RESEARCH ARTICLE

Spatiotemporal variation of phosphorus in the Three Gorges Reservoir: impact of upstream cascade reservoirs

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Abstract

The impoundment of the Three Gorges Reservoir (TGR) and upstream cascade reservoirs (UCRs) has altered the hydrologic regime, with inevitable effects on phosphorus transport processes in the TGR. In order to investigate the effects of impoundment, long-term monitoring data of flow rate, suspended sediment (SS), and phosphorus fractions of six stations in the TGR basin were collected and divided into three periods, period 1 (P1) (1985–2002), period 2 (P2) (2003–2012), and period 3 (P3) (2013–2017), based on the periodic impoundment time. The results indicated that the impoundment of the TGR and UCRs considerably decreased the SS concentration. Efficient sediment interception by the UCRs led to a dramatic decline in the concentrations of total phosphorus (TP) and particulate phosphorus (PP) in the mainstream, while the total dissolved phosphorus (TDP) showed a general increasing trend from 2004 to 2017. Different phosphorus fractions in the mainstream exhibited seasonal variations; among them, the concentrations of TP and PP were highest in the wet season, while the highest TDP concentration occurred in the dry season. Further analysis indicated that the seasonal distribution of TP was significantly homogenized in P3. Additionally, the SS concentration was positively correlated with the concentrations of TP and PP in the mainstream, while the correlations in P3 were significantly lower than that in P2. The findings can provide a scientific reference for future investigations dedicated to the long-term effects of the UCRs on the eco-environment in the TGR as well as the downstream.

Introduction

As the longest river in Asia, the Yangtze River extends over 6300 km, with a total drainage area of 1.8 million km^2 (Chen et al. 2001; Li et al. 2011). Three Gorges Reservoir (TGR), located in the upper mainstream of the Yangtze River, is the

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largest water conservancy and hydropower project in the world (Fu et al. 2010). The TGR provides comprehensive benefits in flood control, water storage, power generation, navigation, and agricultural irrigation (Xu et al. 2011; Zhang and Lou 2011), but unavoidable accompanied by a series of environmental problems, including hydrologic alteration, eutrophication, ecosystem degradation, biodiversity reduction, and habitat destruction (Humborg et al. 1997; Li et al. 2013; Nilsson et al. 2005; Tang et al. 2018a, b; Vorosmarty et al. 2003; Yuan et al. 2013). Eco-environmental issues induced by the TGR have caused widespread concern (Fu et al. 2010; Shen and Xie 2004; Zhang and Lou 2011). Sedimentation and eutrophication are the two significant challenges to be solved after the TGR impoundment (Tang et al. 2018a). The impoundment of TGR considerably altered the hydrologic pattern, mainly manifested as increased water level, reduced flow velocity, prolonged water retention time, sediment deposition, and stratified water temperature (Ma et al. 2015; Mei et al. 2016). The sediment transported to downstream

reaches has greatly decreased due to the retention of reservoirs, although excessive anthropogenic activities have caused increased soil erosion (Syvitski et al. 2005). Sediment deposition in the TGR engendered a significant reduction of sediment load transported to the middle and lower reaches of the Yangtze River in 2003–2011, which was 91% lower than that in 1950–1990. Since water and sediment particles are the key environmental media of nutrients, the hydrologic variations caused by impoundment inevitably affect the transport and transformation of nutrients in the TGR (Miller 2012). And the changes in nutrients may be considered as the physical basis affecting the structure and function of river ecosystems (Zhang et al. 2018; Zhou et al. 2013). Slow flow velocity and sediment deposition caused large amounts of nutrients trapped in the TGR and promoted the risk of eutrophication with increased water transparency in the TGR, which may ultimately damage the eco-environment of TGR (Morris and Fan 1998; Wu et al. 2017).

Phosphorus, one of the essential nutrients supporting aquatic primary productivity, was identified as the crucial limiting factor for eutrophication in the TGR (Conley et al. 2009; Elser et al. 2007; Meybeck 1982). The transport and transformation of phosphorus in the TGR play a vital role in the aquatic eco-environment (Huang et al. 2015). Over the past decades, the concentration of total dissolved phosphorus (TDP) in the TGR has increased significantly due to the increased domestic sewage and agricultural wastewater caused by the growth of the population (Dai et al. 2011). However, the impoundment led to an obvious decline in the concentrations of particulate phosphorus (PP) and total phosphorus (TP) due to the deposition of PP-bounded sediment particle in the TGR. The phosphorus load transported to the downstream decreased by approximately 77% (Zhou et al. 2013), which not only reduced the bioavailability of phosphorus in the downstream but also made the ratio of N to P in the middle and lower reaches of the Yangtze River exceeded the normal value for many years (Duan et al. 2008; Liu et al. 2003; Shen and Liu 2009). Therefore, the fate of phosphorus in the TGR was particularly complicated and worth in-depth study due to the changed hydrologic regime after the impoundment.

Sediment is the vital carrier of PP and makes important contributions in regulating the distribution, composition, and bioavailability of phosphorus (Wu et al. 2016). Statistical data indicated that nearly 98.4% of sediment in the TGR has been transported in the form of suspended sediment (SS) (Mao et al. 2012). SS has a great affinity for phosphorus because of its high specific surface area and surface-active sites (Davis and Kent 1990; Fang et al. 2013). Most DP in the water column tends to be strongly adsorbed by SS and transported in the form of PP and subsequently trapped in the TGR with sedimentation (He et al. 2009; Jensen et al. 2006). Nevertheless, the change of environmental

conditions, including flow velocity, dissolved oxygen content, and pH, may facilitate the sediment phosphorus to be released to the overlying water by desorption or resuspension, increasing the potential risk of secondary pollution (Christophoridis and Fytianos 2006; House and Denison 2002; Tang et al. 2015a, b).

Successive construction and operation of the upstream cascade reservoirs (UCRs), accompanied with appropriate water and soil conservation measures, significantly decreased the amount of sediment input to the TGR. And the transport process and spatiotemporal distribution of phosphorus in the TGR were greatly affected. Previous studies have predominantly concentrated on the fate of phosphorus in the early post-TGR period (Tang et al. 2018a, b; Zhou et al. 2013). However, due to the lack of consecutive and regularly measured data, few detailed studies have been conducted to elucidate the long-term variation characteristics of hydrological regime and phosphorus distribution in the TGR and the related effects of the upstream cascade reservoirs impoundment have not been reported. In addition, numerous researchers have explored the complex factors affecting phosphorus transport (Zhou et al. 2013), mainly focused on the relationships between phosphorus and water flow (Liu et al. 2003; Shen and Liu 2009), but the correlations between phosphorus and sediment remain unclear.

In this study, the distribution characteristics of the flow rate and SS concentration in the TGR were systematically investigated based on the hydrological observations from 1985 to 2017. And the phosphorus data collected after the TGR impoundment (2004–2017) were used to elucidate the spatiotemporal variation of phosphorus in the TGR. Meanwhile, the relationships between phosphorus and hydrological factors including water discharge and sediment were explored. Furthermore, the potential impacts of the TGR and upstream cascade reservoirs on eutrophication were discussed in depth.

Materials and methods

Study area

The TGR is characterized by river-shaped (Wang et al. 2013), with a mainstream length of 663 km, a total water surface area of 1.08×10^3 km^2, and a storage capacity of 39.3 billion m^3 (Fu et al. 2010; He et al. 2011). There are three major inflow rivers in the upper reaches of the TGR, including the Yangtze River, Jialing River, and Wujiang River (Fig. 1). Numerous large reservoirs have been built or under construction in the basins of these three rivers (Yan et al. 2021). Table 1 summarized that the reservoirs with a capacity larger than 1×10^8 m^3 have been or are being constructed since 2013.

All hydrological and nutrient data were collected from 6 representative monitoring stations in the TGR mainstream (4

Fig. 1 Map of hydrological stations in the TGR
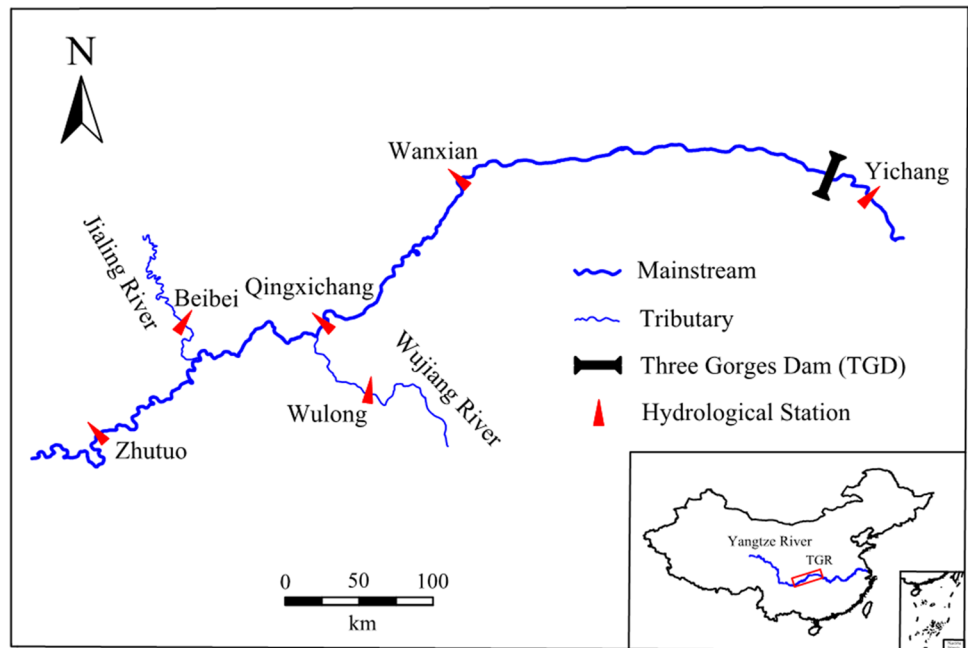
stations) and two upstream tributaries (2 stations). Among these stations, Zhutuo (ZT), Beibei (BB), and Wulong (WL) stations were chosen to represent the inflow stations of the TGR located in the Yangtze River, the Jialing River, and the Wujiang River, respectively. WL is 65 km upstream of the confluence of the Wujiang River and the TGR mainstream, and BB is approximately 56 km upstream of the confluence of the Jialing River and the TGR mainstream. In this study, the sum of flow rate, the flow weighted average concentrations of SS, and phosphorus fractions of three stations (ZT, BB, and WL) are regarded as the resources inflow to the TGR. In the TGR mainstream, ZT, Qingxichang (QXC), and Wanxian (WX) stations are 674 km, 550 km, and 289 km upstream of the Three Gorges Dam (TGD), respectively. The QXC station and its upstream stations are considered as the tail area of TGR, and the WX station is the representative station of the middle region of TGR. Besides, Yichang (YC) station is 38 km downstream from the TGD, which is regarded as the outflow control station of the TGR (Fig. 1).

Data collection and analysis

The observed data of all stations were gathered from Changjiang Water Resources Commission (CWRC), including monthly average data of flow rate and SS concentration

over the past 30 years (1985–2017), as well as the concentrations of phosphorus fractions (TP, PP, and TDP) after the TGR impoundment (2004–2017). In this study, TDP reflects the phosphorus dissolved in the water column, and PP is obtained by calculating the difference between TP and TDP, which represents the phosphorus adsorbed by sediment (Li et al. 2018; Zhou et al. 2013).

In order to clearly reveal the effects of the TGR and UCRs on the hydrologic regime and the transport process of phosphorus, the collected data from 1985 to 2017 were divided into three typical periods for analysis and comparison, including the period 1 (P1) (1985–2002) before the TGR impoundment, the period 2 (P2) (2003–2012) after the TGR impoundment but before the impoundment of UCRs, and the period 3 (P3) (2013–2017) after the impoundment of UCRs. In particular, the phosphorus fractions data from 2004 to 2012 was used to represent that in P2 due to the unavailable data in 2003. Moreover, in order to explore the seasonal distributions of flow rate, SS concentration, and phosphorus fractions, June–September was designated as the wet season, December–March as the dry season, and April–May and October–November as the normal season.

All statistical analyses were performed using SPSS. The analysis of variance (ANOVA) was performed to evaluate

Table 1 Summary of main reservoirs constructed upstream of the TGR since 2013

Basin	Reservoir
Yangtze River	Liyuan (LY), Ahai(AH), Longkaikou (LKK), Ludila (LDL), Guanyinyan (GYY), Jinping-1 (JP1), Guandi (GD), Xiluodu (XLD), Xiangjiaba (XJB)
Jialing River	Miaojiaba (MJB), Tingzikou (TZK)
Wujiang River	Goupitan (GPT), Shatuo (ST)

Fig. 2 Mean annual flow rate and SS concentration (**a**) inflows to the Three Gorges Reservoir (**b**) at Yichang station in 1985–2017
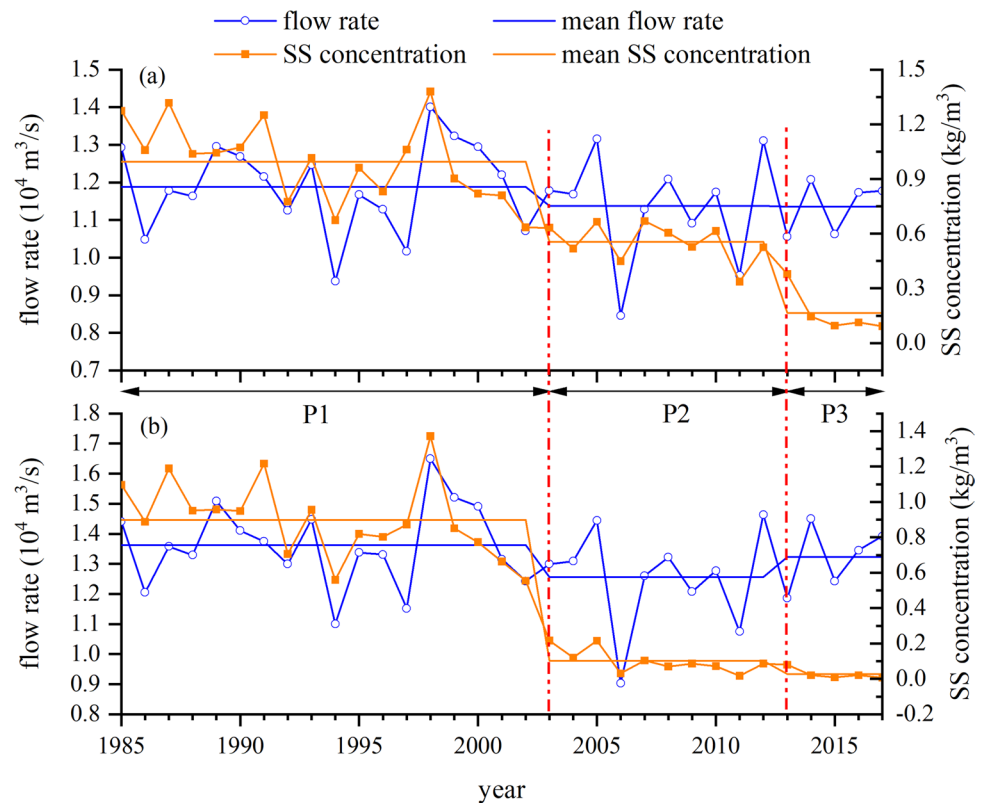
the spatiotemporal differences of flow rate, SS concentration, and phosphorus fractions (TP, PP, and TDP), and the variations reached a significance level when $p < 0.05$. Regression analysis was applied to measure the correlation between phosphorus fractions and hydrologic factors.

Results

Hydrologic regime

As presented in Fig. 2, both mean annual flow rate and SS concentration inflow and outflow of the TGR had a decreasing trend during the investigated period, but the reduction of SS concentration was much more significant, especially

after the year of the impoundment of the TGR (2003) and the UCRs (2013), respectively. The flow rate inflow was relatively stable, with a slight decline, while the SS concentration inflow decreased continuously since the late 1990s (Fig. 2a). Comparing P2 to P1, the rate of mean flow rate inflow reduction was only 4%, while the mean SS concentration inflow decreased about 45% from 1.00 to 0.55 kg/m^3 (Table 2). Moreover, there was no variation of mean flow rate comparing P3 with P2, while the rate of SS concentration inflow reduction was over 70%. Similar to inflow, a slight fluctuation of the mean annual flow rate at YC station could be observed in 1985–2017 about its mean value of 1.32×10^4 m^3/s. However, the mean annual SS concentration saw a salient downward trend since the twenty-first century. Comparing P2 with P1, the mean SS concentration declined

Table 2 The mean annual flow rate and SS concentration at six hydrological stations in different periods

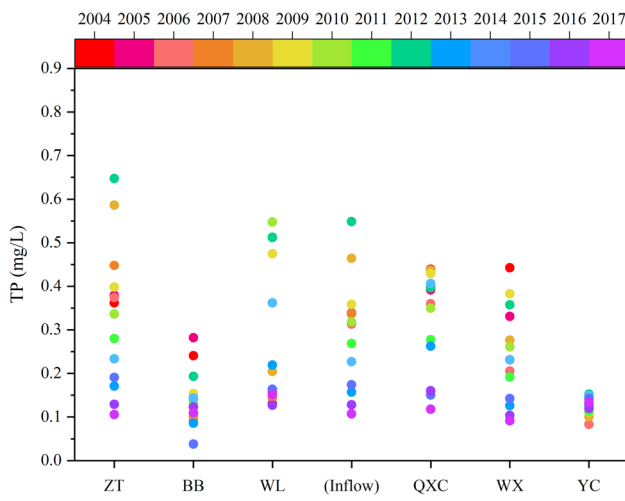| Stations	1985–2017		P1 (1985–2002)		P2 (2003–2012)		P3 (2013–2017)	
	Flow rate (10^4 m^3/s)	SS conc (kg/m^3)	Flow rate (10^4 m^3/s)	SS conc (kg/m^3)	Flow rate (10^4 m^3/s)	SS conc (kg/m^3)	Flow rate (10^4 m^3/s)	SS conc (kg/m^3)
ZT	0.83	0.84	0.85	1.13	0.80	0.65	0.80	0.15
BB	0.19	0.61	0.18	0.81	0.21	0.42	0.18	0.26
WL	0.15	0.25	0.16	0.37	0.13	0.13	0.15	0.06
(Inflow)	1.17	0.74	1.19	1.00	1.14	0.55	1.14	0.17
QXC	1.21	0.70	1.25	0.97	1.18	0.47	1.16	0.16
WX	1.24	0.63	1.30	0.97	1.18	0.30	1.14	0.08
YC	1.32	0.53	1.36	0.90	1.26	0.10	1.32	0.03

Fig. 3 Mean annual TP concentrations in the TGR basin between 2004 and 2017

88.7% from 0.90 to 0.10 kg/m^3, and it went through a drastic reduction in P3, which dropped to only 0.03 kg/m^3.

Spatially, the mean annual flow rate exhibited a moderate upward trend along the mainstream section of the TGR during the research period, increasing from 1.17×10^4 m^3/s of inflow to 1.32×10^4 m^3/s at the YC station (Table 2). However, a considerable decrease of SS concentration occurred from the inflow to the YC station, and the reduction amplitude even exceeded 80% in P2 and P3.

Spatiotemporal variation of phosphorus fractions in the TGR basin

As presented in Fig. 3, the mean annual TP concentrations at all stations were much higher than 0.02 mg/L, which is the critical value causing eutrophication in reservoirs

and lakes. An obvious downward trend of TP concentration from tail area to head area along the TGR mainstream could be observed (ANOVA, $p < 0.05$), and its mean value decreased roughly 60.0% from 0.33 mg/L at ZT station to 0.13 mg/L at YC station. On a multi-year average, the TP concentration was 0.33 mg/L in the mainstream (ZT station) and 0.28 mg/L in Wujiang River (WL station) during 2004–2017, even more than twice of that in Jialing River (BB station). In particular, the TP concentration at WL station dramatically rose to the peak of 0.55 mg/L in 2010 due to the outbreak of severe phosphorus pollution in the upper reaches of Wujiang River and then decreased to 0.15 mg/L in 2017 with the implementation of effective pollution control measures.

Figure 4 showed that phosphorus fractions in the TGR Basin exhibited significant spatial–temporal heterogeneity. Comparing P3 to P2, the TP concentration in the TGR mainstream saw a drastic decrease (ANOVA, $p < 0.05$), but it had no apparent variations at YC station, BB station, and WL station (ANOVA, $p > 0.05$), which indicated that the TP concentrations in the outlet, Jialing River and Wujiang River, were less affected by the construction and operation of the UCRs. Similar to TP, the PP concentration in the mainstream remarkably declined in P3 compared with that in P2 (ANOVA, $p < 0.05$) due to the efficient retention of PP-bounded SS by the UCRs. In particular, the mean PP concentration at the ZT station dramatically dropped nearly 80.0%, from 0.37 mg/L in P2 to 0.08 mg/L in P3. There was a certain decline in the PP concentration at BB station, which decreased from 0.11 mg/L in P2 to 0.05 mg/L in P3, while the variation trend was relatively not apparent (ANOVA, $p > 0.05$). Compared with TP and PP, the TDP concentration did not show an obvious trend in the TGR inner region, Wujiang River and Jialing River, while it increased significantly at ZT station and YC station (ANOVA, $p < 0.05$ at ZT

Fig. 4 Variations of phosphorus fractions in different periods in the TGR basin
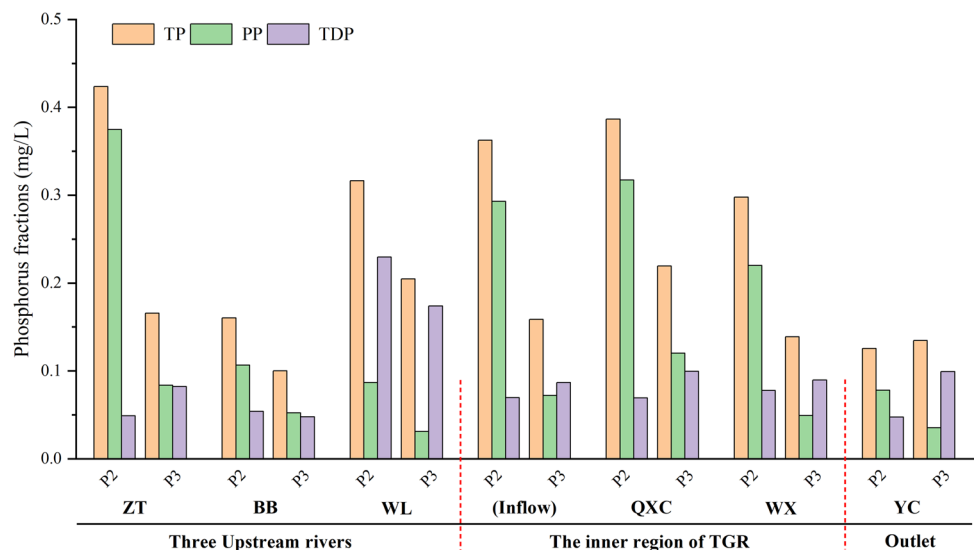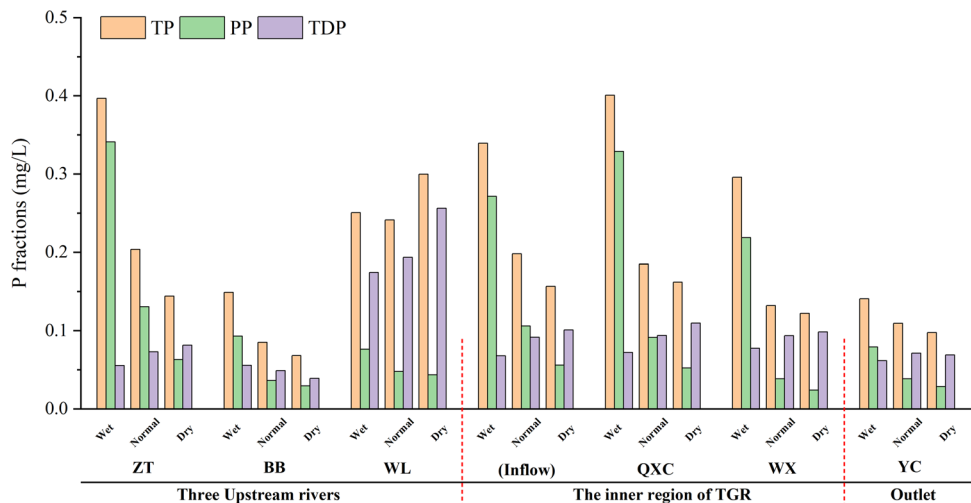
Fig. 5 Seasonal variations of phosphorus fractions in the TGR basin

and YC stations, while $p > 0.05$ at other stations). Besides, the phosphorus composition significantly altered because of the considerable change in the hydrologic regime induced by the operation of UCRs. In the TGR mainstream, PP was the dominant phosphorus fraction in P2, accounting for approximately 60.0–90.0% of TP, while it plunged to no more than 50.0% in P3 (Supplementary Fig. S1). Correspondingly, the TDP:TP ratio in the mainstream displayed a salient upward trend from P2 to P3.

Spatially, both the concentrations of TP and PP showed a significant downward trend along the TGR mainstream, which decreased 70.3% and 79.2% in P2 from ZT station (0.42 mg/L and 0.37 mg/L) to YC station (0.13 mg/L and 0.08 mg/L) separately (Fig. 4), while the rates of reduction in P3 were only 18.9% and 57.7% separately (ANOVA, $p < 0.05$ in P2, while $p > 0.05$ in P3). By contrast, there was no clear trend in the TDP concentration following the flow direction (ANOVA, $p > 0.05$).

The temporal variations of phosphorus fractions in the TGR Basin displayed significant seasonality characteristics (Fig. 5). The PP concentrations at all stations were ranked wet season > normal season > dry season, which had significant seasonal variations (ANOVA, $p < 0.05$). It was noted that the maximum ratio of the PP concentrations in the wet season to those in the dry season was even higher than 9.0, which occurred at the WX station. Similar to PP, obvious seasonal differences in the TP concentrations were observed at all monitoring stations except the WL station (ANOVA, $p = 0.60$ at WL station, while $p < 0.05$ at other stations). Such seasonal patterns of the concentrations of PP and TP could be attributed to increased PP exports caused by intensified soil erosion from the local watershed and upland by enhanced rainfall and runoff in the wet season. However, due to the regulation of TGD on the intra-annual hydrological process, i.e., storing water in the wet season and releasing it in the dry season, the seasonal differences of PP and TP concentrations at the YC station were relatively small.

Except for BB station, the seasonal concentrations of TDP at all stations showed a completely opposite variation trend to those of PP and TP, which ranked dry season > normal season > wet season. Although extreme differences in the TDP concentrations of three seasons could be found in some years, there was no clear trend in the seasonal concentrations of TDP at all stations (ANOVA, $p > 0.05$).

Relationships between phosphorus fractions and sediment in the TGR mainstream

Water flow and sediment play a vital role in the transport and transformation of phosphorus (Conley et al. 2009; Zhou et al. 2013, 2015). As shown in Table 3, the mean monthly concentrations of TP and PP in the mainstream

Table 3 Correlations of the concentrations of TP and PP with SS concentration in the TGR mainstream

Period	Seasons	TP	PP
P2 (2004–2012)	Monthly	$R^2 = 0.64$	$R^2 = 0.78$
	Wet season	$R^2 = 0.63$	$R^2 = 0.94$
	Normal season	$R^2 = 0.48$	$R^2 = 0.62$
	Dry season	$R^2 = 0.16$	$R^2 = 0.40$
	Annual	$R^2 = 0.81$	$R^2 = 0.86$
P3 (2013–2017)	Monthly	$R^2 = 0.21$	$R^2 = 0.60$
	Wet season	$R^2 = 0.51$	$R^2 = 0.56$
	Normal season	$p > 0.05^*$	$R^2 = 0.28$
	Dry season	$p > 0.05^*$	$R^2 = 0.10$
	Annual	$R^2 = 0.44$	$R^2 = 0.58$
Total (2004–2017)	Monthly	$R^2 = 0.62$	$R^2 = 0.75$
	Wet season	$R^2 = 0.63$	$R^2 = 0.72$
	Normal season	$R^2 = 0.39$	$R^2 = 0.61$
	Dry season	$p > 0.05^*$	$R^2 = 0.37$
	Annual	$R^2 = 0.78$	$R^2 = 0.84$

TP total phosphorus, *PP* particulate phosphorus

[*]$p > 0.05$ indicates no correlation

(four stations: ZT, QXC, WX, YC) were positively correlated with SS concentration during 2004–2017, with calculated correlation coefficients of 0.62 and 0.75, respectively. Moreover, the correlation in P3 was considerably weaker than that in P2, with the correlation coefficients decreasing from 0.64 and 0.78 to 0.21 and 0.60, respectively, which could be attributed to the change in the consistency of water and sediment inflow to the TGR after the impoundment of UCRs.

The relevance between SS concentration and the concentrations of TP and PP varied with seasons. As shown in Table 3, TP was positively correlated with SS in the wet season, with correlation coefficients greater than 0.5. However, the relevance was relatively weak in normal and dry seasons, and especially in P3, TP and SS were almost irrelevant in these two seasons. Besides, there were clearly positive correlations between PP and SS in different seasons, with correlation coefficients ranked wet season > normal season > dry season.

Furthermore, there were highly positive associations between the mean annual SS concentration and the concentrations of TP and PP during 2004–2017, with correlation coefficients of 0.78 and 0.84, respectively (Fig. 6). And the corresponding correlations in P3 ($R^2 = 0.44$, $R^2 = 0.58$) were significantly weaker than that in P2 ($R^2 = 0.81$, $R^2 = 0.86$). Additionally, the concentrations of TP and PP were weakly positive relevant to flow rate, with small correlation coefficients of 0.26 and 0.31 (Supplementary Fig. S2), respectively.

Both flow rate and SS concentration have little or almost no correlation with TDP concentration (Supplementary Fig. S3). Nevertheless, the mean monthly TDP:TP ratio was inversely proportional to SS concentration. As presented in Fig. 7, when SS concentration was lower than
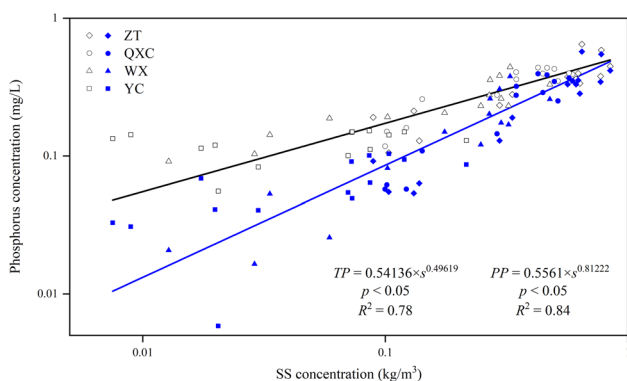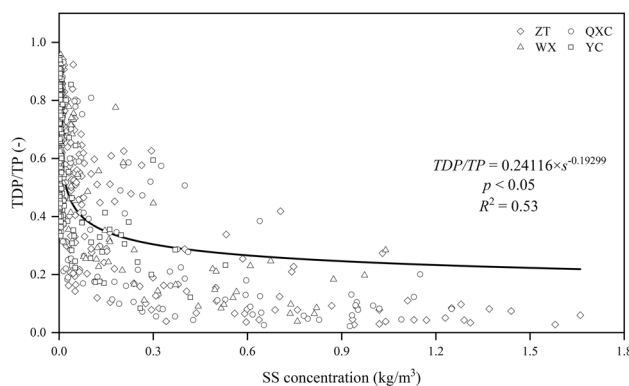

Fig. 7 Relationship between the TDP:TP ratio and SS concentration(s). The monthly data were collected from the TGR mainstream (2004–2017). The bold solid line is the regression tendency, with a coefficient of determination $R^2 = 0.53$

0.3 kg/m³, the TDP:TP ratio plunged with the increment of SS concentration and then gradually decreased, which finally remained steady at about 10.0% since the SS concentration exceeded 1.0 kg/m³.

Discussion

Driving factors of the TDP variation

The periodic and seasonal variations of TDP concentration in the TGR mainstream were significant, and its complex influencing factors should be deeply considered. Comparing P3 to P2, certain increments of TDP concentration could be observed at all stations in the mainstream (Fig. 4). From the external perspective, the phosphorus inputs from upstream inflow should be partially responsible for the increment. There was a salient upward trend of annual TDP concentration at WL station from 2004 to 2012 (Fig. 3), which was mainly related to the exploitation of numerous phosphate mines in the upper reaches of Wujiang River (Han et al. 2016). Consequently, the TDP concentration at the QXC station, which was greatly affected by the input of the Wujiang River, reached a relatively high value of 0.13 mg/L in 2011 (Fig. 3). Besides, the non-point source phosphorus pollution, including a substantial amount of raw domestic sewage and agricultural wastewater (Ongley et al. 2010; Ma et al. 2011), may be another important cause of the increased TDP concentration in the TGR. Previous studies have reported that 70% of the total population in the TGR region lived in rural areas between 2001 and 2016, and farmland was the main land use type (Huang et al. 2016). The annual discharge volume of domestic sewage from the TGR region increased from less than 0.25 billion tons in 1996 to about 0.80 billion tons in 2014, and the annual average use of phosphate fertilizer increased by 16% during the same period (Zhuo

Fig. 6 Correlations of the mean annual concentrations of TP and PP with SS concentration(s). The data were collected from the TGR mainstream (2004–2017). The black hollow symbol indicates TP, and the bold black solid line represents the regression tendency, with a coefficient of determination $R^2 = 0.78$. The blue solid symbol indicates PP, and the bold blue solid line represents the regression tendency, with a coefficient of determination $R^2 = 0.84$

et al. 2017). Moreover, organic phosphorus pesticide was widely applied in the TGR region, which varied in the range of 1.96×10^4–4.60×10^4 t/a and 190.8–593.2 t/a, respectively (MEP 2001–2017).

From the perspective of internal factors, the impoundment of UCRs significantly changed the hydrologic regime in the TGR, which consequently led to temporal variations of phosphorus (Tang et al. 2018b). Considerable sediment interception by the UCRs caused a dramatic decline of the SS concentration in the mainstream since 2013. Therefore, the binding capacity of SS and TDP was decreased with low SS concentration, while the number of phosphorus icons moving freely in the water column was increased (Zhou et al. 2013), which was a major factor contributing to the increased annual TDP concentration. Moreover, phosphorus release from sediment in the TGR tended to aggravate in recent years and mainly took the form of dissolved orthophosphate, which may play a minor part in the increased TDP concentration (Niu et al. 2013). Although it has been reported that the internal release rate of phosphorus in the TGR only varied in the range of 0.15 to 2.55 mg. $m^{-2} \cdot a^{-1}$, which had an almost negligible contribution to the overall phosphorus load in the water column (Niu et al. 2013; Wang et al. 2015). However, after effective control of external phosphorus input in the future, the phosphorus released from sedimentation tends to be a potential threat to the eutrophication in the TGR (Niu et al. 2013).

The seasonal distribution of TDP concentration in the TGR mainstream was characterized by lower in the wet season but higher in normal and dry seasons (Fig. 5), which could be attributed to the following related reasons. Abundant water in the wet season has a stronger dilution ability to the TDP load, and large amounts of TDP are consumed for the growth and propagation of phytoplankton and microorganisms during the wet season. Nevertheless, lower water temperature in the dry season may restrain microbial activities, and the death and decomposition of microorganisms may contribute to the increase of TDP concentration (Dieter et al. 2015). Meanwhile, relatively low SS concentration in normal and dry seasons weakened the binding capacity of SS and TDP, thus increasing the TDP concentration to a certain extent.

Homogenization effects of the UCRs

By storing water in the wet season and releasing it in the dry season, reservoir operation considerably altered the intra-annual distribution of riverine hydrologic processes. Previous studies have reported that the allocations of a runoff between the wet season and the dry season in the Yangtze River Basin have obviously tended to be homogenized in recent decades (Guo et al. 2018; Yan et al. 2021), which was

mainly caused by the operation of TGR in the mainstream and the construction of numerous reservoirs scattered in sub-basins (Chai et al. 2020). In order to reveal the impact of UCRs on the intra-annual distribution of the hydrological process in the TGR, the WX station located in the middle region of TGR was selected as the representative. Comparisons were made between the mean monthly flow rate and SS concentration at WX station in P2 and P3, which were presented in terms of percentage in Fig. 8a. Compared with P2, the flow rate in P3 slightly decreased in the wet season, while obvious increment could be observed in other seasons, especially in the dry season, indicating that the intra-annual distribution of flow rate in the TGR was evened by the operation of UCRs. However, the change of SS concentration exhibited a more uniform pattern, which went through a significant reduction for all months. The reduction rate of SS concentration mainly became larger in the wet season, while it was relatively small in the dry season, and this could be attributed to the UCRs' operation: The major SS load mostly carried by the larger water flow in the wet season was intercepted by the UCRs.

As water and sediment particles are the key environmental media of phosphorus transport in riverine systems, the change of hydrological seasonality distribution caused by the impoundment of UCRs inevitably affects the intra-annual distribution of phosphorus fractions in the TGR. Zhai et al. (2019) reported that the seasonal fluctuations of TP at all monitoring stations in the TGR basically disappeared since 2014, and there was no significant difference in the average TP concentration between the wet season and the dry season from 2014 to 2017. As shown in Fig. 8b, a negative change rate of PP concentration could be observed in all months, and the larger rate of reduction mainly occurred in the wet season, which even reached nearly 90.0%, and this can be explained by the stronger retention effect of UCRs on the PP load in the wet season. The TDP concentration remarkably increased in normal and dry seasons, while it slightly changed in the wet season, which had more non-uniform seasonal distribution in P3. Such variation could be attributed, on the one hand, to the more homogenized intra-annual distribution of runoff under the effect of UCRs and, on the other hand, may be closely related to the increased phosphorus pollution inputs caused by the development of agriculture and industry in the TGR region. There was an apparent change in the monthly TP concentration between P2 and P3, which notably increased in the dry season but decreased in other seasons, especially had a larger rate of reduction (about 40.0–70.0%) in the wet season. Such changes evened the original seasonality distribution of TP concentration in P2 (ranked wet season > normal season > dry season), which in the long run may reduce the risk of eutrophication caused by excessive TP concentration in the wet season.

Fig. 8 The change of monthly distribution of (**a**) flow rate and SS concentration and (**b**) phosphorus fractions at WX station. Comparisons were made between P2 (2004–2012) and P3 (2013–2017)
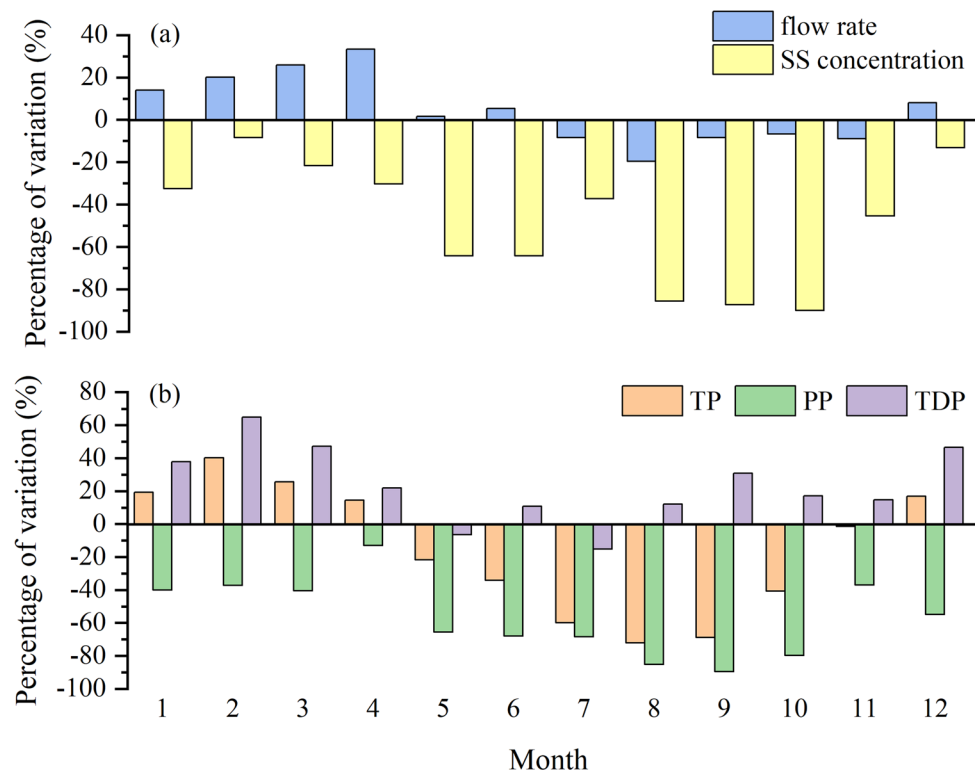
Conclusions

Phosphorus is an essential nutrient limiting life, and its transport and transformation in the riverine system have been significantly affected by the changed hydrologic processes caused by the operation of reservoirs. In this study, for exploring the complicated impact of the impoundment of TGR and UCRs, long-term data of flow rate, SS concentration, and phosphorus fractions of six monitoring stations in the TGR basin were collected and divided into three periods: period 1 (P1) (1985–2002), period 2 (P2) (2003–2012), and period 3 (P3) (2013–2017) based on the periodic impoundment time. The operation of the TGR and UCRs significantly decreased the annual SS concentration. No apparent trend was found in the annual TDP concentration except at ZT and YC stations, while considerable sediment retention by the UCRs dramatically declined the concentrations of TP and PP. There were obvious seasonality variations in different phosphorus fractions. The concentrations of TP and PP ranked wet season > normal season > dry season, while the seasonal distribution of TDP was on the contrary. Comparison analysis showed that the seasonal variation of TP was significantly evened in P3. Positive correlations between the SS concentration and the concentrations of TP and PP in the mainstream were observed, which were more significant in P2 compared with P3.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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