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Stratification and Water Quality Variations in Three Large Tropical Reservoirs

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ABSTRACT

A comparative study was performed for three large and deep hydropower reservoirs in Malaysia to understand stratification stability and water quality pattern. Vertical profiling was carried out over 5-8 locations each in Temenggor, Kenyir and Bakun reservoirs. Lake-water quality was assessed following the national Water Quality Index (WQI) while trophic state was evaluated following Carlson's Trophic State Index (TSI). Stratification variables and water quality variation were analysed using ANOVA. Marked thermal stratification with significant differences in mixed-layer depth and epilimnetic temperature ($p < 0.001$) was observed in all reservoirs. Significance differences in surface conductivity, total phosphorus, turbidity and transparency ($p < 0.001$) was also observed in all reservoirs. The findings on the surface WQI showed that all three reservoirs were still categorized as Clean (Class II), which is suitable for recreational uses with body contact including tourism-based activities. The results on the assessment of TSI (chlorophyll a) indicated all three reservoirs were in mesotrophic state. TSI data based on phosphorus and transparency for Bakun and Kenyir Reservoirs were consistently mesotrophic, while Temenggor Reservoir, which is the oldest amongst the studied reservoirs, showed high TSI (total phosphorus) >53 signifying nutrient-rich environment. Bakun Reservoir, however, showed an increase in total phosphorus values with depth indicating continuing nutrient release from decomposition of freshly drowned vegetation. Ammoniacal nitrogen and total suspended solids increased with depth in all reservoirs.

Key Words: Hydropower Dam; Limnology; Thermocline; Trophic State; Vertical Profile

INTRODUCTION

Reservoirs have continuously been created to support economic development worldwide, either for generation of hydropower or storage of freshwater resources for domestic, agricultural and industrial needs. In Malaysia, more than 80 dams have been created to date for water storage, flood retention, hydropower generation and irrigation, with a total surface area and volume of 1,784 km^2 and 70,390 Mm^3, respectively (NAHRIM 2016). In contrast to water supply reservoirs, which are more shallow, reservoirs that were created for hydropower generation are mostly large and/or deep. Vertical stratification of temperature is not uncommon in deep lakes or reservoirs due to the variation in density resulting from temperature differences between the water layers (Imberger and Patterson 1990, Wetzel 2001).

Thermal stratification studies have shown that reservoirs located at low latitudes are either monomictic, with persistent stratification and mixing occurring once a year if they have moderate to great depth (Lewis 1983, 1987), or polymictic, with stable stratification ranging diurnally, daily or weekly if they are of more shallow depth (Lewis 1983). These findings however were based on large number of tropical lakes located in Africa, South America, Australia and in Ranu Lamongan in Indonesia, which are very well studied (Green et al. 1976, Lewis 1987, Tundisi et al. 1995, MacKinnon and Herbert 1996). These tropical inland water bodies are characterized by large total annual irradiance and high surface temperatures, with low and irregular thermal stability and mixed layer thickness (Lewis 1987, Henry 1999). The presence of thermal stratification leads to vertical distribution of chemical and biological parameters in the water column, depletion of dissolved oxygen (DO), increase in ammonium, electrical conductivity, iron, manganese and carbon dioxide concentrations at the bottom layer, and variation in community structure (Tundisi et al. 1995, Boehrer and Schultze 2008). This subsequently may impact the use of water for other purposes including water supply and aquaculture, or affect downstream habitats if water of low quality is released into the environment.

Limnological studies in Malaysia since the 1970s have concentrated on shallow inland water bodies such as Bera Lake (Sharip and Zakaria 2007). Many of the past and recent studies on stratification of reservoirs in the country have been performed to investigate the potential of the reservoirs for aquaculture and fishery development (DOF 1993, Lee et al. 2012, Yee et al. 2012), while some were carried out to understand water quality, biological characteristics and productivity (Baharim et al. 2011). The suitability for fish production is mostly determined by the surface mixed layer above the thermocline, which usually has higher DO, pH values and warmer temperature, and subsequently better water quality. Long-term studies of Kenyir Reservoir in the 1990s indicate that stronger stratification structure contributed to the control of eutrophication in the lake (Yusoff and Lock 1995). Water-quality studies on other reservoirs in Malaysia have focused on individual lakes with measurements mostly confined to about 20-30 m from the lake surface due to instrument limitation, and how it varies with seasons and changes in surrounding development (Khalik and Abdullah 2012, Yee et al. 2012). There is limited information on vertical assessment of physical and chemical stratification on multiple deep reservoirs including their bottom water characteristics in this part of the region to generalize limnological conditions in particular to accommodate increasing economic demand for multiple uses of reservoirs. The water column characteristics in hydropower reservoirs may also differ with dam age due to hydro-ecological changes and anthropogenic activities within the catchment.

In this study, limnological characteristics of three deep hydropower reservoirs built in different time-spans over the last 40 years were investigated to understand their thermal profile and water quality patterns. Comparative studies of stratification patterns and effects on water quality variation in newly built and old reservoirs are limited. Water quality patterns in newly filled reservoirs are very much influenced by the stratification structure developed in the formation of the reservoir. By investigating the varying differences of stratification structure in these lakes, this study illustrates the water quality patterns associated with the stratification profiles, subsequently contributing to better understanding of underlying factors to assist in management of tropical reservoirs. The hypothesis of this study: (i) there are significant differences in temperature and stratification variables between depths in the three reservoirs; (ii) there are significant differences in water quality and trophic state in these deep reservoirs.

STUDY AREA

A total of three deep and large reservoirs in Malaysia, situated close to the equator, were included in this assessment (Figure 1). The selected reservoirs are highly dendritic, created by damming the major rivers, and have catchments with vast landscapes of tropical rainforest. The characteristics of Kenyir and Temenggor Reservoirs, located in the Malaysian Peninsular, and Bakun Reservoir in the state of Sarawak, West Malaysia, are given in Table 1. Operational since 1975, Temenggor Reservoir is the oldest and smallest among the three reservoirs, and is located at the uppermost point of the Perak River near the Malaysia-Thailand border. The upstream part of the lake comprises the Royal Belum State Park, an important conservation area which houses bountiful biodiversity and globally threatened wildlife species. Kenyir Lake, built on Kenyir River in 1985, is the largest reservoir in Peninsular Malaysia. Strategically located on the east coast of the peninsular, Kenyir Lake has been designated as an important eco-tourism destination and is partly located in Malaysia's largest National Park. Bakun Dam was fully inundated in 2012 with a total surface area of 690 km^2 at full supply levels, and has now become the largest reservoir in Malaysia (Sovacool and Bulan 2013). The reservoir, which was created by damming the Balui River, and is positioned in the upper Rajang catchment on the island of Borneo, has a total catchment area of 14,740 km^2 (Osman 2008, Sovacool and Bulan 2013). Being part of the Sarawak Corridor of Renewable Energy, the reservoir has the largest hydropower-generating capacity in Malaysia, producing 2400 MW of electricity to support future development of energy-intensive industries (Sovacool and Bulan 2013).

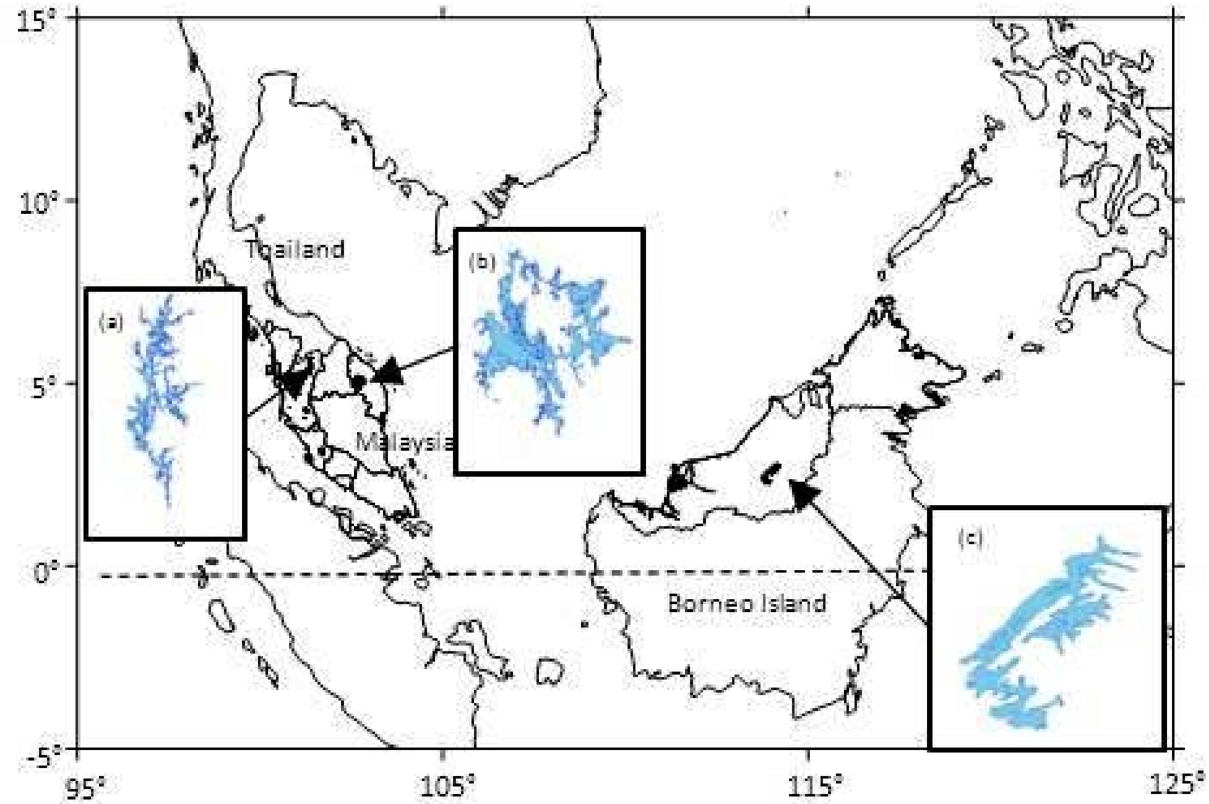

Figure 1: Location of studied reservoirs: (a) Temenggor (b) Kenyir (c) Bakun

Table 1: Characteristics of studied reservoirs

Reservoir	Temenggor, Perak	Kenyir, Terengganu	Bakun, Sarawak
Position	5°31'47.54"N 101°20'46.07"E	5° 6'50.10"N 102°47'12.44"E	2°45'30.15"N 114° 4'14.23"E
Altitude (m a.s.l)	245	145	228
Year construction; operational	1967-1972; 1975	1978-1985; 1987	1996-2012; 2014
Surface area (km^2)	152	370	695
Storage volume (m^3)	5,300	13,600	14,750
Full supply level; Minimum operating level (m a.s.l)	248; 236	153; 120	228; 195
Power generation (MW)	348	400	2400

MATERIALS AND METHODS

Measurement of water quality was performed twice in 2014-2015, during the end of a long dry season or drought period, at 5-8 locations of each lake. Sampling locations were in the pelagic areas, at the centre of the reservoir. Vertical profiles of in-situ parameters such as temperature, DO concentration, conductivity, turbidity and pH values were measured using multi-parameter probe YSI 6600. Due to the limitation of the cable and sensor, vertical measurements in all reservoirs were also performed using Hydrolab DS-5. The two instruments were carefully calibrated and tested for consistencies. Water samples were collected at sub-surface, mid-depth and near-bottom (>85% of total depth) depths using a Van Dorn sampler, stored in 1 l, 500 mL PE bottles, and preserved in a container at 4 C prior to transportation to the laboratory for analysis of chlorophyll a (Chl-a), total phosphorus (TP), total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD) and ammoniacal nitrogen (AN).

All analyses were carried out in accordance with the APHA Standard Methods (APHA 1995). Chl-a was determined by fluorometric method whilst BOD was estimated by 5-days BOD test and COD by closed reflux-colorimetric method. AN was determined by automated phenate method and TSS was calculated by gravimetric technique. TP was analysed by the persulphate digestion and automated ascorbic acid reduction method. Secchi disk transparency (SDT) was measured using a standard Secchi disk. The Malaysian Department of Environment Water Quality Index (DOE-WQI) was calculated based on the sub-index of six parameters multiplied with the weighting factors (DOE 2011, Zainudin 2010). TSI calculations were made in accordance with Carlson (1977).

Additionally, seven stratification variables were analysed against environmental variables. Mixed-layer and thermocline thickness were defined as thickness of isothermal layer in the Ford and Stefan (1980) and mean thickness of the thermocline or metalimnion in each lake. Epilimnetic temperature was characterized as the mean temperature at 1 m, in line with King et al. (1997), whilst hypolimnetic temperature was assessed as the mean temperature at 1 m below the thermocline till the last measured temperature or temperature near lake bottom, whichever was applicable at each sampling point. This assumption was based on isothermic thermal profiles of the hypolimnion at most sampling locations, where temperature difference in hypolimnion was stable at <0.1 C/m. Maximum temperature difference was calculated between epilimnetic and hypolimnetic layers with change in temperature of <1 C at each lake. Epilimnetic and hypolimnetic stability was the mean difference in temperature at each layer.

The environmental variables were checked for normality and multi-colinearity. Any skewed data were log-transformed and standardized prior to analysis of variance (ANOVA). One-way between-groups ANOVA was performed to explore the relationship between the stratification variables and the surface water quality parameters. The relationships between the water quality variations between lakes at each depth were also explored. A two-way between-groups ANOVA was performed to evaluate the interaction effect of depth (surface-, mid- and bottom-depth) and lake location on six environmental variables, namely TP, AN, TSS, BOD, COD and Chl- a. Post-hoc comparisons using Tukey test were used to identify significantly different means. Relationships between thermal stability and environmental variables were analysed using Spearman correlation analysis. All analyses were performed using SPSS version 18. The alpha level of significant was set at 0.05.

RESULTS

Vertical Stratification

Vertical temperature measurements showed all three reservoirs were thermally stratified (Figure 2). The mixed-layer depth varied between lakes: 5 m (Bakun), 8 m (Temenggor) and 12 m (Kenyir). In this study, the thicknesses of the layer with the maximum gradient of temperature or thermocline were around 12.4 m (Kenyir), 13.5 m (Bakun) and 14.9 m (Temenggor). One sampling point in Kenyir, however, showed a slightly different thermal profile, probably influenced by riverine input; this was excluded in the ANOVA. Oxycline occurred unvaryingly in Temenggor (~10 m) and Kenyir (20 m), and fluctuated in Bakun (5-20 m). DO values in the epilimnion were slightly variable for Temenggor, whereas DO values in Kenyir were consistent uniform at 7 mg/L, except for one location. My qualitative observations showed strong wind during the sampling that could induce turbulence and increased DO values in the mixed-layer depth at this point. DO concentrations in Bakun were highly variable. DO concentration reached almost 0 mg/L in both Kenyir and Bakun Reservoirs.

In terms of differences in stratification variables on the three lakes, mixed-layer depth, epilimnetic temperature and stability were found to differ ($p < 0.001$) between the lakes. Post-hoc analysis using Tukey tests indicated significant differences in mixed-layer depth between Temenggor and Kenyir ($p = 0.001$), Temenggor and Bakun ($p = 0.005$) and Kenyir and Bakun ($p = 0.00$). Tukey tests indicated significant differences in epilimnetic temperature between Temenggor and Kenyir ($p < 0.001$) and Temenggor and Bakun ($p < 0.001$), but no difference in epilimnetic temperature between Kenyir and Bakun. ANOVA tests indicated that thermocline depth and hypolimnetic temperature have no significant difference between lakes (Table 2). Mixed-layer depth was positively correlated to transparency ($r = 0.823$, $p = 0.00$) and negatively correlated to conductivity, turbidity

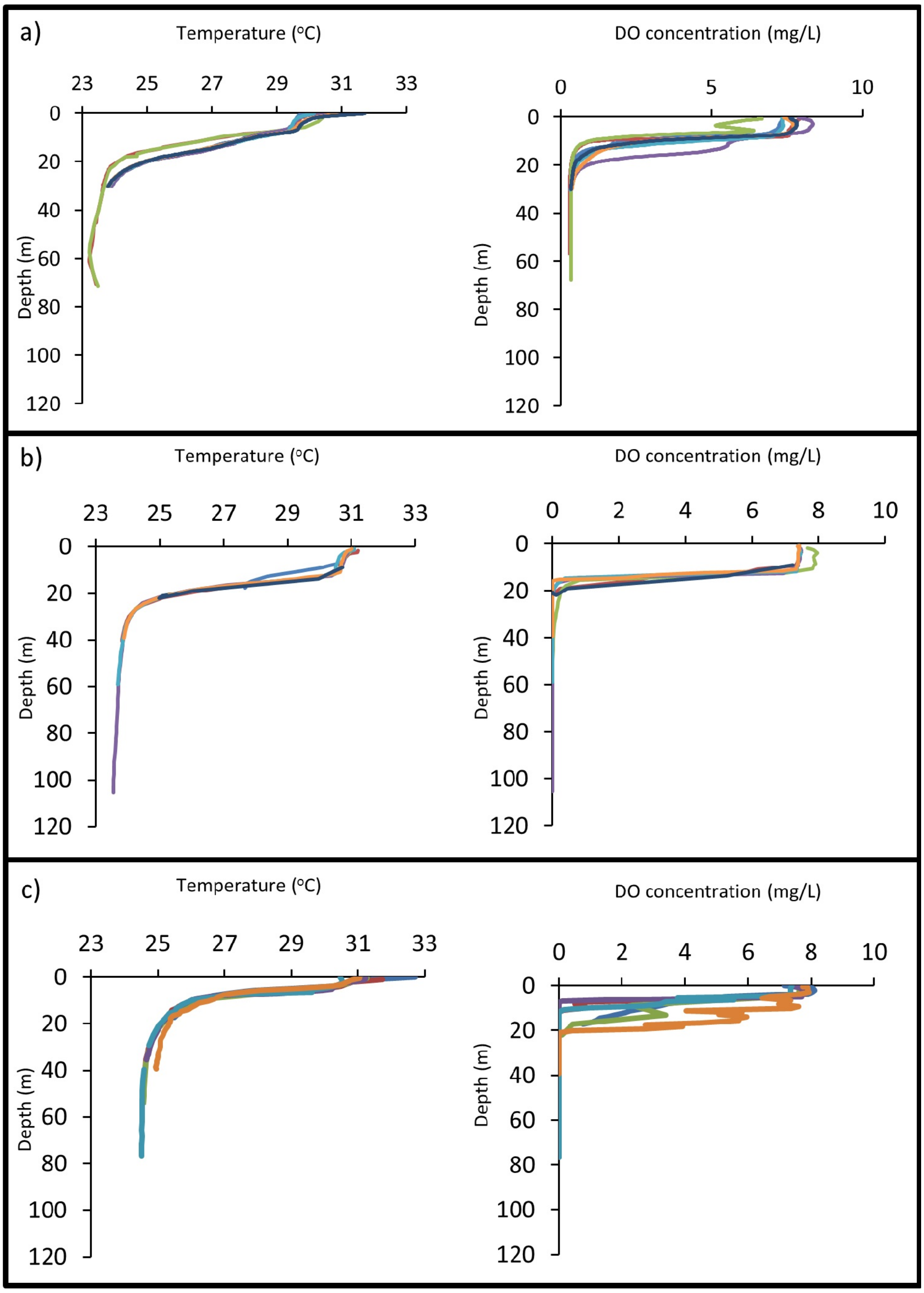

Figure 2. Vertical profiles of temperature and DO in studied reservoirs: (a) Temenggor (b) Kenyir (c) Bakun

and AN ($p < 0.005$), while epilimnetic temperature was negatively correlated to pH ($r = -0.659$, $p = 0.001$) and TP ($r = -0.535$, $p = 0.01$).

Water Quality Variation Between Lakes

The mean and standard deviation of environmental variables are as shown in Table 3. Water quality parameters such as DO, conductivity, AN, Chl-a and TSS were correlated to temperature. DO concentration dropped below 4 mg/L at about 12 m in Kenyir compared to Bakun and Temenggor, where this occurred at depths of around 6 m and around 9 m, respectively. DO levels reached hypoxic to anoxic level at around 17 m in Kenyir, around 14 m in Temenggor and around 10 m in Bakun. The lakes showed no significant differences

Table 2. ANOVA results between stratification variables

Variable	Mean **Temenggor**	**Kenyir**	**Bakun**	**F**	**p-value**
Mixed layer depth, m	7.65	11.02	7.94	29.873	0.0000**
Thermocline thickness, m	14.91	12.43	13.50	1.436	0.2638
Epilimnetic temperature, C	30.01	31.03	31.00	18.037	0.0000**
Hypolimnetic temperature, C	23.92	24.87	25.21	3.176	0.0658
Maximum temperature difference, C	6.09	6.22	5.80	0.294	0.7486
Epilimnetic stability	0.17	0.05	0.45	6.479	0.0076*
Hypolimnetic stability	0.07	0.09	0.03	4.226	0.0313

Note: *p<0.05, ** p<0.01

in terms of WQI, with mean WQI range between 90-95%, and mean TSI (Chl-a) around 38-41 µg/L. TSI values based on TP and SDT were close to TSI (Chl-a), in the range of 32-41 for Kenyir Reservoir. However, TSI (TP) and TSI (SDT) were highly variable for Temenggor and Bakun Reservoirs.

ANOVA test carried out for 16 variables at the surface indicated significance differences in surface conductivity, TP, turbidity and transparency ($p < 0.001$) between the three lakes. Kenyir Reservoir had the highest mean transparency (3.9 m) followed by Temenggor Reservoir (2.2 m) and Bakun Reservoir (1.4 m). Bakun Reservoir had the highest conductivity, suspended solids and turbidity. At the mid-depth, differences in BOD and COD were also significant ($p < 0.001$). Differences in suspended solids were apparent at mid-depth and bottom-depth ($p < 0.001$).

Statistical analysis using two-way ANOVA indicated that the interaction effect between reservoirs and depth was not statistically significant for all environmental variables. However, there was a statistically significant effect of depth for AN, TSS, TP and Chl-a ($p < 0.001$).

DISCUSSION

In line with the hypothesis, thermal stratification were consistent in these reservoirs with strong thermocline developed in all three reservoirs despite the reservoirs have different age. However, differences in mixed layer thickness, epilimnetic temperature and stability were apparent between the lakes ($p < 0.001$). Thermocline that developed in Bakun Reservoir near the dam at around 6 m supported findings by Lee et al. (2012). This study, however, found that thermocline depth was more stable compared to the findings of the earlier study during the filling of the dam. This study is focused in the areas within a 25 km radius of the dam, and thermocline in Bakun Reservoir was apparent in all stations, ranging between 3.9 m to 6.4 m. For Kenyir, mixed-layer depth was almost double the earlier findings of Yusoff (2007), where the epilimnetic layer was reported to be thinner during dryer months in the reservoir. Deepening of thermocline may happen as a result of wind-induced motion (Imberger and Patterson 1990, Boehrer and Schultze 2008). Findings by King et al. (1999) supported that physical forcing dominated thermocline development in large lakes. Increased thickness of the epilimnion to 15 m was observed during the wetter season in Kenyir Reservoir, possibly induced by stormy North-East monsoon (Yusoff 2007). There was rainfall on the night before the sampling and strong wind was observed during the sampling in some locations. Strong wind and cooler environment may have induced differential deepening and increased mixed-layer depth in Kenyir Reservoir. Lower epilimnetic temperature in Temenggor compared to Kenyir and Bakun Reservoirs was possibly due to the position and altitude of this reservoir. Temenggor Reservoir is situated in the middle range of Titiwangsa ranges, which form the backbone of Peninsular Malaysia and surrounded with cool highland air temperature. The epilimnetic and hypolimnetic stability was much lower than the values found in the temperate and deep reservoirs (King et al. 1997), which indicates that tropical reservoirs have higher stratification stability – this is consistent with analysis of tropical lakes by Lewis (1983).

This comparative study of the lakes indicated that Kenyir has the highest water quality. Transparency was

Table 3. ANOVA results between environmental variables

Environmental		Sub-surface			Mid-depth			Near-bottom		
Variables	Reservoir	Mean	Std. Dev.	F	Mean	Std. Dev.	F	Mean	Std. Dev.	F
SDT	Temenggor	2.25	0.28	25.70**						
	Kenyir	3.86	0.99							
	Bakun	1.42	0.38							
DO	Temenggor	7.51	0.35	3.62	0.38	0.09	2.55	-	-	
	Kenyir	7.64	0.17		2.07	2.87		1.46	2.51	
	Bakun	7.04	0.71		0.30	0.76		0.14	0.36	
pH	Temenggor	6.85	0.48	4.79	6.20	0.37	3.36	-	-	
	Kenyir	6.38	0.31		6.49	0.43		6.52	0.46	
	Bakun	6.32	0.25		6.80	0.43		6.72	0.54	
TEMP	Temenggor	30.26	0.60	1.16	24.25	0.99	2.23	-	-	
	Kenyir	31.05	0.25		26.29	2.97		25.08	2.31	
	Bakun	30.73	1.78		24.93	0.26		24.73	0.23	
COND	Temenggor	37.35	1.30	199.99**	49.50	21.66	3.36	-	-	
	Kenyir	32.12	1.36		35.38	4.34		39.50	16.64	
	Bakun	50.57	2.64		54.20	5.89		50.75	5.68	
Log_{10}Turb	Temenggor	-0.25	0.39	23.96	-0.14	0.17				
	Kenyir	-0.38	0.47		0.004	0.84				
	Bakun	0.08	0.09		-	-				
BOD	Temenggor	5.12	2.64	2.20	3.63	1.19	14.35**	3.75	1.67	2.72
	Kenyir	5.75	2.19		4.12	1.25		5.00	1.41	
	Bakun	3.57	0.53		7.29	1.80		5.86	2.19	
COD	Temenggor	17.38	11.02	2.01	11.25	5.52	6.31	14.00	6.74	0.71
	Kenyir	18.50	4.37		12.88	3.64		16.25	3.81	
	Bakun	11.57	1.99		18.86	3.34		17.00	4.16	
Log_{10}AN	Temenggor	-1.91	0.89	1.24	-0.49	0.91	1.66	0.04	0.11	7.68
	Kenyir	-2.30	0.00		-0.94	0.85		-0.68	0.65	
	Bakun	-1.96	0.21		-1.26	0.70		-0.77	0.39	
Log_{10}TP	Temenggor	-0.93	0.09	112.12**	-0.91	0.14	46.37**	-0.74	0.09	38.06**
	Kenyir	-2.15	0.28		-2.26	0.11		-2.09	0.32	
	Bakun	-2.22	0.15		-1.86	0.49		-1.29	0.44	
Log_{10}Chl-a	Temenggor	2.86	1.83	0.737	-0.34	0.51	0.74	-0.26	0.49	0.96
	Kenyir	3.90	2.70		-0.07	0.38		-0.11	0.46	
	Bakun	2.06	0.84		-0.18	0.42		0.13	0.69	
Log_{10}SS	Temenggor	0.00	0.00	2.78	0.50	0.19	7.79*	0.77	0.25	28.36**
	Kenyir	0.00	0.00		0.54	0.47		1.05	0.34	
	Bakun	0.09	0.15		1.30	0.58		1.79	0.17	
WQI	Temenggor	90.25	4.77	0.593	65.12	4.09	1.99	-	-	
	Kenyir	90.62	2.44		72.50	11.61		68.75	12.04	
	Bakun	92.14	2.79		65.20	6.02		57.57	7.39	
TSISDT	Temenggor	48.40	2.01	30.15**						
	Kenyir	40.99	4.18							
	Bakun	55.41	3.90							
TSITP	Temenggor	72.81	2.87	112.11**	73.51	4.68	46.37**	79.30	2.91	38.06**
	Kenyir	32.37	9.26		28.62	3.54		34.35	10.54	
	Bakun	30.23	4.88		41.84	16.26		60.69	14.75	
TSIChl-a	Temenggor	39.23	6.07	0.74	22.87	11.50	0.74	24.61	11.07	0.96
	Kenyir	41.03	8.71		28.91	8.60		28.18		
	Bakun	36.75	4.84		26.53	9.50		33.46		

Note: $*p<0.05$, $** p<0.01$

highest in this man-made lake; this allows light penetration to deeper layers and subsequently affects temperature and enables biological productivity. This could possibly explain slightly higher concentrations of DO at deeper layers. In this study depletion of DO at Kenyir Reservoir occurs at deeper layers compared to the findings of the earlier study, where anoxic conditions occurred at 8-10 m (Yusoff 2007). The anoxic condition in the hypolimnion, in all three reservoirs, is likely to be induced by oxygen depletion resulting from either decomposition of drowned vegetation (Yusoff 2007, Lee et al. 2012) or by oxidation of sinking organic material produced in the epilimnion (Elci 2008). Anoxic conditions promote internal loading, in particular TP and ammonium, and nutrient release from mineralisation of organic matter (Ozkundakci et al. 2011), which is consistent with the high AN on all lake bottoms. Nutrient regeneration rate which were highest near equator (Lewis 1987) is closely associated to high surface temperature, and the resulting oxygen depletion in deeper water column has led to accumulation of ammonia in the hypolimnion as recorded in many tropical reservoirs (Tundisi et al. 1995; Townsend 1999; Gonzalez et al. 2004). In Bakun, TP values were also high at near-lake-bottom depth, indicating nutrient-rich conditions likely associated to decomposition of freshly drowned vegetation. The thermocline, however, separates this nutrient-rich water from the surface.

Bakun Reservoir has the lowest transparency, probably due to the presence of highly dissolved solids from the newly built dam. High values of conductivity and suspended solids are common in newly impounded systems (Lee et al. 2012); they might be attributed to dissolved ions and particles entrained in the water column. Both variables showed an increasing trend with depth, consistently with qualitative observations of turbid water collected at mid- and bottom-depth. Since its impoundment in 2012 the reservoir may be moving towards a stable stratification condition. In this study, pH was not found to be significantly different between lakes; nor did it increase with depth. Earlier findings by Lee et al. (2012) indicated lower pH at the bottom layer. As the reservoir becomes stratified, a reduction in pH in the hypolimnion probably results from the accumulation of CO_2 released from the decomposition process to form carbonate ions (Elci 2008). The increase in conductivity in the hypolimnion found in this study is consistent with the accumulation of ion concentration (Elci 2008).

In terms of WQI, not much difference was found between the reservoirs. All lakes exhibited WQI >90%, and could thus be classified as 'Class II' or 'clean'. This is consistent with a prior study conducted in 2010 at Temenggor Reservoir (Khalik and Abdullah 2012), and in 2012 at Bakun (Lee et al. 2012) and Kenyir (Sharip et al. 2014) Reservoirs. However, water quality status may differ with depth, as DO value decreased whilst TSS and AN concentrations increased. WQI dropped (>90%) at the surface and fell to Class III (WQI ~ 65-75%) at mid-depth. The good surface-water quality in all three reservoirs indicates that the present low development has minimal impact on the reservoir quality; the surface water located at the mixed-layer depth is therefore suitable for recreational purposes and as a source of water intake. However, the use of water from mid- to bottom depth may requires intensive treatment, in particular nutrient reduction, prior to its use.

In terms of TSI, differences were apparent for TP and SDT, which affects the TSI. Temenggor Reservoir had the highest TP concentration whilst Kenyir Reservoir had the lowest; these TP concentrations were homogenized throughout the water column in both reservoirs. At Temenggor Reservoir, levels of nutrients such as TP and AN were highest at the area located near aquaculture activities, indicating a contribution of nutrient sources such as fish feeds or fish waste. Similar high TP values in cage aquaculture and fish ponds were observed by Baccarin and Camargo (2005) and Yee et al. (2012). The furthest point from developed areas also had high nutrients, probably from mineralization of drowned trees. Bakun Reservoir, however, showed an increase in TP values with depth. TSI based on surface Chl-a concentration indicated mesotrophic conditions in all three lakes. High Chl-a concentrations exceeding 30 μg/L were found at around 10 m. TSI values based on Chl-a in Kenyir were within the range found in an earlier study (Sharip et al. 2014). However, the surface TP values were much lower than the values reported in the earlier study, indicating a negligible influx of nutrients in the present survey.

These findings underline current knowledge about thermal profiles in new and old deep reservoirs near the equator, contributing to better understanding of water quality for the development of management strategies. Most hydropower reservoirs, in Malaysia as elsewhere, were specifically designed with a certain design level to contain water at a certain height for power generation. The intakes with outlets are usually located at a higher depth, between 10-35 m from full supply levels, to meet certain environment requirements. For Bakun Reservoir, the minimum requirement for water quality was set at

10-15 m depth (Osman 2008). Such current dam structure is negatively affecting the water column quality by creating hydraulic stratification as a result of the design and functioning of the reservoirs (Henry 1999). Future studies should develop a model to simulate water quality patterns with different dam operations. Dumitran and Vuta (2014) have shown that water column quality, in particular DO concentrations will improve under different operational scenarios, such as frequent use of bottom discharges that allow circulation. However, many studies have shown that water quality and trophic state in tropical reservoirs vary between rainy season and dry periods (Townsend 1999, Gonzalez et al. 2004, Baharim et al. 2011). Numerical models should also be extended to investigate the stratification and mixing pattern in the reservoirs with season and how the structure affects water quality and trophic state. This will ensure better management of reservoirs for their usage for multi-purpose functions.

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