

Effects of river-lake interactions in water and sediment on phosphorus in Dongting Lake, China

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Abstract As a large river connected lake, Dongting Lake is influenced by anthropogenic activities and the discharge from its upstream tributaries in the lake basin and by the water recharge via a connection to the Yangtze River (YR) outside the basin. This makes the lake phosphorous cycle more complex than that in other disconnected lakes. Here, we calculated section fluxes and ran a hydrodynamic model to investigate the phosphorus (P) variations in response to the changing interactions in the water and sediment between the YR, four tributaries, and the lake. Results show that particulate P was the dominant form with a significant linear relationship with suspended sediment ($r^2 = 0.906$). The sediment input reduction from the YR through three water inlets, which is closely related to the Three Gorges Reservoir operation since 2003, led to a decrease in the total P (TP) concentration in the western Dongting Lake. However, the impact and range of this decrease were fairly limited. Compared with the limited effect of the YR, the raised TP flux from the Yuanjiang tributary

controlled the TP concentration at the outlet of the western Dongting Lake. Apart from the influence of the YR and the tributaries, anthropogenic activities (sand dredging) in the eastern Dongting Lake also contributed to a high TP concentration around the S10 area through sediment resuspension. We suggest that, compared with the reduction in TP flux and sediment load from the connected Yangtze River outside the basin, the elements within the basin (increased TP input from tributaries and sand dredging) have a greater effect on the variations of TP in Dongting Lake.

Keywords Dongting Lake · Phosphorus · Composition · Suspended sediment · Three Gorges Reservoir · Yangtze River

Introduction

The continuous increase in nutrient loads has led to the deterioration of water quality over the past decades, which has accelerated the process of eutrophication (Withers and Jarvie 2008) and threatened the health of aquatic ecosystems (Conley et al. 2009). According to monitoring data, the incidence of water eutrophication in China has reached 57.5% (Jin et al. 2005), and the eutrophic area has increased from 135 to 8700 km² (Ni and Wang 2015), which has overtaken Europe, Africa, and the USA, and made China the world's most eutrophicated region (Nyenje et al. 2010). Phosphorus (P) is the limited nutrient in the lake systems of China, with a mean total nitrogen/total phosphorus value of 19 (Ni and Wang 2015). Therefore, managing the P concentration can be an effective means of reducing the primary production that drives eutrophication (Elser et al. 2007). P is mainly affected by weathering under natural conditions (Chen et al. 2008). Almost 90% of river-borne P transported into lakes and estuaries exists as the particulate P species that is easily absorbed

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on the surface of sediment (Withers and Jarvie 2008; Meybeck 1982; Jensen et al. 2006) and migrates and transforms between the water and sediment phases under changing hydrodynamic and environmental conditions (Kronvang et al. 1997). The effect of river sediment as an important source of P has been highlighted in the delivery and cycling of P (Pan et al. 2002, 2013; Jarvie et al. 2005; Wang et al. 2009).

However, anthropogenic activities, such as the operation of dams and large-scale sand dredging, can alter the hydrodynamic conditions and the hydrological sediment processes of rivers via sediment resuspension/deposition (Xia et al. 2016). This could further affect the concentrations, composition, fluxes, and cycles of P and accelerate P enrichment (Teodoru and Wehrli 2005; Yao et al. 2016). Previous studies have shown that the construction of dams and reservoirs have changed the fluxes of sediment and nutrients in rivers and caused sediment and nutrient retention, for example, at the Wilson, John Redmond, and Kanopolis Reservoir in the USA (Cunha et al. 2014), which traps between 64 and 83% of sediment, and the Iron Dam, Saldenbach Reservoir in Germany, and the Seine River Reservoir in France, which retain between 12 and 60% of TP (Bukaveckas et al. 2005; Bocaniov 2002; Sherman et al. 2001; Josette et al. 1999). As the largest hydroelectric dam in the world, the impoundment of the Three Gorges Reservoir (TGR) has caused a 70% reduction of sediment flux (Dai et al. 2014) and 86% reduction of TP flux (Gong et al. 2006) into the sea. Compared with most dams in the world, the reduction of sediment load and TP flux from Yangtze River into the estuary caused by TGR are relatively high, which has altered the hydrological regime and behavior in the downstream of the Yangtze River. As a result of sediment reduction, the riverbed in the TGR downstream area of the Yangtze River has changed from a depositional before the TGR impoundment to an erosional pattern afterwards (Dai and Liu 2013) and decreased along the Yangtze River channel (Mei et al. 2015). As such, although the river runoff showed no significant change, the water level along the river decreased accordingly (Dai and Liu 2013; Mei et al. 2016). The associated issues, including water environmental and ecological impacts, have received considerable concern worldwide (Mueller et al. 2008; Chai et al. 2009). It is thought that the sediment and nutrient transportation and fluxes in the downstream of the Yangtze River have been disturbed (Dai et al. 2011), altering the composition, structure, and fluxes of nutrients and the habitat conditions downstream (Chai et al. 2009; Yao et al. 2009; Chen et al. 2012; Dai et al. 2011). However, whether the composition and fluxes of nutrients of the lakes that are connected to the Yangtze River in the area downstream of the TGR are affected by the dam is unclear.

Dongting Lake is the first large lake in the area downstream of the TGR, which is connected to the Yangtze River, and it exhibits a highly dynamic hydrological regime and high turbidity (Dai et al. 2005). The watershed covers an area of approximately 2.62×10^5 km² and accounts for about 14% of the

entire Yangtze River Basin (Hayashi et al. 2008). Dongting Lake is home to an important international wetland that provides multiple ecological functions. In recent years, Dongting Lake has experienced the accumulation of nutrients (e.g., TP) and serious deterioration of the lake ecosystem (Mueller et al. 2008; Wang et al. 2006). Over 80% of the pollutant loads in Dongting Lake are from three inlets and four tributaries (Tian et al. 2014). The water quality of Dongting Lake Basin is influenced by the anthropogenic activities and the discharge from the upstream tributaries in the lake basin and by the water recharge via the connection to the Yangtze River outside the basin. This has formed complex interactions between the Yangtze River, its tributaries, and the lake (Feng et al. 2013). However, the construction of the dam and the intensification of human activities have altered the interactions, which have great impacts on the water regime and mass balances (Lai et al. 2014; Gao et al. 2013). In particular, the water discharge and sediment load from the three inlets, as well as the exchange interface between the Yangtze River and the Dongting Lake, have already changed after the impoundment of the TGR since 2003 (Zahar et al. 2008; Chang et al. 2010; Sun et al. 2012; Li et al. 2004). However, how the concentrations and characteristics of the P in the lake body respond to the changes of water and sediment conditions in the upper rivers have rarely been discussed. In addition, large-scale sand dredging activities have gradually moved to Dongting Lake since they were prohibited in the mainstream of the Yangtze River in 1998 (Yang et al. 2007). This has caused an increase in the suspended sediment concentrations (SSCs) in water via sediment resuspension, resulting in a series of environmental problems (Wu et al. 2015; Zheng et al. 2016). However, the effects of SSC changes caused by sand dredging on P have been overlooked. It is therefore important to study the spatial and temporal variations in P concentrations and its forms in the basin system that are subject to a range of artificial drivers to help solve the eutrophication problem in lakes.

Using annual data over a period of 20 years for Dongting Lake, the main aims of this study were (1) to analyze the temporal and spatial distribution of P in Dongting Lake and its upper rivers and (2) to discuss the causes of the trends and variations in P under the influence of anthropogenic activities in the water, the upstream tributaries in the Dongting Lake Basin, and the connected Yangtze River outside the basin to prevent further eutrophication and to provide water quality management strategies.

Study area and methods

Study area and water sampling

Dongting Lake is located along the middle and lower reaches of the Yangtze River (111° 53'–113° 05' E; 28° 44'–29° 35' N)

in China, with a water surface area of approximately 2625 km² and a volume of about 1.78×10^{10} m³. The lake has a mean water depth of approximately 6.39 m and a maximum depth of about 18.67 m during the flood season. Dongting Lake receives discharge from the Yangtze River through three inlets located in the northwest (the Songzi, Taiping, and Ouchi water inlets) and four tributary rivers, the Lishui and Yuanjiang rivers in the west and the Zishui and Xiangjiang rivers in the south, which control 91% of the recharge entering the lake. The water network of the Yangtze River, the four tributaries, and Dongting Lake result in complex interactions between the Yangtze River and the lake and also between the four tributaries and the lake. In general, the surface area of Dongting Lake can be divided into the following: East Dongting (ED, 1217 km²), South Dongting (SD, 897 km²), and West Dongting (WD, 284 km²) (Gao et al. 2001).

In this study, surface water samples were collected from a depth of 0.5 m at 18 representative sites (S1–S18), and each site had three sampling points (left, middle, and right). The samples were divided into four spatial groups that covered the water quality of the entire basin: S1–S7 represent flows from the three water inlets and the four tributaries, S8–S12 represent ED, S13–S15 represent SD, and S16–S18 represent WD. Water samples were collected every 3 months (January, May, September) from 1966 to 2004 and monthly from 2005 to 2015 and analyzed for total phosphorus (TP). Water samples for soluble reactive phosphorus (SRP), total dissolved phosphorus (TDP), and SSCs were collected in 1996 and 2015.

Water samples were collected with pre-cleaned polyethylene bottles. All the samples were poisoned by chloroform to inhibit bacterial activity. Samples for SRP and TDP were filtered through a 0.45- μ m cellulose-acetate filter and preserved in polyethylene bottles. Samples for TP were directly preserved (unfiltered) in polyethylene bottles. All samples were stored in a cool room at 4 °C. SRP was analyzed by ammonium molybdate spectrophotometric method (Murphy and Riley 1962). TDP and TP were analyzed by ammonium molybdate spectrophotometric method after digestion with potassium persulfate in an autoclave (2 h) (APHA 1998). The concentrations of dissolved organic phosphorus (DOP) were the difference between dissolved total P (DTP) and SRP. The concentrations of particulate phosphorus (PP) were the difference between TP and DTP. The detection limit for SRP, TDP, and TP was 0.01 mg/L, and detection error was less than 3%. Samples for SSCs were filtered through the pre-weighed 0.45 μ m cellulose-acetate filter. The filters were dried at 45 °C in the laboratory. The dried filters were weighed and SSCs were determined by subtracting original filter weight. Sediment load data for the three water inlets and four tributaries were obtained from the Yangtze River Sediment Bulletin (Fig. 1).

Upper river flux calculation method

The TP flux in each upper river was calculated using the following equation, which has been reported in previous studies examining other materials (Liu et al. 2010)

$$F_i = C_i \times Q_i$$

where F_i is the flux of TP (g/s), C_i is the annual concentration of TP (mg/L), and Q_i is the annual discharge of the upper river (m³/s).

Load and water quality response calculation method

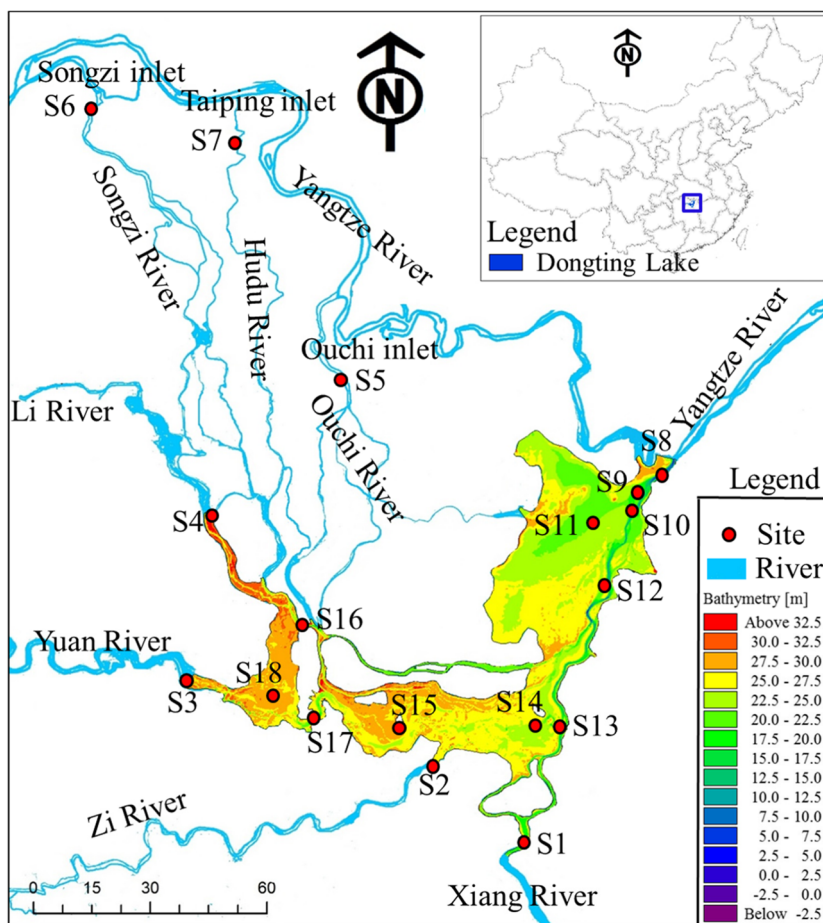
The quantitative calculation between the pollutant load and water quality response was derived from our previously established, calibrated, and validated 2D model for Dongting Lake (Tian et al. 2016). The model is based on a 2D hydrodynamic model linked to a dye tracer approach using the MIKE 21 code. The MIKE 21 code has been extensively applied in various studies (Li and Yao 2015). The study area and bathymetry of the hydrodynamic model of Dongting Lake were presented in the Supporting information (Fig. S1). A 2D grid system with an unstructured triangular grid was adapted to capture the complex bathymetry, and the wetting and drying processes were associated with the considerable variations in the lake area. A higher mesh resolution was applied to the deep and narrow flow channels, whereas a coarse mesh covered the relatively flat plain areas. The grid therefore had 55,778 triangular elements with approximate minimum and maximum element sizes of 25 and 600 m, respectively. The unstructured grid and the variable mesh resolution were presented in the Supporting information (Fig. S2). Daily observed inflows from the three inlets and four tributaries were specified as upstream boundary conditions, and a daily series of observed water levels at the Chenglijing gauging station (connected to the Yangtze River) was specified as the downstream boundary condition in the model. Details of the model building process and parameter settings are described in our previous research on the hydrodynamic model of Dongting Lake (Tian et al. 2016). The quantitative calculation between the pollutant load and water quality response was measured using a concentration of 1 kg/m³ for the calculated boundary and an initial concentration of zero throughout the lake and any other boundaries. Finally, the water quality response field was obtained when the model was run until it reached equilibrium state.

Results

Spatial and temporal distributions of TP in Dongting Lake

The TP concentrations ranged from 0.027 to 0.238 mg/L, with an average of 0.099 mg/L from 1996 to 2015. The main

Fig. 1 Map of Dongting Lake and water sampling sites



polluted area migrated from the western to the eastern area, with the high pollution point occurring at the intensive dredging region near S10 (Fig. 2). The temporal and spatial pattern changes can be divided into three stages based on the TP fluxes of the upper rivers and the spatial distribution characteristics of TP concentrations. The first stage refers to the period from 1996 to 2000, when the TP fluxes is dominated by the three inlets from the Yangtze River, and the TP concentrations decreased from the entrance of the three inlets in WD (0.192 ± 0.03 mg/L) to SD (0.088 ± 0.026 mg/L) and further to the outlet in ED (0.071 ± 0.031 mg/L). The second stage is the period from 2004 to 2008, when the TP fluxes is dominated by the Yuan River, and the TP concentrations decreased from the entrance of Yuanjiang in WD (0.211 ± 0.042 mg/L) to SD (0.16 ± 0.06 mg/L) and further to the outlet in ED (0.117 ± 0.023 mg/L). The third stage is the period from 2013 to 2015, when the TP fluxes is dominated by the Xiang River, and the TP concentrations decreased from the eastern (0.159 ± 0.053 mg/L) to the western (0.091 ± 0.163 mg/L) region, with the highest value occurring at S10 (0.194 ± 0.062 mg/L). In addition, the variations of TP in the lake body had a clear response to the TP fluxes in the upper rivers. If we take the three inlets as an example, the TP

concentrations at the entrance of the three inlets decreased in line with the reduction of the TP flux in the three inlets.

The results of Mann-Kendall (Table 1) showed that the TP concentrations in the three inlets decreased, whereas those in the four tributaries increased significantly. The TP concentrations at the entrance of the three inlets (S16) in WD decreased, while those at the outlet of WD (S17) increased significantly. Most sections of ED had increasing trends, especially the sections near the outlet of the lake.

Spatial and temporal distributions of phosphorus fractions in Dongting Lake

The spatial variation of the P composition in Dongting Lake in 1996 and 2015 is presented in Fig. 3. PP was the major form of P in Dongting Lake in 1996, which accounted for between 51.08% (S11) and 81.17% (S16). The ratios of PP/TP in 1996 decreased in the following order: WD > SD > ED. The highest value of PP concentration appeared at the three inlets (0.189 mg/L), which accounted for 85.74% of TP. PP concentrations in the lake body ranged from 0.037 to 0.173 mg/L and had an average value of 0.074 mg/L.

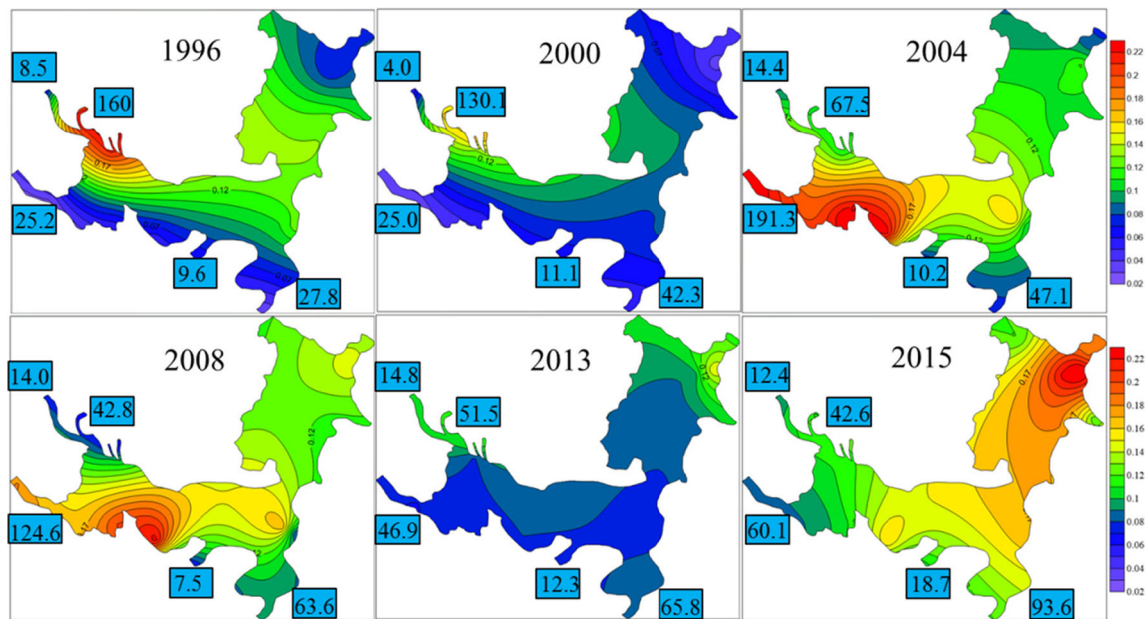


Fig. 2 Spatial distribution of TP concentrations (mg/L) and section fluxes of TP (g/s) in Dongting Lake from 1996 to 2015

However, in contrast to the distribution characteristics in 1996, the ratios of PP/TP in 2015 decreased in the following order: ED > SD > WD, with averages of 64.45, 56.78, and 32.29%, respectively. PP concentrations in the lake body ranged from 0.026 to 0.182 mg/L, with an average value of 0.105 mg/L. The concentrations were significantly positively correlated with TP concentrations ($r = 0.86$, $p < 0.01$) and showed similar spatial variations. Compared with 1996, the concentrations and proportions of PP in the three inlets and at S16 decreased significantly in 2015, while those in the ED sections clearly increased (Fig. 3).

The major fraction of DTP was SRP and, on average, accounted for 68.58% in WD, 77.85% in SD, and 57.49% in ED. SRP concentrations ranged from 0.023 to 0.065 mg/L, with an average value of 0.044 mg/L, and decreased from the three inlets in WD to the outlet in ED.

Spatial and temporal distributions of SSCs in Dongting Lake

The P mainly exists as particulate species that are easily absorbed onto the surface of solid particles (Yao et al. 2016). Therefore, as the main carrier of phosphorus, suspended sediment (SS) plays an important role in the process of phosphorus transport and migration through adsorption/desorption (Ellison and Brett 2006). Unlike algal-type lakes, such as Taihu, Dongting Lake is a sediment-dominated lake with high turbidity and low chlorophyll a (Chl.a) concentrations (Wu et al. 2015; Zheng et al. 2016). Results of the correlation analysis

show that the TP concentrations were highly correlated with SSCs but had little correlation with Chl.a (Table 2). This indicates that SS was an important source of P in Dongting Lake.

The spatial pattern of SSCs changed markedly (Fig. 4). The SSCs in 1996 ranged from 27.56 to 285.51 mg/L, with an average of 164.54 mg/L, and decreased from the three inlets in WD to the outlet in ED. The SSC in the three inlets (350 mg/L) was higher than that in any other tributary. Compared with 1996, the SSC decreased in 2015 (117.51 mg/L), especially in WD (Fig. 4). The SSCs in 2015 increased in the following order: WD < SD < ED, with averages of 29.85 ± 11.32 , 82.93 ± 37.97 , and 210.93 ± 47.19 mg/L, respectively. The higher values were concentrated mainly in the area near S10. The distribution of SSCs was consistent with PP (Figs. 2 and 4), and the two parameters were highly correlated ($r^2 = 0.906$, $p < 0.01$). This was mainly because PP was the predominant P fraction in Dongting Lake, and the concentration and percentage of PP increased with the increase in SSCs. This indicates that the spatial difference of SSCs in the lake body was the major control on the structure and spatial pattern of P.

Table 1 Annual variation trends of TP in the sections of Dongting Lake

Section	S1	S2	S3	S4	S6	S8	S9	S10
Test Z	2.01*	0.88	2.3*	4.09***	-0.62	2.17*	0.91	0.38
Section	S11	S12	S13	S14	S15	S16	S17	
Test Z	1	-0.49	-0.33	2.14	1.12	-1.24	2.51*	

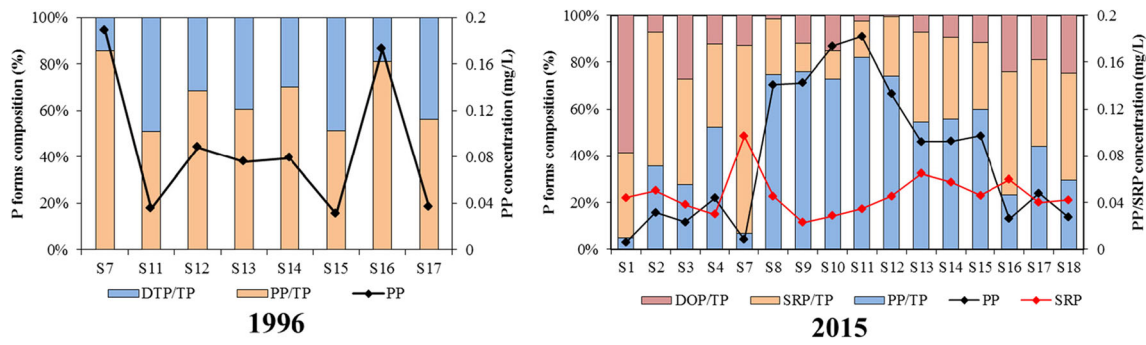


Fig. 3 Phosphorus fraction compositions and concentrations in Dongting Lake in 1996 and 2015

Discussion

Effect of sediment load changes from the Yangtze River via the three inlets after the impoundment of TGR

Figure 2 shows that the reduction of the TP flux in the three inlets from the Yangtze River resulted in the decrease of the TP concentrations at S16 (Mann-Kendall $z = -1.24$), the exchange interface between the three inlets and WD. The spatial distribution also changed from a decreasing (1996–2000) to an increasing (2004–2008) trend from the three inlets to the central WD. Furthermore, the TP flux was closely related to the river discharge and TP concentration. Compared with the decrease of discharge from the three inlets (decrease of 29.54%), the reduction of the TP flux was mainly affected by the decrease of the TP concentrations in the three inlets (decrease of 46.11%), especially the decrease of the PP fraction (decrease of 95.57%; Fig. 5). This may have been related to the changes in the sediment load from the three inlets after the impoundment of TGR.

Previous studies have reported that the delivery of river sediment carried a large amount of PP (Wallin and Håkanson 1992; Nilsson and Jansson 2002). However, the construction of a dam could cause remarkable changes in the forms and distributions of nutrients carried by sediment downstream owing to the removal of sediment (Cunha et al. 2014; Zahar et al. 2008; Dang et al. 2010). Dongting Lake connects with the lower reaches of the Yangtze River through three inlets, and the three inlets are the main sediment source to the lake (73.23%). The water and sand transfer properties between the Yangtze River and Dongting Lake are regarded as typical river-lake interactions. Before the impoundment of TGR (1996–2000), the concentrations of sediment and nutrients attached to particles (e.g., PP) in the mainstream of the

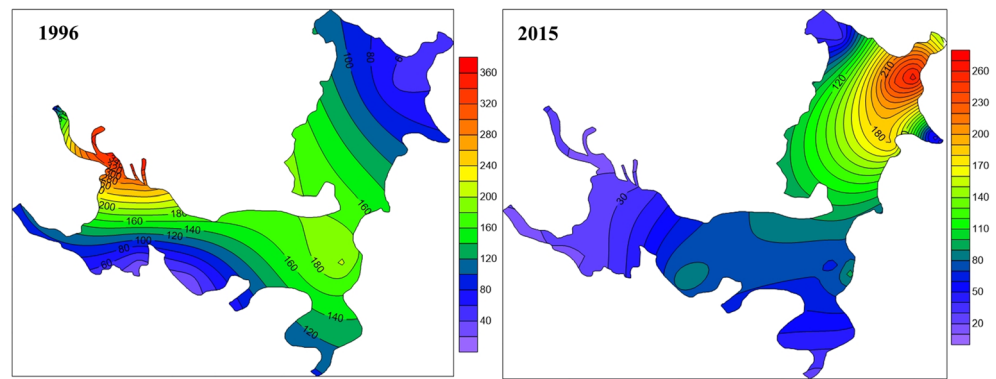
Yangtze River were high, and PP was the dominant form of TP, accounting for over 80% (Yao et al. 2009; Duan et al. 2008). Therefore, large amounts of sediment and PP were delivered to Dongting Lake through the three inlets. After the impoundment of TGR, the sediment load and concentration decreased radically because of the interception by TGR (Dai et al. 2016). For example, the sediment concentration at Yichang station decreased from 1.1 kg/m³ for the period before the impoundment of TGR to 0.15 kg/m³, which significantly altered river-lake interactions (Zhou et al. 2016). As a result, the sediment load in the three inlets reduced (Fig. 5), which led to the blocking of PP transportation (Cunha et al. 2014). As mentioned in the “Spatial and temporal distributions of SSC in Dongting Lake” section, SS was a crucial agent in the migration and transformation of TP in the basin, and there was a significant linear relationship between them ($r^2 = 0.783$). Because of the sediment reduction from the three inlets, the SSC at S16 decreased noticeably from 285.51 to 27 mg/L, and the PP concentration decreased from 0.139 to 0.026 mg/L, which resulted in the decrease in the TP concentration. Furthermore, there was a significant linear correlation between the sediment load and the TP flux at the S16 section, with a linear equation of $y = 0.6323x + 71.372$ ($r^2 = 0.92$). The regression model explained 92% of variation in the TP flux. This proved that the sediment load had a decisive role in the TP transport. Previous studies have also reported that the reduction in sediment load from the three inlets after the impoundment of TGR resulted in the decrease of the TP concentration in WD (Zhang et al. 2016).

Compared with most dams in the world, such as the Wilson, John Redmond, and Kanopolis Reservoir in the USA that traps between 64 and 83% sediment (Cunha et al. 2014) and the Iron Dam, Saldenbach Reservoir in Germany as well as the Seine River Reservoir in France that retain between

Table 2 Correlation coefficients between TP and environmental factors

	Temperature	pH	Dissolved Oxygen	Permanganate Demand	Index of Oxygen Demand	Biochemical Oxygen Demand	Ammonium	TN	Chlorophyll a	SS
r^2	-0.016	-0.022	0.065	0.132		0.003	0.005	-0.050	-0.062	0.783**

Fig. 4 Spatial distribution of SSCs (mg/L) in Dongting Lake in 1996 and 2015



12 and 60% TP (Bukaveckas et al. 2005; Bocaniov 2002; Sherman et al. 2001; Josette et al. 1999), the reduction in sediment (about 70%) (Dai et al. 2014) and TP (86%) (Gong et al. 2006) due to the TGR was more obvious. However, unlike S16, which is the exchange interface between the three inlets and WD, the TP concentration at the WD outlet (S17) increased significantly. This result suggests that although the retention effects of TGR altered the flux and structure of TP in the downstream, the influence on Dongting Lake, which was connected with Yangtze River, was fairly limited. In spite of the PP flux from three inlets clearly declining after the impoundment of TGR, the DTP at S16 instead increased from 0.032 mg/L (accounted for 14.26% of TP) in 1996 to 0.086 mg/L (accounted for 76.83% of TP) in 2015. Therefore, although the operation of TGR had effectively reduced the PP input into WD, it did not reduce the risk of eutrophication in WD because the SRP concentrations remained high in this region.

Effect of TP load changes from tributary (Yuanjiang)

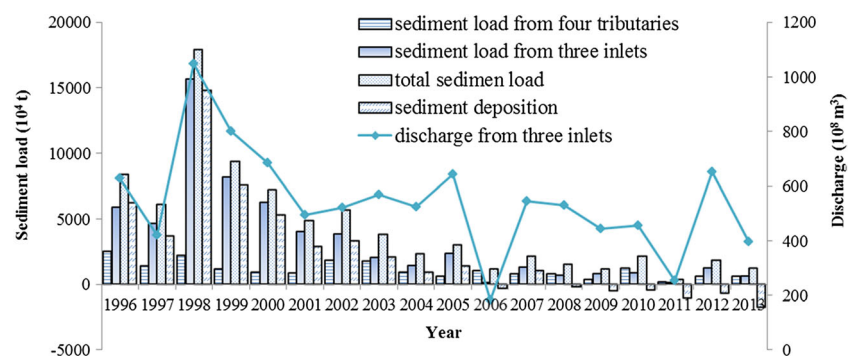
The “Effect of sediment load changes from the Yangtze River via the three inlets after the impoundment of TGR” section explained that the decline of sediment load from the three inlets caused an effective reduction in the TP concentration at S16; however, those at the outlet of WD (S17) clearly increased (Mann-Kendall $z = 2.51$). The water network in WD is complex because it receives pollution load from Yuanjiang, Lishui, and the three inlets from the Yangtze River (Fig. 1).

Correlation analysis showed that the TP concentration at S17 was positively correlated with Yuanjiang ($r^2 = 0.847$, $p < 0.01$) but had little correlation with the three inlets ($r^2 = -0.403$, $p > 0.05$) and Lishui ($r^2 = 0.414$, $p > 0.05$). These relationships suggest that the TP load from Yuanjiang had more of an effect on the TP concentrations at the outlet in WD.

To further quantify the degree and the scope of the TP response of the lake to external loading changes, the response coefficient and the response field of the pollutant load per unit of TP were calculated with a 2D hydrodynamic model linked to a dye tracer approach, which is an effective method for the quantitative evaluation of pollutant response. The modeling results showed that the affected scope of Yuanjiang loading in WD was from the river estuary to the outlet of WD, and the TP response coefficient at S17 reached 0.8 (Fig. 6). The TP concentration at the outlet in WD was therefore mainly controlled by the TP load from Yuanjiang, whereas there was little response to the load from the three inlets and Lishui (Table 3).

Based on the mean annual discharge, Yuanjiang is the largest river entered WD ($639.71 \times 10^8 \text{ m}^3$), which occupies 49.4% of the total discharge in WD. In addition, the Yuanjiang Basin is rich in P resources and many P industries are located in the basin (Tian et al. 2014). The P wastewater discharge from the P industries has caused the increase in TP in Yuanjiang (Mann-Kendall $z = 2.3$). The mean annual TP concentration in Yuanjiang (0.118 ± 0.037) was higher than that in the three inlets (0.096 ± 0.029) and Lishui (0.078 ± 0.016), with the maximum value at some sections exceeding the standard by 213 times (Huang et al. 2005). The

Fig. 5 Sediment load from the three inlets and four tributaries and sediment depositing



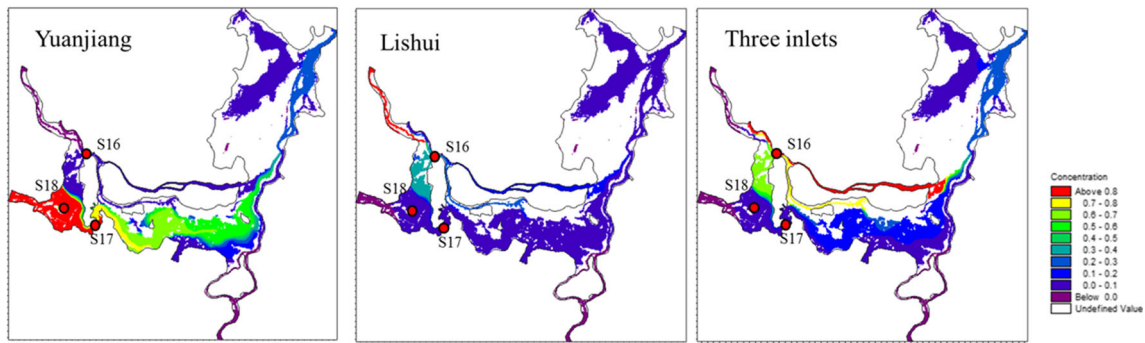


Fig. 6 Response field of the unit load from Yuanjiang, Lishui, and the three inlets on the TP in Dongting Lake

TP concentration at S17 increased under the load increase in Yuanjiang, whereas the decrease in TP at S17 since 2008 was attributed to the implementation of pollution control policies in the upstream of Yuanjiang. In addition, compared with the significant reduction in PP at S16, the composition of P at S17 had no clear change (PP/TP 56.34% in 1996 and 55.89% in 2015). Therefore, although the discharge from the three inlets could reach the S17 section, most of the SS transported by the discharge had deposited onto the lake bottom before reaching S17 and therefore made little contribution to the TP concentration.

Effect of anthropogenic activities (sand dredging) within the lake

The main phosphorus polluted area migrated from the western to the eastern area, and the TP concentrations in the region

near the outlet in ED (S8, S9, and S10) showed a clear increase since 2008 (Fig. 2; Table 1). Based on the concentrations of the P fractions, the increase in TP occurred mainly in the PP fraction (Fig. 3), and the ratio of PP/TP increased from 51.08 to 76.36%. This may have been related to the increase in SSCs in this region.

Previous studies have suggested that the SSC in the shallow lake, such as Dongting Lake, is vulnerable to the sediment discharge from rivers and the sediment resuspension resulting from disturbances. However, although the sediment inflow in Dongting Lake declined after the impoundment of TGR, the sediment outflow increased, and the amount of sediment outflow was higher than that of the inflow since 2008 (Fig. 5). The intensive sand dredging and the sailing vessels in the area from S10 to the outlet may have been the main reason for the increase in the SSCs in this region. In addition, the obviously increased topographic gradient (Mei et al. 2015) and hydraulic

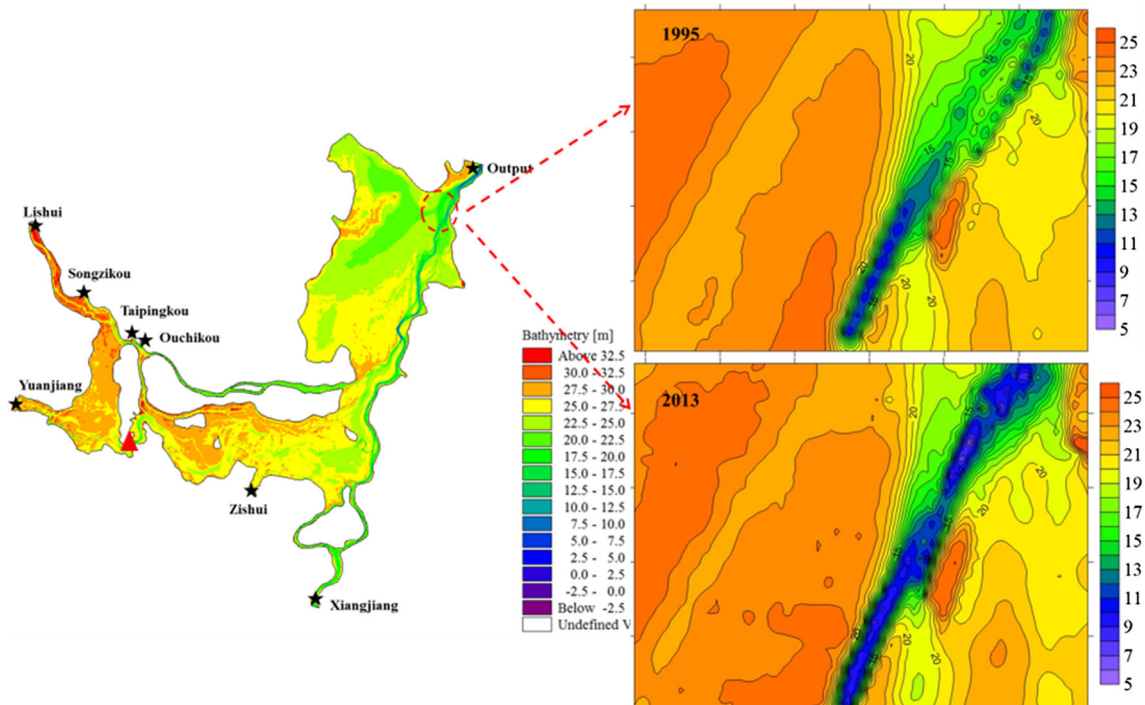


Fig. 7 Bed elevation in the S10 area in 1995 and 2013

Table 3 Response coefficient matrix of sections in WD

	Xinjiangkou	Taipingkou	Ouchikou	Lishui	Yuanjiang
S16	0.62	0	0	0.36	0
S17	0.06	0	0	0.04	0.80
S18	0	0	0	0	0.96

gradient (Yang et al. 2016) between the Dongting Lake and Yangtze River caused by the TGR impoundment has accelerated lake drainage (Mei et al. 2015) and thus induced more suspended sediment discharge from Dongting Lake to Yangtze River, which is probably responsible for the increase of the sediment outflow in Dongting Lake. Compared with 1995, the bed elevation in the S10 area declined significantly, reducing by up to 8 m at the region of the most severe sand dredging (Fig. 7). The disturbance caused by sand dredging resulted in sediment resuspension and directly led to the increase in SSCs in this region (Fig. 4). Our results were in accordance with those reported in previous research (Wu et al. 2015; Zheng et al. 2016). As the SSCs increased, the TP concentration (especially in the PP fraction) increased accordingly.

Because the P concentration in the sediments in ED had a high value of 862 mg/kg, SS with a high P concentration entered the water through the resuspension due to the disturbance by sand dredging and sailing vessels (Pan et al. 2013). This directly led to the increase in PP (Cunha et al. 2014), with the high TP pollution appearing in the S10 area (Fig. 2). In addition, the sedimentation types of ED were mostly shaly sandstone and tufaceous limestone with a finer grain size (Jin et al. 1995), which had high absorption capacities for SRP. The disturbance by sand dredging promoted the resuspension of SS, which increased the SSCs in the water and further absorbed large amounts of SRP (Pacini and Gächter 1999; Reynolds and Davies 2001). Therefore, the high SSC directly led to the increase in the PP concentration by unit volume. The disturbance caused by sand dredging through sediment resuspension was therefore the major control on the increase in TP in ED. ED is located close to Yueyang City, the large economic center of Hunan Province, and therefore large amounts of pollutants entered ED from intensified human activities, which also led to the increase in TP concentrations to a certain extent.

Conclusions

This study analyzed the spatial and temporal variations in the concentration and forms of TP in Dongting Lake during 1996–2015 and discussed the causes of the variations with

section flux calculations and a hydrodynamic model. The results show that the main polluted area of TP migrated from WD to ED, with the highest pollution occurring at the intensive dredging region near S10 in ED. The TP variations in WD were attributed to the changes in TP flux and sediment load from the connected YR and the upstream tributaries (the Yuanjiang river and the Lishui River). Although the reduction of TP flux and sediment load from the connected Yangtze River via three inlets resulted in the decrease of SSC and TP concentrations at S16 in WD after the impoundment of TGR, the extent and range of the impact were fairly limited. The TP concentration at the outlet in WD was mainly controlled by the TP load from the Yuanjiang River, whereas there was little response to the load from the three inlets and the Lishui River. Since 2008, the sediment resuspension caused by the disturbance from the intensive sand dredging and sailing vessels has been the major control on the increase in TP at the S10 area in ED.

On the whole, the concentrations and compositions of P in a large river-connected lake, like Dongting Lake, are influenced by three kinds of main elements, namely the regulation of the water-sand regime in the connected Yangtze river caused by the retention effect of large reservoirs, such as TGR, the P flux from the tributaries and the anthropogenic impact within the lake (sand dredging). They had different impacts on the different lake areas of total phosphorus change. We therefore recommend that the local government should aim to control the pollutant input from Yuanjiang as a priority to control the water pollution in WD and that attention is directed towards sand dredging problems to alleviate the high TP pollution in ED.

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