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Is water replenishment an effective way to improve lake water quality? Case study in Lake Ulansuhai, China

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Lakes are an important component of the global water cycle and aquatic ecosystem. Lake water quality improvement have always been a hot topic of concern both domestically and internationally. Noncompliant outflow water quality frequently occurs, especially for lakes that rely mainly on irrigation return flow as their water source. External water replenishment to improve the water quality of lakes is gradually being recognized as a promising method, which however, is also a controversial method. Lake managers, in the case of constant controversy, hesitate about the appropriateness of lake water replenishing. Thus, taking Lake Ulansuhai in China as an example, this study aimed to construct a lake hydrodynamic and water quality model, under the constraint of multiple boundary conditions, that has sufficient simulation accuracy, and to simulate and analyze the changes in COD (Chemical Oxygen Demand) and TN (Total Nitrogen) concentrations in the lake area before and after water replenishment, and explore whether water replenishment was an effective method for improving lake water quality. The results showed that when the roughness value of Lake Ulansuhai was 0.02, the TN degradation coefficient K was 0.005/d, and the COD degradation coefficient K was 0.01/d; the simulation and measured values had the best fit, and the built model is reasonable and reliable can be used to simulate lake water quality changes. By external water replenishment lasting 140 days in the water volume of 4.925 × 108 m^3, the COD and TN concentrations in Lake Ulansuhai could be stabilized at the Class V water quality requirement, which helped improve the self-purification ability of the lake area. Water replenishment was proved to be an effective method for improving the water quality of the lake, but water replenishment is only an emergency measure. Lake water replenishment is more applicable to areas with abundant water resources. External source control and internal source reduction of lake pollution and protection of lake water ecology are the main ways to improve lake water quality for water-deficient areas under the rigid constraints of water resources. In the future, key technologies for reducing and controlling pollution in irrigation areas, construction of lake digital twin platforms, and active promotion of lake legislation work should be the main research direction for managing the lake water environment.

KEYWORDS

water replenishing, modeling, water quality simulation, effect evaluation, lake management, Lake Ulansuhai

1 Introduction

Lakes are an important component of the ecosystem, playing an irreplaceable role in flood control, water resource regulation, water quality purification, wetland protection, maintenance of biodiversity, local climate regulation, and ecological landscape. They have become a key link in maintaining the health of the regional ecological environment and providing a foundation for human survival and socioeconomic development (Karlsson et al., 2009; Vitense et al., 2019; Liu et al., 2021a). Lakes worldwide are experiencing water shortage, water quality deterioration, and algal blooms under the combined influence of climate change and human activities. Most water pollution in lakes is related to the input of substances such as nitrogen, phosphorus, and salt under human activities (Ho et al., 2019; Geng et al., 2021). Problems such as less precipitation, high evaporation, and insufficient inflow often occur due to the limitation of climatic conditions, especially in lakes located in arid and semi-arid areas (Wu et al., 2017; Fu et al., 2021). Some lakes lack stable and high-quality water sources due to poor water system connectivity, resulting in insufficient water dynamics and low self-purification ability (Huser et al., 2016; Rosińska et al., 2018; Liu et al., 2021b). Meanwhile, with the continuous increase in population, the inflow of agricultural drainage, domestic sewage, and industrial wastewater into lakes has exacerbated eutrophication, caused the degradation of water ecological functions, and created a poor lake water environment (Lürling and Oosterhout, 2013; Schindler et al., 2016; Vinçon-Leite and Casenave, 2019). Currently, lakes globally are encountering significant environmental issues related to water such as declining water quality, worsening eutrophication, decreasing biodiversity, and coastal environmental damage. Improving the quality of lake water and preventing and controlling the damage to lake water ecosystems are urgent issues that have attracted the attention of scholars at home and abroad (Song et al., 2014; Hu et al., 2020; Li et al., 2022).

For large lakes, the real-time monitoring of hydrodynamic conditions and pollutant concentrations in the lake area is difficult to achieve. Numerical simulations of hydrodynamic processes and pollutant concentrations in lakes are an important strategy for exploration (Shen et al., 1995; Parinet et al., 2004; Lai et al., 2013; Munar et al., 2018). Hydrodynamic processes are an essential basis for the transport and transformation of pollutants in lakes and are closely related to the water inflow. Different inflow rates can change the movement trajectory of lake water, thereby affecting the circulation morphology, structure, and flow velocity distribution in the lake area, ultimately affecting the water quality of the lake (Na and Park, 2006). Steinman et al. (2002) found that low flow rates positively affected the process of algal enrichment. Therefore lake water replenishment has become a way to alleviate water quality deterioration. For example, Green Lake in the United States has reduced the nutrient concentration in the lake area and balanced the content of planktonic algae by introducing water into the lake, thus improving the eutrophication level of the lake (Oglesby, 1969). In The Netherlands, the water quality of the Veluwemeer Lake has significantly improved after implementing a water system connection project that regulates the inflow of water into the lake area (Hosper, 1998). In the United States, the hydrodynamic processes in the lake area were strengthened, the self-purification capacity of the lake area was improved, and the degradation trend of the wetlands around the lake area was curbed by introducing Mississippi River water into Lake Pontchartrain (Lane et al., 2001). The hydrodynamic ecological model analysis of Lake Manzala in Egypt found that the significant changes in the water quality of the lake over the past 30 years were closely related to the changes in the inflow of fresh water and land use (Rasmussen et al., 2009). After introducing other water sources, the high-quality population of algae in the Tega Lake in Japan has undergone significant changes, which has played a positive role in improving the water quality of the lake area (Amano et al., 2010). The North-South Water Transfer Project in the United States and the West-East Water Transfer Project in Pakistan have both improved the water quality of the lakes in the receiving areas by introducing a large amount of clean water through dilution and hydrodynamic strengthening (Manghi et al., 2012). Some studies have shown that water transfer has a significant impact on the quality of lake water and can be simulated and calculated using models (Feng et al., 2017; Peng et al., 2020)]. Research on Lake Arrowhead in California, USA, revealed that the changes in precipitation processes could affect the water quality of the lake by changing the water level of the lake (Saber et al., 2020). In China, the Yangtze River-Taihu Lake Water Transfer Project (supplementing Taihu Lake with water from the Yangtze River through the Wangyu River), the Yellow River-Jide Water Transfer Project (introducing water from the Yellow River to supplement Baiyangdian), and the Niulanjiang-Dianchi Lake Water Replenishment Project (introducing water from the Niulanjiang River to supplement Dianchi Lake) have all improved the self-purification capacity of the water body and achieved the comprehensive management goal of the water environment in the lake area (Huang et al., 2015; Wu et al., 2018; He et al., 2020).

Although the lake water quality has been improved successfully through water replenishment both domestically and internationally, the situation of each lake is different. Lakes with low pollution levels or strong water dynamics or with sufficient water volume and high self-purification ability may achieve the goal of improving water quality through short-term water replenishment (Zhang et al., 2012). However, the response of the aquatic ecosystems to the changes in water volume is very sensitive for large shallow lakes or lakes with water resources exceeding the water quality standard, especially shallow lakes with shallow water, weak water dynamics, and complex patterns (Qing et al., 2020). The migration process of pollutants in the lake has a certain time lag effect on the changes in water volume (Liu et al., 2021b), which increases the difficulty of predicting the effect of water replenishment on improving the water quality. Whether water replenishment can really improve the water quality of the lake is a key issue worthy of further research and has practical application value for the protection and restoration of lake ecosystems. Lake Ulansuhai in China is a typical agricultural water retreat lake and closely connected with the Yellow River, in which the hydrodynamic and water quality conditions are complicated. Lake water replenishing has potential effects on pollutant diffusion process and then may causes the polluted water flowing into the Yellow River. It has always been a controversial issue, in recent years, how well does the ecological water replenishment for Lake Ulansuhai works? Is this a temporary measure or a long-term measure to improve lake water quality? The above questions make water resources and water environment management of Lake Ulansuhai more difficult. Thus, Taking the large shallow Lake Ulansuhaias an example, this study aimed to construct a lake hydrodynamic and water quality model, under the constraint of multiple boundary conditions, that has sufficient

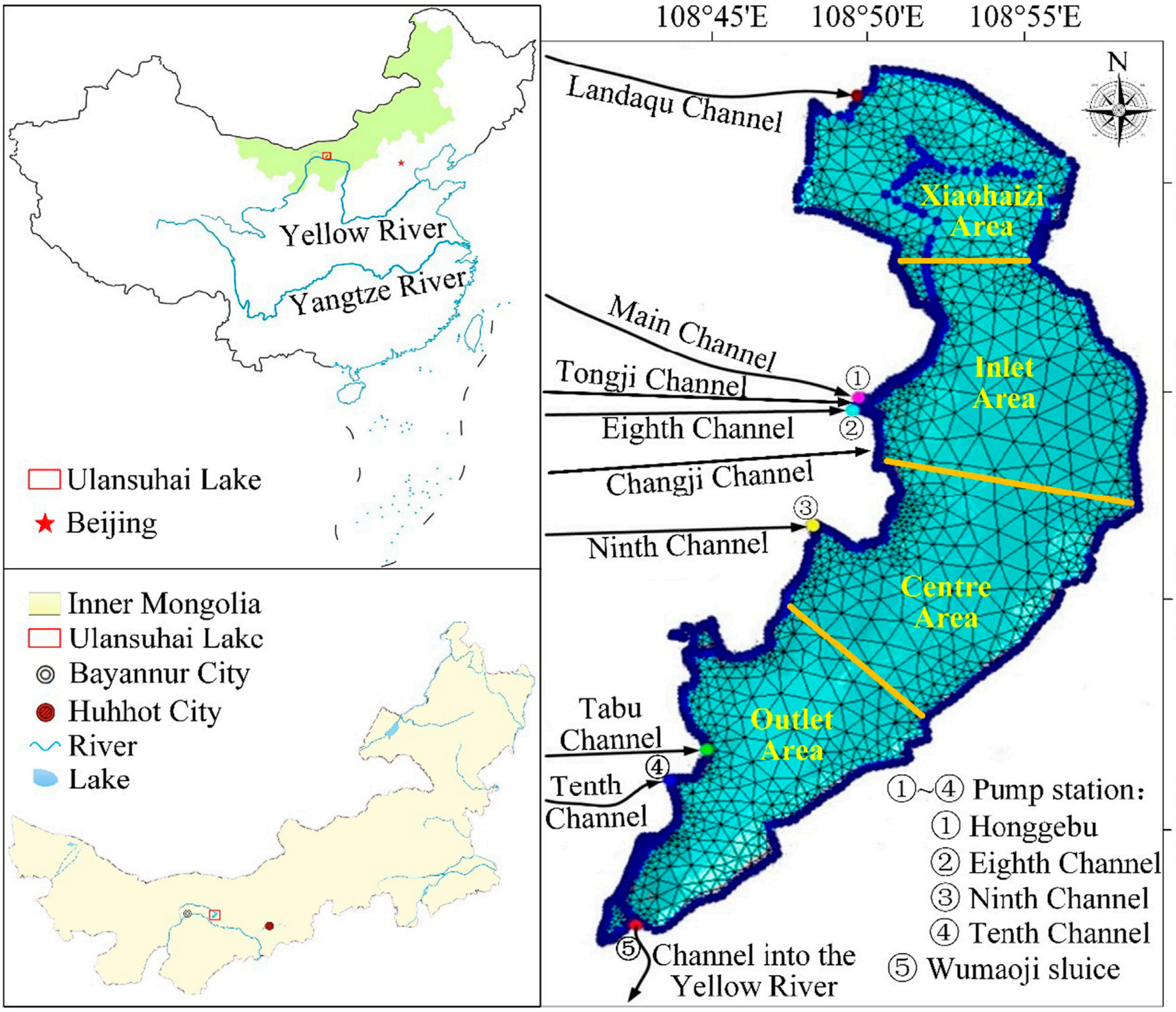

FIGURE 1
The location of Lake Ulansuhai and its key water network.

simulation accuracy, and to simulate and evaluate the effect of different water replenishment schemes on improving lake water quality, and explore the effectiveness and timeliness of water replenishment, so as to provide a reference for comprehensive lake management.

2 Study area

Lake Ulansuhai is one of the eight major freshwater lakes in China, located in Bayannur City, Inner Mongolia (seen in Figure 1). It is situated in a cold and arid region of China, and is a river trace lake formed by the diversion of the Yellow River. It has multiple ecological functions such as water storage for flood control, agricultural irrigation, tourism, and aquaculture. It mainly receives drainage, precipitation, and mountain floodwater from the Hetao Irrigation District and is a typical large shallow lake (Mao et al., 2015). It is also a rare large multifunctional lake in the arid grasslands and desert areas of the world. The geographical coordinates of Lake Ulansuhai are 40°36′–41°03′N, 108°43′–108°57′E, with a storage capacity of 250–350 million m^3 and a total water area of approximately 293 km^2. The measured average water depth is about 1.53 m.

Lake Ulansuhai is long and narrow in shape, resembling a crescent moon, with a length of 35–40 km from north to south and 5–10 km from east to west. More than 90% of the water supply for Lake Ulansuhai comes from agricultural drainage, followed by industrial wastewater, domestic sewage, rainfall, and surface runoff. All of the water sources are collected through various channels, which then flow into the main channel, second channel, third channel, fourth channel, fifth channel, sixth channel, seventh channel, Zhaosha channel, and Yitong channel before entering the main drainage channel. From there, the water flows through the eighth channel, ninth channel, tenth channel, Tongji channel, and Tabu channel before entering Lake Ulansuhai. Finally, the water flows through the Wumaoji sluice and enters the Yellow River (Figure 1).

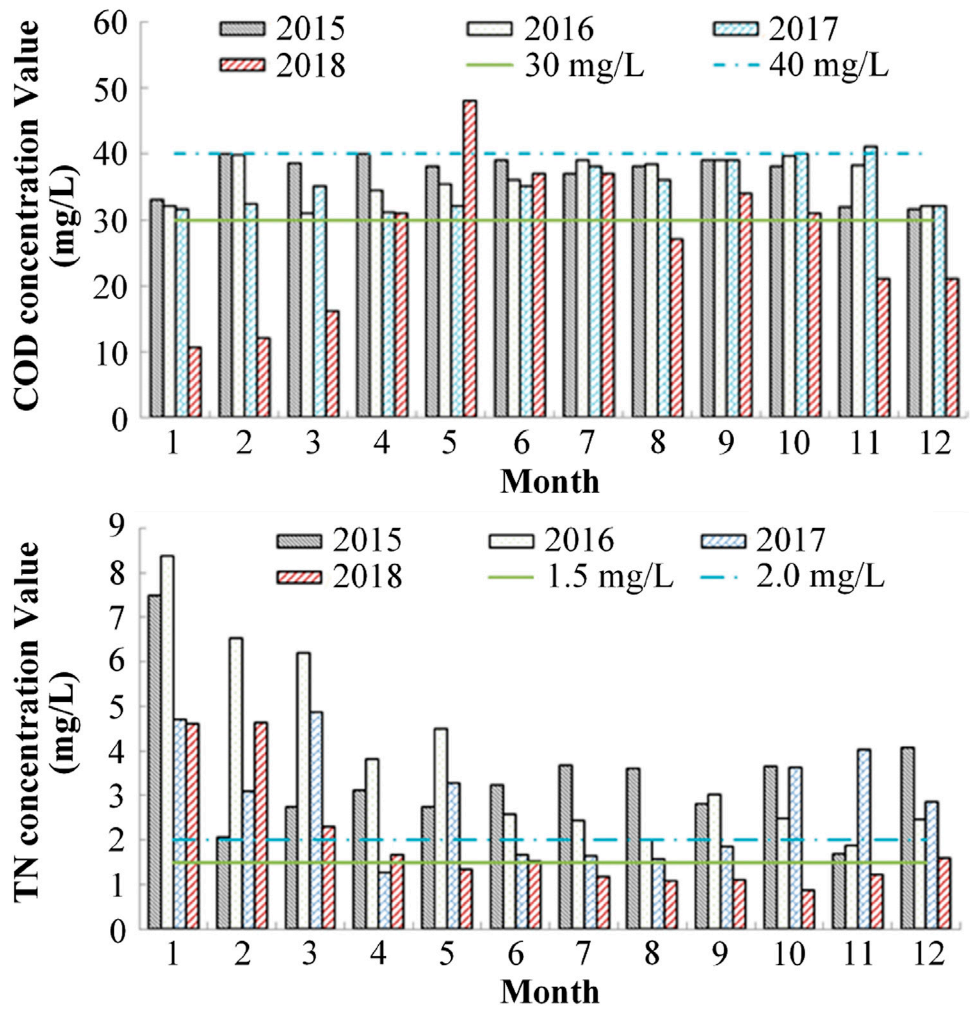

FIGURE 2
Variation characteristics of COD and TN concentration at the Wumaoji sluice.

It can be found that, through the analysis of COD (Chemical Oxygen Demand) and TN (Total Nitrogen) concentration changes at the Wumaoji sluice, in 2015~2018, the average concentration value of COD and TN is 33.90 mg/L and 3.01 mg/L, respectively, the water quality of lake water into the Yellow River in 2018 was worse than that in 2016~2017 (seen in Figure 2), and TN pollution was such a serious problem that it has aroused concerns from the whole society. Meanwhile, the monthly average values of COD and TN concentration showed an unstable state. The high-quality water in the Yellow River has been affected by polluted water from Lake Ulansuhai.

3 Method and data

3.1 Hydrodynamic and water quality model

Considering the unclear hydrodynamic characteristics of Lake Ulansuhai, a two-dimensional hydrodynamic and water quality model was used to simulate the dynamic changes in pollutant transport, diffusion, and degradation under different inflow conditions in the lake area. Based on the topographical features of Lake Ulansuhai, the vertical variation of the lake was ignored, and it was assumed that the hydrodynamic pressure along the water depth followed the distribution of fluid static pressure (Liu et al., 2021b). The two-dimensional depth-averaged hydrodynamic equation of Lake Ulansuhai could be expressed as follows:

$$\frac{\partial \zeta}{\partial t}+\frac{\partial (Hu)}{\partial x}+\frac{\partial (uv)}{\partial y}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+g\frac{\partial \zeta}{\partial x}+\frac{\partial u^2}{\partial x}+\frac{\partial uv}{\partial y}+\frac{gu\left(u^2+v^2\right)^{1/2}}{HC^2}-\frac{A_x}{p}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) - fv - f_W|W|W_x=0 \tag{2}$$

$$\frac{\partial v}{\partial t}+g\frac{\partial \zeta}{\partial y}+\frac{\partial v^2}{\partial x}+\frac{\partial uv}{\partial x}+\frac{gu\left(u^2+v^2\right)^{1/2}}{HC^2}-\frac{A_y}{p}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) - fu - f_W|W|W_y=0 \tag{3}$$

$$H=\zeta+h \tag{4}$$

Where ζ is the lake water level, m; f is the Coriolis force coefficient, and $f = 2\omega\sin\varphi$; h denotes the lake water depth, m; u and v represent mean flow velocity component in the x and y direction, respectively,

m^3/s; C is the Chezy coefficient, $C = 1/n(\zeta+h)^{1/6}$, in which n is the roughness coefficient; f_W represents the wind resistance coefficient; A_x and A_y are the eddy viscosity coefficient in the x and y direction; p is the static pressure, Pa; t is the time, s; W is the wind speed 10 m above the water surface; W_x and W_y are the wind speed component in the x and y direction, m/s; C_d is the wind drag stress coefficient, g is the acceleration of gravity; τ_{xx}, τ_{yx} and τ_{xy} represent the shear stress corresponding to 0°, 45°, 90° of the x-y coordinate axis (Liu et al., 2021b; Liu et al., 2021c).

The lake water quality equation is expressed as follows:

$$\frac{\partial Hp}{\partial t}+\frac{\partial Hup}{\partial x}+\frac{\partial Hvp}{\partial y}=\frac{\partial}{\partial x}\left(HD_x\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(HD_y\frac{\partial p}{\partial y}\right)+kHF(p)+S \tag{5}$$

Where p denotes the concentration of a pollutant, mg/L; k represents the lake degradation coefficient, s^{-1}. The left side of the equal sign of Eq. 5 is the time-varying term, the advection terms in the x and y directions, respectively. The right side of Eq. 5 indicates the diffusion term, biochemical reaction term in the x and y directions, respectively. S represents the lake pollution load, $g/(m^2\cdot s)$ (Liu et al., 2021b; Liu et al., 2021c).

Detailed solving procedures for the above models can be seen in our published articles (Liu et al., 2021b; Liu et al., 2021c).

3.2 Used data

Daily water level data of the Honggebu station and Wumaoji sluice in 1985~2019; Daily inflow data of the Eighth, Ninth, Tenth channels in 1985~2019; And daily pollutant concentration data of COD and TN in the Inlet area, Centre area, Outlet area from 2014 to 2019 are all collected from the Water Conservancy Development Center of the Hetao Irrigation District and the Water Resources Bureau of Bayannur City in Inner Mongolia.

4 Modelling

4.1 Boundary condition

The boundary of Lake Ulansuhai included the Honggebu station, the Eighth, Ninth, and Tenth channels, the Xin'an branch channel, and the Wumaoji sluice. A new Landaqu pumping station was planned to be built. The drainage of the Honggebu station entered the lake, while the drainage of the Tenth channel flowed into the main lake area after 8 km northward through the southwest side of the lake. The lake boundary was set to 0 in the model calculation due to its non-sliding condition. The daily water-level data of the Honggebu station and the daily inflow data of the Eighth, Ninth, and Tenth channels from 1985 to 2019 were selected as the outflow boundary of the two-dimensional hydrodynamic model of Lake Ulansuhai, while the other rivers and channels were ignored. The COD and TN were chosen as the characteristic pollutants of the lake, and the COD and TN monitoring concentrations in the inlet and outlet areas of Lake Ulansuhai from 2014 to 2019 were used as the upper and lower boundaries of the water quality model. The diversion dike and grid waterway constructed in the lake area were generalized as hydraulic structures in the model, and the water loss of Lake Ulansuhai was set to 2.73 mm/d.

4.2 Initial condition

Lake Ulansuhai has a large surface area, shallow average depth, and a winding shoreline with many tributaries flowing into it. Moreover, many water conservancy projects, such as dams, bridges, and channels, are also found in the lake area. The model used nonstructured mesh coupling triangles and rectangles to achieve better simulation results. A simulation area of 329.4 km^2 was chosen for Lake Ulansuhai, with a grid spacing of 300–500 m for the water catchment and lakeshore areas, and 100–200 m for the grid spacing. The simulation grid accuracy was controlled within 1 km^2, and Lake Ulansuhai was divided into 3276 calculation grids (Figure 1). The stability and accuracy of the model was ensured by setting the calculation time to $\triangle t$ = 60 s, the simulation step to 21,600 s, and the water-level starting condition to 1,019.48 m.

The initial water level of Lake Ulansuhai was set at the mean water level of 1,018.79 m (Yellow Sea elevation), and the average water depth was set at the mean water depth of 1.0 m. The initial values of COD and TN were set at the concentration mean values of 33.90 mg/L and 3.01 mg/L, respectively, and the initial flow rate was 0. We set the dry water depth (h_{dry}) at 0.005 m, the flooded water depth(h_{flood}) at 0.05 m, and the wet water depth (h_{wet}) at 0.1 m to avoid instability in the model calculation because Lake Ulansuhai was located at the boundary between wet and dry areas in the model. The eddy viscosity coefficient was estimated using the Smagorinsky formula, and the corresponding Smagorinsky coefficient was set at 0.28 m^2/s. The initial roughness values for the clear water area and the reed area in the lake were set at 32 $m^{1/3}/s$ and 3.7 $m^{1/3}/s$, respectively. The water depth of Lake Ulansuhai was shallow, ranging from 0.7 m to 4.0 m, and was influenced by wind-induced currents (Wang et al., 2021). Based on previous research, the wind speed in the lake area was set at 2.6 m/s, with a southwesterly wind direction. In the water quality model, the pollution sources entering the lake were generalized as point sources.

4.3 Model calibration and validation

The relative error (RE), certainty coefficient (R^2), and Nash coefficient (E_{NS}) were used to evaluate the simulation effect of the Lake Ulansuhai hydrodynamic and water quality model (Liu et al., 2021b; Liu et al., 2021c). Generally, when the RE was ±20%, the simulation results of the model were acceptable. The closer the R^2 was to 1, the higher the degree of agreement between the measured and simulated values. The closer the E_{NS} was to 1, the higher the credibility of the model. The hydrodynamic model was calibrated and validated using daily flow data from the Honggebu station and daily water-level data from the Wumaoji sluice. The water quality model was calibrated and validated using COD and TN concentration data from the inlet, central, and outlet areas. Table 1 shows that when the roughness value of Lake Ulansuhai was 0.02, the TN degradation coefficient K was 0.005/d, and the COD degradation coefficient K was 0.01/d; the simulation and

TABLE 1 Results of model calibration and validation.

Index		Location	Calibration period			Validation period		
			RE(%)	R^2	E_{NS}	*RE*(%)	R^2	E_{NS}
Hydrodynamic	Flow	Honggebu station	0.03	0.90	0.86	−4.63	0.70	0.69
	Water level	Wumaoji sluice	−5.48	0.89	0.78	6.74	0.81	0.69
Water quality	COD	Inlet area	−6.83	0.76	0.84	−6.91	0.71	0.70
		Center area	−6.22	0.80	0.85	7.78	0.69	0.77
		Outlet area	5.48	0.80	0.73	8.62	0.73	0.80
	TN	Inlet area	−5.05	0.75	0.70	6.19	0.76	0.71
		Center area	−0.04	0.74	0.87	12.99	0.80	0.77
		Outlet area	2.05	0.80	0.86	15.07	0.74	0.73

measured values had the best fit. The *RE*s between the simulated and measured values of the Honggebu station flow, Wumaoji sluice water level, and pollutant concentration were all within 10%, and the R^2 and E_{NS} values were both greater than 0.78, indicating that the model parameters were reasonable. In addition, the *RE*s of the model's flow, water level, and pollutant concentration simulations were within ±20%, with a maximum value of 15.07%. The R^2 and E_{NS} values were greater than 0.69, and the errors were within an acceptable range, indicating that the Lake Ulansuhai hydrodynamic and water quality model was reliable and could be used to simulate the water quality changes in the lake area.

5 Results and discussion

5.1 Results

Two lake water replenishment schemes were set up: Scheme 1 did not replenish water throughout the year; Scheme 2 replenished 4.925×10^8 m³ of water into the lake through the Main Channel and Landaqu Channel (according to the research results of the Yellow River Engineering Consulting Co., Ltd, the lake needed to be replenished with a net water volume of 4.925×10^8 m³ to meet the requirements of lake pollution purification and salt dilution), with 3.740×10^8 m³ of water replenished through the Main Channel and 1.185×10^8 m³ of water replenished through the Landaqu Channel. COD and TN were used as pollution indicators employing a simulated duration of 365 days/year, and the constructed model was used for simulation analysis. According to the lake management requirements, the water quality is considered to meet the requirements when the COD and TN concentrations at the outlet of Lake Ulansuhai reach Class V standards in China's Environmental quality standards for surface water (GB 3838-2002) (Table 2).

5.1.1 Scheme 1

Of the 365 days, Lake Ulansuhai met the surface water Class IV standard for COD concentration for 104 days, met the surface water Class V standard for COD concentration for 24 days, and was in the inferior Class V for COD concentration for the remaining days. Using Lake Ulansuhai's water discharge as the evaluation standard for surface water Class V, the annual COD exceedance rate was 64.93%, making it difficult to meet the requirements for entering the Yellow River. The COD concentration change process of Wumaoji sluice is depicted in Figure 3.

Of the 365 days, the TN concentration was in the fifth category of inferior quality for 295 days in Lake Ulansuhai. The annual TN exceedance rate for Lake Ulansuhai's effluent was 80.82% based on the standard of surface water category V. The current purification capacity of the lake could not meet the degradation requirements of TN concentration. The TN concentration change process of the Wumaoji sluice is shown in Figure 4.

5.1.2 Scheme 2

Figures 5, 6 show that the overall trend of COD and TN concentrations in Lake Ulansuhai demonstrated an increase–decrease stabilization pattern. This was because the pollution concentration in the lake area was higher in the north and lower in the south before water replenishment. The pollutants were pushed toward the Wumaoji sluice with the influx of water, causing poor water quality conditions in that area. Subsequently, the newly added water resources enhanced the self-purification ability of the lake area, and the pollutant concentration at the Wumaoji sluice began to decrease. Finally, water replenishment allowed the water quality in the lake area to reach a stable state. The simulation results showed that when the water replenishment period reached 137 days, the COD concentration at the outlet of Lake Ulansuhai met the stable surface water Class V standard. When the water replenishment period reached 140 days, the TN concentration at the outlet of Lake Ulansuhai could stably meet the surface water Class V standard. In other words, by external water replenishment for 140 days, the COD and TN concentrations in the lake could be stabilized at the Class V water quality requirement, which helped improve the self-purification ability and water quality of the lake area. Water replenishment is an effective way to improve the water environment quality of the lake area for lakes requiring irrigation return water and having poor water quality background or weak lake system connectivity, but this method is not sustainable.

TABLE 2 Results of model calibration and validation.

Pollutant	Standard (mg/L) (≤)				
	Class I	Class II	Class III	Class IV	Class V
COD	15.0	15.0	20.0	30.0	40.0
TN	0.2	0.5	1.0	1.5	2.0

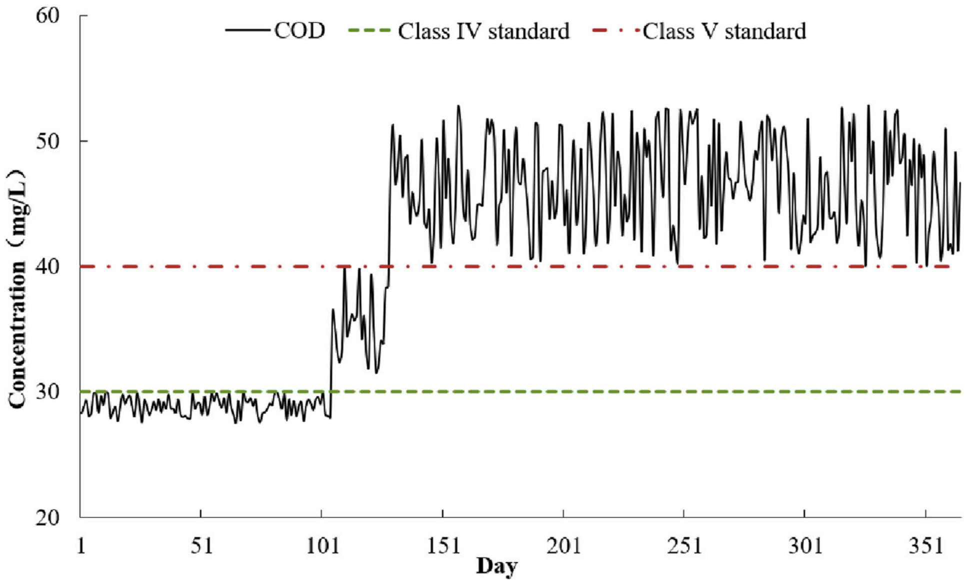

FIGURE 3
COD concentration change process of Wumaoji sluice in Scheme 1.

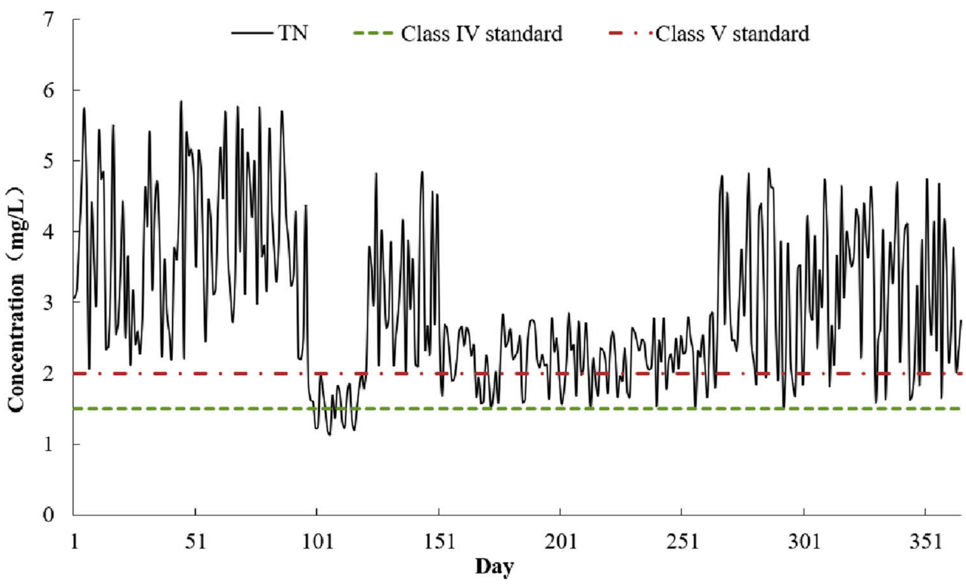

FIGURE 4
TN concentration change process of Wumaoji sluice in Scheme 1.

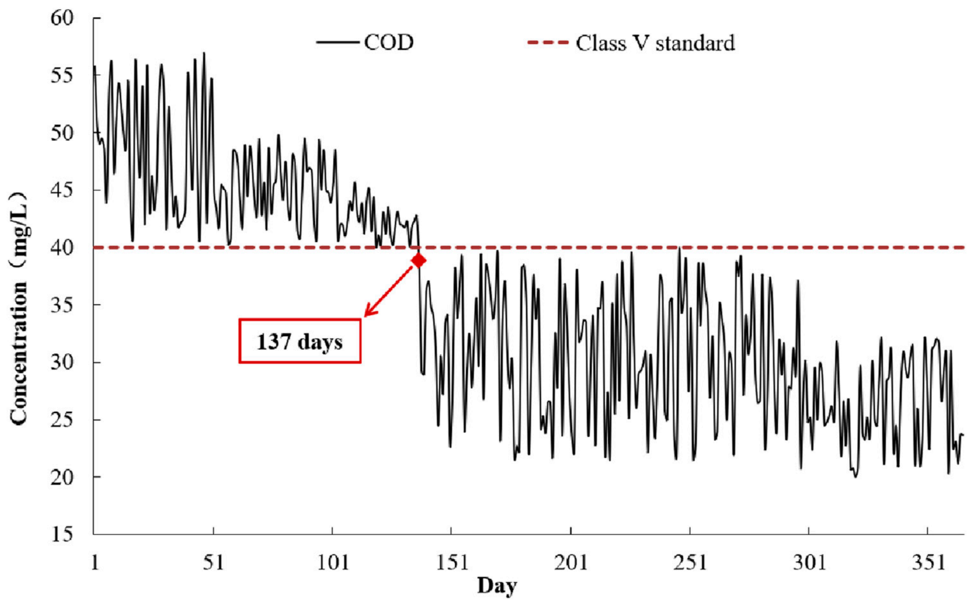

FIGURE 5
COD concentration change process of Wumaoji sluice in Scheme 2.

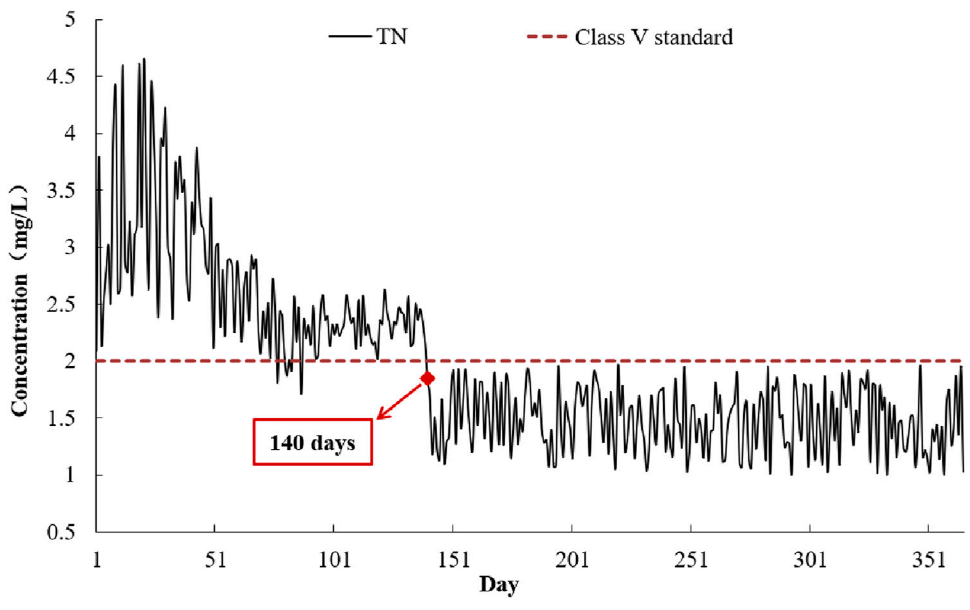

FIGURE 6
TN concentration change process of Wumaoji sluice in Scheme 2.

5.2 Discussion

Lake Ulansuhai is located in the cold and arid region of China, where water scarcity is severe and the supply-demand contradiction of water resources is prominent. The summer irrigation period of the Hetao Irrigation District in Inner Mongolia (the main irrigation period, accounting for about 60% of the total irrigation water) is especially from April to June. In addition, the autumn irrigation period is from July to mid-September, and from late September to October, large-scale flooding is used to reduce land salinization. At the same time, the winter anti-icing task of the Yellow River in Inner Mongolia is heavy. The upstream river channel is prone to form a peak flow especially after the ice is thawed, while the downstream river channel is still frozen, which can easily form ice dams and silt up the river channel, endangering the lives and property of people on both sides of the Yellow River. The Main Channel and Landaqu Channel should be used to replenish water during the irrigation interval in the Hetao Irrigation District to improve the water quality of the lake area so as to minimize the conflict between irrigation water and replenishment water and reduce the risk of ice flood. However, it should be noted that improving the water quality of lakes through water replenishment requires a large amount of freshwater resources. The temporary introduction of excess water resources into the lake to improve the water environment of the lake area is feasible for areas with abundant water resources, both technically and in terms of public opinion. However, it may be challenging to achieve this in water-deficient areas, not because of technical limitations but due to public perception. In areas with limited freshwater resources, using them to control water environmental problems may be considered as a luxury behavior by the public. The simulation results imply that lake water replenishment can reduce the concentration of pollutants in the lake area and ensure the water quality of the lake outflow, but a clear threshold exists for the number of replenishment days, and longer is not necessarily better. This is closely related to factors such as pollutant concentration, replenishable water volume, and lake system connectivity. In other words, water replenishment is effective in accelerating the renewal of lake water and controlling the concentration of pollutants in the lake area. However, water replenishment should have emergency and opportunistic characteristics and should not be implemented as a long-term measure. The real-time evaluation of the ecological water replenishment effect is necessary to reduce unnecessary water replenishment times and for the intensive and efficient use of water resources.

For Lake Ulansuhai, controlling external pollution sources and reducing internal sources, as well as protecting the aquatic ecology of the lake, are important measures for water environmental management. In particular, controlling the discharge of pollutants into the lake is the most direct and effective method. Based on the systematic management concept of “source control-process interruption-end interception-water ecological restoration,” pollution control and interception in the Hetao Irrigation District are emphasized. For example, a water ecological protection zone (consisting of retention ponds, vegetation buffer zones, and so forth) with a width of 20–150 m can be constructed in the area connecting the irrigation area and the lakeshore to intercept agricultural nonpoint source pollution and rainwater with poor water quality in the early rainy season. The heavily polluted inflow channels into the lake should be dredged. The government can adopt market regulation measures to provide tax incentives or funding subsidies for enterprises or individuals who actively reduce pollutant emissions by actively guiding social forces to participate in lake water environmental management. In addition, building an integrated water environmental monitoring and early warning system is also a good method. Digital twin technology has been used to develop a lake environment similar to the actual lake on the computer. Data analysis algorithms and hydrological, hydrodynamic, water quality, and water resource simulation models were integrated into it. The visual effects and intelligent decision-making capabilities of the lake information platform were used to provide technical support for solving practical problems such as “what pollution,” “where pollution,” “how much pollution,” “how to regulate,” “how much water replenishment is needed,” and “how to manage.” In addition, certain explorations have been made at home and abroad for managing lake water resource development and protection; however, no effective measures have been proposed for lake water environment and aquatic ecology protection. It is necessary to organize legislation work for lakes as soon as possible and further improve the legal system for lake protection and management.

Against the backdrop of global warming and intensified human activities, lake water quality has always been a major challenge in the field of global water environment, especially for lakes relying primarily on irrigation return water as their main water source. At present, the research results are still insufficient to support managers in carrying out high-level water environment protection and comprehensively managing them. This study focused on exploring whether supplementary water was an effective means for improving lake water quality; many mechanism issues have not been addressed yet. In the future, dynamic regulation mode research on emergency water replenishment in lakes can be carried out by coupling field observation and model simulation, with real-time rolling updates to optimize water replenishment time, amount, and route. Meanwhile, the mechanism of winter lake water environment evolution can be studied, and the corresponding relationship between lake water environment factors and changing environments can be explored to support the organic updating of the environment management technology for the irrigation area water.

6 Conclusion

Aiming at the core topic of lake water quality improvement using water replenishment, the following conclusions are drawn:

(1) This study took Lake Ulansuhai in China as an example to construct a two-dimensional hydrodynamic and water quality model for cold and arid lake areas. The model simulated the changes in pollutant concentrations of COD and TN in the lake area, and the simulation error was within an acceptable range, indicating that the model constructed in this study was reliable.
(2) The simulation results showed that water replenishment could enhance the self-purification ability of lakes by accelerating the renewal of lake water, thereby achieving the goal of improving lake water quality. However, water replenishment consumes a large amount of freshwater resources. For areas with abundant water resources, water replenishment is an effective measure to improve lake water quality. For water-deficient areas, external source control and internal source reduction of pollutants and protection of lake water ecology are the main ways to manage the lake water environment. Moreover, water replenishment should be used as an emergency and opportunistic measure, and not as a long-term solution, to ensure the sustainable maintenance of the lake water environment.
(3) In the future, for the lakes relying on irrigation area drainage as their main water source, the focus of water quality improvement research should be on key technologies for reducing and controlling pollution in irrigation areas, the

construction of digital twin platforms for lakes, and actively promoting legislation for lakes.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

BL: Conceptualization, Funding acquisition, Methodology, Validation, Writing–original draft, Writing–review and editing. LY: Methodology, Resources, Supervision, Writing–original draft. CC: Funding acquisition, Methodology, Software, Writing–review and editing. WW: Validation, Writing–review and editing, Validation, Writing–review and editing. SL: Validation, Writing–review and editing.

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Conflict of interest

Authors BL, LY, CC, WW, and SL were employed by Yellow River Engineering Consulting Co., Ltd.

Publisher's note

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