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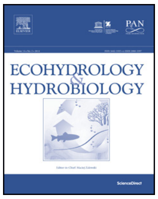

Original Research Article

# Water quality trends in the Three Gorges Reservoir region before and after impoundment (1992–2016)

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ABSTRACT

Reservoirs are essential for the wellbeing of human societies, but can also be subject to negative ecological impacts. The Three Gorges Reservoir (TGR) in the upper Yangtze River is remarkable for its size and engineering; however, its effects on water quality are poorly understood. To the best of our knowledge, this study is the first to describe long-term (1992–2016) monitoring. It showed that the chemical oxygen demand (COD, via the potassium permanganate index) and total phosphorus (TP) have decreased 40.9% ± 9.9% and 22.2% ± 9.7% respectively in the TGR mainstream between impoundment in June 2003 and 2016, while total nitrogen (TN) and ammonium ($NH_4$-N) have increased 1.3% ± 2.4% and 8.2% ± 2.6%. In addition, phytoplankton biomass has increased by a factor of 2.7 (1.1–4.8) over pre-impoundment levels in the mainstream, and tributary algal blooms have increased in frequency since 2004. The reductions in COD and TP were caused primarily by decreases in water flow speed, which lead to sediment settlement. The anti-seasonal operation pattern and water volume increased TGR may also increases the dilution capacity. TN and ammonium are less affected by sediment deposition and have increased slightly under intensified human activities. Decreased water flow speeds and nutrient enrichment have promoted increases in algal biomass, leading to blooms in tributary backwater zones. In situ experiments indicate that phytoplankton growth in the TGR is phosphorus limited during all seasons. Therefore, controlling phosphorus will reduce the short-term eutrophication potential in the reservoir. However, concurrent control of nitrogen and phosphorus inputs are necessary in the long term.

## 1. Introduction

Reservoirs play an important role in water supply, flood control, shipping, fisheries, and power generation, all of which contribute significantly to societal wellbeing. However, reservoirs can also cause negative ecological impacts and potentially dire consequences such as local extinctions by submergence. Negative impacts may include the impedance of fish movement; considerable

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variations in water level, which may lead to intermittent submergence and drying of significant areas; changes in the water regime experienced by aquatic macrophytes; and periodic increases in water residence time, leading to nutrient and sediment accumulation and promoting the formation of harmful cyanobacterial blooms, which pose potential threats to human health. Finally, fishing habitat in deeper hypoxic or anoxic waters may be lost (Cernea, 2008; United Nations Environmental Program, 2007).

Increasing numbers of reservoirs are being constructed in developing countries for hydropower generation, water storage, and flood control (Millikan, 2010; Pittock, 2010). As the largest developing country and the world's second largest economy, China has continued to accelerate the pace of dam construction in recent decades, and the majority of these dams are intended for hydro-power generation. China's reservoirs (26,870 $km^2$) constitute less than one-third of the total area of natural lakes (82,232 $km^2$), but the total reservoir volume (approximately $794 \times 10^9$ $m^3$) is about three times the total lake volume (about $268 \times 10^9$ $m^3$) (Yang and Lu, 2014). These reservoirs serve as critical drinking water sources for hundreds of millions of people living in cities along rivers and as a water supply for industry and agriculture.

The Three Gorges Reservoir (TGR) is a typical flooded river valley reservoir and the world's largest reservoir, when its water fluctuation zone is included. The TGR plays key roles in flood control, power generation, shipping, and the storage of water resources for irrigation and potable water supplies (see Supplementary materials). Because discharge from the upstream Yangtze River is spatially and temporally variable, dam management must balance the retention of water for irrigation and potable water supply with floodwater mitigation; prior to the monsoon season, the TGR falls to its minimum permissible water level. Operation of the TGR is optimized and adjusted to guarantee the demand for water and shipping and provide sufficient high quality, clean electricity. However, the ecological consequences of the modified hydrology have not been adequately considered. Due to its eco-environmental and societal impacts, the Three Gorges Dam project has been one of the most controversial projects in China. Since the reservoir began filling with water in 2003 (to an elevation of 139 m), the emerging environmental concerns have captured the attention of researchers and environmental activists worldwide (e.g., Fu et al., 2010; Stone, 2008, 2011; Wu et al., 2003). Sedimentation and downstream riverbed erosion (Lu et al., 2011; Yang et al., 2006), reservoir-induced seismicity and geological instability (Guo et al., 2007; Wang et al., 2004), and the displacement of human populations from villages in the flooded region have all been causes for concern in the region (Tan, 2008; Xu et al., 2011).

Contentious eco-environmental issues surrounding the TGR have centered on water quality (Bi et al., 2010; Yang et al., 2007). Xu et al. (2013) used China's authoritative 1992 Environmental Impact Statement for the TGR as a benchmark against which to evaluate environmental outcomes since the initial impoundment of the TGR in 2003; they also pointed out that eutrophication is worse than originally predicted. Algal blooms occur frequently in the backwater areas of various TGR tributaries (Liu et al., 2012; Wang et al., 2011a). However, water flow has gradually decreased in the TGR since impoundment, which favors the precipitation of suspended nutrients and inorganic particles (Wu et al., 2016).

Unfortunately, previous studies concerning the TGR have been conducted over limited time periods and/or reservoir areas and therefore cannot reveal the comprehensive impact of the dam on the aquatic eco-environment. Here, we analyze water quality dynamics over 25 years to evaluate the impact of the dam on the reservoir system. In addition, we present in situ experiments conducted to determine the nutrient limitation regime in TGR tributaries, where algal bloom frequently form.

## 2. Materials and methods

### 2.1. Study area

The TGR dam on the Yangtze River commenced construction in 1993 and impoundment in 2003, and was completed in 2009. The maximum water level elevation is 175 m, and the reservoir has a total capacity of 39.3 billions $m^3$ and a total area of 1084 $km^2$. The reservoir is approximately 670 km in length, with an average width of 1.1 km and an average depth of 90 m (in the mainstream). The Three Gorges dam controls the total area of the rainwater catchment (which is referred to as the Three Gorges Catchment, or TGC), which measures more than 1.02 millions $km^2$. The total area of the TGR region, which includes numerous towns and cities in the Chongqing City and Hubei Province areas, is more than 10,000 $km^2$ (Fig. S1).

### 2.2. Data

In order to assess the impact of the dam on water quality, a suite of water quality indicators are analyzed in a 25-year period before and after impoundment. Data on water quality parameters, including the chemical oxygen demand (COD) potassium permanganate index, total phosphorus (TP), total nitrogen (TN), ammonium ($NH_4^+$-N), water level, and Chlorophyll-a were available from the Yangtze Water Environmental Monitoring Center. We performed monthly monitoring of algal bloom conditions, and bloom data were also available from the Ministry of Environmental Protection of the People's Republic of China, *Eco-environmental Monitoring Bulletin of the Three Gorges Project, Yangtze, China* (1997–2016, in Chinese, data available at http://www.cnemc.cn/publish/107/0594/350/newList_1.html).

In order to assess the impact of the dam on total suspended solids (TSS), precipitation, and nutrient concentration along the TGR mainstream, we took a total of 9 L of water samples (3 L each, 10 min sampling time) at sites in Cuntan (in the mainstream upper reach, 670 km from the dam), Wanzhou (in the middle reach, 330 km from the dam), and Zigui (at the head of the mainstream, 2 km from the dam) on May 20, 2015. Water samples were transported to the lab and shaken for 1 min to encourage uniform mixing. We then sampled and filtered 0.3 L of the supernatant liquid at 0 h, 0.5 h, 1 h, 2 h, 4 h, 8 h, and 16 h after shaking. The TSS, TP, TN, and COD in the samples were

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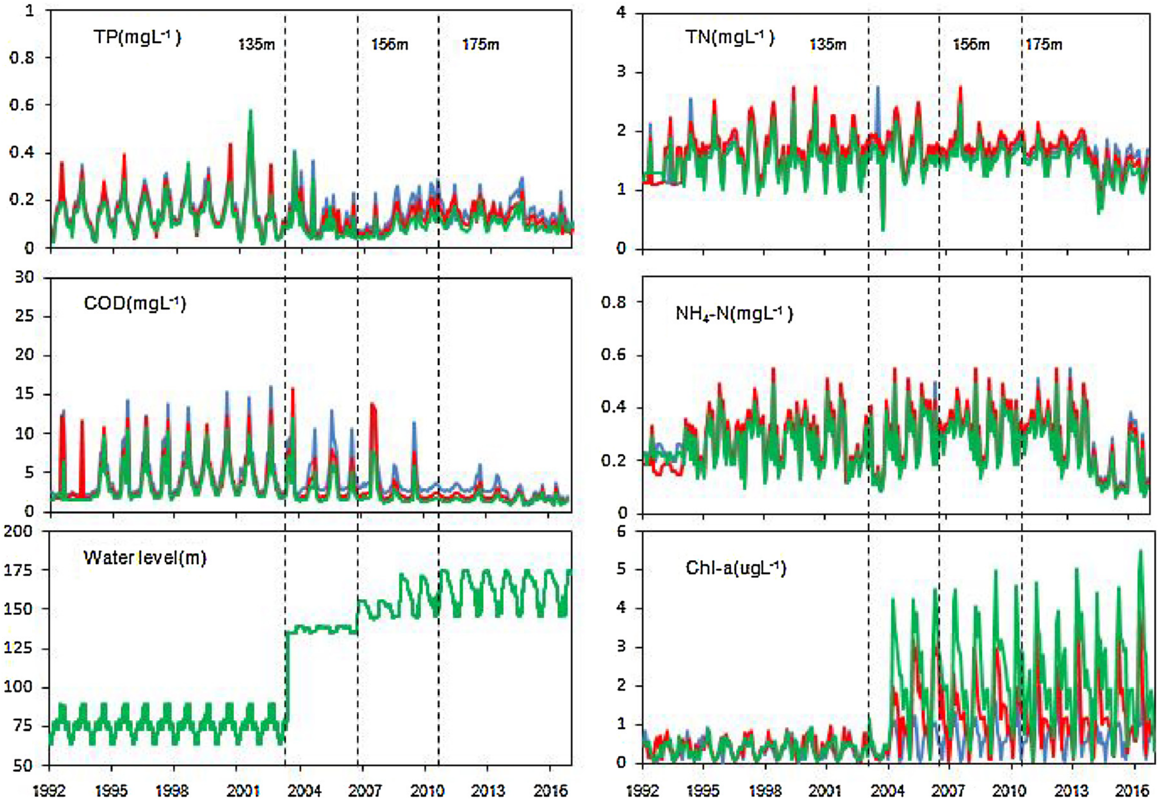

**Fig. 1.** Monthly measurements of eco-environmental parameters in the TGR mainstream between 1992 and 2016. Sample sites: Cuntan (blue, in the TGR mainstream upper reach), Wangzhou (red, in the middle reach of the TGR), Zigui (green, near the TGR dam). The dotted lines indicate when the water impoundment level reached 135 m, 156 m, and 175 m.

measured according to the National Standard Methods used in China: COD by GB/T 15456-2008, TP by GB11893-1989, TN by GB11894-1989, NH4+-N by HJ/T 195-2005, TSS by GB11903-89 and hydrological data by SL 58-1993. In order to assess nutrient limitation, we conducted in situ bioassays (phytoplankton density by GB 7489-87, Chlorophyll-a by146 SL 88-2012) on the Pengxi River, a backwater tributary of the TGR reservoir (see Figs. S4 and S5 in the Supplementary materials).

In order to assess the impact of anthropogenic activities on water quality, we measured land use, sewage generation, population, and economic growth in the TGR region. Data on population, gross domestic product (GDP), and all types of sewage were taken from the local government yearbook. The watershed boundaries of TGR basin were delineated with a resolution of 90 m (available at http://srtm.csi.cgiar.org/index.asp) in Q-GIS software (Version 2.14.3; available at http://www.qgis.org/en/site/). Land use and land cover (LULC) compositions in 1995, 2000, 2005, and 2010 were extracted from 1 km resolution national land cover data for China interpreted from Landsat TM images (available at http://www.resdc.cn/) using ArcGIS 10.1 software. The LULC classes were further grouped into seven categories: forest, grassland, waterbodies, urban areas, bare soil, and cropland (Liu et al., 2003). Population density and GDP data from 1992 to 2016 with 1 km$^2$ resolution (available at http://www.resdc.cn/) were extracted for individual watersheds using ArcGIS 10.1 software. Data on LULC, population density, and GDP were only available for 1995, 2000, 2005, and 2010.

Statistical analyses, including mean values, standard deviations, and *t*-tests, were conducted using EXCEL2013, SPSS8.0, and Origin9.0 software. Significance is indicated by *t*-test results with $p < 0.05$; means are given herein ± their standard deviations.

## 3. Results

### 3.1. Water quality parameters across the TGR before and after impoundment

Water quality parameters across the TGR before and after impoundment are shown in Fig.1. After reservoir filling, the average water flow velocity decreased from $2.12 \pm 0.37$ m s$^{-1}$ to $1.33 \pm 0.26$ m s$^{-1}$ in the Cuntan section, from $1.87 \pm 0.21$ m s$^{-1}$ to $0.58 \pm 0.09$ m s$^{-1}$ in the Wanzhou section, and from $2.15 \pm 0.05$ m s$^{-1}$ to $0.29 \pm 0.01$ m s$^{-1}$ in the Zigui section. Nutrients and COD in the TGR mainstream area are shown before (1992–2003) and after (2004–2016) water impoundment. Monthly TGR water quality monitoring shows that TP and COD decreased significantly ($p < 0.05$) in the 13 years after impoundment (2004–2016) compared to the 12 previous years (1992–2003); TP decreased 22.2 ± 9.7%, while COD

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decreased 40.9 ± 9.9%. In addition, concentrations of TP and COD after impoundment can be ordered as follows: Cuntan > Wanzhou > Zigui. TN increased after impoundment by 1.3 ± 2.4% and ammonium increased by 8.2 ± 2.6%. The annual highest value decreased significantly ($p < 0.05$).

Before TGR impoundment, the reservoir region was a natural river with high flow velocity and largely uninterrupted hydrology; no algal blooms were reported in the region, and phytoplankton species were dominated by Bacillariophyta. After impoundment, the phytoplankton species did not change significantly in this region, but the frequency of *Cyanophyta* and *Chlorophyta* occurrences have increased significantly. The Chlorophyll-a (Chl-a) concentrations have increased by a factor of 2.7 on average (from 0.37 to 1.39 $\mu$g L$^{-1}$). Although no algal blooms have appeared in the reservoir mainstream, blooms occur frequently in the backwater areas of TGR tributaries. More than 8 genera of phytoplankton have been observed to dominate or co-dominate these algal blooms (Table 1), which appear as a scum layer on the water surface and last between 1 and 55 d, covering areas from several square meters to 20 km in length in backwater tributary areas. The genus *Microcystis* blooms most frequently in the TGR tributaries; its first occurrence was recorded in May 2004.

Our experiments show that TSS decreases along the TGR (Cuntan > Wanzhou > Zigui) and with increased settling time. TSS has a significant relationship TP ($p < 0.01$), COD ($p < 0.01$) and TN ($p < 0.05$) (Fig. 2).

### 3.2. Nutrient inputs from major TGR tributaries

Runoff from five major TGR basin tributaries, including the Jinsha, Minjiang, Tuojiang, Jialing, and Wujiang Rivers, accounts for 90% of the flow to the TGR (Table 2). In the Fuling section, the total average TP flux is 1.61 kg s$^{-1}$ and the total average TN flux is 25.01 kg s$^{-1}$ 1 into the TGR mainstream. The monthly nutrient fluxes in 2008–2010 show seasonal patterns in the major tributaries (Fig. 3), where the highest concentrations occur in July and August. The nutrient fluxes in the five major tributaries shows significant relationships with each other (Fig. 4).

**Table 1**
Phytoplankton blooms in tributaries in the TGR region after impoundment.

| Tributary name | Length (km) | Basin area (km$^2$) | Annual runoff (km$^3$) | Bloom species (genus) |
|---|---|---|---|---|
| Xiangxi River | 94 | 3099 | 1.27 | *Microcystis*, *Anabaena*, *Oscillatoria*, *Cyclotella*, *Ceratium*, *Pandorina*, *Synedra* |
| Shenlongxi River | 60.6 | 1047 | 3.3 | *Microcystis*, *Synedra*, *Ceratium*, *Pandorina*, *Synedra* |
| Daning River | 142.7 | 4045 | 5.11 | *Microcystis*, *Anabaena*, *Oscillatoria*, *Cyclotella*, *Ceratium*, *Pandorina* |
| Zhuyi River | 31.4 | 154 | 0.09 | *Microcystis*, *Anabaena*, *Oscillatoria*, *Cyclotella*, *Ceratium*, *Pandorina* |
| Pengxi River | 182.4 | 5173 | 3.58 | *Microcystis*, *Anabaena*, *Cyclotella*, *Ceratium*, *Pandorina*, *Synedra* |
| Zhuxi River | 21.4 | 114 | 0.14 | *Microcystis*, *Oscillatoria*, *Cyclotella*, *Ceratium*, *Synedra* |
| Ruxi River | 54.5 | 720 | 1.49 | *Anabaena*, *Oscillatoria*, *Cyclotella*, *Ceratium*, *Pandorina*, *Synedra* |
| Long River | 164 | 2810 | 0.88 | *Microcystis*, *Oscillatoria*, *Cyclotella*, *Ceratium*, *Pandorina*, *Synedra* |
| Yulin River | 218.2 | 3861 | 1.81 | *Microcystis*, *Anabaena*, *Cyclotella*, *Ceratium*, *Pandorina*, *Synedra* |
| Modaoxi River | 170 | 3167 | 1.99 | *Ceratium*, *Pandorina*, *Synedra* |
| Meixi River | 103 | 1929 | 1.44 | *Peridiniopsis*, *Synedra* |
| Daxi River | 70 | 1587 | 1.21 | *Oscillatoria*, *Cyclotella*, *Ceratium*, *Pandorina*, *Synedra* |
| Changtan River | 93.6 | 1266 | 0.85 | *Microcystis*, *Anabaena*, *Cyclotella*, |
| Caotang River | 33 | 395 | 0.24 | *Cyclotella*, *Ceratium*, *Pandorina* |

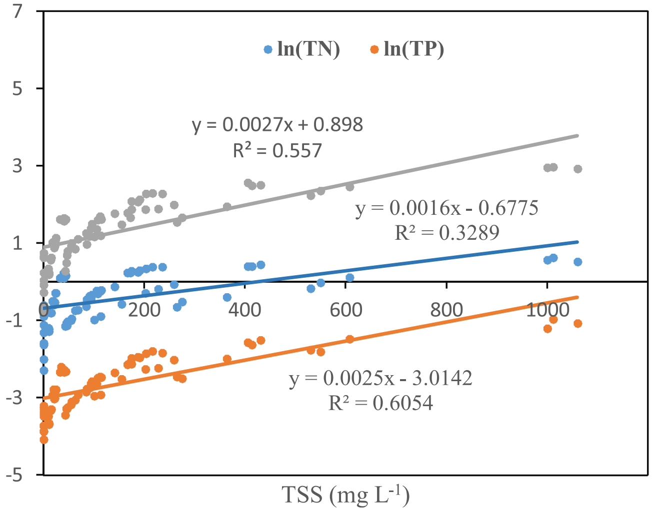

**Fig. 2.** Relationships between total suspended solids (TSS) and total nitrogen, total phosphorus, and the COD potassium permanganate index.

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**Table 2**
Major tributaries in the upper TGR.

| Tributary name | Annual runoff (km$^3$) | Average runoff (m$^3$ s$^{-1}$) | Basin area (km$^2$) | Length (km) |
|---|---|---|---|---|
| Jinsha River | 142.8 | 4750 | 502,000 | 3481 |
| Wujiang River | 50.3 | 1650 | 87,900 | 1037 |
| Minjiang River | 90 | 2830 | 135,881 | 1279 |
| Tuojiang River | 35.1 | 982 | 32,900 | 712 |
| Jialing River | 88 | 2160 | 160,000 | 1345 |
| TGR Mainstream | 451.5 | 14,200 | 1,001,500 | 670 |

Data source: *Eco-environmental Monitoring Bulletin of the Three Gorges Project, Yangtze, China.*

### *3.3. Anthropogenic activities and nutrient loading in the Three Gorges Catchment (TGC)*

The Three Gorges Dam control area catchment measures 1.02 million km$^2$, accounting for 58.9% of the Yangtze River basin and 11.1% of China's mainland area. The TGC includes 4 large cities (Chongqing, Chengdu, Kunming, and Guiyang), many cities and towns, and vast rural areas. The TGC population is 155 million, representing 13.9% of China's total population. In recent decades, the TGC economy has grown quickly, with an average annual economic growth rate of ~10%.

Land use is dominated by cropland, and the TGC features relatively high population density and GDP. The GDP has increased rapidly over the past two decades. However, the population density has remained stable over the same period; hence, the GDP per square kilometer has increased greatly (Fig. 5). Chongqing and Chengdu are the two biggest cities, each with populations exceeding 10 million people. In addition, the interactions between these two cities and others along upper Yangtze River has grown to the point that cities adjacent to the river account for more than half of the population and more than 80% of the GDP in the TGC.

Chongqing (including the main city and other administrative regions), which is the largest city in the TGR region, accounts for more than 80% of the total TGC area and thus has the greatest impact on the TGR eco-environment and water quality. The population in Chongqing is around 30 million. The GDP and per capita GDP have both grown rapidly (Fig. 6, upper panel). Accordingly, domestic wastewater has increased with GDP growth. However, industrial wastewater has gradually deceased, so the overall total amount of sewage discharge has increased slowly and is now nearly stable (Fig. 6, bottom panel).

## 4. Discussion

### *4.1. Nutrients and COD decreased in the TGR mainstream after impoundment*

The concentrations of TP and COD and the annual maximum TN decreased significantly after impoundment (2004–2016). Hence, water quality appears to have improved over pre-impoundment (1992–2003) conditions in the TGR mainstream (Fig. 1). The TGR basin houses a large population and supports rapid economic development, so the pollution loading therein is quite large and increasing rapidly, largely from point-source and non-point-source pollution (Figs. 5 and 6); the pollution input from major tributaries (Fig. 3) and large urban centers (Fig. 6) is substantial. The concentrations of TP and COD show decreasing trends, which indicates that this reservoir has a high capacity for self-purification. This may indicate that the hydrological and ecological characteristics of river reaches in the TGR region have changed since impoundment, leading to increased sedimentation and the dilution of particulate nutrients. The decrease in selected chemical parameters since impoundment may indicate that this aquatic system has become more stable (Fig. 1).

### *4.2. Causes of TP and COD reductions in the TGR*

Firstly, water impoundment in the TGR has increased sediment trapping. Particulate nutrients, as well as biogenic particles, settle readily as water flow speed decreases and retention time is prolonged. Water flow has gradually decreased in the TGR, which favors the precipitation of suspended nutrients and inorganic particles. TP and COD typically become attached to sand particles as the sediments sink and precipitate on the streambed. TSS is positively correlated with TP, TN, and COD in the TGR (Figs. 6 and S3), indicating that the concentrated sediment precipitates along TGR (Wu et al., 2016). Pollutant concentrations near the dam and in the middle of the reservoir are lower than those upstream (Fig. 1). In addition, the water level of TGR has increased greatly since impoundment (80–110 m at the dam site), and nutrients deposited in sediment cannot be released into the upper water column because of the lack of thermocline. The sediments in the TGR have thus become a nutrient "sink." This phenomenon has also been reported by Wu et al. (2016).

Secondly, the anti-seasonal operation pattern, which involves "storing the clean and discharging the muddy" is conducive to maintaining good water quality in the TGR. Usually, the reservoir stores water in October (to an elevation of ~175 m) and begins drainage in April of the following year. The rainy season in the TGR basin spans May to October, during which time the TGR water level remains at approximately 145 m. With the exception of $NH_4$-N, flow is positively correlated with the concentrations of TP, TN, and COD ($p < 0.001$), indicating that precipitation transports pollutants from the TGR basin (Fig. 7). More discharge is associated with higher flow speeds and TGR run at low water level periods is just during the rainy season. Hence, the rapid discharge

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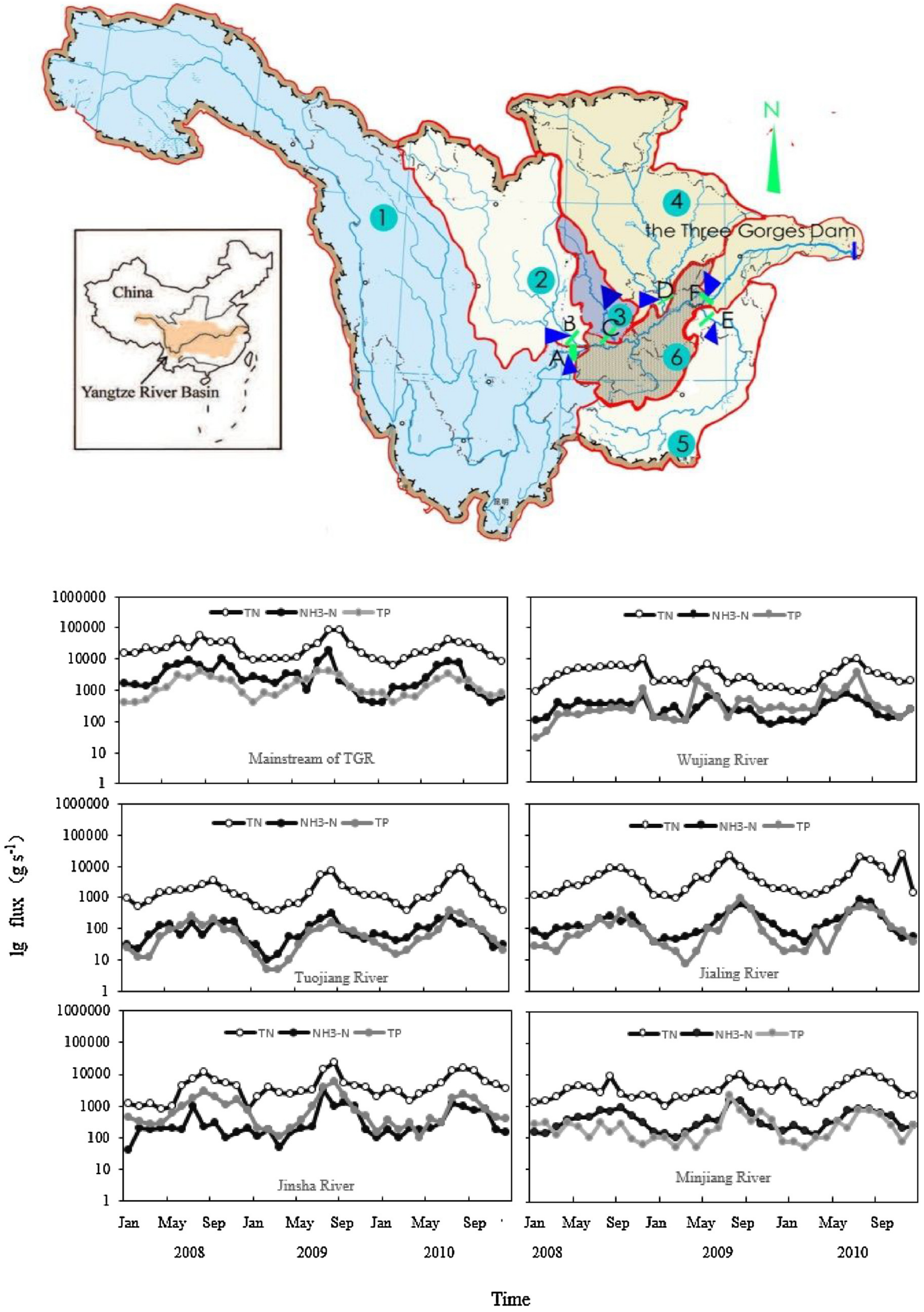

**Fig. 3.** Map of the TGR Basin with the five major tributaries of the TGR (upper panel: (A) Jinsha River; (B) Minjiang River; (C) Tuojiang River; (D) Jialing River; (E) Wujiang River; (F) TGR Mainstream and (lower panels) their nutrients fluxes during 2008–2010.

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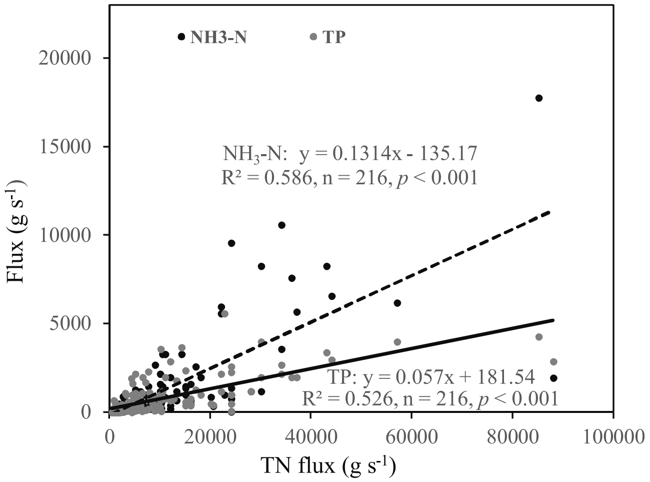

**Fig. 4.** Relationships of total nitrogen with total phosphorus and ammonium in the five major tributaries of the upper TGR and the TGR mainstream.

quickly transported contaminants away from the TGR. During this period, despite enhanced algal growth due to maximum temperatures and optimal light, the high water speeds induced in mainstream by drainage are not conducive for algal (especially cyanobacterial) growth and persistence, which also improves water quality. Anti-seasonal operation pattern and high water flow speed in the mainstream (0.2–2 m $s^{-1}$) makes it cannot form thermocline (Fig. S4). This may also contribute to good water quality.

Lastly, the water volume in TGR region has increased greatly, which may also increase the dilution capacity. After impoundment, the natural river was transformed into a large reservoir with a water volume of approximately 5 times to 60 times higher than before impoundment. Thus, pollutants introduced into the reservoir are diluted.

### 4.3. Pollution control

The Chinese government has expended great effort over the past several decades to reduce nutrient pollution from both point and non-point sources in the Yangtze River (Qiu,2011). The amount of sewage (especially domestic sewage) continues to increase, but, fortunately, sewage treatment has also increased. In Chongqing, the industrial wastewater treatment rate has increased quickly to almost 100%, and the output is regulated under Chinese national standards; hence, the amount of discharge has decreased rapidly (Fig. 6). Therefore, the total amount of pollution discharged into the reservoir has increased relatively slowly. Expanded wastewater treatment capability has contributed to improvements in water quality over the past decade in China (Yang et al., 2014); these improve-

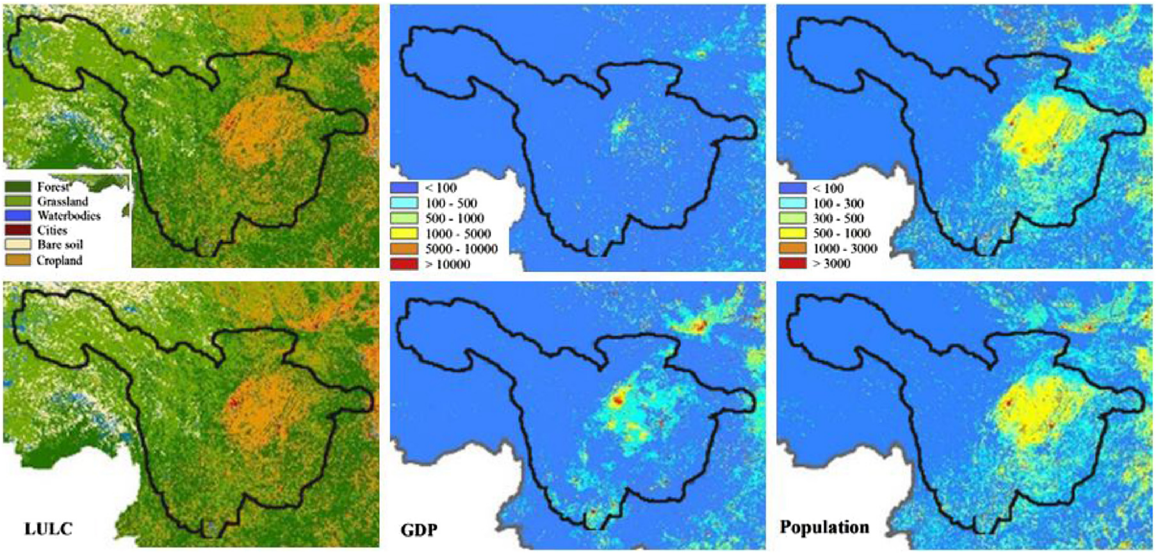

**Fig. 5.** (Left) Land use and land cover (LULC), (middle) gross domestic product (GDP) per square kilometer (RMB $10^4$ Yuan $km^{-2}$), and (right) population density (ca. $km^{-2}$), before (upper images, 1992–2003) and after (lower images, 2004–2016) the TGR basin was filled with water. Data represent averages from annual statistics 1992–2003.

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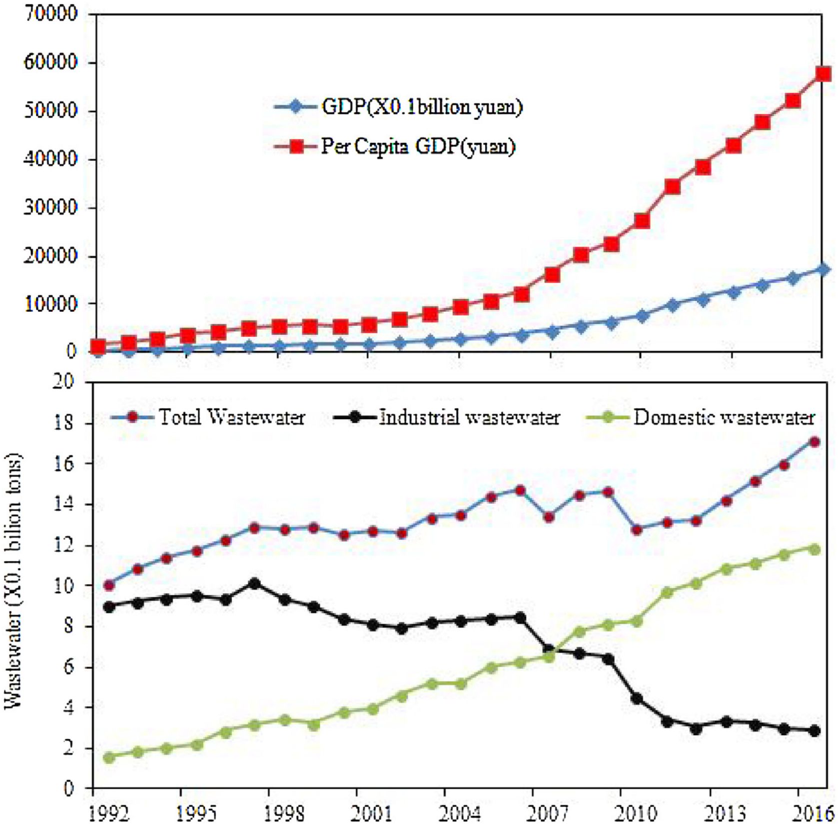

**Fig. 6.** Economic development and wastewater discharge in Chongqing.

ments can be attributed to increased investment in environmental restoration, especially in urban sewer lines.

In the TGR Basin, increased percentages of forest and reduced percentages of cropland during the past several decades (Hu et al., 2015; Yu et al., 2015) have prevented soil erosion (Wang et al., 2011b, 2016; Yang et al., 2014). Soil retention can also improve water quality, as suspended sediment is a significant source of nutrients (Galy et al., 2015). Investment in reforestation and environmental restoration have thus improved water quality, as demonstrated by government-financed actions with positive impacts on water quality (Liu et al., 2008; Ouyang et al., 2016; Zhou et al., 2017).

### *4.4. Phytoplankton blooms in TGR tributaries and nutrient limitation*

After impoundment, the Chl-a levels have remained below 10 $\mu g\ L^{-1}$; hence, algal blooms do not generally occur in the TGR mainstream. Phytoplankton blooms are typically favored by low flow in lowland rivers with established thermal stratification and extended residence times (Baker et al., 2000). However, eutrophication remains an important ecological and environmental problem in the tributaries and is clearly evidenced by tributary algal blooms (Liu et al., 2012; Zeng et al., 2006). After impoundment, algal blooms have appeared frequently in low flow regions of the TGR. Various phytoplankton species have been observed to dominate or co-dominate these blooms (Table 1), which indicates species diversity and aquatic environment variations in the TGR tributaries experiencing algal blooms. The genus *Microcystis*, a particularly problematic cyanobacterial genus, is widespread globally in eutrophic lakes and reservoirs, such as in Lake Taihu (Ma et al., 2016) and Lake Erie (Harke et al., 2016); it is also dominant in TGR tributary blooms, indicating that these regions are experiencing declining water quality.

In situ N and P addition experiments show that tributary algae growth is P-limited in all four seasons; however, concurrent nitrogen and phosphorus additions yield the highest amount of biomass (Fig. 8). This indicates that both nitrogen and phosphorus control should be part of the long-term algal bloom control strategy (Paerl et al., 2016).

### *4.5. Outlook for the TGR aquatic eco-environment*

Overall, we conclude that the system is still in a state of ecological change and that its future remains unclear. Damming can increase water retention times, which reduces sediment transport downstream (Wang et al., 2011b, 2016; Yang et al., 2014). Excess sediment entering the reservoir will affect the lifetime of the reservoir, and sediments also constitute a large accumulation of stored

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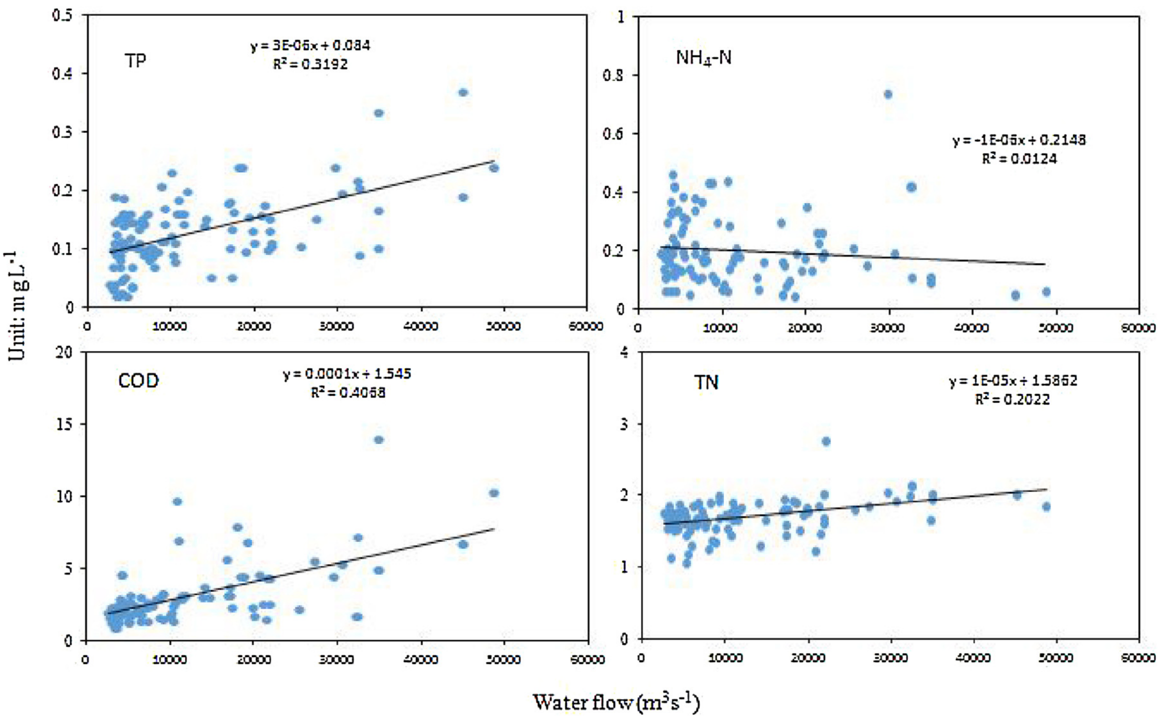

**Fig. 7.** Linear relationships between water flow and TP, COD, Ammonia, and TN in the TGR ($n$ = 108; monthly data from 1994, 2003, and 2013 at the Cuntan, Wangzhou, and Zigui hydrological stations).

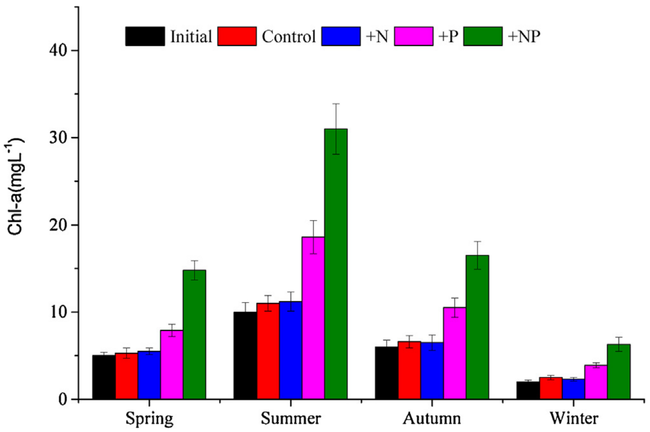

**Fig. 8.** In situ bioassays in the Pengxi River showing phytoplankton growth control by TGR nutrients.

"legacy" nutrients. The water quality management department has developed solutions to address these issues. For example, the key roles of Xiluodu and Xiajiaba Reservoirs in sediment control have been identified in the upstream of TGR. Therefore, sediment loading in the TGR is expected to decrease in the future. Future studies should address how sediment control will affect the self-purification capacity of the reservoir and how much sand is needed to ensure sufficient self-purification capacity. Sedimentation will also gradually raise the TGR bed height over time, which will reduce the water depth and may increase nitrogen and phosphorus availability via enhanced internal cycling. Assessing this possibility and developing solutions will be important aspects of future research.

Future studies should also address the maintenance of good water quality in the TGR mainstream if the tributary algal blooms continue to expand. Research on eutrophication, algal bloom formation in the tributaries, and relevant control strategies will enhance our understanding of TGR eco-environmental patterns and assist in the management of this exceptionally large water project.

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## 5. Conclusions

Measurements from 1992 to 2016 indicate that the concentrations of COD and TP in the TGR region have decreased since impoundment. These COD and TP reductions were caused primarily by reductions in flow, which led to enhanced sedimentation. TN and ammonium were less affected by sediment deposition and display slight upward trends due to intensified human activities. Water flow speed decreased, and nutrient enrichment promoted phytoplankton biomass increases in the TGR mainstream and frequent algal blooms in the tributaries (especially in backwater zones). Because the reservoir is P-limited, controlling phosphorus inputs will control primary productivity. However, concurrent control of nitrogen and phosphorus inputs is essential long-term.

## Conflict of interest

None declared.

## Ethical statement

Authors state that the research was conducted according to ethical standards.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ecohyd.2018.08.005.

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