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Assessing the impact of water-sediment factors on water quality to guide river-connected lake water environment improvement

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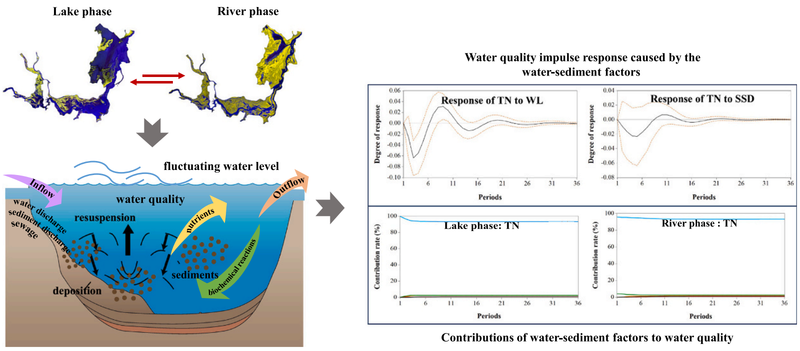
HIGHLIGHTS

- Water-sediment factors and water quality displayed drastic fluctuations.
- Impulse response of water quality to water-sediment factors gradually decayed.
- The contribution of water-sediment factors to water quality varied from 9 % to 21 %.
- Impact pattern of water-sediment factors on water quality exhibited differences.

GRAPHICAL ABSTRACT



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ABSTRACT

The substantial impacts of exogenous pollutants on lake water quality have been extensively reported. Water-sediment factors, which are essential for regulating water quality in river-connected lakes, have not been studied in depth under different hydrological conditions. This study has combined a 31-year water environmental dataset (1991–2021) regarding Dongting Lake and a vector autoregression model (VAR) in order to investigate the impulse response characteristics and contributions of water quality caused by water-sediment factors across different periods. Our analysis suggests that total nitrogen (TN) exhibited a significant increasing trend, whereas total phosphorus (TP) increased to 0.17 mg/L, and then decreased to 0.07 mg/L from 1991 to 2021. The inflow of suspended sediment discharge (SSD) decreased significantly during the study period, mainly because of the decrease in SSD in the three channels (TC). In the pre-Three Gorges Dam (TGD) period, water discharge (WD) and SSD were the Granger causes of TN and TP. In the post-TGD periods this relationship disappeared because of the construction of the TGD, which reduced the inflow of SSD and WD into the lake.

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Water quality indicators showed an instant response to the shock from themselves with high values, whereas the impulse response of the water quality to water-sediment factors exhibited lagged variations. This meant that the water quality indicators displayed a high impact by themselves across the different periods, with values varying from 67 % to 95 %. Water level (WL) and SSD were the predominant water-sediment factors for TP in the pre-TGD period, with the impact on TP changes accounting for 11 % and 9 %, respectively, whereas the contribution of SSD decreased to 2 % in the post-TGD period. WL was the most crucial water-sediment factor for COD_{Mn} during the different periods, with contributions varying from 17 % to 20 %. To improve the water quality of Dongting Lake, in addition to the implementation of strict controls on excessive external nutrient loading, regulating water-sediment factors according to the hydrological features of Dongting Lake during different periods is vital.

1. Introduction

Global natural lakes cover approximately 4.20×10^6 km^2 of the Earth, which accounts for only 3 % of the land area (Downing et al., 2006). However, lakes play a unique role in maintaining regional and global ecological balance, regulating flooding and drought, and providing food (Woolway et al., 2020; Zhang et al., 2022a). The International Geosphere–Biosphere Programme (IGBP) aims to survey the distribution, production, and transport of pollutants and related processes in lakes, with an emphasis on ensuring water quality and improving various lacustrine ecological functions (Murase et al., 2005; Rispoli and Olsakova, 2020). However, a substantial number of pollutants have been discharged into lakes owing to rapid industrialization and high-intensity agricultural activities over the years. This had led to severe water pollution and various ecological problems, such as lake eutrophication and biodiversity decline (Landrigan et al., 2018; Cai and Yan, 2021). Therefore, it is necessary to obtain data on lake water quality trends, changes, and related driving forces via long-term water quality observations as well as to improve lacustrine ecological functions and establish sustainable lake management by water management authorities.

The inflow of substantial amounts of exogenous pollutants, such as domestic and industrial sewage and agricultural nonpoint source pollution, into lake ecosystems negatively impacts water quality (Akurut et al., 2017). Hydrological factors such as water discharge, suspended sediments, and water level are crucial in determining lake water quality and succession direction, which influence biogeochemical cycles in relation to water quality (Geng et al., 2021a; Peng et al., 2021a). Pollutants entering lakes owing to surface runoff may be diluted and transported by water discharge, which subsequently affects the spatial distribution of water quality by driving the flow velocity within the lake (physical reaction) (Waltham et al., 2014). Moreover, the transformation, oxidation, and reduction processes (biochemical reactions) of pollutants occurring at the water-sediment interface of lakes substantially influence water quality (Karakoc et al., 2003). The amount of sediment-released P depends primarily on the duration and areal extent of anoxia, which is associated with the water level and suspended sediment concentration (Li et al., 2016a; Kim et al., 2019). Many studies have confirmed that water-sediment-associated factors are important components of water–quality interaction systems in lakes (Zhu et al., 2019; Perera and Gomes, 2022). Quantifying the interaction strength and impact patterns of water-sediment factors on lake water quality is crucial to advancing the understanding of variations in the water environment and improving sustainable lake management.

Correlations between water quality and water-sediment factors can cause different ecological responses across different types of lakes. For example, lentic lakes are important sinks for N and P because they offer the ideal conditions for N and P burial in the sediments present, that is, high pollutant input and low water disturbance (Harrison et al., 2009; Beaulieu et al., 2019). Wang et al. (2021) investigated N and P burial in sediments from global lakes and they put forward that N and P burial in lakes cannot be overlooked as an important global sink of N. However, the hydrological conditions of river-connected lakes vary drastically with periodic rhythms, which alter the relationship between water quality and water-sediment factors, thereby resulting in the spatiotemporal heterogeneity of lake water quality (Geng et al., 2021b; Zhang et al., 2022b). Dongting Lake, which is connected to the Yangtze River, is China's second largest freshwater lake and is a typical river-connected lake that serves critical ecosystem functions for water regulation and biodiversity protection (Pan et al., 2018; Zhu et al., 2022a). This lake receives water and sediments from the Xiang, Zi, Yuan, and Li rivers (four tributaries) from its catchment area and the Songzi, Hudu, and Ouchi rivers (three channels) from the Yangtze River, which then flow back to the Yangtze River at the Chenglingji outlet (Zhu et al., 2022a). The specific geographical conditions and river-lake system of Dongting Lake determine the characteristics of drastic fluctuations in water-sediment. Furthermore, the water quality of Dongting Lake greatly influences the ecological safety and economic development of surrounding human settlements. The deteriorating water quality of Dongting Lake, attributed to anthropogenic activities and extreme climate change, has led to several pressing environmental issues including local eutrophication, drinking water crises, and biodiversity reduction (Liu et al., 2012; Geng et al., 2021a). In addition, the hydrological conditions of Dongting Lake vary dramatically with a clear seasonal rhythm comprising a low water level in the river phase and a high water level in the lake phase, which may cause spatiotemporal differences in water quality (Geng et al., 2022). After the construction of the Three Gorges Dam, which is the largest dam in the world, the sediment discharge entering Dongting Lake via the three channels of the Yangtze River decreased significantly because of the dam intercepting the sediment, resulting in the occurrence of an early, prolonged, low water level period (Hu et al., 2018). We previously indicated that these changes in hydrological conditions disrupted the dynamic equilibrium between pollutants and water-sediment factors in Dongting Lake, leading to high ecological risks and new spatiotemporal patterns in the water quality across the lake (Geng et al., 2021a; Geng et al., 2021b). However, understanding the dynamic response of water quality to water-sediment factors and their contributions during various periods remains unclear. This lack of clarity may cause challenges in elucidating the driving mechanisms related to water quality in river-connected lakes and affect the establishment of environmental policies for river-connected lakes.

Researchers have studied forecasting and variation trends in lake water quality based on different methods, such as the ordinary regression and grey forecasting models (Deng, 2019; Kumar et al., 2019). However, the accuracy of the model may decrease significantly when raw data fluctuate sharply, because these models focus heavily on data fitting to search for sequence rules (Kasza and Wolfe, 2014). The vector autoregression (VAR) model, an effective approach to the AR-based model, considers all endogenous variables, thereby reducing the uncertainty in the simultaneous equation model due to subjective errors. This model has been applied in several different fields such as economics, energy engineering, and environmental sciences (Li et al., 2016b; Kalli and Griffin, 2018; Man et al., 2019). Moreover, the VAR model has several advantages, including the relative ease of estimating parameters and long-term predictions, allowing its potential application in lake water pollution research (Man et al., 2019). No reported applications of VAR models to river-connected lakes have been performed to study variations in their water quality and the underlying mechanisms.

In this study, we combined a 31-year monitoring dataset (1991–2021) with the VAR model to examine spatiotemporal water quality variations and their relationship with water sediment factors in Dongting Lake during different periods. This study primarily aims to 1) explore water quality and water-sediment factor variation trends and their temporal heterogeneity across Dongting Lake in different periods, 2) elucidate the potential impulse response of water quality to water-sediment factors, and 3) detect the contribution and impact patterns of water-sediment factors on water quality in different periods.

2. Materials and methods

2.1. Study area

Dongting Lake (28°30′–30°20′N, 111°40′–113°10′E) is located at the middle and lower reaches of the Yangtze River Basin in China (Fig. 1), with a surface water area of approximately 2691 km^2 and a volume of 174×10^8 m^3 (Zhang et al., 2021; Zhu et al., 2022b). The lake comprises three regions: east (EDTL), south (SDTL), and west (WDTL) Dongting Lake, all of which are characterized by valuable and exclusive biodiversity. These regions are among the global 200 Ramsar sites and are the most crucial conservation priority ecoregions worldwide (Olson and Dinerstein, 1998). Owing to the Asian monsoon circulation with abundant rainfall and the complex lake-river water network, the hydrological condition of Dongting Lake varies dramatically, with the water level fluctuating from approximately 18.78 to 35.92 m, and the surface water area of the lake annually increasing from 500 km^2 in the dry season to 2691 km^2 during the flood season (Geng et al., 2021b). Dongting Lake is the lake nearest to the Three Gorges Dam (TGD) on the Yangtze River. A difference of approximately 120–140 m in elevation has been observed between the TGD and Dongting Lake (Xie et al., 2015; Zou et al., 2019). Overall, the original processes of water input and output modes, sediments, and nutrients in Dongting Lake changed following the construction of the TGD, influencing the lake's long-term spatiotemporal water quality variations.

2.2. Data descriptions

Nine sampling sites were selected in Dongting Lake based on regional representation and geographical features. Monthly water quality data at the sampling sites between 1991 and 2021 were obtained from the China National Environmental Monitoring Centre (http://www.cnemc.cn/) and the National Field Scientific Observation and Research Station of the Dongting Lake Wetland Ecosystem in Hunan Province. As physicochemical properties and nutrient constituents are the most important characteristics of lake water quality, four representative water quality parameters were selected according to the Environmental Quality Standards for Surface Water of China (GB-3838-1, Chinese Environmental Protection Agency, 2002) (Geng et al., 2021a). These were: total nitrogen (TN), total phosphate (TP), ammonia nitrogen (NH_3-N), and the permanganate index (COD_{Mn}). The hydrological data of the national hydrological monitoring stations for four tributaries (FT) including the Xiang, Zi, Yuan, and Li rivers and three channels (TC) including the Songzi, Hudu, and Ouchi rivers were obtained from the

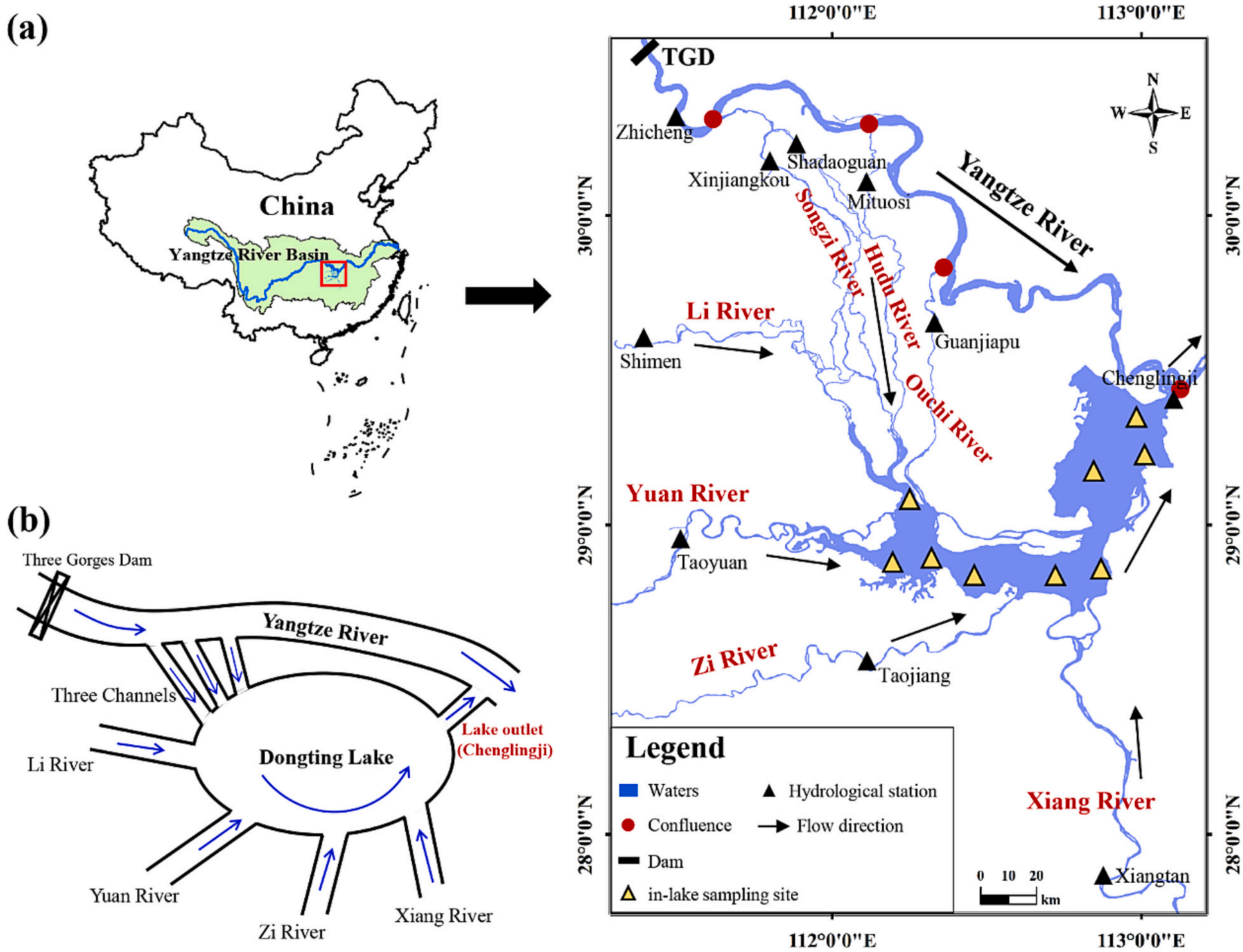

Fig. 1. (a) Location of Dongting Lake in China; (b) schematic diagram depicting the relationship between Dongting Lake and the river system. The blue arrows indicate flow direction.

Hydrology and Water Resources Survey Bureau of Hunan Province (http://slt.hunan.gov.cn/hnsw/) and Changjiang Water Resources Commission of the Ministry of Water Resources (http://www.cjw.gov.cn/). This data encompassed the daily water discharge (WD), daily water level (WL), and yearly suspended sediment discharge (SSD). In China, complete monthly riverine SSD data are not easily accessible, especially early historical SSD data; however, the WD and SSD in rivers exhibit a strong relationship with each other (Li et al., 2020). Thus, the distribution coefficient method, in combination with the yearly SSD of the rivers, was used to calculate the monthly SSD data across various rivers. We used the existing monthly WD and SSD data (2019–2021) to construct the prediction models and compared the verification time-series dataset (2016–2018) with the prediction results. Mean absolute percentage error (MAPE) was used to evaluate the performance of the prediction models. The MAPE was 7.31 % for SSD, indicating that the prediction model was suitable for forecasting the monthly SSD of the different rivers from 1991 to 2015. The suspended sediment concentration (SSC) was calculated as the SSD to water discharge ratio.

To illustrate and describe the variations in water-sediment factors, the hydrological data were preprocessed according to the river network features. The sum of the WD and SSD at the Xinjiangkou, Shadaoguan (Songzi River), Mituosi (Hudu River), and Guanjiapu (Ouchi River) stations represented the contribution of the TC. Similarly, the sum of WD and SSD through the Xiangtan (Xiang River), Taojiang (Zi River), Taoyuan (Yuan River), and Shimen (Li River) stations represented the contribution of the FT. Next, the total water and sediment input to Dongting Lake was calculated as the sum of TC and FT. Multiple rigorous quality control measures were conducted to confirm data quality.

2.3. *Division of research periods*

Dongting Lake has undergone drastic interannual variations in its hydrological environment, especially after the construction of the TGD in 2003, which has exacerbated the spatiotemporal heterogeneity of water-sediment factors and water quality. To quantify these influences, we divided the long-term series dataset into a dataset before the operation of the TGD (pre-TGD, 1991–2003) and another dataset after the operation of the TGD (post-TGD, 2004–2021), which indicated the influence of natural conditions and anthropogenic activities on Dongting Lake. Notably, Dongting Lake experiences annual periodic floodplain inundation, with water-rich conditions in the lake phase and water-poor conditions in the river phase. Thus, we divided the dataset into lake (April–September) and river (October–March) phases, according to Shi et al. (2012), to better understand the intra-annual dynamic variations in the water environment.

2.4. *Statistical analyses*

The Shapiro–Wilk test was used to analyze whether the data were normally distributed. Data that failed the normality test were logarithmically transformed, if necessary, to satisfy normality assumptions. Regression analysis was used to investigate the variation trends in water quality and water-sediment factors across Dongting Lake during the entire study period. An analysis based on the random forest model was performed to detect the associations between water quality indicators and water-sediment factors during different periods. The aforementioned statistical analyses were performed using the SPSS 23.0 software for Windows (SPSS Inc., Chicago, IL, United States) and the “party” package in R v4.2.0.

2.5. *Vector autoregression model*

The vector autoregression (VAR) model is an effective method based on the statistical properties of data that regards each exogenous variable as a function of the lagged value of the endogenous variable. Thus, the model is a multi-equation model (Man et al., 2019). The key advantage of the VAR model lies in its ability to construct a regression model by considering each endogenous variable as a function of the lag terms of all variables to investigate the dynamic interaction between multiple variables. Moreover, the VAR model is not analyzed through regression coefficient estimation but through Granger causality testing, impulse response function analysis, and variance decomposition. The mathematical form of the VAR model with *p*-order is shown in Eq. (1) as follows:

$$Y_t = \Phi_1 Y_{t-1} + \Phi_2 Y_{t-2} + \ldots + \Phi_p Y_{t-p} + \varepsilon_t \tag{1}$$

where *Y* represents the n-dimensional vector of the endogenous variables, Φ_i is the corresponding coefficient matrix, *P* is the lag order of the endogenous variables, ε_t is an unobservable independent identically distributed zero-mean error. In this study, we analyzed the dynamics of four water quality indicators (TN, TP, NH_3-N, and COD_{Mn}) in response to changes in four water-sediment factors (WD, SSD, SCC, and WL) in Dongting Lake.

2.5.1. *Augmented Dickey-Fuller test*

After establishing the VAR model, its stability of the VAR model should be tested to ensure that it does not result in spurious regression. The augmented Dickey-Fuller (ADF) test was used to determine sequence stability. If the criteria were not met, differencing was performed until the ADF test results were satisfactory.

2.5.2. *Granger causality test*

Granger causality was used to test whether all lagging values of one variable affected the current values of the other. If the effect was significant, Granger causality existed between this variable and the other variables; otherwise, there was no Granger causality. The regression model is expressed in Eqs. (2)–(3) as follows:

$$x_t = \alpha_0 + \sum_{i=1}^{p} \omega_i x_{t-i} + \sum_{j=1}^{q} \varphi_j y_{t-j} + e_t \tag{2}$$

$$y_t = \beta_0 + \sum_{i=1}^{s} \delta_i x_{t-i} + \sum_{j=1}^{t} \eta_j y_{t-j} + v_t \tag{3}$$

where *x* and *y* represent cause and effect, respectively. If only null hypothesis H_1 is rejected, variable *x* leads to variable *y*. However, if both null hypotheses H_0 and H_1 are rejected, a causal relationship between *x* and *y* exists. A probability value of 0.05 is generally considered acceptable at the wrong boundary level. Thus, if the probability value is lower than 0.05, the original hypothesis must be rejected; otherwise, it is acceptable.

In this study, the Granger causality test was used to test the causality between water quality and water-sediment factors. When all lagged values of one water-sediment factor have a significant impact on the current value of water quality, the water-sediment factor has Granger causality for water quality.

2.5.3. *Impulse response function analysis*

The impulse response function can be used to describe the overall complex dynamic response of disturbances generated by one endogenous variable to other variables in the VAR model, specifically, how the variables in the model respond to the shocks of other variables over time. This study focused on the entire dynamic process of water-sediment factors affecting water quality. The tracking period of the response function was set to 36, according to the long-term impact of water -sediment factors on water quality in the lake and the effect of different single variables on the established VAR mode. The detailed formula is shown in Eqs. (4)–(7) as follows:

$$Y_t - \sum_{i=1}^{p} A_i Y_{t-i} = \alpha + \varepsilon_t \tag{4}$$

$$Y_t = \left(I - A_1L - A_2L^2 - \ldots - A_pL^p\right)^{-1}\alpha + \left(I - A_1L - A_2L^2 - \ldots - A_pL^p\right)^{-1}\varepsilon_t \tag{5}$$

where L and I are the lag operation and the unit matrix, respectively.

$$Y_t = \dot{\alpha} + \sum_{i=0}^{\infty} C_i\varepsilon_{t-i} \tag{6}$$

$$Y_t = \dot{\alpha} + \sum_{i=0}^{\infty} D_iW_{t-i} \tag{7}$$

where $D_i = C_iH$, $W_{t\text{-}i} = H'\varepsilon_{t\text{-}i}$. Eq. (6) is the only sequence unaffected by the current random shock items that are unrelated and orthogonal to sequence. When a shock occurs in a variable, the impact of the other variables is revealed based on the value of D_i.

2.5.4. *Variance decomposition*

Variance decomposition determines the extent to which variability in the dependent variable is lagged by its variance. Furthermore, the variance decomposition determines which independent variable has a greater impact on accounting for changes in the dependent variable over time. In this study, the variance decomposition of the error was used to further evaluate the importance of different water-sediment factors on water quality by analyzing the contribution of endogenous variables. Fig. 2 presents a flowchart of the primary research process.

3. Results

3.1. *Variations in water quality*

3.1.1. *Inter-annual variations*

The TN concentration increased significantly from 1.15 mg/L in 1991 to 1.76 mg/L in 2021, with a total range of 1.12–2.05 mg/L during the entire study period (Fig. 3). The TP concentration showed a fluctuating variation during the entire study period, which increased from 0.04 mg/L in 1991 to 0.17 mg/L in 1999 and then decreased to 0.07 mg/L in 2021. Generally fluctuating and decreasing trends for NH_3-N was observed from 1991 to 2021, with fluctuations ranging from 0.09 mg/L to 0.47 mg/L for NH_3-N. No significant changes were detected in the COD_{Mn}, with the variations ranging from 1.74 mg/L to 3.09 mg/L.

3.1.2. *Intra-annual variations*

Both the TN and TP showed significant differences between the lake and river phases, with average values of 1.61 mg/L and 1.72 mg/L for TN and 0.08 mg/L and 0.10 mg/L for TP, respectively (Fig. S1). No significant differences were observed in NH_3-N and COD_{Mn} between the two periods, with the average value of 0.22 mg/L and 0.31 mg/L for NH_3-N and 2.28 mg/L and 2.25 mg/L for COD_{Mn} during the lake and river phases, respectively.

3.2. *Variations in water-sediment factors*

3.2.1. *Inter-annual variations*

The inflow of WD displayed a fluctuating trend from 1991 to 2021, which ranged from 1.30×10^{11} to 3.25×10^{11} m^3/a, with an average of 2.29×10^{11} m^3/a (Fig. 4a). The inflow of WD for TC and FT exhibited a similar trend, which ranged from 0.18×10^{11} to 1.05×10^{11} m^3/a and 1.03×10^{11} to 2.20×10^{11} m^3/a, respectively. The inflow of SSD decreased significantly ($p < 0.01$) during the study period, from 1.25×10^8 t/a in 1991 to 0.08×10^8 t/a in 2021 (Fig. 4b). Both the SSD of the TC and FT showed similar temporal variations, with significant decreases from 1.03×10^8 t/a and 0.22×10^8 t/a in 1991 to 0.05×10^8 t/a and 0.04×10^8 t/a in 2021, respectively.

The WL fluctuated during the study period, with values ranging from 23.63 m to 26.86 m (Fig. 4c). The SSC displayed a similar decreasing trend as that in SSD, decreasing significantly from 0.53 g/L in 1991 to 0.04 g/L in 2021.

3.2.2. *Intra-annual variations*

Significant changes were detected in the WD during the lake and river phases, which were 0.73×10^{11} and 0.08×10^{11} m^3/a, 1.96×10^{11} and 0.86×10^{11} m^3/a, and 2.69×10^{11} and 0.94×10^{11} m^3/a in TC, FT, and the total inflow, respectively (Fig. S2). Significant differences were found in SSD between the lake and river phases, with the average values of 0.30×10^8 t/a and 0.01×10^8 t/a (TC), 0.11×10^8 t/a and 0.01×10^8 t/a (FT), and 0.42×10^8 t/a and 0.03×10^8 t/a (the total input of SSD), respectively. The WL of the lake phase was significantly higher than that of the river phase, with average values of 27.74 m and 22.56 m, respectively. SSC showed significant differences during the lake and river phases, which were 0.13 g/L and 0.63 g/L, respectively.

3.3. *Impulse response of water quality to variations in water-sediment factors*

3.3.1. *Variable unit root test*

The results of the ADF unit root test showed that the ADF statistic value was less than the critical values of 1 % and 5 % after adjusting for the availability of the intercept and trend combined with the first-order difference, which indicated that the variables were stationary time-series data (Table S1). Therefore, the data were adopted for further calculations to guarantee the effectiveness of the analysis based on the VAR model.

Four 8-variate VAR models were established after the ADF unit root test (Fig. 5). The Akaike information criterion (AIC) and final prediction

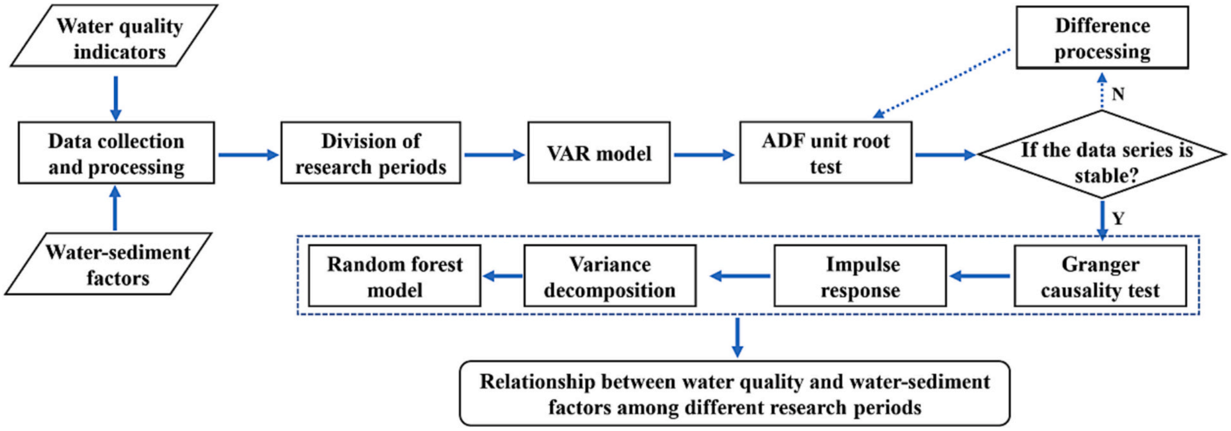

Fig. 2. Flowchart of the research process.

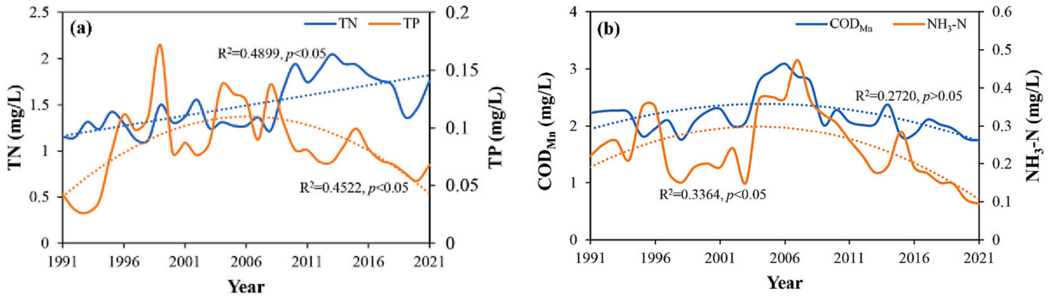

Fig. 3. Inter-annual variations in (a) TN, TP, (b) COD_{Mn}, and NH_3-N from 1991 to 2021.

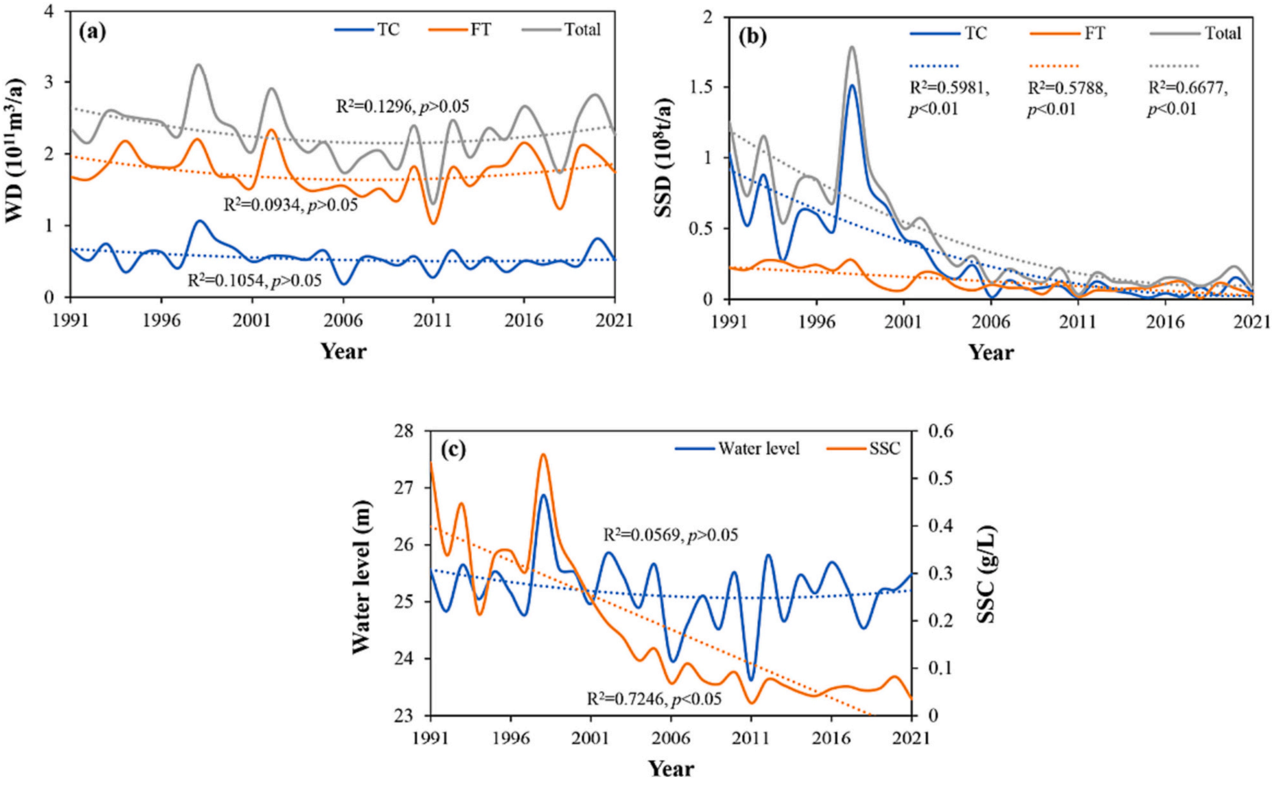

Fig. 4. Inter-annual variations in (a) water discharge (WD), (b) suspended sediment discharge (SSD), (c) water level (WL), and suspended sediment concentration (SSC) in Dongting Lake from 1991 to 2021.

error (FPE) were used to determine the number of lag orders in the models. The corresponding lag order was two for the four VAR models according to the minimum number of lags among the appropriate ranges. Furthermore, all characteristic roots are present within the unit circle, indicating that the four VAR models were stationary and suitable for the Granger causality test.

3.3.2. *Granger causality test*

The Granger causality between the water quality indicators and water-sediment factors in the VAR models was tested at the 5 % confidence level during different periods (Table S2). In the pre-TGD period, the null hypotheses that WD does not Granger cause TN ($p = 0.0473$) and SSD does not Granger cause TP ($p = 0.0368$) were rejected, indicating that WD and SSD are Granger causes for TN and TP, respectively. In lake phase, WL was the Granger cause for TP ($p = 0.0356$); moreover, WL ($p = 0.0037$), WD ($p = 0.0025$), and SSD ($p = 0.0046$) were Granger causes for TN, as well as for NH_3-N (with $p = 0.0000$, 0.0001, and $p = 0.0456$ for WL, WD, and SSD). In the river phase, the null hypothesis that WD does not Granger cause TN ($p = 0.0113$) was rejected, and the null hypothesis that WL ($p = 0.0181$) and WD ($p = 0.0039$) do not Granger cause NH_3-N was rejected, implying that WD is the Granger cause of TN and that WL and WD are the Granger causes of NH_3-N.

3.3.3. *Impulse response*

During the pre-TGD period, the impulse response that the TN brought to itself was positive during the first 12 periods, decreasing from 0.23 to 0.01 and gradually converging to a stable state (Fig. 6). Similarly, TP, NH_3-N, and COD_{Mn} showed a similar impulse response to the shock from themselves, which were instant responses with high values of 0.02, 0.12, and 0.40 for TP, NH_3-N, and COD_{Mn}, respectively. The impulse response of water quality to water-sediment factors exhibited lagged variations and dramatic fluctuations, which then gradually converged to 0. For instance, the impulse response of TN to WL decreased to −0.06 in the first three periods, and then increased to 0.03 in the eighth period, with a fluctuation range of 0.09. The impulse response of TP to SSD was always positive and gradually decayed after 23 periods. The impulse response of water quality to water-sediment factors differed among the different periods. For example, the impulse response of NH_3-N to WD was long lasting in the pre-TGD periods, with a tracing period of 21, whereas this effect rapidly decreased in the 18 post-

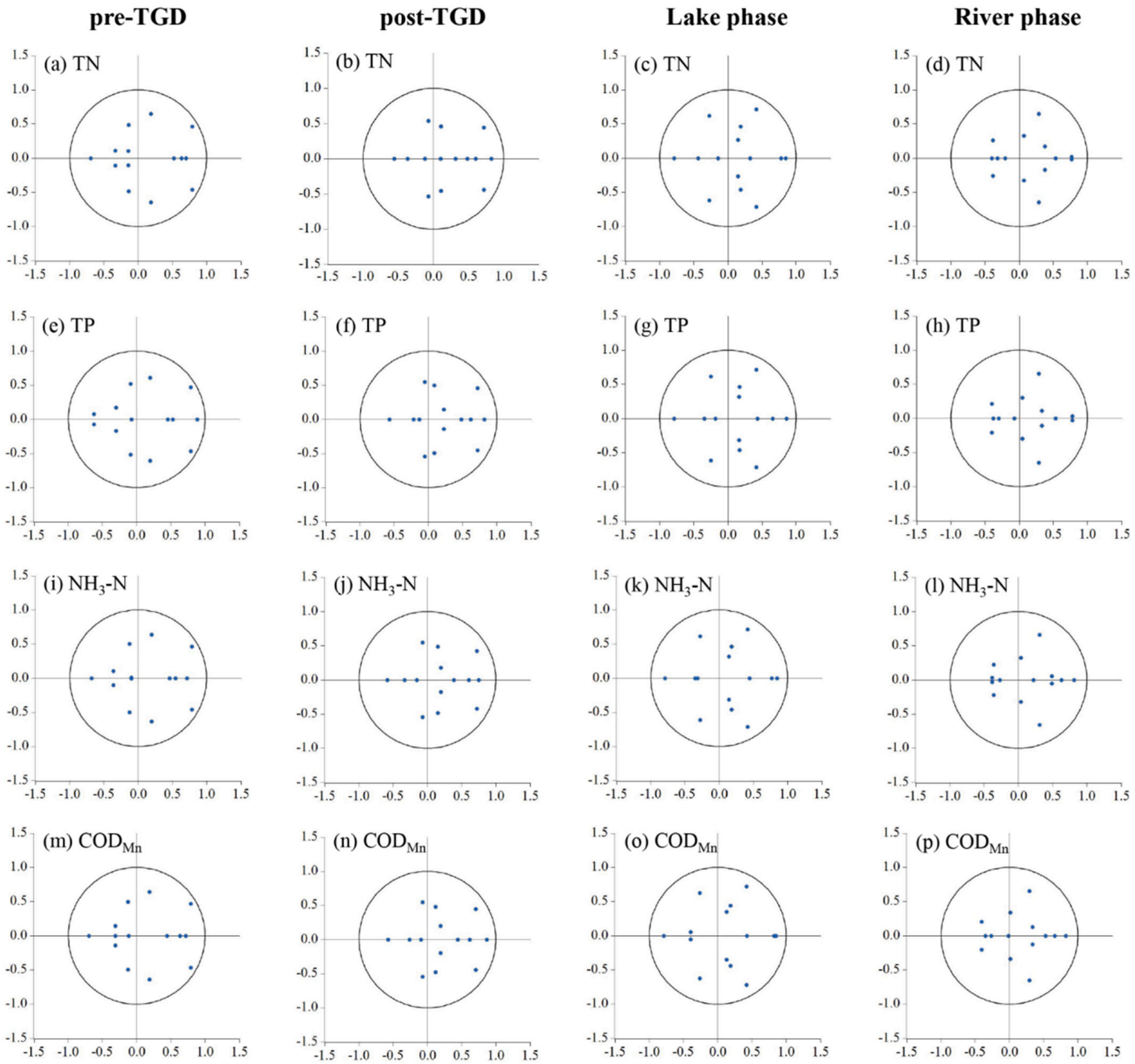

Fig. 5. VAR model stationary test.

TGD periods (Fig. S3). The impulse response of water quality to water-sediment factors exhibited lagged variations and dramatic fluctuations, which then gradually converged to 0.

3.4. Impact patterns of the water-sediment factors in regard to water quality

The significance of the water-sediment factors varied depending on the water quality indicators and research periods. The most crucial variable for TN was WD_FT, followed by SSC and SSD_FT. The importance of WD_FT in the post-TGD period was higher than in the pre-TGD period, with values of 0.440 and 0.265, respectively (Fig. 7). WD_FT had the highest influence on TP, with the highest value during the lake phase (0.363). Sediments also played an important role on the TP, with values ranging from 0.162 to 0.240 for SSC and 0.085 to 0.238 for SSD_FT. WD_FT and SSC were consistently the most important variables across all of the research periods studied for NH$_3$-N, especially the SSC of the lake phase, which exerted a relatively large influence on NH$_3$-N. The importance ranking of the water-sediment factors for COD$_{Mn}$ was similar to that of the other water quality indicators. Notably, WD_FT was the highest variable for COD$_{Mn}$ in the river phase, with a value of 0.441.

During the post-TGD period, the TN changes were primarily influenced by their own impacts, reaching 100 % in the first period, followed by a declining trend over time, and stabilizing at approximately 92 % after the seventh period (Fig. 8). Similarly, other water quality indicators also displayed a high impact by themselves among different periods, with contributions varying from 67 % to 95 %. WL and SSD were the predominant water-sediment factors for TP in the pre-TGD period, with the impact on TP changes accounting for 11 % and 9 %, respectively, whereas the contribution of SSD decreased to 2 % in the post-TGD period. The contribution of WL to the COD$_{Mn}$ change in in Dongting Lake during the pre- and post-TGD periods was 19 % and 21 %, respectively. The effects of WL and WD on COD$_{Mn}$ change in the lake phase increased slightly over time and then remained at approximately

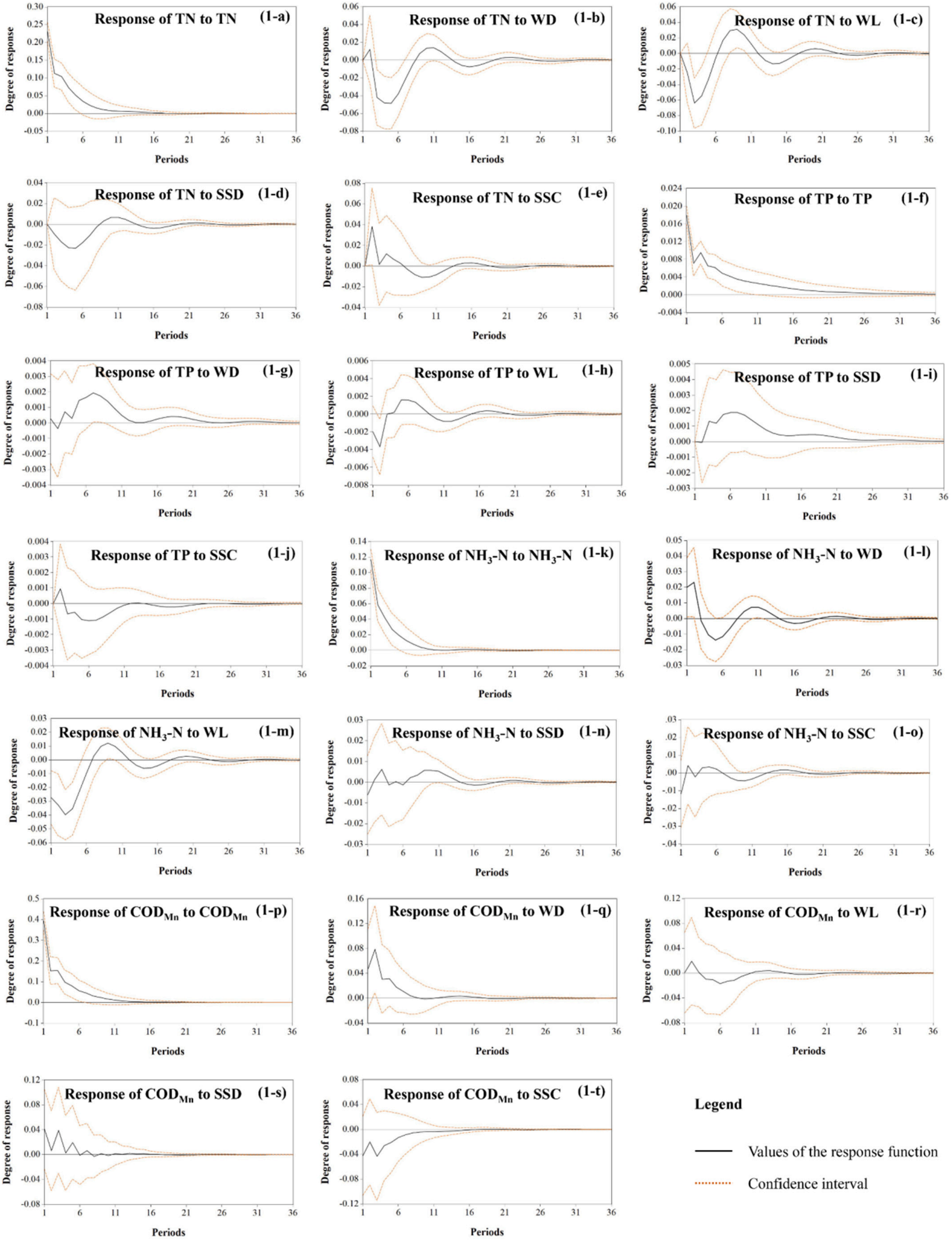

Fig. 6. Water quality impulse response caused by the water-sediment factors in the pre-TGD period.

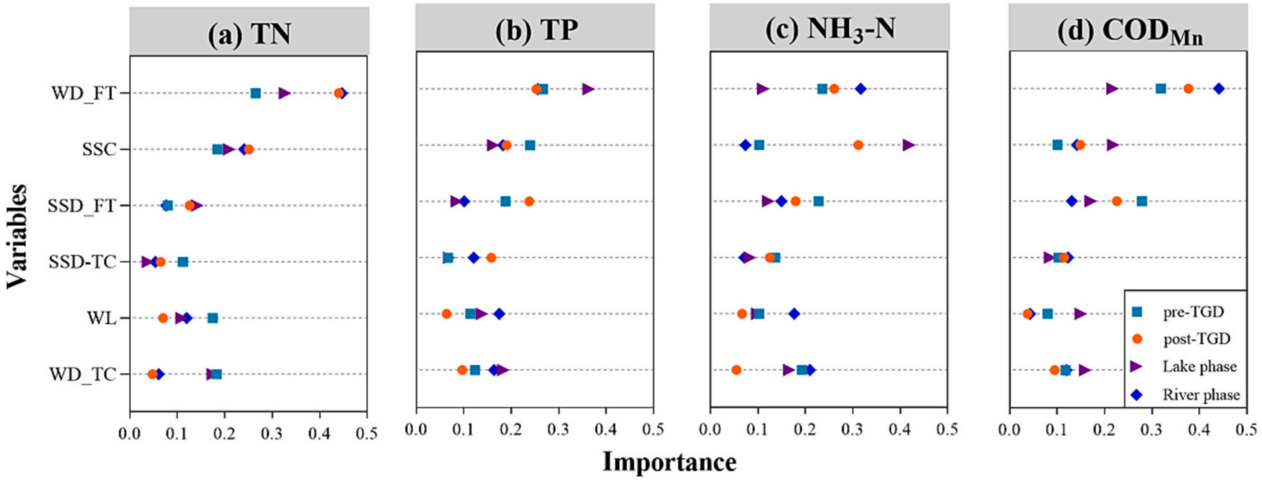

Fig. 7. Importance ranking of water-sediment factors involved within the (a) TN, (b) TP, (c) NH_3-N, and (d) COD_{Mn}. WD: water discharge; SSD: suspended sediment discharge; SSC: suspended sediment concentration; WL: water level. FT: four tributaries; and TC: three channels.

17 % and 10 %, respectively.

4. Discussion

4.1. *Variation trends in water quality and its association with water-sediment factors*

Our study identified significant changes in the water quality of Dongting Lake between 1991 and 2021, with a significant increasing trend in TN and an initial increase followed by a decrease in TP. This finding was mainly attributed to increased pollutant loading, which was confirmed by the contribution analysis (Fig. 8), indicating that external pollutant loading is the predominant factor regulating lake water quality. The Dongting Lake area is a major grain-producing region in China, with a total annual average grain yield of 1.48×10^3 million tons, which plays an important role in ensuring ecological regulation, economic development, and national food security (Yin et al., 2015). Between 1990 and the 2000s, with the widespread application of pesticides and fertilizers and the substantial increase in sewage discharge, many pollutants entered Dongting Lake via overland runoff, thereby accelerating the deterioration of lake water quality. Other lakes worldwide have also exhibited a deteriorating trend in water quality during this period (Ho et al., 2019; Peng et al., 2021b). Pollutant concentrations (e.g., TP, COD_{Mn}) displayed a decreasing trend after 2010 due to substantial investments by the government related to lake ecological restoration; for example, the Central Government of China introduced the Guidelines on Strengthening Water Environmental Protection for Critical Lakes in 2008 and the Water Pollution Control Action Plan in 2015, which effectively improved the water quality of Dongting Lake (Huang et al., 2019). Moreover, the local government has limited the use of detergent-containing phosphate, and nearly 100 paper mills along the banks of the Dongting Lake have been abandoned. These changes contributed to decreases in TP and COD_{Mn} (Geng et al., 2021c).

Despite the substantial reduction in external nutrient loading in Dongting Lake, the deterioration of water quality is still not sufficiently controlled. It is difficult to achieve Level III water quality (the basic level of drinking water), particularly for TP and TN, owing to the internal contamination loading related to water-sediment factors (Table S3). The adsorption and desorption of pollutants between the sediment and lake surface water are coupled processes that result in variations in the pollutant content in the water. For instance, sediments are major contributors of P in the Dongting Lake, with an average release amount of 40.33 mg/(kg·a) according to Zhu and Yang (2018). This value combined with a sediment deposition of 7.54×10^8 t/a from 1991 to 2021 indicates a high potential risk of P release to the overlying water. A similar result was reported for Dianchi Lake, where the internal P and N loading contribution to lake water quality was 72 % (Wu et al., 2017). Generally, the processes of pollutant exchange at the sediment-water interface are complex. First, the adsorption and desorption reactions of a pollutant may occur between the sediment and interstitial water, which are affected by dissolution, mineralization, and microbe release. Second, pollutants in the interstitial water may interact with the overlying water via diffusion or convection, thereby affecting lake water quality. Dongting Lake is a river-connected lake with significant variations in hydrological conditions. Large amounts of pollutants are released from sediments into lake water through scouring and resuspension, resulting in the deterioration of the water quality. Similar findings were also found in the Yangtze River, where the resuspension of sediments through scouring and agitation of water discharge increased the concentration of TP in the water (Duan et al., 2008). Moreover, the physicochemical properties of the sediments may have influenced the pollutant content of Dongting Lake. The main components of the sediments in Dongting Lake are muddy sandstone and tuffaceous, and the sediments contain different types and sizes of adsorption sites or surface lattices, which can easily adsorb or fix pollutants (e.g., particle P and ammonia nitrogen) and release them into the lake water under suitable conditions. Furthermore, hydrodynamic conditions should not be neglected as they may affect the transportation and distribution of water nutrients in a river-connected lake. The water flow direction is from west to east, resulting in higher pollution levels in the EDTL region. Previous studies found that algal bloom events often occurred in the northwestern area of the EDTL, with much higher pollutant concentrations (Chen et al., 2016; Tian et al., 2017). This phenomenon transpires because the flow velocity quickly decreases in the northwestern EDTL area, similar to the conditions in a backwater bay (Fig. S4), which led to the accumulation of a considerable number of pollutants, thereby changing the distribution pattern of water quality in Dongting Lake.

4.2. *Response characteristics of water quality on water-sediment factors during different periods*

The water regime of Dongting Lake has been significantly altered by the operation of the TGD, including a decrease in the water level and an extension of the dry period. In addition, a significant downtrend was observed in the SSD of the Three Channels from the Yangtze River before and after the commencement of operation of the TGD, which decreased from 1.03×10^8 t/a to 0.05×10^8 t/a, thereby changing the original processes of water and sediment exchange and breaking the dynamic

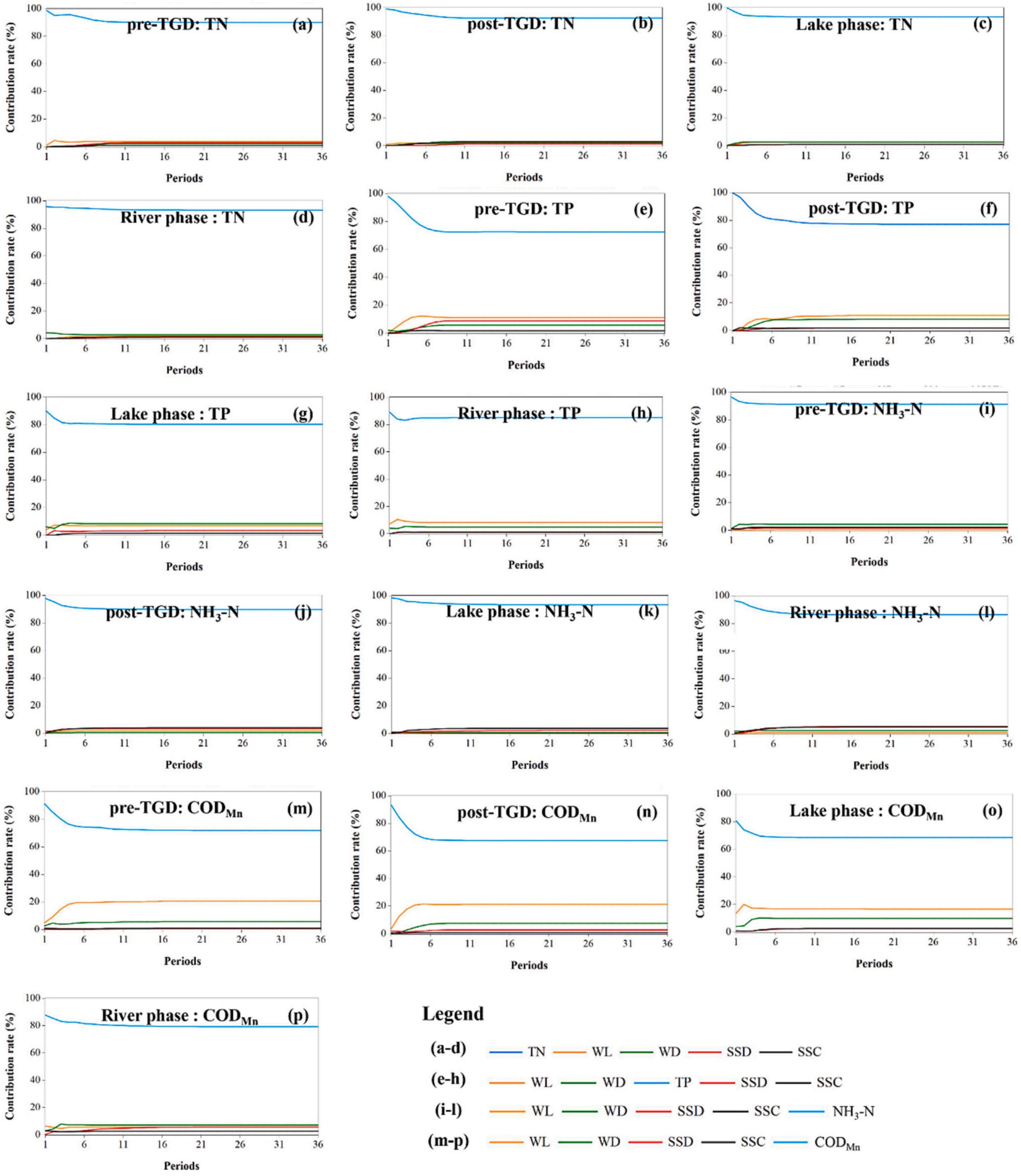

Fig. 8. Contributions of water-sediment factors to (a–d) TN, (e–h) TP, (i–l) NH_3-N, and (m–p) COD_{Mn} during different periods.

equilibrium of the relationship between the river and lake. Specifically, the decrease in the SSD during the post-TGD period may have contributed significantly to the variation in water quality. On the one hand, over 42 % of the TP, along with a large amount of sediment, was trapped within the dam, and the severe riverbed incision of the Yangtze River could potentially cause a significant separation between the TC and Dongting Lake due to an increase in elevation (Bao et al., 2018; Dai et al., 2018). In contrast, the sedimentary regime of Dongting Lake changed from deposition during the pre-TGD period to erosion during the post-TGD period (Fig. S5), and the continuous scouring and migration of sediment by water discharge resulted in the movement of the bulk of the TP from the lake. These factors may have contributed to the decrease in TP in Dongting Lake. Moreover, a significant decrease in water discharge was detected across Dongting Lake after the commissioning of the TGD, which weakened the dilution effect of water on TN and contributed to an increase in the TN concentration in Dongting Lake (Zhao et al., 2016). The variations in water quality and water-sediment factors conformed to the results of the Granger causality test and Hurst exponent, which showed that the influence of water-sediment factors on lake water quality was reduced to varying degrees, and this reduction continued following the construction of the TGD (Fig. S6). Notably, finer sediment particles have a stronger phosphate adsorption capacity and resuspension ability (Wang and Liang, 2016; Zhu and Yang, 2018). Coarse sediment particles were mainly retained in the dam at the start of the TGD operation, resulting in the discharge of a large amount of small sedimentary particles into Dongting Lake, which contributed to the deterioration of water quality (Lu et al., 2018). However, the median grain size of sediment (D_{50}) via the TC increased to 0.019 mm after commissioning the TGD, and D_{50} via the FT decreased to 0.011 mm (Fig. S5), suggesting that sediments from the FT in the catchment gradually played a more important role than those of the TC in the water quality of Dongting Lake.

Dongting Lake's water regime is affected by the East Asian summer monsoon, which results in significant annual fluctuations in water-sediment factors (Geng et al., 2021c). In this study, WD, SSD, and WL in the lake phase were significantly higher than those in the river phase, resulting in different water qualities in the two phases. Many studies have concluded that pollutant migration is closely related to water movement and has a significant impact on the dispersal and degradation of pollutants (Ouyang et al., 2006; Gerling et al., 2014). During the lake phase, a considerable number of water from the TC and FT was discharged into Dongting Lake, which resulted in the dilution of TN in the lake. In addition, a backwater effect occurred in Dongting Lake during the lake phase, with a high WL and low flow velocity (Huang et al., 2014), which contributed to the deposition of sediments and pollutants, thereby reducing the deterioration of water quality in the lake phase. Conversely, poor water quality was detected in the river phase with high TN and TP concentrations. This occurrence is because the river phase was at dry season with less water discharge, the water converges in main lake channels and "concentrates" the lake pollutants, leading to the increase in pollutant concentration in the Dongting Lake during the river phase. Moreover, pollutants deposited along with sediments in the lake phase may be released by the high flow velocity (high water-sediment disturbance) in the river phase, resulting in secondary pollution of water quality during the river phase. Notably, high SSC concentrations in the river phase decrease the transparency of the water and affect the growth of aquatic organisms associated with biological processes. This process can subsequently lead to the accumulation of large amounts of pollutants in lakes during the river phase. Similar results were reported for Poyang Lake, China (Li et al., 2019).

4.3. Precautionary measures to regulate the water quality of Dongting Lake considering water-sediment factors

Drastic human activities, droughts, and flooding events have recently occurred, disrupting the ecological balance of the nutrient cycle in Dongting Lake (Liu et al., 2012). Therefore, scientific measures are urgently needed to improve the water quality of Dongting Lake. Major preliminary work led by the local government was conducted to improve the water quality of Dongting Lake. For instance, a large amount of farmland concentrated around Dongting Lake has been returned to wetlands to maintain its natural state (Yin et al., 2017). Ecological restoration projects have been implemented to restore aquatic vegetation and improve lake water quality (Zhang et al., 2020). However, remediation of lake water quality and the ecological environment by controlling the entry of exogenous pollutants is challenging. Additionally, various approaches associated with water-sediment factors should be integrated such that water quality can be effectively improved, especially for river-connected lakes such as Dongting Lake (Huang et al., 2021). This study provides evidence that the water quality of Dongting Lake varies synchronously with changes in water-sediment conditions, and a certain time-lagged effect of water-sediment factors on water quality was detected, which then gradually diminishes before disappearing. This unique relationship between water quality and water-sediment factors in Dongting Lake inspired us to take targeted measures against the deterioration of water quality. During the lake phase, large quantities of sediments containing pollutants were transported and deposited in Dongting Lake via water discharge. Sediment dredging technology can be applied to maximize the removal of internal pollution in Dongting Lake during the river phase, which has been confirmed globally as an efficient method to increase the storage capacity of lakes, reduce the sediment nutrient load, and produce significant improvements in water quality after dredging (Chen et al., 2020). However, this technology remains controversial because dredging may have negative effects on the lake's benthic ecosystem. Therefore, a pilot project conducted in Dongting Lake was necessary to evaluate the effects of dredging (Meng et al., 2020).

Hydrological connectivity exerts a significant influence on the water environment in river-connected lakes, driving the exchange of water, sediment, pollutants, and organisms between the floodplain and main channel (Li et al., 2021). This study found that the water-sediment factors of Dongting Lake changed significantly after the construction of the TGD, including a sharp reduction in SSD and a decrease in WL. Chen et al. (2016) also concluded that the hydraulic residence time increased from 18 to 29 d before and after the construction of the TGD. These variations in hydrological conditions may have altered the hydrological connectivity, resulting in spatiotemporal differences in the water quality of Dongting Lake. Building dikes, water diversions, and regular dredging are effective methods for regulating the hydrological connectivity of Dongting Lake (Zhu et al., 2022a). In summary, the use of a single restoration measure is ineffective. To improve the water quality of Dongting Lake effectively, it is necessary to integrate various complementary approaches. However, decision-makers require a robust scientific assessment of these measures according to the water-sediment factors varied by periodic hydrological rhythm to provide effective support for water environmental restoration.

5. Conclusion

In summary, our results have shown that TN significantly increased and TP exhibited a decreasing trend after the commissioning of the TGD, which was associated with a sharp decrease in suspended sediment and water discharge. In the pre-TGD period, WD and SSD were Granger causes of TN and TP, whereas the relationship disappeared in the post-TGD period due to the construction of TGD reducing the inflow of SSD and WD into the lake. Water quality indicators showed an instant response to the shock from themselves, whereas the impulse response of water quality to water-sediment factors exhibited lagged variations and then they gradually converged to 0. The relationship between water quality and water-sediment factors gradually decreased during the post-TGD period and river phase, primarily because of the sediment regime change from deposition to erosion, sediment particle variation from fine to coarse, and the time-lagged effect of water-sediment factors on water quality. In conclusion, the impact pattern of water-sediment factors on water quality varied in the hydrological phase. To maintain the nutritional balance of Dongting Lake, in addition to implementing strict controls on excessive external nutrient loading, it is necessary to regulate the water-sediment factors according to the hydrological features of Dongting Lake during different periods. This study provides new insights into water quality management and ecological restoration of river-connected lakes. The mechanistic studies concerning the physicochemical processes of pollutants at the water-sediment interface under different hydrological conditions are required in the future.

CRediT authorship contribution statement

Mingming Geng: Conceptualization, Methodology, Writing – original draft. **Zhan Qian:** Data curation. **Heng Jiang:** Data curation. **Bing Huang:** Data curation, Methodology. **Shuchun Huang:** Data curation, Methodology. **Bo Deng:** Methodology. **Yi Peng:** Data curation,

Methodology. **Yonghong Xie:** Investigation, Supervision. **Feng Li:** Methodology, Writing – review & editing. **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.scitotenv.2023.168866.

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