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Is water resources management at the expense of deteriorating water quality in a large river-connected lake after the construction of a lake sluice?

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ABSTRACT

River-connected lakes with floodplain characteristics have substantial effects on terrestrial hydrologic cycles and are highly sensitive to external disturbances; thus, large-scale hydraulic projects are often constructed in such lakes to mitigate problems in the water environment. However, the spatiotemporal dynamics of the water environment in river-connected lakes and the differences in the water environment before and after the hydraulic project operation have received little attention. Here, a well-established coupled hydrodynamic–water quality model was applied to estimate the effects of the Chenglingji Sluice (CS) operation on the hydrodynamic features and water quality of Dongting Lake, a typical river-connected lake in China. The model successfully reproduced the water level and water quality dynamics of Dongting Lake, with a Root Mean Square Error (RMSE) of 0.29–1.24 m for water level and a Mean Relative Error (MRE) of 5.76–10.28% and 6.25–8.14% for total nitrogen (TN) and permanganate index (COD_{Mn}), respectively. The spatiotemporal fluctuation of lake water levels was observed over different hydrological periods. Water quality varied considerably spatially, with considerable pollution in East Dongting Lake and the Xiang River inlet. Concentrations of NH_3-N (ammonia nitrogen), TN, and total phosphorus (TP) first decreased and then increased during the study period, whereas COD_{Mn} concentrations displayed the opposite trend. After the CS operation, the water level increased to 27.11 m and the water surface area increased by 19.29% in the dry period; furthermore, the water quality in the CS operation scenario had low concentrations compared to that of the baseline scenario in the dry period, with concentrations ranging from 0.03 to 0.24 mg/L for TN, 0.001 to 0.015 mg/L for TP, 0.006 to 0.09 mg/L for NH_3-N, and 0.02 to 0.22 mg/L for COD_M, effectively improving the water environment of Dongting Lake. However, the subsequent reaction of the lake environment to changes in hydrological conditions after the CS operation requires further attention.

1. Introduction

Lakes cover less than 1% of the Earth's surface. However, they are key components of the hydrosphere with indispensable ecological functions such as water purification, regional climate regulation, wildlife habitat, and agricultural and industrial water supply (Liu et al., 2010; Roozen et al., 2003; Wang et al., 2012). For instance, ecosystem services in lake wetlands account for 23.2% of the total global value of ecosystem services, with over 100,000 species living within or on the lakeshore (Costanza et al., 2014; Dudgeon et al., 2006). Therefore, protecting the aquatic environment of global lakes is vital for various ecosystem services and human life.

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River-connected lakes undergo dramatic inflow and outflow regimes with considerable water level fluctuations at inter- and intra-annual time scales, in contrast to lentic lakes (Fergus et al., 2020; Li et al., 2019a; Wu and Liu, 2016). Due to climate change, such lakes regularly endure intense floods and prolonged droughts, resulting in the complex characteristics of lake-river water systems (Tal, 2019). Intense human activities, such as land-use changes, also have a direct impact on regional hydrological regimes, exacerbating the hydrological sensitivity of river-connected lakes (Akbarzadeh et al., 2019; Guo et al., 2020; Peng et al., 2021a). Therefore, regulating the aquatic environment of river-connected lakes is challenging. Dongting Lake, China's second-largest freshwater lake, is a typical river-connected lake (Xie et al., 2015; Zou et al., 2017). Because of its strategic geographic location, it plays a pivotal role not only in regulating the Yangtze River volume but also in a variety of other functions, including floodwater storage, agricultural irrigation, water supply, and climate management (Dai et al., 2018). Dongting Lake is influenced by seasonal dynamic interactions with watershed rivers and the Yangtze River; hence, the water regimes of Dongting Lake vary under different hydrological periods (Chen et al., 2016; Geng et al., 2021a). For instance, the water level varies by more than 10 m within a year, resulting in an inevitable variation in water quality (Geng et al., 2021a). Dongting Lake is a typical river-connected lake and, therefore, an ideal subject for investigating the relationship between hydrological conditions and water quality variation. Such an investigation is critical for effective water resource management in the face of a changing climate and disruptive human activities.

The Three Gorges Dam (TGD), spanning the upper and lower reaches of the Yangtze River, is the largest hydroelectric project in the world (Xie et al., 2015). Due to the operation of TGD in 2003, Dongting Lake's hydrological conditions, including reduced water exchange and unusual seasonal drought, changed substantially (Geng et al., 2021b). Additionally, the water regimes of Dongting Lake have begun to exhibit the new condition of "flood-drought coexistence" due to climate change and anthropological activities in recent years. Moreover, domestic and industrial wastewater from the cities surrounding the lake has been discharged indirectly or directly into Dongting Lake (Geng et al., 2021b; Li et al., 2016). The factors mentioned above resulted in lake body shrinkage, water pollution, and biodiversity reduction, which aggravated the degeneration of the lake's ecological function (Zhu et al., 2021; Zou et al., 2017). Notably, the hydrological condition of Dongting Lake is continuously affected by extreme drought events; the current drought in Dongting Lake has been prolonged by approximately 30% (Huang et al., 2014). Dongting Lake underwent a particularly severe and unprecedented drought in 2022, with the water level at Chenglingji station dropping from 30.28 m in 2021 to 20.67 m in 2022 during the same period (Fig. 1).

Therefore, effective measures to improve the water environment of Dongting Lake are urgently required. The Chenglingji Hydraulic Project (CHP) was proposed by the local government (Liu et al., 2019), and the Chenglingji Sluice (CS) was installed at the outlet of Dongting Lake to manage water levels during the dry period. Although the CS is regarded as useful for controlling water levels and ensuring the safety of the lake's water environment, it may have multiple effects on the water environment. On the one hand, the operation of the sluice increases the dilution capacity of the lake by retaining more water within the lake, which is conducive to improving water quality (Peng et al., 2021c). On the other hand, sluice operations can impact the exchange of matter between water and sediment, ultimately changing the direction of nutrient cycling in a lake, particularly in relation to phosphorus absorption and release in sediments (Maavara et al., 2020). Therefore, dramatic variations in the water level induced by the sluice may substantially affect the original hydrological features and ecological functions of Dongting Lake (Hu et al., 2018; Liang et al., 2023). The influence of lake hydrodynamics on pollution transport following sluice operations in Dongting Lake remains unknown. Thus, there is a need to investigate the spatiotemporal water quality variations and processes in Dongting Lake during hydrological regime changes, an exercise that is also critical for lake ecological conservation.

In conjunction with observational data, coupled hydrodynamic and water quality models are considered an efficient tool for revealing the underlying interaction mechanisms of lake system changes (Yan et al., 2019; Yin et al., 2020). A well-established 2D hydrodynamic–water quality model, MIKE 21, has been developed by the Danish Hydraulic Institute (DHI, 2007). This model, which can simulate water level variations and flows in lakes or rivers by the response to a variety of forcing functions, is widely used in hydrology, meteorology, and geology to describe numerous physical, chemical, and biological processes that occur within lake systems (Li et al., 2017; Maest et al., 2020; Weng et al., 2021). To date, the MIKE 21 model has been adopted to explore the sensitivity of lake flooding to the relative timing of peak flows (Li et al., 2017), the hysteretic relationships of extensive floodplains (Zhang and Werner, 2015), and water quality response to hydrodynamic variations (Li et al., 2018a). All these exercises verified the reliability of the model in hydrodynamic studies of lakes. In this study, we employed a well-established hydrodynamic–water quality model to quantify the impacts of CS operations on the spatial and temporal dynamics of the hydrodynamic conditions and water quality parameters of Dongting Lake. The objectives of this study were as follows: 1) to identify complex water and pollutant exchange processes in Dongting Lake, watershed rivers, and the Yangtze River, and 2) to quantify the effects of CS on the hydrodynamic and water quality behaviors in Dongting Lake. We anticipate that by conducting these studies, we can explore the influence of CS on the natural environment of Dongting Lake and provide technical guidance for sluice operation.

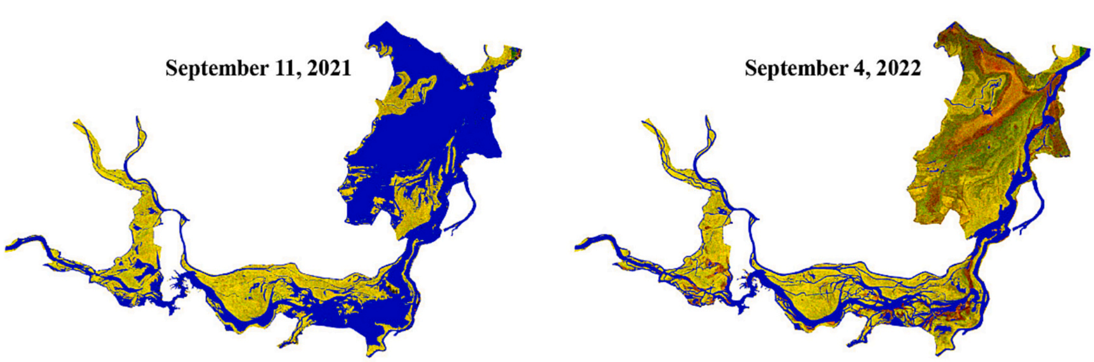

Fig. 1. Comparison of water surface area of Dongting Lake in September 2021 and 2022. Blue indicates water. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Materials and methods

2.1. Study area

Dongting Lake (111° 53′–113° 05′ E; 28° 44′–29° 35′ N), the second-largest freshwater lake in China (Geng et al., 2021b), is located on the south bank of the middle-lower Yangtze River in Hunan Province (Fig. 2). The mean annual temperature of the lake ranges between 16.4 and 17.0 °C, and the average annual precipitation in this area is approximately 1382 mm (Li et al., 2018b). This lake can be considered under three sections: East Dongting Lake (EDTL), South Dongting Lake (SDTL), and West Dongting Lake (WDTL), all of which are Ramsar Sites (Hu et al., 2018). The water discharge from Dongting Lake is principally from the “Four Tributaries” (the Xiang, Zi, Yuan, and Li Rivers, accounting for 78.4% of total water discharge) and the Yangtze River via the “Three Channels” (the Songzi, Hudu, and Ouchi Rivers, accounting for 21.6% of total water discharge). It then flows back into the Yangtze River via the Chenglingji outlet (Zheng et al., 2016). Dongting Lake represents a typical floodplain lake system with complex topography, hydrological conditions, and an East Asian summer monsoon (Xie et al., 2015). The water level and area of the lake vary over the year, with a range of 20.21–33.28 m for water level and 710–2670 km^2 for area (Liu et al., 2019; Tian et al., 2017b). Moreover, the hydrological condition of Dongting Lake typically varies from dry (December–February), rising (March–May), flooding (June–August), and falling (September–November) (Pan et al., 2017), indicating that the lake is susceptible to changes in the aquatic environment.

2.2. Data collection and pre-processing

Hourly hydrological data, including that for water discharge and levels from October 2017 to December 2018, which was a typical hydrological year, were acquired from the Hydrology and Water Resources Survey Bureau of Hunan Province (http://www.hnwr.gov.cn/). Monthly water quality observations for Dongting Lake and its tributaries from 2004 to 2018, including ammonia nitrogen (NH_3-N), total phosphorus (TP), total nitrogen (TN), and permanganate index (COD_{Mn}) concentrations, were obtained from the China National Environmental Monitoring Centre (http://www. cnemc. cn/) and the Yueyang City Eco-Environment Monitoring Center.

We pre-processed the hydrological data of the Three Channels according to the characteristics of the Dongting Lake River system (Tian et al., 2017a), and the water discharge of the Three Channels was calculated as the sum of data from the Songzi, Hudu, and Ouchi Rivers.

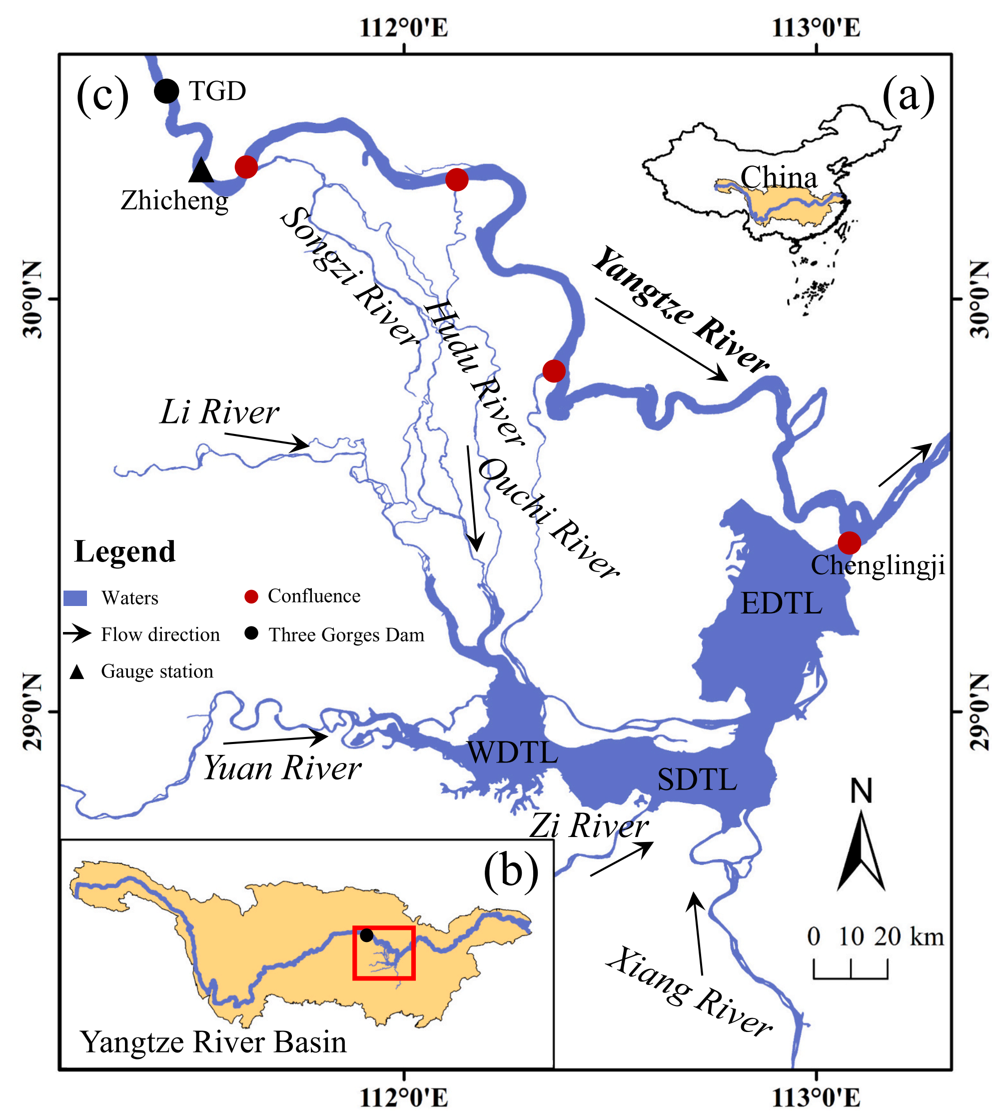

Fig. 2. (a) Location of the Yangtze River Basin in China. (b) Location of Dongting Lake in relation to the Yangtze River Basin, as well as the relationship between Three Gorges Dam (TGD) and Dongting Lake. (c) Map of Dongting Lake and its main rivers.

Because water quality data for the Three Channels are difficult to obtain, nutrient concentrations of the Yangtze River (Zhicheng gauge station, the nearest gauge station located upstream of the Three Channels) were employed as a proxy for the water quality of the Three Channels.

2.3. MIKE 21-coupled hydrodynamic-water quality model

Since Dongting Lake is a river-connected lake with no obvious stratification, a MIKE 21 flow model (FM) was chosen to simulate the hydrodynamics. The MIKE 21 FM is the best suited to 2D free-surface flows and has been widely used in research to simulate hydrodynamic indices such as water level, flow direction, and flow velocity (Li et al., 2020b; Li et al., 2015; Liu et al., 2019). Here, we utilized the MIKE 21 model to investigate spatiotemporal variations in water quality in Dongting Lake under major hydrological regime shifts.

2.3.1. Model setup

The model covered the entire Dongting Lake area and was constructed using 21,430 nodes and 40,450 triangular elements to depict intricate lake bathymetry (Fig. S1). Notably, too big or small triangular elements will cause failure of the model simulation. In the hydrodynamic module (HD), given that the Three Channels from the Yangtze River (i.e., the Songzi, Hudu, and Ouchi rivers) were characterized by complex water systems, and the channels eventually merged in West Dongting Lake (Tian et al., 2017a). Therefore, we generalized the inlet of the Three Channels as a single model upstream boundary, which helped improve the computational efficiency. The Xiang, Zi, Yuan, and Li Rivers were the other four upstream boundary conditions and were specified as hourly inflow records of rivers. The downstream boundary condition used the hourly water-level data from the Chenglingji outlet.

The initial conditions of the transport module (TR) were set up based on the previous simulation findings of water quality (hot start). The average values of the multiannual monthly water quality indicators of the five upstream rivers were interpolated using linear regression to eliminate any outliers and were given as the upstream boundary conditions of the TR model. The Chenglingji outlet was specified as a Neumann open boundary to simulate pollutant transportation. Therefore, we investigated the effect of various hydrological conditions on water quality changes within the lake while the same pollutant load was discharged into the lake.

2.3.2. Parameterization

The parameter values of the MIKE 21 hydrodynamic model were obtained from previous studies on Dongting Lake (Jiang et al., 2007; Liu et al., 2019). The minimum and maximum time steps of the model were set to 0.1 s and 3600 s, respectively (Li et al., 2021). Precipitation and evaporation data were used to describe the effects of weather conditions on the lake's hydrological environment (Hou et al., 2021). Manning's roughness coefficient (M), the essential parameter in lake hydrodynamic modeling, was used as an Excel macro to calculate the Manning roughness coefficient distribution of Dongting Lake. The value of M in this model ranged from 25 $m^{1/3}/s$ to 49 $m^{1/3}/s$, which corresponded well with the bathymetric variation of Dongting Lake (Fig. S2). To obtain an optimal value within the recommended value range for parameters with values that were not immediately available, a series of model runs were conducted by trial and error to test the goodness-of-fit between the simulation results and measured data.

2.4. Model calibration and validation

The hydrodynamic and water quality models were calibrated between October and December 2017 and validated between January and December 2018. Furthermore, the model was validated using the measured water level at the lake stations (i.e., Lujiao, Yingtian, Xiaohezui, and Jiangjiazui, Fig. S1) throughout 2018, which comprised the entire hydrological phase of Dongting Lake within a year. To evaluate the goodness-of-fit of the model fit, the determination coefficient (R^2), Nash-Sutcliffe efficiency coefficient (NSE), and root mean square error (RMSE) were used. The formulations were as follows:

$$R^2 = \left[\sum_{i=1}^{N}(h_m - \overline{h}_m)(h_s - \overline{h}_s)\right]^2 \Bigg/ \left[\sum_{i=1}^{N}(h_m - h_m)^2 \sum_{i=1}^{N}(h_s - \overline{h}_s)^2\right] \tag{1}$$

$$NSE = 1 - \sum_{i=1}^{N}(h_m - h_s)^2 \Bigg/ \sum_{i=1}^{N}(h_m - \overline{h}_m)^2 \tag{2}$$

$$RMSE = \sqrt{\sum_{i=1}^{N}(h_m - h_s)^2 \Big/ N} \tag{3}$$

where h_m(m) is the measured water level, h_s(m) denotes the predicted water level, and $\overline{h}_m$(m) and $\overline{h}_s$(m) represent the average values of the measured and predicted water levels, respectively. i denotes the current time step, and N represents the total number of time steps. The ideal R^2 and NSE values were 1, whereas the optimal RMSE value was 0 m.

2.5. Chenglingji Sluice operation strategy

To alleviate the scarcity of water in Dongting Lake during the dry period, the local government proposed a plan to construct the Chenglingji Sluice (CS) at the outlet of the lake to balance water distribution and improve the ecological functions of the lake. The CS was designed to be built in the northeastern part of Dongting Lake, at the junction of the outlet of Dongting Lake and the Yangtze River. The sluice regulates lake outflows and plays multiple roles in water supply, flood regulation, irrigation, and water transport. It is 3533.65 m long and includes a regulating lock, navigation lock, and fish pass (Cai et al., 2018). Fig. S3 is a conceptual representation of CS.

To correspond with the water rhythm of Dongting Lake, the CS remains open during the flood season (April–August) to maintain connectivity between the lake and the Yangtze River. During the dry season, the CS gradually closes to maintain the lake water level above 23 m from September to March of the following year. Subsequently, if the water level of the Yangtze River reaches 23 m, the CS is opened. In our study, we set up two scenarios: baseline (T1), natural flow, no sluice operation, and sluice operation (T2). The CS would be used to regulate the lake water level during the dry period to examine the impact of CS operation on hydrodynamic and water quality variations within the lake under the same pollutant load. The remaining model parameters and boundary conditions would remain unchanged.

3. Results

3.1. Model validation

3.1.1. Hydrodynamic simulation

The model successfully simulated water level fluctuation at four stations in Dongting Lake, particularly at the Xiaohezui and Jiangjiazui stations (Fig. 3c, d). The RMSE values ranged from 0.29 to 1.24 m, the NSE values were greater than 0.90 except at Yingtian station, and the R^2 values were greater than 0.85, indicating that the simulated findings agreed with the measured data throughout the study period (Table 1). Notably, the water level difference in the lake was much greater in the east than in the west. In the eastern lake, the values obtained were 10.87 m in Lujiao and 10.86 m in Yingtian, and in the western lake, the values were 4.16 m in Xiaohezui and 4.97 m in Jiangjiazui. Thus, it was evident that there were considerable temporal and spatial variations in the water level in Dongting Lake.

The hydrodynamic model accurately simulated the rising and falling lake water level processes as well as the backwater effect between the Yangtze River and Dongting Lake, which occurs at the Chenglingji outlet

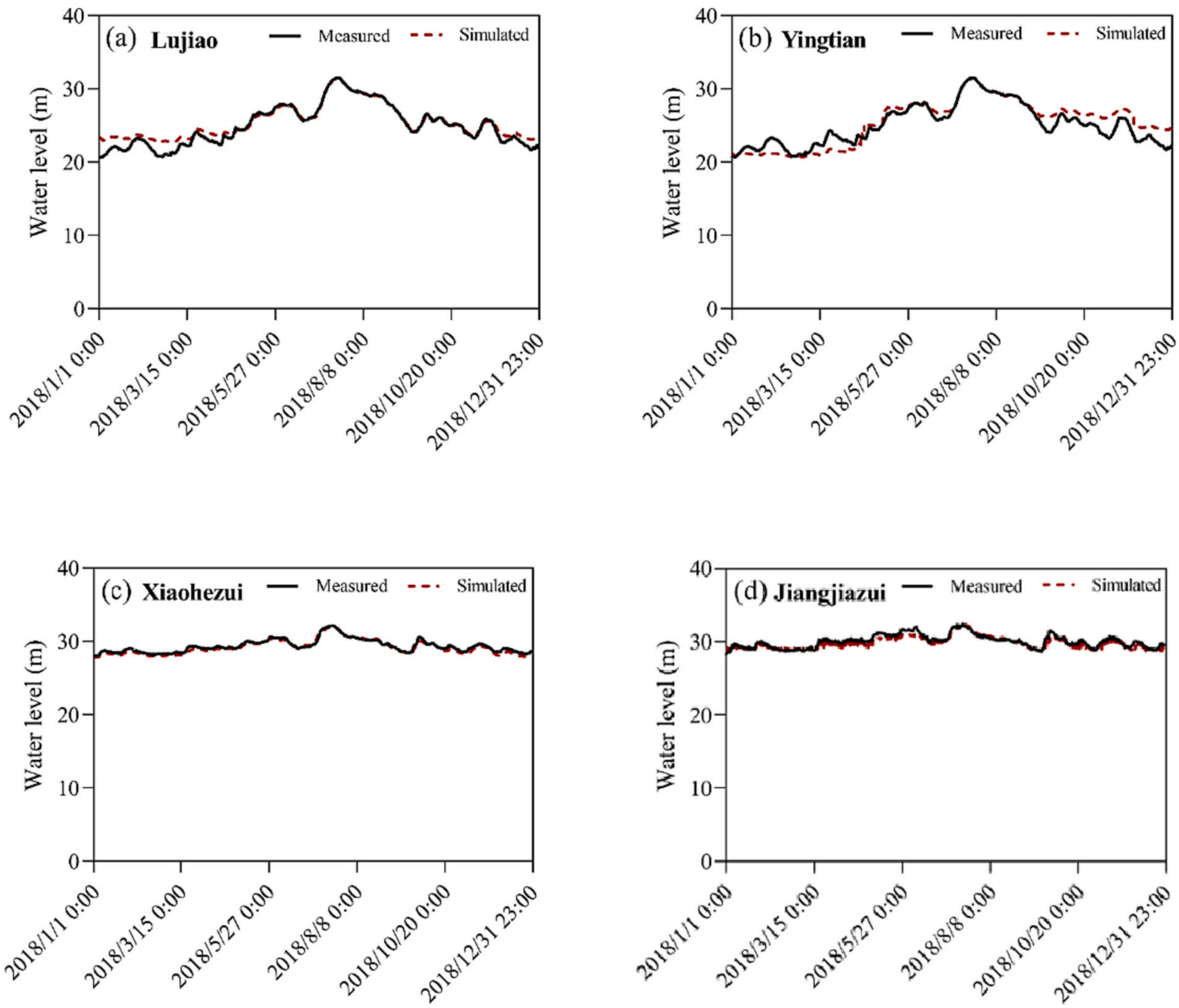

Fig. 3. Measured and simulated water level at Lujiao, Yingtian, Xiaohezui, and Jiangjiazui stations.

Table 1
Performance of water level simulations of Dongting Lake for the hydrodynamic model.

Hydrological stations	R^2	NSE	RMSE (m)
Lujiao	0.96	0.91	0.79
Yingtian	0.85	0.82	1.24
Xiaohezui	0.97	0.90	0.29
Jiangjiazui	0.98	0.92	0.37

Table 2
Mean relative error of water quality between simulated and measured values.

Stations	TN	TP	NH_3-N	COD_{Mn}
Lujiao	10.07	14.14	35.92	8.14
Yingtian	9.09	9.66	42.37	6.65
Xiaohezui	5.76	19.43	16.60	7.59
Jiangjiazui	10.28	21.45	23.46	6.25

on occasion during July when the water level in the Yangtze River is higher than that in the lake (Fig. S4). Thus, the HD module developed in this study could accurately depict the spatiotemporal water-level changes and water balance of the lake.

3.1.2. *Water quality simulation*

The simulated fluctuations in water quality indicators closely mirrored the observed data and accurately captured the spatiotemporal variations in water quality for Dongting Lake. At the Yingtian station, a dramatic variation in TN, a rapid decrease, and an increasing trend in NH_3-N were also successfully captured (Fig. S5). Simulated TN and COD_{Mn} performances were substantially superior, with MRE values ranging from 5.76 to 10.28% and 6.25 to 8.14%, respectively (Table 2). Nevertheless, the MRE values for NH_3-N ranged from 16.60 to 42.37%, which was less than 50% and could be considered a satisfactory simulated performance (Tang et al., 2018). Spatially, Xiaohezui station exhibited a well-simulated performance, with MRE values of 5.79 (TN), 19.43 (TP), 16.60 (NH_3-N), and 7.59 (COD_{Mn}). Notably, the water quality exhibited considerable spatial variation within a year. For example, the TN, NH_3-N, and COD_{Mn} concentrations were substantially greater in the eastern lake basins (Lujiao and Yingtian) than in the western lake basins (Xiaohezui and Jiangjiazui), whereas the TP concentrations exhibited the opposite trend.

3.2. *Spatiotemporal variations of water level and water quality*

3.2.1. *Water level*

The model accurately simulated the spatiotemporal fluctuation of Dongting Lake's water level over distinct hydrological periods; that is, the water level was substantially higher in the west than in the east part of the lake, with much higher levels during the flooding period than during the dry period (Fig. 4). The water levels across the entire lake were 26.89 m (dry period), 28.01 m (rising period), 30.54 m (flooding period), and 27.31 m (falling period). During the dry period, the lake's surface water area was reduced to the main river channels within the lake, and the lake's water level was at its lowest in a year. The water surface area and level had the appearance of a lake phase during the rising and falling periods, and some small lakes were fully or partially connected to the main lake. The lake's water level peaked during the flooding period when the entire lake was filled with water.

3.2.2. Water quality

The geographic patterns of TN, TP, NH_3-N, and COD_{Mn} concentrations were similar, with the eastern basin of the lake suffering from high concentrations, particularly in the East Dongting Lake and the Xiang River inlet (Fig. 5). In the dry period, the TN concentrations for the Xiang River inlet, East Dongting Lake, and West Dongting Lake were 2.52 mg/L, 2.02 mg/L, and 1.79 mg/L, respectively. Seasonally, TN, TP, and NH_3-N concentrations first decreased and then increased over the year. In contrast, the COD_{Mn} concentration exhibited the opposite trend.

3.3. The effect of CS operation on lake water level and water quality

3.3.1. Water level

During the flooding period, the water level in both scenarios fluctuated similarly, peaking in July with a water level of 31.39 m (Fig. 6). However, under the CS operation scenario (T2), the water level fluctuated slowly during the rising and falling phases, and the water level at Chenglingji station exceeded 23 m within a year. The water level in the baseline scenario (T1) displayed substantial rising and falling patterns ranging from 20.10 to 31.39 m. The water level variations between the two different scenarios within the year were 11.29 m (T1) and 8.32 m (T2).

The spatiotemporal fluctuations in water level of T2 were similar to those of T1, with the lake water area first increasing and then decreasing over the year (Fig. 7). However, the lake water area and water level differed between the two scenarios for the same period, particularly during the dry season, during which the water area in T2 was 19.29% greater than in T1, and the lake water levels were 27.11 m (T2) and 26.89 m (T1).

3.3.2. Water quality

The NH_3-N, TN, and TP concentrations in both scenarios first decreased and then increased (Fig. S6). The three water quality indicators showed similar variations with dramatic fluctuations during the flooding period. However, during the dry period, the water quality in T2 had low concentrations compared to that in T1, with the concentration difference ranging from 0.03 to 0.24 mg/L for TN, 0.001 to 0.015 mg/L for TP, and 0.006 to 0.09 mg/L for NH_3-N. In contrast to the other three water quality indicators, the COD_{Mn} concentration showed an opposite trend, first increasing and then decreasing. Furthermore, during the dry period, the COD_{Mn} concentration in T2 was lower than that in T1, with the difference ranging from 0.02 mg/L to 0.22 mg/L. Notably, the water quality of Dongting Lake exhibited considerable spatial heterogeneity at the sub-lake scale, with the greatest concentration in EDTL, moderate concentrations in SDTL, and the lowest concentration in WDTL over the study period (Table 3). Additionally, the water quality in T2 was better than that in T1, with the exception of COD_{Mn} concentrations in the rising and falling periods and TN and TP concentrations in the flooding period.

During the CS operation phase, the water quality in the western basin of the lake was considerably lower than that in the central and eastern basins, with much smaller variations. The concentrations of TN, TP, NH_3-N, and COD_{Mn} in the eastern lake basin increased slowly compared to the baseline scenario (Fig. 8). Seasonally, TN, TP, and NH_3-N concentrations were higher in the dry period than in other periods, with lake-average concentrations of 1.98 mg/L, 0.14 mg/L, and 0.36 mg/L for TN, TP, and NH_3-N, respectively. In contrast, the spatiotemporal variations in COD_{Mn} concentrations followed a pattern opposite to that of NH_3-N, TN, and TP.

4. Discussion

4.1. Performance of the coupled hydrodynamic–water quality model

The hydrodynamic model developed in this study captured the complex lake topography and characterized the spatiotemporal fluctuations in hydrological conditions. Furthermore, the backwater effect between Dongting Lake and the Yangtze River at the Chenglingji outlet was observed during the flooding season. We obtained an R^2 value ranging from 0.85 to 0.98, indicating that the simulated lake hydrodynamics had high model accuracy and were comparable to the Dongting Lake hydrodynamic models produced by Tian et al. (2017a) and Liu et al. (2019). Notably, some of the hydrodynamic model uncertainty resulted from the interpolation of the terrain, constructed mesh, and upstream discharge boundary conditions (Wright et al., 2017). In this study, the simulated water level at the Lujiao and Yingtian stations during the dry season was less accurate than that during other periods because the performance of the hydrodynamic model was influenced by decreased water discharge, lake topography, and the mesh grid. Overall, the computational efficiency and accuracy of the model were evaluated, ensuring that the steady use requirements were met.

The strong performance of the well-established hydrodynamic model laid the groundwork for the water quality simulations. The findings showed that the water quality model accurately simulated the TN, TP, NH_3-N, and COD_{Mn} variation trends and met the use requirements. However, there were some deviations between the simulated and measured data during the dry period because the pollutant flux at the inflow boundary was obtained using the interpolation algorithm combined with monthly water quality data. Furthermore, in a real lake environment, water quality fluctuation processes are highly complex and involve many physicochemical reactions, such as internal pollutant release from sediment, microbial degradation, and plant and algal absorption (Girbaciu et al., 2016; Tibebe et al., 2019). In this study, we focused on the impact of hydrological variations on water quality; thus, the transport module (TR) we selected met the simulation requirement, which could hide other biogeochemical interference related to water quality. The water quality indicator simulations indicated that the

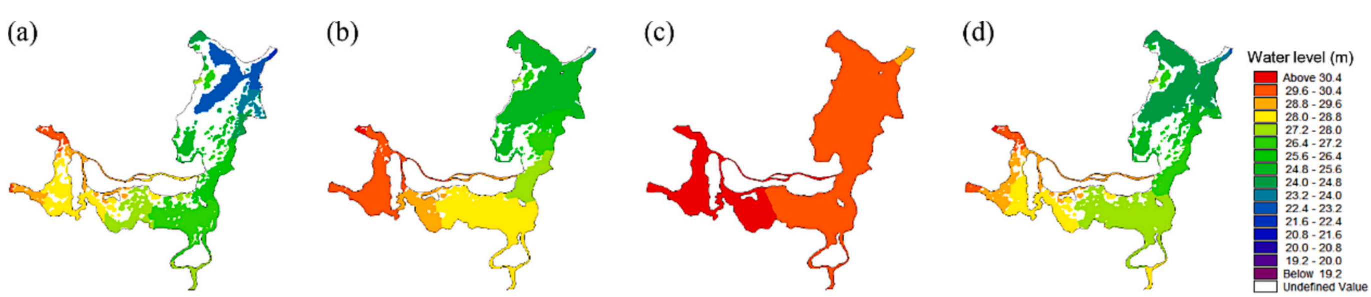

Fig. 4. Spatial variations of water level in (a) dry, (b) rising, (c) flooding, and (d) falling periods under the baseline scenario.

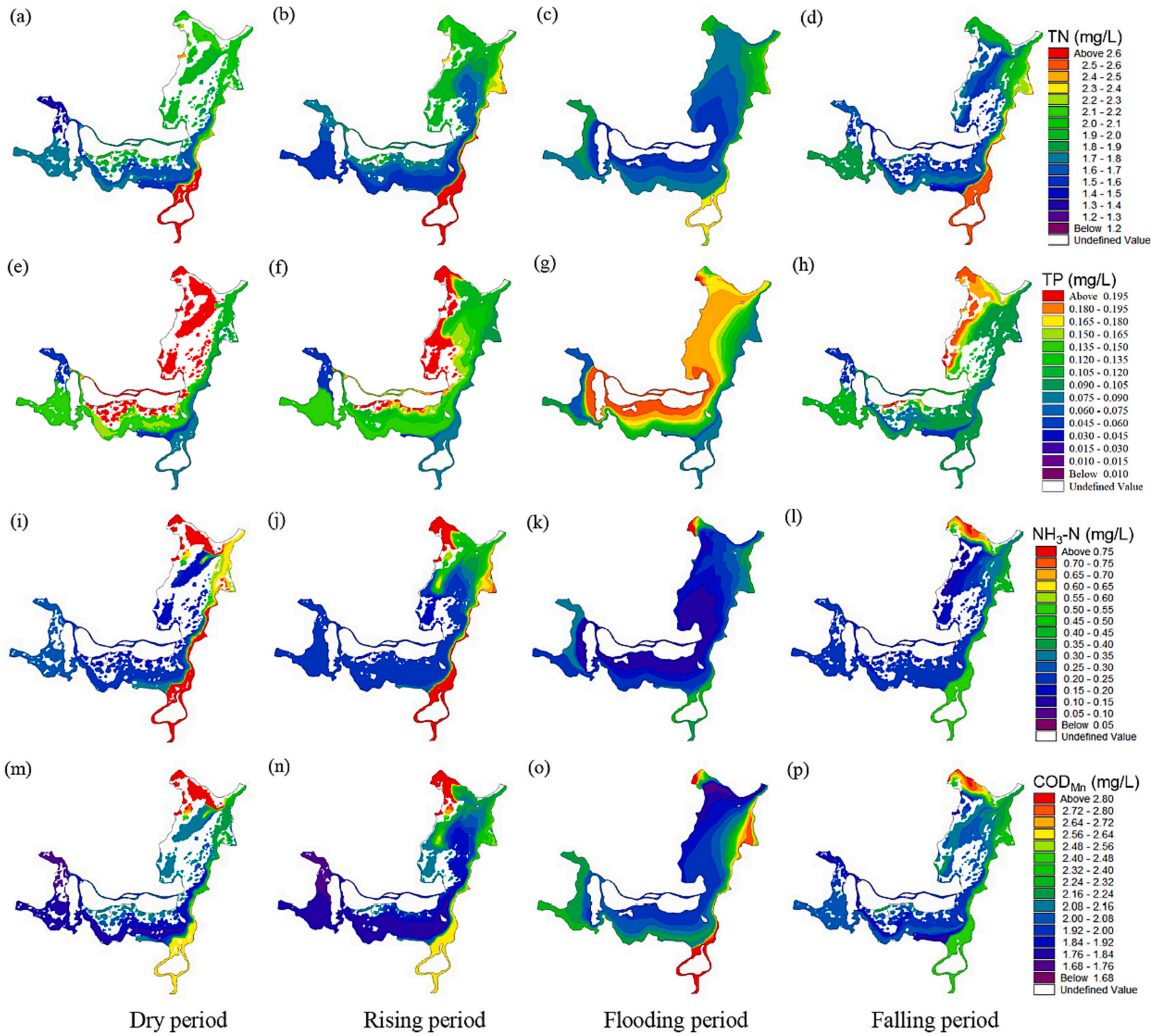

Fig. 5. Spatial variations in TN, TP, NH_3-N, and COD_{Mn} during the (a) dry, (b) rising, (c) flooding, and (d) falling periods under the baseline scenario.

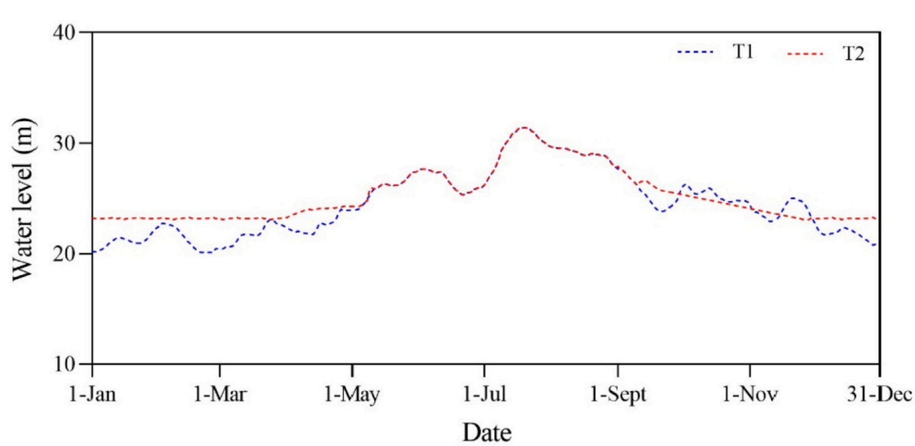

Fig. 6. Water level time series at Chenglingji station under various scenarios. (T1: baseline scenario. T2: CS operation scenario).

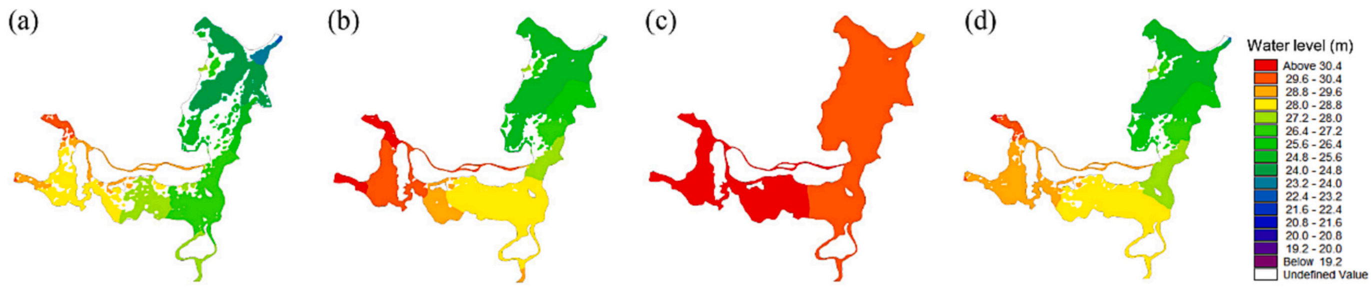

Fig. 7. Spatial variations of water level during the (a) dry, (b) rising, (c) flooding, and (d) falling periods in the CS operation scenario.

Table 3
Comparison of the water quality parameters in Dongting Lake at various sub-lakes and hydrological periods. T1: baseline scenario, T2: CS operation scenario, EDTL: East Dongting Lake, SDTL: South Dongting Lake, WDTL: West Dongting Lake, DTL: Dongting Lake.

Water quality parameters (mg/L)	Scenarios	Dry period				Rising period			
		EDTL	SDTL	WDTL	DTL	EDTL	SDTL	WDTL	DTL
TN	T1	2.289	1.891	1.668	1.949	2.157	1.976	1.675	1.936
	T2	2.186	1.857	1.662	1.902	2.034	1.899	1.796	1.910
TP	T1	0.128	0.115	0.101	0.115	0.112	0.104	0.101	0.106
	T2	0.132	0.118	0.092	0.114	0.105	0.106	0.088	0.100
NH_3-N	T1	0.623	0.398	0.284	0.435	0.510	0.362	0.240	0.371
	T2	0.586	0.371	0.296	0.418	0.471	0.310	0.244	0.342
COD_{Mn}	T1	2.378	2.012	1.798	2.063	2.357	2.027	1.791	2.058
	T2	2.305	2.048	1.800	2.051	2.257	1.995	1.928	2.060
Water quality parameters (mg/L)	Scenarios	Flooding period				Falling period			
		EDTL	SDTL	WDTL	DTL	EDTL	SDTL	WDTL	DTL
TN	T1	1.873	1.818	1.718	1.803	1.974	1.901	1.785	1.887
	T2	1.863	1.827	1.725	1.805	1.893	1.789	1.760	1.814
TP	T1	0.093	0.086	0.070	0.083	0.096	0.075	0.078	0.083
	T2	0.102	0.078	0.072	0.084	0.091	0.076	0.074	0.080
NH_3-N	T1	0.264	0.227	0.211	0.234	0.388	0.358	0.218	0.321
	T2	0.253	0.203	0.180	0.212	0.356	0.330	0.223	0.303
COD_{Mn}	T1	2.693	2.378	2.158	2.410	2.197	2.059	1.999	2.085
	T2	2.356	2.209	2.142	2.236	2.191	2.115	2.034	2.113

simulated TN and COD_{Mn} were more accurate than the simulated TP and NH_3-N, implying that lake water quality is controlled not only by pollutant input but also by physicochemical reactions related to water quality in the lake water. Overall, the hydrodynamic-water quality model established in this work could accurately reproduce the variations in the water environment in Dongting Lake and satisfy the requirements for future scenario modeling.

4.2. Spatiotemporal variations of water level and water quality in Dongting Lake

River-connected lakes such as Dongting Lake are geomorphologically dynamic systems characterized by highly complex hydrological processes and exchanges (Yu et al., 2018). In this study, the spatial variations in water level and water surface area under natural conditions showed considerable rising and falling trends throughout the year, consistent with the actual morphology of Dongting Lake. This substantial variation reflects the floodplain characteristics and unstable hydrodynamic conditions of Dongting Lake, which may impact the spatial pattern of lake water quality. According to the water quality modeling results, pollutant concentrations across Dongting Lake showed considerable spatiotemporal fluctuations as a function of pollution inputs and lake hydrodynamics.

The main channel and the eastern section of the lake had elevated pollutant concentrations, particularly at the Xiang River inlet, indicating that the rivers that discharged into Dongting Lake were major sources of contaminants. Furthermore, the lake's hydrodynamic features influence lake water quality. The flow direction of Dongting Lake is from west to east (Fig. 2). The accelerated lake currents encourage the transport of pollutants from West Dongting Lake and South Dongting Lake to the more polluted East Dongting Lake (Geng et al., 2021c), resulting in a further rise in the pollutant concentrations in the eastern part of Dongting Lake. Similar findings have been reported for the Poyang and Eric lakes (Li et al., 2020a; Prater et al., 2017). Notably, several water quality indicators, such as TP, COD_{Mn}, and NH_3-N, had substantially higher concentrations in the northwestern part of East Dongting Lake, which was attributed to low velocity (low water disturbance) and poor water exchange. Substantial levels of contaminants are retained, resulting in poor water quality and cyanobacterial blooms (Xue et al., 2020). Additionally, a large amount of pollution, including non-point source pollution and industrial and domestic pollution from the surrounding homes and factories, is discharged directly into East Dongting Lake, contributing to the lake's water quality deterioration (Geng et al., 2021b).

4.3. Effects of CS operations on the lake water environment

To mitigate shifts in the hydrological regime and improve the aquatic environment of Dongting Lake, the use of the Chenglingji Sluice (CS) is recommended to control the water level during dry seasons. In this study, the operation of CS obstructed the outflow of lake water, resulting in a marked increase in the water surface area of Dongting Lake in dry seasons. Following the CS operation, the water environment of Dongting Lake improved substantially, with the water level difference decreasing from 11.29 m to 8.32 m and the lake surface water area increasing by 19.29% in the dry period compared to natural conditions. These results achieved the desired effect of preserving the water supply and ensuring the ecological functions of Dongting Lake during the dry season. However, a change in the periodic inundation rhythm may have a series of uncertain consequences for the eco-hydrological environment of

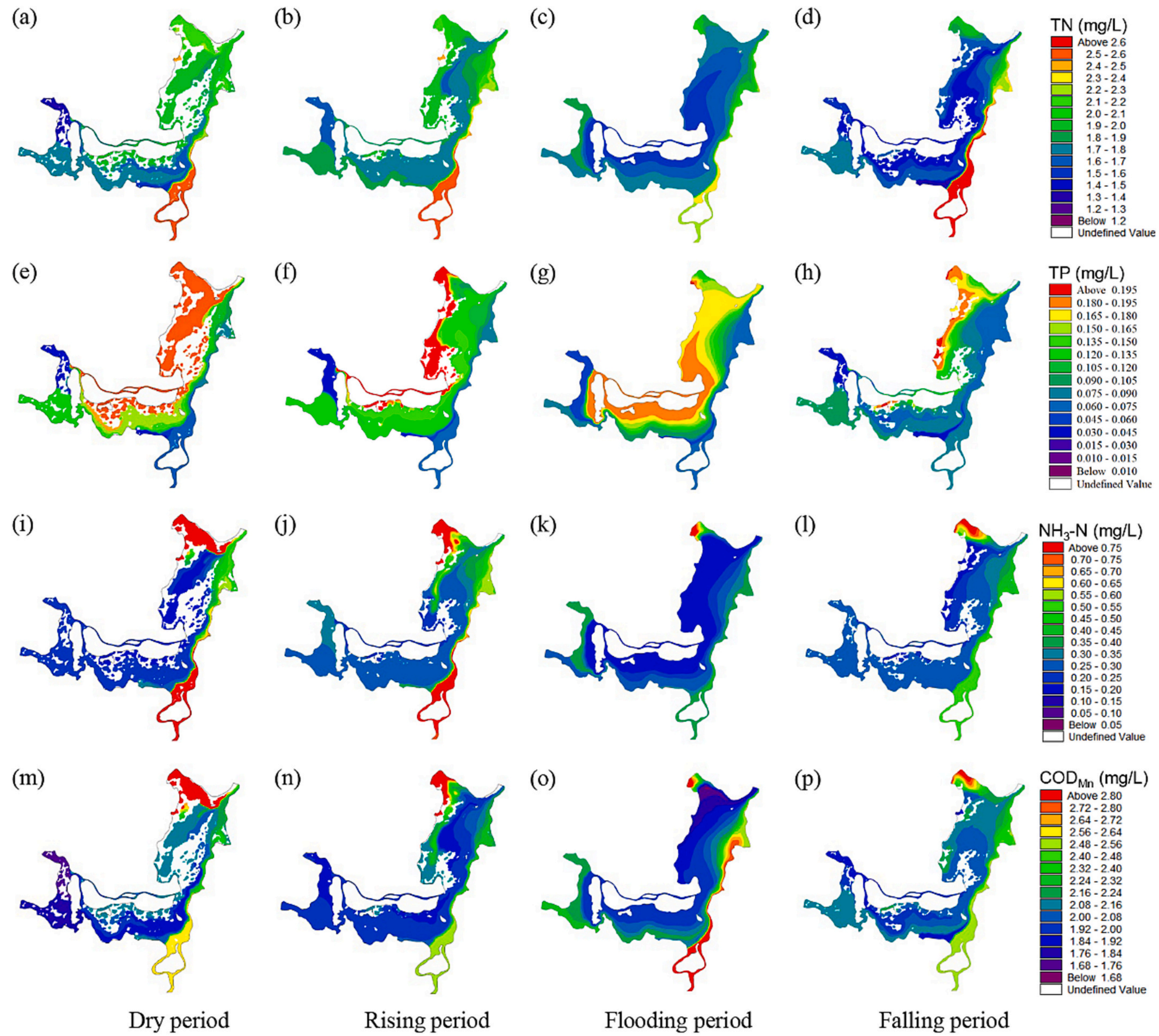

Fig. 8. Spatial variations in TN, TP, NH_3-N, and COD_{Mn} during the (a) dry, (b) rising, (c) flooding, and (d) falling periods in the CS operation scenario.

Dongting Lake (Dai et al., 2017). According to water quality simulation results, the water quality in the CS operation scenario had low pollutant concentrations compared to the natural conditions during the dry period because the large volume of water retained within the lake diluted the pollutant (Zhu et al., 2023). In addition, the decrease in pollutant concentrations at low water levels during the dry period (winter) may be related to the weakness of biogeochemical processes due to low temperatures and poor hydrological connectivity in Dongting Lake (Zhao et al., 2016). However, the pollutant concentrations were still high, satisfying the requirement for lake eutrophication (Schindler et al., 2008). Despite the low flow velocity and long hydraulic retention time, which weaken water exchange and have a flushing effect on algal communities, no widespread algal bloom events have been reported from Dongting Lake to date. This is due to algal growth constraints caused by light limitations and low temperatures during the dry period (Zhi et al., 2016). Xu et al. (2019) found that sluice operation strategies determine the trophic state of lakes or reservoirs by influencing the biogeochemical processes associated with nutrient cycling. According to Liu et al. (2019), closing the sluice might weaken the connectivity between Dongting Lake and the Yangtze River (e.g., matter exchanges). Additionally, CS operations could increase the water-filled area of the lake and aggravate hypolimnetic hypoxia caused by high water levels during the dry period, promoting the release of sediment pollutants (Gerling et al., 2014). Furthermore, anthropogenic influences on the lake water environment affect both the horizontal and vertical soil nutrient properties, particularly the conversion of nitrate to gaseous nitrogen (Sabater et al., 2003). Notably, the water quality variations affected by sediment pollutant release are delayed and weak in comparison to substantial external contamination (Tian et al., 2017a), while the long-term environmental implications of CS operations must also be carefully examined.

4.4. Limitations and uncertainties

The capacity of hydrodynamic models to compute continuous and dynamic hydrological fluctuations is strong, although cell resolution remains a key issue for capturing complex floodplain environments (Hu et al., 2020; Li et al., 2019b). The present study used a locally refined mesh resulting from extensive trade-offs between simulation accuracy and processing time. Furthermore, a fundamental limitation of our study lies in the relatively coarse water quality boundary conditions, which were produced using linear interpolation of monthly observed water quality data. Although monthly sampling has been proven to be acceptable in the presence of certain model uncertainties, future work should focus on enhancing the accuracy of the water quality boundary and quantifying the uncertainty of model outputs.

Aside from data limitations, the internal nonlinear and high-dimensional processes among lake ecosystem variables, as well as interactions between lake variables and external landscape variables, are complex (Peng et al., 2021b). Hence, the realistic relationship between hydrodynamic factors and water quality parameters may be considerably more complicated than the simulated relationship. The well-calibrated hydrodynamic model developed in this study revealed the spatiotemporal water environment variations of Dongting Lake and allowed us to isolate the individual effects of CS operation from many external causes, achieving the objective of the study. This study is considered an initial step in the investigation of the spatially dynamic patterns of hydrodynamic water quality in Dongting Lake. Future research is required to collect regular water quality data to fully calibrate and validate the model and to apply it to diverse hydrological observations of lakes with floodplain characteristics.

5. Conclusion

This project developed a hydrodynamic–water quality model to investigate the spatiotemporal variations in the water level and quality of Dongting Lake, as well as the follow-up impacts of CS operations on the lake's water environment. The model accurately represented the spatiotemporal fluctuations in water level under the obvious floodplain characteristics of Dongting Lake, with a higher water level and greater surface water area during the flooding period and an opposite trend during the dry season. The water level was much higher in the western part of the lake than in the eastern part. Furthermore, we detected a unique hydrological phenomenon: a backwater effect between the Yangtze River and Dongting Lake. The main river inlets were the primary sources of pollution, particularly the Xiang River inlet, resulting in high concentrations of pollutants in the eastern part of the lake. Moreover, hydrological factors played a key role in water quality, affecting pollutant degradation and transport in the lake. The CS operation raised the water level during the dry period and substantially affected the spatial patterns of water quality within the lake by various physical and biochemical reactions, reflecting the importance of hydrological conditions to water quality. This study may be extended to other river-connected lakes with floodplain characteristics by providing an improved understanding of the impacts of large sluice gate operations on lake ecosystems and promoting effective water resource management under various hydrometeorological conditions.

CRediT authorship contribution statement

Mingming Geng: Conceptualization, Methodology, Writing – original draft. **Kelin Wang:** Conceptualization. **Zhan Qian**: Data curation. **Heng Jiang**: Data curation. **Yunliang Li:** Methodology. **Yonghong Xie:** Investigation, Supervision. **Feng Li:** Methodology, Writing – review & editing. **Youzhi Li:** Conceptualization, Methodology. **Yeai Zou:** Methodology. **Zhengmiao Deng:** Formal analysis. **Jing Zeng:** Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoleng.2023.107124.

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