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Impacts of hydraulic structures on lake water quality deterioration and eutrophication in Malaysia

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Abstract: Reservoirs serve many essential purposes, including water resource, flood mitigation, recreation, and hydropower generation. However, these reservoirs created by constructing hydraulic structures across the waterways encounter substantial challenges in water quality. One of the issues is eutrophication, which demands attention in reservoir management. This study employs a two-dimensional (2D) depth-averaged hydrodynamic model, utilising Delft3D, to analyse the spatial distributions and hydro-environmental processes occurring in Putrajaya Lake, Malaysia. The model effectively simulates various scenarios for both dry and wet seasons. Calibration and validation were performed using measured data from 72 points within the lake. The water quality modelling focuses on key parameters (i.e. phosphate, nitrate, and chlorophyll *a*). The results indicate higher phosphate concentrations during dry seasons, ranging from 0.1 to 0.4 mg·dm^{-3}, compared to wet seasons, suggesting a higher risk of eutrophication during dry seasons. In assessing lake eutrophication, a modified Lamparelli index was developed and adopted to evaluate the lake's eutrophication status. The findings indicate that increasing phosphorus concentration to 0.35 mg·dm^{-3} at the upstream inflow will likely trigger eutrophication in Putrajaya Lake. We recommend this phosphorus concentration as a critical threshold value at all drainage inlets as the best management practice to prevent eutrophication. A detailed assessment of water quality can be established from this finding as one of the design criteria for any hydraulic structures that could jeopardise water quality, rather than an afterthought. Addressing water quality problems through rehabilitation after they arise can be costly and often irreversible.

Keywords: eutrophication, numerical modelling, Putrajaya, tropical lake, water quality

INTRODUCTION

Natural eutrophication is part of the ecological succession where lakes evolve from oligotrophic (nutrient-poor) to eutrophic (nutrient-rich) states over time (Safwan Miswan *et al.*, 2019). Human activities, such as agriculture and urbanisation, significantly accelerate eutrophication by increasing nutrient runoff into water bodies. In many regions, anthropogenic activities have heavily impacted lakes and reservoirs, leading to frequent harmful algal blooms (Sulastri, Henny and Susanti, 2020).

Phosphorus promotes algal blooms that deplete oxygen and can create dead zones (Sheela, Letha and Joseph, 2011). During blooms, oxygen consumption exceeds production, and the breakdown of dead algae further depletes oxygen, risking fish and aquatic life mortality (Anda de *et al.*, 2022). Paudel's *et al.* (2024) study on Ghodaghodi Lake Complex (GLC) and associated lakes in Nepal identifies nutrient loading from surrounding agriculture and domestic wastes as the lake complex's most pressing eutrophication problem, elevating phosphate while lowering dissolved oxygen and threatening aquatic life. Timalsi-

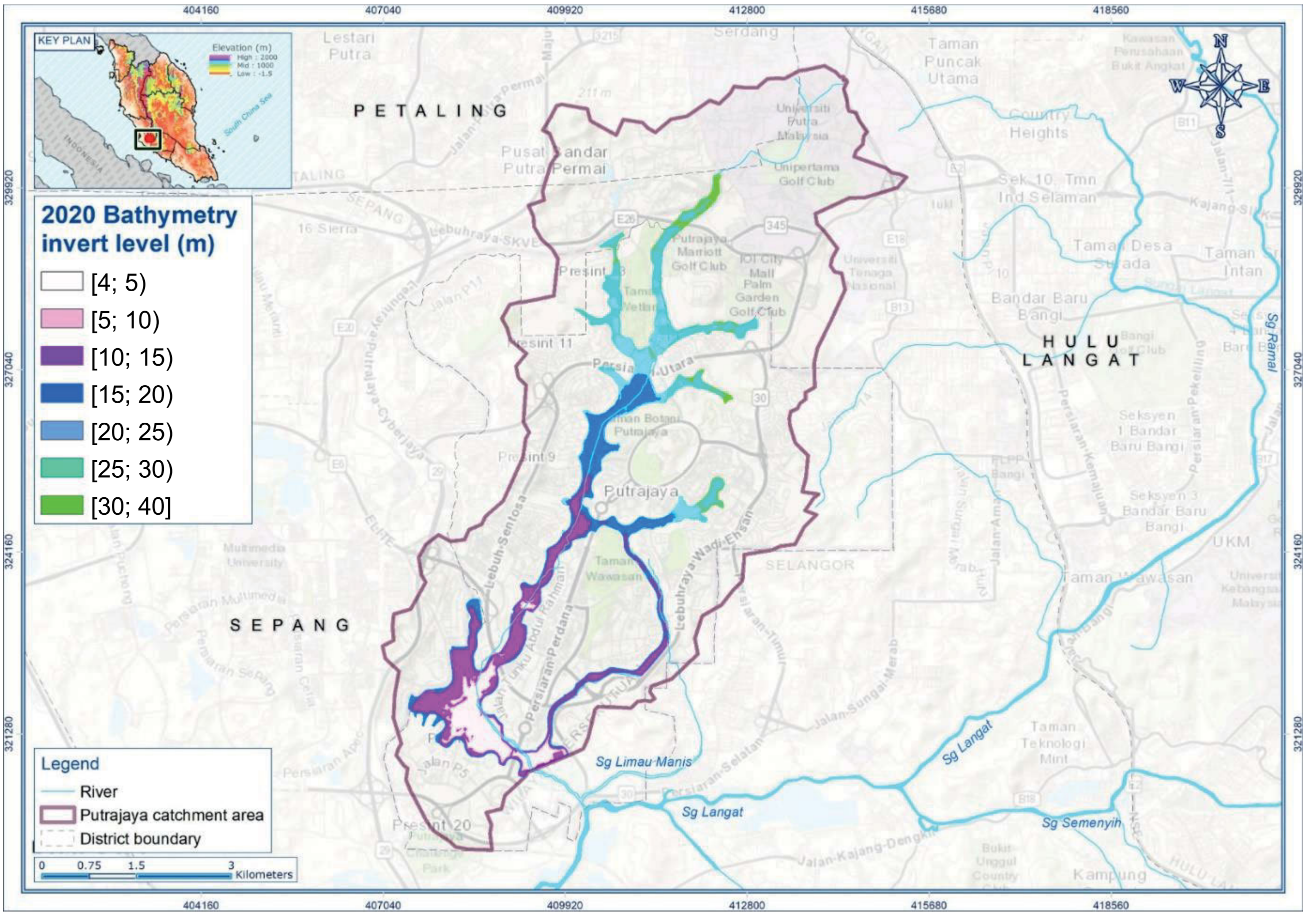


Fig. 1. Domain of the study area, Putrajaya Lake; source: Global Water Consultants and University of Nottingham Malaysia

na's *et al.* (2025) study on Phewa Lake, Nepal identified fertiliser-laden agricultural runoff and untreated domestic sewage driven nutrients to eutrophic warning levels.

Eutrophication, particularly in tropical lakes, is an emerging concern due to high rainfall, elevated temperatures, and uncontrolled nutrient inputs from both point and nonpoint sources (Liu *et al.*, 2021), such as agricultural runoff and urban discharge (Sperling von, 1997). Putrajaya Lake, a tropical artificial lake in Malaysia, has been subject to increasing nutrient enrichment, raising concerns about water quality and ecological health. Managing eutrophication in such environments requires a comprehensive understanding of hydrodynamic flows and water quality processes, as these factors directly influence nutrient transport and algal dynamics (Sharip *et al.*, 2020). There is no specific threshold value of phosphorus concentration established yet in monitoring Putrajaya Lake. The objective of this study is to establish a threshold value of phosphorus to be adopted in monitoring Putrajaya Lake as a preventive action for lake eutrophication.

Various models used in recent studies on lakes and reservoirs show that while regions face similar eutrophication challenges, different modelling techniques were deployed. In Poyang Lake, seasonal changes in nutrient concentration are linked to hydrological flows (Li *et al.*, 2018), while Putrajaya Lake's pollution patterns are significantly impacted by high-wind events that affect pollutant dispersion (Sharip, Yanagawa and Terasawa, 2016). Mokhtar *et al.* (2020) did not test the lake-specific threshold; their findings in Bukit Merah Reservoir showed that even modest phosphorus concentrations (e.g., 0.0158 mg·dm^{-3} orthophosphate) were associated with changes in chlorophyll *a* and water quality parameters, supporting the sensitivity of lake systems to phosphorus enrichment. Khwairakpam's *et al.* (2021) study eutrophication risk in Loktak Lake in India, focusing on phosphorus concentrations as well, using the MIKE 21 ECO Lab model. This study deployed a two-dimensional (2D) numerical modelling approach to investigate the spatial distribution of hydrodynamic conditions and water quality in Putrajaya Lake. Numerical modelling is a valuable tool that complements water quality sampling works, which are often limited by high costs and logistical constraints, particularly in large water bodies (Ho *et al.*, 2021). By integrating hydrodynamic and water quality modelling, this study provides a detailed assessment of the lake's eutrophication status, supporting effective lake management strategies.

MATERIALS AND METHODS

STUDY AREA

Putrajaya Lake was formed by damming Sungai Chuau in 2002, as shown in Figure 1. The dam is considered a large dam, with a height of from 18 to 30 m and a length of 750 m. It straddles the waterway of Sungai Chuau, Sungai Bisa, and three other small tributaries to form the lake. The lake has a surface area of 400 ha with a 38 km shoreline and 26.5 mln m^3 of water storage (PPJ, 1999; PPJ, 2000). The lake can be divided into three parts for ease of discussion, following its features named Putrajaya Lake north (PLN), Putrajaya Lake east (PLE), Putrajaya Lake south (PLS) and Putrajaya Lake west (PLW) as shown in Figure 1. The PLE starts from the Central Wetland overflow weir, which separates the wetland upstream and the lake downstream. The weir level is 23.5 m m.s.l., dropping to a lake level of 21.0 m m.s.l., which is controlled by a weir at the dam. The PLW started from Upper Bisa weir, which separated the wetland upstream and the lake downstream of this area, meeting the PLS at precinct 4. The weir level is also at 23.5 m m.s.l., dropping into the lake at 21.0 m m.s.l. The PLS covers the main lake area, starting where PLE ends toward the southeast before discharging from the lake at the dam spillway (Akashah *et al.*, 2015). The PPJ (Ind.: Perbadanan Putrajaya) has recorded a long-term water quality monitoring program since its lake formation in 2002. The PPJ has provided 12 years of data from 2010 to 2021 for this research study. Water quality measurement and sampling were conducted fortnightly at 17 stations since the dam was constructed. Catchment changes at the upper catchment happen in the early years, and the changes in the catchment in recent years are rather minimal.

NUMERICAL MODELLING

Numerical modelling was employed in this study to simulate the hydrodynamics and eutrophication processes in Putrajaya Lake using the Delft3D modelling suite. The methodology consisted of two primary components: hydrodynamic modelling using Delft3D-FLOW and water quality modelling using Delft3D-WAQ (Delft, 2025a; Delft, 2025b). Delft3D-FLOW simulated water circulation within Putrajaya Lake, capturing essential hydrodynamic parameters such as water levels, current velocities, and flow directions. These parameters are critical for understanding the movement of nutrients and the dynamics of algal growth within the lake (Sharip, Yanagawa and Terasawa, 2016).

The water quality module, Delft3D-WAQ, was applied to model the concentrations of phosphorus and chlorophyll *a*, primary indicators of eutrophication. Additional water quality parameters, including temperature, dissolved oxygen (DO), ammonia (NH_3), nitrate (NO_3), phosphate (PO_4), pH, biological oxygen demand (BOD), and chemical oxygen demand (COD), were incorporated to represent the existing environmental conditions better. Based on records, the water temperature during dry weather is in the order of 30°C, as compared to wet weather in the order of 28.5°C. The hydrodynamic outputs from Delft3D-FLOW provided boundary conditions for Delft3D-WAQ, ensuring a dynamic and accurate representation of water quality conditions within the lake (Delft, 2025a; Delft, 2025b).

MODEL SETUP

The model of Putrajaya Lake was set up with a computational grid, which covers an area of approximately 400 ha and has a resolution of 10 × 10 m. The fine grid resolution was necessary to capture the complex current field resulting from interactions between wind and various structures within the lake. Bathymetric data collected in 2011 by PPJ, as shown in Figure 2a, were used to set up the model bathymetry. The bathymetry invert level refers to the mean sea level as datum, with the lowest value in the southern part and the highest value in the northern part. The bathymetry data indicated that the southern part is deeper than the northern part. For example, the invert level +5 m is deeper than the invert level of +30 m. Therefore, in terms of depth in Figure 2, the southern part is deeper than the northern part.

Three open boundaries were defined for the model: the inflow from the Central Wetland (CW) weir, the inflow from the Upper Bisa (UB) weir, and the downstream boundary representing the outflow at the Putrajaya dam weir. Water level data for these boundaries were sourced from PPJ and applied as input in this study. These boundary conditions are crucial for accurately

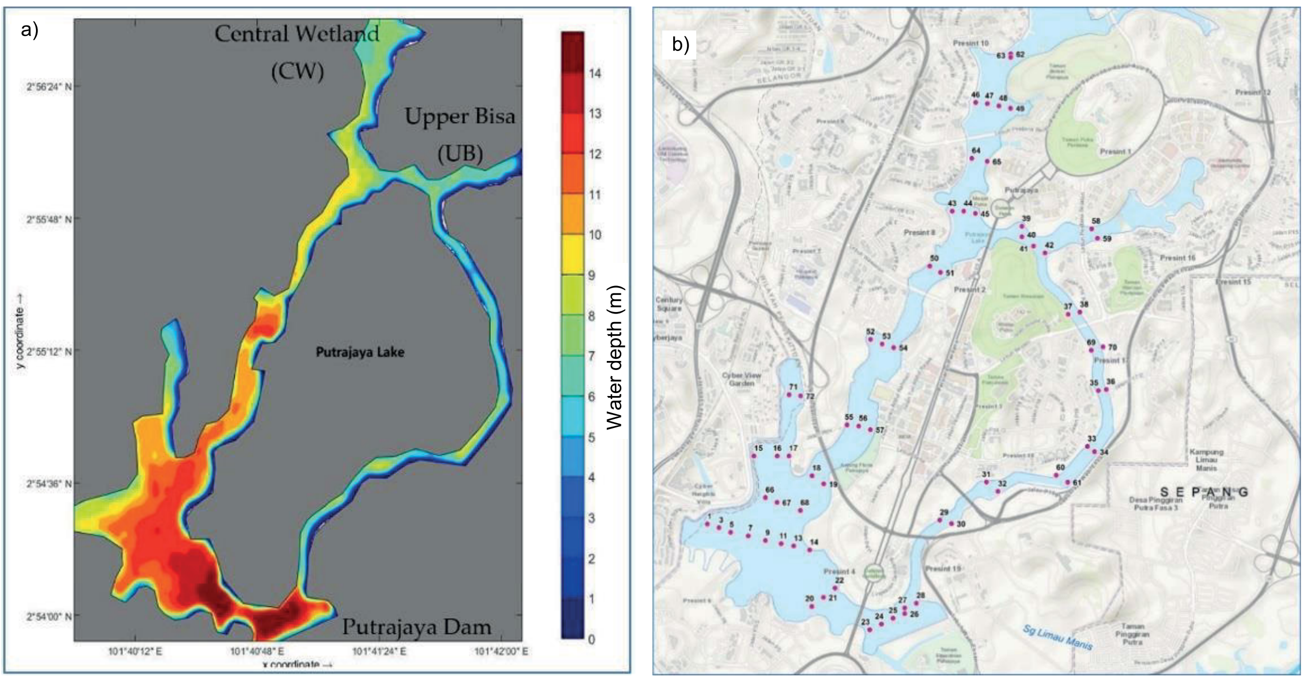


Fig. 2. Study area: a) model coverage and bathymetry, b) current measurement points; source: Global Water Consultants and University of Nottingham Malaysia

simulating the hydrodynamic behaviour of the lake and the associated water quality processes. The drainage discharge point represents drainage inflow to the reservoir, primarily from stormwater and surface runoff originating from the surrounding urban catchment areas. In the model, this inflow was assumed to be constant during each simulation period.

MODEL CALIBRATION AND VALIDATION

The numerical model was calibrated and verified by comparing the simulated results with the measured water level, current speed, and current direction. To achieve this, field measurements were carried out in 2021 under dry and wet weather conditions. Water level and current data for dry weather were collected in September, while wet weather data were obtained in December using an acoustic Doppler current profiler (ADCP). The ADCP was deployed at 72 locations across Putrajaya Lake to ensure comprehensive spatial coverage to produce an accurate model. Figure 2b illustrates the locations of the ADCP measurements. Based on the rainfall data recorded at the dam site station, Weather Monitoring Station No. 2 (WMS 02), the rainfall amount during the dry weather period is 19.8 mm. The average rainfall during this month, February 2021, is less than 100 mm, which is the driest month. The total 14-day rainfall during the wet period is 246.6 mm, which is the wettest month in 2021, the highest in December 2021, with an average total monthly rainfall of 700 mm. The Manning roughness coefficient was kept constant for both dry and wet periods in the simulation. A value of 0.02 was applied throughout the model domain to represent bottom roughness. This value was selected based on literature for similar lakebed conditions and was validated during the model calibration process. The time step adopted in all simulations is 30 s.

MODEL SCENARIOS

The study encompassed four distinct simulation cases, as shown in Table 1, to evaluate the hydrodynamic and water quality characteristics of Putrajaya Lake under varying conditions. Each modelling case provided valuable insights into the lake's behaviour, helping to assess its response to different hydrological and climatic factors. The water levels in the reservoirs were configured to remain constant during the simulation for cases 1 and 2, as there is no variation of water level within a single day. For cases 3 and 4, the water level at the boundary varies according to the recorded water level. Water levels differ between the dry and wet periods. During the dry period, the water level at the dam spillway ranges from 21 m (which is the spillway crest level) to 21.02 m, corresponding to a flow of 0.22 $m^3 \cdot s^{-1}$ to 1.43 $m^3 \cdot s^{-1}$. During the wet period, the water level at the spillway ranges from 20.01 m to 21.11 m, with a flow range from 0.32 $m^3 \cdot s^{-1}$ to 46.4 $m^3 \cdot s^{-1}$.

IMPACT OF PHOSPHORUS ON EUTROPHICATION

Trophic state indices (*TSIs*) are widely used tools for assessing lake eutrophication by quantifying the trophic state based on selected water quality parameters (Alprol *et al.*, 2021; Sui *et al.*, 2022). Among the various *TSI*s, the Lamparelli index is regarded as the most accurate for representing the trophic state of Putrajaya Lake. While this index provides a stable and realistic classification, it can be further refined to reflect the specific environmental conditions of the lake. To address this, a modified version of the Lamparelli index, known as the modified Lamparelli trophic state index (*TSI*-mL), was developed under this study.

Chlorophyll *a* (CHL) and phosphorus (P) are the index's key parameters. Phosphorus acts as a nutrient that fuels algal growth, thereby influencing chlorophyll *a* concentrations. The *TSI*-mL map of Putrajaya Lake for dry and wet weather was established. In order to study the impact of phosphorus on eutrophication, phosphorus loading at the upstream boundary was varied. This helps to identify the threshold at which increased phosphorus loading may trigger eutrophication in the lake. Three scenarios were simulated, i.e., scenario 1 (P = 0.05 $mg \cdot dm^{-3}$), scenario 2 (P = 0.35 $mg \cdot dm^{-3}$), and scenario 3 (P = 0.42 $mg \cdot dm^{-3}$).

Scenario 1 was carried out by starting with a phosphorus value following the Putrajaya Lake water quality standard (PLWQS) of 0.05 $mg \cdot dm^{-3}$. Setting this value also implied that the lake should be in a healthy condition in terms of eutrophication status. Various values of phosphorus were simulated, but only the values of 0.35 and 0.42 $mg \cdot dm^{-3}$ are presented in this paper, as 0.35 $mg \cdot dm^{-3}$ starts to indicate eutrophication in some areas, and 0.42 $mg \cdot dm^{-3}$ indicates extensive eutrophication in the lake.

The *TSI* values for Putrajaya Lake were calculated for each scenario, and the eutrophication status was evaluated using the classification system presented in Table 2. The *TSI* value is computed using the *TSI*-mL formula developed under the study, as indicated below (Eq. 1), modified based on the Lamparelli index.

Table 1. Model cases

Model case	Description
Model calibration	the goal of this scenario was to ensure that the simulated water levels, current speeds, and directions matched the actual conditions observed at the site during wet weather conditions
Model validation	this scenario was run using the calibrated model parameters to validate the simulation results; it was conducted in dry weather conditions, and the simulated results were compared with the observed data to verify the model's accuracy
Wet weather conditions	simulate over a 14-day period to study hydrodynamic characteristics and water quality during wet weather conditions
Dry weather conditions	simulate over a 14-day period to study hydrodynamic characteristics and water quality during dry weather conditions

Source: Global Water Consultants and University of Nottingham Malaysia.

Table 2. Modified Lamparelli trophic state index (*TSI*-mL) classification

Index	*TSI*-mL
Ultraoligotrophic	*TSI* < 47
Oligotrophic	[47; 52)
Mesotrophic	[52; 59)
Eutrophic	[59; 63)
Supereutrophic	[63; 67)
Hypereutrophic	*TSI* ≥ 67

Source: Global Water Consultants and University of Nottingham Malaysia.

$$TSI\text{-mL} = \frac{TSI\ (\mathrm{CHL})\ +\ 0.75\,TSI\ (\mathrm{P})}{2} \tag{1}$$

where: *TSI*-mL = new index proposed under the study (modified Lamparelli trophic state index), CHL = chlorophyll *a*, P = phosphorus.

The same *TSI* classification, as indicated by the Lamparelli index in Table 2, was adopted.

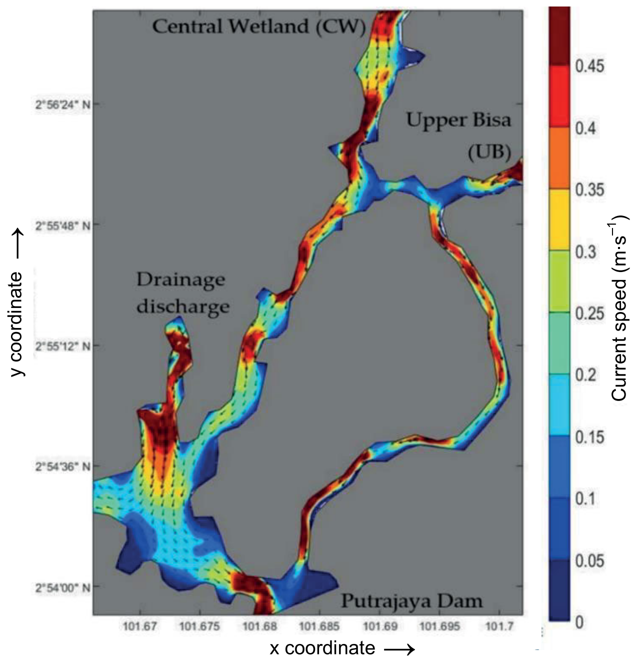


Fig. 3. Simulated current speed and direction during wet weather conditions; source: Global Water Consultants and University of Nottingham Malaysia

RESULTS AND DISCUSSION

WET WEATHER HYDRODYNAMIC SIMULATION

Model calibration was essential to ensure the simulation's accuracy in reproducing observed hydrodynamic behaviour. Lake hydrodynamic simulation was carried out for wet weather conditions on December 09, 2021 and served as model calibration. Key parameters such as roughness coefficients and eddy viscosity were fine-tuned within acceptable limits to match acoustic Doppler current profiler (ADCP) measured data.

In Figure 3, simulated current speeds and directions are shown under wet weather conditions. The colour gradient indicates velocity, with blue as the lowest (0 m·s^{-1}) and dark red as the highest (>0.45 m·s^{-1}). Velocities above 0.3 m·s^{-1} appear in narrow, shallow upstream channels in Putrajaya Lake east (PLE) and most of Putrajaya Lake west (PLW), where the flow drops 2.5 m from the Central Wetland weir before heading downstream toward the dam. Conversely, velocities decline to 0.1–0.3 m·s^{-1} in deeper regions of Putrajaya Lake south (PLS), and to below 0.1 m·s^{-1} in fringe areas and the dam's left flank (viewed downstream). High velocities occur upstream of the dam spillway, where flow accelerates down from 21 m m.s.l. to downstream via the 135 m length labyrinth spillway.

Flow arrows indicate a dominant north-to-south direction from the Central Wetland and Upper Bisa weirs toward the dam spillway, driven by increased inflow during wet periods. Local recirculation is evident near PLS's fringes and shallow zones, aligning with patterns noted by Sharip, Yanagawa and Terasawa (2016).

In Figure 4, simulated and measured current speeds are shown. The model successfully captures the general trend and reproduces key peaks and troughs, indicating its ability to simulate flow changes due to channel geometry and bathymetry. However, it slightly underestimates stations 36–41 and 67–69 speeds, likely due to underestimated inflow from nearby drainage discharges. The different spikes occasionally at some measurement points are mainly due to localised site conditions or activities, which are not possible to capture in the numerical model. However, overall, the results are within an acceptable magnitude and trend.

DRY WEATHER HYDRODYNAMIC SIMULATION

A simulation was conducted under dry weather conditions on September 07, 2021, to verify the hydrodynamic model. In Figure 5, the current speed and flow direction are shown. While

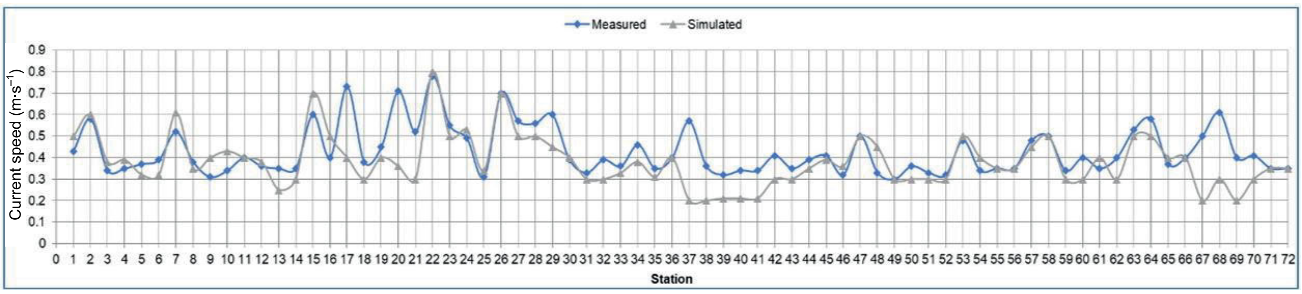


Fig. 4. Measured and simulated current speed during wet weather conditions; source: Global Water Consultants and University of Nottingham Malaysia

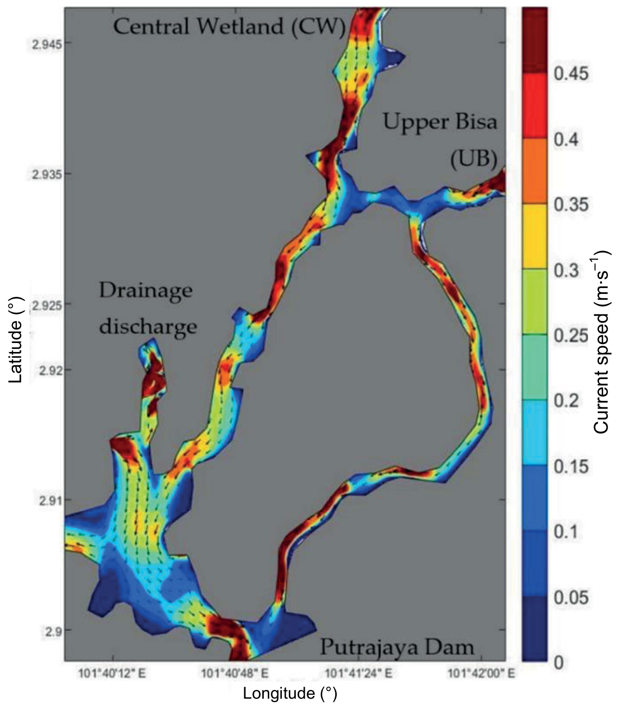


Fig. 5. Simulated current speed and direction during dry weather conditions; source: Global Water Consultants and University of Nottingham Malaysia

the overall velocity pattern is similar to that in wet weather, with faster flows in narrow channels and slower flows in wider areas, a key difference is observed in the drainage discharge zone, where velocities are higher during dry weather.

This increase is due to reduced external inflows, which shift the system's hydrodynamic balance. Unlike wet weather, when stormwater inputs cause broader flow dispersion and lower localised velocities, dry conditions reduce water volume and lower water levels (Chow, Yusop and Teo, 2016). According to the continuity equation (Eq. 2), velocity rises when the cross-sectional area narrows, thus increasing flow speed in confined channels.

$$Q = A \cdot V \tag{2}$$

where: Q = volumetric flow rate through a pipe or conduit, A = cross-sectional area, V = average fluid velocity.

In Figure 6, measured and simulated current speeds during dry conditions are compared. The model replicates the general trend well, accurately reflecting major peaks and troughs. However, some discrepancies exist. Notably, simulated speeds exceed measured values at stations 1–10 near the confluence of flows from the Central Wetland and drainage discharge. These differences may stem from field data uncertainty or unaccounted-for inflows/outflows in hydraulically complex areas.

Results indicated that the dry periods showed higher differences between the measured and calculated velocity values. This could be due to lower current speed during dry periods, with a flow range between 0.1 and 0.2 m·s^{-1}, as compared to wet periods of 0.3 and 0.5 m·s^{-1}. Any local site conditions, such as a boat passing through, will create a larger difference during dry periods. Overall, the model effectively captures the lake's hydrodynamic behaviour and is considered reliable. The Nash–Sutcliffe efficiency (*NSE*) and root mean square error (*RMSE*) for calibration are 0.72 and 0.047 m·s^{-1}. While the validation model has an *NSE* of 0.45 and an *RMSE* of 0.061 m·s^{-1}, its outputs will be integrated into the water quality model to simulate phosphorus and chlorophyll *a* concentrations, which are the indicators of eutrophication, enhancing the prediction of nutrient dynamics and ecological impacts on Putrajaya Lake.

STAGNANT FLOW AREAS IN THE LAKE

It is important to note that although the dam successfully created a visually appealing lake with an extensive water surface area (Wong *et al.*, 2022), water quality issues are likely to emerge over time, particularly in areas with limited flow, as highlighted in Figures 1 and 2. The Putrajaya dam design, which only allows water to flow downstream at the surface layer of the water column from the spillway at elevation 21.0 m m.s.l., results in near-stagnant conditions at the bottom layers of the lake, where the invert lies around 5.0 m m.s.l. This stratification can lead to deterioration in water quality, especially in the lower depths. Stagnant water conditions can lead to the accumulation of nutrients such as nitrogen and phosphorus, which are often derived from agricultural runoff, wastewater, and aquaculture activities (Wojewódka-Przybył *et al.*, 2024). These nutrients can promote eutrophication, which results in excessive algal blooms which deteriorate water quality by depleting oxygen levels and releasing toxins (Montero *et al.*, 2021).

Internal phosphorus recycling (IPR) from the benthic layer of a lake system can present significant challenges. Elevated rates of IPR can perpetuate eutrophication by continuously supplying phosphorus, even after external nutrient inputs are reduced, thereby complicating lake restoration efforts (Tay *et al.*, 2022b). Since its construction in 2001, Putrajaya Lake has likely

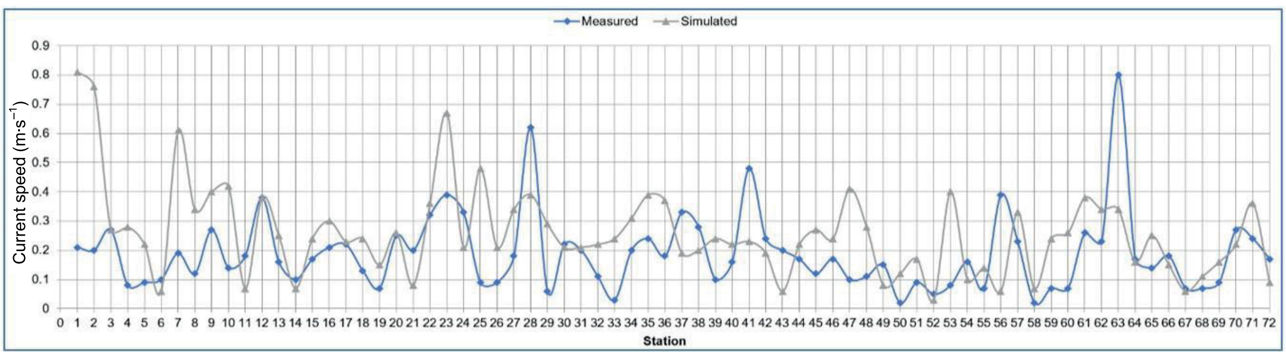


Fig. 6. Measured and simulated current speed during dry weather conditions; source: Global Water Consultants and University of Nottingham Malaysia

experienced substantial sediment accumulation at its bottom. Over time, this deposited sediment, combined with organic matter, settles and forms a benthic layer capable of releasing phosphorus back into the water column, further exacerbating water quality issues. The persistence of IPR can undermine restoration efforts, as it may continue to supply phosphorus even after external inputs are reduced (Navarrete *et al.*, 2019). The subsequent results of the water quality modelling highlight the threat of eutrophication to Putrajaya Lake if the nutrient loading is uncontrolled.

WATER QUALITY MODELLING

Water quality modelling is crucial in understanding the complex interactions between physical, chemical, and biological processes in aquatic systems. Water quality modelling enables the simulation of interactions among nutrients, phytoplankton, and dissolved oxygen, capturing the dynamics of eutrophication and nutrient cycles in water bodies (Ho *et al.*, 2021). In the context of Putrajaya Lake, water quality modelling is essential for assessing the impact of various environmental factors on key indicators of eutrophication, such as phosphorus and chlorophyll *a* concentrations.

Phosphate

Phosphate (PO_4^{3-}) is an essential nutrient that is crucial in eutrophication within aquatic ecosystems. In many freshwater systems, phosphate acts as the primary limiting factor for the growth of algae and aquatic plants. Elevated phosphate concentrations can trigger excessive algal growth, resulting in dense algal blooms that reduce water clarity and restrict sunlight penetration. This process disrupts submerged aquatic vegetation and alters the ecological balance of the water body (Sulastri, Henny and Susanti, 2020).

Water quality modelling was carried out for both dry and wet weather conditions. The external phosphorus loading is set as a boundary condition at the upstream. While the internal phosphorus loads are considered within the model by defining parameters related to sediment-water exchange, i.e., release rates and equilibrium concentrations.

In Figure 7, the spatial distribution of phosphate concentrations in Putrajaya Lake during dry and wet weather conditions is illustrated. The concentration levels, represented by a colour gradient, range from low values (blue, approximately 0.0 mg·dm^{-3}) to higher concentrations (red, approximately 0.5 mg·dm^{-3}). During the simulated dry weather covering 14 days from February 1, 2021, to February 14, 2021, phosphate accumulation is more pronounced, particularly in upstream sections and narrow channel regions, where concentrations range between 0.3 and 0.5 mg·dm^{-3} (yellow to red zones). This value is much higher than the phosphorus concentration value of 0.05 mg·dm^{-3} according to the Putrajaya Lake water quality standard (PLWQS). These findings align with those reported by Zahari *et al.* (2018), who studied phosphorus distribution in the Putrajaya Wetland and Central Wetland. Their study indicated that phosphorus levels in the wetland reached close to 1 mg·dm^{-3} at the highest, while the Central Wetland exhibited lower concentrations, ranging from 0 to 0.5 mg·dm^{-3}. During the dry season, reduced water inflow and limited mixing contribute to phosphate retention in specific areas. The lack of flushing leads to nutrient accumulation, increasing the risk of eutrophication. Simulation for 14 days of wet weather conditions from December 15, 2021, to December 31, 2021, indicated that phosphate concentrations are significantly lower, as shown in Figure 7b, with most areas showing levels below 0.05 mg·dm^{-3} (blue regions), which is within the PLWQS limit.

The most important spatial pattern is that during dry weather conditions, phosphate accumulation is more pronounced, particularly in upstream sections of PLW and narrow channel regions of PLE, where concentrations range between 0.3 and 0.5 mg·dm^{-3} (yellow to red zones). These results highlighted the areas of concern, especially during dry weather conditions.

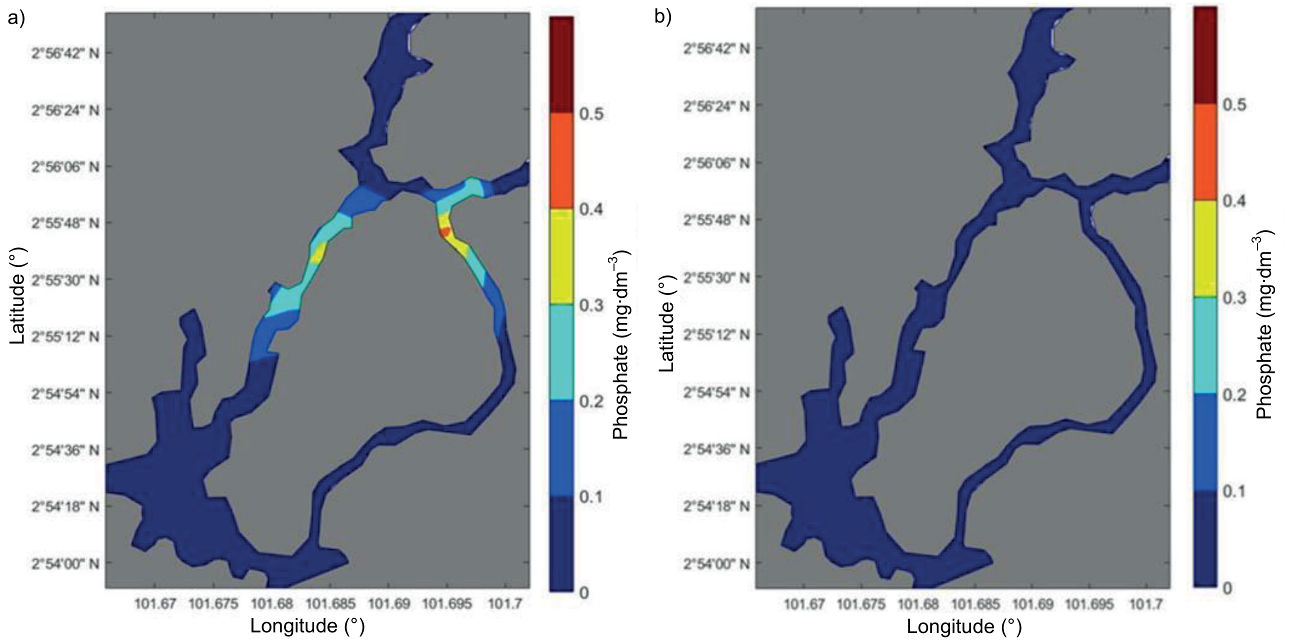


Fig. 7. Phosphate (PO_4) concentrations during: a) dry weather conditions, b) wet weather conditions; source: Global Water Consultants and University of Nottingham Malaysia

Unlike the dry season, where localised phosphate accumulation is evident, the wet season exhibits a more uniform distribution with minimal high-concentration zones. Increased water inflow and enhanced flushing rates contribute to the dilution of phosphate, preventing excessive accumulation. More excellent hydrodynamic activity facilitates nutrient dispersion, reducing the likelihood of localised eutrophication.

The above results highlight a higher risk of eutrophication during dry weather conditions, especially at the upper part of PLE and the middle part of PLW, as shown in Figure 7a. Wet weather conditions help mitigate phosphate accumulation through natural dilution, whereas dry periods create conditions that favour nutrient retention, increasing eutrophication risks.

Chlorophyll *a*

High chlorophyll *a* concentrations are linked to increased total phosphorus (TP) and total nitrogen (TN), which are critical factors in evaluating eutrophication (Sui *et al.*, 2022). As an indicator of algal biomass, high chlorophyll *a* levels often suggest increased phytoplankton activity and eutrophication risks. In Figure 8, the spatial distribution of chlorophyll *a* in Putrajaya Lake under dry and wet weather conditions is presented. Colour gradients represent concentrations from low (~0 mg·dm^{-3}, blue) to high (~15 mg·dm^{-3}, red).

Elevated chlorophyll *a* levels with values exceeding 10 mg·dm^{-3} are concentrated in upstream sections and narrow channels, while downstream areas show lower concentrations. Notably, wet and dry weather levels exceed the PLWQS threshold of 0.7 mg·dm^{-3}.

Hydrodynamic and environmental factors drive this spatial pattern. Narrow channels facilitate nutrient build-up due to restricted flow, encouraging algal growth. Shallower upstream areas allow greater sunlight penetration, further promoting photosynthesis. Conversely, expansive and deeper downstream regions experience better water mixing and lower light availability, limiting phytoplankton proliferation.

Seasonally, chlorophyll *a* concentrations are higher during dry weather. Limited water movement and longer residence times in stagnant zones enable algae accumulation. In contrast, the wet season brings higher flow and mixing, enhancing flushing and reducing algal retention, resulting in lower chlorophyll *a* levels. These findings underscore how hydrodynamics and seasonal flow variations influence algal distribution and the potential for eutrophication.

IMPACTS OF PHOSPHORUS ON EUTROPHICATION

Three scenarios were simulated to evaluate the impact of phosphorus on eutrophication in Putrajaya Lake, and the results were presented as trophic state index (*TSI*) maps using the *TSI*-mL formula (Fig. 9). In scenario 1, the phosphorus concentration was set at 0.05 mg·dm^{-3} following the PLWQS. The value of 0.05 mg·dm^{-3} is slightly higher than that of 0.035 mg·dm^{-3} according to the national lake water quality criteria and standards (NAHRIM and NRE, 2015). With 0.05 mg·dm^{-3} of upstream boundary inflow into the lake, the lake remains in a healthy state, with ultraoligotrophic conditions (*TSI* < 47) in the upstream area and oligotrophic conditions (*TSI* 47–51) downstream. This suggests balanced nutrient levels, preventing excessive algal growth, and the value of 0.05 mg·dm^{-3} is suitable according to PLWQS.

At 0.35 mg·dm^{-3} phosphorus (scenario 2), where the phosphorus modelling shows it can happen during dry weather (see Fig. 9), eutrophic conditions expand beyond Upper Bisa to stagnant zones in the lower reaches of the lake. Areas near drainage outlets, curved riverbanks, and narrow channels with restricted flow show increased phosphorus accumulation, exacerbating eutrophication risks. To mitigate this, phosphorus loading should be limited to 0.35 mg·dm^{-3} at all drainage inlets.

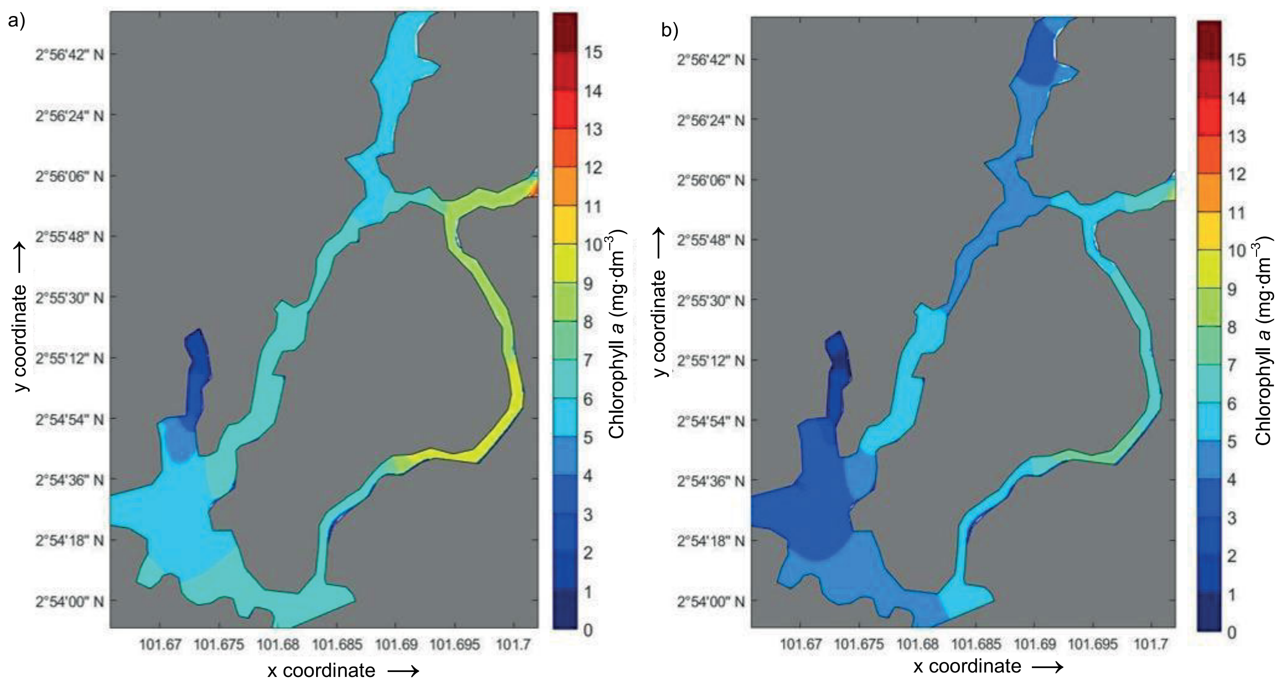
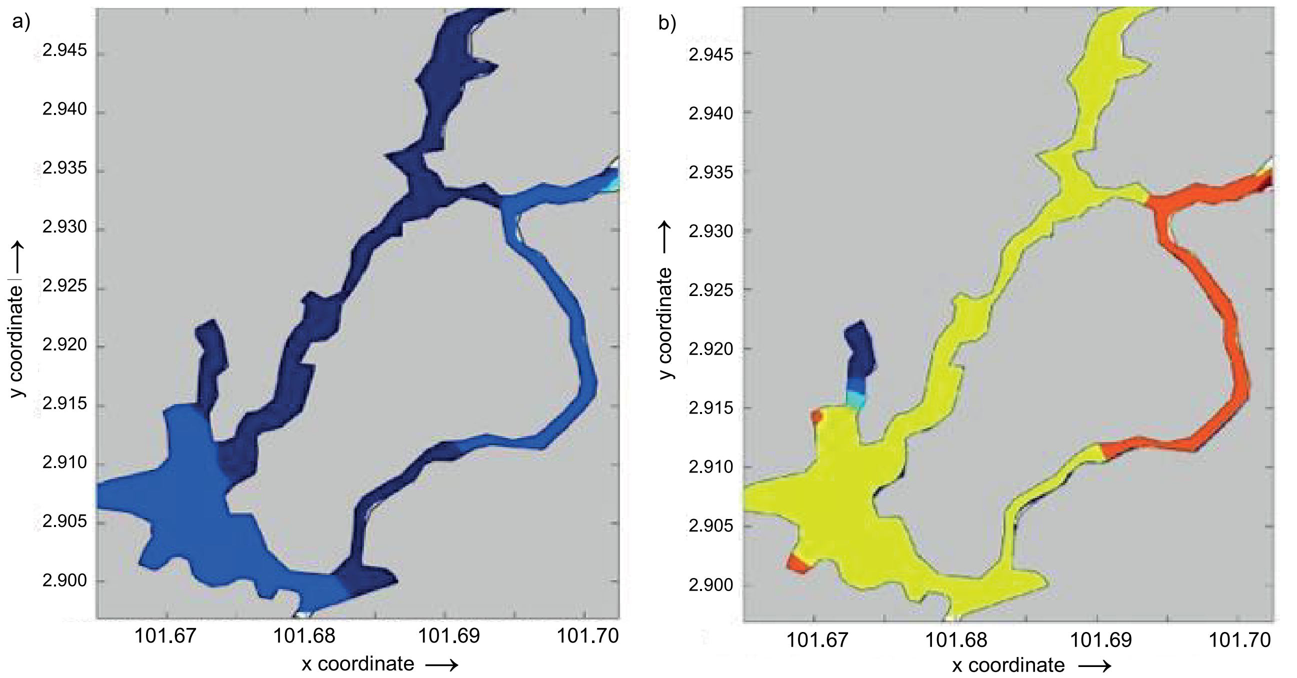


Fig. 8. Chlorophyll *a* concentration during: a) dry weather conditions, b) wet weather conditions; source: Global Water Consultants and University of Nottingham Malaysia



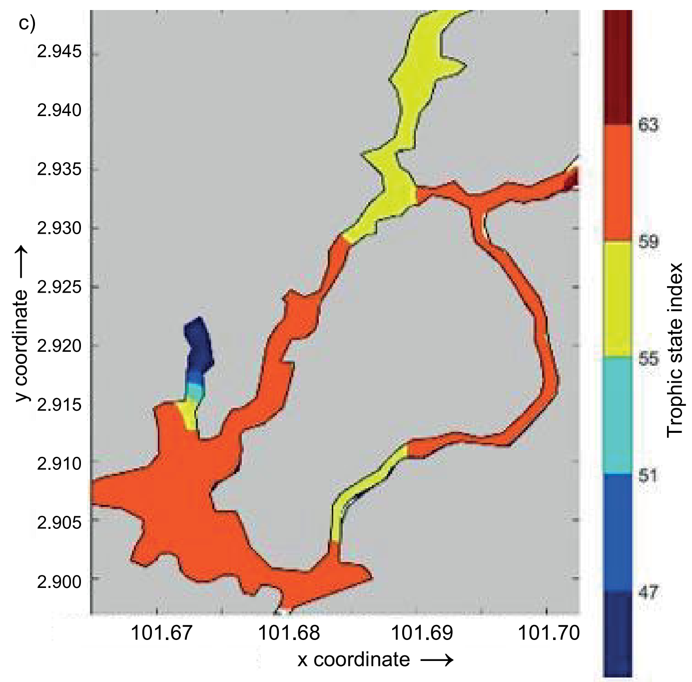


Fig. 9. Trophic state index maps under different phosphorus (P) loading scenarios: a) P = 0.05 mg·dm^{-3}, b) P = 0.35 mg·dm^{-3}, c) P = 0.42 mg·dm^{-3}; source: Global Water Consultants and University of Nottingham Malaysia

In the worst-case scenario (scenario 3), where 0.42 mg·dm^{-3} phosphorus concentration reaches 0.42 mg·dm^{-3}, nearly the entire lake transitions to eutrophic conditions, posing severe risks to water quality. This level of nutrient enrichment exceeds the lake's capacity to assimilate phosphorus, increasing the likelihood of algal blooms and oxygen depletion. External phosphorus loading (EPL) is primarily from industrial effluents, agricultural runoff, and urban sewage, contributing significantly to lake nutrient enrichment. The interplay between EPL and internal phosphorus recycling (IPR) creates complex dynamics that require careful management. High IPR can lead to unexpected increases in algal concentrations and reduce the resilience of lakes (Tay *et al.*, 2022a). Effective phosphorus control strategies to control EPL and IPL are crucial to prevent such deterioration.

CONCLUSIONS

The simulation results reveal a strong link between phosphorus loading and eutrophication in Putrajaya Lake, highlighting the need for proactive phosphorus management.

At a baseline concentration of 0.05 mg·dm^{-3}, the lake remains in an oligotrophic state, indicating that natural flushing and nutrient cycling effectively regulate phosphorus levels. At 0.35 mg·dm^{-3}, eutrophic conditions expand into stagnant zones, where limited water circulation exacerbates nutrient accumulation. These high-risk areas require mitigation measures such as improved water exchange and localised nutrient management to prevent further deterioration. In the worst-case scenario (0.42 mg·dm^{-3}), widespread eutrophication severely degrades water quality, increasing the likelihood of harmful algal blooms and oxygen depletion. To prevent this, phosphorus levels should be maintained below 0.30 mg·dm^{-3}, with stricter controls in stagnant zones and inflow points.

This study presents an innovative approach for managing phosphorus loading and mitigating eutrophication in tropical lakes through numerical modelling techniques. While the approach was applied to Putrajaya Lake, its methodology is adaptable to other tropical lakes by calibrating site-specific hydrodynamic and nutrient parameters. The findings highlight the critical role of proactive phosphorus management in maintaining lake water quality and preventing eutrophication. Compared with other trophic state indices (*TSI*), the new index developed under the study (*TSI*-mL) provides a more accurate assessment of the trophic state for Putrajaya Lake and is recommended for adoption in the Putrajaya Lake assessment. The index is also recommended for use in other lakes or reservoirs in Malaysia and other tropical lakes. By using this index, lake managers and environmental agencies can more accurately assess the trophic status of their water bodies.

It is also recommended that policymakers or lake managers establish the threshold value of their lake based on the same approaches. Immediate action to control the inflow of the identified critical water quality parameters is required by installing gross pollutant traps (GPTs) at drainage inlets to the lake as one of the practical control measures. Nutrient reduction is the most urgent control measure. It is also recommended that wetlands be installed along the lake shoreline to filter nonpoint sources of pollutants from entering the lake via surface runoff.

The research highlights that the configuration of the hydraulic structures is critical in preventing the deterioration of water quality in a man-made reservoir. It is essential to conduct detailed and comprehensive water quality modelling to assess the potential risk of eutrophication during the study and design stages. Further research is needed on the internal phosphorus loading impact, the influence of water temperature, the benthic layer, longer simulation periods and mitigation measures, etc. Other possible confounding factors, such as catchment management, inflow variability, and unmonitored input sources, should also be considered in the research.

Water quality should be addressed in the early stages of the design process and included as a key design criterion for hydraulic structures, rather than being considered an afterthought, since post-construction rehabilitation work is often costly and irreversible.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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