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Research Article

Effects of Opened and Closed Spillway Operations of a Large Tropical Hydroelectric Dam on the Water Quality of the Downstream River

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Water quality downstream of a hydroelectric dam is potentially affected by dam operations and other land uses in the river basin. Previous short-distance studies below the large Bakun Dam indicated poorer water quality during closed spillway. However, the extent of the impact is still unknown. Such knowledge is essential for mitigating the impact of the dam. Thus, the objectives of this study were to determine the water quality up to a distance of 210 km under two spillway operations, namely, closed and opened spillways, and also to determine the changes in water quality from the predam condition. Physicochemical parameters were measured at 15 stations along the Rajang River. Results of this preliminary study indicated that there were significant differences in eight out of nine water quality parameters between opened and closed spillway operations with opened spillway showing better water quality. During closed spillway, as we approached the dam, there was an increasing acidity and a decreasing oxygen content. Furthermore, as the water flows downstream, the unhealthy DO level (<5 mg/L) extended up to 165 km and the linear model showed an increasing DO rate of 0.09 mg/L per km. With opened spillway, DO decreased exponentially from 9.74 mg/L towards the downstream direction to 7.67 mg/L. The increasing turbidity and TSS in the downstream direction indicate contributions from erosion due to other land uses. The river is polluted with organics as indicated by COD of Class IV or V with sources from the dam and the activities in the river basin. Compared to the predam condition, the regulated river is less turbid but warmer and higher in ammonia. Closed spillway led to lower DO and acidic water. However, opened spillway water pH and DO were similar to those in the predam condition. Thus, it is recommended that DO be consistently high enough for the health of sensitive aquatic organisms downstream.

1. Introduction

Energy from hydroelectric dams is a beneficial alternative to fossil fuels as it is renewable. Abundance of rainfall in a tropical country such as Malaysia provides the water flow needed for hydropower generation. Thus, the largest dam in Malaysia, the Bakun Hydroelectric Dam, was constructed across the longest river, the Rajang River, providing an installed capacity of 2400 MW [1], which started operation in November 2011. Just like most rivers in the world, the Rajang River also functions as a means of transportation, source of food and water, and habitat to various floras and faunas. However, the building of dams has been reported to impact the agricultural land and wildlife habitats of the flooded area, and downstream from the dam, floodplain hydrology, movement of sediments, channel structure, ecology, and biodiversity have also been impacted [2–4]. In addition, the structural design and operation of a dam determine the flow regime and affect the downstream river in various ways including the water quality. In the Bakun

Dam Reservoir, water quality studies during and after the impoundment [1, 5, 6] showed the impact of damming the Rajang River where dissolved oxygen decreased as depth increased. When the hypolimnion water is released downstream through spillways and turbines, there is a potential impact on sensitive aquatic organisms. It has been reported that dams can affect the downstream river up to hundreds of kilometers [7]. It is therefore important to minimize the impact of the damming of a river on the ecosystem downstream. For downstream of Bakun Dam, knowledge on water quality is scarce. A downstream study conducted up to 32 km distance showed that there was a large difference between water quality during opened spillway and closed spillway [8]. Results of another study conducted at the Pelagus area, more than 150 km downstream from the dam, showed low dissolved oxygen when the spillway was closed [9]. Thus, more studies are needed downstream to assess the water quality under different operation regimes and the extent of the impact in terms of distance which is essential for management purpose.

Therefore, the present study focused on determining the physicochemical parameters of water quality along the Rajang River downstream of Bakun Dam under two different operation regimes, namely, opened and closed spillways, covering a distance of approximately 210 km. In addition, a comparison was made with the water quality of the Rajang River prior to the impoundment.

2. Materials and Methods

The study area was located at Rajang River, Sarawak, below Bakun Dam, from Long Baagu to Kapit Town. Fifteen stations along the river were selected for this study as shown in Figure 1. Table 1 shows the global positioning system (GPS) coordinates, location description, weather condition, distance of each station from the dam, and the time of sampling conducted at each station. The selection of first four stations was based on major villages: station 5 was based on the town area, stations 6 to 13 were based on the major tributaries of the river, station 14 was located 1 km below the rapid, and station 15 was located about 1 km from the coal loading jetty near the Kapit Town area. The distance along the river from Bakun Dam to the furthest station above Kapit Town was approximately 210 km. The sampling trips were conducted on 12 April and 6 September 2016. For each trip, all the stations were covered on the same day. On 12 April 2016, the spillway was opened to release water in addition to the discharge through the turbines, whereas on 6 September 2016, the spillway was closed. The spillway was built for the purpose of flood control. The discharge of water during opened and closed spillways and the total volume of discharge are shown in Table 2.

At every station, the *in situ* parameters measured were the temperature, pH, dissolved oxygen (DO), turbidity, and transparency. The measurements of temperature, pH, dissolved oxygen, and turbidity were carried at *in situ* by using a multiparameter sonde instrument (YSI 6920 V2-2). The transparency of water was measured by using a Secchi disk with a measuring tape. Triplicates of water samples were taken at the subsurface of the river water by immersing a 1 L acid-washed polyethylene bottle that was rinsed with the river water about 2 to 3 times without leaving any air bubbles. They were labelled and kept in a cooler box for *ex situ* analyses which included total suspended solids (TSS), chemical oxygen demand (COD), nitrite-nitrogen (NO_2-N), nitrate-nitrogen (NO_3-N), and ammonia-nitrogen (NH_3-N). COD was analysed by using the closed reflux, titrimetric method; NO_2-N was analysed by using the Hach 8507 Diazotization Method, NO_3-N was analysed by using the Hach 8192 Cadmium Reduction Method, and NH_3-N was analysed by using the preliminary distillation step followed by Nessler's method. The analyses of NO_2-N and NO_3-N were determined by using Hach methods [10], and the concentrations were determined using DR900 in the field. The TSS, BOD, COD, and NH_3-N were analysed according to the methods outlined in Standard Methods [11].

The analysis of TSS was done by filtering at most 1 L of water through a 1.0 μm pore-sized glass filter paper (Sartorius), dried in an oven at 105°C to constant weight. The final weight of the TSS was calculated by using the following equation:

$$\text{TSS (mg/L)} = \frac{W_\text{f} - W_\text{i}}{V}, \tag{1}$$

where W_f = final weight of the dried filter paper with residue (mg), W_i = initial weight of the dried filter paper (mg), and V = total volume of water filtered (L).

As for COD and NH_3-N, after the river water was collected in triplicates in a 120 mL acid-washed polyethylene bottle, it was added with 1 mL of concentrated H_2SO_4 and kept cool at 4°C to preserve the water sample to be analysed in the laboratory. The analysis of COD was done according to the closed reflux method. To every 2.5 mL of the water sample in a culture tube, 1.5 mL of digestion solution and 3.5 mL of H_2SO_4 were added. The tubes containing water samples and reagents were digested at 150°C for at least two hours. They were left to cool and transferred to a conical flask. A few drops of ferroin indicator solution were added to the conical flask. Every water sample in the conical flasks was titrated with 0.025 M FAS until the colour changed from bluish green to reddish brown. COD was calculated by using the following equation:

$$\text{COD as mg } O_2/\text{L} = \frac{(A - B) \times M \times 8000}{2.5\,\text{mL}}, \tag{2}$$

where A = mL FAS used for the blank, B = mL FAS used for the sample, M = molarity of FAS (0.025 M), and 8000 = milliequivalent weight of oxygen × 1000 mL/L.

The standard method NH_3-N involved two steps which were the preliminary distillation step and Nessler method [11]. Instead of using distilled water, ammonia-free water was used in the whole analysis to avoid external contamination of ammonia. The procedure started by taking 100 mL of water samples and adding 10 mL of borate buffer, and the pH was adjusted to 9.5. The water samples were distilled using a semiautomatic distillation unit (VELP Scientifica, UDK 139). The distillate was added with 10 mL of boric acid, and the pH was adjusted to 7 by using 1 N NaOH. The distillate was then

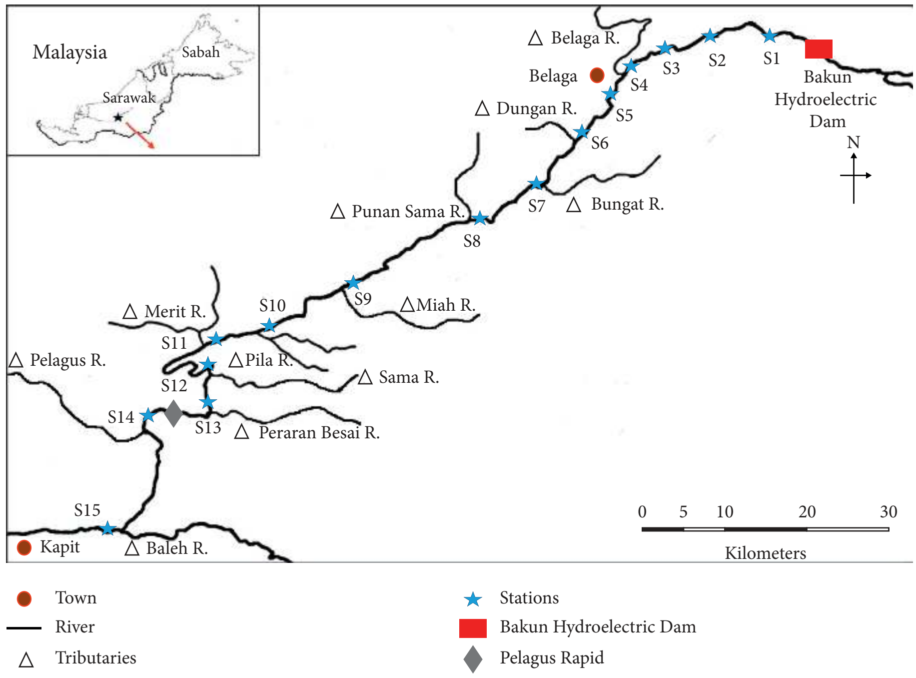

FIGURE 1: The location of the 15 sampling stations along the Rajang River, below Bakun Dam to Kapit in Sarawak, Malaysia.

TABLE 1: Sampling stations with distance from Bakun Dam, GPS coordinates, location description, time, and weather conditions during opened and closed spillways.

Stations (distance from the Bakun Dam)	GPS coordinates	Location descriptions	Opened spillway (12 April 2016)		Closed spillway (6 September 2016)	
			Time	Weather	Time	Weather
St. 1 (4.4 km)	N02°46′21.8″, E114°01′41.6″	Long Baagu	12.14 pm	Sunny	2.43 pm	Sunny
St. 2 (11 km)	N02°47′02.0″, E113°58′43.2″	Lubok Metjawah (right above Metjawah)	11.34 am	Sunny	2.16 pm	Sunny
St. 3 (20.1 km)	N02°45′08.7″, E113°53′01.7″	Right below longhouse Lehanan Long Somuang	10.56 am	Sunny	12.35 pm	Cloudy
St. 4 (28.5 km)	N02°44′34.5″, E113°50′21.8″	Right above longhouse Kejaman Neh	10.22 am	Sunny	11.52 am	Raining
St. 5 (38.3 km)	N02°42′02.9″, E113°46′46.3″	Below Belaga Town	9.33 am	Sunny	10.58 am	Cloudy
St. 6 (50.3 km)	N02°37′28.8″, E113°43′59.8″	1 km above Dungan River	4.38 pm	Sunny	3.35 pm	Cloudy
St. 7 (63.7 km)	N02°32′20.2″, E113°39′35.3″	Right below Bungat River	4.00 pm	Sunny	2.49 pm	Drizzling
St. 8 (81.3 km)	N02°29′05.1″, E113°32′19.3″	1 km above Punan Sama River	3.15 pm	Sunny	1.49 pm	Drizzling
St. 9 (104.3 km)	N02°23′41.7″, E113°22′34.6″	1 km above Miah River	1.56 pm	Cloudy	1.03 pm	Cloudy
St. 10 (123.4 km)	N02°19′23.5″, E113°14′32.2″	1 km above Pila River	1.15 pm	Sunny	12.08 pm	Cloudy
St. 11 (131.9 km)	N02°17′16.8″, E113°08′02.7″	1 km above Merit River	12.44 pm	Sunny	11.07 am	Raining
St. 12 (154.1 km)	N02°15′46.9″, E113°08′54.6″	1 km above Sama River	11.43 am	Sunny	10.28 am	Raining
St. 13 (168.1 km)	N02°11′21.6″, E113°07′57.9″	1 km above Peraran Besai River	11.04 am	Sunny	9.51 am	Raining
St. 14 (178.4 km)	N02°10′54.9″, E113°03′36.4″	Base of Pelagus Rapid (Kaki Wong)	10.25 am	Sunny	9.16 am	Sun shower
St. 15 (210 km)	N02°01′06.5″, E113°00′29.4″	1 km below Batu Arang (coal loading jetty)	9.22 am	Sunny	8.03 am	Sun shower

Table 2: Discharge from turbines and spillways during opened and closed spillways on the two sampling dates.

Spillway operation	Date	Turbine discharge (m^3/s)	Spillway discharge (m^3/s)	Total discharge (m^3/s)
Opened	12 April 2016	874	1586	2,460
Closed	6 September 2016	921	0	921

made up to 100 mL. After the preliminary step, the Nessler method was used. The samples were prepared by filling 25 mL of the sample into a mixing cylinder. The blank was prepared by filling ammonia-free water into the mixing cylinder. Three drops of the polyvinyl alcohol dispersing agent, 3 drops of mineral stabilizers, and 1.0 mL of the Nessler reagent were added to each mixing cylinder. The solution was mixed and stabilized for one minute. The sample absorbance was measured at 425 nm using a DR3900 spectrophotometer, and concentration was determined using a calibration curve.

NO_2-N and NO_3-N were analysed in the field according to Hach [9] using a DR900 colorimeter. NO_2-N was analysed by taking 10 mL of water into a sample cell. The NitriVer 3 reagent powder pillow was added into the sample cell. The cell was swirled and left to react for 20 minutes before taking the final reading. The blank was prepared by using the original sample water. NO_3-N on the contrary was done using 2 reagents, namely, the NitriVer 3 reagent powder pillow and NitraVer 6 reagent powder pillow. The water sample (15 mL) was taken and placed into a mixing cylinder. Then, the NitraVer 6 reagent powder pillow was added into the cell. The cell was shaken for 3 minutes before left to react for 2 minutes. Then, 10 mL of the sample was taken for the mixing cylinder and poured into a sample cell. The NitriVer 3 reagent powder pillow was added and mixed thoroughly for 30 seconds. The sample was left to react for 15 minutes before obtaining the final reading. The blank was prepared using the original sample water.

Differences in water quality parameters at the 15 stations were tested using the one-way ANOVA. The paired t-test was also conducted to compare the means of the two spillway operations. Correlation analysis was conducted. All data analyses were done using the SPSS version 24 package. The linear model (Equation (3)) and exponential model (Equation (4)) were explored for their suitability to estimate the change in DO as a function of distance during closed and opened spillways:

$$C = bD + a, \tag{3}$$

$$C = bD^a, \tag{4}$$

where C is the concentration of DO (mg/L), a and b are constants in the regression fit, and D is the distance from the dam (km).

3. Results and Discussion

3.1. In Situ Water Quality Parameters. Temperature is important for the ecological behaviour and distribution of aquatic organisms as temperature influenced their psychological processes such as food consumption, digestion, and immunity [12].

The temperature during opened spillway ranged from 26.88°C to 27.80°C where the highest mean was recorded at station 10 (123.4 km from Bakun Dam) and the lowest mean was recorded at station 5 (38.2 km from Bakun Dam) (Figure 2). The temperature during closed spillway ranged from 27.09°C to 27.93°C where the highest mean was recorded at station 15 (210 km from Bakun Dam) and the lowest mean was recorded at station 5 (38.2 km from Bakun Dam). During opened spillway, stations 1 to 5 showed lower temperatures than closed spillway due to the flow of colder water from the spillway of Bakun Dam as it was a rainy season. Statistical analysis also shows that, during opened spillway, the mean temperature of the whole stretch studied was significantly lower than that during closed spillway ($p < 0.05$) (Table 3). The fluctuation in temperature during each trip was due to the impact of the time of sampling in the day coupled with the weather condition, whereby temperature was observed to be higher in the afternoon than morning. The energy transport process and heat fluxes influenced the temperature of the water surfaces [13]. However, comparing stations studied at about the same time in the day gives an indication of the general trend of temperature as the water flows downstream along the Rajang River. For instance, during opened spillway, comparisons on the pairs of stations, 2 and 12, 4 and 14, and 5 and 15, gave an indication of an increasing trend of temperature as distance from the dam increased; similarly, during closed spillway, the pair of stations 5 and 11, though not as much increases, is significant ($p < 0.05$).

The pH during closed spillway ranged from 5.60 to 6.46, whereas during opened spillway, it ranged from 6.25 to 6.48 (Figure 3). Statistical analysis of the mean pH of the two spillway operations shows that, during closed spillway, pH was significantly lower than that during opened spillway ($p < 0.05$) (Table 3). In both occasions, as we approached the dam from downstream, pH decreased with the lowest pH observed at station 1 (4.3 km) which is the nearest station to the Bakun Dam. In addition, during closed spillway, the water pH was lower than that during opened spillway up to a distance of 178 km away from the dam after which the pH values were similar to those during opened spillway. pH during both trips falls in the range of 4.93–7.36 near the water intake point in the reservoir [6]. During opened spillway, at the beginning in station 3, as the water flows downstream, pH stayed relatively constant. The higher pH during opened spillway was similar to that reported in [8] when the water was studied up to a distance of 32 km from the dam. The pH values of stations 4 and 5 during closed spillway were significantly higher most likely due to increasing photosynthesis in response to nutrients from settlements along the river and the dilution of tributary river water. This is supported by the significant correlation

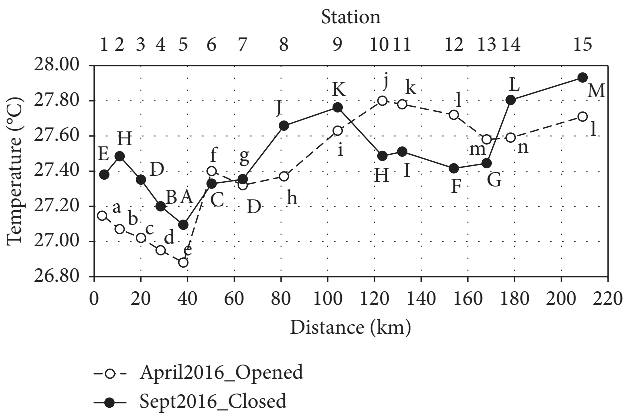

Figure 2: Temperature at the 15 stations downstream of Bakun Hydroelectric Dam during opened spillway (o) and closed spillway (•). The same letter indicates no significant difference ($p > 0.05$).

Table 3: Mean and standard deviation of the water quality parameters in the Rajang River during opened and closed spillways.

Parameters	Opened spillway	Closed spillway
Temperature (°C)	27.40 ± 0.00^a	27.48 ± 0.00^b
pH	6.42 ± 0.00^a	6.12 ± 0.00^b
DO (mg/L)	8.60 ± 0.00^a	4.46 ± 0.00^b
Turbidity (NTU)	71.08 ± 0.35^a	98.83 ± 0.87^b
TSS (mg/L)	47.14 ± 1.44^a	66.79 ± 3.84^b
COD (mg/L)	111.11 ± 7.21^a	91.02 ± 12.39^b
NH_3-N (mg/L)	0.22 ± 0.04^a	0.24 ± 0.03^a
NO_3-N (mg/L)	0.080 ± 0.010^a	0.019 ± 0.004^b
NO_2-N (mg/L)	0.004 ± 0.001^a	0.003 ± 0.000^b

Means in the same row with the same letters are not significantly different ($p > 0.05$).

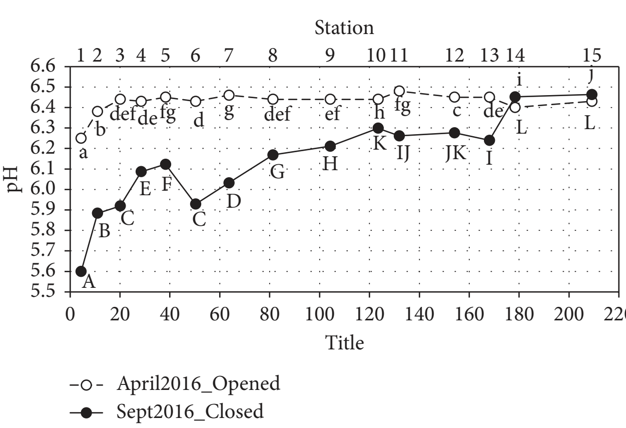

Figure 3: pH at the 15 stations downstream of Bakun Hydroelectric Dam during opened spillway (o) and closed spillway (•). The same letter indicates no significant difference ($p > 0.05$).

between pH and DO ($r = 0.755$, $p < 0.05$) as DO is produced during photosynthesis and carbon dioxide is consumed in the process. In both trips, station 5 showed a significantly higher pH value than station 4 due to the inflow from a big tributary (Belaga River). During closed spillway, there was more fluctuation in pH than during opened spillway, indicating higher susceptibility to the surrounding environmental influence such as diurnal variation in solar radiation which affected pH through algae photosynthesis and respiration and also inputs from settlement and tributaries. In terms of classification, during opened spillway, the pH values complied with Class II according to NWQS at all the stations (Table 4) [14]. However, during closed spillway, the pH values at stations 1, 2, 3, and 6 dropped below 6.0 and thus were classified as Class III, while the other stations were classified as Class II. The pH value classified into Class III and below will negatively affect the sensitive fish species such as a deterioration in their appetite, growth capacity, and their tolerance to toxicity [15].

Dissolved oxygen (DO) is an important parameter for the health of sensitive aquatic organisms. During opened spillway, the DO concentrations were high, ranging from 7.67 mg/L to 9.74 mg/L (Figure 4). The highest mean was recorded at station 1, the nearest to Bakun Dam, and the lowest mean was recorded was at station 15, the furthest from the dam. As we approached the dam, there was an increasing trend in DO. However, during closed spillway, the opposite was observed, whereby the DO values ranged from 3.50 mg/L to 6.02 mg/L with the highest mean recorded at station 15, the furthest from Bakun Dam, and the lowest mean recorded at station 1, the nearest to the dam. As we approached the dam from station 15, there was a general decreasing trend in DO with a few exceptions such as stations 2, 3, and 5. Comparing the values of DO, during opened spillway, all the stations showed higher DO than closed spillway and the difference between the means was significant ($p < 0.05$) (Table 3). When the spillway was opened, the highest DO value was observed at station 1 due to the rapid aeration from the flip bucket spillway design which contributed to the additional oxygen gas bubbles from the atmosphere entering the water [16].

The DO level during opened spillway started decreasing against distance due to the decrease in reaeration as distance increased and also mixing with lower DO water. In spite of that, the DO level still exceeded 7.0 mg/L which is ideal for the sensitive aquatic organisms. During closed spillway, the low DO at station 1 was due to the low DO content water from the reservoir flowing out through the turbines of the dam. According to the water intake structure, it was designed to withdraw from the top 10 m. However, the DO in the Bakun Reservoir, near the water intake, had been shown to drop sharply from about 4 m depth and by 6 m depth, and it was anoxic [6]. DO during the closed spillway gradually increased along the downstream of the river as the water is aerated and diluted with higher DO river water and from the tributaries. Even then, the DO continued to be less than 5 mg/L up to about 165 km from Bakun Dam. Although the tropical aquatic organisms can withstand low DO levels, the ideal DO required for the sensitive aquatic organism's growth is at the minimum of 5 mg/L [17]. Stations 2 and 14 were below rapids where higher reaeration occurred resulting in an increase in DO from station 1 to station 2 and from station 13 to station 14. From station 4 to station 5 and from station 12 to station 13, the increase was due to the inflow of higher DO water from Belaga River and Peraran

Table 4: Classification of water quality parameters for all stations during opened and closed spillways according to NWQS [14].

Station	Opened spillway								Closed spillway							
	pH	DO	Turbidity	TSS	COD	NH_3-N	NO_2-N	NO_3-N	pH	DO	Turbidity	TSS	COD	NH_3-N	NO_2-N	NO_3-N
1	II	I	II	II	V	III	I	I	III	III	>II	II	IV	I	I	I
2	II	I	>II	I	V	II	I	I	III	III	II	II	IV	II	I	I
3	II	I	>II	I	V	II	I	I	III	III	>II	II	V	II	I	I
4	II	I	>II	II	V	II	I	I	II	III	>II	II	V	II	I	I
5	II	I	>II	II	V	III	I	I	II	III	>II	III	V	III	I	I
6	II	I	>II	III	V	II	I	I	III	III	>II	II	IV	III	I	I
7	II	I	>II	II	V	II	I	I	II	III	>II	III	IV	II	I	I
8	II	I	>II	III	V	II	I	I	II	III	>II	III	IV	II	I	I
9	II	I	>II	II	V	II	I	I	II	III	>II	III	IV	II	I	I
10	II	I	>II	II	IV	II	I	I	II	III	>II	II	IV	II	I	I
11	II	I	>II	II	IV	II	I	I	II	III	>II	III	V	II	I	I
12	II	I	>II	III	IV	II	I	I	II	III	>II	III	V	II	I	I
13	II	I	>II	II	IV	II	I	I	II	II	>II	III	V	II	I	I
14	II	I	>II	III	V	II	I	I	II	II	>II	III	IV	II	I	I
15	II	I	>II	III	V	III	I	I	II	II	>II	III	V	III	I	I

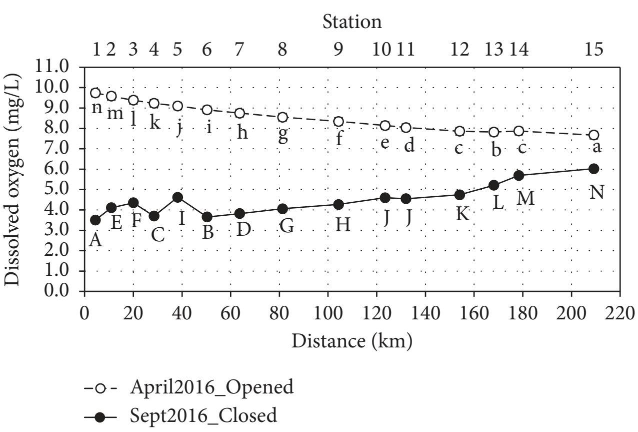

Figure 4: Dissolved oxygen at the 15 stations downstream of Bakun Hydroelectric Dam during opened spillway (o) and closed spillway (•). The same letter indicates no significant difference ($p > 0.05$).

Besai River, respectively. Low DO downstream of a dam is also reported below Nam Ngum I Reservoir where along the 5 km stretch, monthly measured DO was mostly below 5 mg/L [18]. The DO during opened spillway was classified as Class I, while during closed spillway, the DO was classified as Class II from station 13 to station 15 and Class III from station 1 to station 12 (Table 4). During closed spillway, the linear model used to estimate the change in DO during closed spillway shows that the rate of increase was only 0.009 mg/L per km from station 1 to station 15 inclusive of rapids reaeration and inflows from big tributaries along the way. As for opened spillway, the loss rate in DO (−0.010 mg/L per km) estimated from data of stations 6 to 12 using the linear model was similar to that during closed spillway. However, from station 1 to station 12, that is, up to a distance of 154 km away from the dam, the exponential decay model fits the DO data better than the linear model with the coefficient of distance, b, of 9.648 and exponent, a, of −0.001 as shown in Figure 5.

The turbidity during opened spillway ranged from 48.23 NTU to 90.26 NTU, and the highest mean recorded was at station 15, the furthest from the dam, while the lowest mean recorded was at station 1, the nearest to the dam (Figure 6). There is a general trend of increasing turbidity at a rate of 0.15 NTU per km as the water flows downstream. During closed spillway, the turbidity values ranged from 47.97 NTU to 229.65 NTU with the highest mean recorded at station 15 and the lowest mean observed at station 2. Station 2 turbidity was the lowest due to the slower flow of water than the other stations which means less turbulence, and thus, deposition of solids took place. Similar to opened spillway, turbidity values during closed spillway showed a general increasing trend with the increasing distance from the dam. However, there were significantly higher turbidity values recorded at some stations such as stations 7, 8, 11, to 15 due to the rain which contributes to the high turbidity as the interaction of rainfall and the exposed soil causes erosions of sediments contributing to the addition of silts, clays, and suspended solids which increases the turbidity of water [11]. This is supported by the high correlation between turbidity and TSS (r = 0.857, $p < 0.05$). In this study, the turbidity of the river falls in the range between 50 mg/L and 250 mg/L. However, the turbidity measurements conducted in the past studies stated that the turbidity is less than 50 mg/L at the depth of 10 m to 20 m in the dam reservoir in

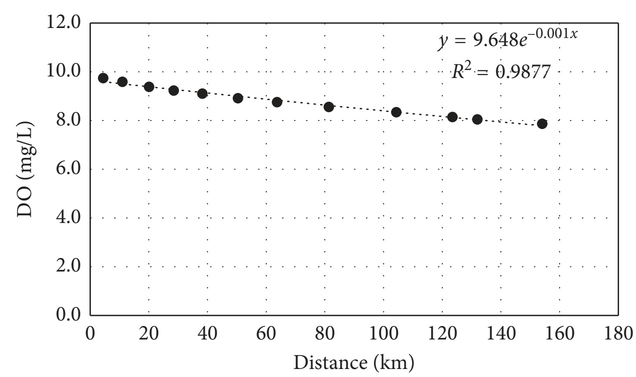

Figure 5: Exponential decay model fit of DO up to a distance of 154 km away from the Bakun Dam during opened spillway.

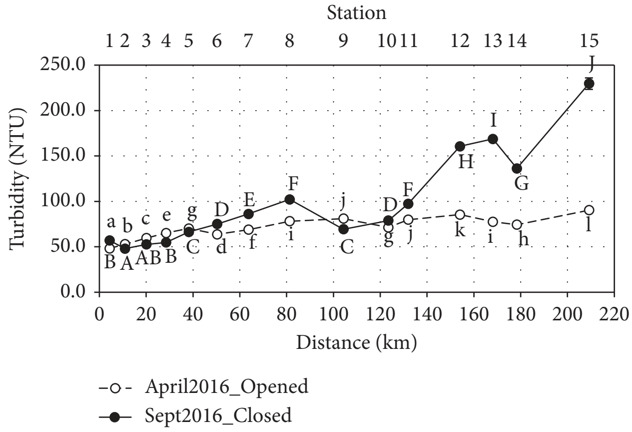

Figure 6: Turbidity at the 15 stations downstream of Bakun Hydroelectric Dam during opened spillway (o) and closed spillway (•). The same letter indicates no significant difference ($p > 0.05$).

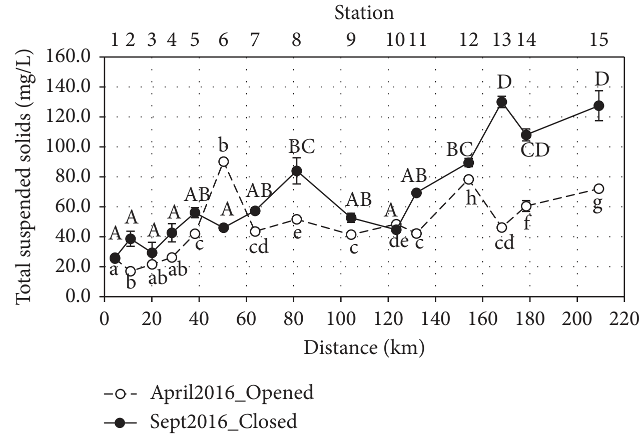

Figure 7: Total suspended solids at the 15 stations downstream of Bakun Hydroelectric Dam during opened spillway (o) and closed spillway (•). The same letter indicates no significant difference ($p > 0.05$).

2015 [5, 6]. Thus, the spillway and turbine outflow of Bakun Dam is not the source of the high turbidity downstream. The means between the two trips for turbidity were significantly different from each other ($p < 0.05$) (Table 3). During opened spillway, the turbidity at all of the stations exceeded 50 mg/L except station 1. For closed spillway, all the stations also showed turbidity exceeding 50 mg/L except station 2. Thus, according to NWQS, all stations during the two trips exceeded Class II with the exception of station 1 during opened spillway and station 2 during closed spillway which are classified as Class II (Table 4).

3.2. Ex Situ Water Quality Parameters. The total suspended solids (TSS) during opened spillway ranged from 17.0 mg/L to 90.2 mg/L, whereas higher values ranging from 26.0 mg/L to 130.0 mg/L were observed during closed spillway (Figure 7) with the means between two trips significantly different from each other ($p < 0.05$) (Table 3). The trends of TSS during both opened and closed spillways were similar to that of the turbidity (Figure 6). During both opened and closed spillways, increasing TSS were observed from station 3 onwards. This is due to the erosion from numerous cleared forest logging activities and oil palm plantation development activities. During closed spillway, TSS increased significantly from station 7 to station 8 and from station 12 to station 13 due to heavy rain during the sampling time which resulted in resuspended sediments. In addition, the sharp increase in TSS from station 12 to station 13 was also due to erosion from a large logging area with exposed soil. During opened spillway, there was a significant increase in turbidity from station 4 to station 6. This is due to the input from the large Belaga tributary where upstream there was active logging and oil palm plantation development activities resulting in soil exposure to rainfall events as it was the rainy season. The heavy rain generated the surface runoff which moved sediments into the river increasing the TSS as supported by a previous study in Baleh River which showed that there was a tenfold increase in TSS after the rain compared to that before the rain [19]. A previous study at the Pelagus area also reported a high TSS concentration of 380 mg/L in the Rajang River observed after raining the night before sampling. Significantly higher TSS at station 15 were mainly due to the soil erosion from the exposed land due to logging activities [20] and the exposed soil at the coal mining loading bay. Station 15 is also below the coal mine loading bay where such an activity increases soil exposure and erosion. TSS during open spillway were mostly Class II except for stations 2 and 3, which were Class I, and stations 6, 8, 12, 14, and 15, which were classified as Class III (Table 4). During closed spillway, six stations (1, 2, 3, 4, 6, and 10) were classified as Class II, while nine stations (5, 7, 8, 9, 11, 12, 13, 14, and 15) were classified as Class III of NWQS.

Chemical oxygen demand (COD) measures the amount of oxygen required to oxidize the chemically oxidizable compounds. During opened spillway, the COD concentration ranged from 61.3 mg/L to 173.3 mg/L as shown in Figure 8. The highest mean recorded was at station 1 which is nearest to the dam and the lowest mean recorded was at station 10, 123.4 km away from the dam. There was a significant decrease from station 1 to station 4 ($p < 0.05$) followed by no significant difference between stations 4 and 5 ($p < 0.05$). The decrease was countered by the input from the Belaga tributary and wastewater inflow from Belaga Town. During closed spillway, the concentration of COD ranging from 53.3 mg/L to 130.6 mg/L was lower than that during opened spillway at most of the stations. Overall, the COD during opened spillway was significantly higher than that during closed spillway ($p < 0.05$) (Table 3). The COD during closed spillway peaked at station 5, indicating organic waste inputs from the Belaga Town and Belaga tributary where there are human settlement, oil palm activities, and logging camps. Sources of organic substances are from both the Bakun Dam outflow and the development in the river basin itself. According to past research, the COD concentration in the Bakun Reservoir ranged from 6.7 mg/L to 118.7 mg/L from 0 to 30 m depth in 2013 [5], and BOD_5 exceeded Class II at 0–20 m depth [6], indicating oxygen demand due to organic materials in the reservoir. Organic materials are also

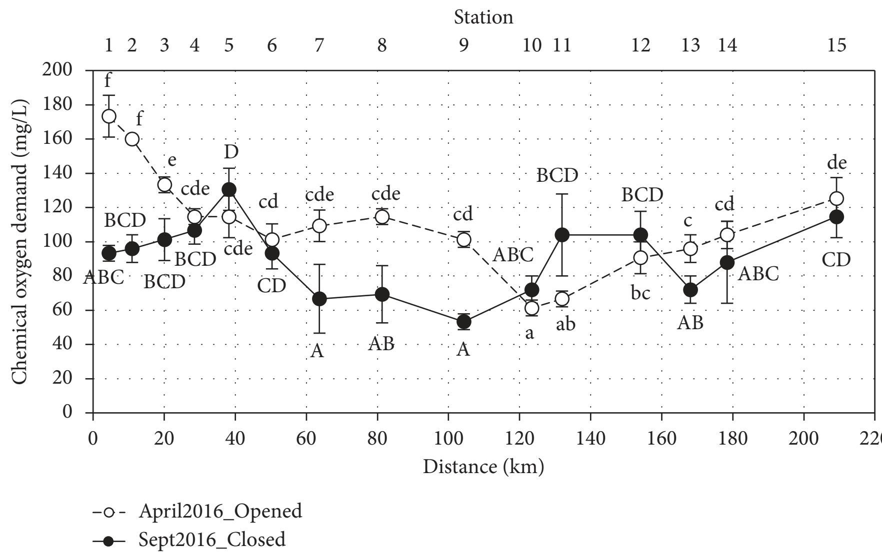

Figure 8: Chemical oxygen demand at the 15 stations downstream of Bakun Hydroelectric Dam during opened spillway (o) and closed spillway (•). The same letter indicates no significant difference ($p > 0.05$).

attributed to the domestic wastewater and runoff from the settlement near to Bakun Dam, logging camps, oil palms, and towns and villages along the main Rajang River and its tributaries as shown by other studies [6, 9, 21, 22]. COD of household wastewater from a residential area in Kuching has been reported to be 165 mg/L [23]. There is a significant correlation between COD and NO_3-N ($r = 0.638$, $p < 0.05$) and COD and NO_2-N ($r = 0.390$, $p < 0.05$), indicating organic waste. The closed spillway turbine outflow COD of 93.3 mg/L in the present study is close to that in the previous study, but the opened spillway COD is higher than the value reported (80 mg/L) [8]. In comparison with the range of COD (43.8 mg/L to 61.4 mg/L) in the past study in Sembrong Dam, Johor, in 2015 [24], the range of COD concentrations in the present study in Rajang River is observed to be higher for both opened and closed spillways. During opened spillway, all stations except stations 10 to 13 have COD concentration higher than 100 mg/L, and they fall into Class V of NWQS (Table 4). Stations 10 to 13 on the contrary were classified as Class IV. During closed spillway, all stations are in Class IV (50–100 mg/L) except six stations (3, 4, 5, 11, 12, and 15) with concentrations exceeding 100 mg/L, and thus, they are classified as Class V of NWQS.

Ammonia-nitrogen (NH_3-N) is one of the three main forms of nitrogen which indicates the status of organic nutrients enrichment and the condition of the water bodies [3, 25]. During closed spillway, the NH_3-N values ranged from 0.12 mg/L to 0.37 mg/L. The highest mean was recorded at stations 5 and 6, while the lowest mean was recorded at station 3. The NH_3-N during opened spillway ranged from 0.06 mg/L to 0.49 mg/L as shown in Figure 9. The highest mean recorded was at station 5 (38.2 km from Bakun Dam), and the lowest mean recorded was at station 9 (104.3 km from Bakun Dam). During the opened spillway, the NH_3-N concentration was significantly higher in stations 1, 5, and 15. The input from spillway contributes to the high concentration of NH_3-N which was also observed in a previous study on the 32 km stretch [8]. The past research conducted in the Bakun Dam showed that the area nearest to the water intake has a range of 0.016 to 0.35 mg/L for NH_3-N [5]. Station 5 was significantly higher than station 4 during both trips due to the waste input from Belaga Town and Belaga River through the runoff and waste from commercial and residential areas. Main nitrogen-ammonia sources along the river are residential areas, sewage systems, and commercial areas [26]. Station 15 on the contrary has significantly higher ammonia-nitrogen due to the waste from active coal mining activities. The overall means for NH_3-N between two trips were not significantly different from each other ($p < 0.05$) (Table 3). The NH_3-N during opened spillway was classified as Class II for all stations except for stations 1, 5, and 15 which were classified as Class III (Table 4). During closed spillway, all the stations were classified as Class II, except for stations 5, 6, and 15 which were classified as Class III. Stations 5 and 15 consistently fall into Class III.

Figure 10 shows the concentrations of nitrate-nitrogen (NO_3-N) during opened and closed spillways. The concentration of NO_3-N during opened spillway ranged from 0.04 mg/L to 0.13 mg/L. The highest mean recorded was at station 2, and the lowest mean was recorded at stations 10, 13, and 14. When the spillway was opened, stations 1 to 4 NO_3-N was observed to be not significantly different from one another and the highest among the stations due to the formation of NO_3-N from the oxidation of ammonia in the presence of high DO (Figure 4), which is supported by the significant and high correlation between NO_3-N and DO ($r = 0.867$, $p < 0.05$), with the corresponding decrease in NH_3-N (Figure 9). During closed spillway, the NO_3-N values, ranging from 0.00 mg/L to 0.04 mg/L, were lower at all the stations. The low NO_3-N at stations 1 and 2 concurs with previous observation at the station near the water intake in the Bakun Reservoir, where the values less than 0.004 mg/L from 0 to 10 m depth [27], 0.008–0.020 from 0 to 10 m depth [6], and 0.023–0.027 from 0 to 15 m depth were

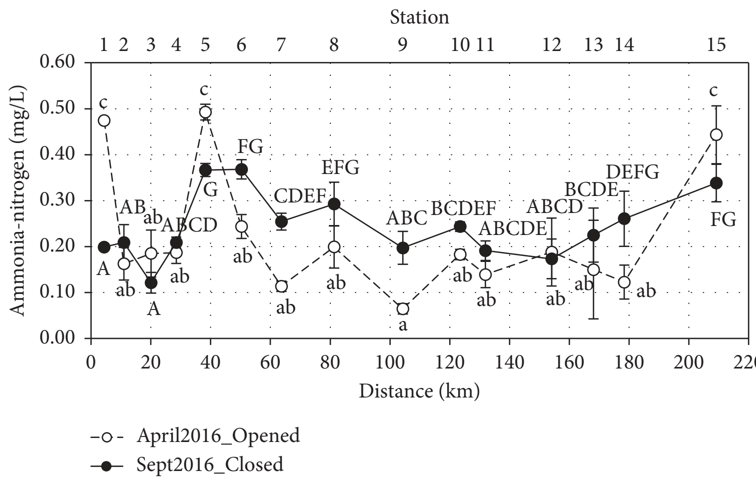

FIGURE 9: Ammonia-nitrogen at the 15 stations downstream of Bakun Hydroelectric Dam during opened spillway (o) and closed spillway (•). The same letter indicates no significant difference ($p > 0.05$).

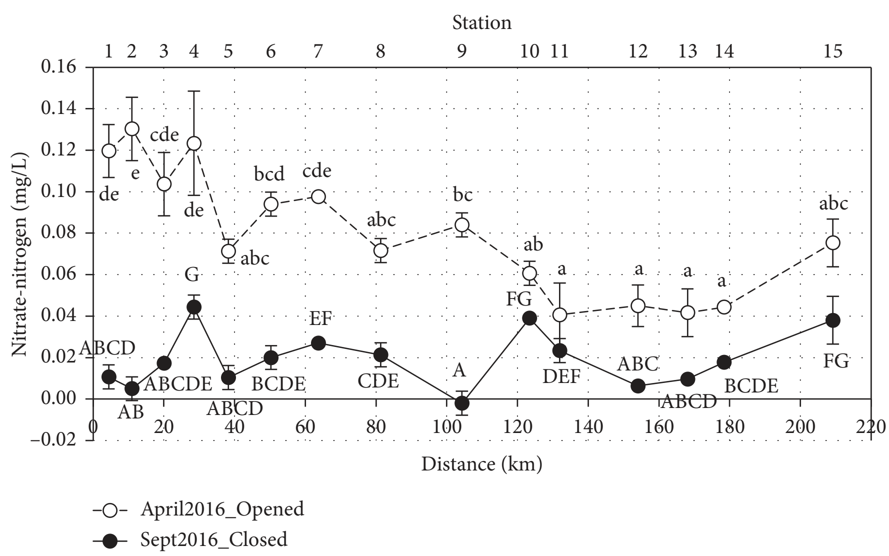

FIGURE 10: Nitrate-nitrogen at the 15 stations downstream of Bakun Hydroelectric Dam during opened spillway (o) and closed spillway (•). The same letter indicates no significant difference ($p > 0.05$).

observed [5]. The highest mean was recorded at stations 5, 10, and 15, while the lowest mean was recorded at station 9. The higher valued stations were most likely contributed by domestic waste. The means for NO_3-N between two trips were significantly different from each other ($p < 0.05$) (Table 3). The concentration of NO_3-N in all stations for the two trips complied with Class II of NWQS for Malaysia (Table 4).

The nitrite-nitrogen (NO_2-N) is less dominant than NO_3-N in river as NO_2-N is the intermediate compound when ammonia is oxidized to NO_3-N [28]. NO_2-N during opened spillway ranged from 0.002 mg/L to 0.008 mg/L as shown in Figure 11. The highest mean recorded was at station 15, and the lowest mean recorded was at station 7. Spikes were observed at stations 5 and 8. From station 11, the reading began to increase until station 15. During closed spillway, the NO_2-N values at almost all the stations were lower (0.000–0.005 mg/L). The highest mean was recorded at station 15, while the lowest mean was recorded at station 13. Similar to NO_3-N, the Bakun Dam in past research has concentration of NO_2-N more than 0.004 mg/L [5]. During closed spillway, only station 15 was observed to have significantly higher NO_2-N concentration more than 0.004 mg/L. This is due to the presence of coal mine in the area. Excavation and mining of coals from coal mines cause possible leaching of nitrogen elements into the river [29]. In addition, DO increased as distance from the dam increased providing oxygen needed for the oxidation of ammonia to nitrite, as supported by the significant correlation between NO_2-N and DO ($r = 0.403$, $p < 0.05$), and subsequently to nitrate. Thus, this increases the concentration of NO_2-N in the river particularly at station 15. The means for NO_2-N between two trips were significantly different from each other ($p < 0.05$) (Table 3). The concentration of NO_2-N at all stations for the two trips complied with Class II of NWQS for Malaysia (Table 4).

A comparison of water quality of Rajang River in the present study based on the dam operations, namely, opened

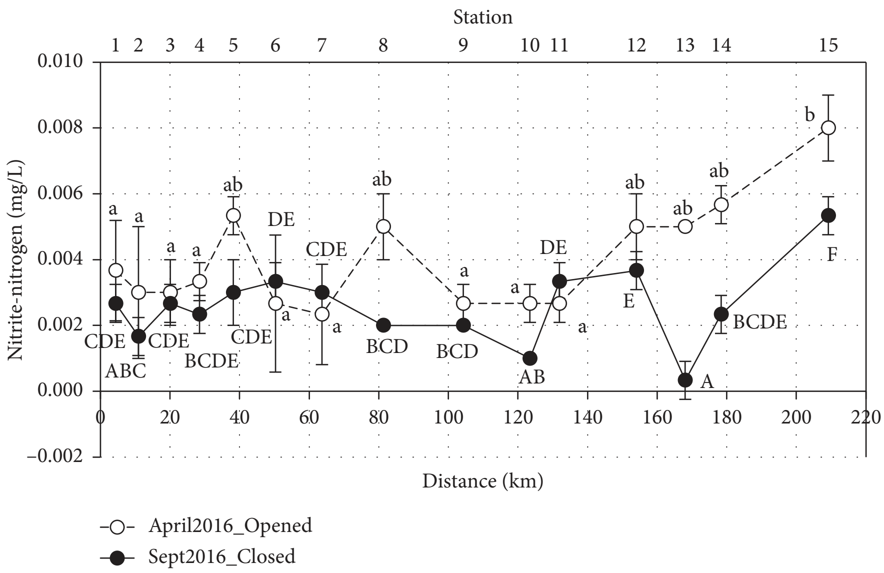

Figure 11: Nitrite-Nitrogen at the 15 stations downstream of Bakun Hydroelectric Dam during opened spillway (o) and closed spillway (•). The same letter indicates no significant difference ($p > 0.05$).

Table 5: Water quality parameters of the present study compared with the values before building the Bakun Dam [30].

Parameters	Before building the dam	Values of the present study (closed spillway)	Values of the present study (opened spillway)
pH	6.4	5.6–6.4	6.2–6.5
Temperature (°C)	24.7–25.5	27.0–27.9	26.9–27.8
Dissolved oxygen (mg/L)	8.3–8.5	3.5–6.1	7.6–9.8
Total suspended solids (mg/L)	250–1500	26.0–127.5	25.4–90.2
Ammoniacal-N (mg/L)	0.009	0.12–0.37	0.11–0.49
Nitrate-N (mg/L)	0.047	0–0.04	0.04–0.13

and closed spillways, with that before building the Bakun Dam is shown in Table 5. The present study shows that when the spillway was closed, there was a lowering of pH, DO, and TSS and an increase of temperature and NH_3-N. When the spillway was opened, there was also a lowering of TSS with pH and DO being comparable with that before damming. This indicates that damming has the advantage of lowering TSS in the water. In addition, the impact on the aquatic life downstream could be mitigated by opening the spillway which will raise the DO and pH.

4. Conclusions

This study shows that there is a significant effect of the operations of Bakun Dam spillway on the water quality of the 210 km stretch of the downstream river towards Kapit Town. With closed spillway, as we approach the dam, there was a general decreasing trend in pH and DO, indicating that the water was increasing in acidity with less oxygen content and it became much more acidic and much less in DO than opened spillway water. The impact of unhealthy DO stretched to a distance of about 165 km from the dam. As the water flows downstream from the dam, it is more susceptible to other influences such as input from settlements, tributaries, and diurnal changes in solar radiation when the spillway was closed than when opened except for parameters such as turbidity and total suspended solids from large tributaries where there is erosion during opened spillway which coincided with the rainy season. The river suffers organic pollution as indicated by COD which falls either into Class IV or into V with opened spillway showing worse condition than closed spillway. The high ammonia in opened spillway water and from the Belaga area was quickly oxidized to nitrate due to the abundance of oxygen. Comparisons of spillway operations with natural river prior to the dam construction show that, during closed spillway, there was a decrease in pH and DO, and under both spillway operations, there was a decrease in TSS but an increase in temperature and ammonia. When the spillway was opened, pH and dissolved oxygen are comparable with the natural river prior to dam construction. As such, it is recommended that, during closed spillway, DO should be increased for the health of sensitive aquatic organisms along the river downstream.

Data Availability

The raw data and processed data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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