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Effect of hydrodynamic conditions on the water quality in urban landscape water

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ABSTRACT

In this study, a 2D hydrodynamic and water quality model was built based on MIKE 21 to investigate the relationship between hydrodynamic condition and water quality, and then applied in an urban landscape lake in Tianjin, China. Moreover, an engineering experiment was carried out to confirm the comprehensive degradation coefficients of chemical oxygen demand (COD), total phosphorus (TP), nitrogen ammonia (NH_4^+-N), and total nitrogen (TN) (0.014 d^{-1}, 0.024 d^{-1}, 0.019 d^{-1}, and 0.005 d^{-1}, respective). Circulation system was the main force that expedited water changes and pollutant movement, increased the lake average water speed from 0.003 m/s to 0.008 m/s, and could effectively reduce the COD, NH_4^+-N and TN concentration nearly by 35, 32, and 5%. The high concentrations nitrogen and phosphorus in the reclaimed water would accelerate the deterioration of water quality, and the concentrations of TP, NH_4^+-N, and TN in the lake increased from 0.080 mg/L, 0.53 mg/L, and 1.53 mg/L to 0.090–0.096 mg/L, 0.71–0.81 mg/L, and 1.89–2.08 mg/L, respectively. The circulation system could slow the water quality deterioration but cannot eliminate the eutrophication risk. Improving the hydrodynamic conditions was proposed for enhancing water quality in urban landscape lakes.

Key words: landscape water, MIKE 21, numerical model, reclaimed water, water quality simulation

HIGHLIGHTS

- Four scenarios of urban landscape water were set in the simulation to study the relationship between hydrodynamic conditions and the water quality.
- The Mike 21 was used to simulate the hydrodynamics and water quality.
- The circulation system could improve the water quality.
- The reclaimed water would accelerate the deterioration of water quality.
- The reclaimed water should be treated before enter the lake.

1. INTRODUCTION

Urban landscape water is an important component of unban ecosystem and it plays an important part in regulating precipitation, reducing the tropical island effect, supplementing water resource, and strengthening the human power against calamities and plagues. Different from natural lakes, urban landscape lakes are characterized by enclosed or semi-closed ecosystems, small surface area, shallow depth, low flow rate, poor self-purification capacity, and eutrophication is the primary threat (Huang *et al.* 2018; Chang *et al.* 2020). Meanwhile, with shortages of urban water resources, reclaimed water has been widely used to replenish the urban landscape water to counteract the water loss caused by evaporation and keep a stable water level due to its stability and controllability (Ao *et al.* 2018b). Whereas the reclaimed water would also bring large amounts of nitrogen and phosphorus when added to the urban landscape water.

Numerous scientific studies have focused on the factors affecting the water quality, such as the salinity, light, temperature, nitrogen, phosphorus, redox, and watershed landscape (Mahanty *et al.* 2016; Huang *et al.* 2018; Li *et al.* 2020). The hydrodynamic condition cannot only dilute pollutant concentrations, accelerate water exchange and the re-oxygenation rate, and improve the self-purification capacity but also resuspend the sediments to release large amount of nitrogen and phosphorus into the overlying water (Kang *et al.* 2018; Schroeder *et al.* 2020). Zhang *et al.* (2019) found that the increasing shear velocity accelerated the release of total phosphorus from sediment. The organic detritus deposited in the sediment would be re-suspended under turbulent condition, the organic detritus residence time would be prolonged, and the aerobic degradation would be more complete. Huang *et al.* (2014) has proven that the water quality was better in the lakes with good hydrodynamic conditions than in those with bad hydrodynamic conditions. Tang *et al.* (2018) discovered that water transfers could accelerate water movement and improve water quality. Therefore, the study of hydrodynamic analysis has attracted more and more attention.

Numerical simulation is a useful tool to test hypotheses, simulate various scenarios, analyse the influence of hydrodynamic condition on the water quality, and evaluate the regulation alternatives before project implementation (Dunn *et al.* 2014). Xu *et al.* (2020) used a high-fidelity hydrodynamic-eutrophication-sediment model to investigate spatiotemporal variation in sediment phosphorus retention and release in Danjiangkou Reservoir. The MIKE 21 FM model was applied to investigate the effects of water diversion on water quality (Yang *et al.* 2021). Quijano *et al.* (2017) coupled the Environmental Fluid Dynamics Code (EFDC) with the Water Quality Analysis Simulation Program (WASP) to analyse the influence of combined sewer overflows on the hydrodynamics and water quality of the Chicago Area Waterway System. However, the urban landscape lakes have not received widespread attention, and a few simulation cases focused on the hydrodynamics and water quality (Yang *et al.* 2016, 2021). Present researches on the effect of hydrodynamic conditions have been mainly concerned with large natural lakes and there is a lack of understanding of the effects on urban landscape lakes. Hence, it is necessary to investigate the factors that influence hydrodynamic processes and solute transport, and degradation mechanisms in urban landscape lakes.

In this paper, a previously developed two-dimension (2D) numerical model was established to investigate the effect of hydrodynamic conditions on the water quality in urban landscape water. Further, numerical simulation was used to study the water quality changes, especially when the reclaimed water was added. This study is critical for urban landscape water quality management and predicting the behaviour of the water system under different scenarios.

2. METHODS

2.1. Governing equations

MIKE 21 developed by Danish Hydraulic Institute (DHI) was used to establish a 2D hydrodynamic model and water quality model. The model has already been successfully applied to the research of hydrodynamics, water quality and eutrophication studies (Tang *et al.* 2018; Yang *et al.* 2021).

2.1.1. Hydrodynamic model

Due to the shallow water depth, the vertical acceleration is rather small compared to gravity acceleration, hence the momentum equation along the vertical direction could be reduced to the hydrostatic law. The water is considered as uncompressible fluid and to be obedient to pressure distribution of stagnant water at the vertical direction. The MIKE 21 hydrodynamic model was established to simulate the lake flow. In the Cartesian coordinate, the hydrodynamic models ground on the depth averaged shallow water equations (DHI 2014a), including continuity equation and momentum equation, are written as follows:

The continuity equation:

$$\frac{\partial H}{\partial \mathrm{t}} + \frac{\partial \rho u}{\partial \mathrm{x}} + \frac{\partial \rho v}{\partial \mathrm{y}} = 0 \quad (1)$$

The momentum equation in x and y direction:

$$\frac{\partial \rho u}{\partial t} + \frac{\partial(\rho u u)}{\partial x} + \frac{\partial(\rho u v)}{\partial \mathrm{y}} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(\mu_x \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_y \frac{\partial u}{\partial y}\right) \quad (2)$$

$$\frac{\partial \rho v}{\partial t} + \frac{\partial(\rho v u)}{\partial x} + \frac{\partial(\rho v v)}{\partial \mathrm{y}} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(\mu_x \frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_y \frac{\partial v}{\partial y}\right) \quad (3)$$

where H is the water depth (m); t is the time (s); x and y are the horizontal and lateral directions (m), respectively; v and u are the velocities in the y-lateral and x-horizontal directions (m/s), respectively; ρ is the water-mass density (kg/m^3); p is the local atmospheric pressure (Pa); and μ_y and μ_x are the vertical and horizontal eddy viscosity coefficients, respectively.

2.1.2. Water quality model

In shallow lakes, the concentrations of contaminants in water are mainly controlled by the advection-dispersion process which ignore the vertical changes. The depth-averaged advection-dispersion equation can be used to describe the contaminant movement (DHI 2014b).

The advection-dispersion equation:

$$\frac{\partial \mathrm{C}}{\partial \mathrm{t}} + u\frac{\partial (u\mathrm{C})}{\partial x} + v\frac{\partial (v\mathrm{C})}{\partial y} = \frac{\partial}{\partial x}\left(\mathrm{D_x}\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mathrm{D_y}\frac{\partial C}{\partial y}\right) + S \tag{4}$$

where C is the concentration of contaminant (mg/L); t is the time (s); x and y are the horizontal and lateral directions (m), respectively; v and u are the velocities in the y-lateral and x-horizontal directions (m/s), respectively; D_x and D_y are the diffusion coefficients in the x-horizontal and y-lateral directions calculated as the eddy viscosity used in solution of the flow equations multiplied by scaling factor (m^2/s), respectively, and S is the external sources or sinks of the constituent.

The concentrations of non-conservative substances, such as chemical oxygen demand (COD), nitrogen (N), and phosphorus (P), are also controlled by degradation process according with the first-order kinetic equation (Pan *et al.* 2020).

The first-order kinetic equation:

$$\frac{\partial C}{\partial \mathrm{t}} = -KC \tag{5}$$

where C is the concentration of contaminant (mg/L); t is the time (s); K is the comprehensive degradation coefficient of contaminant (d^{-1}). The comprehensive degradation process mainly consists of the chemical function in the water, the biological function of microorganisms, the absorption and purification of aquatic plants, and the adsorption and release between sediments and overlying water.

2.2. Study area and engineering experiment

In this study, an urban landscape lake (Figure 1) was chosen as a case study site. Around the lake, there is a residential area to the northeast of the lake, a convention centre to the southeast, and planning area to the west. As an artificial lake, the lake has an average depth of 2.5 m, the total water surface area of nearly 420,000 m^2, and the lake bottom has no obvious fluctuation. There is no inflow and outflow and the lake is an enclosed ecosystem.

Owing to the shortage of urban water resources, the reclaimed water will be used as a potential alternative source of urban landscape lake to counteract the water loss caused by evaporation. The reclaimed water will be added to the lake at two points (Z1 and Z2). Unfortunately, the significantly high concentration of N and P in reclaimed water from wastewater treatment plants lead to high algae growth potential and the reclaimed water will be equivalent to foreign pollution source. The qualities of the lake water and reclaimed water were characterised by COD, TP, NH_4^+-N and TN. The concentrations of these indexes were 74, 0.080, 0.53 and 1.54 mg/L, respectively, in lake water and 50, 0.500, 8.00 and 15.00 mg/L, respectively, in reclaimed water.

An engineering experiment (Figure 1), beside the lake, was carried out to obtain proper simulation parameters (the comprehensive degradation coefficients of COD, TP, NH_4^+-N, and TN, and the diffusion coefficients). In the engineering experiment, the water pump promoted the water to flow and the water velocity was between 0.006–0.01 m/s.

2.3. Sampling and water quality analysis

In the engineering experiment, sample points were set at four locations (P1, P2, P3, and P4) to determine the water quality, and daily water samples were collected from September 28 to October 24, 2017. In the lake, water samples were collected from points W1, W2, W3, and W4 every two or three days from May 12 to June 24, 2018. Three-litre water samples were collected from 0.5 m below the surface at each sampling site and then sent to laboratory immediately for testing. COD was determined with a Digital Reactor Block 200 and a HACH DR 2800 spectrophotometer according to the standard calibration and operation. TP was measured by the ammonium molybdate spectrophotometric method; NH_4^+-N was measured by Nessler's reagent spectrophotometry and TN was measured by ultraviolet spectrophotometry.

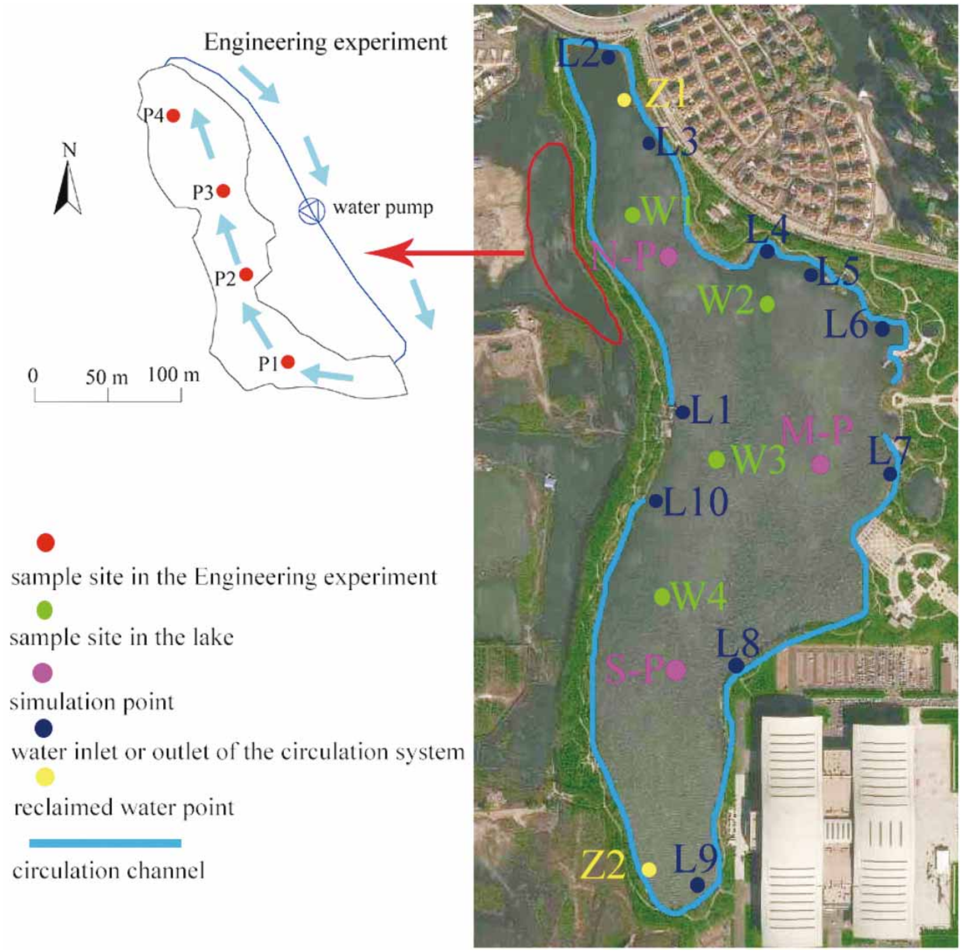

Figure 1 | Study area.

2.4. Parameters

2.4.1. Hydraulic parameters

2.4.1.1. Flood and Dry. Water level between water and land boundary can be determined by flood and dry. It will be involved in the calculation if the water level computed has good fitting with the observation; if not, it will secede from the calculation. In this paper, drying depth, flooding water depth, and wetting depth are adopted as 0.01 m, 0.05 m, and 0.1 m, respectively.

2.4.1.2. Eddy Viscosity. Due to the turbulence, subgrid scale fluctuations, and vertical integration, the effective shear stresses in the momentum equations involve momentum fluxes. In this paper, the eddy viscosity coefficient is specified in a time-varying function of the local gradients in the velocity field and the horizontal eddy viscosity is set to 0.28 according to the Smagorinsky formulation (DHI 2014a).

2.4.1.3. Bed Resistance. The mean depth of the lake is 2.5 m and the lake bottom has no obvious fluctuation, and thus the Manning number is set to 32 $m^{1/3}\,s^{-1}$ (DHI 2014a).

2.4.1.4. Wind Forcing. Wind friction coefficient is a weak function of wind velocity. With regard to the strong winds in an open water body, such as sea or ocean, wind resistance coefficient is set to 0.0026 to get good results. While for the breeze, a smaller coefficient is suitable. The main wind direction is southeast and the max wind speed in the study area is smaller than 5 m/s (data from Tianjin Meteorological Bureau), so the friction coefficient is adopted as 0.00125.

2.4.1.5. Precipitation-Evaporation. Precipitation and evaporation are important for the simulation. According to the atmospheric data collected by the Tianjin Meteorological Bureau, the evaporation rate is set to 3.35 mm/day.

2.4.1.6. Sources. The reclaimed water carries a lot of pollutants which will lead to eutrophication and is considered as an isolated source.

2.4.1.7. Initial Condition. According to the daily water level, the type of initial condition is constant, the surface elevation is set as 2.5 m and the v and u are both set to 0 m/s.

2.4.1.8. Boundary Condition. The land boundary is the lake shoreline, which is represented using a zero normal velocity.

2.4.2. Water quality parameters

2.4.2.1. Dispersion. In the 2D model, the dispersion usually describes transport due to non-resolved processes. Especially in the horizontal directions, the effects of non-resolved processes can be significant, in which case the dispersion coefficient formally should depend on the resolution. The flow and contaminant movement are being driven mainly by the wind and inflowing water flow in the lake (Tang *et al.* 2018). A field tracing experiment was carried out using rhodamine B as a tracer. During the experiment, water levels, velocities and other physical parameters were recorded to determine the dispersion coefficient. The dispersion coefficient is set to 0.045 m^2/s at wind-induced current and 0.12 m^2/s when the water flow was promoted by pump through experiments.

2.4.2.2. Decay. The comprehensive degradation coefficients (K) is the most important parameter in water quality simulation. Pan *et al.* (2020) studied the degradation coefficient of NH_4^+-N under different flow conditions in the laboratory and found that the degradation coefficient of NH_4^+-N was between 0.047 d^{-1} (0.01 m/s) and 0.203 d^{-1} (0.30 m/s). The environmental channel experiment is conducted and showed that the processes of COD and NH_4^+-N were consistent with the first-order kinetic equation and the degradation coefficients of COD was between 0.011 d^{-1} and 0.071 d^{-1} (Huang *et al.* 2017). According to the references and the lake's features, an engineering experiment was carried out to determine the degradation coefficients of COD, TP, NH_4^+-N, and TN.

In the engineering experiment, the water flowed from eastsouth to northwest promoted by a water pump, then the water vertical mix and transfer efficiency of oxygen from atmosphere to water were enhanced. During the experiment, the water DO concentration kept above 4.5 mg/L. The high DO concentration could not only improve the activity of microorganism, accelerate the metabolism, and strengthen the decomposition of organic materials but also inhibit the release of phosphorus from the sediments (Kang *et al.* 2018).

During the engineering experiment, all the concentrations of COD, TP, NH_4^+-N, and TN showed decline tendencies. The dots are the observed concentrations and the lines represent the predicted concentrations. The fitting results for the first-order kinetics model are shown in Figure 2 and Table 1. Analysis of variance was performed to illustrate the statistical significance ($p < 0.05$) between the observed data and the fitting data. The observed data and the fitting data (COD, TP, NH_4^+-N, and TN) exhibited no significant difference (F_{COD} (0.0014), F_{TP} (0.1091), F_{NH4+-N} (0.0024), and F_{TN} (0.1580) were lower than F_{crit} (4.0982)). The maximum relative percent deviation of COD, TP, NH_4^+-N, and TN were 12.17%, 19.85%, 19.66%, and 9.54%, respectively, and the correlation coefficients R^2 in the first-order kinetics equation were all above 0.5, indicating the degradation processes can be described by the first-order kinetics model. The K_{COD}, K_{TP}, $K_{NH4^+_-N}$, and K_{TN} were calculated as 0.014 d^{-1}, 0.024 d^{-1}, 0.019 d^{-1}, and 0.005 d^{-1}, respectively.

3. RESULTS AND DISCUSSION

3.1. Model calibration

The water quality and velocity data of the landscape lake collected during May 12 to June 30, 2018 were used to calibrate the water quality model and the hydrodynamic model. Water velocities at W1 and W3 were used to calibrate the hydrodynamic

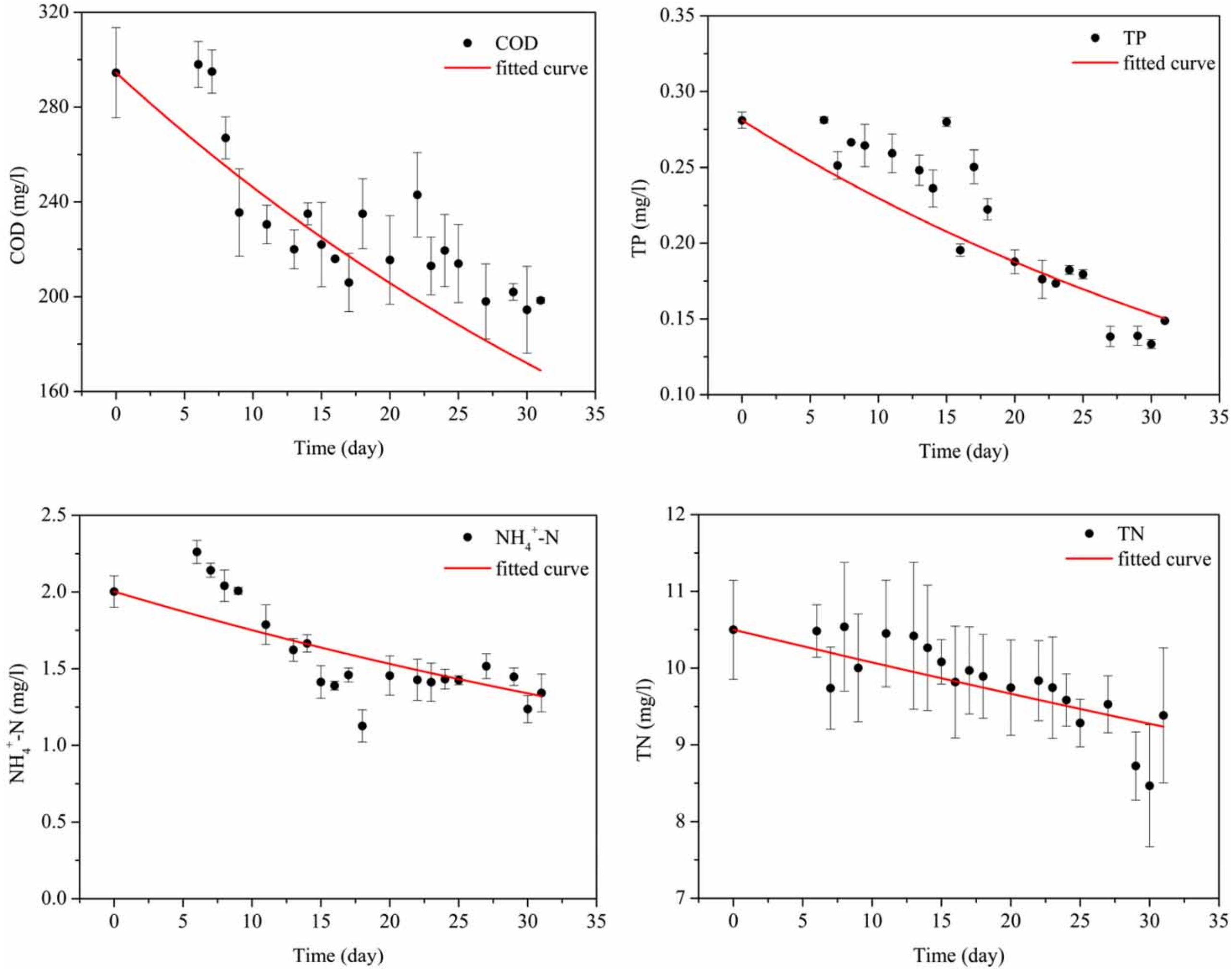

Figure 2 | The concentrations of COD, TP, NH3-N and TN in the engineering experiment and the fitted curves.

Table 1 | Fitting results of K_{COD}, K_{TP}, $K_{NH4\text{-}N}^{+}$, and K_{TN}

			Statistics	
Index	**K Value**	**Equation**	**Reduced Chi-Sqr**	**Adj.R-Square**
COD	0.014	$C_{COD} = 294 \times e^{-0.014 \times t}$	282.10	0.724
TP	0.024	$C_{TP} = 0.281 \times e^{-0.024 \times t}$	1,022.70	0.894
NH_4^+-N	0.019	$C_{NH_4^+-N} = 2.00 \times e^{-0.019 \times t}$	14.63	0.589
TN	0.005	$C_{TN} = 10.50 \times e^{-0.005 \times t}$	0.33	0.687

model, and W2 and W4 were used to validate the hydrodynamic model. The calibration and validation errors at the four locations were listed in Table S1. The observed water velocities had a small fluctuation of less than 0.0006 m/s in the model calibration and validation, which meant that the hydraulic parameters were reasonable in this study. In addition, the absolute error of the simulated water velocities did not exceed 0.0006 m/s in both the model calibration and validation, and the maximum relative error was below 18.7%, which also showed that the established hydrodynamic model can be used to simulate the lake hydrodynamics.

The simulated results of MIKE 21 and observed data in Figure 3 indicated similar trends for COD, TP, NH_4^+-N, and TN at points W1–4. According to the validation results of the water quality models (Table S2), all the relative errors (REs) did not

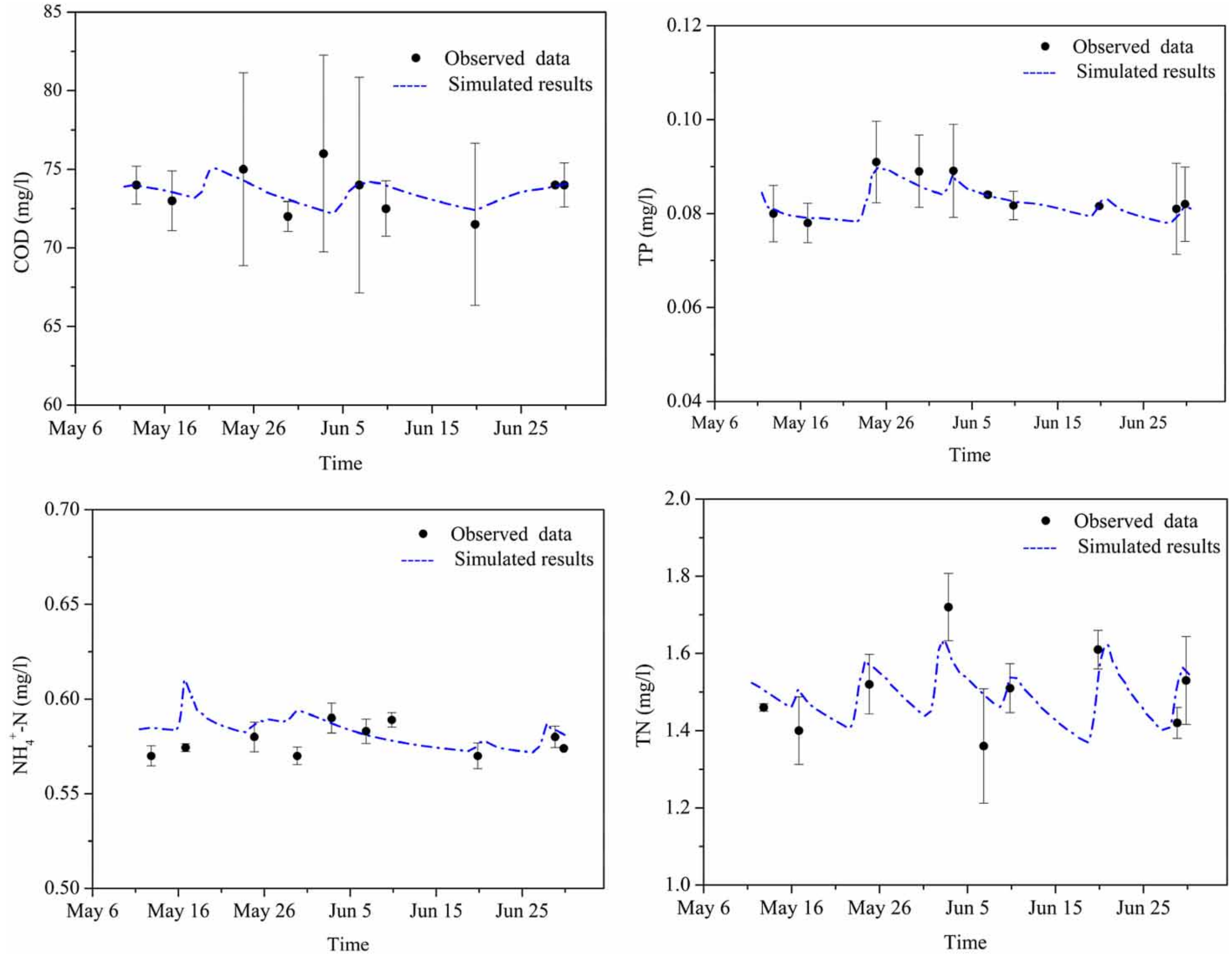

Figure 3 | Comparison of MIKE 21 simulated results and observed data in the lake from May 12 to June 24 in 2018.

exceed 10%. Relative RMSEs of COD, TP, NH_4^+-N, and TN were far less than 50%, which showed a good performance of the water quality model for the lake in this study (Tang *et al.* 2018). Furthermore, the calculated correlation values (R^2) between the observed data and simulated results were larger than 85% at a confidence level of 95%. This also indicated that the MIKE 21 simulated results had acceptable correlation with the observed data and the parameters were rational. Therefore, the MIKE 21 model was able to capture the principal characteristics of the lake.

Moreover, water quality model inputs (dispersion coefficient and degradation coefficient) were considered as the main sources of uncertainty, resulting in the differences of the model outcome. In order to qualify and address the uncertainty of the model, sensitivity analysis was implemented to identify the sensitivity of different water quality parameters and the response of model performance to a range of parameter variations was investigated. In this study, the perturbation method was used and a constant perturbation ($\pm$30%) was imposed on input water quality parameters, just as shown in Table S3. W1–W4 have also been selected to show the sensitivity analysis results. Just as shown in Table S3, the degradation coefficient of COD and NH_4^+-N were relatively sensitive, the degradation coefficient of TN and TP were general sensitive, while the dispersion coefficient of the COD, TP, NH_4^+-N, and TN were insensitive.

3.2. Scenarios of simulation

In order to investigate the effect of hydrodynamic conditions on the water quality in urban landscape water, four different scenarios (Table 2) were considered in this study, including the effects of circulation system and reclaimed water. Scenarios 1 and 2 evaluated the effects of reclaimed water, scenarios 1 and 3 evaluated the effects of the circulation system, and scenarios 2 and 4 evaluated the effects of circulation system on the reclaimed water.

Table 2 | The description of four scenarios

Scenario no.	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Circulation system	no	no	yes	yes
Reclaimed water	no	yes	no	yes

The circulation system was designed to be made by building circulation channels along the lakeside to push the lake water flow and then improve the hydrodynamic condition. According the study of Guo *et al.* (2016), some of the water would discharge from point L1, run through the north channel then run back to lake at points L2–L6, and the other water would flow from point L10, run through the south circulation channel then return back to the lake at points L7–L9 (Figure 1). The water velocity at the inlet points L2–L9 were 0.029 m/s, 0.082 m/s, 0.266 m/s, 0.174 m/s, 0.212 m/s, 0.065 m/s, 0.176 m/s, and 0.083 m/s, respectively. The lake water cycle period was about 30 days and the circulation system would work 8 h each day. In order to make up the water losses caused by evaporation, reclaimed water would be added to the lake. Assuming that the last year was high flow year and the next year was a low flow year, the amount of reclaimed water should meet the minimum ecological water environment demand, therefore, 30,000 m^3 reclaimed water would be added into the lake from Z1 and Z2 during 30 days. Scenarios assessment was carried out to understand the site-specific relationships among hydrodynamic condition, pollution loading, and water quality.

3.3. Hydrodynamics simulation

In order to determine the influence of wind and the circulation system on water movement, the water velocity fields were simulated. The hydrodynamic models of scenario 1 and scenario 2 were developed considering only the wind force, while the hydrodynamic models of scenario 3 and scenario 4 were developed considering water circulation system and wind force. In addition, the reclaimed water volume was rather small compared to the whole lake volume (less than 3%), so the influence of reclaimed water on the lake flow field could be neglected. The hydrodynamic simulation results of the four scenarios were shown in Figure 4.

For scenarios 1 and 2, the flow field distribution was shown in Figure 4(a). Due to the local meteorological condition, the wind speed and wind stress were small, the average wind-driven water speed was 0.003 m/s and no vortex was found in the lake. The proportion of stagnation area ($\leq$0.001 m/s) in the lake was about 14%. While for scenarios 3 and 4, the water flow was controlled by both wind and the circulation system, and the flow field distribution was showed in Figure 4(b). It was obvious that there were large vortices in the middle of the lake. Compared with scenarios 1 and 2, the average velocity markedly increased from 0.003 m/s to 0.008 m/s, and the proportion of stagnation area in the whole lake area reduced from 14% to 6%. It was not difficult to conclude that the circulation system was the main force that affected the water flow and even led to large vortices. The result was opposed to the study of Tang *et al.* (2018) which concluded that wind was the main force affecting the water flow and leading to large vortices. Circulation system mainly led to the changes in the water velocity field, especially in the velocity near water inlets and outlets. Due to the small water volume, even in the areas farther away from the inlets and outlets, obvious velocity vectors were also observed. This also demonstrated that the surface velocity driven by the circulation system was much larger than that driven by wind force. Based on this conclusion, when there was no circulation system, the lake water movement was mainly driven by the wind, and wind controlled the lake velocity which was harmful for pollutant diffusion.

3.4. Water quality simulation

Three typical points (N-P, M-P and S-P) in the landscape lake area were chosen to analyse the changes of COD, TP, NH_4^+-N, and TN concentrations under the four scenarios (Figure 5 and Figure S1).

The COD concentration of reclaimed water (50 mg/L) was little lower than that in the lake (74 mg/L) and the reclaimed water volume was little in comparison with the whole, hence for the scenarios of 1 and 2, COD almost kept unchanged and slightly increased. For scenario 3, the concentrations of COD decreased from 74 mg/L to 48.6 mg/L, 48.6 mg/L, and 49.4 mg/L at points N-P, M-P, and S-P, respectively. And for scenario 4, the concentrations of COD decreased from 74 mg/L to 48.3 mg/L, 48.4 mg/L, and 49.1 mg/L at points N-P, M-P, and S-P, respectively. The circulation system could increase the dissolved oxygen and stimulate the aerobic decomposition process (Babamiri *et al.* 2021). In addition, the process of COD concentration over

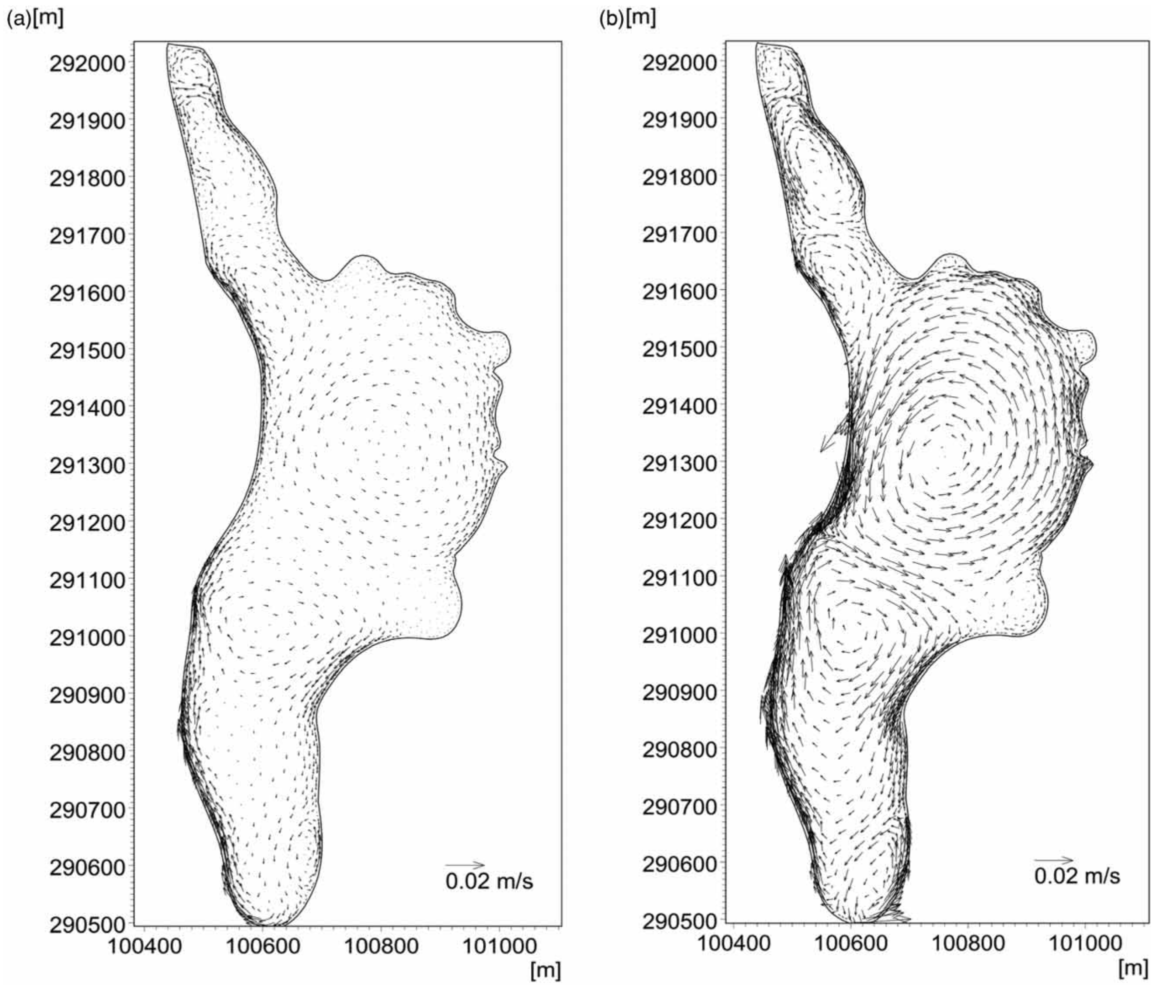

Figure 4 | Hydrodynamics simulation in the lake.

time was consistent with the first-order kinetic equation and the degradation coefficient was positively associated with the flow velocity (Huang *et al.* 2017). Hence, COD showed a significant downward trend along the time line for the scenarios of 3 and 4. Compared with scenarios 1 and 2, the COD concentrations in scenarios 3 and 4 reduced by 35%.

The concentration of TP in scenario 1 slightly increased from 0.080 mg/L to 0.084 mg/L in the three points, while in scenario 3 the TP concentrations at the three points almost stayed unchanged. The results showed that without any effective measures, the lake would face a risk of water quality deterioration. When the reclaimed water added, for scenario 2, the concentrations of TP increased from 0.080 mg/L to 0.096 mg/L, 0.090 mg/L, and 0.090 mg/L at points N-P, M-P, and S-P, respectively, and for scenario 4, the concentrations of TP increased from 0.080 mg/L to 0.100 mg/L, 0.091 mg/L, and 0.093 mg/L at points N-P, M-P, and S-P, respectively. The TP showed a significant upward trend along the time for the scenarios of 3 and 4, and the TP concentration in scenario 4 was little higher than that in scenario 3. That was because the high concentration of TP in the reclaimed water (0.500 mg/L) and the circulation system would further the spread of reclaimed water around the whole lake. Ao *et al.* (2018a) has also proved that the continued use of reclaimed water for replenishment significantly increased the risk of eutrophication due to the high phosphorus content.

For scenario 1, the concentration of NH_4^+-N slowly increased from 0.53 mg/L to 0.59 mg/L, while for scenario 3, the concentration of NH_4^+-N decreased significantly from 0.53 mg/L to 0.37 mg/L, 0.36 mg/L, and 0.37 mg/L at points N-P, M-P, and S-P, respectively. The circulation system increased the mean velocity and improved the hydrodynamic condition of the lake, which would help improve the degradation coefficients of the NH_4^+-N (Huang *et al.* 2017). Whereas, the results disagreed with the study of Yang *et al.* (2021) which found that an accelerated flow did not necessarily enable a more effective impact on NH_4^+-N concentration. The inconsistency might be due to the shape of lake. When the reclaimed water was

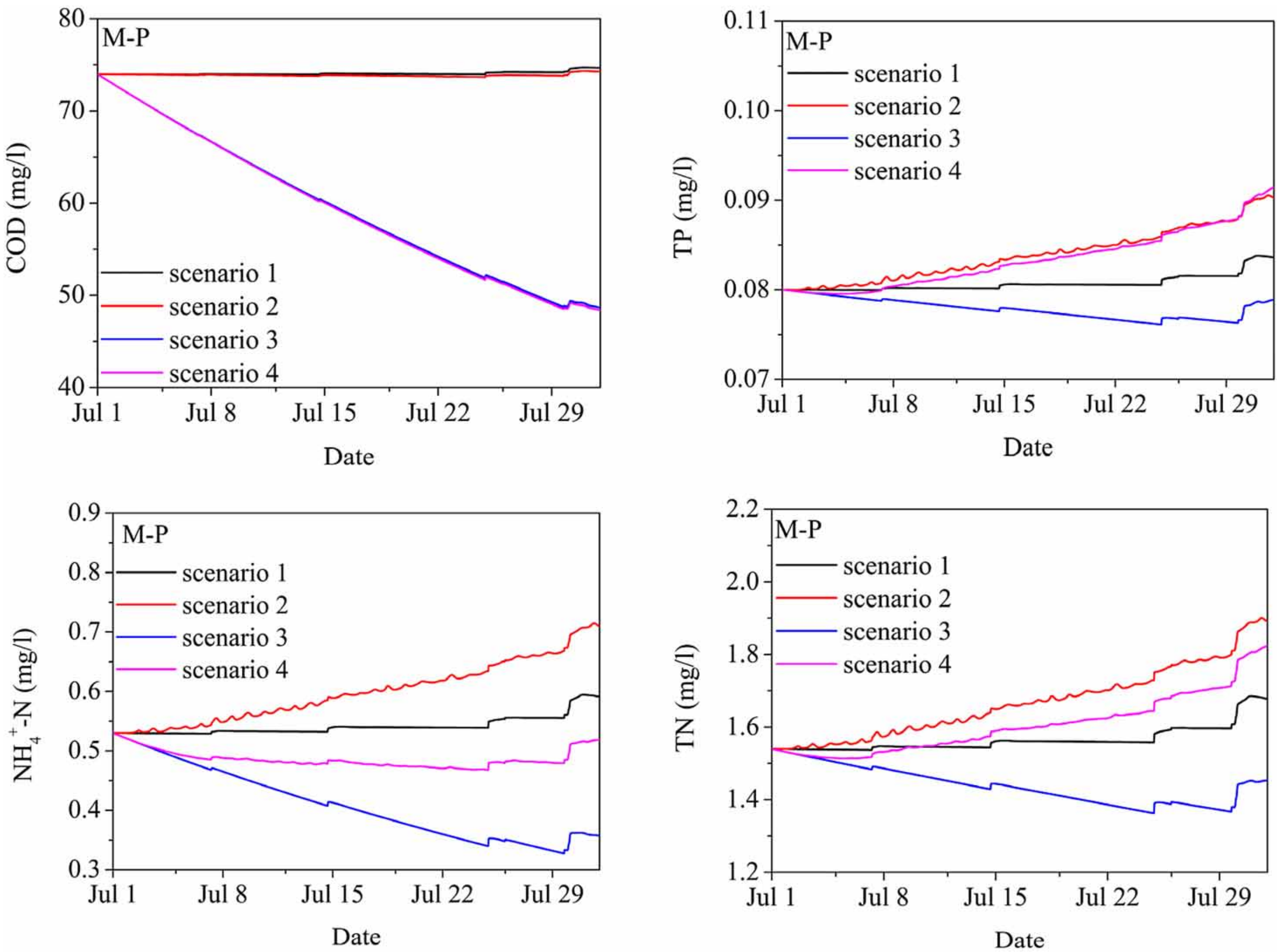

Figure 5 | Water quality simulation results for the four scenarios (M–P).

added, the NH_4^+-N concentration increased in both scenarios 2 and 4. Compared with scenario 2, the concentrations of NH_4^+-N in scenario 4 reduced nearly by 24%. Especially in M-P, the NH_4^+-N concentration almost stayed unchanged; that might be because the large vortices in the middle of the lake.

For scenario 1, the concentrations of TN increased from 1.53 mg/L to 1.70 mg/L. while for scenario 3, the concentrations of TN showed a downward trend along the time and decreased from 1.53 mg/L to 1.45 mg/L. When the reclaimed water was added, the concentrations of TN in both scenarios 2 and 4 increased. For scenario 2, the concentrations of TN increased from 1.53 mg/L to 2.08 mg/L, 1.89 mg/L, and 1.89 mg/L at points N-P, M-P, and S-P, respectively. For scenario 4, the concentrations of TN increased from 1.53 mg/L to 2.09 mg/L, 1.82 mg/L, and 1.87 mg/L at points N-P, M-P, and S-P, respectively. It can also be drawn that the circulation system could enhance the lake water self-purification and weaken the influence of reclaimed water on the lake water quality to some extent. However, due to the high concentration of N and P in the reclaimed water, the circulation system could not totally eliminate the effects caused by the reclaimed water, and the reclaimed water should be treated to reduce the nutrient level before it enters the lake.

4. CONCLUSIONS

In this study, a 2D hydrodynamic and water quality model was built based on MIKE 21 to investigate the relationship between hydrodynamic condition and water quality, and applied in an urban landscape lake in Tianjin, China. Moreover, an engineering experiment was carried out to confirm the comprehensive degradation coefficients of COD, TP, NH_4^+-N, and TN (0.014 d^{-1}, 0.024 d^{-1}, 0.019 d^{-1}, and 0.005 d^{-1}, respectively). Circulation system was the main force that expedited water changes and pollutant movement. In addition, due to the small water volume of the lake, even in the areas farther away from the inlets and outlets, obvious velocity vectors were also observed. The average wind-driven water speed was 0.003 m/s and the circulation system-driven water speed was 0.008 m/s. Based on the water quality model, four different scenarios were considered, including the effects of circulation system and reclaimed water. The circulation system could effectively reduce the COD, NH_4^+-N and TN concentration nearly by 35%, 32%, and 5%. When the reclaimed water was added to counteract the water loss and meet the minimum ecological water environment demand, the high concentrations N and P in the reclaimed water would accelerate the deterioration of water quality, and the concentrations of TP, NH_4^+-N, and TN in the lake increased to 0.090–0.096 mg/L, 0.71–0.81 mg/L, and 1.89–2.08 mg/L. The circulation system could improve water quality to some extent, but not eliminate the eutrophication risk caused by reclaimed water, and the reclaimed water should be treated to reduce the concentrations of N and P before enter the lake. This study provides a new approach and a practical tool for planning and management policy and operations to protect the urban landscape water quality. However, it should be noted that reclaimed water cannot be the sole source for water replenishment, and other water sources, such as rainfall, tap water and river water, should also be further considered. Besides, this study just considered the sensitivity of individual parameter change on water quality model, and the interactions among parameters were not taken into account.

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DATA AVAILABILITY STATEMENT

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

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