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ORIGINAL ARTICLE

Implications of eutrophication for biogeochemical processes in the Three Gorges Reservoir, China

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Abstract

Although the Three Gorges Reservoir (TGR) is the largest man-made lake in the Changjiang River, it traps only a small fraction of the nitrogen (N) and dissolved silicate (DSi) inflows. Internal dissolution processes of exogenous biogenic silica (BSi) to DSi within TGR may control the overall silica (Si) retention, while the primary diatom production plays a minor role in DSi removal. Transformations of reactive N caused an increase of the dissolved inorganic nitrogen (DIN) load by 3% during transport through the TGR, while retention of dissolved inorganic phosphorus (DIP) is enhanced by biological production. As a result, the TGR causes an increase of the molar DIN/DSi, DSi/DIP, and DIN/DIP ratios, and a decrease of DIN/RSi (reactive Si, the sum of DSi and BSi), leading to an enhanced phosphorus limitation downstream of the TGR. The overall impact of the changing stoichiometry as expressed by the Index for Coastal Eutrophication Potential (ICEP) is an excess production of 27 Tg C/year of non-diatom, potentially harmful phytoplankton. More intensive monitoring is thus needed to better understand the biogeochemical processes in the TGR and to support policy development aimed at improving the water quality in the Changjiang River.

Keywords Changjiang River (Yangtze River) · Nitrogen · Nutrient limitation · Phosphorus · Silicon · Stoichiometry · Three Gorges Reservoir

Highlight
(1) The Three Gorges Reservoir acts as a trap for biogenic silica, not for dissolved silicate.
(2) The Three Gorges Reservoir enhances the Si and P limitation in the Changjiang River and its estuary.
(3) Currently, Changjiang export causes excess production of 27 Tg C/year of non-diatom, potentially harmful phytoplankton.

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Introduction

Important human perturbations of freshwater ecology and nutrient biogeochemistry are related to human interference of the hydrology of rivers (Humborg et al. 1997). For securing food production, humans influence the hydrology in many rivers by extracting irrigation water from the river or from constructed reservoirs; for reducing flood risks, or improving navigability, many rivers have been canalized by dam construction; for securing energy supply, humans have constructed hydropower dams (Lehner et al. 2011). These interferences in the hydrology have major consequences for nutrient transport through and retention in aquatic ecosystems because they impact the travel time of water along the aquatic continuum (Wisser et al. 2010). Dam construction implies a disconnection of upstream and downstream parts of a river (Ward and Stanford 1983). In addition, there are serious concerns about the environmental impacts of large dams on the nutrient stoichiometry through differential retention and transformation processes which change N:P:Si ratios (Billen et al. 1991; Garnier et al. 2010; Maavara et al. 2015). When N and P are discharged in excess over silicon (Si) with respect to the requirements of siliceous algae (diatoms) (Brzezinski 1985; Redfield 1958), non-diatoms, often undesirable harmful algal species, will develop (Billen and Garnier 2007; Zhou et al. 2008).

There are more than 50,000 dams in the Changjiang (Yangtze) River basin (Lehner et al. 2011; Zarfl et al. 2015), the major river draining into the East China Sea (ECS). This paper focuses on the Three Gorges Dam (TGD; Fig. 1) in the Changjiang River, which is the world's largest hydropower dam. The TGR has a length of 650 km along the Changjiang River and has a capacity of 39 km^3 after the full operation of TGD, which is about 10% of the annual discharge at the Yichang hydrological station (Fig. 1). The change of material loading caused by TGR impoundment since 2003 is quite significant (Dai et al. 2011; Yang et al. 2015). Most importantly, the Changjiang River differs from other large global rivers due to the massive increase in population, urbanization, food production, and dam construction, particularly since the 1960s (Liu et al. 2018). Coinciding with the increasing number of dams in the Changjiang River, severe coastal eutrophication occurred in the ECS (Dai et al. 2011). This may be attributed to increasing nitrogen (N) and phosphorus (P) loads from the rivers draining into the ECS and simultaneous decreasing of the dissolved silicate (DSi) concentration in the Changjiang River by one third between the 1960s and 2000s (Dai et al. 2011; Li and Chen 2001). Such changes in nutrient ratios in the Changjiang River may cause a shift in algal dominance in the ECS from siliceous diatoms to non-diatom algae (Jiang et al. 2014; Zhou et al. 2008), like in many other coastal marine ecosystems in the world (Glibert et al. 2012; Humborg et al. 2000; Ragueneau et al. 2006).

Our hypothesis is that the damming of Changjiang River increases the water residence time and water temperature, decreases turbidity, modifies thermal stratification, and, therefore, enhances the carbon and nutrient transformation rates, which affect the nutrient discharge (Conley 2002; Wisser et al. 2010). Also, the Si retention by sedimentation in the TGR is stimulated by N and P loading due to enhanced diatom growth causing a shift in the N:P:Si ratios downstream the reservoir. In this paper, we synthesize recent research data to test this hypothesis.

Description of the Three Gorge Reservoir

The Changjiang River is the largest river in China and Asia, and the third longest river in the world with a mean discharge of 900 km^3 year^{-1} over the past 50 years. It drains 1.8 million km^2 of land area and delivered about 320 Mt year^{-1} (Mt, million tons) of sediment before 2002 to the Changjiang River estuary and the ECS and Yellow Sea (together ECSYS) (Yang et al. 2015).

The construction of the TGR in the Changjiang River started in 1994 and was completed in 2009 forming a 650-km-long man-made lake with a capacity of nearly 39 km^3 (Wu et al. 2003). The filling of TGR occurred in four steps since 2003. A 135-m water level above sea level in Wusong, Shanghai City, was reached in June 2003, and further to 156 m in October 2006. By November 2008, the reservoir level was 172 m, and in 2009, it reached 175 m, which is the ultimate water level after full operation with a residence time in the reservoir of about 1 month. The TGR is a valley-type reservoir with a water surface area of 1100 km^2, which lacks clear stratification (Ran et al. 2013). A typical feature is the formation of large bays in the mouth of the various tributaries. Besides the TGR, the Xiluodu and Xiangjiaba Dams have been built recently in the upstream Changjiang River with capacities of 5.2 and 12.8 km^3, respectively, which act as sediment traps that reduce the sediment load into the TGR.

Sampling and measurement

After the 135-m filling level was reached in 2003, a series of surveys were made in the TGR between 2004 and 2007 to investigate the retention of N, P, and Si. In addition, during the period June 2013–May 2014, water samples were collected on a monthly basis along a transect with three sampling points in the Jiangyin reach (main channel of Changjiang River), Jiangsu Province, downstream of Datong, to investigate the variability of DSi and BSi concentrations and to determine the influence of TGR on riverine nutrient loading.

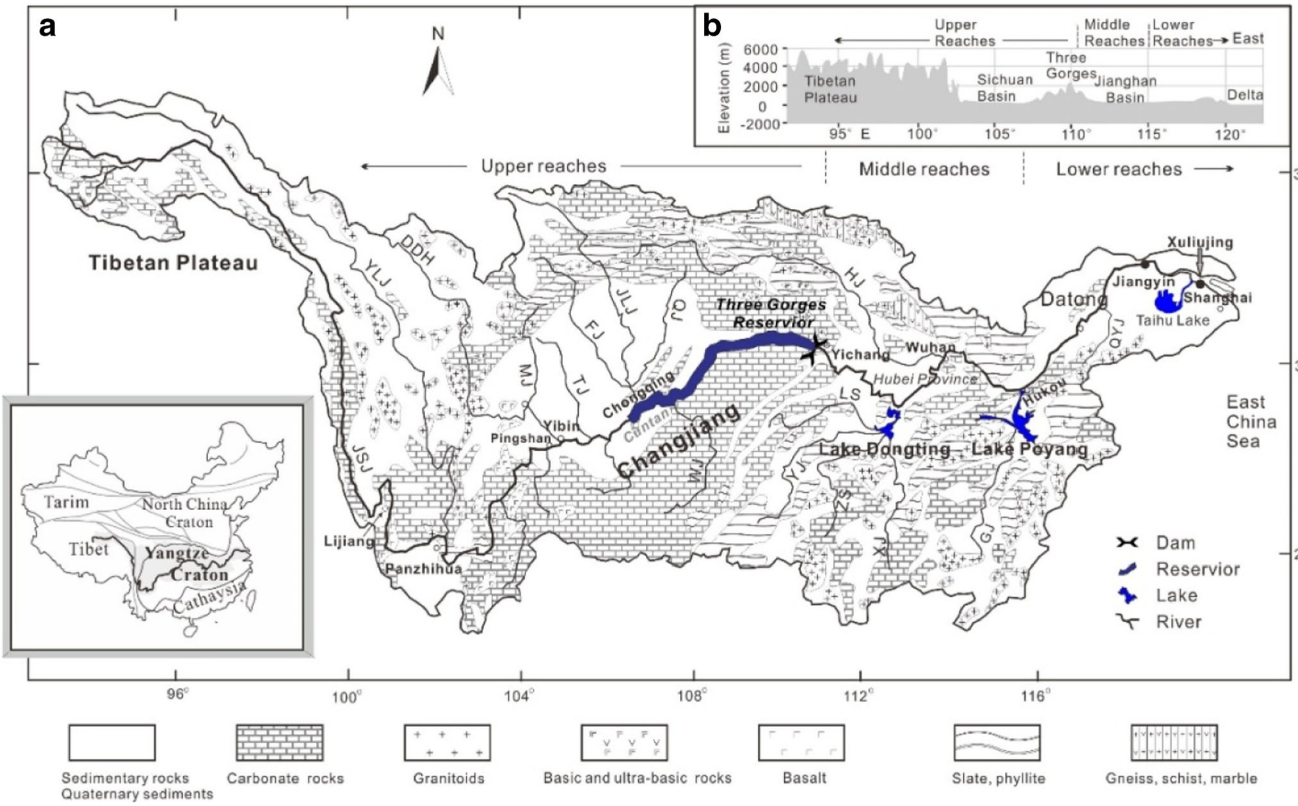

Fig. 1 Map of the three gorges reservoir in the Changjiang River basin

Details on sampling can be found in the Supplementary Information, Text S1 and Table S1, and on the measurements in Text S2 and Table S2.

The nutrient retention is calculated using a mass balance approach as follows:

$$F_R = F_{IN} + F_T - F_{OUT} \tag{1}$$

where F_R represents the nutrient retention, F_{IN} is the upstream inflow, F_T represents inflow from the tributaries in the TGR, and F_{OUT} is the outflow. Groundwater inflow only occurs in the tributaries of the TGR, and direct groundwater discharge into the TGR is therefore negligible, since the river banks along the main channel of TGR consist of solid rock over almost the entire length.

Silica transport and retention

Recent data suggest that during the filling stage of the TGR, retention was at most 4% of the DSi loading (Fig. 2), through sedimentation of biogenic silica (BSi) particles (Ran et al. 2013), which is similar to the global value for Si retention efficiency by reservoirs (Maavara et al. 2015). Although the TGR with its immense size was previously considered to be a sink for Si, most of the DSi retention actually occurs in the many side-bays and not in the reservoir itself (Ran et al. 2010). Like other reservoirs in the world (Maavara et al. 2015), TGR apparently more efficiently retains reactive particulate Si than dissolved Si (Ran et al. 2016a) (Fig. 2). This is the result of BSi retention and internal dissolution processes of exogenous BSi to DSi within TGR which control the overall Si retention, while the primary diatom production plays a minor role in DSi removal (Ran et al. 2016a; Ran et al. 2013) (Fig. 2 and Fig. S1).

The sink of DSi due to diatom utilization and decaying diatom biomass in the TGR was actually balanced by BSi loading from upstream of Fuling (Fig. S1), the outflow point of the reservoir (Ran et al. 2016a; Ran et al. 2013). Data from inflow and outflow points of the TGR during a full hydrological year show that sedimentation accounts for DSi retention in TGR of up to 1.8 Gmol/year, comprising 4% of the incoming DSi load (Fig. 2), which is less than the previously suggested retention of 10%/year (Li et al. 2007). Independently, it was estimated that in 2007, an amount of 170×10^6 tons/year of suspended particulate matter (SPM) (70% of the incoming load) was trapped by TGR (Changjiang Hydrological Committee 2008). About 6.25‰ or 38 Gmol/year of the SPM transported by the Changjiang River is actually BSi (Fig. 2) (Ran et al. 2013, 2016a). This trapping of allochthonous BSi exceeds the autochthonous BSi sedimentation of 1.8 Gmol/year by more than one order of magnitude (Ran et

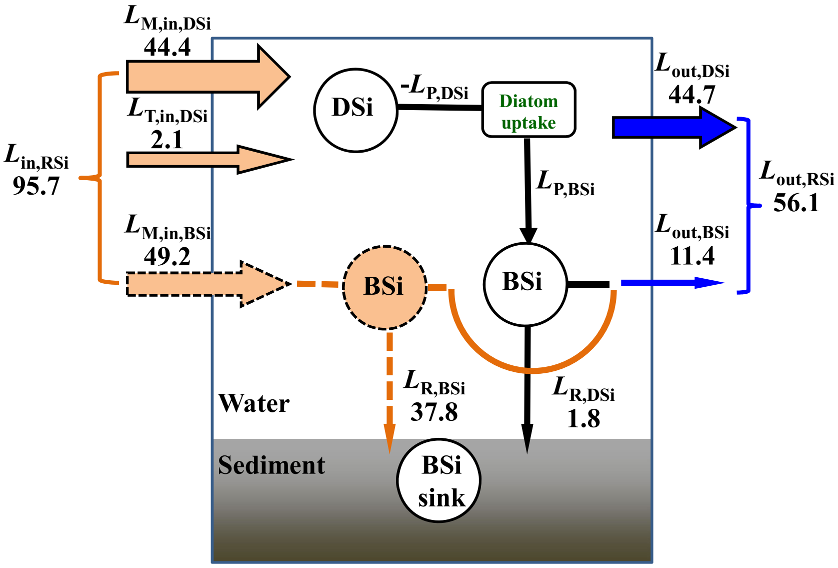

Fig. 2 Current annual retention of reactive silica in the Three Gorges Reservoir (annual DSi fluxes from Ran et al. (2013); annual BSi fluxes were calculated by the sediment loadings (Changjiang Hydrological Committee 2008) and their BSi contents (Ran et al. 2016a)), $L_{in,RSi}$ inflow RSi flux of the TGR; $L_{M,in,DSi}$ DSi flux at the inflow point; $L_{M,in,BSi}$ BSi flux at the inflow point of the TGR; $L_{out,DSi}$ DSi flux in the outflow from the TGR; $L_{out,BSi}$ BSi flux in the outflow of the TGR; $L_{T,in,DSi}$ DSi flux of the tributaries in the TGR; $L_{R,DSi}$ DSi retention in the TGR by the diatom fixation; $L_{R,BSi}$ upstream (autochtonous) BSi retention in the TGR; $L_{out,RSi}$ outflow RSi flux from the TGR; the loads are in gram moles per year

al. 2013). Therefore, there is annually a significant retention of total silica (BSi and DSi), mainly due to trapping of the BSi inflow to the TGR. On the basis of sediment BSi analyses, the annual BSi dissolution within the TGR was calculated as 4–16% of the riverine DSi load downstream the TGD (Ran et al. 2016a). Hence, trapping and dissolution of upstream BSi supplies part of the DSi exported by the TGR, which was neglected in all previous studies (Cook et al. 2010; Lauerwald et al. 2012; McGinnis et al. 2006).

Nitrogen and phosphorus retention

Prior to the TGD completion, an annual retention was expected of 10% of the inflow of DIN and 40% of DIP (Zhang et al. 1999). However, a nutrient balance study did not indicate a considerable difference between total N inflow and outflow (Fig. S2) (Ran et al. 2017). Transformations of DON, nitrite, and ammonia caused an increase of the DIN load by 3% (Ran et al. 2017) (Fig. 3), which is the balance between DIN formation and losses. Hence, transformations of dissolved reactive N that stem from the upstream part of the Changjiang River caused an increase of the DIN load in the TGR (Fig. 3). At the same time, approximately 7% of inflowing total dissolved nitrogen (TDN; Fig. 3) was lost as a result of denitrification and uptake (Ran et al. 2017). Due to the short water residence time of about 30 days, DIN loss by denitrification and uptake/sedimentation in the TGR was less than that in other reservoirs with longer residence times (Cook et al. 2010; Garnier et al. 1999; Grantz et al. 2014; Levine and Schindler 1992).

About 30% of the DIP was retained within the TGR in 2007, the year in which TGR reached its present storage capacity (Ran et al. 2016b) (Fig. 4). This estimate, based on a mass balance approach, is close to the P retention (40%) predicted prior to the TGR completion (Zhang et al. 1999). The difference between inflow and outflow of DOP based on time-series data is only small (Fig. 4) (Ran et al. 2016b), suggesting that the mechanism controlling the outflow of dissolved P species in the reservoir is the transformation of DIP to particulate phosphorus (PP) and its sedimentation (Fig. S3). It should be noted that the transformation of DIP to PP may be significant due to production under the prevailing P limitation (molar DIN:DIP > 100) in the TGR. As a result of accumulation of P in the reservoir, the TDP outflow from the TGR is much less than the inflow.

Stoichiometrical change

The BSi retention in the Changjiang River calculated from the BSi proportion in SPM showed an increasing trend over the past 30 years due to the increasing reservoir volume, which resulted in a major decrease in BSi/RSi ratios in the Changjiang River outflow (Ran et al. 2016a). With an even enhanced BSi retention in the past decade, the TGR has

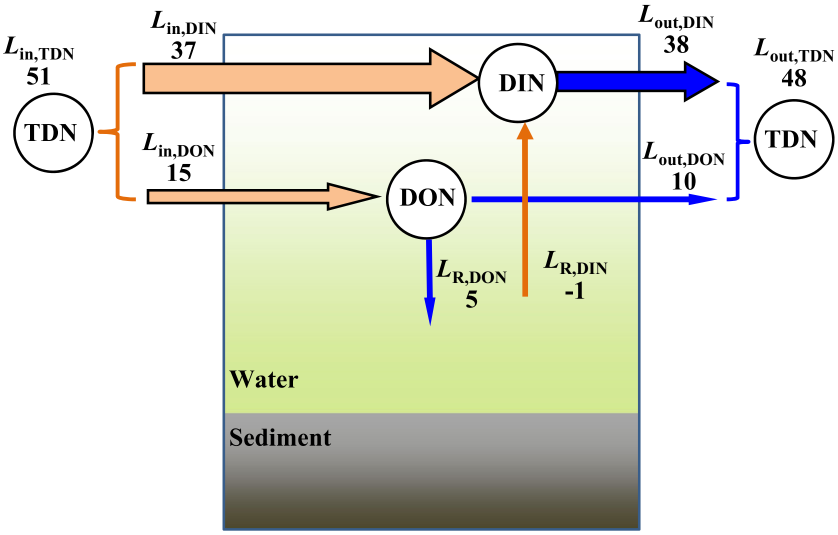

Fig. 3 Retention of nitrogen in the Three Gorges Reservoir in (Ran et al. 2017). $L_{in,TDN}$ TDN flux at the inflow to the TGR including the mainstream input and that from tributaries; $L_{out,TDN}$ TDN flux at the outflow of the TGR; $L_{in,DIN}$ DIN flux at the inflow to the TGR including the mainstream input and that from tributaries; $L_{out,DIN}$ DIN flux at the outflow of the TGR; $L_{R,DIN}$ DIN retention in the TGR; $L_{in,DON}$ DON flux at the inflow to the TGR including the mainstream input and tributaries fluxes; $L_{out,DON}$ DON flux in the outflow of the TGR; $L_{R,DON}$ DON retention in the TGR; the loads are in gram moles per year

probably induced a substantial BSi depletion in the coastal ECS. The inflow of BSi, DON, and DOP from the upstream part of Changjiang River and subsequent transformations are important (Figs. 2, 3, and 4) (Liu et al. 2003; Ran et al. 2016a), and BSi dissolution contributes 4–16% to DSi outflow from the TGR. The TGR therefore acts as a converter of nutrients rather than a trap (Ran et al. 2016b).

The biogeochemical processing together with the inflow composition in the TGR can cause an increase in the DIN/DSi, DSi/DIP, DIN/DIP, and RSi/TDP ratios ($p < 0.01$, Fig. 5a,c d and f), and a decrease of the DIN/RSi ratio (Fig. 5b). However, there is almost no change of TDN/TDP between the inflow and outflow (Fig. 5e). N concentrations are relatively high compared to those of P and Si in the Changjiang River (Liu et al. 2003). If the retention of P and Si exceeds that of N (Ran et al. 2013, 2016b), the P and Si limitation in water downstream the TGR may be enhanced compared to the inflow. Also, the molar N:P:Si ratio in the sediment of about 7.8

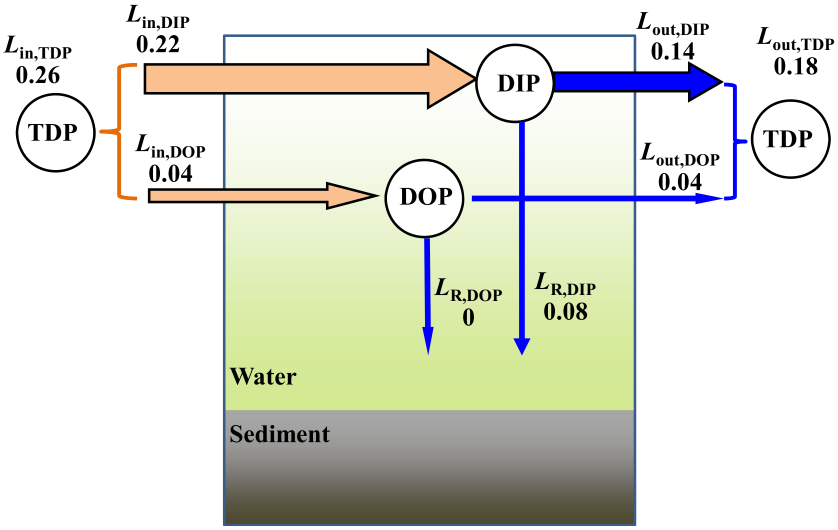

Fig. 4 Current annual retention of phosphorus in the Three Gorges Reservoir (Ran et al. 2016b). $L_{in,TDP}$ TDP flux at the inflow in the upstream of the TGR including the mainstream input and that from tributaries; $L_{out,TDP}$ TDP flux at the outflow of the TGR; $L_{in,DIP}$ DIP flux at the inflow in the upstream of the TGR including the mainstream input and that from tributaries; $L_{out,DIP}$ DIP flux in the outflow of the TGR; $L_{R,DIP}$ DIP retention in the TGR; $L_{in,DOP}$ DOP flux in the inflow to the TGR including the mainstream input and that from tributaries; $L_{out,DOP}$ DOP flux at the outflow of the TGR; $L_{R,DOP}$ DOP retention in the TGR; the loads are in gram moles per year

(± 3.1):1.0 (± 0.2):8.2 (± 0.9) in the TGR (Ran et al. 2013; Zhao et al. 2017) is significantly different from that in the water column ($p < 0.05$; Fig. 5) and indicates an enhanced P burial in the reservoir in comparison with N and Si.

The DIN and DIP fluxes in the Changjiang River strongly increased in recent decades (Yan et al. 2010), while DSi and BSi fluxes have rapidly decreased between 1960 and 2013 (Liu et al. 2016; Ran et al. 2016a). As a result, the N/Si ratios have changed significantly. Before the 1970s, the N/Si ratios were stable (Duan et al. 2007; Maavara 2017) while N/Si ratios increased from 0.2 in the 1970s to about 0.5 in the early 1980s (Duan et al. 2007), and from less than 0.8 in the 1980s to around 1 before TGD operation (Liu et al. 2003).

A major increase of the molar ratio of total N:total P has been observed in the Changjiang River since the 1960s to values exceeding 35 (Liu et al. 2018), which is higher than the Redfield molar ratio of 16 (Redfield 1958). This implies an ongoing and increasing distortion of the nutrient stoichiometry with much higher N/Si and N/P ratios than a few decades ago (Fu et al. 2012; Xing et al. 2016) due to the increasing nutrient loadings from agricultural areas in the Changjiang River basin (Liu et al. 2018). In comparison with the nutrient ratios before the 1960s and 1970s, the Changjiang River has witnessed a shift from N and P limitations to a P limited ecosystem. Due to the significant retention of RSi in the TGR, a potential Si limitation could develop downstream the TGD (Fig. 5). The nutrient stoichiometrical changes may be partly responsible for the recent increase in the frequency and extent of harmful algal blooms (mainly in non-siliceous algae) in the ECSYS (Fu et al. 2012; Jiang et al. 2014; State Oceanic Administration People's Republic of China 2014). Harmful algal blooms are also increasingly observed in the Changjiang River and its tributaries and in Chinese coastal waters.

We computed the Index of Coastal Eutrophication Potential (ICEP; Billen and Garnier 2007). ICEP is calculated by comparing the N, P, and Si loading to the Redfield ratios expressing the requirements of marine diatom growth. The ICEP represents the potential impact of the riverine delivery to the coastal zone. ICEP does not take into account the particular morphological, climatic, and hydrological conditions such as stratification, and the impact of upwelling of nutrients that locally determine the response of the marine algae in the receiving coastal zone (GEOHAB 2006). We calculated ICEP using the total N and total P export data for 2010 from Liu et al. (2018) and the DSi and BSi export by the Changjiang River in 2013/2014 (Ran et al. 2016a). The result for this P limiting system is a positive value, i.e., an excess carbon production of 27 Tg/year over the Si requirements of diatoms, assuming that both DSi and BSi contribute to diatom production. Positive values of ICEP indicate an excess of N or P over Si, which may lead to production of non-diatom, possibly harmful algae species.

Implications

There are more than 50,000 dams along the Changjiang River and its tributaries. The decrease in riverine sediment loading is largely attributed to dam construction. Recent changes in the nutrient stoichiometry in water flowing through the Changjiang River to ECSYS clearly show that the TGR is likely to induce an increasing P limitation over time. Also, the enhanced permanent BSi sedimentation in the TGR would

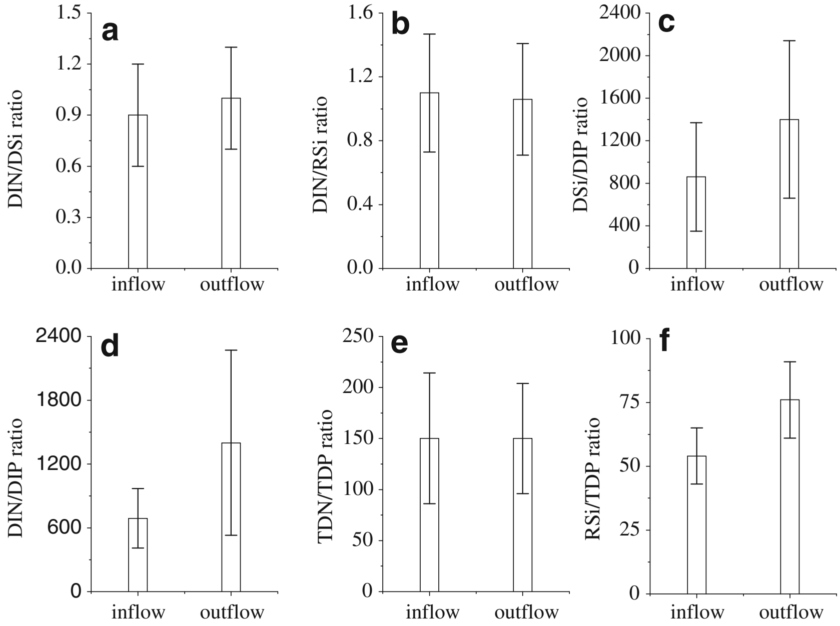

Fig. 5 Stoichiometrical change during transport through the TGR. Ratios are on atomic basis, and error bars indicate the standard deviation

affect the reactive Si cycling in the adjacent area of the Changjiang River estuary and, thereby, limit the diatom primary production in the ECSYS close to the Changjiang River estuary and stimulate the proliferation of undesirable harmful algae (Gong et al. 2006; Liu et al. 2016; Zhou et al. 2008). With the prevailing P limitation in the Changjiang River estuary and adjacent coastal waters, the dinoflagellate *P. donghaiense* dominates the diatom *S. costatum* in their competition (Zhou et al. 2008), and there is also evidence that harmful algal blooms of both non-siliceous and siliceous algae are enhanced at high N levels and high N:P ratios (Li et al. 2009; Zhao et al. 2016; Zhou et al. 2008). The change of algae composition in Changjiang River estuary responding to the enhanced P limitation may continue in the future with the planned construction of new dams in the Changjiang River. Therefore, managing dams in the Changjiang River should aim at improving the P (and Si) limitation parallel to strategies to reduce nutrient discharge to surface water from agriculture and sewered urban areas. To better quantify the retention and transformation processes in the TGR and to better predict future changes in the stoichiometric nutrient balance, we need to improve our understanding of the biogeochemical processes in the river basin that affect the ON, OP, and BSi transfer and dissolution during their transport to the ECSYS (Fig. 6). Estimates of both N and Si retention in the TGR presented here are different from previous studies. There was an increase of the whole-basin soil nutrient (N and P) pool and nutrient delivery to surface water in the Changjiang River in the period 1900–2010 due to the increasing fertilizer and manure use in agricultural areas (Liu et al. 2018). Continued intensive monitoring is required and should ideally be specifically targeted to determine the influence of the TGR and other reservoirs on the nutrient cycling and stoichiometrical changes in the Changjiang River, which may help to identify strategies to protect water quality.

Conclusion

Following the operation of the TGD since 2003, and with increasing nutrient loads and the changing nutrient source cocktail, the TGR export shows an increase of the molar DIN/DSi, DSi/DIP, and DIN/DIP ratios, and a decrease of DIN/RSi (reactive Si, the sum of DSi and BSi), leading to an enhanced phosphorus limitation downstream of the TGR. Internal dissolution processes of exogenous biogenic silica (BSi) to DSi within TGR may control the overall silica (Si) retention, while the primary diatom production plays a minor role in DSi removal. Transformations of reactive N caused an increase of the dissolved inorganic nitrogen (DIN) load by 3% during transport through the TGR, while retention of dissolved inorganic phosphorus (DIP) is enhanced by sedimentation. The overall impact of the changing stoichiometry as expressed by the Index for Coastal Eutrophication Potential (ICEP) is an excess production of 27 Tg C/year of non-diatom, potentially harmful phytoplankton. We therefore conclude that the change in nutrient stoichiometry observed after the construction of the TGR, and with rapidly increasing nutrient loads with changing composition, has severe environmental impacts in the ECSYS, and comprehensive studies are needed to improve our knowledge for advising environmental

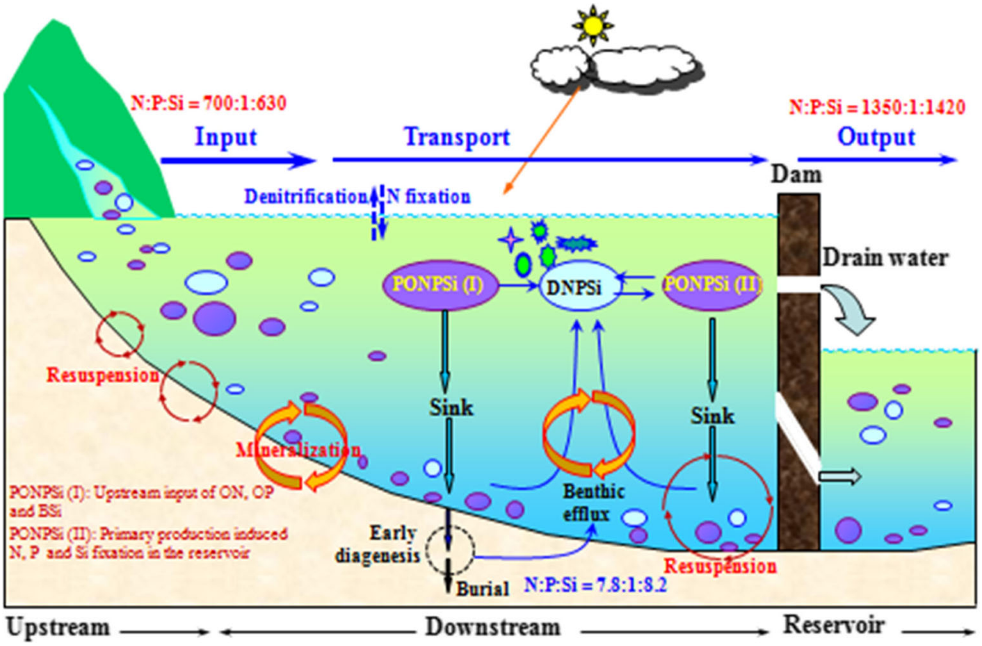

Fig. 6 The different processes involved in nutrient transformations and retention in the TGR. ON and OP are organic nitrogen and organic phosphorus, respectively, and PONPSi is the abbreviation of particulate ON, OP, and BSi. Ratios are on atomic basis for inorganic forms in the water and total species in the sediment

managers and policy makers on appropriate nutrient reduction measures.

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Author contribution X.B.R. and Z.G.Y. designed the research; X.B.R. A.F.B., and J.L. wrote the paper; J.L. worked on the figures.

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