Assessing the spatial water quality dynamics in Putrajaya Lake: a modelling approach

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Abstract Putrajaya Lake and Wetlands being the centrepiece of Malaysia's administrative city is an important destination for recreation, sports and tourism in the country. The urban water body system with a total surface area of 400 hectares was designed and built so as to encircle the core island creating a complex morphometry. To ensure the water quality remains in its highest-level condition since its beginning, to perform its multi-functional uses, managing the lake catchment is of paramount importance. This paper describes the application of numerical simulation of Putrajaya Lake using coupled three-dimensional hydrodynamic-ecosystem model to assess the spatial dynamics of the lake water quality. The hydrodynamic model simulates the flow pattern under different meteorological forcing variables. The ecosystem model simulates the resulting spatial and diurnal water quality pattern. Wind is the dominant forcing variable driving the flow field. The lake exhibits spatial variation of physico-chemical variables with an overall high-quality of surface water. The model simulation illustrates the impact of potential discharges on the lake water quality, such as spread of pollutants, subsequently provides a useful tool to enhance the management of the lake sustainably under changing environment.

Keywords 3-Dimensional hydrodynamic-ecosystem model · Lake basin management · Putrajaya · Urban lake

Introduction

Putrajaya Lake is a prominent feature of Putrajaya, Malaysia's administrative city, one that provides a scenic and self-sustaining ecosystem for recreation, sports and tourism purposes. In operation since 2001, it is an important urban lake created by the inundating of the Chuau and Bisa Rivers, covering a total area of 400 ha. Applying the ecohydrological management approach, artificial wetlands, designed using the multi-cell, multi-stage approach, that were constructed upstream of the Putrajaya Lake have become an important filtering system that treats pollutants and storm water run-off before draining water into the Putrajaya Lake. To ensure that the Putrajaya Lake and Wetlands remains a balanced and beneficial urban ecosystem, an integrated catchment and water-quality management approach has been adopted, encompassing comprehensive monitoring and assessment of the ecosystem's overall status (Majizat et al. 2010; Majizat et al. 2016).

The use of a numerical model as a tool to understand the eco-hydrological dynamic for sustainable management of these urban water-bodies is necessary in order to monitor the aquatic environment's response to the (constantly increasing) continuous development and land-use changes within the catchment. Models have initially been used to design wetlands for the control of the pollutant's concentration in order to establish a waterbody of high water quality (Perbadanan Putrajaya 2000). However, the urbanized and developing condition of the open system catchment makes the water-bodies vulnerable to pollution

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such as sewage and pesticides (used in parks and gardens) that could contribute to an increase in organic matter, and N and P concentration. Algae bloom incidents, such as involving *Euglena sanguine* sp., have occurred a couple of times in the upstream areas of wetlands that receive discharges from the stakeholders that lie outside the Putrajaya's boundaries (Salleh et al. 2003; Majizat et al. 2010). Algae blooms incidents involving green algae (*Botryococcus braunii*) have been observed occasionally due to mostly from the leakage of the underground sewerage lines (Majizat et al. 2010; Abdullah 2013). The use of high-resolution modelling approaches has enabled successful management of temperate lakes (Antenucci et al. 2004) including the control of algal dominance (Imteaz et al. 2009; Islam et al. 2012). Numerical model has been widely used to assess relevant ecosystem processes and predict impact of environmental alteration to the lake and wetland ecology worldwide (Taguchi and Nakata 1998; Omlin et al. 2001; Kara et al. 2012; Ishak 2012; Rucinski et al. 2014; Sharip et al. 2015).

In order to elucidate the relevant lake-ecosystem processes, and predict the impact of environmental alterations to the lake, a numerical hydrodynamic-ecosystem model was configured and applied to the Putrajaya Lake. The main objective of the study was to assess the spatial dynamics of the Putrajaya Lake's water quality such as dissolved oxygen and nutrient levels, and the potential impact of discharges on the water quality patterns. The overall aim is to synthesize understanding of the eco-hydrodynamic of this man-made lake system and develop a tool to aid in the monitoring and management of the lake's water quality. This paper, however, only presents the model's description and numerical simulation of the Putrajaya Lake. This is the first study to explore the potential of the scenario analysis using coupled three-dimensional hydrodynamic-ecosystem model for the water quality assessment of a complex tropical lake ecosystem specifically the Putrajaya Lake. The study attempts to fill the gaps in employing high dimensional numerical simulation to predict eutrophication impact on the urban tropical lake system.

Site description

The Putrajaya Lake and Wetlands (101.6883E 2.936361N) together have a catchment area of 51.0 km², which is largely located in the Federal Territories of Putrajaya, with 30 % in the state of Selangor. This catchment area forms part of the Langat River Basin as shown in Fig. 1. The lake has a surface area of 400 ha and an average depth of 6.6 m, while the wetlands comprise six arms with 24 cells, covering a total area of approximately 200 ha (Majizat et al. 2010). The morphology of the lake is uniquely built with a core island established at the centre inducing waterways of

~100–300 m in width surrounding the island. Located in the equatorial region, this warm polymictic lake has a mean hydraulic retention time of 132 days (Majizat 2003). Prior to the creation of Putrajaya, the catchment largely comprised oil palm plantations and rubber estates. The new city was designed in such a way that approximately 56 % of the run-off from the whole catchment discharges into wetland cells, while the remaining 46 % flows directly into the lake.

Materials and methods

The eco-hydrodynamic model, developed by Chuden (2011) was used for the hydrodynamic and ecosystem simulation. The hydrodynamic simulation of the Putrajaya Lake was carried out between the periods of 15 May 2011 and 30 May 2013. The water-quality assessment of the Putrajaya Lake was performed over the dry season, based on data collected between the periods of 15 May and 31 July 2011. The models were further calibrated based on temperature data collected in December 2012 and between the periods of 6 April 2013 and 30 May 2013. Spearman correlations and visual inspections of observed and simulated trend were used to assess model performances.

Data collection

Meteorological data

Hourly meteorological data were based on measurements recorded at the Putrajaya weather-monitoring station (101.700796E 2.94376N). The weather-monitoring system (LSI, Milano, Italy) measured wind speeds and directions, relative humidity, rainfall and air temperature. Hourly total rainfall values were also recorded at four other stations within the Putrajaya catchment. Solar radiation data and missing values were collected at the KLIA Sepang meteorological station, located about 20 km from the Putrajaya. Flow and water-level measurements were recorded bi-weekly, one at the inlet of the upper-north area of the wetlands (UN8) and one at the downstream outlet of the dam. All rainfall, flow, water level and meteorological data were provided by Putrajaya Corporation while solar radiation and missing meteorological data was obtained from Malaysian Meteorological Department.

In situ water quality measurements

In situ measurements of dissolved oxygen (DO), pH, temperature and conductivity were carried out at 17 stations at the Putrajaya Lake and 13 stations at the Putrajaya wetlands as shown in Fig. 1 using a YSI 6600 multi-parameter probe as part of the monitoring programme. Water

Fig. 1 Bathymetric results of the Putrajaya Lake and land use within the catchment area. *Inset* study site location within the Langkat River Basin

samples were collected, using a Niskin sampler, before being stored, preserved and transported to the laboratory for nutrient, chlorophyll-*a*, biological oxygen demand (BOD) and chemical oxygen demand (COD) analysis. The sampling and analysis of ammonium (NH_4), nitrate (NO_3), phosphate (PO_4), total phosphorus (TP), total nitrogen, total suspended solids (TSS), BOD and COD were based on standard methods (APHA 1995).

Additionally, diurnal measurements were performed at three stations at an hourly intervals over a 24-h period in June 2011 and December 2012. The measurements were recorded at three depths (surface, middle and bottom depths) and includes in situ measurements of temperature, pH, DO, turbidity and conductivity, and water collection for the analysis of ammoniacal-N, NO_3 , TP and dissolved phosphorous and chlorophyll-*a*. Additional temperature sensors were deployed by buoy at one station near the dam

to record temperature at three depths over the period of April to May 2013.

As part of Putrajaya's comprehensive water-quality programme, biological monitoring surveys were carried out on a monthly basis at six monitoring stations situated throughout the lake. The biological data were used to determine the species' distribution and diversity, and to form a useful indicator for changes in water quality that are induced by pollutants. Phytoplankton samples were collected using a Van Dorn water sampler at three depths (surface, middle and bottom). Samples from the three depths were mixed and preserved, kept in polyethylene bottles and transported to the laboratory. Zooplankton samples were collected by vertical hauls using a 60 μm net. The samples were preserved in a 5 % formalin solution and sent to the laboratory for analysis. Taxonomic levels of the phytoplankton and zooplankton species were determined

microscopically using an inverted microscope and a compound microscope, respectively.

Point sources' analysis

Based on the Putrajaya's drainage master plan, more than 30 drainage-system or urban run-off outlets were identified as flowing into the Putrajaya Lake (Perbadanan Putrajaya 2000). However, all drainage run-off outlets were equipped with a gross pollutant trap, a detention pond and/or a water quality-control pond prior to the water having flowed into the lake (Perbadanan Putrajaya 2000). In this study, seven (7) drainage systems were evaluated for the analysis of point-source impacts (Fig. 2). Selections were based on different land-use and development activities, historical conditions based on observation and the environmental-impact potential resulting from the discharges. Two residential areas (both of which are managed by the Putrajaya Corporation), one mixed development area that is located outside the Putrajaya's territory and managed by the Sepang City Council, two government complex with a park precincts and one commercial area that is still being developed were selected for this study. Two of the areas have experienced near-miss incidents. Accidental discharges containing nutrients flowing into the lake have been observed from the residential areas located in the north (Point 1) but the spread was controlled, whilst

eutrophication and algal bloom were reported in the detention and/or water-quality control pond near Cyberjaya (Point 2), but this did not spread into the lake (unpublished data). For this study, input of pollutant was based on nitrate loading. Transient pollution inputs of nitrate and ammoniacal-N have been reported in the literature (Abdullah et al. 2003).

Model set-up

The model was set-up based on data from a hydrographical survey conducted by Putrajaya Corporation in 2010 for bathymetric details, in order to provide basic lake shoreline and depth data for boundary simulations. The bathymetric survey was carried out as part of periodic monitoring of lakebed and sedimentation statuses. The survey covers the whole of the lake and wetlands area. The bathymetric survey was performed using acoustic, high-resolution multi-beam sonar systems that generate fine resolution details, with a horizontal resolution of between 1.0 and 5.0 cm (with a horizontal accuracy of 2.0 cm) and a vertical resolution of 1.0–2.0 cm.

Due to the complexity of the Putrajaya Lake and Wetlands' system, the model was set-up for the lake and the wetlands separately. The hydrodynamic model comprises of momentum and heat balance, and continuity and state equations as described in Nakata et al. (2003) and Sharip

Fig. 2 Map of drainage outlets into the Putrajaya Lake. Stars represent the locations of drainage outlets; numbers represent the simulated drainage outlets. (Map source: google earth)

et al. (2015). As the Putrajaya Lake is relatively deep, the effects of turbulent transportation may dissipate with depth, depending on the strength of the kinetic energy. The stratification intensity is considered in the model by introducing the Richardson number (Ri) in the estimation of the vertical viscosity and diffusivity coefficients (Eq. 1a, 1b, 1c), as described in Chuden (2011):

$$A_z = C_\mu L \sqrt{e} \times f(Ri) \quad (1a)$$

$$K_z = \frac{C_\mu}{Pr_T} L \sqrt{e} \times f(Ri) \quad (1b)$$

$$Ri = -\frac{g}{\rho} \times \frac{\partial \rho / \partial z}{e} \times L^2 \quad (1c)$$

where e represents sub-grid-scale (SGS) turbulent kinetic energy, L is a characteristic length scale corresponding to mixing length, Pr_T is the turbulent Prandtl/Schmidt number and c_μ is an empirical constant, A_z and K_z the vertical viscosity and diffusivity coefficients ($\text{cm}^{-2} \text{s}^{-1}$). The SGS turbulent energy e is determined by the following equation (Eq. 2) that describes the processes of turbulent transport, production and dissipation:

$$\begin{aligned} & \frac{\partial}{\partial t} (h_k e_k) + \mathbf{v}_k \times \nabla (h_k e_k) + (we)|_{-H_{k-1}} - (we)|_{-H_k} \\ & = \left[\nabla \times \left(h_k \frac{A_H}{\sigma_T} \nabla \right) \right] e_k + \left(\frac{A_z}{\sigma_T} \frac{\partial e}{\partial z} \right) \Big|_{-H_{k-1}} - \left(\frac{A_z}{\sigma_T} \frac{\partial e}{\partial z} \right) \Big|_{-H_k} \\ & + S - C_D h_k \frac{e^{3/2}}{L} \end{aligned} \quad (2)$$

where σ_T is the turbulent Prandtl/Schmidt number, h_k ($k = 1, 2, \dots, K$) are thickness (cm) of each k layer, ∇ the

horizontal gradient operator, A_H the horizontal viscosity coefficients ($\text{cm}^{-2} \text{s}^{-1}$) and C_D is an empirical constant. P_k and B_k the representing shear production and buoyancy production/dissipation, respectively.

The cell size for the model was selected as $100 \text{ m} \times 100 \text{ m}$, with the maximal allowable time step s for the grid area in order to meet the Courant–Friedrichs–Lewy Condition (CFL) stability criterion of 2 s. The vertical grid resolution was set to 0.5 m in the first metre, and progressively divided into 1 m layers towards the deepest areas of the lake. The total grid cells in the computational domain were 163,216. As there are no direct inflow measurements into the lake, the inflow into the lake from the contributing sub-catchments of the wetlands' arms were estimated using the designed flow ratio, based on the average flow measured at UN8.

The ecosystem model was configured to simulate DO, phytoplankton, zooplankton, detritus, dissolved organic matter (DOM) and inorganic nutrients. Bi-weekly water-quality data, namely DO, NH_4 , PO_4 , NO_3 and TSS levels collected at various stations in the lake, were used to run the ecosystem model. DOM and particulate organic carbon were estimated from the COD concentration. The water-quality variables are subject to advection, mixing and boundary forcing by using the hydrodynamic results as an input in order to run the simulation. The modelling process combining the hydrodynamic and ecosystem modelling is as shown in simplified flowchart (Fig. 3). Physiological parameters were based on dominant species being identified during the biological survey. The maximal time step

Fig. 3 Model set up and simulation

for the ecosystem model was 100 s. Model parameters were based on values from the literature (Taguchi and Nakata 1998; Sharip and Jusoh 2010; Sharip et al. 2015), and were further fine-tuned in order to obtain close agreement between simulation results and measured values. Ecosystem model calibration was based on DO values.

The general description of the coupled physical and biogeochemical model is based on Eq. (3):

$$\begin{aligned} \frac{\partial B}{\partial t} + \underbrace{(v \times \nabla)B}_{\text{horizontal advection}} + \underbrace{(w + w_p) \frac{\partial B}{\partial z}}_{\text{vertical advection}} \\ = \underbrace{[\nabla \times (K_H \nabla)]B}_{\text{horizontal diffusion}} + \underbrace{\frac{\partial}{\partial z} \left(K_z \frac{\partial B}{\partial z} \right)}_{\text{vertical diffusion}} + \underbrace{\left(\frac{dB}{dt} \right)^*}_{\text{local change}} + \underbrace{q}_{\text{External fluxes}} \end{aligned} \quad (3)$$

where B = concentration of an arbitrary compartment, $v = (u, v)$ is the horizontal component of flow velocity, w is the vertical velocity component, w_p is the sinking rate for a particulate organic compartment, $\nabla = (\partial/\partial x, \partial/\partial y)$ = the horizontal gradient operator, K_H , K_z = the respective horizontal and the vertical components of eddy diffusivity, $(dB/dt)^*$ = the change in concentration, and Q = fluxes due to external sources/sinks such as nutrient loading from the land, benthic nutrient release and oxygen consumption.

Results and discussion

Hydrological and meteorological characteristics

The Putrajaya Lake and Wetlands experienced tropical climate conditions, with a daily temperature range between 22 and 30 °C and a mean annual rainfall of 2700 mm (1997–2009) (Majizat et al. 2010). The annual rainfall showed a seasonal pattern with minimal rainfall between the period of March and July, and heavier rainfall between the periods of August and January (Majizat et al. 2010).

The hourly forcing variables over the assessment period (dry months) are shown in Fig. 4. The average wind speed during this period was $1.04 \pm 0.89 \text{ m s}^{-1}$. Based on the Osgood index, the mixis estimation is $3.3 \ll 6$, which implies that the lake itself is governed by wind-driven mixing. Most high wind events flow from the south-west of the Putrajaya. Mean air temperature and relative humidity are $27.3 \pm 2.8 \text{ °C}$ and $77.9 \pm 13.1 \%$, respectively. The wetland's discharges into the lake during this period were small, ranging between 0.06 and $2.1 \text{ m}^3 \text{ s}^{-1}$. Groundwater exchange was not considered in this initial study.

Water quality data

The water quality of the Putrajaya Lake has been designed to meet Class IIB of the Malaysian Water Quality Index for recreational purposes. Class IIB water quality requires DO

Fig. 4 Meteorological data (wind speed, rainfall, air temperature and humidity)

levels between 5 and 7 mg L⁻¹, pH ~6–9, ammonical nitrogen ≤ 0.3 mg L⁻¹, BOD ≤ 3 mg L⁻¹, COD ≤ 25 mg L⁻¹. The water should not contain visible debris and has low faecal coliforms, ≤ 400 count per 100 ml

(Perbadanan Putrajaya 2000). The water-quality levels over the studied period complied with the Class IIB requirement; however, some of the parameters, such as chlorophyll-*a*, total coliform and ammoniacal-N levels, have been

Fig. 5 Diurnal temperature and dissolved oxygen profiles at **a** Seri Bistari Bridge, **b** Seri Wawasan Bridge and **c** Dam

Fig. 6 Comparison of the simulated (*lines*) and observed (*circles*) surface temperatures in June 2011 at **a** Seri Bistari Bridge, **b** Seri Wawasan Bridge and **c** Dam

observed to exceed the corresponding Putrajaya Lake and Wetlands Water Quality Standards, as is consistent with prior findings that suggest the existence of pollution inputs (Abdullah et al. 2003). Mean chlorophyll *a* and TP concentrations during the study period were $5.6 \mu\text{g L}^{-1}$ and 0.02 mg L^{-1} , respectively. The mean monthly transparency range was between 1.47 and 2.20 m. Hourly water-quality measurements taken in June 2011 indicated the diurnal stratification of temperature during the day, and complete mixing at night (Fig. 5). Similar patterns were observed in diurnal temperature measurements taken in December 2012. Weak stratification of dissolved oxygen was observed at some stations during the day.

Chlorophyta was the most dominant phytoplankton group during the sampling period, contributing to 64 % of the total phytoplankton populations, followed by Bacillariophyta (25 %) and Cyanophyta (6 %). The most dominant phytoplankton species were *Cyclotella* sp. (Diatom), *Staurostrum* sp. and *Scenedesmus* sp. The most dominant zooplankton group was copepod, followed by cladoceran and rotifer.

Hydrodynamic simulation

The hydrodynamic model was compared with hourly water-temperature data collected at three different stations. Figure 6 shows the simulated time evolution of the vertical

temperature at different stations. The model produced reasonably well matched simulations of the observed surface temperatures. Surface water temperatures were high during the mid-afternoon, due to the high solar insolation. Higher temperatures were observed in the northern area due to a shallower water depth and a smaller volume of water. However, the middle and lowest temperatures need further verification. The simulated temperature showed a relatively good match with observed results over the longer time period in April–May 2013. Strong correlation were perceived between simulated and observed temperatures at all depths ($p < 0.01$). Despite its small size, the use of one dimensional model was unsuccessful in previous study due to limitation of model to consider the topographic influences, and complex mixing pattern induced by meteorological forcing such as temperature and wind (Ishak 2012). This three dimensional modelling approach has advantages over the earlier models by providing better consideration of morphometry effects and complex physical processes in the model.

Water inflow has only a small influence on the whole hydrodynamic pattern of the lake. This is related to the small size of the lake in comparison to its retention time. Wind and solar radiation levels were important forcing variables in this system. An increase or decrease in wind speed and solar radiation alters the mixing and circulation pattern, which may affect the movement of pollutants and

Fig. 7 Comparison of simulated surface velocity for **a** a high-wind event $>5 \text{ m/s}$ and **b** a calm wind $<0.5 \text{ m/s}$

water-quality dynamics. Higher surface velocities were frequently observed in the southern part of the lake due to the larger surface area.

The patterns of velocity under different wind events are shown in Fig. 7. Depending on the wind's direction, a high wind event (a wind speed of 5.4 ms^{-1}) indicated that pattern of the surface water circulation within the lake system is shaped by the lake's morphometry. In contrast to the natural flow of water with the lake depth, which increases towards the downstream or southern part of the lake, waters were frequently transported in the larger arm of the lake in the reverse direction, due to the wind forces that flow from a south-westerly direction, thus providing a larger spread of the water-quality dynamic. The water at the lake's bottom was transported in a reverse direction to that of the surface flow, completing the water's circulation in the lake. Additionally, water was occasionally transported from the main arm of the lake to its secondary arm by the south and south-westerly wind.

In contrast, the thermally induced motion might be driving the water motion under a low-wind event, due to the density difference between the shallow and deep areas. This density-driven process was apparent in the southern part of the lake. The density-driven motion could also be transported in the channels resulting from differences in temperature between shallower areas in the north and deeper areas in the south, but this needs to be studied further. For further research, it is recommended that lake water-flow (current) measurements are carried out during the intensive data-collection programme.

Ecosystem simulation

The simulated water-quality data were calibrated according to changing parameters, with water-quality measured diurnally (Table 1). The simulated DO pattern matched reasonably well with the observed DO data at some of the stations (not shown). The surface water-quality patterns

Table 1 Numerical values of parameter for phytoplankton, zooplankton and organic matter

Parameter	Unit	Value
A. Phytoplankton		
Maximal growth rate of phytoplankton	day^{-1}	$0.40\text{exp}(0.0857T)$
Respiration rate	day^{-1}	$0.02\text{exp}(0.0524T)$
Maximal nutrient uptake rate	day^{-1}	N:2, P:4
Half-saturation constant for nutrient uptake	$\mu\text{mol L}^{-1}$	N:1.0, P:0.2
C/P in phytoplankton	By weight	161.3
C/N in phytoplankton	By weight	15.9
C/Chl- <i>a</i>	By weight	50.0
Natural mortality rate	$\text{m}^3 \text{mgC}^{-1} \text{day}^{-1}$	$6 \times 10^{-5}\text{exp}(0.0693T)$
Sinking rate	cms^{-1}	0.0002
Photosynthetic light optimum, I_{opt}	$\text{cal cm}^{-2} \text{day}^{-1}$	150
Light extinction coefficient	–	$0.04 + 0.0088\text{Chla} + 0.054\text{Chla}^{2/3}$
B. Zooplankton		
Maximal feeding rate	day^{-1}	$0.03\text{exp}(0.0588T)$
Ivlev's exponent for the food limitation	$\text{m}^3 \text{mgC}^{-1}$	0.007
Respiration rate (basic metabolism)	day^{-1}	$0.0214\text{exp}(0.0637T)$
Energy expenditure in grazing activity	%	50
Assimilation efficiency	%	70
Natural mortality rate	$\text{m}^3 \text{mgC}^{-1} \text{day}^{-1}$	$5 \times 10^{-5}\text{exp}(0.0693T)$
Body-tissue C/P ratio	By weight	60
Body-tissue C/N ratio	By weight	6.5
C. Other organic matter		
Mineralization rate of DOM	day^{-1}	$0.0015\text{exp}(0.0693T)$
C/P in DOM	By weight	41.7
C/N in DOM	By weight	5.6
Mineralization rate of detritus	day^{-1}	$0.01\text{exp}(0.0693T)$
Sinking rate of detritus	cms^{-1}	0.0005
C/P in detritus	By weight	47.6
C/N in detritus	By weight	13.3

during initial conditions are shown in Fig. 6. Higher phytoplankton concentrations were observed at the northern and eastern part of the lake. This could be associated with the presence of a higher nutrient concentration, a

relationship that needs to be determined further upon the availability of detailed data.

DO concentrations were highly influenced by mixing processes and biological metabolisms. Strong wind

Fig. 8 Surface **a** dissolved oxygen and **b** phytoplankton patterns during initial conditions. Simulated DO for **c** a high-wind event and **d** a calm wind

conditions provided good mixing throughout the system for the even distribution of dissolved oxygen (Fig. 8). Higher DO concentrations were observed under the conditions of low wind-events and possibly high phytoplankton growth (Fig. 8).

Discharges' impact analysis and recommendations

Simulation of the point sources indicated that discharges from any location would have varying impacts on the lake's water quality due to the shape of the lake and hydro-meteorological conditions. Discharges near the dam (Point 2 and Point 6) have the largest impact on the overall water quality of the lake (Fig. 9). Due to the larger wind-fetch range, the movement of pollutants would cover a larger area, depending on wind intensity. The predicted results

indicate that water-quality changes are more apparent near the lake's bottom, as the discharge's temperature was slightly lower than that of the surface's water temperature, and wind-induced motion may mix the pollutant throughout the water column. Since the area near Point 6 is still under development, future development activities should consider adequate control measures in order to avoid any possible discharges into the lake.

Discharges near the residential areas in the east (Point 4 and Point 5) have an impact on the lake arm, but impacts are more localized. Discharges near the north-east of the lake (Point 1) would have a bigger impact, as they will be transported downstream to the main channels by the water's movement. However, the impact of pollutant discharges can be controlled by curtaining off the area or the northern arm immediately upon the observation of such

Fig. 9 Comparison of simulated current velocities under the condition of a wind speed ~ 3 m/s and a pattern of current from **a** Discharge Outlet 1, **b** Discharge Outlet 2, **c** Discharge Outlet 3, **d** Discharge Outlet 4, **e** Discharge Outlet 5 and **f** Discharge Outlet 6

events. Possible discharges from the core island, such as from Point 3 and Point 7 (not shown), need to be monitored frequently, as they will entail impacts throughout the main channels within the arm resulting from water movement in both directions, depending on wind events. Detecting and controlling any loading or discharges is crucial for the Putrajaya Lake in order to reduce algal bloom developments.

Simulating the nitrate discharges based on loading at $\sim 7.3 \text{ kg s}^{-1}$ at Points 1 and 2 showed the different effects of the spreading of pollutants (Fig. 10). Under low wind events, at Point 1, it took about 2 h for the movement of nitrate from a near outlet to a position about 400 m away, whilst at Point 2, it took 3 h for the movement of a pollutant over a similar distance. The faster movement of the pollutant at Point 1 is likely due to the constricted channel area, which led to an increased flow velocity and the faster transportation of the pollutant. However, as the wind speed

and surface area increased, a spread of similar nitrate loadings from Point 2 covered an area of 2 km radius at three different directions and at lower concentrations, compared to the spread of a nitrate concentration discharged from Point 1, in which water with higher nitrate concentration was transported in the main channel, reaching an area of 3.4 km radius after 72 h.

The data from the various sampling locations provided good information on the lake's water quality in particular to characterise the potential pollutant induced by the point sources (Abdullah et al. 2003). Most of the ambient stations were positioned close to the discharge outlet. Our model provide additional information on the water quality characterisation by illustrating the impact of the point source discharges to the water bodies which is useful to enhance the management efforts to maintain the lake water quality. Despite the practicality of ambient water quality monitoring as a tool to monitor compliance to water quality

Fig. 10 Comparison of simulated nitrate spreads from **a** Discharge Outlet 1 and **b** Discharge Outlet 2

standards, such observation provide only a snapshot of lake water quality conditions at the time of sampling (Bartram and Ballance 1996; Chapman 1996). We recommend use of the automated water-quality measurement in order to assess the biological productivity that varies with time and hydro-meteorological conditions in certain areas, such as the most upstream part of the lake near the central wetlands, and the area close to Cyberjaya.

As all products of the drainage system within the core island of Putrajaya will discharge into the lake, additional control measures are needed to ensure that discharges into the lake contain little or no pollutant that can affect the quality of lakes. Toilets and other public amenities, including residential ones, were observed to occasionally experience backflows or overflows of sewage during events or public holidays (Abdullah 2013). Elevated water quality monitoring parameters such as related to sewage have been reported in the water quality monitoring findings (Abdullah et al. 2003). Toilets near areas that are frequently used to host events need to be monitored, and the community, including developers of events, need to be engaged and participate in minimizing discharges that can potentially overflow or backflow into drains and affect the lake's water quality. The lake model that has been configured here was able to simulate the direction of the movement of the water discharges and their spread. However, the model was not linked to the catchment to assess the direct influences of changing catchment land use to the lake. Future study should consider linking this lake model with the catchment model to predict non-point source pollution scenarios and exploring the necessary mitigation programme for the sustainable management of the ecosystem.

Conclusion

The objective of this study was to develop a coupled hydrodynamic-ecosystem model for the Putrajaya Lake that can provide a better understanding of the ecosystem in order to aid in the management of the water-bodies. The simulation relates to the physical-biochemical processes and the spatial water-quality dynamic. The result model was validated by comparing it to data collected in June 2011 and December 2012. The model offered a relatively good match between the actual hydrodynamic and water-quality variations and patterns in the system. This finding shows that the model is suitable to be used for further analysis of environmental-impact simulations. The model provided information on the impact of potential discharges on the lake's water quality, such as the spread of pollutants depending on the meteorologically specific wind conditions. The model is proposed to be linked to catchment

model to enhance its usefulness to predict non-point source effects on lakes, thus developing a comprehensive tool to support the management of Putrajaya Lake water quality.

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