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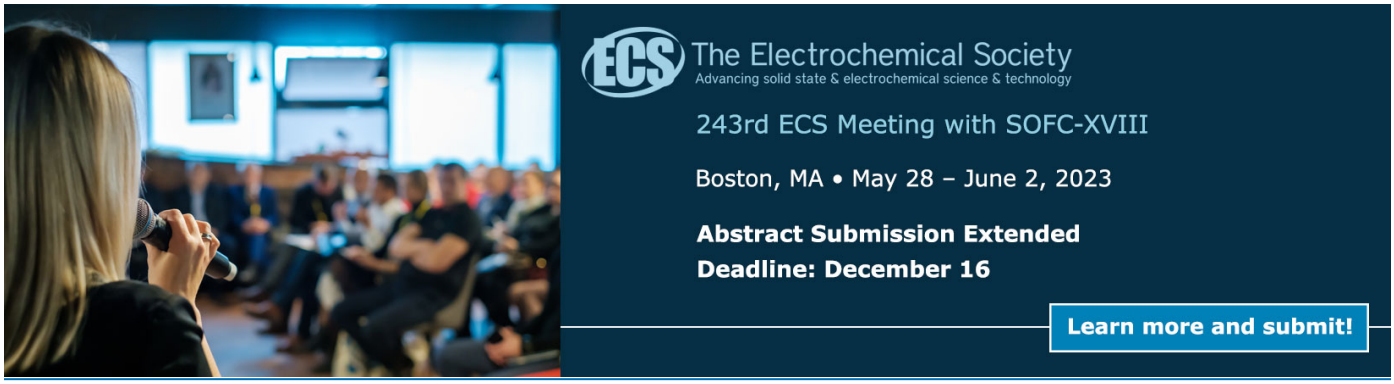

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Comparative limnology of natural and man-made tropical lakes

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Abstract. This paper assessed and compared physicochemical profiles and biodiversity indices of two shallow lakes namely the natural Bera Lake and Bukit Merah reservoir in Peninsular Malaysia. Variations in relation to hydro-meteorological variables, including rainfall, wind speed and air temperature were also measured during the field sampling. The results showed clear distinctions between natural and man-made lakes in terms of physical and chemical properties of lake waters and their relationships to the hydro-meteorological dynamic. Persistent oxygen and temperature differences between the epilimnion and hypolimnion were clearly detected in Bukit Merah reservoir under low winds and strong heat. Oxycline also persist during flooding or high turbidity levels indicating their enriched bottom waters. On the other hand, the natural Bera lake showed temporary stratification during the dry season with low winds but the water columns were thoroughly mixed during the wet season when the water temperature was lower and wind speed was higher. Plankton diversity in Bera lake was significantly higher ($p < 0.05$) than the Bukit Merah reservoir, probably due to the much longer history of the natural lake compared to the man-made one. Due to the longer residence time of the reservoir compared to the natural lake, the former tends to be more vulnerable to eutrophication if subjected to uncontrolled nutrient enrichment.

1. Introduction

Extensive limnological studies in Malaysia have been undertaken since 1970s [1] starting with Bera lake followed by Paya Bungor and Ulu Lepar, Kenyir and Loagan Bunut [2,3]. To date various limnological studies including lake profiles and lessons learned briefs have been published in approximately 26 lakes in the country such as the Chini lake, Temengor reservoir, Putrajaya lake, Batang Ai reservoir and Loagan Bunut lake [4]. Most of these studies were focused on one lake and based on field experiment alone. In-depth comparative studies of lakes were limited to provide generalization for management purposes. Understanding such limnological characteristics is crucial for management and governance improvement.

In this study, we characterize the limnological features of natural and man-made shallow lakes in Malaysia and their seasonal physico-chemical-biological changes using field experiments and numerical simulation results. The main objective of the study was to illustrate the limnological characteristics of natural and man-made lakes in order to provide better understanding of their variation to aid in

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developing strategies for sustainable management of lakes by combining results from field measurements and modelling. Bera lake and Bukit Merah reservoir, representing natural and man-made lake respectively, were selected due to the reported catchment pressures that affects their water quality and trophic state [5, 6]. Bera lake is the oldest and largest freshwater lake in Malaysia while Bukit Merah reservoir is one of the oldest reservoirs created for irrigation and flood mitigation [5, 6]. These two lakes were shallow and are important sites for ecological biodiversity and conservation.

2. Materials and method

Sampling were performed at both Bera Lake and Bukit Merah reservoir (figure 1) during a wet season (October - December) and dry season (March - May) at three sites. *In situ* measurements of physico-chemical profiles (depth, temperature, dissolved oxygen, pH and turbidity) were carried out at approximately 10 cm below the lake surface till the deepest depth using a multi-parameter probe, YSI 6600 (YSI Inc., Yellow Springs. OH, USA). Water samples were collected using a Van Dorn sampler and was preserved in cooler boxes at 4 °C and transported to laboratory for analysis of chlorophyll-a (Chl *a*) using fluorometric method and total phosphorus (TP) using persulphate digestion and automated ascorbic acid reduction method [7]. Water for chlorophyll-a samples was filtered on site to prevent pigment deterioration.

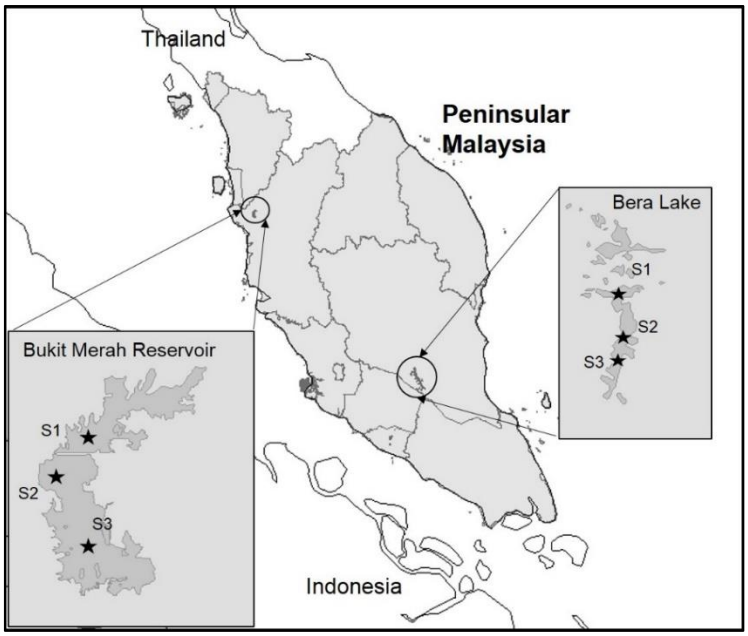

Figure 1. Study site and sampling area.

For phytoplankton, one litres of water samples were collected below the surface of water column of the lake and samples were fixed with Lugol's iodine to achieve 1% final solution and transported to the laboratory. In the laboratory, all preserved samples were left to settle to the bottom of the measuring cylinder. The samples were concentrated to a 100 ml working volume and identified to the lowest taxa based on descriptions, taxonomic keys and illustrations in [8, 9] and densities were computed in terms of number of cells/ml. For zooplankton, samples were collected in vertical hauls using a 63 μm plankton net by lowering the net to near lake bottom to the surface. The samples were poured into 500 ml bottles and fixed with buffered formalin to provide 5% formalin final solution. Samples were collected in duplicates at each site for each season. The zooplankton samples were identified to the lowest taxa [10, 11] and densities were counted as the number of individuals per litre of water sample.

Daily meteorological data were collected at two meteorological stations that were deployed at the two sites for measurement of wind speed, rainfall and water temperature (figure 2). Additional physical

chemical data under different meteorological conditions were obtained from simulation results of a well-calibrated model that have been established using 3-dimensional model using Coastal Environment Simulation System (CENSIS) software [12]. Simulation were carried out under calm condition (wind speed <0.5 m/s), average wind condition and maximum wind speed (>7 m/s).

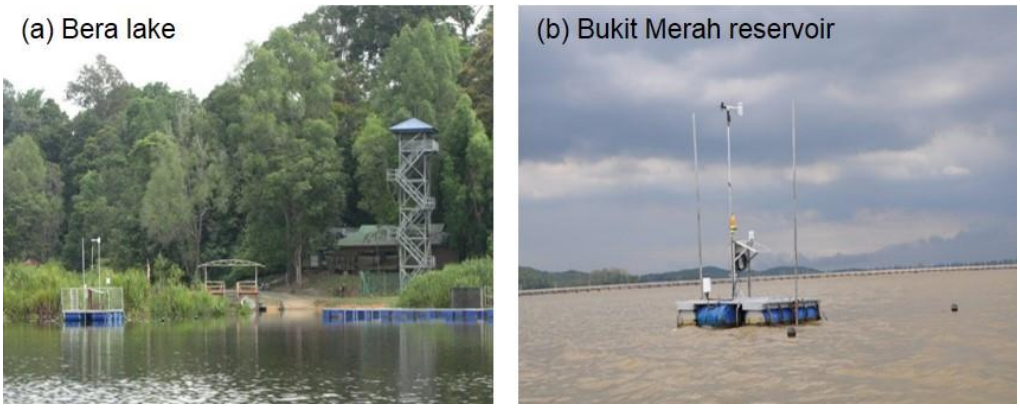

Figure 2. Weather monitoring stations deployed for the study.

All environmental variables and plankton data were assessed for normality prior to statistical testing. Nutrient, phytoplankton and zooplankton data were log-transformed to improve normality and balance contribution of the overall abundances. Species diversity and richness were examined using the Shannon-Wiener diversity index (H') and Margalef species richness index (d), respectively. Independent t-test was used to detect differences in environmental variables between the two lakes. All statistical analyses were performed using SPSS version 22.

3. Results and discussion

3.1. Physico-chemical profiles

The results showed clear distinctions between natural and man-made lakes based on mean and ranges of environmental variables (table 1). Due to its surrounding forested catchment, the minimum water temperature in Bera lake was lower than Bukit Merah reservoir ($p < 0.05$). Bukit Merah reservoir showed higher mean DO and pH levels. Low dissolved oxygen and pH levels in Bera Lake indicated its dystrophic environment. Higher dissolved organic contents and humic acids have been reported in swampy lakes such as Bera, indicating the presence of peaty environmental condition and characteristics of a brown/black water system [6, 13]. Chlorophyll-a values were also low likely due to low pH levels that limits phytoplankton growth [13]. Trophic state index based on chlorophyll-a indicated Bera lake is oligotrophic-mesotrophic while Bukit Merah reservoir is mesotrophic-eutrophic. Previous study has illustrated that the trophic status of Bukit Merah reservoir has fluctuated between mesotrophic and eutrophic states [6, 14].

Table 1. Mean ± SD and ranges (in brackets) of physico-chemical parameters between Bera and Bukit Merah lakes.

	Bera lake	Bukit Merah reservoir	*p* value
Temperature (ºC)	29.7 ± 0.9 (28.1 – 31.2)	30.3 ± 0.85 (29.4 – 32.2)	0.047
Dissolved oxygen (mg/L)	4.6 ± 1.8 (2.8 – 7.3)	7.2 ± 0.8 (4.8 – 8.3)	0.000
pH	5.6 ± 0.6 (4.2 - 5.8)	6.7 ± 0.7 (5.8 – 8.3)	0.000
Turbidity (NTU)	8.2 ± 6.6 (1.6 – 21.7)	23.2 ± 32.8 (1.2 – 146.3)	0.02
Total phosphorus (mg/L)	0.04 ± 0.04 (<0.01 – 0.16)	0.04 ± 0.03 (<0.01 – 0.12)	0.676
Chlorophyll-a (µg/L)	4.0 ± 4.1 (<0.5 – 11.1)	9.5 ± 8.9 (<0.5 – 36.7)	0.005
Trophic State Index (Chl *a*)	23.8 – 57.1	30.6 – 65.9	

3.1.1. Dry season.

Dry season was observed during the south-west monsoon season that occurs from May to September. In the natural Bera lake, warmer temperature was observed in deeper sites with temperature differences of 3 ºC between the surface and 1.5 m depth (figure 3a). In the man-made Bukit Merah reservoir, vertical temperature pattern varied between sites. Generally surface temperature was cooler than the surface temperature in Bera lake indicating the influence of wind speed (average wind speed was >1.0 m/s). Thermal layer at sites deeper than 3 m were not weakened by the wind probably due high density differences between water layers, a typical condition for a tropical lake. Both temperature and turbidity differences with depth might have contributed to the persistent thermocline. Persistent oxygen differences between the epilimnion and hypolimnion were detected in both lakes under low winds and strong heat. Dissolved oxygen levels were high (> 6 mg/l) near the surface to about 2 m depth and DO concentration started to decrease at deeper depths in both lakes (figure 3c, d). High wind events provided good mixing and increased the surface mixed layer in the large man-made lake.

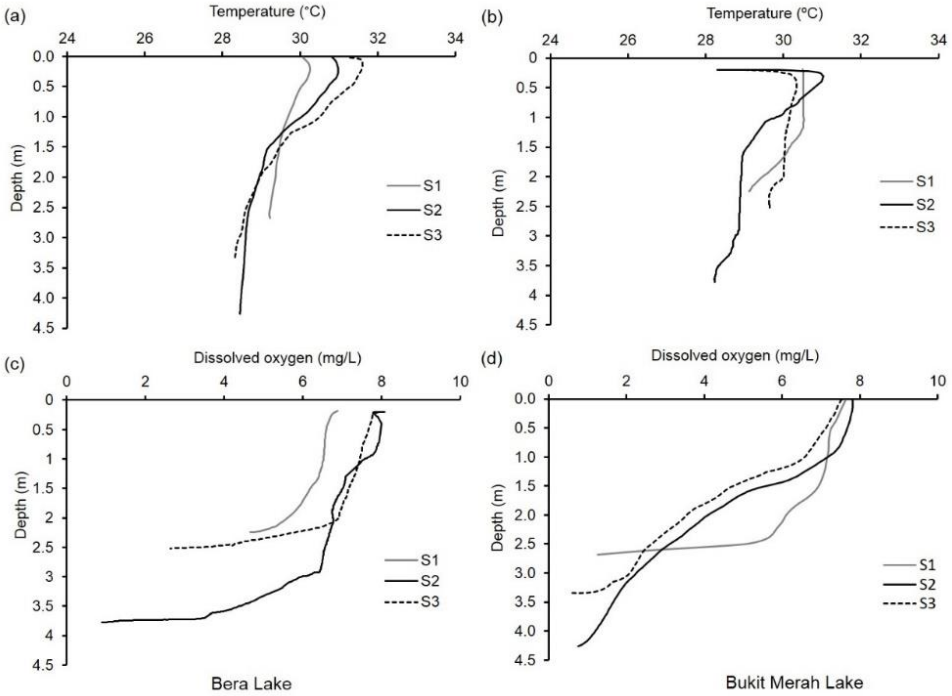

Figure 3. Vertical profiles of temperature and dissolved oxygen during the dry season.

3.1.2. Wet season.

Wet days were observed during the north-east monsoon season which normally occurs from November to March. Water levels in the natural Bera lake almost doubled during the wet season over the study period with depth variations of 4.5 m during the low water (dry days) to 9.0 m in the high-water period (wet days). Surface temperature dropped from 31.2 ºC during dry days to 28.1°C during wet days. Similarly, surface DO levels in Bera Lake dropped to below 6 mg/L during the wet days. Oxycline persisted in these wet days possibly due to flooding or high turbidity levels from the backflow of the Pahang river indicating their enriched bottom waters. Bera lake also showed weak thermal stratification during the wet season with low winds and the water columns were thoroughly mixed when the water temperature was lower and wind speed was higher (figure 4a). Physico-chemical profiles in Bera Lake were consistent with other floodplain lakes located in the black water system in the Amazon, Brazil [15].

In contrast, the man-made Bukit Merah lake did not experience significant increase in water levels during this wet period due to water level regulation. Vertical temperature profiles highly varied with sites. Thermal bar was formed at 1.0 m depth for sites with water columns deeper than 2 m. Oxycline also persisted during flooding or high turbidity levels indicating their enriched bottom waters. Dissolved oxygen levels remained high (> 6 mg/L) in Bukit Merah reservoir from the surface to a depth of about 2 to 3 m (figure 4d). Diurnal changes on thermal regime are well reported in tropical lakes located in Brazil with diurnal stratification during the day and nocturnal mixing during the night which shape vertical variation of other chemical properties such as pH and chlorophyll-a [16,17]. Thermal structure induced by solar heating are weakened by stronger wind action [12, 18]. Numerous studies have shown the influence of meteorological conditions on the hydrodynamic of lakes, which are in turn influenced by the latitude [18, 19]. Wind speed and its direction do not only shape thermal mixing and surface mixed layer in Shikinawa Lake but also an important transport mechanism of pollutants in Putrajaya lake [18, 20]. Latitudinal gradient played an important role in solar irradiance which differentiate the limnological characteristics in tropical lakes with the ones in the temperate zone [21].

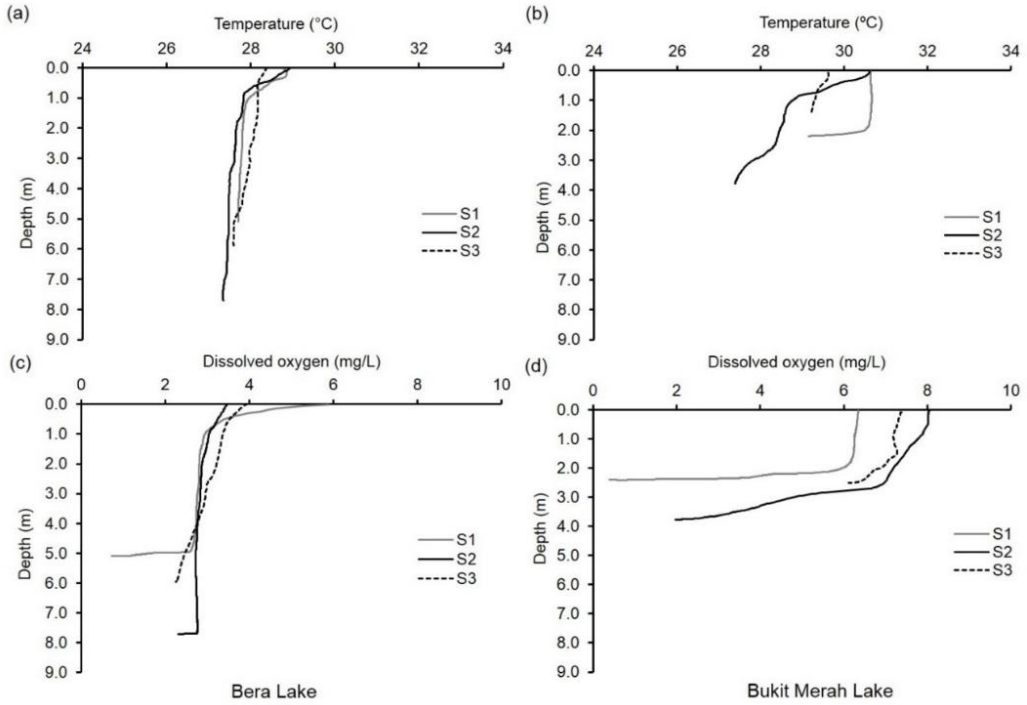

Figure 4. Vertical profiles of temperature and dissolved oxygen during wet season.

3.1.3. Calm and windy conditions.

Wind speed varied seasonally at the two lakes (figure 5a). Calm condition usually occurred in the early morning during the sampling period. Highest hourly wind speed was recorded in Bukit Merah reservoir during the wet season (~4 m/s, around 4 pm) while the highest hourly wind speed was recorded in Bera lake during the dry season (~ 3.2 m/s, around 3 am). Mean daily wind speeds were almost half in Bera lake compared to the mean daily wind speeds in Bukit Merah reservoir (figure 5b). Higher wind speeds in Bukit Merah reservoir could be higher due to larger open surface area surrounded by oil palm plantations, and thus higher wind fetch. Bera Lake is more dendritic in shape and a large part of the lake is covered by wetland marshes while its shoreline is sheltered by forest, and these terrestrial and aquatic vegetation protected the lake from wind effects [6, 13].

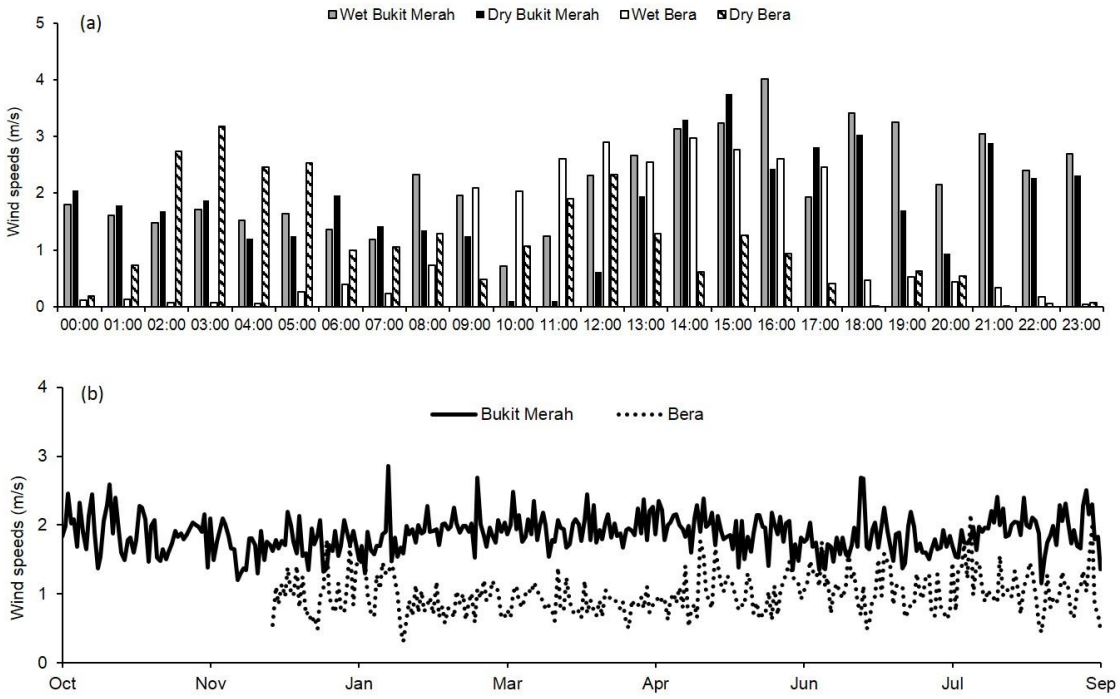

Figure 5. Wind speed profiles (a) diurnally during wet and dry seasons (b) daily from wet season (Oct) to dry season (Sept).

High wind speeds provided good mixing throughout the Bukit Merah reservoir (figure 6). High winds events resulted in not only a well-mixed temperature profile spatially, but also vertically throughout the water column. During calm winds, spatial variations of temperature were apparent; warmer temperature were localised in the sedimented area in the east while cooler temperature was observed in the southern area dominated by submerged vegetation. In Bera lake, isothermic conditions persist at all sites under calm condition during the late evening and early morning. Temperature-depth profile showed weak pattern of stratification during the day despites weak wind conditions (figure 7). Lake thermal structure and the associated nutrient availability and extent of euphotic zone influenced the vertical distribution of primary productivity in Lake Tanganyika [21].

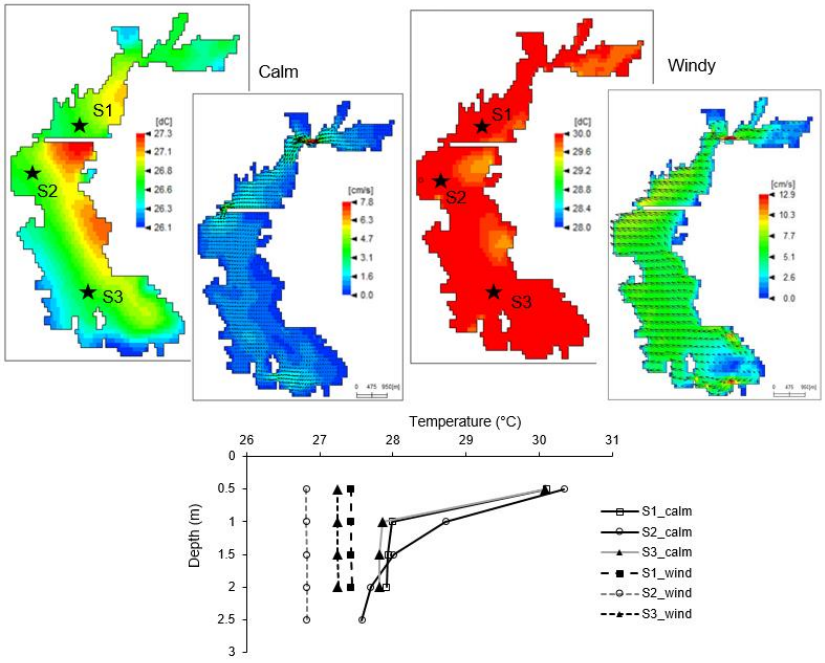

Figure 6. Spatial and vertical temperature-depth profiles during calm and windy conditions in Bukit Merah reservoir.

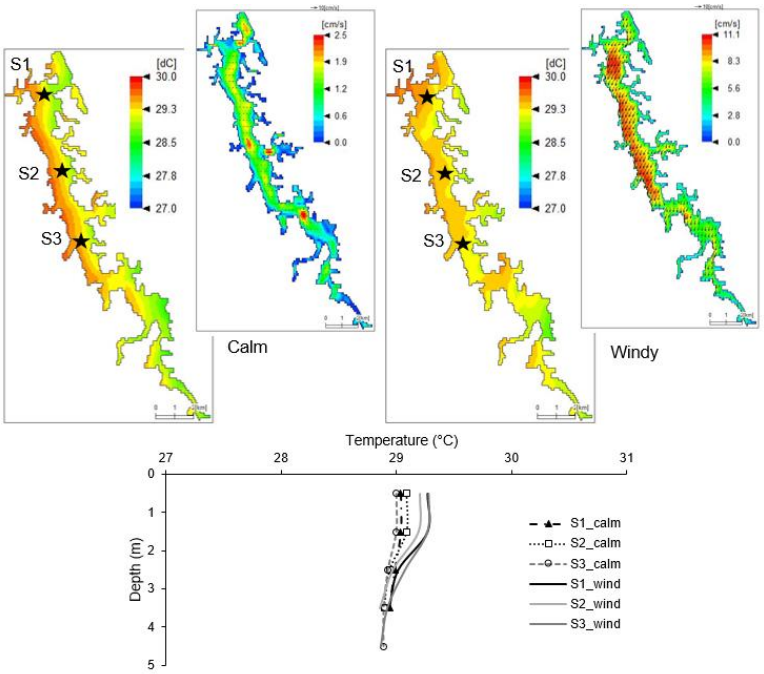

Figure 7. Spatial and vertical temperature-depth profiles during calm and windy conditions in Bera lake.

3.2. Plankton profiles

The total phytoplankton density was significantly higher in Bukit Merah reservoir compared to Bera lake ($p = 0.001$). Lower phytoplankton density could be due to lower pH levels that limit growth as well as the presence of massive macrophytes stands that limits nutrient availability for phytoplankton [9]. Species richness was significantly different ($p < 0.05$) between lakes. Higher phytoplankton species richness in Bera lake than Bukit Merah reservoir was possibly due to the longer history of the former, which was estimated to be more than 4500 years [22].

In terms of zooplankton, total density was higher in Bukit Merah reservoir compared to Bera lake ($p = 0.003$). Higher zooplankton density in this man-made lake was reported to be associated to higher density of food namely the phytoplankton [13]. However, zooplankton species richness was higher in the natural Bera lake compared to the created Bukit Merah lake (table 2).

Table 2. Phytoplankton and zooplankton density and diversity in Bera lake and Bukit Merah reservoir.

	Bera Lake		Bukit Merah reservoir	
	Dry	Wet	Dry	Wet
Phytoplankton				
Total density	248.4	342.8	9350.8	17117.2
Species richness	1.78	1.99	0.84	0.89
Diversity Index	1.51	1.69	1.21	1.11
Zooplankton				
Total density	14.6	22.1	683.0	1217.0
Species richness	2.51	4.03	0.59	0.61
Diversity Index	1.21	1.14	1.37	1.15

4. Conclusion

The results of these studies showed clear differences between natural and man-made lakes in terms of physical and chemical properties of their water columns, and their relationships to the hydro-meteorological dynamic. Limnological characteristics of natural and man-made lakes were different. Unlike the man-made lake, water level of the natural lake was strongly influenced by hydrological conditions. Large man-made lake such as Bukit Merah reservoir was shaped by meteorological conditions such as wind effects. Plankton diversity in Bera lake was significantly higher than the reservoir probably due to the much longer history of the natural lake compared to the man-made one. In general, longer residence time of a reservoir compared to a natural makes the former more vulnerable to eutrophication if subjected to uncontrolled nutrient enrichment. The use of both measurements and numerical simulations provided better understanding of lake physical-chemical characteristics and their seasonal changes. This information is valuable in the establishment of sustainable management plans of the lake ecosystem.

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