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Assessing dissolved oxygen dynamics in Pasig River, Philippines: A HEC-RAS modeling approach during the COVID-19 pandemic

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ABSTRACT

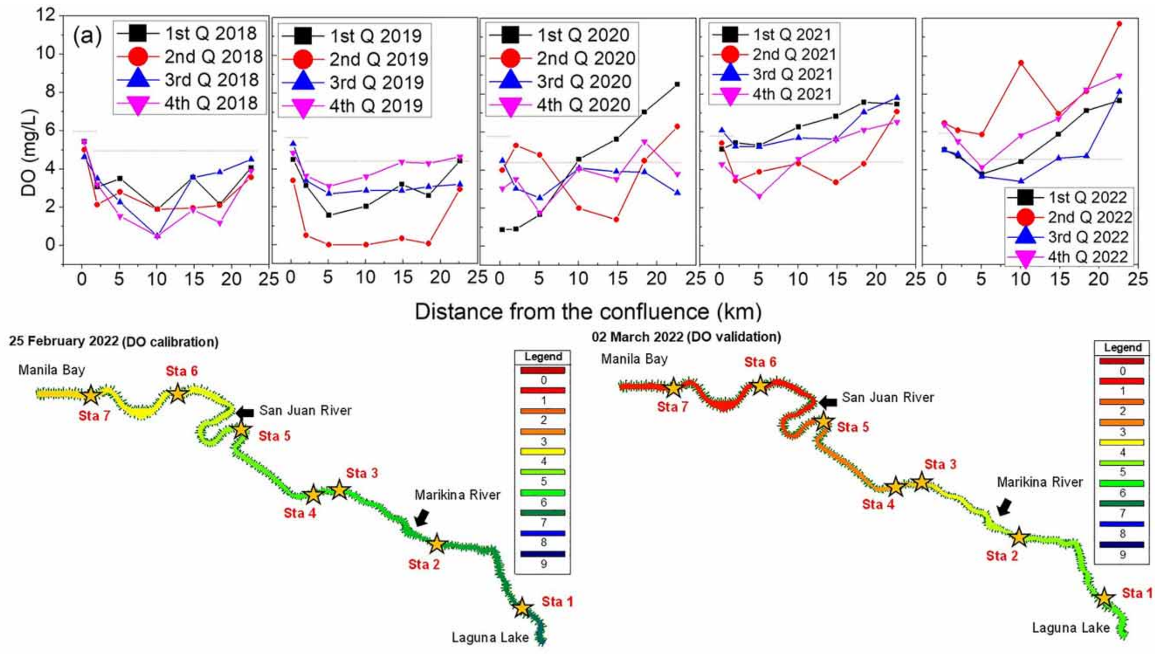
The water quality in Pasig River has been impacted by urbanization, industrialization, and the pandemic conditions. This study involved comparative analysis of dissolved oxygen (DO) levels before and during the pandemic. Field measurements, including water temperature, salinity, and DO, were conducted during neap and spring tides. To further understand and simulate DO distribution, a one-dimensional mathematical model, specifically Hydrologic Engineering Center-River Analysis System, was employed. Results showed that DO increased during the pandemic, ranging from 3.26 to 7.25 and 1.08 to 5.69 mg/L during neap and spring tide. From the minimum standard DO level, out of eight stations, seven passed during neap tide, while one station passed during spring tide. Salinity levels were higher during spring tide, which may have affected the DO. Salt intrusion was evident until 4 km from the confluence. The hydraulic model yielded average water level differences of 5.1 and 8.3 cm during calibration and validation, respectively. The DO calibration and simulation exhibited very good statistical evaluation outcomes, with values of 0.9 for Nash-Sutcliffe Efficiency and 0.3 for Root Mean Standard Deviation Ratio. These findings hold significant potential for formulation of water quality enhancement plans and implementation of solid waste management and pollution policies.

Key words: COVID-19, dissolved oxygen modeling, HEC-RAS, Pasig river, water quality

HIGHLIGHTS

- Dissolved oxygen (DO) increased during the pandemic in upstream and downstream areas.
- The hydraulic model showed very good statistical evaluation results of 0.94 for Nash–Sutcliffe efficiency (NSE) and 0.24 for root mean standard deviation ratio (RSR) for calibration and 0.91 for NSE and 0.29 for RSR for validation.
- The hydraulic model validation generated average water level difference of 8.3 cm during spring tide.
- The DO simulation showed very good statistical evaluation results of 0.9 for NSE and 0.3 for RSR during the neap and spring tide, respectively.

GRAPHICAL ABSTRACT



INTRODUCTION

River systems often get heavily degraded with pollution caused by wastewater and improper garbage disposal. Water quality must be monitored and well-studied to ensure the safety of the community near the river. In the Philippines, there are 18 major river basins, 421 principal rivers, and 79 lakes. Of the principal rivers, 180 suffer from water pollution due to domestic, industrial, and agricultural wastes (Tuddao & Gonzales 2020). Water quality standards are developed by environmental protection agencies to regulate, evaluate, and manage water bodies, yet problems still occur. The Pasig River is one of the major waterways in Manila. The 5-year average (2009–2013) biochemical oxygen demand (BOD) level of 30.79 mg/L exceeded the acceptable 7 mg/L BOD standard. The highest annual (1998–2014) BOD concentration of 39.03 mg/L was recorded in the year 2014. To improve the water quality at the downstream portion, dredging operations have been done. However, with the pandemic in 2020, new pollutants emerged like face masks, gloves, and other personal protective equipment (PPE). It is interesting to determine the water quality conditions during this unusual event.

During the early part of 2020, the world was severely hit by the Corona Virus Disease 2019 or COVID-19. As of 12 January 2023, 229 countries were affected by COVID-19 (Worldometers.info 2023). A global lockdown was implemented to contain the COVID-19. The lockdown affected the economy, communities in isolation, industries, and transportation, and human activity suddenly slowed down. The Philippines is one of the countries with the longest and strictest lockdowns. An initial quarantine policy was implemented in the National Capital Region (NCR) on the Luzon Island on 16 March 2020 before it was expanded later to the whole of Luzon Island due to an increase in community transmission. Individuals were required to wear masks, do physical distancing, stay indoors, and a pass must be secured to travel and buy essential items, which lasted up to April 2022. Limited services were allowed including medical and sanitation operations, while others such as transactions, gatherings, and business works were prohibited. While numerous studies have reported the occurrence of PPE in the marine environment, due to the lockdown, improvement in water quality was expected because of a reduction in wastewater discharges since malls and restaurants were closed. Similar findings were observed in other places in the world. In Venice, Italy, canals were found clearer after the lockdown because of reduced boat traffic resulting in lower sediment concentrations near the water surface (Hallema *et al.* 2020). The San Francisco Bay, California, had reduced water pollution mainly due to reduction in traffic with less toxic particles emitted by cars. In a severely polluted freshwater lake in India, the impact of the lockdown due to the COVID-19 spread on water quality was evaluated through satellite images. The analysis of suspended particulate matter concentrations showed a decrease of 15.9% on average, up to 8 mg/L decrease) compared with the pre-lockdown period (Yunus *et al.* 2020).

Several runoff risk assessments have been conducted in Pasig River, but very limited assessments are done on water quality modeling. Most of the studies in the Metro Manila area involve flood modeling and simulation (Badilla 2008; Dasallas *et al.* 2022). For water quality modeling in Pasig River, numerical models (Belo 2008) and remote-sensing methods (Escoto *et al.* 2021) were used in estimating water quality parameters. Other modeling tools such as the Water Evaluation and Planning (WEAP) model (Kumar *et al.* 2018) and Systems Thinking, Experimental Learning Laboratory with Animation (STELLA) (Bornilla *et al.* 2019) were also utilized. Numerical models are less complicated, but physical models are more accurate and reliable. The credibility of physical modeling is noted as one of its strengths as it is a conventional and extensively used method in hydraulic studies (Sutherland & Barfuss 2011). Physical models can be replicated or reproduced, given that the scale and the conditions are considered in the creation of the model. Event patterns or processes are apparent and can be observed, thus easier to understand (van Os *et al.* 2004; Erpicum *et al.* 2018).

To evaluate water sustainability for specific purposes, the measurement of water quality is crucial. Dissolved oxygen (DO) serves as a key indicator in assessing water quality, given its vital role in supporting aquatic life, making it a common parameter for such evaluations (Manitcharoen *et al.* 2020). The utilization of water quality models for estimating the distribution of water quality parameters in a specific area has been gaining traction in recent times.

Considering the limited studies on simulating water quality conditions in the Pasig River, it is imperative to develop a model capable of examining the influence of various factors, including the unique circumstances presented by the pandemic. This study aims to investigate the substantial changes in water quality within the Pasig River during the COVID-19 pandemic. An in-depth analysis of the distinctive neap and spring tide water quality, coupled with the hydrodynamic features of the Pasig River, has been conducted, and a water quality model has been developed for this purpose.

MATERIAL AND METHODS

Study site

Pasig River is located at 14.5944 N, 120.9556 E, which stretches an approximate length of more than 25 km from Manila Bay (MB) to Laguna Lake (LL). The width varies from 70 to 120 m and the depth ranges from 0.5 to 5.5 m. The river tides alternate from mixed semi-diurnal to diurnal between spring and neap tides. The river connects two important water bodies, namely, Laguna de Bay (freshwater source) and MB (source of saltwater intrusion). According to the Department of Environment and Natural Resources (DENR), Pasig River is classified as Class C, intended for fishery, recreational activities, and industrial water supply. The minimum DO level in a class C surface water body is 5.0 mg/L.

Pasig River was declared biologically dead in the year 1990 due to 295 tons per day of discharged BOD from domestic (44%), industrial (45%), and solid (11%) wastes (Gorme *et al.* 2010). The Pasig River Rehabilitation Commission was created in 1999 to supervise, monitor, and enforce rules for the river. The BOD in the year 1999 decreased to 140 tons per day (Qian *et al.* 2000) and below 7 mg/L (Gorme *et al.* 2010). Despite the government initiatives, the river continues to deteriorate over time. The Pasig River Unified Monitoring Stations (PRUMS) program was established to provide coherent water quality reports for the public interest. As of 2019, 19 stations are being monitored monthly for water quality. In this study, eight stations were utilized for onsite water measurement and analysis (Figure 1 and Table 1). The annual PRUMS water quality reports from 2018 to 2022 were used in this study. The 5-year DO secondary data were analyzed and compared as pre-pandemic and during pandemic conditions.

Marikina River and San Juan River are considered major tributaries of the Pasig River. This three-river system makes up a total catchment of 621 km^2. Water movement starts from LL down to the Napindan Channel before the Marikina River joins at the boundary of Taguig and Pasig. Further downstream, the San Juan River joins as a tributary until the water discharges into the MB. Due to some circumstances such as heavy rainfalls or typhoons, overflowing of the three major waterways occurs (Kumar *et al.* 2018). The drainage pattern of the system was adapted thereby considering the inflow of the Marikina River and San Juan River as boundary inputs in the hydraulic model development.

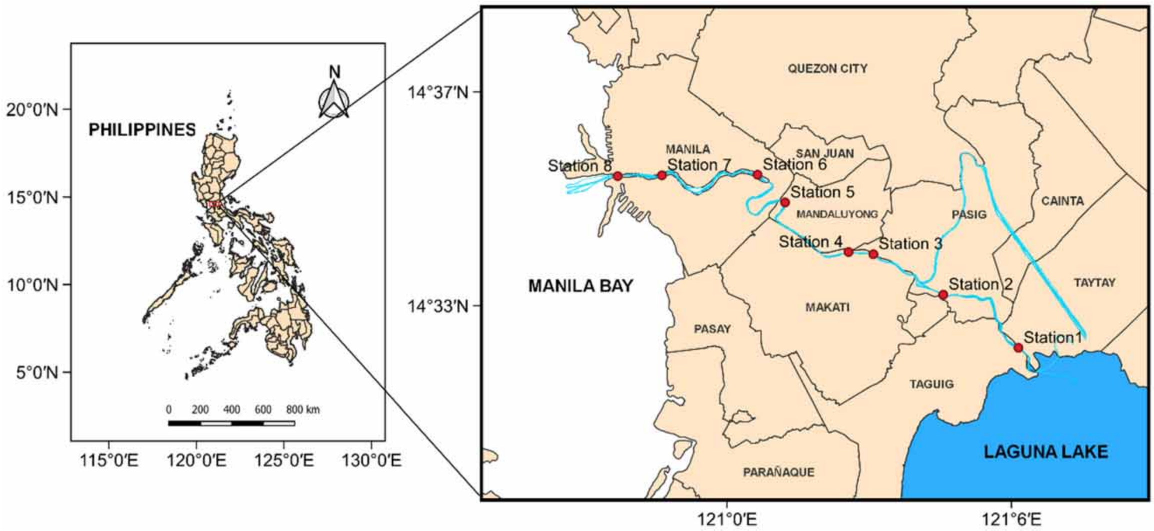


Figure 1 | Location of the Pasig River and the eight sampling stations.

Table 1 | Data measurement points location

Station number	Station name	Coordinates		Distance from confluence of MB and Pasig River[a] (km)
		Latitude (N)	Longitude (E)	
1	Napindan Bridge	14.5351	121.1022	22.6
2	Bambang Bridge	14.5536	121.0759	18.4
3	Buayang Bato	14.5690	121.0496	14.97
4	Guadalupe Viejo	14.5675	121.0402	13.9
5	Lambingan Bridge	14.5864	121.0200	10.07
6	Nagtahan Bridge	14.5954	121.0016	5.08
7	Jones Bridge	14.5955	120.9774	2.03
8	MB	14.5957	120.9612	0.3

[a]Distances are approximately plus 1.7 km from the mouth of the Pasig River.

Field measurement

Water quality measurements were done on 25 February 2022 (neap tide, low tide) and on 2 March 2022 (spring tide, low tide) in eight stations, starting from the Napindan Channel (upstream portion) until the MB (downstream portion). These eight stations were approximately near to the PRUMS coordinates and locations to ensure proper data comparison. The ProDSS multiparameter digital water quality meter was used to measure the vertical water temperature, salinity, and DO concentration on site. Table 1 shows the location details of the stations. It must be noted though that the downstream station, Station 8, is located 1.7 km from the junction of MB and the mouth of the Pasig River.

Model development

The study followed the general methodology for the development of the hydraulic model of Pasig River, Philippines (Figure 2(a)). The Hydrologic Engineering Center-River Analysis System (HEC-RAS) version 5.0.7 was utilized to model the flow and DO concentration along the Pasig River. It is a software developed by the U.S. Army Corps of Engineers, which allows the user to perform steady and unsteady flow simulations, sediment transport, and water quality modeling. In this study, the unsteady flow and water quality modeling components (for DO in Figure 2(b)) were incorporated into the model development. One-dimensional (1D) HEC-RAS is a vertically integrated model that is applicable only for well mixed estuaries. For stratified estuaries, two-dimensional modeling is required. Previous and current fieldworks show that salinity data are well mixed; hence, the 1D HEC-RAS model was utilized.

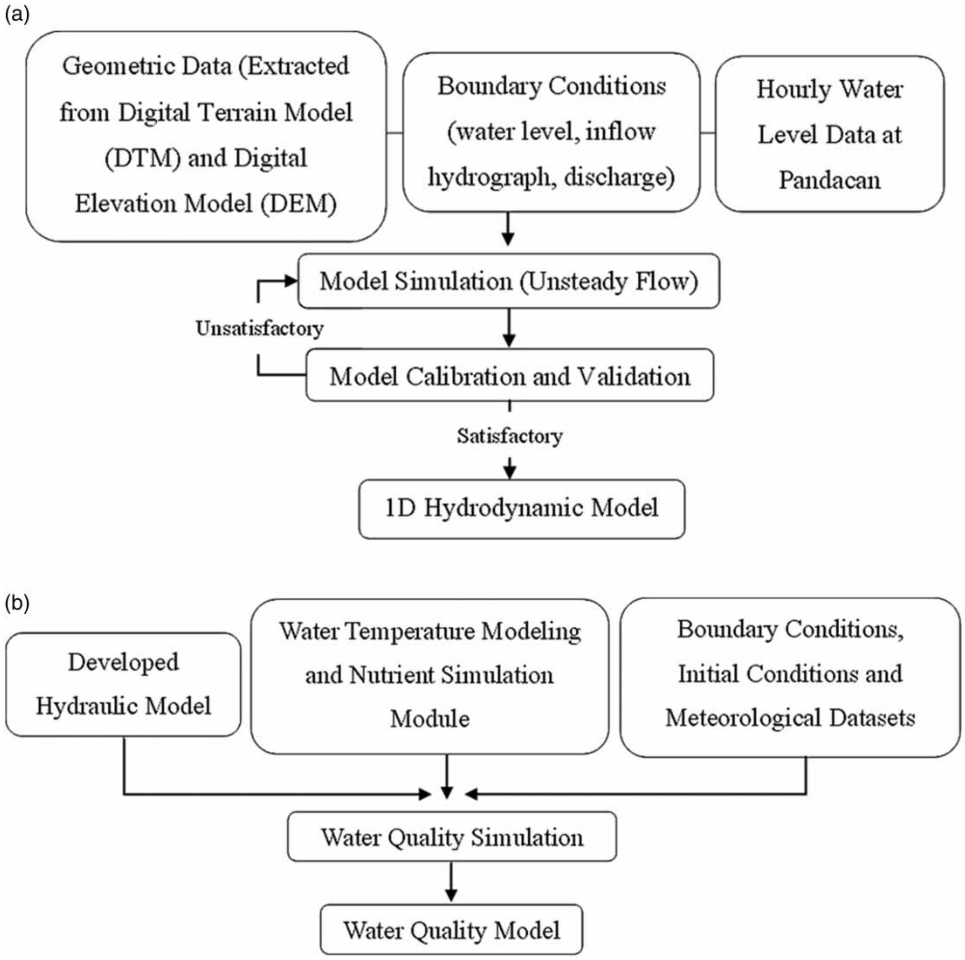


Figure 2 | Schematic diagram for (a) hydraulic and (b) DO model development.

Currently, numerical models, particularly 2D and 3D models, have gained popularity in environmental studies due to their ability to offer enhanced spatial and temporal detail. However, in the context of DO) prediction, 1D models can be effectively employed. This choice is driven by the advantages of reduced computational cost and time compared to their 2D and 3D counterparts.

The preference for 1D models in predicting DO levels is rooted in their ability to strike a balance between computational efficiency and predictive accuracy. While 2D and 3D models excel in capturing intricate spatial and temporal dynamics, the specific requirements for DO prediction may not always necessitate such high-dimensional representations. In scenarios where a more streamlined approach is viable, 1D models prove to be a pragmatic choice.

This strategic utilization of 1D models for DO prediction optimizes computational resources and minimizes the time required for simulations, without compromising the accuracy of results. It underscores the importance of selecting a modeling approach tailored to the specific objectives and constraints of the study, reflecting a judicious balance between model complexity and computational efficiency.

Hydrodynamic model

One-dimensional unsteady flow hydraulic component of HEC-RAS is governed by two principles, namely, the conservation of mass (continuity) principle (Equation (1)) and the conservation of momentum principle (Equation (2)), which are defined as follows:

$$\frac{\partial A_T}{\partial t} + \frac{\partial S}{\partial t} + \frac{\partial Q}{\partial x} - q_1 = 0, \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (VQ)}{\partial x} + gA\left(\frac{\partial z}{\partial x} + S_f\right) = 0, \tag{2}$$

where Q is the flow or discharge, A is the cross-sectional area, S is the storage from non-conveying portions of the cross-section, q_1 is the lateral inflow per unit distance, x is the distance along the channel, t is the time, g is the gravity acceleration, v is the velocity, z is the flow depth, and S_f is the friction slope.

The development of the hydraulic model required several data including geometric and water level data. The Pasig River profile was drawn based on the detailed channel cross-sections, which include the elevation, downstream reach lengths, Manning's n values, main channel bank stations, and the contraction and expansion coefficients. Digital Terrain Model and Digital Elevation Model were used to extract the cross-section data. The river line was represented by the conjunction between the Pasig River and LL, and the conjunction between the Pasig River and MB. With this confluence limitation, Station 8 (MB Station) was not included in the modeled river reach. The cross-sections were drawn with approximate lengths of around 45–100 m between each (Figure 3). Manning's roughness coefficient for the riverbed was theoretically calculated using Cowan's (1956) empirical method, which was described by the equation:

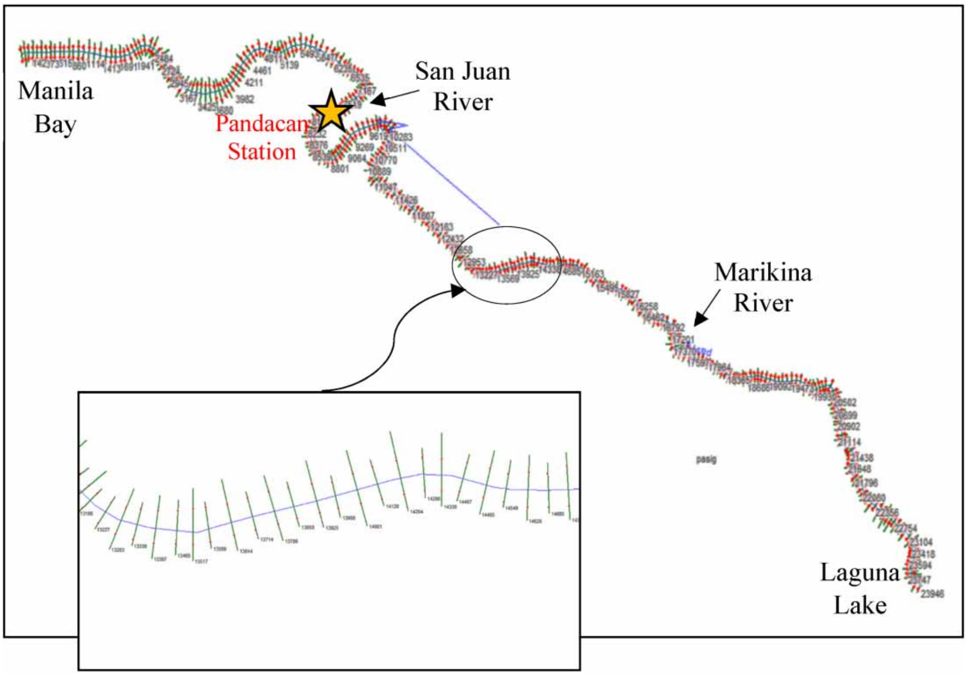


Figure 3 | Pasig River schematic generated from HEC-RAS.

$$(n_0 + n_1 + n_2 + n_3 + n_4) \times m_5 = n, \quad (3)$$

where n_0 is the basic value, for a straight, uniform channel, n_1 is the irregularities of the bottom, n_2 is the variations in the geometry of the channel, n_3 is the obstacles, n_4 is the vegetation, and m_5 is the correction factor for meandering.

Boundary conditions were set based on the upstream and downstream conditions of the river channel. Hourly stage or water levels of the LL and MB from 25 February 2022 to 2 March 2022 were used for the upstream and downstream conditions, respectively. In addition, an inflow hydrograph of the Marikina Tributary based on the Santo Niño rating curve from Monjardin *et al.* (2019) and a constant discharge measurement (assuming uniform flow) for the San Juan Tributary were also used as boundary conditions.

Water quality model

The developed hydraulic model was used to create the water quality model of the Pasig River, specifically for the DO parameter. Water quality simulation was done using the Nutrient Simulation Module of HEC-RAS software. The basis for this model is the principle of mass conservation wherein it solves a 1D transport equation (advection-dispersion transport equation) for each water quality constituent (Macholo 2016). The equation is given as:

$$\frac{\partial}{\partial t}(VC) = -\frac{\partial}{\partial x}(QC)\Delta x + \frac{\partial}{\partial x}\left(AD_x\frac{\partial C}{\partial x}\right)\Delta x + S_L + S_B + S_K, \tag{4}$$

where V is the volume of the water quality cell, C is the pollution concentration, Q is the water inflow, x is the distance, A is the cross-sectional flow area, D_x is the dispersion coefficient, t is the time, S_L is the source or sink for direct and diffuse loading rate, S_B is the source for boundary loading rate, and S_K is the source or sink for biogeochemical reaction rate. The equation is solved in HEC-RAS using the QUICKEST-ULTIMATE explicit numerical scheme.

To simulate the nutrient module, water temperature modeling was required. Hence, measured data of DO and water temperature were used as boundary conditions of the model. Values of other water quality parameters were assumed to be negligible. Boundary points used in the hydraulic model were also utilized in the DO model. Since there were no measured data for the two internal boundaries (Marikina and San Juan Tributaries), interpolation of data was done. Initial condition values were the same as the boundary conditions. The required dispersion coefficient was assumed based on the Fischer *et al.* (1979) equations and was computed on the most upstream part of the river. A fixed value of 489 m^2/s was computed and was plugged into the model. The meteorological dataset including the daily measurements of atmospheric pressure, humidity, air temperature, solar radiation, wind speed, and cloudiness factor, from the Science Garden Station was also added.

Model calibration and validation

Model calibration and validation were done to determine the sensitivity of the simulated values to the observed values. In this study, calibration of the hydraulic model was done by adjusting the Manning's roughness coefficient (n). The flow roughness factor and automated roughness calibration features of HEC-RAS were utilized. This allowed certain flow ranges to be calibrated using the base Manning's coefficient in the geometric data. Simulated water levels from 25 to 26 February 2022 were compared to the Effective Flood Control Operational System (EFCOS)–observed water level at Pandacan Station. Further validation was done by comparing the simulated water level from 1 to 2 March 2022 to the EFCOS-observed water level at the same station.

The water quality model was calibrated using the seven stations utilized during the field measurement. Water quality computational cells were set to 100, with the RS or cross-section representation of the seven stations established as fixed faces. The simulated values were compared to the February 25 (neap tide) observed values. Further evaluation was done by comparing the simulated values to the March 2 (spring tide) observed values.

Model evaluation

Model evaluation was done to measure the performance rating of the developed hydraulic and DO model. Two model performance evaluation statistics equations were used: the Nash–Sutcliffe Model Efficiency Coefficient (NSE) and the RMSE-Root Mean Standard Deviation Ratio (RSR), which are presented below, respectively:

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(\mathrm{OBS}_i - \mathrm{SIM}_i)^2}{\sum_{i=1}^{n}(\mathrm{OBS}_i - \overline{\mathrm{OBS}})^2}, \tag{5}$$

$$\mathrm{RSR} = \frac{\sqrt{\sum_{i=1}^{n}(\mathrm{OBS}_i - \mathrm{SIM}_i)^2}}{\sqrt{\sum_{i=1}^{n}(\mathrm{OBS}_i - \overline{\mathrm{OBS}})^2}}, \tag{6}$$

where OBS_i is the observed value, SIM_i is the simulated value, OBS is the mean of the observed values, and n is the total number of observations.

Adapting the descriptive rating developed by Moriasi *et al.* (2007, 2015), based on the performance evaluation of a watershed model, the descriptive rating of the two performance statistic equations is presented in Table 2.

Table 2 | Descriptive rating of the two performance statistic equations

	Statistics	
Rating	**NSE**	**RSR**
Good	NSE > 0.80	0.00 < RSR ≤ 0.50
Good	0.70 < NSE ≤ 0.80	0.50 < RSR ≤ 0.60
Satisfactory	0.50 < NSE ≤ 0.70	0.60 < RSR ≤ 0.70
Unsatisfactory	NSE ≤ 0.50	RSR > 0.70

Source: Moriasi *et al.* (2007, 2015).

RESULTS AND DISCUSSION

Pre-pandemic and pandemic condition DO levels

The DO in six stations (Napindan Bridge, Bambang Bridge, Guadalupe Ferry, Lambingan Bridge, Nagtahan Bridge, and Jones Bridge) along the main Pasig River plus the MB station, from 2018 to 2023, were compared. Based on the secondary data from the PRCMO, the DO concentration from 2018 to 2019 in all of the stations failed to meet the minimum standard value (Figure 4(a)). However, an increase in DO concentration was observed in several locations in the year 2020. In 2021–2022, the DO levels were above the minimum standard not just in the upstream freshwater areas (18.4–22.6 km) but also in downstream areas. However, after the lock-down eased up, DO values again went below the minimum standards. The average annual BOD at the six main Pasig River stations considered in this study from 2018 and 2019 were 27.8 and 24.2 mg/L, respectively (Figure 4(b)). The values decreased to 13.8 mg/L in the year 2021 and 12.7 mg/L in the year 2022. This signified that the water quality conditions improved due to fewer discharges from industrial and commercial establish-ments when strict quarantine restrictions were enforced. The BOD levels are still low in 2023, which could be attributed to the ongoing clean-up operations and current laws that are implemented more effectively.

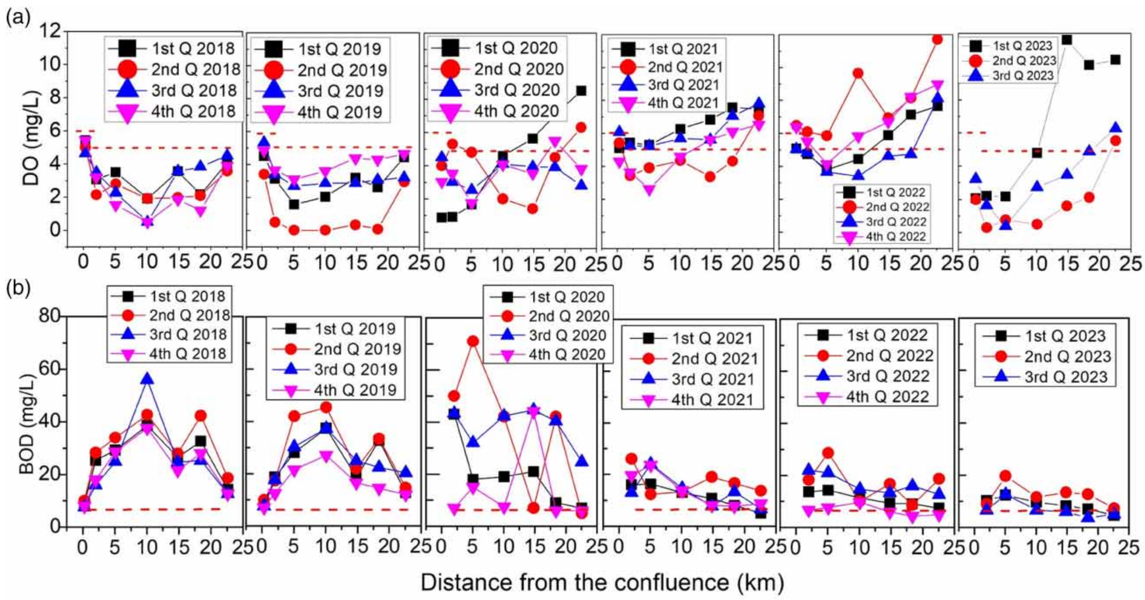


Figure 4 | Comparison of the surface water (a) DO levels (mg/L) and (b) BOD (mg/L) from 2018 to 2023. The red dashed lines indicate the minimum standard for Class C freshwater and Class SB coastal and marine water.

The DO parameter is commonly a good indicator of water quality status for a given water body. Low DO concentration indicates high water pollution, among other factors affecting it (Debska *et al.* 2021). Low levels of DO were evident in the second quarter of 2020 and 2021 is attributed to the increase in water temperature during the warm months of March and April. During the data gathering of the PRCMO in the second quarter of 2020, several plastics, Styrofoam, papers, rubber, and glass bottles were observed in most of the stations. This was the time of strict lockdowns where there was a surge in the use and disposal of single-use PPEs. There was also a huge dependence on food delivery services and online shopping leading to the substantial increase in plastic packaging from online shops and deliveries.

In the Pasig River, the domestic sector stands out as the primary contributor to pollution, responsible for over 60% of the total pollution load (Belo 2008). The low-income families and informal settlers residing around the Pasig River tend to purchase products such as soap, shampoo, and food in affordable sachets and cans, as opposed to more expensive bulk commodities. Unfortunately, improper disposal of these sachets and cans results in their accumulation in the river.

According to the National Water Quality Status Report (2014–2019), Metro Manila generated a total domestic pollution load of 19,988 tons of BOD per year. The implementation of community stay-at-home lockdowns and the closure of malls, restaurants, and establishments during the pandemic led to a reduction in garbage disposal activities, resulting in less direct and indirect pollution entering the river. This temporary reduction in human activity had a positive impact on mitigating pollution in the Pasig River.

Onsite neap tide and spring tide water quality comparison

The vertical plots of temperature, salinity, and DO, measured on site, are shown in Figure 5. The DO levels were higher in the upstream stations near LL (Station 8, 22.6 km), which had lower water temperatures. The downstream stations, however, had lower DO, higher temperature, and salinity intrusion was evident. Strict community quarantine was still imposed during the days when the fieldworks were conducted. There was a massive surge of COVID-19 cases in the Philippines in January 2022 (Yadav & Moon 2022). The Omicron variant, a specific strain or mutation of the COVID-19 virus, emerged in late 2021 (Kannan *et al.* 2022).

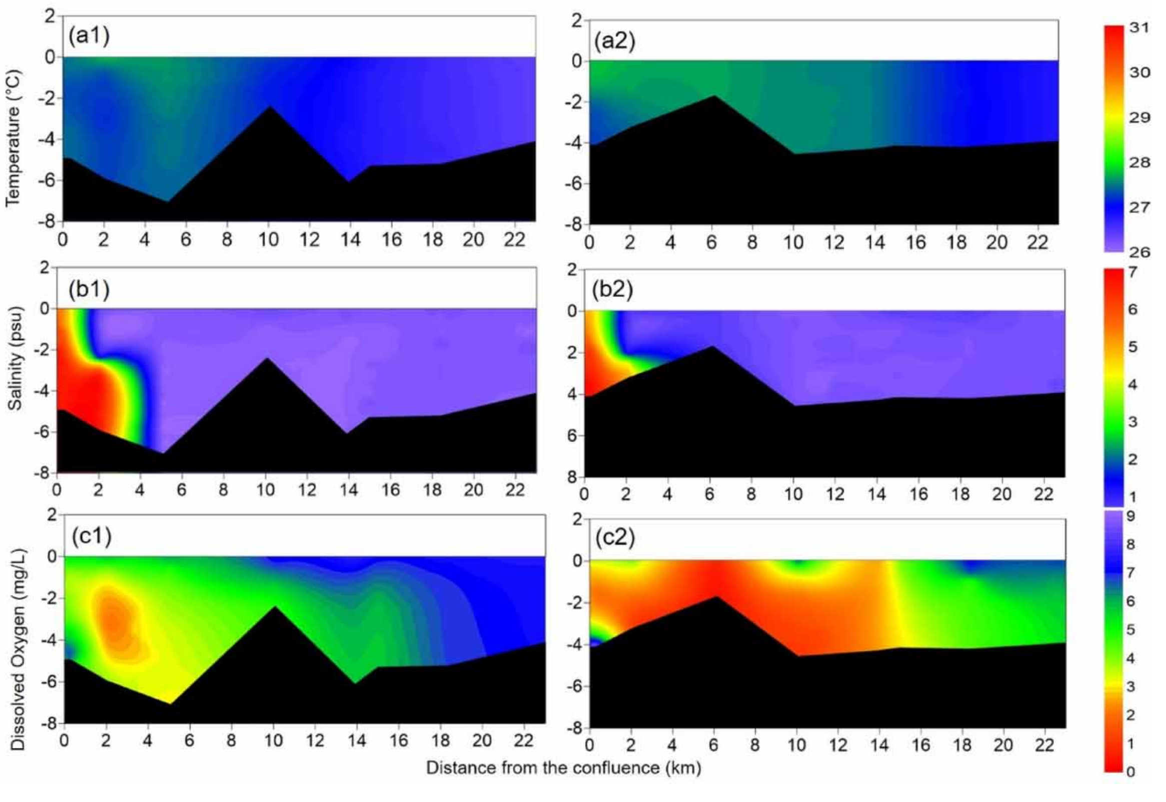


Figure 5 | Vertical water profiles of (a) temperature (°C), (b) salinity (psu), and (c) DO (mg/L) on (1) 25 February 2022 neap tide and (2) 02 March 2022 spring tide.

Water temperature

Water temperature values ranged from 26.4–27.4 to 26.8–27.6 °C during neap tide and spring tide, respectively. The highest recorded temperature during neap tide was observed at Station 6 and Station 8, while Station 5 exhibited the highest temperature value during spring tide (Figure 5(a)). The water temperature along the river channel was almost identical for both date measurements. The maximum temperature values were observed on the downstream portion of the river due to the sampling time. Data gathering started in the morning at the upstream areas when the temperature is colder while the downstream area water quality was measured after around 4–7 h between noon to afternoon with warmer temperatures. Furthermore, less stratification was observed on the upstream portion of the river.

Salinity

Salinity levels during both neap tide and spring tide exhibited a range of 0.09–6.82 and 0.29–to 6.81 psu, respectively. The measured values during spring tide were relatively higher compared to those during neap tide, as illustrated in Figure 5(b). This difference could be attributed to the elevated water levels, leading to a greater freshwater flow from LL during the low neap tide, while water levels at the MB are comparatively lower. Notably, salinity intrusion was more pronounced during neap tide.

At Station 8, located at the confluence, exceptionally high salinity values were observed. Moreover, Station 7 exhibited elevated salinity before a noticeable drop to less than 1 in the remaining stations. This variation in salinity levels may be attributed to the station's proximity to the confluence and the dynamics of water mixing (Casila *et al.* 2017). A discernible decreasing trend in salinity was noted upstream along the river, possibly due to the significant influence of freshwater input from the upstream lake and tributaries.

Dissolved oxygen

DO values during neap tide were higher compared to the spring tide measured values. DO values ranged from 3.26 to 7.25 mg/L and from 1.08 to 5.69 mg/L during neap and spring tide, respectively. Station 1 displayed the highest DO concentration during neap tide while both Stations 1 and 8 had relatively high DO concentration during spring tide. Station 1, being the upstream most station, receives freshwater from the LL. A decreasing trend was observed from upstream going downstream. Station 3 had low DO due to the Marikina River tributary, which has big establishments, residential, and commercial areas (Casila *et al.* 2023). Stations 6 and 7 have very low DO due to the presence of dead water hyacinths and inflow of poor water quality from San Juan River, which is a major tributary of the Pasig River. DO became higher at the outlet in MB, which is likely due to lower BOD and influences of the bathymetry where the river width is increasing as the channels lead to the river mouth. The discharge of fresh domestic and industrial water to the Bay could also affect the DO because Pasig River is largely influenced by the freshwater flow, allowing flushing water with poor quality.

According to the DENR Administrative Order (DAO) 2016-08, Water Quality Guidelines (WGS) and General Effluent Standards (GES) of 2016, water body classification and usage of freshwater, waters under Class C are intended for fishery, recreational (Class II), agriculture, irrigation, and livestock water supply. Seven (Station 1–7) of the eight stations fall under this classification. On the other hand, MB (Station 8) falls under Class SB classification of Coastal and Marine Waters as MB is considered a marine water source. This is intended for recreational water (Class I), fishery water (Class II), and tourist zone. The standard minimum value for the DO parameter for Class C and Class SB is 5 and 6 mg/L, respectively.

During neap tide, six of the eight stations passed the minimum value. These were Stations 1–5 and Station 8, with Station 8 exhibiting the highest DO level among all. Alternatively, only Station 1 met the standard minimum value during spring tide, and the rest exhibiting low DO levels (Figure 6(c)).

Hydraulic model

Velocity profile

The water movement followed the difference in water level between LL and MB during model simulation. For instance, water flowed from LL to MB during times when the water level in LL is higher compared to that in MB (e.g., during low tide). Figure 7 shows the simulated velocity profile of the Pasig River during the neap tide condition. A maximum velocity of 0.89 m/s was simulated at the upstream while a minimum velocity of 0.15 m/s was simulated at the downstream portion of the river. The actual averaged onsite measurements of velocity were 0.98 and 0.19 m/s in the upstream and downstream stations, respectively. As seen in the figure, a few

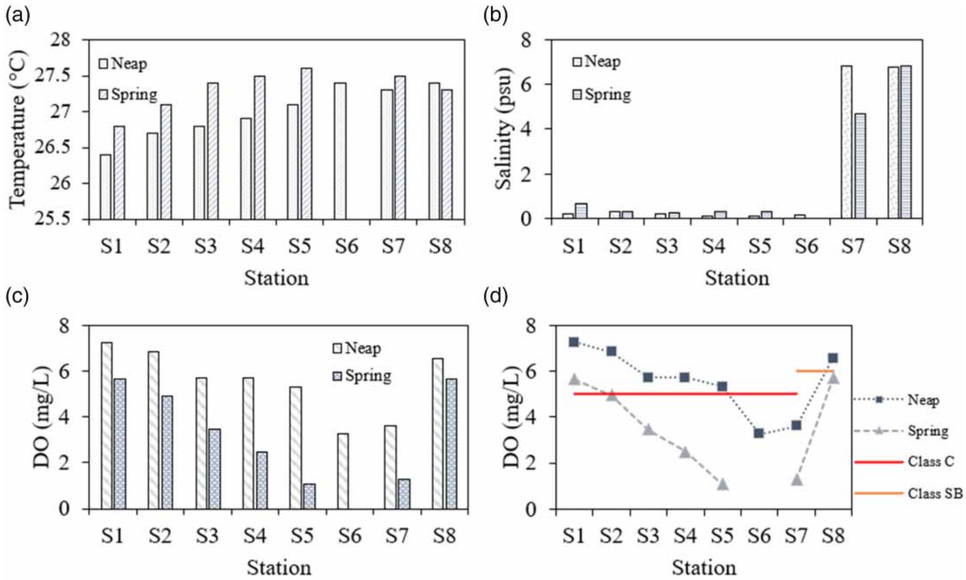


Figure 6 | Neap and spring tide variations of (a) temperature (°C), (b) salinity (psu), (c) DO (mg/L), and (d) DO levels (mg/L) compared with Class C and Class SB standards.

fluctuations can be observed along the river reach, signifying that the velocity variation within the river is heavily affected by the changes in its geometry, bathymetry, and meandering sections. The velocity was higher at areas around 13–15 km, which may be due to the straight channels. The highest velocity upstream was due to the large freshwater inflow from the lake during low tide. Low velocities were generated at areas around 10 km, which may be due to the presence of meandering channels.

Hydraulic model calibration and validation

Model calibration was done from 25 to 26 February 2022, involving the simulation of water levels and a comparison with EFCOS-observed water level data at the Pandacan Station (refer to Figure 7(b)). The optimal Manning's n coefficients were determined, ranging from 0.015 to 0.045. To refine the model, particularly at lower water stages, the flow roughness factor and automated Manning calibration were applied. The calibration process resulted in an average error of 0.051 m, indicating that the simulated water level at the Pandacan Station deviated by approximately 5.1 cm.

Subsequent to calibration, model validation occurred from 1 to 2 March 2022, utilizing water level data from the Pandacan station (see Figure 7(c)). An average error of 0.083 m was computed, demonstrating that the simulated water level differed by approximately 8.3 cm. This suggests a slightly higher degree of variation in the simulated values during the validation period.

Hydraulic model evaluation

Once the hydraulic model was calibrated and validated, evaluation was done to assess the capacity of the model to accurately simulate the water level along the Pasig River. Two performance statistic equations were used: NSE and RSR. A value of NSE = 1 shows a very fit model, indicating that the simulated values perfectly coincide with the observed values. On the other hand, as the RSR value approaches 0, the simulation performance of the model is better. Table 3 presents the calculated values for the two indicators during the calibration and validation stages. Both results showed a very good rating, indicating positive performance of the developed hydraulic model in water level prediction.

DO model

DO model simulation during neap tide and spring tide conditions

The developed hydraulic model was used to simulate the DO model of Pasig River. Water temperature and DO values were used as input. However, only the DO parameter was evaluated as the water temperature parameter was only used as a baseline data for the model simulation. DO model simulation was done during neap and spring tide conditions at the seven stations utilized in the study (excluding Station 8 near the confluence due

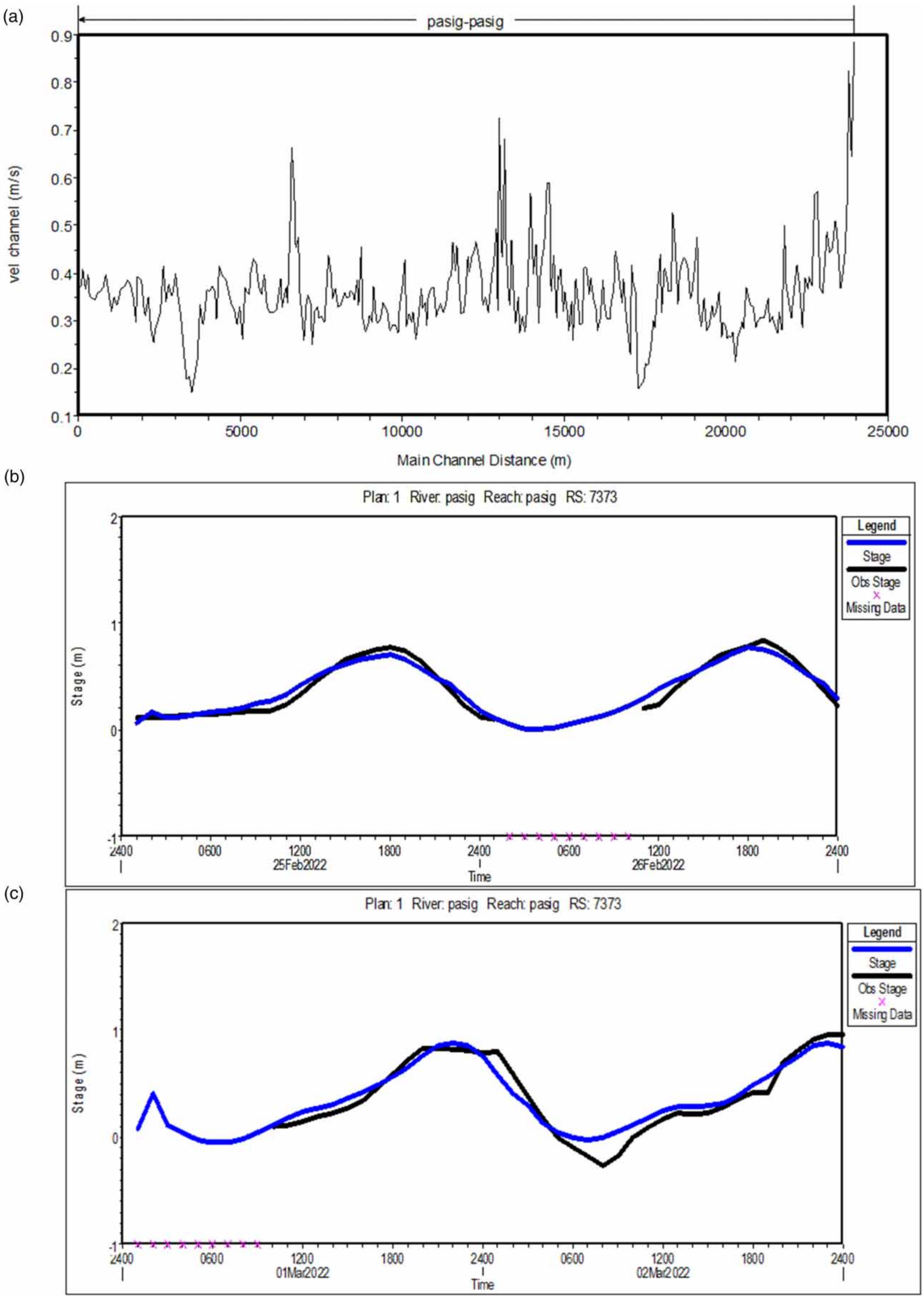


Figure 7 | Simulation results of the (a) velocity profile during 25 February (neap tide) and EFCOS-observed water level at Pandacan Station during (b) calibration and (c) validation.

to modeling software limitation). The model was further evaluated by determining its performance rating using the same equations used in the hydraulic model evaluation. The testing conditions encompass a defined simulation period, allowing for the observation of changes in DO levels over time. This period is chosen to capture relevant trends and variations in water quality.

Table 3 | Performance evaluation of the developed hydraulic model

Station	Statistics rating			
	NSE		RSR	
Calibration stage				
Pandacan station	0.9418	Very Good	0.2412	Very Good
Validation stage				
Pandacan station	0.9147	Very Good	0.2921	Very Good

Source: Moriasi *et al.* (2007, 2015).

During neap tide, a decreasing trend from upstream to downstream stations can be seen (Figure 8(a)). The highest simulated value was 7.091 mg/L, located at Station 1 (22.6 km), which is at the upstream portion of the river. On the other hand, the lowest simulated value was 3.789 mg/L, observed at Station 7 (2.03 km), which was located near the river mouth. A maximum discrepancy of −0.832 mg/L was computed, indicating that the model overestimated the DO concentration at certain locations.

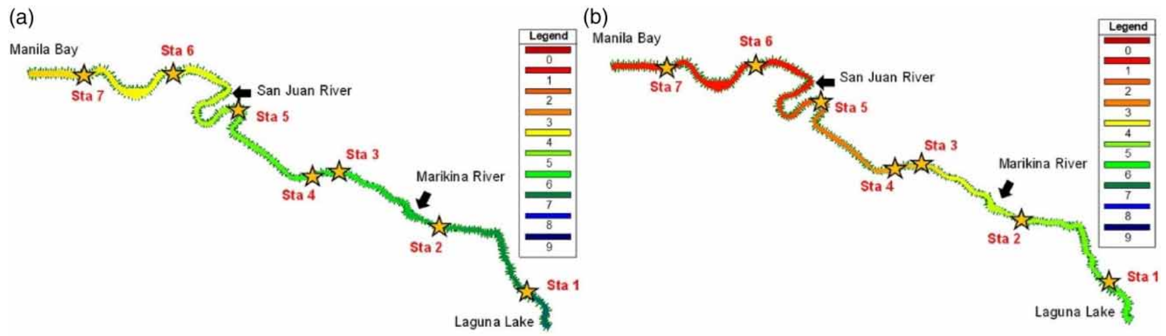


Figure 8 | Spatial plot of simulated DO concentration during (a) 25 February (neap tide) and (b) 2 March (spring tide) from LL (upstream) to MB (downstream).

On the other hand, the DO model was run again during the spring tide condition (Figure 8(b)). Similarly, a decreasing trend of DO concentration was observed from the upstream to the downstream portion of the river. A maximum simulated value of 5.1 mg/L was observed at Station 1, while the minimum simulated value was 1.235 mg/L, located at Station 7. The maximum discrepancy during the spring tide was −0.976 mg/L.

DO model evaluation

The results of the DO model evaluation are outlined in Table 4. For the neap tide simulation, NSE and RSR values of 0.9212 and 0.2807 were computed, respectively (Figure 9(a)). Conversely, during the spring tide simulation, NSE and RSR values of 0.8983 and 0.3188 were derived, respectively (Figure 9(b)). Both simulations demonstrate a high degree of accuracy in replicating observed values, indicating a very good fit. However, it is noteworthy that overestimations were identified at certain stations in both simulations. DO was lower during spring tide than neap tide, which could be attributed to salinity intrusion (Figure 8(b)) that mixes unoxygenated saltwater from the bay with freshwater from upstream.

Table 4 | Performance evaluation of the developed water quality model

Condition	Statistics	
	NSE	RSR
Neap tide	0.9212	0.2807
Spring tide	0.8983	0.3188

Source: Moriasi *et al.* (2007, 2015).

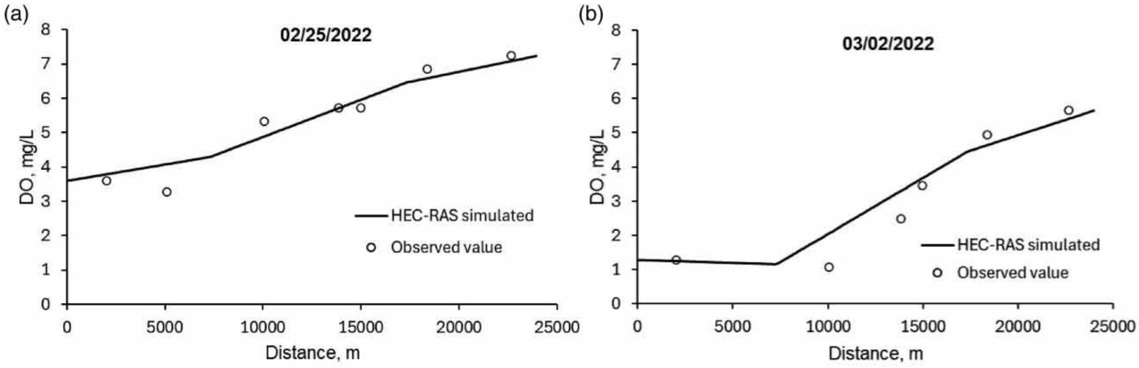


Figure 9 | Comparison of the observed vs simulated DO values during (a) 25 February (neap tide) and (b) 2 March (spring tide).

Factors affecting Pasig River hydrodynamics and water quality

The hydrodynamic activity of the Pasig River is intricately influenced by the dynamic interaction between LL and MB. In this study, these two water bodies were treated as an integrated system, interconnected by the Pasig River. The ebb and flow of water level within the upstream segment (LL) and the tidal fluctuations at the river mouth (MB) play a pivotal role in determining the overall water movement. In addition, the impact of the surrounding tributaries, such as the Marikina River and San Juan River, was taken into account to comprehensively understand the complex hydrodynamics of the Pasig River.

Pasig River's location experiences two pronounced seasons: dry and wet seasons. The former prevails from November to April while the latter occurs from May to October. During the dry season, LL's water level is considered low, peaking at its lowest elevation at the end of April or May (JICA & Yachiyo Engineering Co. 2014). Thus, tidal waves on MB mainly dictate the flow direction, resulting in salinity intrusion. On the other hand, the water level at the LL increases during rainy seasons due to excessive rainfall. Provided that the Pasig River is the only outlet of the lake, water is discharged into the river, allowing salt flushing (Szekielda *et al.* 2014). This study was conducted during the dry season.

The hydraulic model was developed and utilized to create the water quality model of the Pasig River. The geometry created and computed velocities influenced the movement of the constituents in the water quality model (Haddout *et al.* 2015). The longitudinal variation of the DO concentration along the Pasig River follows a decreasing trend starting from the upstream and going downstream for both measurement conditions. Simulated DO values during neap tide were higher compared to the values during spring tide. The addition of internal boundaries prevented the model from simulating a linear water quality result, allowing consideration of the drop in DO concentration in some parts of the river.

The upstream portion of the river is urbanized. Going midstream to the downstream portion, the drop in DO concentration was very evident. This is due to industrial buildings and informal settlers surrounding both banks, especially between the area of Delpan Bridge and Jones Bridge around 2–10 km distance from the MB, where factory berths are apparent (JICA & Yachiyo Engineering Co. 2014; Jalilov 2017). The Pasig River is composed of major and minor tributaries that affect the river's water quality. These tributaries or estuarial creeks are located between highly congested cities, where they catch various wastes (Ancheta 2021). Based on the findings of the study, the area around Lambingan Bridge to Jones Bridge is heavily polluted, which can be due to the water discharge of San Juan River and nearby estuaries, including Estero de Paco, Estero de Binondo, and Estero de San Miguel that contributes 50% of the total BOD (Clemente 2020). Thus, the results of the present study can be extended to propose the assimilation capacity of the river to organic loading, thereby giving insight on the total maximum daily load (TMDL) for the river. This will support policymakers to recommend comprehensive management action plans to enhance water quality. Future investigations could explore the intricate relationship between TMDL and the river's assimilation capacity to further refine water quality management strategies.

CONCLUSIONS

Historical data showed that the DO did not meet the minimum standards from 2018 to 2019, but the levels increased from 2020 up to 2022. Field measurements of water temperature, bottom depth salinity, and bottom depth DO, performed during the COVID-19 lockdown condition, revealed varying neap and spring tide river water quality conditions. The hydrodynamics of the Pasig River show the interaction between the LL and the MB. Low DO levels were most evident at the downstream areas near the Pasig River confluence to MB. Despite certain assumptions adopted, both neap and spring tide models produced very good ratings. Adapting computer-aided models is an effective tool in estimating the water quality condition of a water body without the need for time-consuming and expensive fieldwork. It is especially useful in areas where observed data are not available.

The study's findings have significant implications for authorities involved in planning and executing water quality improvement initiatives. Notably, during the pandemic, the water quality in the Pasig River experienced improvements due to reduced direct discharge and water pollution from temporarily closed restaurants and establishments. To ensure sustained progress, future efforts should focus on enhancing the implementation of waste disposal policies, such as the Solid Waste Management Act, improving material recovery facilities, and expediting the completion of the sewerage master plan to enforce strict compliance with GES for commercial and industrial establishments. In addition, addressing the relocation and providing sustainable livelihoods for informal settlers is crucial. Strengthening information, education, and communication initiatives will be essential for maintaining and sustaining the improvements in the Pasig River. Furthermore, the study suggests potential support for management, policy-making, and plans advocating for river transportation (by the Pasig River Ferry Service Office) over road transportation to reduce the significant carbon footprint.

However, it is essential to acknowledge the study's limitations. The research focused on neap tide and spring tide data during the COVID-19 lockdown dry season, with a calibration period covering a short timeframe. To enhance the study's validity, further validation efforts using longer time series are recommended. In simulating the water quality module, continuous input data are preferred for accurately modeling parameters. The developed water quality model in this study concentrated solely on the DO parameter. To comprehensively assess water quality, modeling other relevant parameters is advisable. Finally, enhancing the model's robustness and reliability can be achieved by simulating it under various scenarios.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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