Assessing the Hydrodynamic Pattern in Different Lakes of Malaysia

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Abstract

Hydrodynamic simulations using three-dimensional numerical model were carried out in three different shallow tropical lakes to understand the characteristics of water movement in the respective water bodies. The models were based on meteorological data from the nearest stations and calibrated with current measurement, temperature, or water-level data. The results show good agreement between measured and simulated velocities and/or temperature at certain depth. This study found that the major driving forces of the hydrodynamic pattern were different in the three lakes. Hydrodynamic simulations showed that Bukit Merah and Durian Tunggal reservoirs were more sensitive to wind-driven motion. Floodplain lakes, such as Bera Lake, are more sensitive to flood inflow by the main river during the monsoon season. Convective motion driven by water temperature gradient was important for Bukit Merah and Bera Lake.

Keywords: circulation, convective motion, hydrodynamic simulation, numerical modeling, wind-driven motion

1. Introduction

Hydrodynamic studies in water bodies are important areas of study for researchers and managers to understand patterns of surface water movement and pollutant transport. Variations in hydrodynamics among lakes have been associated with differences in morphological geometries and the surrounding topographies as well as hydrometeorological and geochemical influences [1]. Simulations of hydrodynamic pattern using high-dimensional numerical models have become useful for understanding the complex role of different forcing mechanisms. For example, wind-driven motion was an important forcing mechanism to induce observed basin-scale cyclonic gyre in Lake Maracaibo [2]. Bailey and Hamilton showed that the effects of changing wind direction were found to have a greater influence on the sediment concentration distribution compared to advection and diffusion in lakes having directionally varying strong winds such as Thomsons Lake in Australia [3]. Numerous earlier works have established the spatial variability of winds and temperature on lake dynamics including horizontal and vertical mixing and stratification pattern [4].

Many recent studies have also used hydrodynamic simulation to assess the impacts of climate change on lakes [4, 5]. One-dimensional hydrodynamic model was used to identify potential drawbacks of climate change in Lake Ammersee, Germany. The study found that global warming of the atmosphere increased water temperatures, subsequently extending duration of stratification and increasing thermal stability on the lake ecosystem [6]. In [7], simulation results indicated global warming led to possible increase in water transparency in Lake Mangueira, Brazil due to nutrient limitation and submerged macrophyte growths, while increase in inflows and low water levels changed the lake hydrodynamic behavior leading to algal bloom [8].

Despite known significant advances in lake hydrodynamic information published in literature, understanding on the circulation patterns in different lakes, in particular in the trophic zone, remains inadequate due to the absence of long-term monitoring data and technical knowledge on numerical model simulation [4]. The aim of this study is to improve understanding of the hydrodynamic characteristics in different tropical lakes located in Malaysia. Understanding such hydrodynamic pattern is necessary to enable effective management purposes.

2. Research method

The study has focused on three shallow water bodies namely Bukit Merah reservoir, Durian Tunggal reservoir and Bera Lake (**Figure 1**). Bera Lake is a natural floodplain lake with a mean depth of about 2.8 m, while Durian Tunggal is a water supply reservoir with a mean depth about 6 m. Bera Lake (N3°7′00″, E102°36′00″) is a dendritic, alluvial peat and freshwater swamp system situated in Bera District, Pahang [9], while Durian Tunggal Lake is located in the Malacca State, Malaysia (N2°20′00″, E102°18′00″). Bukit Merah reservoir is a multi-function shallow reservoir (mean depth of about 2.5 m) created for irrigation and flood mitigation. The reservoir is located in Northern Perak State at N5°2′00″, E100°40′00″. Durian Tunggal reservoir is small (surface area about 5.8 km^2), while Bukit Merah reservoir is large (surface area of about 33 km^2). Both Bera Lake and Durian Tunggal Lake are mesotrophic, while Bukit Merah Lake is mesotrophic-eutrophic [10].

Meteorological and hydrological data were obtained from automatic weather monitoring stations deployed at each lake or the nearest weather or rainfall stations over the study period. Meteorological data, such as wind, water discharge, and morphological properties, were important elements for three-dimensional hydrodynamic model application and calibration of the model. Bathymetry data for Bukit Merah Reservoir were attained from hydrographic survey results provided by Kerian Drainage and Irrigation Department. Hydrographic surveys were carried out for Bera Lake and Durian Tunggal reservoir. Survey area for Bera Lake

Figure 1. Map of study lakes in Peninsular Malaysia.

Lake	Bera	Durian Tunggal	Bukit Merah
Horizontal grid designs	100 m uniform mesh model	100 m uniform mesh model	200 m × 200 m; 5 m mesh for channel
Vertical grid (m)	1.0	1.0	0.5
Simulation period	March-June 2015	January-March 2014	February-August 2014
Computational area (m)	3180 × 3500	4300 × 5200	6500 × 9500
Maximum time step (s)	3	2	10
Surface drag coefficient	$0.0007 + 0.0004\sqrt{Wind \quad speed(\mathrm{m/s})}$		
Vertical eddy viscosity and diffusivity	Predicted by the turbulence closure model		

Table 1. Hydrodynamic model set up and computational setting.

was limited to open lake areas due to extensive presence of macrophytes. The bathymetry and shoreline data were meshed into three-dimensional grids (**Table 1**). Smaller vertical grid (0.5 m) was selected for the Bukit Merah reservoir due to its shallowness (~4 m) while vertical grid of 1 m was chosen for Bera and Durian Tunggal lakes. Bukit Merah Lake has nonuniform mesh type with larger grid for open water and smaller grid in channel connecting the north and south of the lake. For Durian Tunggal Lake, focus was given to the larger part of the lake in the east with areas separated by road excluded in the analysis due to the lack of observation data. The bathymetry of the three lakes is shown in **Figure 2**. Flow data at nearest station within each lake catchment were obtained from the Drainage and Irrigation Department of

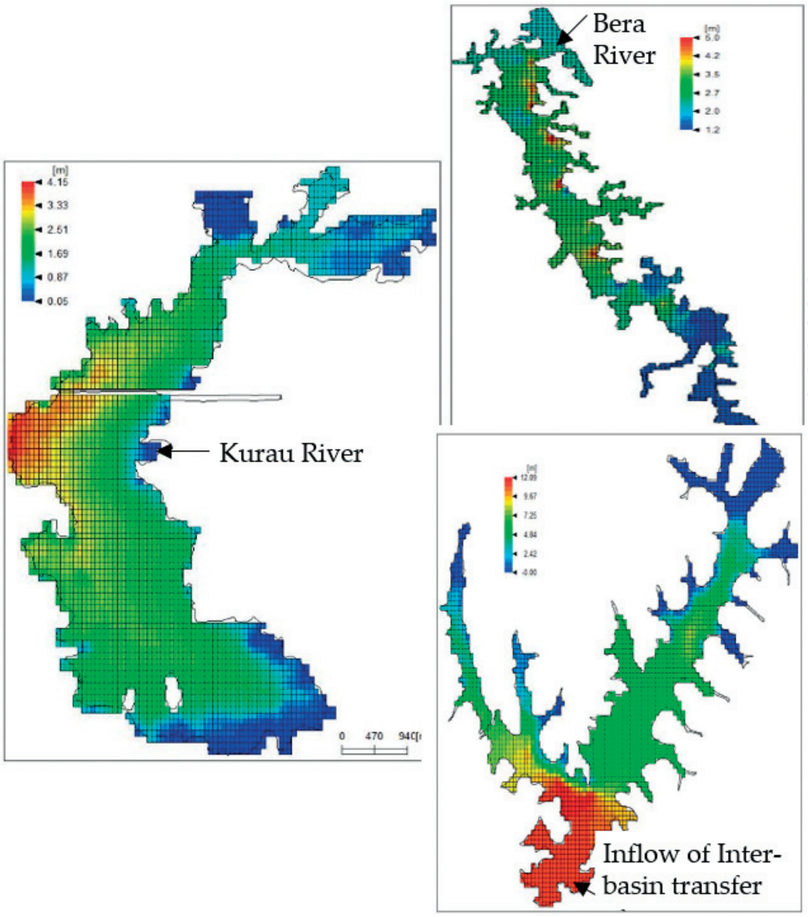


Figure 2. Bathymetry of study lakes and their major inflow.

Malaysia or published information in [11, 12]. Additional measurements of main river discharges were also carried out in Bukit Merah and Bera lakes. Current data were based on current measurements using Acoustic Doppler Current Profiler (ADCP).

This study used a three-dimensional rectilinear grid hydrodynamic model to simulate the hydrodynamic structures of the lakes. The numerical model comprises integrated momentum, continuity, and heat transfer equations together with the equation of state developed by National Institutes of Japan [9]. The physical processes are described by fluid motion (Eq. (1)), flow continuity (Eq. (2)), state equation (Eq. 3), and heat transfer conservation (Eq. (4)), and the numerical schemes are adapted in-line with the methodology described in [13, 14].

For each layer k, the depth integrated momentum equation is described as follows:

$$\begin{aligned}\frac{\partial \mathbf{M}_k}{\partial t} &+ (\mathbf{v}\cdot\nabla)\mathbf{M}_k + (\mathbf{v}w)|_{-H_{k-1}} - (\mathbf{v}w)|_{-H_k} - f_0\mathbf{k}\times\mathbf{M}_k \\ &= \frac{h_k}{\rho_k}\left(\boldsymbol{\Psi}_k - \frac{1}{2}gh_k\nabla\rho_k\right) + [\nabla\cdot(A_H\nabla)]\mathbf{M}_k \\ &+ \left(A_z\frac{\partial \mathbf{v}}{\partial z}\right)\bigg|_{-H_{k-1}} - \left(A_z\frac{\partial \mathbf{v}}{\partial z}\right)\bigg|_{-H_k}\end{aligned} \tag{1}$$

$$\frac{\partial \varsigma}{\partial t} = w - \nabla \cdot M_1, w_{k-1} = w_k - \nabla \cdot M_k \quad \left(2 \leqq k \leqq K^{-1}\right), \tag{2}$$

$$\rho = \rho(S, T) \tag{3}$$

$$\begin{aligned} &\frac{\partial}{\partial t}(h_k \cdot \theta_k) + \nabla \cdot (\mathbf{M}_k \cdot \theta_k) + (w\theta)|_{-H_{k-1}} - (w\theta)|_{-H_k} \\ &= [\nabla \cdot (h_k K_H \nabla)] \cdot \theta_k + \left(K_z \frac{\partial \theta}{\partial z}\right)\bigg|_{-H_{k-1}} - \left(K_z \frac{\partial \theta}{\partial z}\right)\bigg|_{-H_k} \end{aligned} \tag{4}$$

In these equations, h_k (k = 1, 2, …, K) represents thickness (cm) of each k layer, H the still-water depth (cm), $\boldsymbol{v} = (u, v)$ the horizontal velocity components ($\text{cm}\cdot\text{s}^{-1}$) in the x, y direction, w the vertical velocity ($\text{cm}\cdot\text{s}^{-1}$), ρ the seawater density ($\text{g}\cdot\text{cm}^{-3}$), ζ the sea-surface level (cm), f_0 the Coriolis parameter (s^{-1}) which is described as $f_0 = 2\omega \sin \varphi_0$ with the angular velocity ω (s^{-1}) of the earth rotation and the mean latitude φ_0 of the lake, g the gravitational acceleration (= 980 $\text{cm}\cdot\text{s}^{-2}$), and P_a the atmospheric pressure ($\text{g}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$). $\boldsymbol{M}_k = \text{h}_k\cdot\boldsymbol{v}_k$ is volume transport integrated into vertically in each layer, ∇ the horizontal gradient operator, A_H and K_H the horizontal viscosity and diffusivity coefficients ($\text{cm}^{-2}\cdot\text{s}^{-1}$), A_Z and K_Z are vertical viscosity and diffusivity coefficients ($\text{cm}^{-2}\cdot\text{s}^{-1}$), and θ is the conservative physical value such as temperature. T and S represent water temperature (°C) and salinity (ppt), respectively.

The model employs the turbulence closure scheme, the k–L model, that considers turbulence kinetic energy (k) and mixing length (L) for hydrodynamic simulation due to the importance of vertical turbulence transport processes. The buoyancy effect due to stratification was based on Munk-Anderson empirical relationship [13]. Knudsen's expression was adopted for calculating the water density from water temperature and salinity. The heat exchange calculation through the water surface is estimated based on the contribution from the sensible heat flux, and latent heat flux, short wave radiation and long wave radiation. Meteorological data, such as air temperature, wind speed, and solar radiation, provide the input for the surface heat balance.

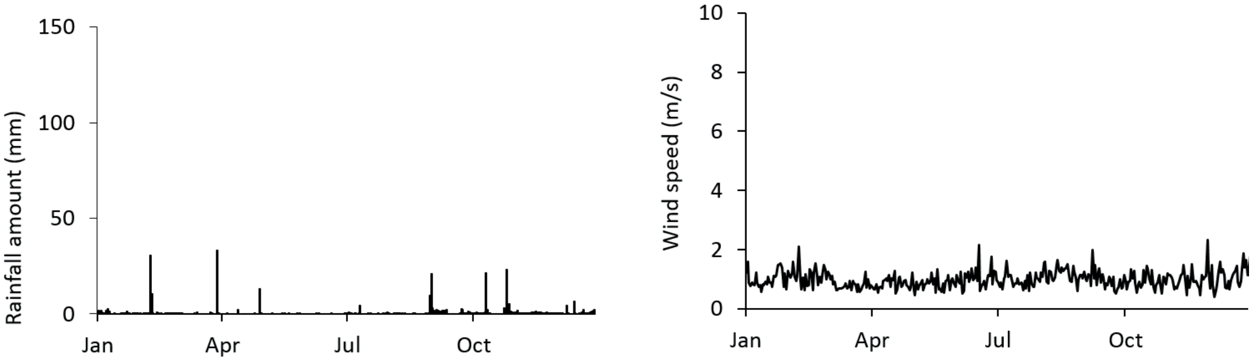
The main inputs of the model were the river inflow; meteorological parameter, such as wind, rainfall, and air temperature; and bathymetry data. Comparison between different wind speeds and under calm wind conditions was made to evaluate the circulation pattern and transport phenomena. The model assumes no physical effect of the flow field and no contribution from the groundwater. Despite the fact that a large quantity of macrophytes, such as submerged species *Cabomba furcata* in Bukit Merah Lake and emergent plants *Pandanus helicopus* in Bera Lake, may shape the hydrodynamic features, this effect was not considered in the study. The bathymetry data for Bera Lake only cover open surface areas where accessibility is not limited, while the presence of submerged species in Bukit Merah was highly variable during the study period. The maximal allowable time step for the models follows the Courant-Friedrichs-Lewy (CFL) condition stability criterion with values completed at 3, 10, and 2 s for Bera, Bukit Merah, and Durian Tunggal, respectively. In this respect, we discuss the impact of drought and water management on the hydrodynamic pattern of the water bodies. The main characteristics of runs are explained in **Table 1**.

3. Results and discussion

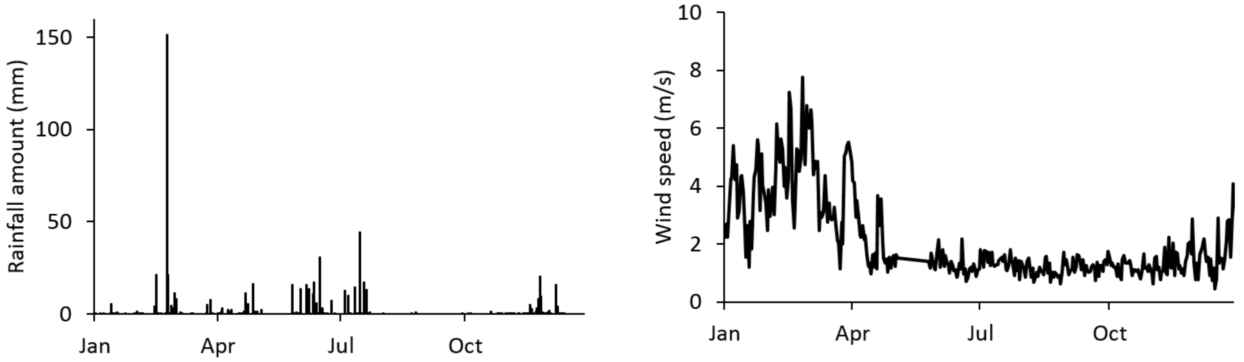
3.1. Hydrological and meteorological characteristics

Wind speed and rainfall pattern vary between the three lakes (**Figure 3**). Rainfall amount and wind speed in 2016 was highest in Durian Tunggal Lake compared to Bera and Bukit Merah lakes. Highest daily rainfall amount recorded was 151, 50, and 33 mm in Durian Tunggal, Bukit Merah, and Bera lakes, respectively. Wind speed was also highest in Durian Tunggal Lake followed by Bukit Merah and Bera lakes. Mean daily wind speeds were relatively higher

(a) Bera Lake



(b) Durian Tunggal Lake



(c) Bukit Merah Lake

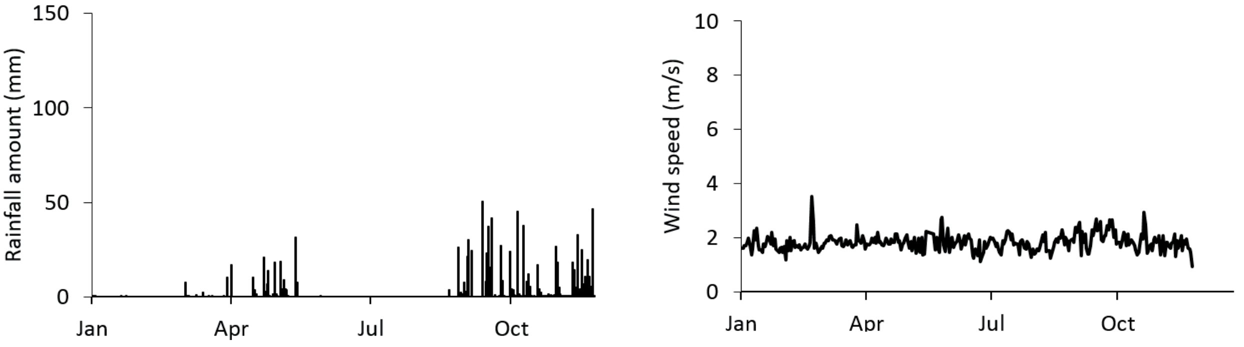


Figure 3. Rainfall amount and wind speed in three lakes in 2016.

in Durian Tunggal and Bukit Merah, namely 2.1 and 1.8 m/s compared to Bera Lake of 1.0 m/s. The highest daily mean wind speeds recorded in Durian Tunggal, Bukit Merah, and Bera Lake were 7.8, 7.7, and 2.6 m/s, respectively.

The main rivers that flow into the Bukit Merah Lake are Kurau River and Merah River. Kurau River covers a large catchment with total surface area of 337 km^2 and thus contributing bigger flow into the lake. Mean flow recorded at DID Pondok Tanjung monitoring station for the period 1960–2004 was 16.5 m^3/s. Measurement recorded in 2012 showed flows of 26.7 and 1.3 m^3/s for Kurau River and Merah River, respectively [15]. The discharge of Kurau River based on measurement was approximately 13 m^3/s. The main river that flows into Bera Lake is the Tembagau River and Bera River, which channel backflow of water from Pahang River during monsoon season. Inflows from Bera River range between <1 and 12.2 m^3/s, while inflows from tributaries are almost negligible for Durian Tunggal Lake. Durian Tunggal lake is more dependent on the inter-water transfer scheme from Muar River [16] consistent with qualitative observation. Generally, the small catchment and large conversion of forested land to agriculture in Durian Tunggal Basin are likely reducing the natural water resource supply within the catchment. In contrast, Bera Lake and Bukit Merah have large forest reserve and water catchment storage subsequently more inflows.

3.2. Model calibration

In this chapter, evaluation of the model performance was based on the visual inspection of observed and simulated trends and correlation coefficients of determination (r^2). Flow field of east, north, and vertical directions was measured at one location in Bukit Merah using ADCP and used to calibrate the hydrodynamic model. The results show good agreement between measured and simulated velocities at 1-m depth (**Figure 4a**). However, proper agreement of velocities at different depths and water level was difficult to achieve due to many uncertainties connected with hydrology and water demand management. Additionally, temperature sensor was also deployed to calibrate the hydrodynamic model. Simulated temperature yields very good agreement with measured temperature (**Figure 4b**). Based on the coefficients of determination (r^2) between model output and observed data, the simulated current has higher correlation with the observed values at 1 m level. The coefficient of determination for temperature was 0.742. In Durian Tunggal and Bera Lake, temperature-depth profiling was carried out at few sites for calibration purposes. The coefficient of determination for temperature was 0.762 and 0.6 for Durian Tunggal and Bera Lake, respectively.

3.3. Model analysis

Hydrodynamic simulation in Bukit Merah Lake indicated that the major driving force of the hydrodynamic pattern in the reservoir is wind-driven motion. The hydrodynamic patterns at surface level as shown in **Figure 5** were averaged from air-water interface to 0.5 m depth. The circulation pattern analyzed and modeled showed mixing and water movement in the lake, which is closely related to wind velocity and direction. For example, a northeast wind, with magnitude approximately greater than 3 m/s, can cause a substantial transport and circulation of water mass in Bukit Merah Lake. A much higher wind speed exceeding 7 m/s was recorded

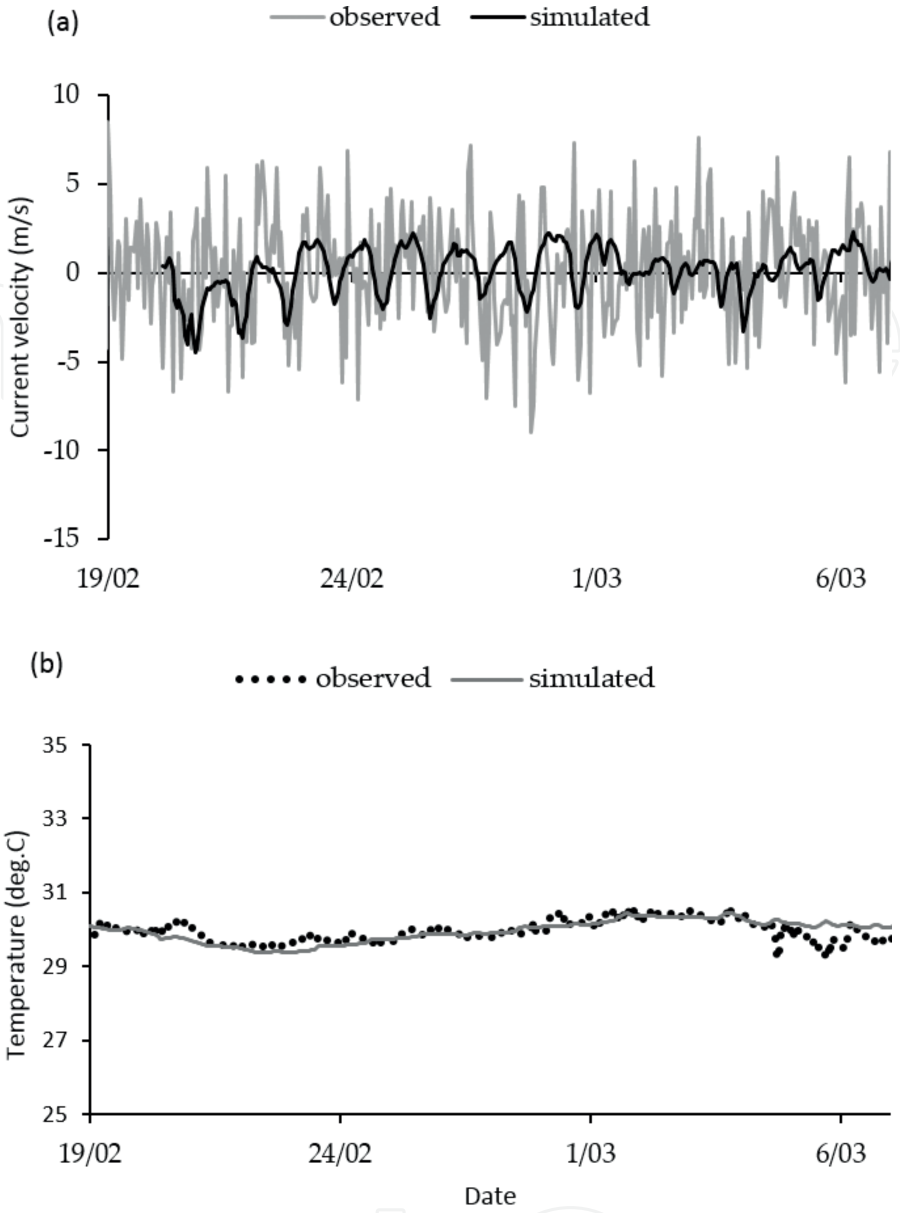


Figure 4. Calibrated results of (a) current velocity and (b) temperature in Bukit Merah Lake.

in an earlier observation in 2014, and most wind direction was observed to be from north-east [17]. Wind-induced storm has been observed to have transported floating vegetation island from north to south of the lake [17]. In our simulation, water movement responded along the wind direction. As shown in **Figure 5a**, north-east wind moved water toward southeast direction. High wind exceeding 7.5 m/s induced mean surface current about 7.2 cm/s. Higher current of 14.4 cm/s occurs near constricted channel. Warmer temperature was observed in the west, while lowest temperature was observed in the southeast. High wind effects homogenized the surface temperature and induced turbulence that could well mix the water column (**Figure 5a** and **b**).

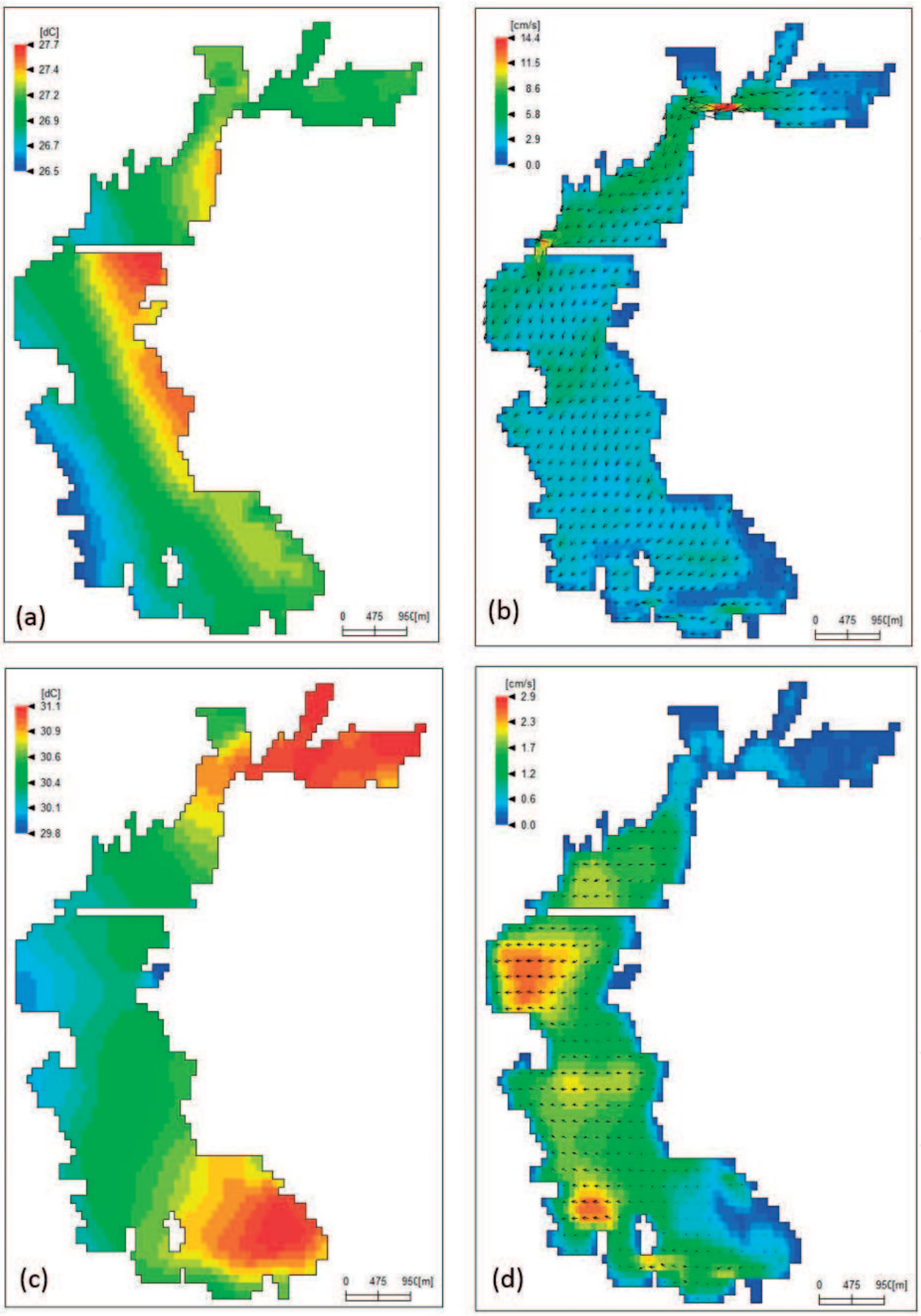


Figure 5. Pattern of (a) temperature and (b) current velocity pattern under high wind events and (c) temperature and (d) current velocity pattern under low wind events in Bukit Merah Lake.

In addition to winds, inflows from tributaries are also important for Bukit Merah Lake. Water movement from Kurau River from simulated result responded directly with the inflow of Kurau River. The water mass moved from the river mouth in the east to the deeper area in the west and south. Wind effects conveyed further the water mass and spread in to larger areas depending on the speed and direction. Under low wind events or calm conditions, temperature gradient between shallow and deep areas promoted convective motion. Convective motions can be driven by differential heating and cooling of water mass of differed depth and volume. Since the lake depth was less than 5 m deep, both wind-induced and nocturnal mixing in Bukit Merah Lake extended to the lake bottom consistent with mixing pattern in other shallow lakes [18]. Well-mixed lakes were like to be more supersaturated with oxygen and thus more productive due to better light environment and nutrient supply such as from sediment. This hydrodynamic feature may support the findings on phytoplankton characterization between the three lakes, which indicated higher productivity in Bukit Merah Lake compared to the two lakes [19].

Unequal heating of surface layer between shallow and deep regions resulted in higher rate of change in temperature in the shallow areas due to small volume of water contained. This differential heating can induce movement of warm waters over the cooler waters [20]. Similarly, differential cooling or unequal cooling between shallow and deep regions resulting from larger heat loss in the shallow regions or weaker winds due to wind shelters resulted in downslope movement of cold waters to deeper regions [20]. Most of the areas at the south and west of Bukit Merah are shallower compared to the east side of Bukit Merah which induced movement of water toward the deeper areas in the east or center due to differential heating in the shallow areas during calm conditions (**Figure 5c** and **d**). In contrast to current velocity during wind events, current velocity during calm weather were small, in the range of nil to 2.9 cm/s. Differential cooling was observed in other large lake, such as the Lake Tanganyika in Africa, which induced large-scale convective motion throughout the lake [21]. Drought associated with long dry season may have strong impact on the Bukit Merah Lake due to its large size. Continuous abstraction of water for irrigation and higher evaporation rates can lead to significant drop of water level in the lake. Low water level reduces the lake volume and affects the hydrodynamic patterns with stronger mixing and temperature gradient in agreement with atmospheric forcing including wind, temperature, and solar radiation pattern.

Hydrodynamic simulation in Bera Lake indicated that the major driving force of the hydrodynamic pattern in the reservoir is river inflow. Bera Lake is mostly surrounded by riparian forest and subsequently is sheltered from wind motions. Wind records showed low wind conditions with average winds of about 1 m/s. Wind-driven motion has low effects on this natural lake. However, higher wind speed (>3 m/s) occasionally alters water movement in the lake (**Figure 6a**). Similar to the nearby Chini Lake, this floodplain lake is very much influenced by inflows of the main river, namely the Pahang River that backflows into the lake through Bera River during monsoon and rainy seasons. Simulation showed the water movement responded directly with inflow from the Pahang River (**Figure 6b**). The inflow of cold and turbid water from the Pahang River is heavier and enters into the lake as underflows. Our qualitative observation revealed that inflows into the lake from all tributaries were negligible during dry period and drought, and together with no rain input led to severe drop of lake’s water level.

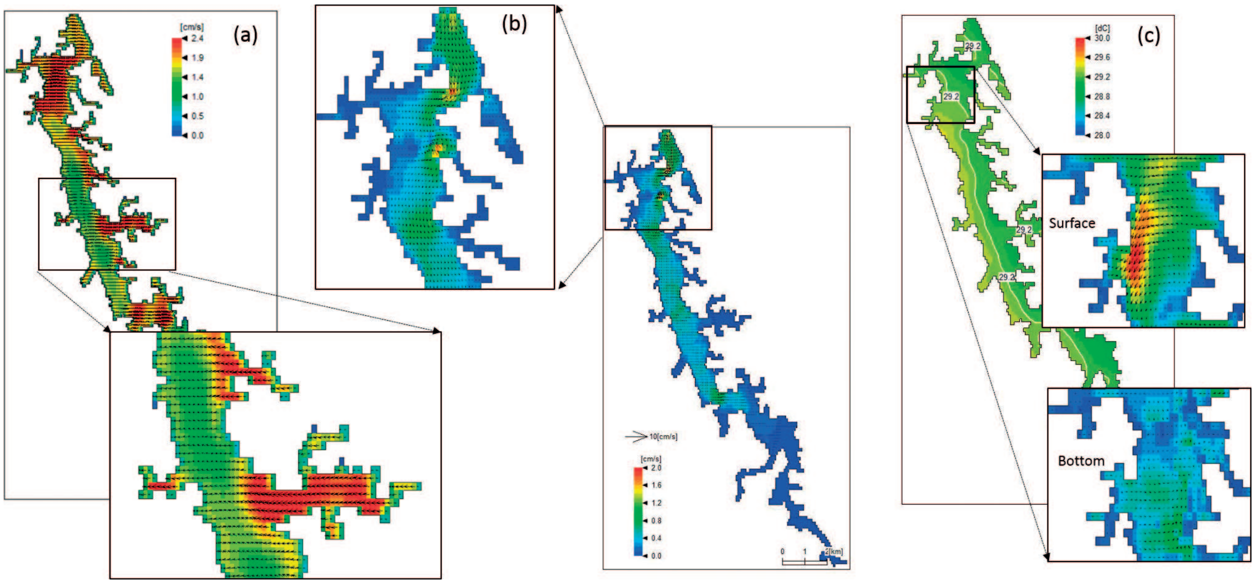


Figure 6. Temperature and current velocity pattern in Bera Lake during (a) high winds, (b) strong inflow from Bera River, and (c) calm wind and low flow.

The turbid water from the Pahang River may also induce vertical density gradient as surface temperature increases at the surface water due to reduction in penetration of solar radiation to a smaller depth as observed in the nearby floodplain Chini Lake [19]. Convective motion driven by water temperature gradient was also important in Bera Lake. In this lake, under still wind conditions and low flow, movement of current or convective motion was detected by the simulation which was likely driven by unequal temperature gradient between the macrophytes (shallow) and open water (deeper). During the night, warmer temperature at the deeper area in the east moved to shallower area in the west at the surface, while cooler water in the shallow areas move to the deeper areas of the open water at the lake bottom (**Figure 6c**). Density-driven flow was observed between reed beds and open water in a shallow lake in southern Sweden [22] and in laboratory experiments [23]. Current velocities induced by differential cooling and heating between floating-leaved bed and open water reported in the literature were between 1.6 and 1.9 cm/s [19]. Higher horizontal density flow was reported between open water and reed beds (1.5–2.8 cm/s) [22] and between the wetland and lake (3–5 cm/s) [24]. In this study, simulated current movements under no winds as illustrated in the simulation were in the range of 1.0–3.0 cm/s.

Hydrodynamic simulation in Durian Tunggal Lake showed the importance of wind effects in driving the hydrodynamic pattern in the reservoir. Wind records showed high wind conditions exceeding 6 m/s with wind direction mostly from the northeast. Durian Tunggal Lake was deeper compared to the other two lakes and may experience more apparent stratification. Lake isotherm under different wind conditions is shown in **Figure 7**. High wind speeds exceeding 6 m/s led to strong mixed layer throughout the water column within the upper (**Figure 7a**). In mid-afternoon and high solar radiation, increased surface heating and weak winds induce differential heating near surface layer (**Figure 7b**). The lake may also experience differential heating due to variation in heat absorption, given the high turbidity level in the

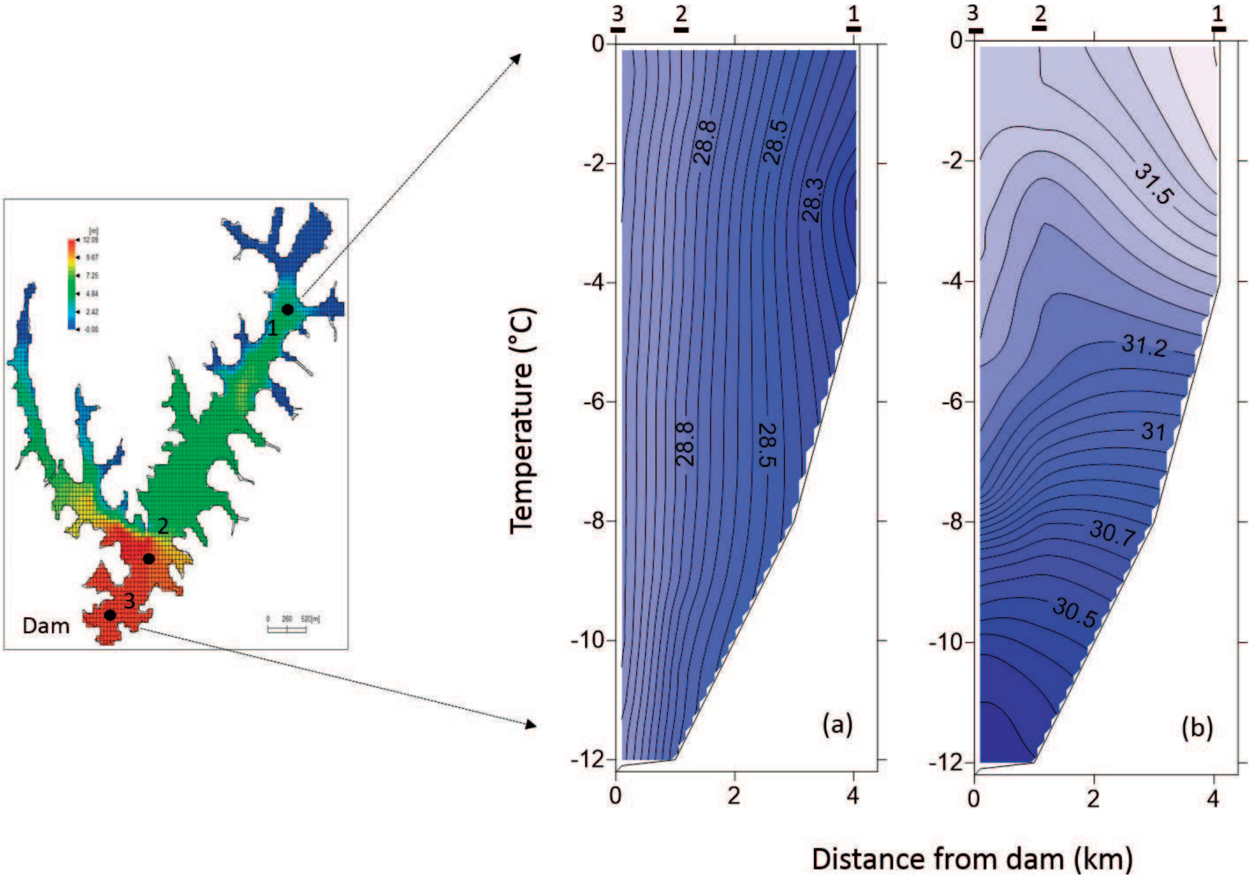


Figure 7. Isotherm in the Durian Tunggal Lake during (a) high wind, well-mixed condition and (b) low wind, differential heating condition. Numbers represent profiling locations.

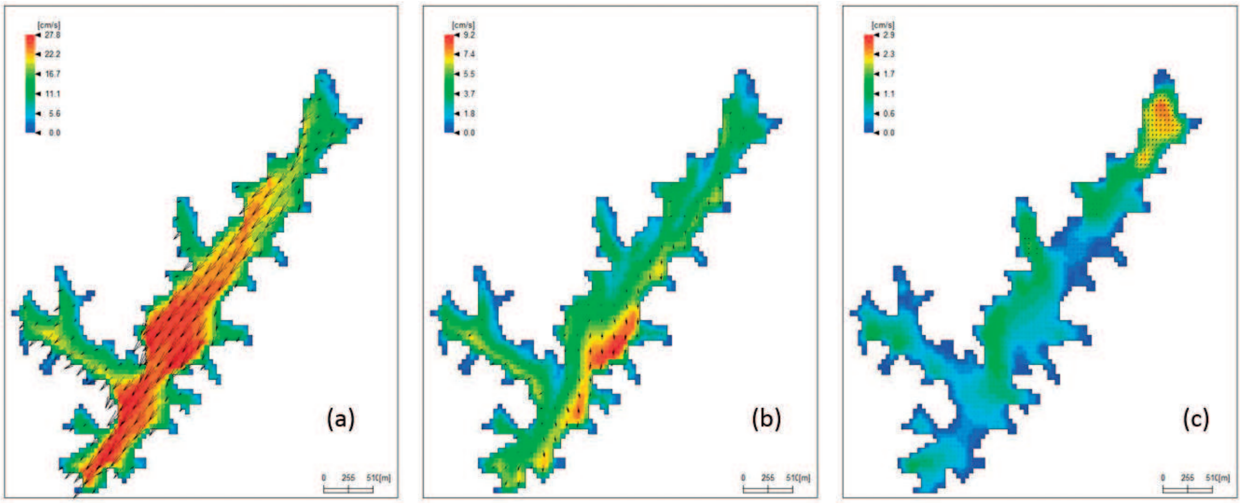


Figure 8. Temperature and current velocity pattern in Durian Tunggal Lake during (a) high wind, (b) mid-wind speed, heavy rain, and (c) low wind.

water from interbasin water transfer from Muar River into the lake. Similar to Bukit Merah, northeast winds are common for Durian Tunggal Lake and such wind direction moved water toward southeast direction (**Figure 8a**). Mid-wind speeds and heavy rain exceeding 50 mm induced mean surface current more than 9.0 cm/s in certain western part of the lake (**Figure 8b**), while low wind induced wind surface current less than 2.5 cm/s (**Figure 8c**). Additionally, higher salinity of the water from interbasin water transfer was reported occasionally which may affect the hydrodynamic features [10]. However, this dynamic is not studied here due to limited observation data. Water level in this man-made lake is very much influenced by the water abstraction.

4. Conclusion

The hydrodynamic studies of the three lakes in Malaysia here indicate distinct variation of the circulation. The mixing regime is shaped by the bathymetry of the lakes in relation to changes in winds, temperature-solar radiation, and inflows. This study found variation in the major driving force of the hydrodynamic pattern between lakes. Hydrodynamic simulations showed that the Bukit Merah and Durian Tunggal reservoirs are more sensitive to wind-driven motion. Bera Lake is more sensitive to flood inflow by the main river during the monsoon season. Convective motion driven by water temperature gradient was important for Bukit Merah and Bera Lake. The horizontal gradient in the former was driven by variation in depth between shallow and deeper regions, while in the latter it was influenced by variation between sheltered areas and open areas. The hydrodynamic models were capable of evaluating the changes in the stratification pattern and physical process created by the effect of the wind on the lake. This will aid in identifying upwelling and downwelling areas and spatial water quality variation and plankton community structure.

The model provides tool for understanding the hydrodynamic characteristics of lakes. The findings from the hydrodynamic analysis, such as water column and circulation pattern generated by the model, will become useful as the basis for the study of the water quality and environmental variations in water bodies.

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References

[1] Beletsky D, Schwab D. Modeling circulation and thermal structure in Lake Michigan: Annual cycle and interannual variability. Journal of Geophysical Research. 2001;**106**(C9): 19745-19771

[2] Laval B, Imberger J, Findikakis A. Dynamics of a large tropical lake: Lake Maracaibo. Aquatic Sciences. 2005;**67**(3):337-349

[3] Bailey MC, Hamilton DP. Wind induced sediment resuspension: a lake-wide model. Ecological Modelling. 1997;**99**:17-228

[4] Imberger J. Thermal characteristics of standing waters: An illustration of dynamic processes. Hydrobiologia. 1985;**125**:7-29

[5] Lam DCL, Schertzer WM. Potential climate change effects on Great Lakes hydrodynamics and water quality. Reston, VA: ASCE Publications; 1999

[6] Weinberger S, Vetter M. Using the hydrodynamic model DYRESM based on results of a regional climate model to estimate water temperature changes at Lake Ammersee. Ecological Modelling. 2012;**244**(0):38-48

[7] Fragoso Jr CR et al. Potential effects of climate change and eutrophication on a large subtropical shallow lake. Environmental Modelling & Software. 2011;**26**(11):1337-1348

[8] Vilhena LC, Hillmer I, Imberger J. The role of climate change in the occurrence of algal blooms: Lake Burragorang, Australia. Limnology and Oceanography. 2010;**55**(3):1188-1200

[9] Wetland International-Asia Pacific, UPEN. Tasek Bera RAMSAR site—Integrated Management Plan. Kuantan: Pahang State Economic Planning Unit (UPEN); 1999. p. 178

[10] Sharip Z, Yusoff FM. Plankton community characterization in shallow tropical lakes. Journal of Environmental Biology. 2017;**38**(6):1365-1374

[11] Hidzrami SA. Bukit Merah Perak, Lake Brief. Managing Lakes and Their Basins for Sustainable Use in Malaysia (Lake Briefs Report Series 1). Kuala Lumpur: Akademi Sains Malaysia; 2010. pp. 29-72

[12] Hasan ZA, Hamidon N, Yusof MS, Ghani AA. Flow and sediment yield simulations for Bukit Merah Reservoir catchment, Malaysia: A case study. Water Science and Technology. 2012;**66**:2170-2176

[13] Taguchi K, Nakata K. Analysis of water quality in Lake Hamana using a coupled physical and biochemical model. Journal of Marine Systems. 1998;**16**:107-132

[14] Sharip Z, Yanagawa R, Terasawa T. Eco-hydrodynamic modelling of Chini Lake: model description. Environmental Modelling and Assessment. 2016;**21**(2):193-210. DOI: 10.1007/s10666-015-9464-4

[15] Perak DID. A preliminary status of Ecosystem Health of Bukit Merah Lake—Final Report. 2012. p. 57

[16] Durian Tunggal AR. Dam—Current status and lesson learned. In: Proceedings of the National Seminar on Research and Management of Lakes and Their Basins for Sustainable Use (Lake Brief Report Series 3). Seri Kembangan: National Hydraulic Research Institute of Malaysia; 2013. pp. 34-55

[17] Sharip Z, Zaki AT. The effects of season and sand mining activities on thermal regime and water quality in a large shallow tropical lake. Environmental Monitoring and Assessment. 2014;**186**:4959-4969

[18] Tundisi JG, Forsberg BR, Devol AH, Zaret TM, Tundisi TM, Santos AD, Ribeiro JS, Hardy ER. Mixing patterns in Amazon lakes. Hydrobiologia. 1984;**108**:3-15

[19] Monismith SG, Imberger J, Morison ML. Convective motions in the sidearm of a small reservoir. Limnology and Oceanography. 1990;**35**(8):1676-1702

[20] Verburg P, Antenucci JP, Hecky RE. Differential cooling drives large-scale convective circulation in Lake Tanganyika. Limnology and Oceanography. 2011;**56**(3):910-926

[21] Sharip Z, Hipsey MR, Schooler SS, Hobbs RJ. Physical circulation and spatial exchange dynamics in a shallow floodplain wetland. International Journal of Design & Nature and Ecodynamics. 2012;**7**:274-291

[22] Lovstedt CB, Bengtsson L. Density-driven current between reed belts and open water in a shallow lake. Water Resources Research. 2008;**44**(10):1-13

[23] Zhang XY, Nepf HM. Density-driven exchange flow between open water and an aquatic canopy. Water Resources Research. 2008;**44**(8):1-12

[24] Nepf HM, Oldham CE. Exchange dynamics of a shallow contaminated wetland. Aquatic Sciences. 1997;**59**:193-213