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Research Article

Assessment of the Water and Sediment Quality of Tropical Forest Streams in Upper Reaches of the Baleh River, Sarawak, Malaysia, Subjected to Logging Activities

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The study of the impact of logging activities on water and sediment quality of Sarawak forest streams is still scarce despite Sarawak being the largest exporter of timber in Malaysia. This study was aimed at determining the water and sediment quality of forest streams in Sarawak and the potential impact of logging activities. *In situ* parameters were measured, and water and sediment samples were collected at six stations before rain. Additionally, water quality was investigated at three stations after rain. The results showed that canopy removal resulted in large temperature variation and sedimentation in the forest streams. Lower suspended solids were found at stations with inactive logging (<2 mg/L) compared to active logging (10–16 mg/L) activities. The highest concentration of total nitrogen and total phosphorus in water and sediment was 4.4 mg/L, 77.6 μg/L, 0.17%, and 0.01%, respectively. Besides, significantly negative correlation of sediment nitrogen and water total ammonia nitrogen indicated the loss of nitrogen from sediment to water. Water quality of the streams deteriorated after rain, in particular, suspended solids which increased from 8.3 mg/L to 104.1 mg/L. This study reveals that logging activities have an impact on the water quality of Sarawak forest streams particularly in rainfall events.

1. Introduction

Sarawak is the largest state in Malaysia with about 70% of the state categorized as forested land. Sarawak's forestry plays a significant role in its socioeconomic development. In 2012, the export earnings from timber and timber products in Sarawak were 2.4 billion USD [1]. The majority of Sarawak forests are subjected to logging which has been a major contributor to the Malaysian economy. It has been reported that Sarawak exported a total of 1,388,894 m^3 of logs worth 244 million USD from January to June 2015, contributing 88.7% compared to Sabah's 10.5% and West Malaysia's 0.8% [2]. The high production of timber renders deforestation problems in Sarawak. Deforestation and degradation of forests in Sarawak are occurring at a rate of 0.64% annually [3]. Nearly 80% of the land surface of Sarawak was impacted by previously undocumented, high-impact logging or clearing operations from 1990 to 2009 [4].

Deforestation often results in the degradation of water quality which includes an increase in temperature, sedimentation, and nutrient enrichment [5–9]. In Malaysia, soil loss from logging activities had been predicted to highlight the potential risk posed by logging within water catchment areas [10]. Besides, the amounts of sediment, wood, and detritus accumulations were examined in four headwater tributaries after timber harvesting in the Bukit Tarek Experimental

Watershed, Peninsular Malaysia [11]. Recently, [12] studied the effects of logging activities on ecological water quality indicators in the Berasau River, Johor, Malaysia. However, less attention has been paid to Sarawak forest streams despite the fact that Sarawak is the largest exporter of logs in Malaysia. Hence, the water and sediment quality of Sarawak forest streams that are subjected to logging activities were collected in order to investigate the potential impact of the logging activities on the streams.

The forest streams selected in the present study were located at the upper reaches of the main tributaries of Batang Baleh. Batang Baleh is one of the main tributaries of the Rajang River (551 km) which is the longest river in Malaysia. This river flows through the Kapit Division which is a mountainous region mostly (80%) covered by dense primary forests. Most of the 534 longhouses in the division are located along major rivers and tributaries of the Rajang River. Thus, the Rajang River and its tributaries are the main means of transportation in the division. A hydroelectric project has been proposed at Batang Baleh. Dam construction is often associated with environmental degradation and water quality deterioration [13–22]. However, different anthropogenic sources make it difficult to identify the pollution sources on the river once a dam is constructed, thereby making it rather complex to assess the true impact of dam construction alone. Hence, this study is necessitated to serve as baseline data for any potential mitigation measures if or where necessary, in the future.

2. Materials and Methods

2.1. Study Area and Sampling Stations. The study area is located at the hill forest land [23] characterized as mixed dipterocarp forest (MDF) and secondary forest in Sarawak, Malaysia [24]. The lands are covered mainly by the Red-Yellow Podzolic soils in the Sarawak classification system [25]. The Red-Yellow Podzolic soils of both river basins consist of sandstone and shale bedrocks from the Belaga and Nyalau Formations [26]. Annual rainfall as measured at Kapit (45 km from the study area) is among the highest ones found in Sarawak which exceeds 5000 mm in most years. There is usually an average of 250 days per year of measureable precipitation. Temperature is high throughout the year with a mean annual daily maximum temperature of 33°C [27]. Field sampling was carried out at the upper reaches of two main tributaries of Batang Baleh ("batang" denotes big river) (coordinates: 2°1′0″ N and 113°1′1″ E), namely, Sg. Gaat and Sg. Mengiong in Sarawak (Figure 1). All sampling stations were located at the upper reaches of the two tributaries. Station 1 was located at the right tributaries of Sg. Mengiong, namely, Sg. Ugak, while station 2 and station 3 were located at the left tributaries of Sg. Mengiong, namely, Sg. Meranu and Sg. Entajum. Station 4 was located upstream of Sg. Gaat while station 5 and station 6 were located at Sg. Marang and Sg. Ramong which are the right tributaries of Sg. Gaat. Presently, the study area is subjected to extensive land use activities from commercial timber harvesting, *Acacia* tree plantation, and subsistence farming. Land use activities nearby each of the sampling stations are given in Table 1. In addition, station coordinates, sampling regime, and weather condition during sampling were also included in Table 1.

2.2. Field Collection and Laboratory Analysis. Water quality was investigated by measuring *in situ* parameters and, for *ex situ* analyses, water and sediment samples were collected at six sampling stations (stations 1–6) on a sunny day while the *in situ* parameters measurement and water samples were collected at three sampling stations (stations 4–6) after a rainfall event (Table 1). *In situ* parameters including temperature, pH, and conductivity were measured using a pH meter (Orion 3 Star, Thermo Scientific) and a microprocessor pH meter (TI9000, Walklab), respectively. Dissolved oxygen (DO), turbidity, transparency, depth, and flow velocity were measured using a DO meter (ExStik® II, Extech EC600), a turbidity meter (Mi415, Milwaukee), a Secchi disc with measuring tape, a depth sounder (PS-7, Hondex), and a stream flowmeter (Geopacks), respectively.

Triplicate water samples were taken for the analysis of chlorophyll *a* (chl-*a*), total suspended solids (TSS), five-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total nitrogen (TN), total ammonia nitrogen (TAN), nitrite nitrogen (NO_2^--N), nitrate nitrogen (NO_3^--N), total phosphorus (TP), soluble reactive phosphorus (SRP), and total sulphide (TS). All sampling bottles were acid-washed, cleaned, and dried before use. Sediment samples were kept in sediment plastic bags for the analysis of sediment pH, water content, organic matter (OM), total organic carbon (TOC), total phosphorus (TP), and total nitrogen (TN). Analysis of BOD_5, TAN, NO_2^--N, NO_3^--N, SRP, and TS was conducted in the field immediately after sampling. Water samples (acidified to pH < 2) and sediment samples were placed in an ice box and transported to the laboratory for further analysis [28].

For water analysis, the triplicate samples were composited prior to analyses. All water analyses were performed according to standard procedures in triplicate unless otherwise mentioned [28, 29]. Concentrations of chl-*a* were determined from adequate samples filtered through 0.7 μm glass fibre filter (Sartorius Stedim MGF) and extracted for 24 h using 90% (v/v) acetone. TSS were assayed as the difference between initial and final weight of the 1.2 μm retention glass fibre filter (Sartorius Stedim MGC), after filtration of an adequate sample volume and drying at 105°C. BOD_5 was determined as the difference between initial and five-day DO content, after five-day incubation of the undiluted sample. COD was determined by closed reflux titrimetric method [28]. TN and TAN were determined by persulfate method and Nessler's method, respectively [28]. NO_2^--N and NO_3^--N were determined by diazotization method (low range) and cadmium reduction method, respectively [29]. Water sample was filtered through a 0.7 μm glass fibre filter (Sartorius Stedim MGF) prior to the analysis of TAN, NO_2^--N, and NO_3^--N. TP was determined by ascorbic acid method after persulfate digestion of samples [28]. SRP was determined by the colorimetric ascorbic acid method [29] after filtration

Table 1: The sampling regime and description of the six stations surveyed in the present study.

Station	Date	Weather	Description of the sampling station
Station 1: Sg. Ugak N 01° 38′ 46.1″ E 113° 07′ 47.1″	6/8/2014	Sunny	Old secondary forest with partly open canopy cover Profuse sedimentation and heavy erosion on riverbanks Presence of logging activities
Station 2: Sg. Meranu N 01° 30′ 57.4″ E 113° 14′ 41.4″	6/8/2014	Sunny	Old secondary forest with partly open canopy cover Slight bottom sedimentation Presence of logging activities and replantation
Station 3: Sg. Entajum N 01° 33′ 37.8″ E 113° 05′ 01.2″	7/8/2014	Sunny	Old secondary forest with open canopy cover Presence of riparian vegetation, trees, grasses, shrubs, and herbs Slight bottom sedimentation Inactive logging activities
Station 4: Sg. Gaat N 01° 38′ 54.0″ E 113° 04′ 53.6″	6/8/2014 8/8/2014	Before rain with thunder Raining	Old secondary forest with open canopy cover Slight bottom sedimentation Presence of logging activities
Station 5: Sg. Marang N 01° 38′ 04.7″ E 113° 05′ 21.8″	7/8/2014 8/8/2014	Sunny Raining	Old secondary forest with open canopy cover Inactive logging activities Replantation of softwood
Station 6: Sg. Ramong N 01° 38′ 49.7″ E 113° 07′ 48.6″	7/8/2014 8/8/2014	Sunny Raining	Old secondary forest with open canopy cover Slight bottom sedimentation Active logging activities at approximately 5 km upstream

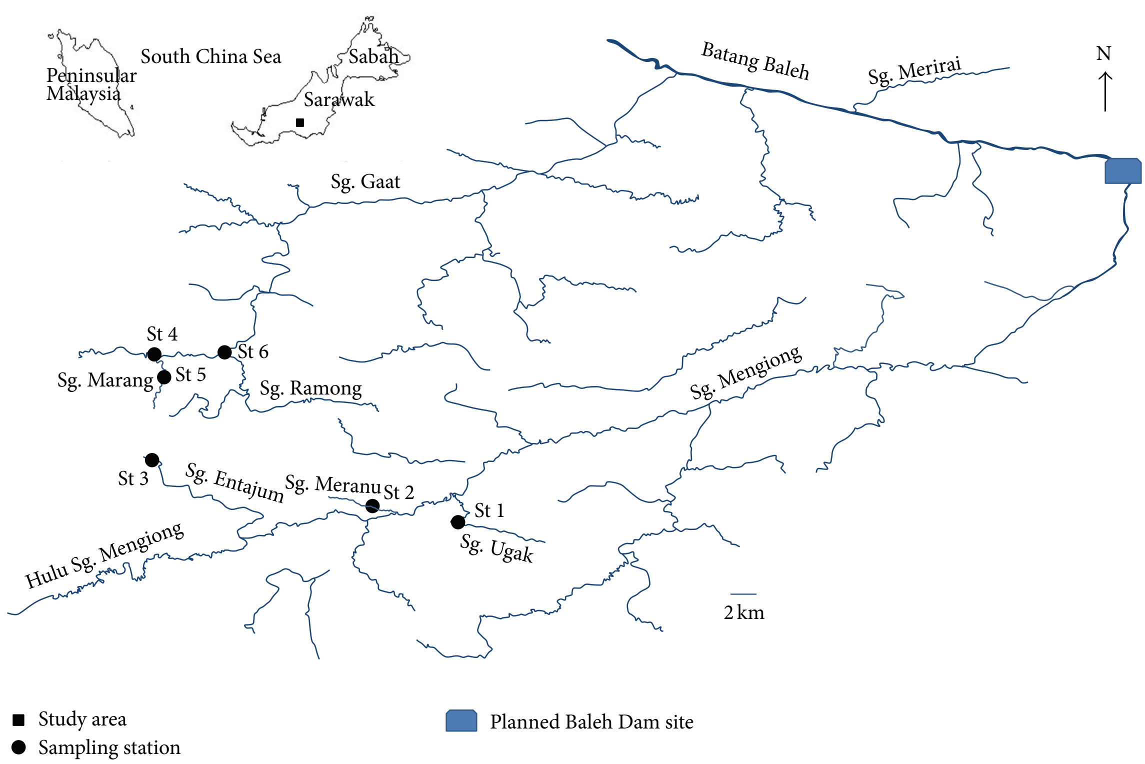


Figure 1: The study area in Sarawak state and location of the sampling stations in the present study.

through a 0.45 μm cellulose acetate membrane filter (Sartorius Stedim). TS was analyzed using the methylene blue method [29]. H_2S was calculated according to [28] with the following equation:

$$H_2S = \frac{TS}{10^{pH\text{-}pK'}} + 1, \quad (1)$$

where H_2S is unionized hydrogen sulphide, TS is total sulphide, and pK' is conditional first dissociation constant of hydrogen sulphide for freshwater.

Calibration curve was constructed for each chemical analysis. Blank and standard solutions were treated in a similar way as the sample. The detection limits for TAN, NO_2^--N, NO_3^--N, TN, SRP, TP, and TS were 0.097 mg/L, 0.01 mg/L, 0.01 mg/L, 0.335 mg/L, 3 μg/L, 12 μg/L, and 0.01 mg/L, respectively.

For sediment analysis, pH value of sediment was determined from a mixture of 10 g of air-dried sediment sample and 10 mL of deionized water [30]. After 10 minutes of stirring, the pH was measured from the suspension by using a pH meter (Orion 3 Star, Thermo Scientific). Water content of a sediment sample was assayed as the difference between initial and final weight of the sediment after drying at 105°C [31]. Sediment samples were air-dried and sieved using a <0.5 mm sieve for the determination of OM, TOC, TP, and TN. Organic matter and TOC were determined by loss-on-ignition method and Walkley-Black method, respectively [32]. Total phosphorus was determined by ascorbic acid method after perchloric digestion of samples [33]. Total nitrogen was determined by cadmium reduction method [29] after persulfate digestion of samples [28]. Calibration curve was constructed for TP and TN analyses. Blank and standard solutions were treated in a similar way as the sample. Particle size analysis was done according to the pipette method of [34].

2.3. Water Quality Index (WQI). Water quality index (WQI) which combines the six variables of DO, BOD, COD, TSS, AN, and pH was calculated according to the equation of department of environment [35]:

$$\begin{aligned} WQI = {} & 0.22 * SI_{DO} + 0.19 * SI_{BOD} + 0.16 * SI_{COD} \\ & + 0.15 * SI_{AN} + 0.16 * SI_{SS} + 0.12 * SI_{pH}, \end{aligned} \quad (2)$$

where SI indicates the subindex for each parameter, SI_{DO} is subindex DO (% saturation), SI_{BOD} is subindex BOD (mg/L), SI_{COD} is subindex COD (mg/L), SI_{AN} is subindex AN (mg/L), SI_{SS} is subindex SS (mg/L), and SI_{pH} is subindex pH.

2.4. Statistical Analysis. All data were tested for normality and equality of variance with Shapiro-Wilk test and Levene's test, respectively. The nonparametric test was used in the subsequent statistical analysis due to the violation of the normal distribution and equal variance assumptions of the parametric tests. The Kruskal-Wallis test was carried out to determine if there was any significant difference in the results between the six sampling stations. The Wilcoxon sign-rank test was used to compare the results between a sunny day before rain and that after rain. The Spearman rank correlation was used to determine the relationship among all the parameters. Cluster analysis (CA) was used to investigate the grouping of the six sampling stations. Z-score standardization of the variables and Ward's method using Euclidean distances as a measure of similarity were used. All the statistical analyses were carried out by the Statistical Software for Social Sciences (SPSS Version 22, SPSS, Inc., 1995).

3. Results

3.1. In Situ Water Quality Parameters. Figure 2 illustrates the *in situ* parameters collected at the six sampling stations. Station 4 which was located at the main stream of Sg. Gaat was the deepest station (72.7 ± 1.5 cm) with the highest flow rate (0.112 ± 0.001 m/s) compared to the other stations. Station 4 was significantly deeper than stations 1, 2, and 3 (p value ≤ 0.05) and the stream flow velocity was significantly faster than stations 3, 5, and 6 (p value ≤ 0.05). Besides, stations 1, 2, and 3 which were located at the tributaries of Sg. Mengiong were shallower than tributaries of Sg. Gaat, particularly, station 3, which was significantly shallower than station 5 (p value = 0.006) and station 6 (p value = 0.039).

Temperature of the streams ranged from 24.7 ± 0.2°C to 28.8 ± 0.3°C. Temperature at station 3 was significantly lower than stations 4, 5, and 6 (p value ≤ 0.05) while temperature of station 1 was significantly lower than stations 5 and 6 (p value ≤ 0.05). All the streams were generally well-aerated with the mean DO value of 6.8 mg/L. Dissolved oxygen at stations 1 and 4 was significantly higher than stations 3 and 5 (p value ≤ 0.05). The pH value of the streams ranged from 7.00 ± 0.02 to 7.74 ± 0.03. The highest pH value recorded at station 4 was significantly higher than stations 2, 3, and 6 (p value ≤ 0.05). Conductivity value of the streams ranged from 25.9 ± 0.1 μS cm^{-1} to 49.1 ± 0.6 μS cm^{-1}. The lowest value was recorded at station 1 whereas the highest value was recorded at station 4. The conductivity value at station 4 was significantly higher than stations 1, 2, and 6 (p value ≤ 0.05) whereas station 1 was significantly lower than stations 3, 4, and 5 (p value ≤ 0.05). All the streams were clear as indicated by the low turbidity and high transparency values. The turbidity value ranged from 1.5 ± 0.0 NTU to 7.7 ± 0.0 NTU while the transparency value was almost the same with the depth of the stream except for station 5 and station 6.

3.2. Ex Situ Water Quality Parameters. Figure 3 illustrates the *ex situ* water quality parameters of the six sampling stations in the present study. The lowest and the highest chl-*a* concentrations were found at station 1 (0.3 ± 0.1 mg/m^3) and station 3 (2.3 ± 0.1 mg/m^3), respectively. Chlorophyll *a* at station 1 was significantly lower than stations 3, 5, and 6 (p value ≤ 0.05) while chl-*a* at station 3 was significantly higher than stations 1, 2, and 4 (p value ≤ 0.05). Total suspended solids were low at stations 3 and 5 (≈2 mg/L) and the highest TSS was found at station 1 (16.3 ± 1.5 mg/L). Total suspended

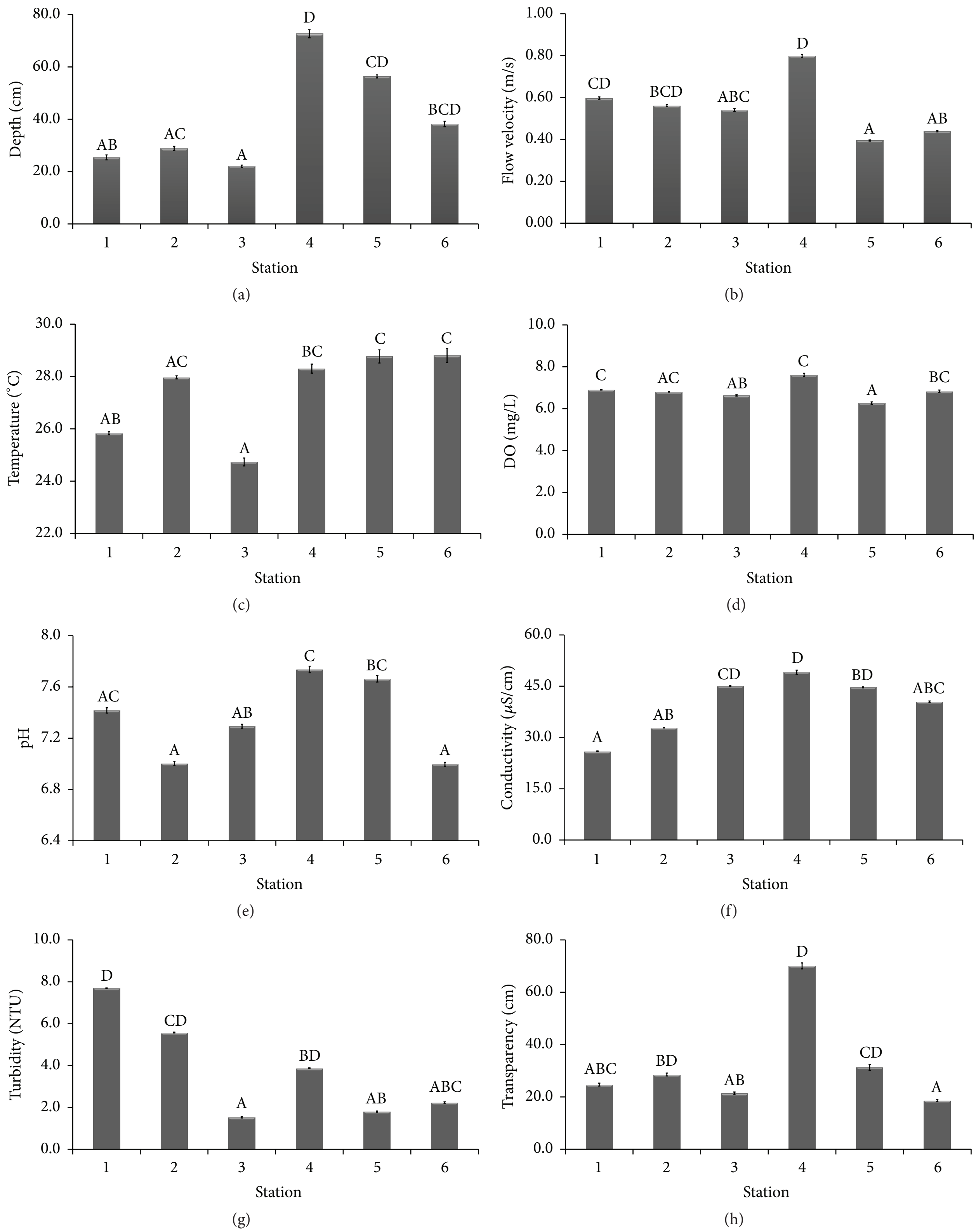


Figure 2: *In situ* water quality parameters of (a) depth, (b) flow velocity, (c) temperature, (d) DO, (e) pH, (f) conductivity, (g) turbidity, and (h) transparency collected at the six sampling stations located at the upper reaches of two main tributaries of Batang Baleh (different letters indicate significant difference at p value ≤ 0.05).

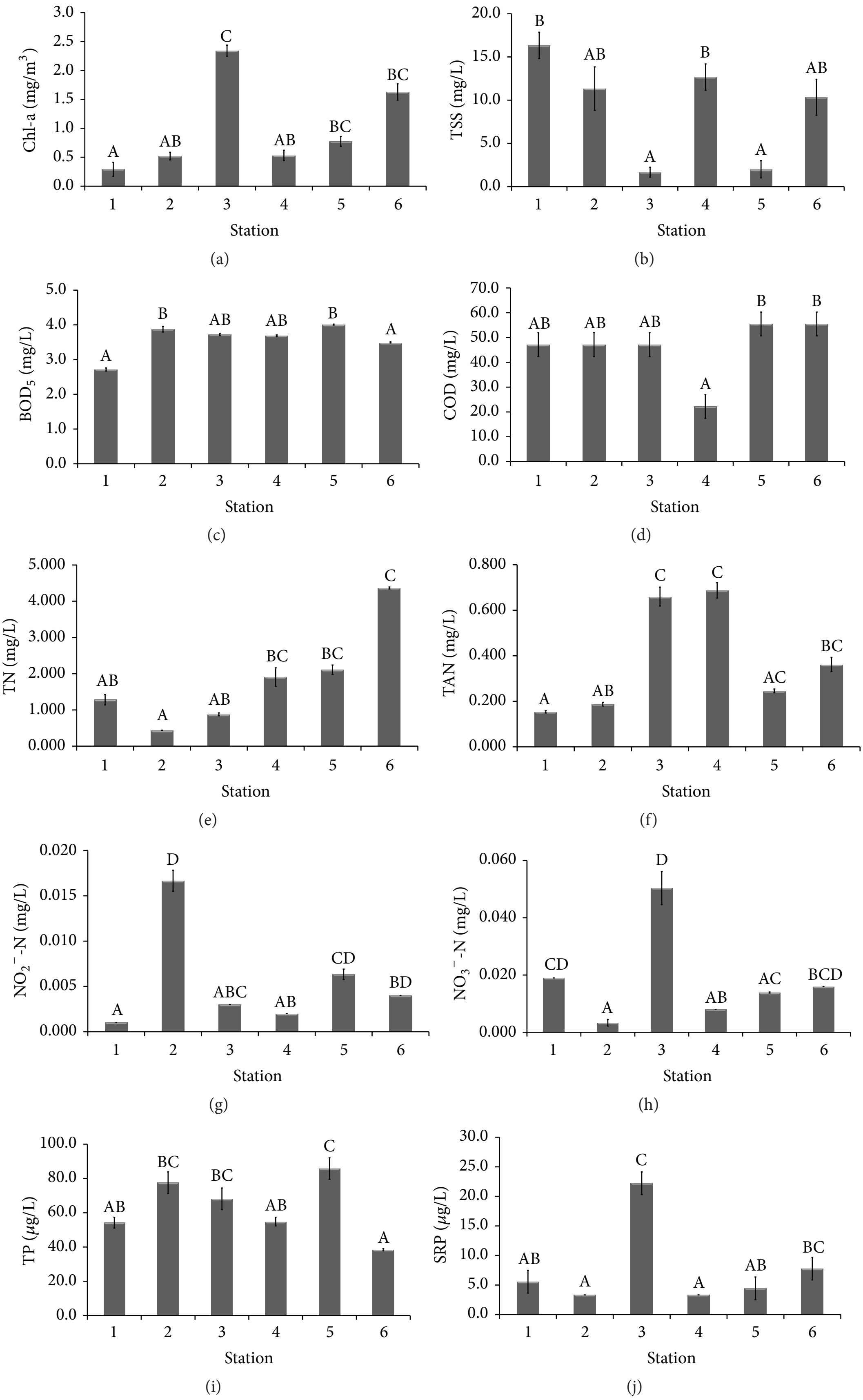
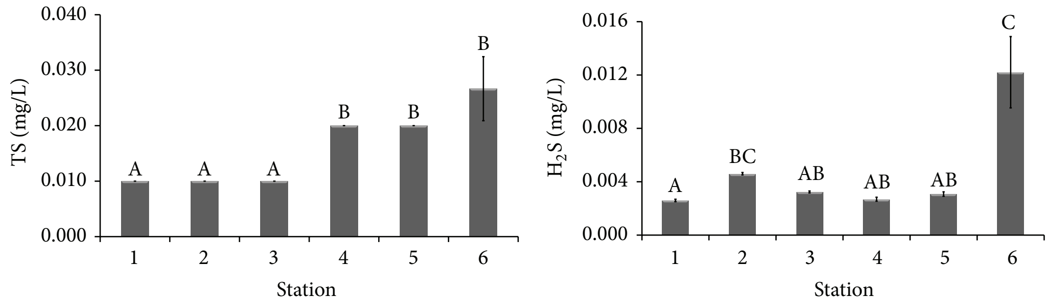


Figure 3: Continued.



(k) (l)

Figure 3: *Ex situ* water quality of (a) chlorophyll *a* (chl-*a*), (b) total suspended solids (TSS), (c) five-day biochemical oxygen demand (BOD_5), (d) chemical oxygen demand (COD), (e) total nitrogen (TN), (f) total ammonia nitrogen (TAN), (g) nitrite nitrogen (NO_2^--N), (h) nitrate nitrogen (NO_3^--N), (i) total phosphorus (TP), (j) soluble reactive phosphorus (SRP), (k) total sulphide (TS), and (l) hydrogen sulphide (H_2S) collected at the six sampling stations located at the upper reaches of two main tributaries of Batang Baleh (different letters indicate significant difference at p value ≤ 0.05).

solids were significantly higher at stations 1 and 4 compared to stations 3 and 5 (p value ≤ 0.05). Five-day biochemical oxygen demand ranged from 2.7 ± 0.0 mg/L to 4.0 ± 0.0 mg/L. Stations 2 and 5 were significantly higher than stations 1 and 6 (p value ≤ 0.05). The lowest COD value was found at station 4 (22.2 ± 4.8 mg/L) which was significantly lower than stations 5 and 6 (p value ≤ 0.05).

Total nitrogen at stations 1, 2, and 3 which were located at Sg. Mengiong (0.434 ± 0.006 to 1.282 ± 0.142 mg/L) was generally lower than stations 4, 5, and 6 which were located at Sg. Gaat (1.907 ± 0.256 to 4.366 ± 0.028 mg/L). Additionally, total nitrogen at stations 1, 2, and 3 was significantly lower than station 6 (p value ≤ 0.05). Total ammonia nitrogen was high at stations 3 and 4 ($\approx$0.674 mg/L) and low at stations 1 and 2 ($\approx$0.171 mg/L). Stations 3 and 4 were significantly higher than station 1 (p value ≤ 0.05). The highest NO_2^--N concentration was found at station 2 (0.017 ± 0.001 mg/L) which was significantly higher than stations 1, 3, and 4 (p value ≤ 0.05). The highest NO_3^--N concentration was found at station 3 (0.050 ± 0.006 mg/L) which was significantly higher than stations 2, 4, and 5 (p value ≤ 0.05).

The trend of soluble reactive phosphorus was similar to NO_3^--N where the highest SRP was observed at station 3 (22.2 ± 1.9 μg/L) and it was significantly higher than stations 2, 4, and 5 (p value ≤ 0.05). The highest TP concentration was found at station 5 (85.8 ± 6.3 μg/L) and significantly higher than stations 1, 4, and 6 (p value ≤ 0.05). Total sulphide ranged from 0.010 ± 0.000 mg/L to 0.027 ± 0.006 mg/L whereas H_2S ranged from 0.003 ± 0.000 mg/L to 0.012 ± 0.000 mg/L. The highest TS and H_2S concentrations were found at station 6. Total sulphide at stations 1, 2, and 3 was significantly lower than stations 4, 5, and 6 (p value ≤ 0.05) whereas H_2S at stations 1, 3, 4, and 5 was significantly lower than station 6 (p value ≤ 0.05).

3.3. Sediment Quality. Figure 4 shows that soil texture of the sampling stations was mostly sand (69.9% to 83.4%), followed by clay (6.6% to 26.7%) and silt (0.2% to 14.8%). Station 2 had the highest percentage of sand but the lowest percentage of clay, while station 3 had the lowest percentage of sand but the highest percentage of clay. Station 1 and station 5 had extremely low percentage of silt whereas station 4 had the highest percentage of silt. Figure 5 illustrates the sediment quality of the six sampling stations. Sediment pH of the study area ranged from 4.80 ± 0.01 to 6.11 ± 0.01. The lowest pH value was found at station 3 which was significantly lower than stations 1, 2, and 4 (p value ≤ 0.05). Stations 4 and 6 had high water content ($\approx$1.83%) and OM ($\approx$3.0%) while stations 1 and 2 had low OM (0.1%) and TOC ($\approx$0.15%). Water content of stations 4 and 6 was significantly higher than stations 1 and 5 (p value ≤ 0.05). Organic matter at stations 1 and 2 was significantly lower than stations 4 and 6 (p value ≤ 0.05) while TOC at stations 1 and 2 was significantly lower than stations 5 and 6 (p value ≤ 0.05). The highest sediment TN was found at station 1 (0.17%) followed by station 2 (0.05%) which was significantly higher compared to the other stations (p value ≤ 0.05) while sediment TP at station 4 (0.01%) was significantly higher than stations 2, 3, and 5 (p value ≤ 0.05).

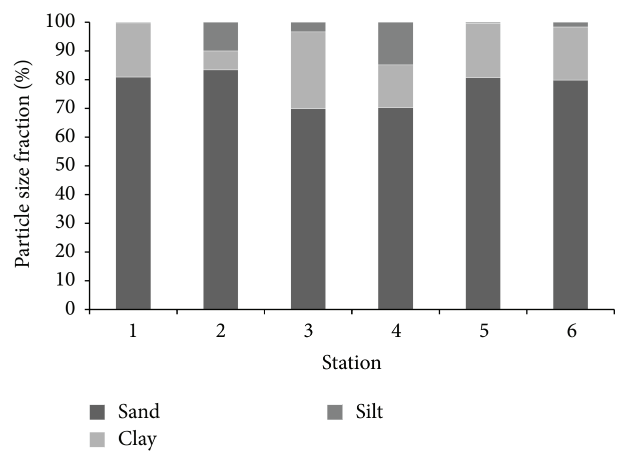


Figure 4: Particle size fraction of sediment collected at the six sampling stations located at the upper reaches of two main tributaries of Batang Baleh.

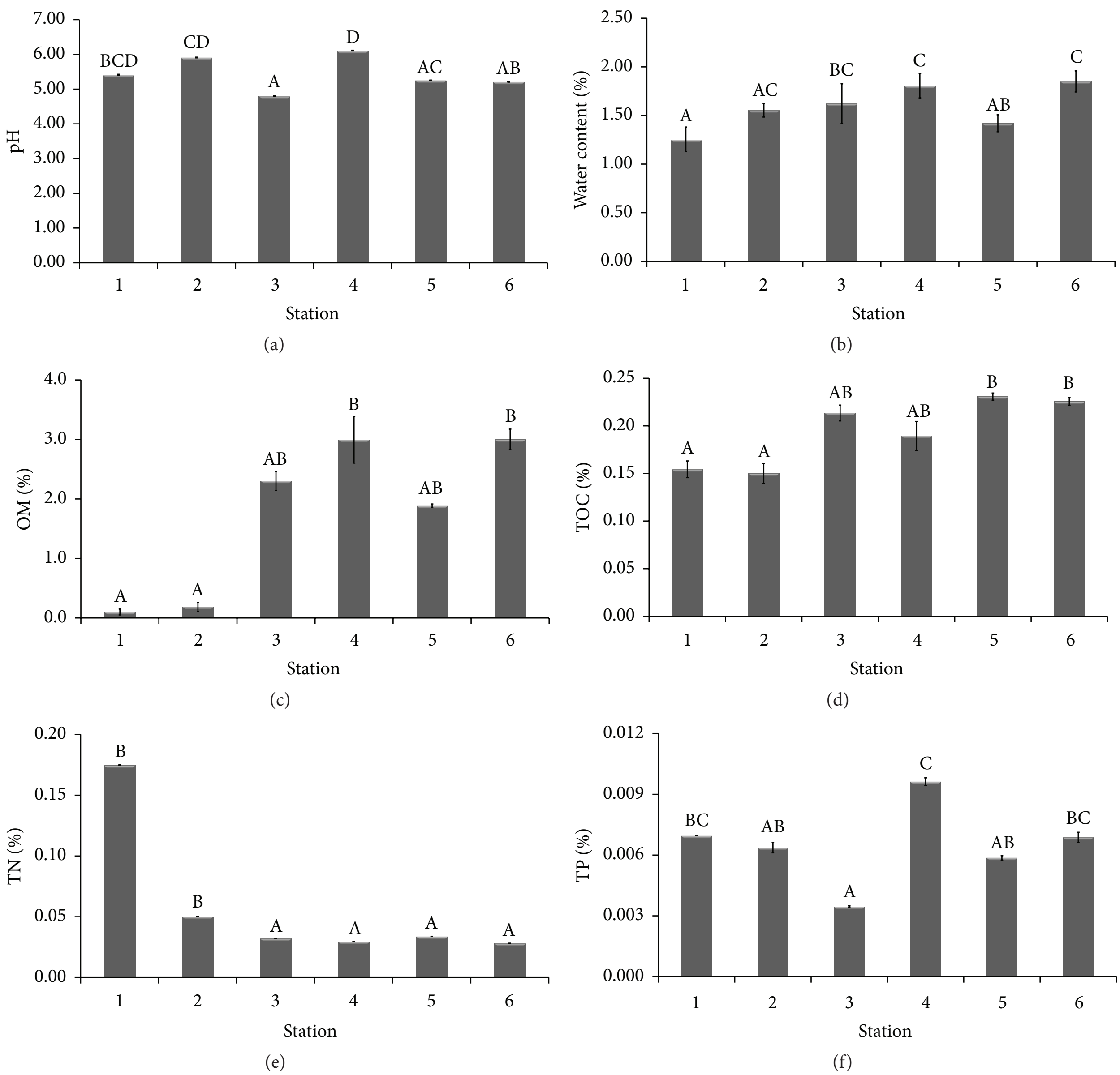


Figure 5: Sediment quality of (a) pH, (b) water content, (c) organic matter (OM), (d) total organic carbon (TOC), (e) total nitrogen (TN), and (f) total phosphorus (TP) collected at the six sampling stations located at the upper reaches of two main tributaries of Batang Baleh (different letters indicate significant difference at p value ≤ 0.05).

3.4. Correlation. Table 2 summarizes the correlation of *in situ* and *ex situ* parameters collected from the six sampling stations. Among them, NO_2^--N had no significant correlation with other parameters. The stream flow velocity was significantly and positively correlated with DO ($r = +0.90$, p value ≤ 0.05) but negatively correlated with COD ($r = -0.93$, p value ≤ 0.05). Chl-*a* was significantly negatively correlated with sediment pH, turbidity, and TSS ($r = -0.81$ to -0.93, p value ≤ 0.05). Positive correlation was found among temperature, TS, and TN ($r = +0.81$ to $+0.93$, p value ≤ 0.05). TAN was significantly and negatively correlated with sediment TN ($r = -0.85$, p value ≤ 0.05) but positively correlated with sediment OM and conductivity value ($r = +0.90$ to $+0.94$, p value ≤ 0.05). NO_3^--N was significantly and positively correlated with SRP ($r = +0.93$, p value ≤ 0.05). TP was significantly and positively correlated with BOD_5 ($r = +0.93$, p value ≤ 0.05) whereas sediment TP was found to be significantly and positively correlated with DO ($r = +0.84$, p value ≤ 0.05).

3.5. Cluster Analysis (CA). Cluster analysis (CA) was applied to detect similarities among the sampling stations using the *in situ* and *ex situ* water parameters and sediment quality of the stations. A total of 29 variables were subjected to CA. The dendrogram showing the cluster of the sampling stations is presented in Figure 6. The result shows that the six sampling stations can be grouped into three clusters. Cluster 1 consisted

TABLE 2: Correlation matrix of 25 *in situ* and *ex situ* parameters collected from the six sampling stations. The NO_2^--N was excluded as it has no significant correlation with other parameters.

	S_{pH}	S_{WC}	S_{TOC}	S_{OM}	S_{TP}	S_{TN}	Temp	DO	Turb	Trans	pH	Cond	Depth	Flow	TSS	BOD_5	COD	TS	H_2S	TN	TAN	NO_3^--N	TP	SRP	Chl-*a*
S_{pH}																								−.93	−.81
S_{WC}				.93																					
S_{TOC}						−.84																			
S_{OM}		.93				−.86															.90				
S_{TP}								.84																	
S_{TN}			−.84	−.86					.85			−.85									−.85				
Temp													.81					.89		.81					
DO					.84									.90	.87										
Turb						.85									.94										−.93
Trans																								−.84	
pH																			−.84						
Cond						−.85															.94				
Depth							.81																		
Flow								.90									−.93								
TSS								.87	.94																−.93
BOD_5																							.93		
COD														−.93											
TS							.89													.93					
H_2S											−.84														
TN							.81											.93							
TAN				.90		−.85						.94													
NO_3^--N																								.93	
TP																.93									
SRP	−.93									−.84												.93			
Chl-*a*	−.81								−.93						−.93										

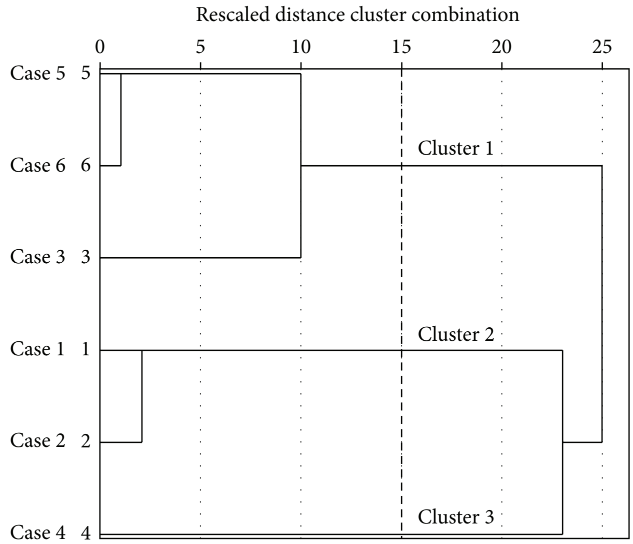


Figure 6: Cluster of the six sampling stations.

of stations 3, 5, and 6. Station 4 which is located at the main river of Sg. Gaat is grouped as cluster 3. Cluster 2 consists of stations 1 and 2 which are the tributaries of Sg. Mengiong.

3.6. The Influence of the Rainfall Event. The *in situ* and *ex situ* water quality data were also taken at three selected stations after rain in the present study. Table 3 summarizes the significant difference of the parameters before and after rain. Temperature, transparency, and pH of the sampling stations decreased significantly after the rainfall event (p value ≤ 0.05) while DO, turbidity, and flow velocity increased significantly (p value ≤ 0.05). Total suspended solids, COD, TN, NO_2^--N, TP, and SRP increased significantly after rain (p value ≤ 0.05) whereas chl-a and TS decreased significantly (p value ≤ 0.05) after rain.

Table 3: Mean difference of *in situ* and *ex situ* water quality parameters before and after rain ($N = 9$).

Parameters	Mean difference	p value
In situ		
Temperature	**−4.3**	**0.008**
DO	**+0.3**	**0.047**
Turbidity	**+425.7**	**0.008**
Transparency	**−28.6**	**0.008**
pH	**−0.5**	**0.007**
Conductivity	+2.9	0.859
Depth	−0.1	1.000
Flow velocity	**+0.4**	**0.000**
Ex situ		
Chlorophyll a	**−0.7**	**0.008**
Total suspended solid	**+95.8**	**0.008**
Five-day biochemical oxygen demand	−0.02	0.856
Chemical oxygen demand	**+19.4**	**0.049**
Total nitrogen	**+1.576**	**0.011**
Total ammonia nitrogen	+0.145	0.051
Nitrite nitrogen	**+0.009**	**0.007**
Nitrate nitrogen	+0.009	0.066
Total phosphorus	**+56.2**	**0.008**
Soluble reactive phosphorus	**+12.2**	**0.008**
Total sulphide	**−0.010**	**0.005**
Unionized hydrogen sulphide	−0.001	0.952

Positive value of mean difference indicates parameter studied increased after rain whereas negative value indicates a decrease after rain. The significant difference at p value ≤ 0.05 was indicated in bold.

3.7. Water Quality Index (WQI). All of the sampling stations are classified as Class II according to the water quality index (WQI). Among the six parameters, pH and TSS are classified as Class I whereas COD at most of the stations are classified as Classes III and IV. The water quality of the three selected stations deteriorated after the rain, particularly station 6 which changed from Class II to Class III. The status of the streams also changed from being "clean" to "slightly polluted" due to the rainfall event. The parameter most influenced by rain was TSS where it changed from Class I to Classes III and IV after the rain (Table 4).

4. Discussion

Forestry activities, either forest harvesting or replanting, can modify water and sediment quality in many ways that affect the aquatic habitat and organisms. For instance, canopy removal which exposes forest stream to direct solar radiation can increase water and sediment temperature [36]. In the present study, the significant lower temperature at stations 1 and 3 (p value ≤ 0.05) was measured in the morning whereas other stations were measured in the afternoon. The large variation of the forest streams temperature in one day indicates that the logging activities have increased the extent of direct solar radiation of the forest streams, subsequently leading to the significant increase of temperature in the afternoon. Temperature of the forest streams in the present study is relatively higher than the Berasau River in Johor, Malaysia, (25.23–26.47°C) which is also subjected to logging activities [12] but is relatively lower than the peat swamp forest that was converted into oil palm plantation (26.85–32.90°C) in Batang Igan, Sibu, Sarawak [37].

Logging can also lead to increased sedimentation of streams [36]. Slight sedimentation of the streams was observed in the field during sample collection. The presence of logging activities renders the higher turbidity and TSS values observed at stations 1, 2, 4, and 6 compared to stations 3 and 5 which have the lowest turbidity and TSS values due to inactive logging at those stations. However, overall all streams were still considered clear with high transparency and low turbidity (<10 NTU) and TSS (<20 mg/L) values indicating that logging activities did not increase the sedimentation of the streams to a polluted level when there was no rainfall event. Similarly, [38] demonstrated that there was no significant pollution through erosion occurring at the peat swamp forest that was converted into oil palm plantation although

Table 4: Classification of water quality of the six sampling stations before and after rain according to WQI.

Station	Class							Status
	AN	BOD_5	COD	DO	pH	TSS	WQI	
1	II	II	III	II	I	I	II	Clean
2	II	III	III	II	I	I	II	Clean
3	III	III	III	II	I	I	II	Clean
4	III	III	II	I	I	I	II	Clean
5	II	III	IV	II	I	I	II	Clean
6	III	III	IV	II	I	I	II	Clean
4r	III	III	IV	I	I	III	II	Slightly polluted
5r	III	III	III	I	I	III	II	Slightly polluted
6r	III	III	IV	II	II	IV	III	Slightly polluted

r: after rain.

the TSS value of the oil palm plantation site is higher than the natural peat swamp forest. In spite of that, the significant correlation of chl-*a* (p value ≤ 0.05) with turbidity and TSS indicates that light penetration is the main factor in regulating the chl-*a* concentration in the present forest streams.

There is no sign of acidification of the stream water (pH ≥ 7) and all streams are well-aerated (DO ≥ 6 mg/L). DO is significantly correlated with stream flow velocity (p value $\leq$ 0.05) in the present study indicating reaeration of the faster flowing stream. According to the WQI, the pH values at all six sampling stations are classified as Class I while DO is classified as Class I and/or Class II. Besides, NO_2^--N, NO_3^--N, SRP, and TP concentrations in the present study were also classified as Class I according to the National Water Quality Standards for Malaysia [35]. H_2S concentration in the present study is also lower than the threshold of 0.05 mg/L in drinking water [39].

However, BOD_5 values at all stations are classified as Class III except station 1, and AN values at stations 3, 4, and 6 are classified as Class III while COD values at stations 5 and 6 are classified as Class IV. The significant negative correlation between stream flow velocity and COD (p value ≤ 0.05) indicates that the organic matter is accumulated at the slow flowing stream; in particular, station 6 with slow flow was found significantly higher in OM and TOC in sediments (p value ≤ 0.05). Significantly lower sediment TN was observed at stations 3 to 6 compared to stations 1 and 2 (p value ≤ 0.05) indicating the loss of nitrogen from sediment to water. This is further proven by the significantly negative correlation between sediment TN and TAN concentration in water (p value ≤ 0.05). Logging can lead to increased mineralization and nitrification, with a subsequent loss of minerals and nutrients from soil into water [6]. Significant positive correlation between TN and TS (p value ≤ 0.05) and positive correlation between TP and BOD_5 (p value $\leq$ 0.05) suggested that the pollution was derived from the same source. Besides, SRP was significantly correlated with NO_3^--N (p value ≤ 0.05) indicating that the inorganic pollution was from the same source.

According to CA, station 4 which is located at the main river of Sg. Gaat is grouped as an independent cluster from other tributaries. Stations 1 and 2 which are located at the tributaries of Sg. Mengiong are grouped as the same cluster. Stations 5 and 6 which are located at the tributaries of Sg. Gaat are grouped as another cluster. However, station 3 which is located at one of the tributaries of Sg. Mengiong is grouped together with the two tributaries of Sg. Gaat (stations 5 and 6) due to its proximity to those stations. We can see from the CA that the characteristic of the main river is different from the tributaries and the tributaries of Sg. Gaat are different from the tributaries of Sg. Mengiong, except for Sg. Entajum.

Overall, the WQIs of the six sampling stations are classified as Class II which are considered clean and can be used as water supply after conventional treatment. Similarly, the Berasau River in Johor, Malaysia, which is also subjected to logging activities is classified between Classes II (good) and III (moderate) of river water quality [12]. Also, the qualities of surface waters draining from a secondary forest and an oil palm plantation in the Lower Kinabatangan River catchment, Sabah, Malaysia, fall into Class II as well [40]. However, in the present study, the water quality of the forest streams deteriorated significantly after rain (p value ≤ 0.05). After the rainfall event, turbidity, TSS, and most of the nutrients increased significantly with the stream flow velocity (p value ≤ 0.05). Suspended sediment and chemical oxygen demand were also found higher during the wet season in the Lower Kinabatangan River catchment, Sabah, Malaysia [40]. The deterioration of water quality is most likely due to the sediment inflow from the logging areas coupled with resuspended stream sediment. On the other hand, after rain, stream DO was significantly higher due to the higher velocity of the water which increases reaeration of the stream water. In addition, temperature which was significantly lower (p value ≤ 0.05) indicates cooler water which holds more oxygen. According to WQI, TSS was the parameter that was influenced the most by the rainfall event where it changed from Class I to Class III and/or IV at stations 4, 5, and 6 after the rain. Before the rain, logging activities had minimal impact on the increase of sediment in the water column of the streams as indicated by low turbidity and TSS. However, the impact of the logging activities on water column sediment was noticeable after the rain. The WQI of station 6 which is located downstream of active logging activities changed from Class II to Class III. The status of all three sampling stations also changed from "clean" to "slightly polluted" after rain. The impact of logging resulting in soil erosion and subsequently high turbidity in stream water was also reported in other rivers in the state, where in the Belepeh River that flows into Bakun Dam in the upper Rajang River, increase of turbidity from 8.5 to 126.8 NTU was observed resulting in a change of Class II compliance to noncompliance [41]. In addition, the Kebhor River, a tributary of the Balui River, was also reported to be high in turbidity (94 NTU) due to soil erosion as a result of logging [42].

5. Conclusions

Forest streams in the present study are well-oxygenated with pH values that are nearly neutral. Prior to a rainfall event, the water is high in transparency and low in turbidity and TSS values. Soil texture of the stream sediment is mostly sand, followed by clay and silt. However, logging activities around the study area have an impact on the water and sediment quality of the forest streams. Canopy removal in the study area renders significant changes of stream temperature over a day. Suspended solids are higher at stations with the presence of logging activities compared to the stations with inactive logging activities. Nutrients concentrations in the present study complied with the national and/or international standard except for AN, BOD_5, and COD. WQI indicated that, without rain, the forest streams in the present study are still of good quality but suffer from organic pollution with high AN, BOD_5, and COD. Nitrogen loss from sediment to water and accumulation of OM and TOC were also observed in the study area. The water quality of the forest streams deteriorates after a rainfall event where suspended solids are the most affected parameter. This calls for appropriate management of forests to reduce deterioration of water quality after rainfall events.

Competing Interests

The authors declare that they have no competing interests.

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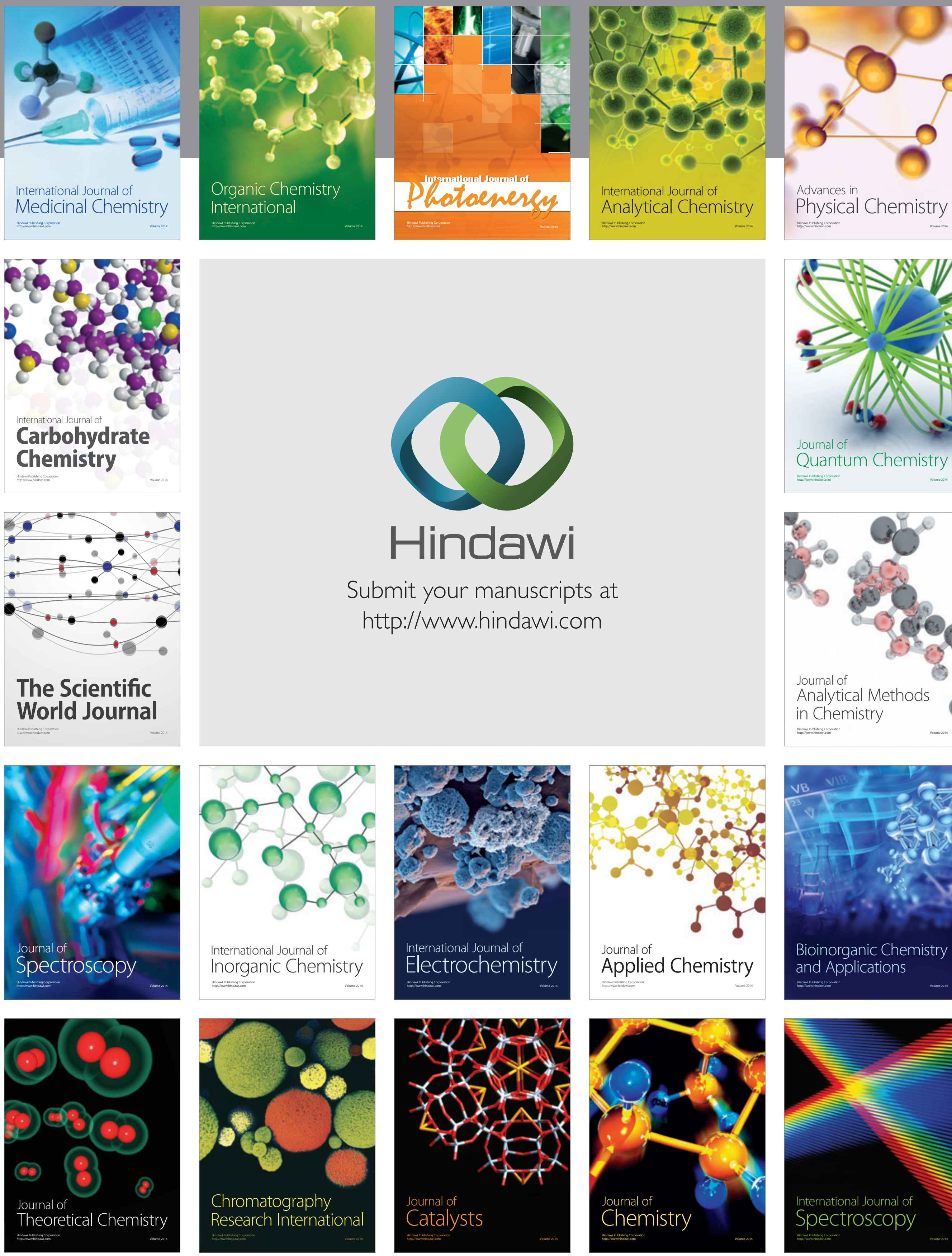
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