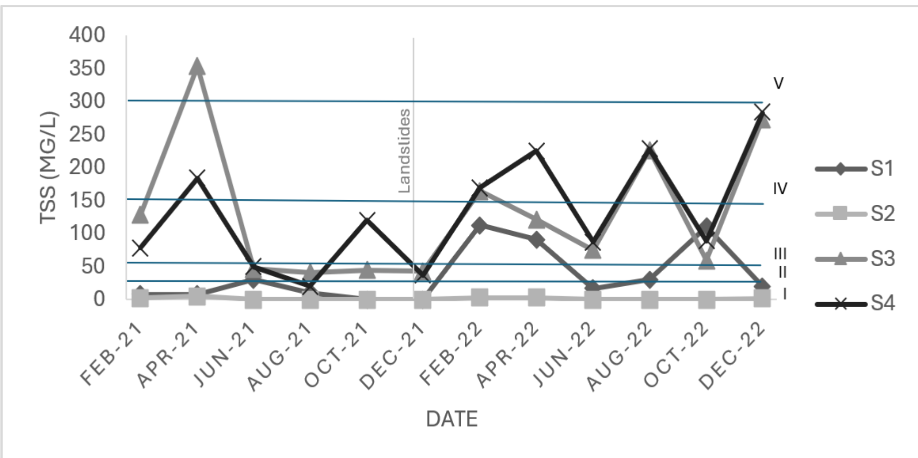


Fig. 9. Trend of total suspended solids in Batang Penar River on 2021 and 2022, with labelling of Water Class (I, II, III, IV, V) according to NWQS, DOE

The factors of variation in the trend between water quality stations include the location of the sampling stations. S1 station is located in the upper stream of Batang Penar River, S2 is within the Terip Dam at the middle path of the river, while S3 and S4 are sampling close to each other at the lower part of the catchment (Figure 6). The low TSS level recorded in S2 (Class I) indicates that the sediment amount in the water of Terip Dam is at low concentration, as the water flow in the dam is slow and calm. According to Southard (2006), the amount of sediments suspended in a water body increases with the stream flow rate. In addition, the locations of the S3 and S4 stations downstream of the S1 station cover a larger catchment area and consist of longer drainage lengths. The positive correlation of sediment yield with total drainage length might be due to the lower sediment deposition rate, increased stream erosion, and lower infiltration of runoff at longer drainage lengths [24].

TSS levels recorded in S1 in 2021 fall within Class I, except in June 2021, which falls in Class II. In 2022, the value record varied from Class I to III. In the S2 station, the TSS recorded was fall in Class I throughout the period. Next, the S3 station recorded TSS levels that fell in Class III and V in February and April respectively, followed by a TSS level fall in Class II in the later samplings of 2021. In 2022, the TSS level varied from Class III to IV. Lastly, the TSS level in the S4 station varies from Class I to IV in 2021, and from Class II to IV in 2022.

The temporal variation of the TSS level trends in S1, S3, and S4 shows that Batang Penar River was mostly higher in TSS level in 2022 as compared to 2021. This may be due to the occurrence of the landslides on December 18, 2021, which contributed to the suspended solid and sediment yield increment in Batang Penar River. In addition, this variation in TSS level may be due to the variation in rainfall amount and intensity before the data collection. However, the changing of land use and land cover in the upper stream area before the S1 station from agricultural fields into forest land may influence the sediment yield by reducing sediment from agricultural practice. According to study [25], the formation of a broad platform terrace and cutting of natural slope is a major source of soil erosion from the vegetable production in Cameron Highlands. Therefore, the ceasing of agriculture practices followed by forest restoration can reduce sediment yields and water pollution.

3.5.2 Biochemical Oxygen Demand (BOD)

In terms of spatial variation, there is no significant visual difference between the BOD level trend of the stations, which varies from Class I to II, except a BOD level of Class IV recorded in Oct 2021 in the S4 station (Figure 10). The high BOD level indicates the increment of oxygen demand for the decomposing of organic matter in the Batang Penar River. This may be due to the discharge of waste material or effluent that is high in organic matter from the industrial area in the catchment of the S4 station during the sampling date, as it is the only catchment consisting of an industrial area (Figure 5).

In 2021, the biochemical oxygen demand (BOD) levels at the S1 station generally fell within Class I, with the exception of June, which recorded Class II. A similar trend was observed in 2022, except for April, which also fell into Class II. The S2 station consistently maintained Class I BOD levels throughout both years. At the S3 station, BOD levels remained in Class I, except for June 2021, which recorded Class II. Conversely, the S4 station exhibited a range of BOD classifications from Class I to IV in 2021, and Class I to II in 2022, with notably high BOD levels in October 2021. Overall, there were no significant trends indicating the impact of the December 18, 2021 landslide event on BOD levels in the Batang Penar River, suggesting that temporal variations were likely influenced by rainfall amounts and intensities prior to sampling.

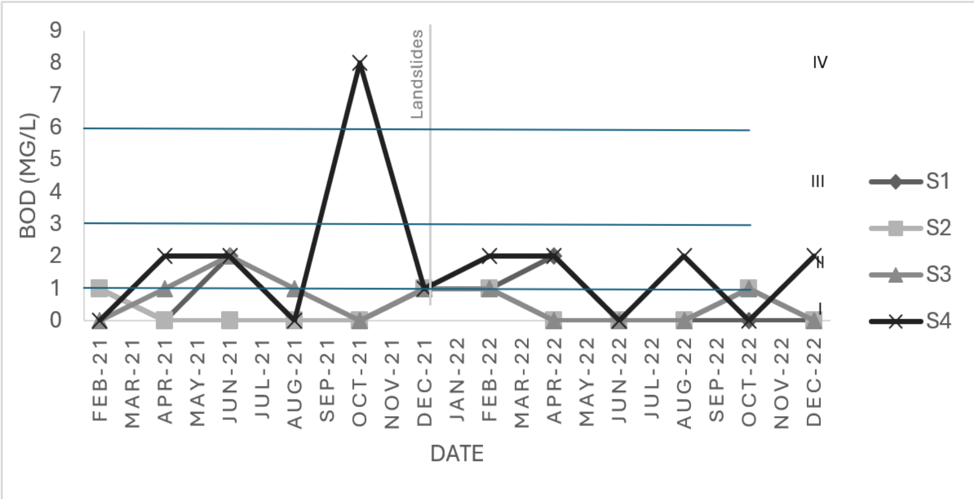


Fig. 10. Trend of biochemical oxygen demand in Batang Penar River on 2021 and 2022, with labelling of Water Class (I, II, III, IV) according to NWQS, DOE

3.5.3 Chemical Oxygen Demand (COD)

Regarding chemical oxygen demand (COD), the S4 station consistently recorded higher levels, ranging from Class I to III, except in February and April 2021, when it was lower than that at S3 (Figure 11). The elevated COD levels at S4 can be attributed to its position at the lowest point of the stream, where chemical pollutants accumulate. The S3 station typically showed higher COD levels than S1, likely due to the greater concentration of pollutants from agricultural and residential areas downstream. This aligns with findings from the Utrata River in Poland, where increased COD levels were linked to pollutant accumulation from agricultural runoff and municipal discharges [26]. The S2 station recorded the lowest COD levels most frequently, likely due to the clean water inflow from the protected watershed area, primarily covered by forest.

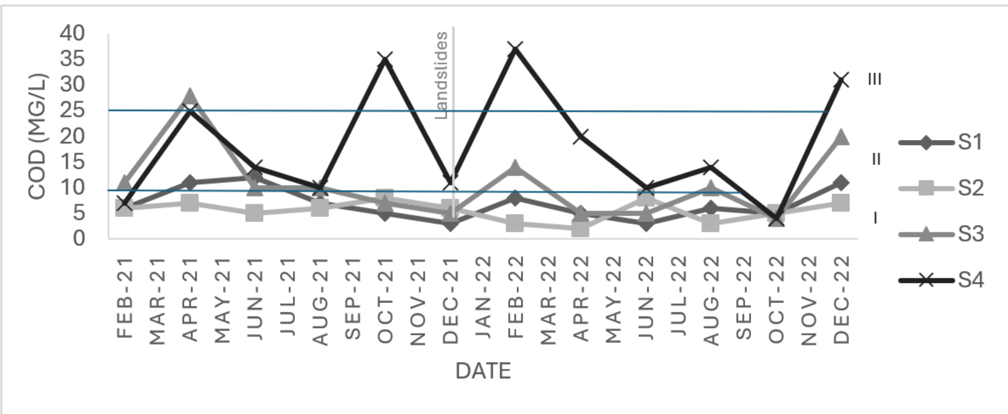


Fig. 11. Trend of chemical oxygen demand in Batang Penar River on 2021 and 2022, with labelling of Water Class (I, II, III) according to NWQS, DOE

The chemical oxygen demand (COD) levels at S3 and S4 stations exhibited similar variations throughout the sampling periods, except in October 2021, when S3 recorded a lower level compared to prior samples, while S4 showed an increase. S1 also displayed a similar trend, with a notable rise in June 2021. In contrast, S2's COD levels remained consistently within Class I with a gradual variation. The observed temporal variations are likely influenced by rainfall patterns and pollutant inputs from agricultural runoff and municipal discharges. Interestingly, all four stations recorded similar COD levels in October 2022, with S1 and S2 at 5 mg/L and S3 and S4 at 4 mg/L, suggesting that factors beyond drainage distance and chemical pollution, such as solid waste concentration and bacterial decomposition, may also play a role [27].

3.5.4 Ammoniacal Nitrogen (AN)

For ammoniacal nitrogen (AN), all stations remained within Class I, except for S4, which fluctuated between Class I and IV, consistently showing the highest AN levels (Figure 12). S3 followed with the second-highest levels, except in early and late 2021, when S1 surpassed it. Variations in AN levels among stations are attributed to their locations, with S1 being upstream, S2 located in Terip Dam, and S3 and S4 positioned downstream. Additionally, land use type along the stream significantly impacts nitrogenous pollutant accumulation, with agricultural, industrial, and urban areas contributing more than grassland or forested regions [28]. Consequently, the highest AN levels were recorded at S4 due to drainage from the surrounding industrial area [29].

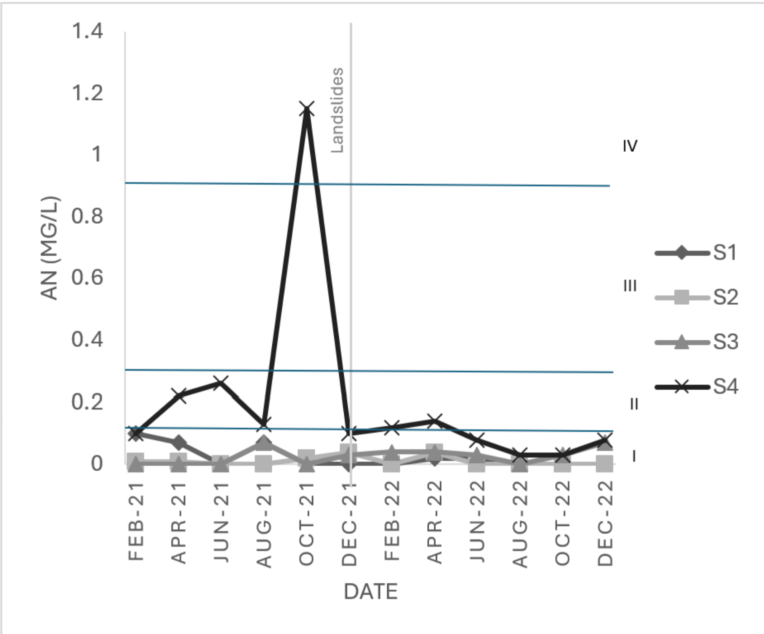


Fig. 12. Trend of ammoniacal nitrogen in Batang Penar River on 2021 and 2022, with labelling of Water Class (I, II, III, IV) according to NWQS, DOE

According to Figure 12, the AN level ranged in Class I throughout the period among the stations, except the S4 station which ranged from Class I to IV in 2021, and Class I to II in 2022. This may indicate that the concentration of ammoniacal pollutants is higher in 2021 as compared to 2022 resulting from the catchment of the S4 station. On another hand, the AN level in the S1 station in 2021 is higher as compared to 2022. This variation may be due to the land use land cover change, as the land use in the proximity of S1 was changed from the agricultural field into a forest area from 2021 to 2022 (Figure 5), which caused a reduction in agricultural runoff and sewage discharge to the river stream.

For the period from December 2021 to August 2022, the AN levels of S1, S3, and S4 show some similar increments and decreases between the sampling dates. This similarity indicates some factors of AN level that are shared by the three stations, such as rainfall amount and intensity. The high level in AN level at the S4 station in October 2021 is coherent with the BOD level recorded. This may indicate that there is some correlation between AN and BOD levels. The correlation between AN and BOD levels can be explained by the activity of nitrifying bacteria and microorganisms that consume dissolved oxygen to oxidise ammonia into nitrite and nitrate (EPA, 2023).

3.6 T-test Analysis of Water Quality Parameters

The T-test analysis was conducted to examine the difference in the mean of water quality parameters of 2021 and 2022, excluded samplings of the S2 station that were independent of the landslide events. There is a significant difference between the mean of TSS of Batang Penar River in 2021 and 2022, while there is no significant difference in BOD, COD, and AN (Table 7). This indicates that the TSS level was changed after the landslide events on December 18, 2021, while there is no influence of landslides on the other three water quality parameters. This shows that the landslide events have influenced the water quality in Sg. Batang Penar by increasing the sediment supply, while the variation of BOD, COD and AN levels may originate from other environmental and climatic factors, such as the variation of rainfall and land use land cover. As discussed by study [30], landslides can contribute to sediment supply by the subsequent fluvial action on the landslide flow path and scars with soil erosion during rainy events.

Table 7
T-test analysis of the water quality parameters in Batang Penar River on 2021 and 2022

Parameter	Mean		Variance	t	Critical point (one-t)	Critical point (two-t)	P (one-tailed)	P (two-tailed)
	2021	2022						
TSS	66.833	132.28	Unequal	-2.285	1.6909	2.0322	0.0143*	0.0287*
BOD	1.23	0.92	Equal	0.9479	1.7171	2.0739	0.1767	0.3535
COD	10.63	10.00	Equal	0.0910	1.6909	2.0322	0.4640	0.9280
AN	0.10	0.03	Unequal	1.3867	1.7341	2.1009	0.0912	0.1825

Significance level: $\rho < 0.05$
* Correlation is significant at the 0.05 level (one- and two-tailed)

3.7 Correlation between Water Quality and Rainfall
3.7.1 Simple Linear Regression (SLR)

The simple linear regression (SLR) model was developed in between rainfall and water quality parameters as shown in Figure 13 to Figure 16. However, based on the validation with the t-statistic of the slope, the slope of all of the SLR models is not significantly different from zero. Therefore, there is no sufficient evidence to conclude that the slope calculated can significantly estimate water quality parameters by using rainfall value. This may be due to the low number of samples per water quality parameters (n = 18), as a false null hypothesis may not be rejected due to the small sample that is unable to indicate the significance difference [31]. Nevertheless, the low R2 value indicates there might be other confounding factors influencing the correlation between rainfall and water quality, such as variation due to monsoon and temperature. Hence, this suggests that a multivariate regression analysis should be conducted to identify and control the confounding factors while studying the relationship between rainfall and water quality parameters.

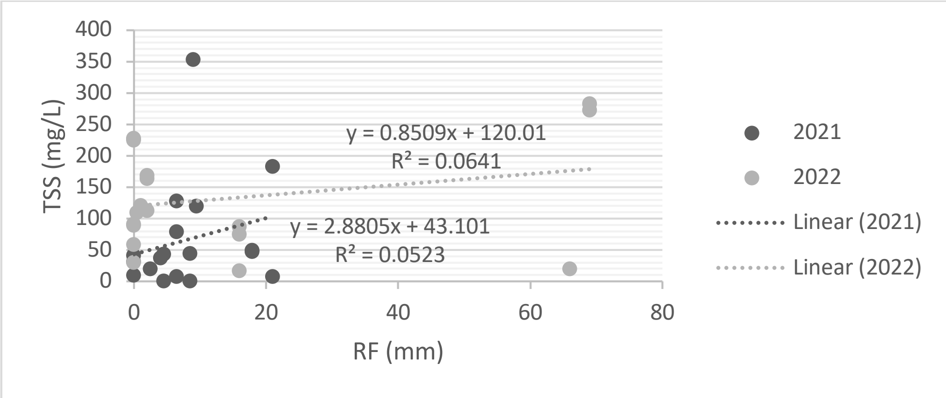


Fig. 13. The simple linear regression between total suspended solids (TSS) and rainfall (RF) amount in Batang Penar River on 2021 and 2022

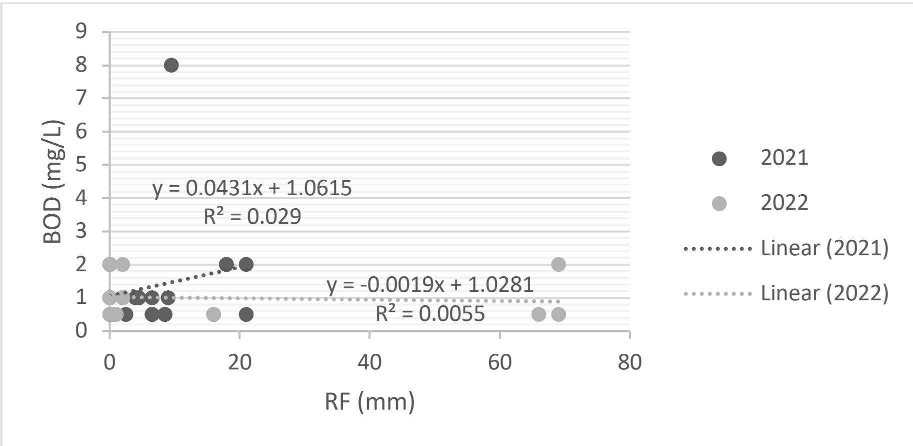


Fig. 14. The simple linear regression between biochemical oxygen demand (BOD) and rainfall amount (RF) in Batang Penar River on 2021 and 2022

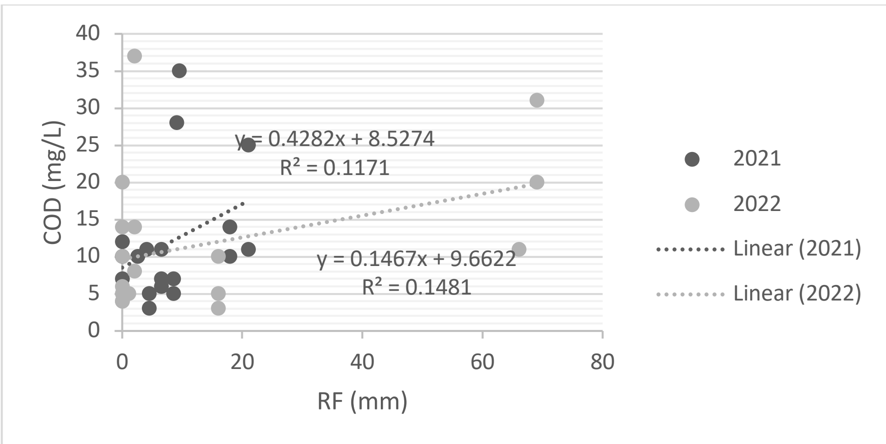


Fig. 15. The simple linear regression between chemical oxygen demand (COD) and rainfall amount (RF) in Batang Penar River on 2021 and 2022

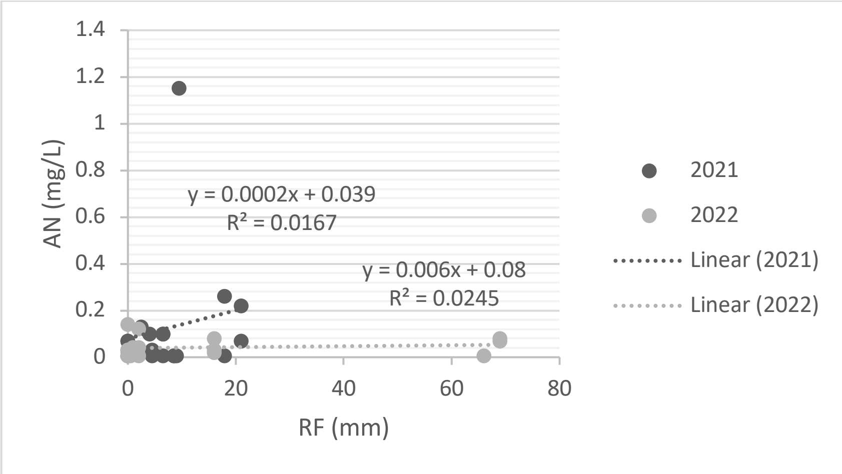


Fig. 16. The simple linear regression between ammoniacal nitrogen (AN) and rainfall amount (RF) in Batang Penar River on 2021 and 2022

3.7.2 Pearson Product Moment of Correlation Coefficient

The rainfall shows no significant correlation with all water quality parameters in both year 2021 and 2022, suggesting there is no influence of rainfall on water quality of the river According to study by Salih *et al.,* [32] high rainfall intensity can saturate soils, thereby elevating the risk of landslides. The sediments generated from these landslides directly contribute to increased Total Suspended Solids (TSS) levels in rivers. However, this contradicts with the current study, as rainfall shows no significant correlation with sedimentation. The increment of TSS detected from 2021 to 2022 may be due to the disturbance in the river, i.e., construction in the vicinity of the river and river sand dredging. The rainfall and BOD are weak positive correlated and weak negative correlated in 2021 and 2022 respectively (Table 8 and 9). The difference in correlation direction indicates that other factors influence the BOD level besides rainfall amount. As stated in study by Chen *et al.,* [33] the main factor influencing BOD is the biological properties of water, rather than physical properties. The relationship between rainfall and COD level and rainfall with AN level is positively correlated.

On the other hand, rain intensity shows a significant correlation with TSS in 2021. This may indicate the sedimentation increased when the rain intensified. As the finding in the study [34], higher sediment loss was observed along with the higher rain intensity. However, the relationship became insignificant in 2022, indicating there are other stronger influences on TSS. TSS and COD show an intermediate positive relationship in both of the years, which indicates there is some influence of TSS towards the COD level in the river stream. The content of natural organic matter in the suspended solid can influence the COD level of natural water, especially when the concentration of the suspended solid is high [35]. Besides, COD also shows an intermediate and strong positive relationship with BOD levels in 2021 and 2022 respectively. This is because BOD and COD both include measurement of oxygen demand for decomposition of organic matter, which varied with the presence of organic matter [36]. Lastly, BOD and COD show an intermediate positive correlation with AN, which can be explained by the increment of pollution from urban, industrial and agricultural runoff that occurred concurrently due to the rainfall events. This increases the demand for oxygen for nitrification of ammonium ions to nitrate ions in the river water [37].

The correlation between rainfall amount with rain intensity, TSS, and COD are not significant in both years before and after the landslides (Table 9 and 10). This indicates the increment of sedimentation from 2021 to 2022 was not contributed directly by the landslides on December 18, 2021. Hence, this suggests the occurrence of landslides has no impact on the water quality in Batang

Penar River, while new sources of sedimentation arise or or and other sources of sedimentation exacerbate throughout the study period.

Table 8
Pearson Product Moment of Correlation Coefficient between each rainfall and water quality parameters in 2021

2021	RF	RI	TSS	BOD	COD
RF					
RI	.4564				
TSS	.2287	.5404*			
BOD	.1704	(-) .1412	.1966		
COD	.3422	.2512	.7405*	.7307*	
AN	.1565	(-) .0704	.1498	.9376*	.7051*

*Correlation is significant at the 0.05 level (2-tailed)

Table 9
Pearson Product Moment of Correlation Coefficient between each rainfall and water quality parameters in 2022

2022	RF	RI	TSS	BOD	COD
RF					
RI	.9611*				
TSS	.2533	.1919			
BOD	(-) .0743	(-) .0697	.4904*		
COD	.3849	.3705	.6795*	.6187*	
AN	.1291	.0534	.5165*	.5370*	.7470*

*Correlation is significant at the 0.05 level (2-tailed)

3.8 Limitations of the Study
3.8.1 Missing data estimation

The estimation of missing data with a single reference from a nearby rainfall station in this study posed uncertainty in the rainfall amount from May to August 2021. The rainfall amount estimated was highly dependent on the reading in the Kg. Tanjung Limau station and the regression between rainfall in the study station and reference station was explained by 20.68% in the estimation model. Nevertheless, the specific rainfall data that is required for analysis and being influenced by this estimation is the rainfall 24 hours before water quality measurement in June and August 2021, which contributes to 2 out of 12 measurements (16.67%). Hence, the impact of uncertainty in missing data estimation was limited to a minor part of the study and could be accepted in the overall analysis.

3.8.2 Study period

The study period involved two complete annual cycles from January to December 2021 and 2022. However, this relatively short study period as compared to the usual practice of 5 to 10 years in hydrological analysis constrains the temporal variation to only a single year pre- and post-landslide. The constrained temporal variation excludes the impacts of annual rainfall varied due to the global climate pattern and the long-term effects of land use and land cover changes on water quality variations, i.e. recovery of vegetation from conversion of agricultural field to forest land. Therefore, the result and conclusion of this study could only present a short-term impact of landslide towards water quality variation in a water catchment, meanwhile, the uncertainty of long-term variation may persist.

3.9 Implication of the Study

The landslide events in this study occurred in the hilly and mountainous region of Batang Penar Catchment up to 900 m above sea level. There is one-third of the land terrain in Peninsula Malaysia characters with hills and mountains, range at the central axis of the Peninsula Malaysia [38]. In Eastern Malaysia, the hilly and mountainous region spread mainly in the middle of Borneo, forming the territory boundaries between Malaysia and Indonesia. The hilly regions contribute to the water catchments in Malaysia for water supply and hydropower generation, e.g. Kenyir Lakes in Hulu Terengganu. In addition, these catchments are mostly protected areas prohibited from public intrusion and forest production activities. Therefore, the occurrence of landslides in their protected forest is the main disturbance to the watershed. The impacts of the landslide in these regions towards the lower stream water quality considering land use land cover along the drainage could be demonstrated by this study.

On the other hand, the study catchment was located in the humid tropical region, covered with a hill Dipterocarp ecosystem in the upper region and primarily agricultural land in the lower region. The reviews on studies in highland areas, specifically in Cameron Highland, on land use land cover changes were discussed in the study [39]. The conversion of forest to agricultural land contributes is the main cause of water quality deterioration in the Cameron Highland, due to the increasing runoff and pollution from agricultural chemical usage. This was similar to the study in the lower region where the pollution in drainage increased after passing through the farming regions. However, the participation of landslides in water quality pollution was not discussed in the previous study. The study on sediment budget [40] found that the episodic landslide contributes far more sediments than the slopewash, soil creep, and tree throw. This agreed with the current study in which total suspended solid concentration is higher after the landslide events.

4. Conclusion

The analysis of rainfall and land use in the Batang Penar Catchment from 2021 to 2022 provides critical insights into water quality dynamics following the landslide event on December 18, 2021. Rainfall data indicates a consistent increase in both rainy days and total annual rainfall, with notable peaks aligning with the Southwest and Northeast monsoon seasons. The December 18 landslide, corresponding to the highest daily rainfall, significantly impacted sediment levels, especially Total Suspended Solids (TSS), with a marked increase in 2022 across all water quality stations except S2. In contrast, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Ammoniacal Nitrogen (AN) saw decreases in 2022, suggesting a shift from nutrient pollution in 2021 to sediment-dominated loads. This distinction underscores the landslide's direct impact on sedimentation without markedly affecting other water quality parameters.

Spatial analysis shows that each water quality station exhibits unique variations based on land use, catchment area, and drainage length before reaching each site. The S4 station consistently recorded the highest levels of BOD, COD, and AN, likely due to industrial effluents, while S2, situated within the protected Terip Dam, had the lowest values, highlighting the positive influence of protected upstream areas on water quality. Notably, TSS levels were significantly higher in 2022 than in 2021, corroborated by T-test results, while BOD, COD, and AN showed no significant temporal variation, affirming that the landslide’s sediment increase was not mirrored in organic and chemical pollutants.

Contrary, correlation analysis of rainfall and water quality parameters reveals no significant correlation, countering the role of rainfall and landslides in intensifying sediment loads. This indicates these parameters are more influenced by pollutant sources from land use and other disturbance rather than rainfall and landslides. The positive correlations between TSS and COD, and between BOD and COD, underscore a shared influence of organic matter and chemical oxygen demand within the suspended sediments. This emphasize the higher impacts of land use as the source of sedimentation and pollution in the catchment. The study thus concludes that the December 18, 2021 landslide contributes no significant impact to the sedimentation and water quality indicators of Batang Penar River.

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