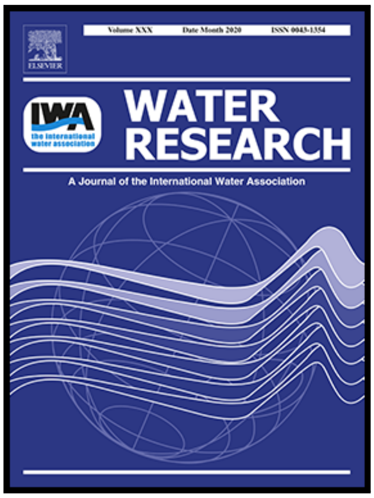
Journal Pre-proof



Water quality variation in tributaries of the Three Gorges Reservoir from 2000 to 2015

Rong Xiang , Lijing Wang , Hong Li , Zebin Tian , Binghui Zheng

PII: S0043-1354(21)00191-3
DOI: https://doi.org/10.1016/j.watres.2021.116993
Reference: WR 116993

To appear in: *Water Research*

Received date: 23 December 2020
Revised date: 11 February 2021
Accepted date: 28 February 2021

Please cite this article as: Rong Xiang , Lijing Wang , Hong Li , Zebin Tian , Binghui Zheng , Water quality variation in tributaries of the Three Gorges Reservoir from 2000 to 2015, *Water Research* (2021), doi: https://doi.org/10.1016/j.watres.2021.116993

Highlights:

- Water quality, hydrology and pollution were explored in TGR tributaries in 2000–2015
- Hydrodynamic and pollution heterogeneity caused variation in water quality
- Eutrophication and blooms occurred frequently downstream in spring
- High nutrient levels in tributaries were caused by impoundment and pollution loads
- Water quality was best in tributaries upstream areas during the impoundment period

Water quality variation in tributaries of the Three Gorges Reservoir from 2000 to 2015

Rong Xiang[a,b], Lijing Wang[a,]*, Hong Li[a], Zebin Tian[a], Binghui Zheng[a,b,]*

a. National Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China

b. School of Environment, Tsinghua University, Beijing 100084, China

*** Corresponding author:** Lijing Wang, Binghui Zheng

E-mail address: wanglj@craes.org.cn, zhengbinghui@craes.org.cn (B. Zheng).

Abstract

The Three Gorges Reservoir (TGR) underwent staged impoundment during 2003–2010. Periodic water impoundment included drainage (March to early June), low water level (June to August), impoundment (September to October), and high water level (November to February) periods. However, the impacts of the Three Gorges Dam (TGD) and impoundment on water quality of TGR tributaries remain poorly understood, especially in the long term and across the entire TGR drainage basin. Herein, water quality and hydrological indices of 27 tributaries, eutrophication of 38 tributaries, and pollution load of the TGR were determined during 2000–2015 to explore spatiotemporal variations in water quality. The results revealed slower flow velocity in tributaries and an extended residence time with the water level rising, and the water quality of tributaries was mainly affected by the mainstream backwater movement. Water quality was good in more than 60% of tested sites, had the best condition in the impoundment period, and it increased over time. Spatially, water quality in tributary upstream was better than in the backwater area, and worst in the tributary estuary. Among water quality indices, total nitrogen (TN) and total phosphorus (TP) were the key pollution indices, with median range of 1.619–2.739 and 0.088–0.277 mg/L, respectively. Additionally, water quality indices of TGR tributaries displayed temporal and spatial heterogeneity due to different hydrodynamic and pollution load conditions. A total of 38 tributaries displayed eutrophication, the frequency of blooms concentrated in spring and increased from the upper tributaries to the downstream area. These results expanded the theory of hydrodynamic variation and the associated evolution of the water environment after impoundment, could provide theoretical references for water quality management in river-type reservoir.

Keywords: Three Gorges Reservoir; tributary; water quality; hydrology; pollution load; spatiotemporal variation

1. Introduction

The Three Gorges Dam (TGD), the largest hydropower project in the world, is 2309.5 m long and 185 m high, located in Sandouping, Yichang, Hubei Province, and took 17 years to build and become fully operational (Wang et al., 2013a; Fu et al., 2010). The Three Gorges Reservoir (TGR) is 663 km long, covering a total area of 1084 km^2, and includes 22 districts and counties in Chongqing and 4 in Hubei province (He et al., 2011). The population of the TGR region in 2016 was 14.79 million, the urbanisation rate was 56.52%, and the Gross Domestic Product (GDP) of the industry was 388.1 billion yuan, accounting for 50% of total GDP (MEP, 2002–2017).

The TGR is a natural riverine ecosystem with a water level no higher than 80 m before the TGD was built, but the area was turned into a reservoir ecosystem following TGD construction and impoundment (CNEMC, 1998–2016). Impoundment caused the water level to rise to 135 m in 2003 (first impoundment stage), 156 m in 2006 (second impoundment stage), and finally 175 m in 2010 (third impoundment stage) (Tang et al., 2014). Since 2010 (after full impoundment stage), the TGR has been fully operational and has a water level fluctuation zone vertical height of 30 m (Bao et al., 2015). The water level fluctuates periodically between 145 and 175 m each year (Bao et al., 2015), and periodic impoundment is consisted of four distinct phases (Xu et al., 2011a; Zhang and Lou, 2011); drainage period (175 to 145 m) during which the water level is reduced to free-up storage capacity for flood control; low water level period (145 m) during which the water and sediment is discharged outside of the TGR; impoundment period (145 to 175 m) during which the water level is raised due to store water; and high water level period (175 m) during which the water and sediment is retained in the TGR (Zheng et al., 2016; Xiang et al., 2021).

The TGD and periodic water impoundment have made great contributions to shipping, hydropower generation, flood manipulation and irrigation in China (Zhang and Lou, 2011; Zhao et al., 2013). However, this has been accompanied by a suite of environmental problems, especially soil erosion (Xu et al., 2011b; Ma et al., 2016), water quality deterioration (Stone, 2011; Xia et al., 2018), eutrophication and algal blooms (Liu et al., 2012; Yang and Zhang, 2014), and hydrological alterations including increased water level, a slower flow velocity, extended water retention time, trapped sediments, and large water temperature fluctuations (Zhang and Lou, 2011; Ma et al, 2015), all of which have attracted wide attention.

At present, the TGR water ecosystem is in evolution period, changes in the water environment are of great significance to grasp the succession process of the new large-scale reservoir ecosystem and guide the protection of it. Studies on the mainstream water quality calculated a mean total nitrogen (TN) concentration of approximately 1–3 mg/L, and mean total phosphorus (TP) of 0.05–0.61 mg/L, hence they are key pollution indices (Gao et al., 2016; Xia et al., 2018). Other research investigated tributary bays close to the TGD and found that eutrophication and algal blooms occurred frequently after impoundment (Zhang, 2012a; Tang et al; 2015), possibly due to changes in pollution load (Ren et al., 2015; Ran et al., 2017), land use patterns (Huang et al., 2016; Zhang et al., 2019) and hydrology and hydrodynamics (Zhang and Lou, 2011; Yang et al., 2010). However, research on water quality, eutrophication and algal blooms in the tributaries of the TGR is lacking, especially long-term effects over the entire TGR drainage basin.

The river system in the TGR is well developed (Table 1), including 36 tributaries with a drainage area over 1000 km^2 in Chongqing alone (Wang et al., 2013b). Before impoundment, the water level is 145 m which is the flood control water level, the mainstream and tributaries are natural rivers (CWRC, 1992). After impoundment (from 145 to 175 m), the backwater can reach and impact the upstream tributaries of the TGR located in Jiangjin, Chongqing (Bing et al., 2016). In addition, mainstream backwater flowing back into the tributaries led to the formation of the backwater area, which affected the water quality and hydrology of the tributaries (Yu and Wang, 2011). In fact, water quality deterioration, eutrophication and algal blooms in the tributaries of the TGR are reported every year (MEP, http://www.mee.gov.cn/). However, the relationship between TGR impoundment mode and tributaries water quality remains unclear.

Based on work carried out over more than 10 consecutive years, nutrients, biochemical indices, eutrophication, blooms, hydrology and pollution load were measured during 2000−2016. The present study aimed to (1) probe the spatiotemporal variation in water quality indices and identify the key pollution indicators in the tributaries of the TGR, (2) assess the water quality of TGR tributaries using an appropriate water quality index, (3) investigate the spatiotemporal variation of eutrophication and blooms in the TGR tributaries, and (4) investigate variation in pollution load and hydrology and discuss their impact on water quality in the tributaries of the TGR. This study could be helpful for expanding the theory of hydrodynamic variation and the associated evolution of the water environment after impoundment, and providing a reference for water environment protection and scientific water regulation in river-type reservoirs.

2. Materials and Methods

2.1. Study area

Due to TGD construction and impoundment, a group of backwater zones constituting the TGR was formed upstream of the Yangtze River, stretching from Jiangjin County, Chongqing City to Yichang City, Hubei province. The regional geomorphology of the TGR is dominated by mountains, hills and canyons, with large longitude and vertical differences (Tang et al., 2014; Bao et al., 2015). A subtropical monsoon humid climate predominates, featuring mean annual precipitation ranges from 650 mm to 2100 mm (http://data.cma.cn/site/index.html), an annual average temperature varies in the range of 17–19°C, and 30–40 foggy days per year (Tong et al., 2006; Wang et al., 2011). Based on the TGR impoundment characteristics, a typical year can be divided into four distinct phases; drainage (March to early June), low water level (June to August), impoundment (September to October), and high water level (November to February) periods (Zheng et al., 2016).

The present study investigated 66 water quality sampling sites (S1–S66) of 27 tributaries in the TGR (Table 1, Fig. 1). These sites were divided into three groups based on the intensity of impact by mainstream backwater, including 25 in tributary upstream areas were unaffected, 21 in backwater areas were moderately affected, and 20 in tributary estuary areas were strongly affected. In addition, 38 eutrophication sampling sites in the backwater area of 38 tributaries were measured (Fig. 1).

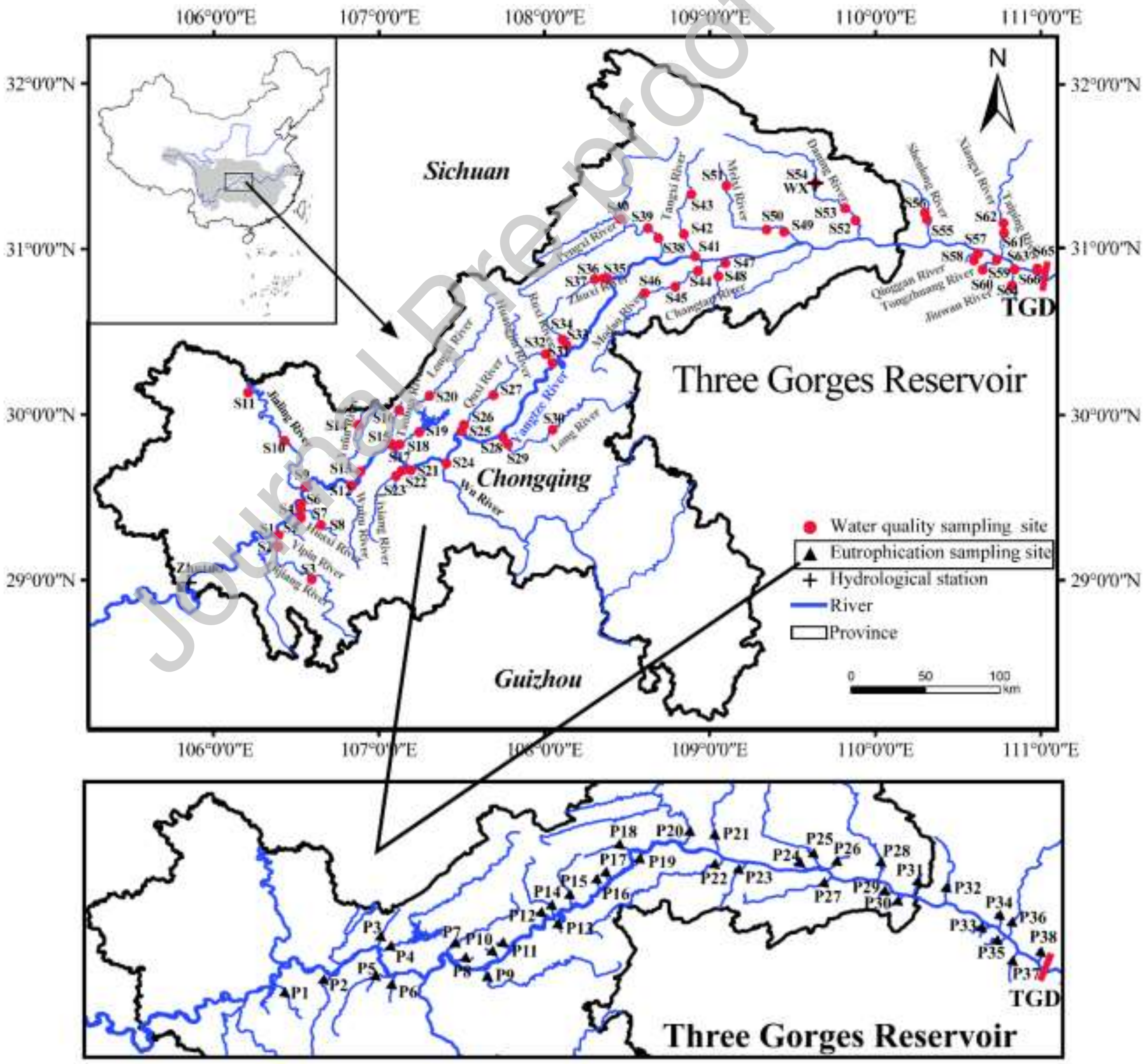


Fig. 1. Sampling sites in the Three Gorges Reservoir of the Yangtze River.

Table 1. Basic characteristics parameters and sampling point settings of 27 Three Gorges Reservoir tributaries

River	Administrative division	River basin area (km^2)	Length in the TGR (km)	Annual average flow (m^3/s)	Distance from estuary to the TGD (km)	Tributary estuary	Backwater area	Tributary upstream
Qi River	Jiangjin	4394	153	122	654	S1	S2	S3
Yipin River	Banan	363.9	45.7	5.7	632	S4	S5	
Huaxi River	Banan	271.8	57	3.6	620	S6	S7	S8
Jialing River	Yuzhong	157900	153.8	2120	604	S9		S10, S11
Wubu River	Banan	858.2	80.8	12.4	573.5	S12		
Yulin River	Yubei	908	58.4	50.7	556.5	S13		S14
Taohua	Changshou	363.8	65.1	4.8	528	S15		S16
Longxi River	Changshou	3248	218	54	526.2	S17	S18	S19, S20
Lixiang	Fulin	850.6	13.6	13.6	506.2	S21	S22	S23
Wu River	Fulin	87920	65	1650	484	S24		
Quxi River	Fengdu	923.4	93	14.8	459	S25	S26	S27
Long River	Fengdu	2810	114	58	429	S28	S29	S30
Huangjin	Zhongxian	958	71.2	14.3	361	S31	S32	
Ruxi River	Zhongxian	720	11.9	11.9	337.5		S33	S34
Zhuxi River	Wanzhou	228.6	30.6	4.4	277	S35	S36	S37
Pengxi River	Yunyang	5172.5	117.5	116	247		S38,	S40
Tangxi River	Yunyang	1810	108	56.2	222	S41	S42	S43
Modao River	Yunyang	3197	170	60.3	218.8	S44		S45, S46
Changtan	Yunyang	1767	93.6	27.6	206.8		S47	S48
Meixi River	Fengjie	1972	112.8	32.4	158		S49	S50, S51
Daning	Wushan	4200	142.7	98	123	S52	S53	S54
Shenlong	Badong	350	60	20	74		S55	S56
Qinggan	Zigui	523	54	19.6	48	S57		S58
Tongzhuang	Zigui	248	36.6	6.4	42	S59		S60
Xiangxi	Zigui	3095	110.1	47.4	32		S61,	
Juwan River	Zigui	514	42.1	17.5	20		S63	S64
Taiping	Yichang	63.4	16.4	1.3		S65	S66	

2.2. Sampling and data sources

Water was collected from tributaries (left, middle and right basins) in 500 ml plastic bottles during 2003–2012, and 2014, and taken to the lab to measure water quality and eutrophication indicators. The average annual concentrations of TN, TP, pH, dissolved oxygen (DO), potassium permanganate index (COD_{Mn}) and five-day biochemical oxygen demand (BOD_5) in 2000–2002, 2013 and 2015 were calculated from previous research data. The overall dataset included 484 samples from 11 TGR tributaries in 2000, 465 samples from 10 tributaries in 2001 (Luo, 2004), 420 samples from 21 tributaries in 2002 (Luo, 2004;

Peng, 2005), 255 samples from 31 rivers in 2013 (Xia, 2014) and 94 samples in 2015 (Zhang et al., 2019). Additionally, data were collected for pollution load during 2001–2016 (MEP, 2002–2017). The inflow pollution load of the TGR was expressed as the product of the concentration of pollutants and the flow at Zhutuo hydrological station, and flow data of Zhutuo and WX were obtained from the Hydrology Bureau of the Changjiang Water Resources Commission.

2.3. Analytical methods

2.3.1 Water quality and eutrophication indicator measurements

Methods employed for the determination of water quality, eutrophication indicators, and water temperature (WT) are given in Table S1. River transparency was measured on-site by the Secchi disc (SD) method (Secchi, 1864). Combined with historical data and remote sensing technology, the volume of tributaries at different water levels and some other basic river characteristic parameters in Table 1 are measured. Residence time (Tr) can be derived from the equations Tr = V/Q, where Q is the annual average flow (m^3/s) and V is the average capacity (m^3) when the water level is 145 m and 175 m. In addition, the average monthly flow rate (v) was calculated according to the equation v (m/s) = monthly average flow / average area of the tributary section, where the average area of the tributary section (m^2) = V / river length. Furthermore, the runoff volume (W) of WX during different impoundment periods was calculated from the equations W (m^3) = $Q \times \Delta t$, where Q is the monthly average flow (m^3/s) and Δt is the time of each impoundment period.

2.3.2 Chlorophyll a and trophic level index measurements

Chlorophyll a (Chl-a) was extracted with 90% acetone and measured spectrophotometrically according to the methods of Nusch (1980). Trophic level index (TLI) was assessed from Chl-a, TP, TN,

COD_{Mn} and SD (Zhang, 2012a).

2.3.3 Mann-Kendall (MK) test

The MK test is commonly used for detecting changes in hydrological and climate time series. This test is a non-parametric trend test and does not require the sequence under testing to follow a certain presumed distribution (Hamed and Rao, 1998). Additionally, it can effectively judge the fluctuation trend of natural processes. For this reason, the MK test is widely applied in water quality, rainfall and runoff sequences (Chang, 2008, Mustapha, 2013, Bayazit, 2015). In this study, the MK test was used to analyse the temporal variation tendency of water quality parameters in the TGR tributaries, using the ‘trend’ package in R software v3.6.1 (R core development team, 2019).

2.3.4 Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI)

The CCME-WQI has been widely used and recognised in different countries (Hülya, 2010; El-Jabi et al., 2014) because it can be applied flexibly with slight modification based on specific local conditions and issues (CCME, 2001; Khan, 2003; Hurley et al., 2012). It can easily assess whether the overall water quality meets the specified water quality goals, and indicate the water status category. To explore the water quality of the TGR tributaries, the CCME-WQI and China’s Environmental Quality Standard for Surface Water (GB) Class III (MEP, 2002) were both used. The Class III standards are listed in Table S1 and the detailed calculation procedure was described in previous studies (Dede et al., 2013, Zhao et al., 2016). The index value can vary in the range of 0–100, corresponding to five categories: poor (0–44), marginal (45–64), fair (65–79), good (80–94), and excellent (95–100).

3. Results and Discussion

3.1 High nutrient levels in tributaries are mainly derived from impoundment and pollution loads in the TGR

Following building of the TGD and periodic impoundment, nutrients can vary and this requires close attention. Previous research has explored nutrient levels in the TGR mainstream, and TN and TP always exceed GB class III standards (MEP, 2002), confirming them as key pollution indices (Zhao et al., 2016; Gao et al., 2016). Xia et al. (2018) showed that TN and TP were more than 1.5 and 0.1 mg/L during 2008–2014, while Li et al. (2019) demonstrated that the TN and TP were higher than 1.5 mg/L and 0.05 mg/L from 1992 to 2016. However, research on nutrient levels in the TGR tributaries is lacking. In the present study, TN and TP were measured for 27 tributaries in the TGR, and all far exceeded GB Class III standards (MEP, 2002, Fig. 2a). Both were identified as key pollution parameters (Fig. 2a), with median values of 1.581 and 0.074 mg/L during 2003–2012, respectively (Fig. 2b).

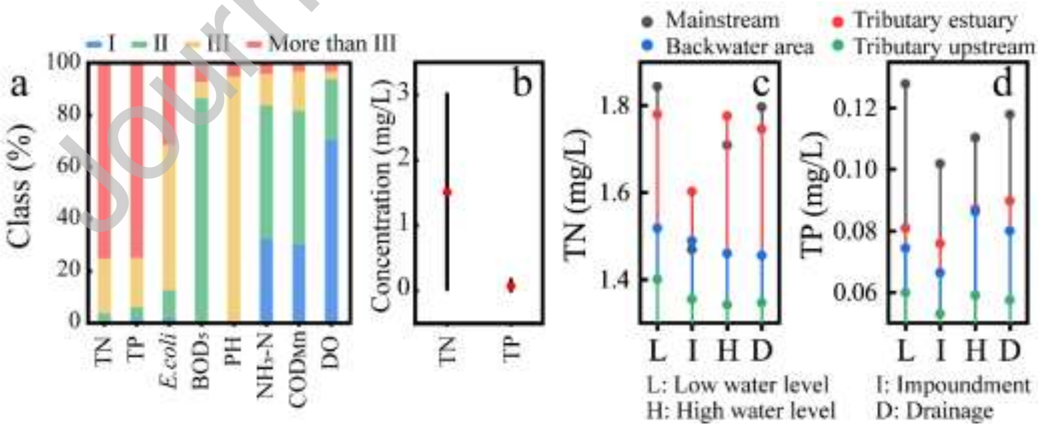


Fig. 2. (a) Classification of water quality parameters of the TGR tributaries from 2003 to 2012 based on the China Environmental Quality Standard for Surface Water (MEP, 2002). (b) Median TN and TP values during 2003–2012. (c, d) Variation in TN (c) and TP (d) in the mainstream (Xiang et al., 2021), tributary

estuary, backwater area, and tributary upstream of the TGR during 2003–2012.

There are several reasons for the high nutrient levels in the TGR tributaries. Firstly, the water level of 145 m is the flood control water level in the TGR, with the flood control capacity 22.15 billion m^3, the water level of 175 m is the normal impoundment level, with the capacity 39.3 billion m^3 (CWRC, 1992). However, the sum volume of the 21 tributaries is 6.48 billion m^3 during the high water level period, which was 41.35% of mainstream volume based on flood control capacity (Fig. 3a). The average volume ratio of WX station to Daning River during 2001–2016 was 28.39%, 23.52%, 58.79% in impoundment, high water level, and drainage period (Fig. 3b), respectively. Therefore, according to the water balance, mainstream volume was higher than tributaries, and mainstream backwater volume was higher than tributary upstream areas with the water level rising. Thus, after TGR impoundment, a plenty of mainstream backwater was input into tributaries. Ran et al. (2010) showed that the mainstream contributed about 76% and 73% of water in the Xiangxi and Daning Rivers, respectively. In present study, TN and TP in mainstream and tributary estuary area >backwater area >tributary upstream area (Fig. 2c–d). TN of mainstream and tributary estuary area and TP of the four areas showed an increasing trend after low water level period, and TP before impoundment was lower than that after (Fig. 2c–d). It means that mainstream backwater probably caused nutrients increase in tributaries after impoundment.

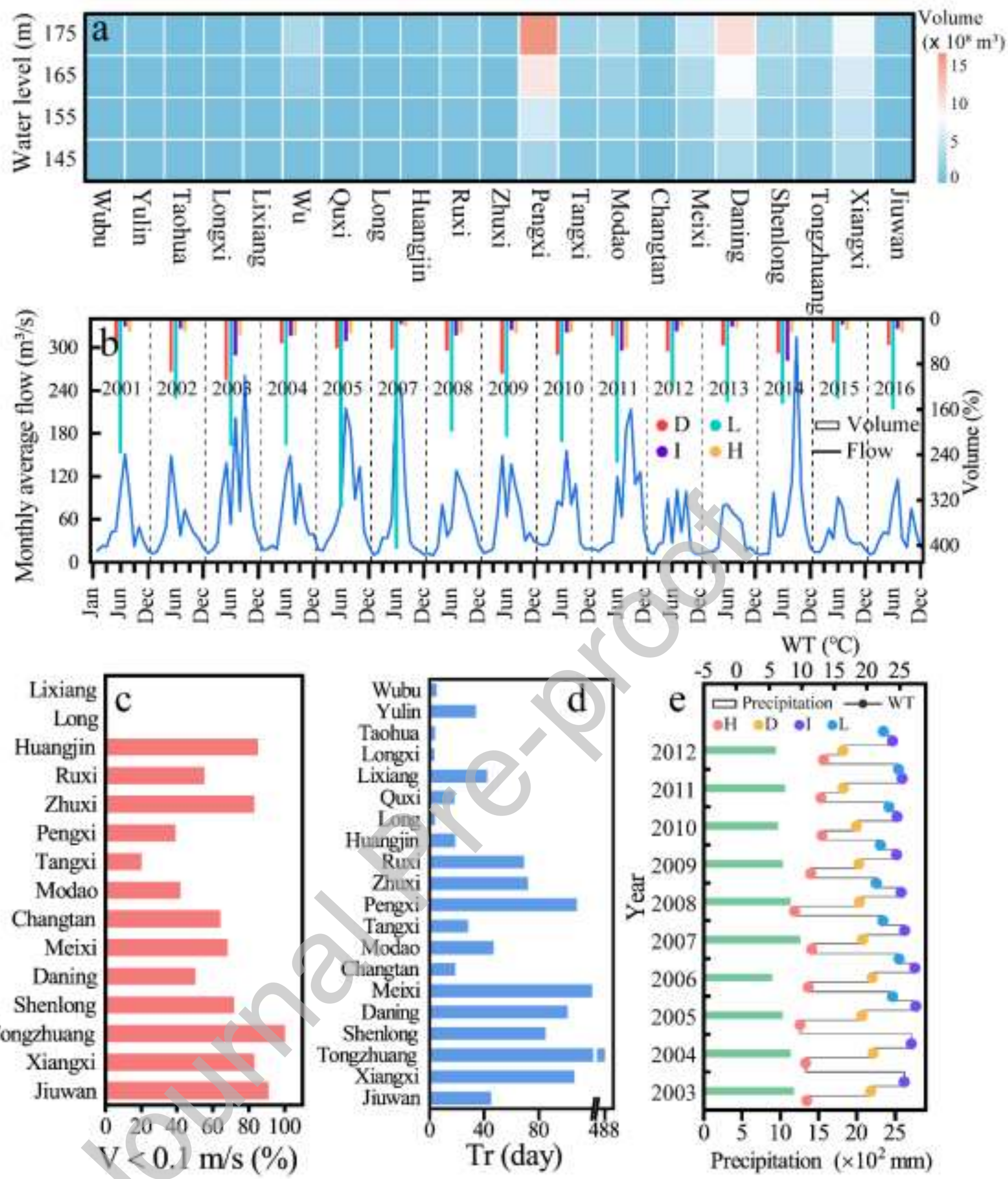


Fig.3. (a) Volume of tributaries at different water levels. (b) The monthly average flow of the WX station and the proportion of WX station runoff volume to the Daning River's total volume during different water periods. (c) Monthly average flow velocity (V) of TGR tributaries at 139 m water level. (d) Retention time (Tr) of TGR tributaries. (e) Water temperature and precipitation in the TGR between 2003 and 2012.

Moreover, the flow velocity has slowed down due to TGD construction and impoundment, which provided a convenient condition for the mainstream backwater to import into tributaries. In the mainstream, before and after impoundment values were reduced from 2.12 to 1.33 m/s in the upstream, from 1.87 to 0.58 m/s in the midstream, and from 2.15 to 0.29 m/s in the downstream area of the TGR (Li et al., 2019). In tributaries, the proportion of the monthly flow velocity less than 0.01 m/s accounted for 40−100% in the mid-downstream of TGR tributaries when the water level was 139 m (Fig. 3c).

Secondly, mainstream and tributary in the TGR had minimal volume in the low water level period (Fig. 3a), was a natural river. TN of the four areas all reached its maximum value during this period, then it showed a decreasing trend in backwater area and tributary upstream area over time (Fig. 2c). TP of the four areas were higher than GB Class III standards (MEP, 2002; Fig. 2d). The average flow in this period was 172.84% of the annual average flow at WX station during 2001−2016 (Fig. 3b). These results show that abundant rainfall promoted the migration of non-point source pollutants into the TGR during the low water level period (Xie et al., 2017), which possibly contributed a large amount of nutrients to tributaries.

In addition, non-point-source pollutants were dominant in all pollution loads of the TGR (Ren at al., 2015; Ran et al., 2017), and inflow from upstream of the Yangtze River was higher than that from the TGR (Fig. 4). The average TN and TP load of inflow from the upper Yangtze River into the TGR was 28.91×10^4 t/a and 3.17×10^4 t/a during 2003–2012, respectively (Fig. 4a). In the TGR, farmland is the main land use type (Huang et al., 2016; Zhang et al., 2019), and the crop area was in the range of 0.39–0.70 million hectares during the period covered in the present study (Fig. 4e). Nitrogen and phosphate fertiliser application in the TGR ranged from 5.85×10^4 to 11.1×10^4 and from 1.96×10^4 to 4.60×10^4 t/a, respectively (Fig. 4e), while organic nitrogen and phosphorus pesticide application was in the range of 40–289.6 and 190.8−593.2 t/a, respectively, during 2001−2016 (Fig. 4f). Therefore, a large amount of non-point-source pollutants promoted high TN and TP levels in the TGR.

Finally, mobile and point source pollution also contributed to high TN and TP values (Fig. 4c−d).

From 2001 to 2016, the average number of ships sailing in the TGR was 7226, and the domestic wastewater generated by ships was 3.367 million t/a, including TN pollution of 230.76 t/a and TP pollution of 35.39 t/a (Fig. 4c). The TN content in domestic wastewater during 2001–2003 was 1.25×10^4 t/a, and the TP content between 2001 and 2007 was 0.15×10^4 t/a (MEP, 2002–2017).

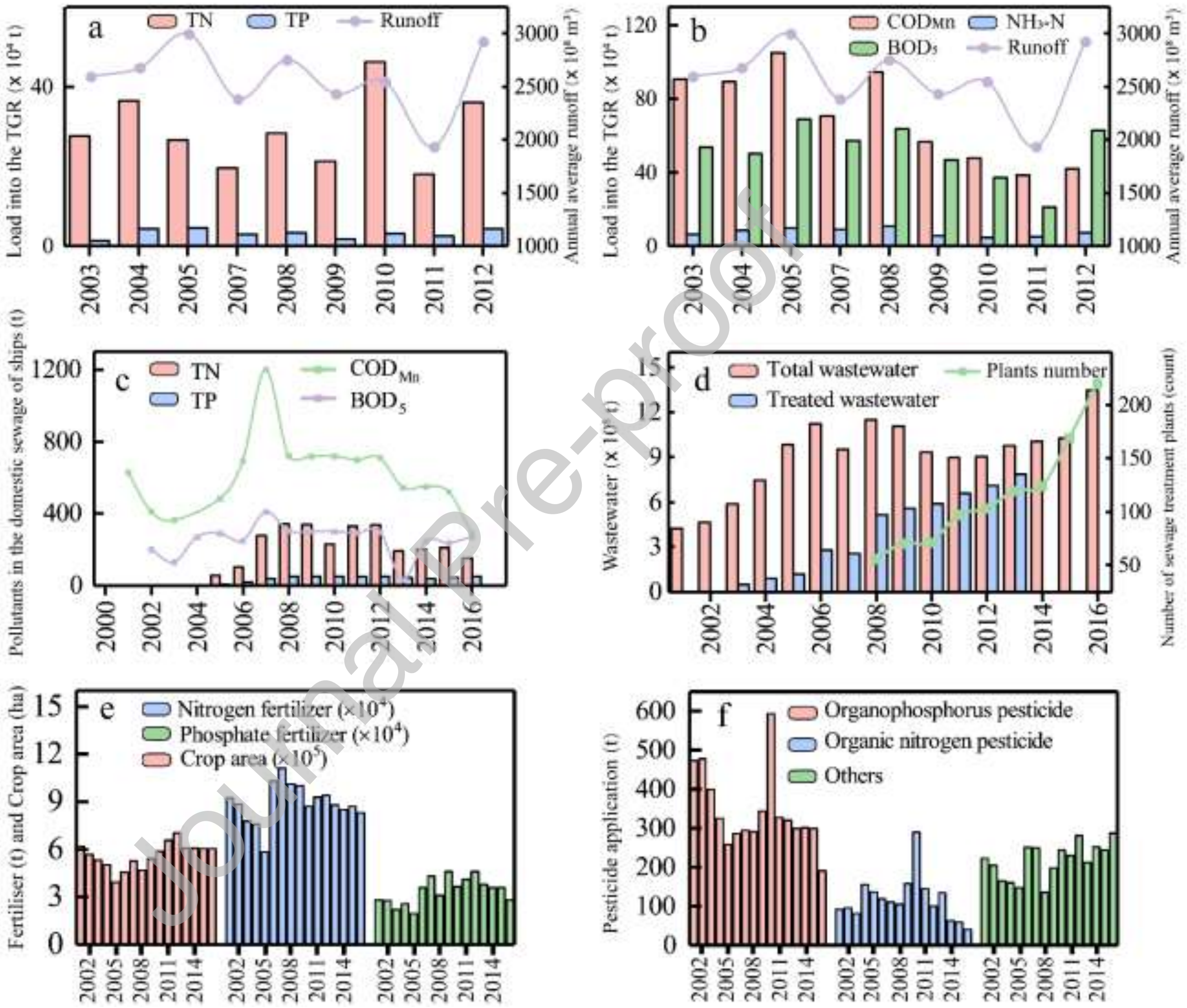


Fig. 4. (a, b) Pollution load input into the TGR from upstream of the Yangtze River, including TN, TP, COD_{Mn}, NH_3-N and BOD_5 load. (c) mobile pollution load from ships, (d) point source pollution load, and (e, f) non-point source pollution load during 2001–2016.

3.2 Hydrodynamic and load regional heterogeneity cause spatial variation in water quality indicators

Water quality indicators are related to urbanisation, industrial and agricultural production, land use type, and environmental protection infrastructure in each tributary drainage basin (Zhang and Lou, 2011; Zhang, 2012b; Huang et al., 2016). The Chongqing urban and Wanzhou districts are the most densely populated areas in the TGR, where annual average industrial and domestic wastewater accounted for more than 50% of the total volume of the TGR during 2003–2012 (MEP, 2002–2017). In the present study, TN, TP, COD_{Mn}, BOD_5, ammonia nitrogen content index (NH_3-N) and *Escherichia coli* (*E.coli*) in rivers in this area were higher than in the downstream reaches of the TGR, and all indices had high values in Yipin, Huaxi, Taohua and Zhuxi Rivers (Fig. 5). TN values in these four rivers were 3.163, 3.462, 3.184 and 3.085 mg/L, TP values were 0.116, 0.219, 0.182 and 0.301mg/L, NH_3-N, COD_{Mn}, BOD_5 and *E. coli* values varied in the range of 0.765–1.702, 3.725–5.336, 2.737–4.956 mg/L and 3.301×10^4–2.412×10^5 A/L.

Pollutants in tributaries has five major input channels; input from upstream of tributaries, recharge of the mainstream, the release of internal sources, pollution from point and non-point sources, and the release of soil in the fluctuating zone (Zhao et al., 2015; Yang et al., 2013). Non-point-source loads were dominant in all pollution loads of the TGR (Fig. 4), and large amounts of rainfall and runoff will increase the pollutants content in tributaries during the low water level period. Therefore, TN, TP, NH_3-N, and *E. coli* of the 27 tributaries increased from tributary upstream areas to mainstream during this period (Fig. 2, 6). However, as the water level rose, these four indices in the mainstream and tributary estuary kept the same growth trend and were higher than that in other two areas (Fig. 2, 6), mainstream backwater volume was larger than tributary upstream areas (Fig. 3a–b), suggesting that impoundment increased these four indices levels in tributaries. Therefore, strengthening loads control to reduce pollutants, expanding plant coverage to increase tributaries upstream flow, and properly scheduling the timing and magnitude of water release out of reservoir, may be helpful to decrease their contents (Tranmer et al., 2020).

By contrast, COD_{Mn} and BOD_5 in tributaries decreased with water level rising, while both indices and DO in mainstream increased (Fig. 6a–b). In addition, all three parameters were higher in tributary than mainstream (Fig. 6), illustrating that the abundant backwater diluted pollutant concentrations (Yang et al., 2013; Fig. 3a–b). MK test results (Fig. 7) showed that TN, TP, NH_3-N, COD_{Mn}, BOD_5 and *E. coli* levels for all sites decreased over time, but DO increased, suggesting that the water quality of the tributaries will gradually improve over time.

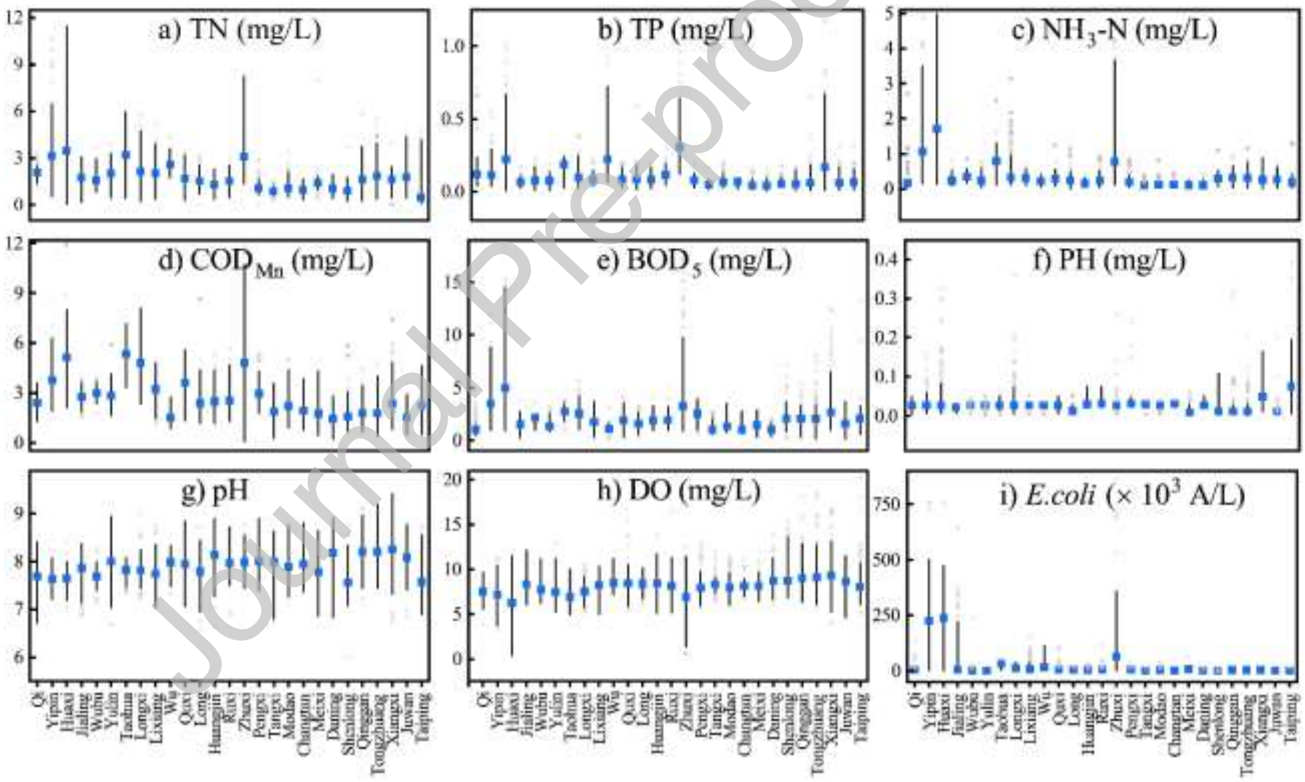


Fig. 5. Median water quality parameters for each river.

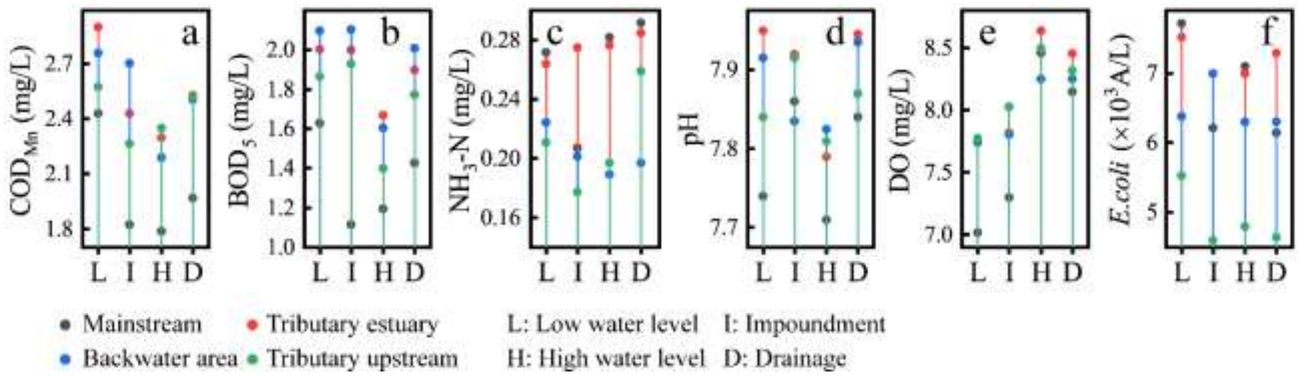


Fig. 6. Median variation in water quality indices among mainstream (Xiang et al., 2021), tributary estuary, backwater area and tributary upstream during 2003–2012.

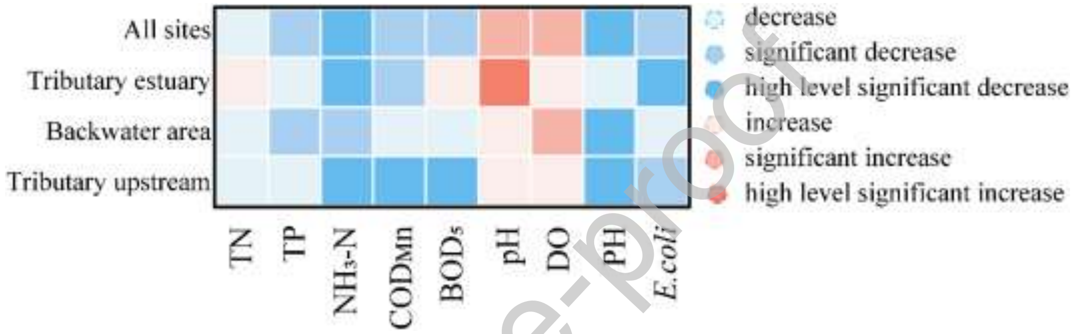


Fig. 7. Mann-Kendall test results for water quality parameters in TGR tributaries.

3.3 Staged and periodic impoundment affects temporal variation in water quality indicators

As shown in Fig. 8, the annual average values for TN and TP during 2000–2015 were in the range of 1.619–2.739 and 0.088–0.277 mg/L, respectively. The mean TN concentration of the first, second and third impoundment stage was lower than that of the other two impoundment stages. The mean TP, COD_{Mn} and BOD_5 values before impoundment were 0.172, 3.919 and 2.207 mg/L, respectively, which were lower than in the first impoundment stage, but all three indices decreased over time thereafter. The annual average NH_3-N, petroleum hydrocarbon (PH) and *E. coli* values varied in the range of 0.328–0.976, 0.022–0.057 mg/L and 7.974×10^3–7.015×10^4 A/L, respectively, and all decreased over time. However, DO after impoundment was lower than that before, but DO and pH increased from the first impoundment to the full impoundment stage over time.

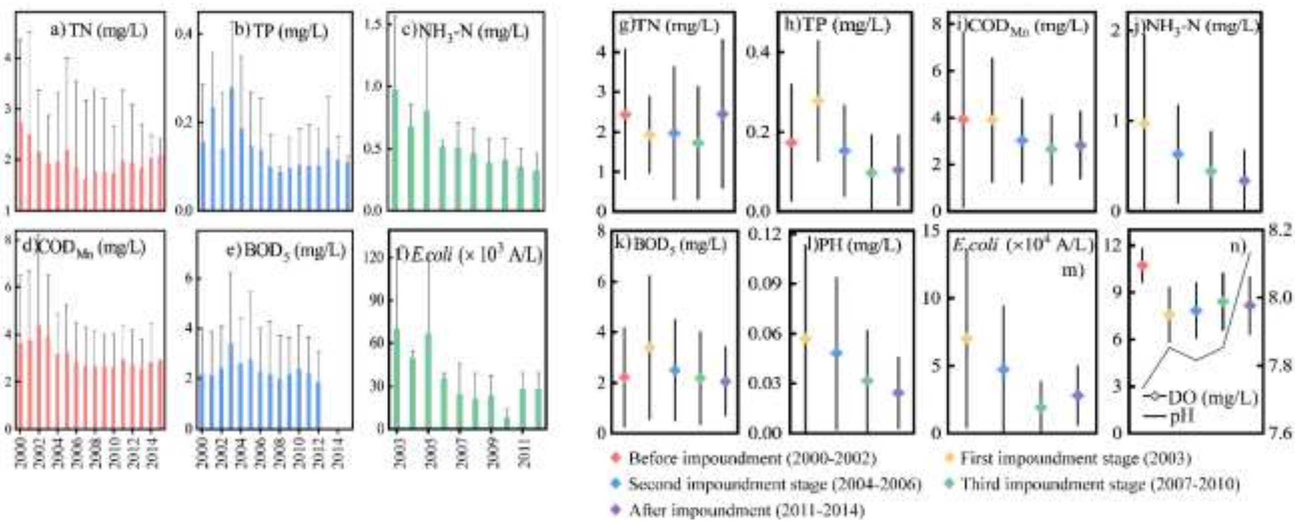


Fig. 8. Left, Inter-annual variation of TN (a), TP(b), COD_{Mn} (d) during 2000–2015, NH_3-N (c) and *E.coli* (f) during 2003–2012, and BOD_5 (e) during 2000–2012 in TGR tributaries. Right, Comparison of average water quality parameters at different impoundment stages.

Non-point loads were the main sources of TN, especially agricultural activity (Ren et al., 2015, Fig. 4). However, due to the resettlement project for TGD construction, the crop area and nitrogen fertiliser application were reduced (Fig. 4), hence TN during the construction period (2003–2010) was lower than that before impoundment (2000–2002). An increasing trend was observed after full impoundment (2010–2015), possibly due to the recovery of agricultural activities (Fig. 4). In addition, pH rose over time (Fig. 8n) might due to the increasing trend of eutrophication and algal bloom (Liu et al., 2012; Xu at al., 2013).

The slowing of the flow velocity, rising water level, and extended residence time caused large amounts of pollutants from submerged soil and plants to be released into the TGR during the impoundment stage (Liu et al., 2004; Dai et al., 2010; Xiao et al., 2017). Therefore, TP, COD_{Mn} and BOD_5 were increased from before impoundment (2000–2003) to the first impoundment stage in 2003 (Fig. 8h–i, k). However, TP, COD_{Mn}, BOD_5, NH_3-N, pH and *E. coli* then decreased over time (2004–2015; Fig. 8), possibly because the self-purification capacity increased (Wei et al., 2011). Additionally, the pollutant concentrations in mainstream backwater tended to decrease over time (Fig. 4a–b). Furthermore, environmental management and governance efficiency improved, since municipal wastewater treatment plants increased from 56 in 2008 to 220 in 2016 (Fig. 4d), and the domestic sewage treatment efficiency improved from 12.49% in 2003 to 99.87% in 2016 (MEP, 2002–2017).

The TN, COD_{Mn}, BOD_5, and *E.coli* peaked in the low water level period (Fig. 9), the median of 27 rivers were 1.792, 2.795, 1.901 mg/L, and 7.846×10^3 A/L. Moreover, the number of rivers with the highest concentration of these four indices were largest in this period (Fig. S1a). These results indicate that stronger precipitation and runoff (Fig. 3b) with large amount of non-point source loads (Fig. 4) greatly promoted the concentration of these four indices (Xie et al., 2017). However, the NH_3-N (0.313 mg/L) and TP (0.086 mg/L) reach their maximum value in the drainage period (Fig. 9), and both indices in this period had the largest number of rivers with the highest concentration (Fig. S1a). This might be due to the mixing of the mainstream flow and the upstream flow from the tributaries caused the deposited nutrients to enter the water body (Yang et al., 2013), and the increasing rainfall (Fig. 3b) could also bring some pollutants from the tributary upstream basin.

After TGR impoundment, a plenty of mainstream backwater was input into tributaries (Ran et al., 2010; Fig. 3a–b), thereby diluting the pollutant concentrations in tributaries (Yang et al., 2013). Therefore, all parameters except DO were minimal in the impoundment (NH_3-N and TP) and high water level (TN, COD_{Mn}, BOD_5, and *E.coli*) period (Fig. 9), and these indices with the lowest concentration had the largest number of rivers during the two periods (Fig. S1b). In addition, DO was maximal in the high water level period (Fig. 9 and S1a).

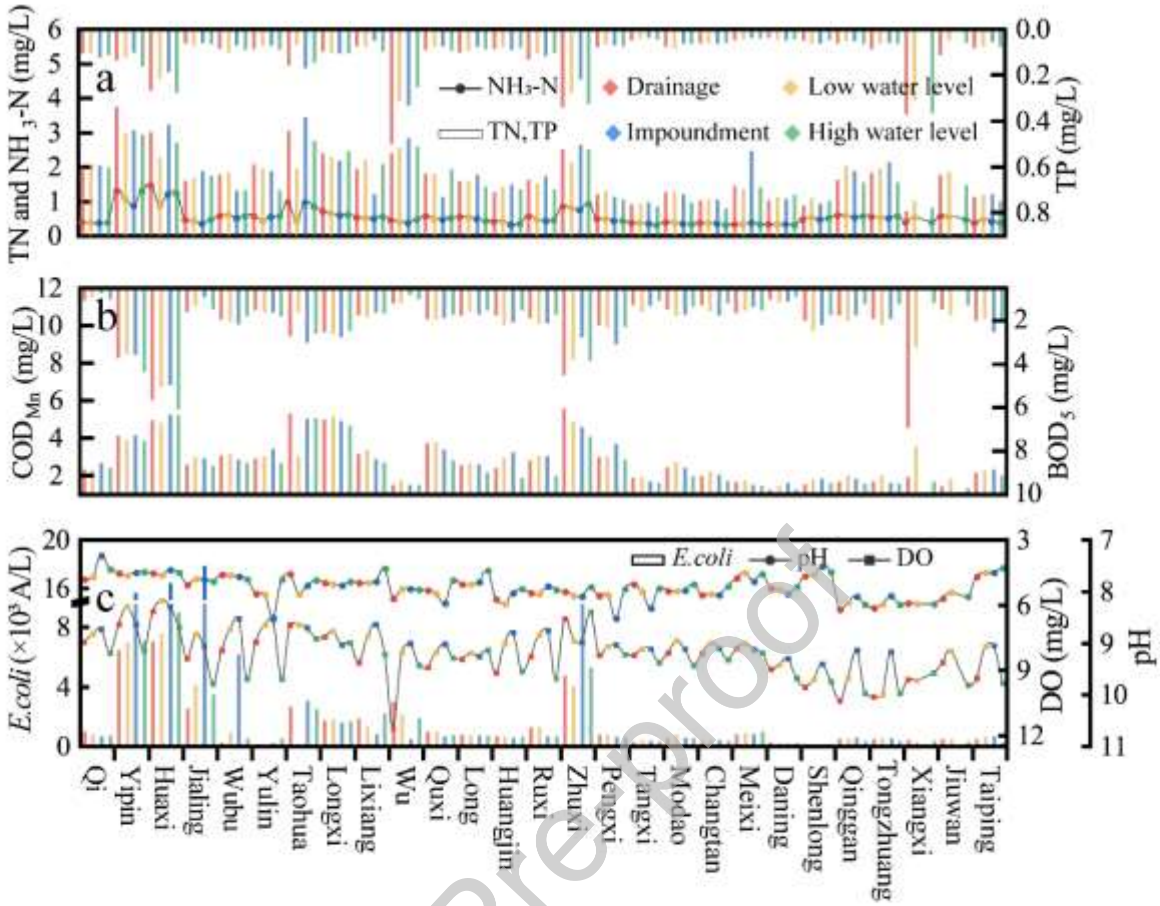


Fig. 9. Comparison of median water quality parameters in TGR tributaries in different operation periods.

3.4 Stress effects of hydrodynamic changes on tributary eutrophication

Eutrophication is the most widespread global water environmental problem (Sinha et al., 2017), and eutrophication has become more serious since the first impoundment in the TGR in 2003 (Yang et al., 2010; Zhang, 2012a; Xiao et al., 2016). Herein, all 38 tributaries displayed eutrophication, and the eutrophication ratio was higher than 50% in 11 rivers (Fig. 10a). Furthermore, the comprehensive trophic level index (TLI) of 38 TGR tributaries was higher than 50 during 2004–2012, except for 2007 (Fig. 10d). Therefore, tributary eutrophication in the TGR was prominent, and the reason probably was the high nutrient levels (Fig. 2) caused by impoundment and non-point source loads (Fig. 3–4). The eutrophication percentage of P1−P19 was higher than that of P20−P38 from 2004 to 2012 (Fig. 10a), which might be due to the nutrient spatial variation (Fig.5a–b).

According to the Reservoir Water Quality Management (Strskraba and Tundisi, 1999), the river type is complete mixing when retention time (Tr) <20 days, the transitional type is moderate intensity stratification when Tr is between 20 and 300 days, and the lake type is stable layered when Tr >300 days. In the present study, 65% of 20 tributaries had a Tr more than 20 days, 40% exceed 50 days, Tongzhuang River reached 488 days, and Tr increased from upper to lower tributaries of the TGR (Fig. 3d). Of the 30 rivers within a distance of 560 km from the TGD, 21 belong to the transitional type, 1 falls into the lake type, and 8 are the river type (Fig. 3d). Therefore, as the residence time increased, many tributaries changed from river type before impoundment to lake type thereafter, indicating the mixing intensity of tributaries decreased, while the possibility of water stratification and algal blooms increased (Yang et al., 2010; Xu et al., 2011a). In fact, the frequency of blooms increased after impoundment, it was 8 in 2004, 34 in 2006, and 197 in 2004–2012 (Fig. 10f), and it increased from upstream tributaries to downstream tributaries (Fig. 10c). In addition, 18 tributaries displayed exceptionally high Chl-a eutrophication values (10 mg/m^3) during 2004–2012 (Fig. 10b).

During the high water level period, large flows of mainstream backwater were input into tributaries (Ran et al., 2010; Fig. 3a–b) diluting the pollutant concentrations (Yang et al., 2013; Fig. 9 and S1). Thus, TGR tributaries showed serious eutrophication and high Chl-a levels during March–September (Fig. 10g–h). However, the highest frequency of blooms occurred from March to June (Fig. 10i), and were dominated by diatom and dinoflagellate bloom (Xu et al. 2011c). It was mainly due to the slowing flow velocity (Fig. 3c), extending Tr (Fig. 3d) and increasing water temperature (Fig. 3e) promoted water column stability during the drainage period (Henson, 2007; Xu et al. 2011b–c). In addition, high-concentration nutrient from mainstream backwater was another cause (Luo et al., 2011; Sinha et al.

2017; Fig. 6). Herein, the median TN and TP values were 1.581 and 0.074 mg/L between 2003 and 2012, respectively (Fig. 2), which are sufficient to support algae growth and proliferation (Xu et al., 2011a). However, the mainstream characterised by high nutrients (Fig. 2), but never be reported stratification and algal blooms (MEP, 2002–2017), suggesting that nutrients might not be the primary factors limiting spring bloom in tributaries, while hydrodynamic conditions were.

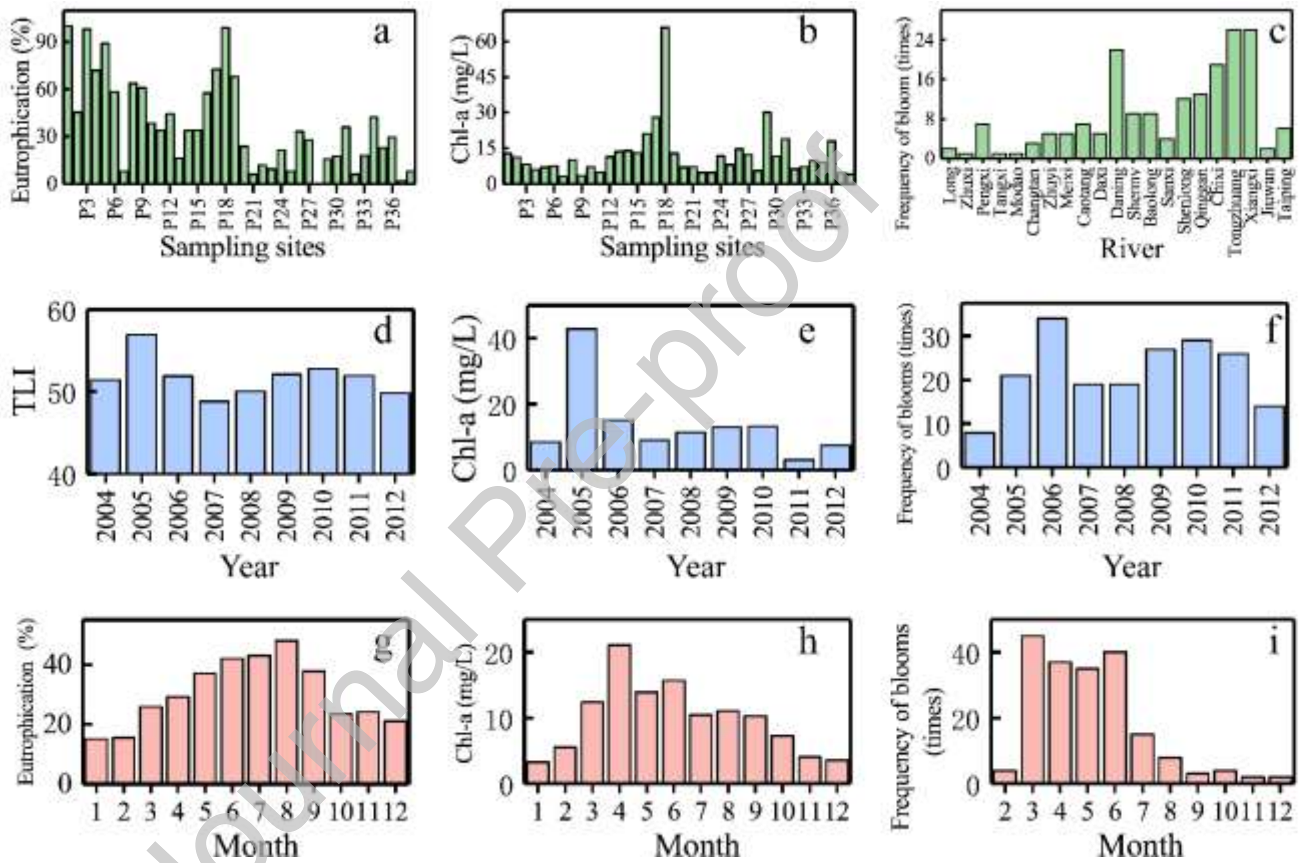


Fig. 10. (a) The proportion of eutrophication in tributary backwater areas between 2004 and 2012. (b) Chlorophyll a (Chl-a) concentration variation in tributary backwater areas during 2004–2012. (c) Frequency of algal blooms in tributaries between 2004 and 2012. (d–f) Annual changes in the comprehensive trophic level index (TLI; d), Chl-a in tributary backwater areas (e) and the frequency of blooms in the TGR (f) from 2004 to 2012. (g–i) Monthly changes in eutrophication (g) and Chl-a (h) in tributary backwater areas, and frequency of blooms (i) in the TGR during 2004–2012.

3.5. TGR operation drives variation in tributary water quality

Water quality changes across space and time in TGR tributaries are illustrated in Figure 11. Water quality was mainly ranked between fair and good, and at least 60% of sampling sites were categorised as good. The CCME-WQI values were ordered tributary estuary <backwater area <tributary upstream, with mean values of 75.141, 78.023 and 82.017, respectively (Fig. 11a). This might because high nutrients in tributary estuaries (Fig. 2 and 6), presumably due to high pollution loads and backwater movement from the mainstream (Yang et al., 2010; Liu et al., 2012; Fig. 3–4). The median CCME-WQI values for Yipin (S05), Huaxi (S06 and S07) and Zhuxi (S35 and S36) Rivers were 53.410, 50.409 and 56.735, respectively (Fig. 11a), indicating poor water quality. This was mainly due to the dense human population and extensive production activities (MEP, 2002–2017).

In addition, the CCME-WQI value increased over time, and was ranked first impoundment stage (2003) <second impoundment stage (2004–2006) <third impoundment stage (2007–2010) <after full impoundment (2011–2012), with mean values of 70.469, 75.159, 79.662 and 80.242, respectively (Fig. 11a). Firstly, the improved water quality of TGR tributaries was consistent with water quality indices decreasing over time with successive impoundments (Zheng et al., 2011; Tang et al., 2014; Fig. 8). Secondly, this may be attributed to government protection and restoration measures. Sewage treatment plants increased from 56 in 2008 to 220 in 2016, the amount of treated domestic wastewater increased from 0.05 billion tons in 2003 to 0.79 billion tons in 2013, and the sewage treatment rate increased from 12.50% in 2003 to 99.87% in 2013 (Fig. 4d). Finally, fertiliser application decreased after full impoundment (Fig. 4e).

Furthermore, there was no obvious change in the CCME-WQI value during high water level, drainage and low water level period, while all three periods were significantly lower than that in the impoundment period ($p < 0.01$, ANOVA; Fig. 11b–c). The rapid rise in water level from 145 to 175 m during the impoundment period promoted large mainstream flows to input into tributaries (Fig. 3a–b) and diluted pollutants (Yang et al., 2013; Fig. 9), hence this period displayed the highest water quality.

The impact of the TGD and impoundment on the water environment is a complex issue, and the succession and stability of large-scale reservoir ecosystem is a long-term process. The loads are the sources of pollutants, and water flow control the transportation and migration of pollutants (Xiang et al. 2021), they were the main cause of the spatiotemporal differences in water quality, high nutrients, and serious blooms of the TGR tributaries in this study. Therefore, based on the reservoir operations and climatic conditions, proper flow regulation (inflow from tributaries upstream areas or outflow from dam), control of pollution sources, and improvement of biodiversity may greatly improve the management of river-type reservoirs (Tranmer et al., 2020).

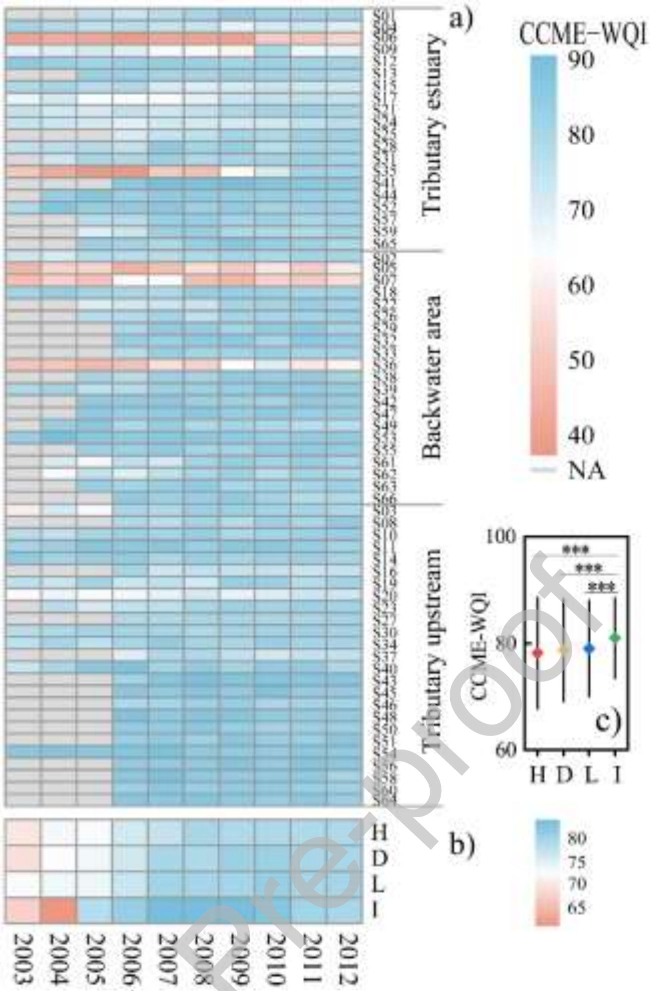


Fig. 11. Spatial and temporal variation in CCME-WQI in TGR tributaries between 2003 and 2012. H, High water level period; D, Drainage period; L, Low water level period; I, Impoundment period. *** indicates a P value <0.01

4. Conclusions

Non-point loads and impoundment were the main cause of high nutrient levels in tributaries. The mean TN and TP values varied in the range of 1.619–2.739 and 0.088–0.277 mg/L during 2000–2015, respectively, hence both were key pollution parameters.

Water quality indices of the upper tributaries in the TGR had higher values due to the dense human population and extensive production activities. The difference in water volume and pollutant content between the mainstream and tributaries resulted in the spatial change of water quality indicators. TN before impoundment was higher than that after, while TP, COD_{Mn} and BOD_5 showed the opposite trend. The water quality indices of tributaries were minimal in the impoundment and high water level periods, because they were diluted by a large amount of mainstream flow input.

Following the impoundment, the raised water level, slower flow velocity, proper temperature, extended water retention time caused frequent eutrophication and blooms in the tributary backwater area. All 38 tributaries displayed eutrophication, and the frequency of blooms was concentrated in spring, and increased from the upper tributaries to downstream. The CCME-WQI value of the TGR tributary was categorised as good at more than 60% of sites, decreased from tributaries upstream to tributaries estuary, and was maximal in impoundment period. Moreover, the CCME-WQI value and MK test results show that the water quality improved over time.

Acknowledgements

The research was financially supported by National Key Research and Development Program (No. 2017YFC0404702) and National Natural Science Foundation (No. 51609225) of China.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Bao, Y. H, Gao, P., He, X. B. 2015. The water-level fluctuation zone of three gorges reservoir—a unique geomorphological unit. Earth-Science Reviews 150,14-24. https://doi.org/10.1016/j.earscirev.2015.07.005

Bayazit, M. 2015. Nonstationarity of hydrological records and recent trends in trend analysis: a state-of-the-art review. Environmental Processes 2(3), 527-542. https://doi.org/10.1007/s40710-015-0081-7

Bing, H. J., Zhou, J., Wu, Y. H. 2016. Current state, sources, and potential risk of heavy metals in sediments. Environmental Pollution 214, 485-496. https://doi.org/10.1016/j.envpol.2016.04.062

CCME (Canadian Council of Ministers of the Environment), 2001. Canadian water quality guidelines for the protection of aquatic life: CCME water quality index 1.0, User's manual., Canadian Council of Ministers of the Environment, Winnipeg.

Chang, H. 2008. Spatial analysis of water quality trends in the Han River basin, South Korea. Water Research 42(13), 3285-3304. https://doi.org/10.1016/j.watres.2008.04.006

CNEMC (China National Environmental Monitoring Centre), 1998–2016. Bulletin of Ecological and Environmental Monitoring of the Three Gorges Project in theYangtze River. Ministry of Environmental Protection of the People's Republic of China. (in Chinese)

CWRC (Changjiang Water Resources Commission). 1992. Preliminary design report of the Three Gorges Project of the Yangtze River (in Chinese).

Dai, H., Zheng, T., Liu, D. 2010. Effects of reservoir impounding on key ecological factors in the three gorges region. Procedia Environmental Sciences 2, 15-24.

https://doi.org/10.1016/j.proenv.2010.10.004

Dede, O. T., Telci, I. T., Aral, M. M. 2013. The use of water quality index models for the evaluation of surface water quality: a case study for Kirmir Basin, Ankara, Turkey. Water Quality, Exposure and Health 5(1), 41-56. https://doi.org/10.1007/s12403-013-0085-3

El-Jabi, N., Caissie, D., Turkkan, N. 2014. Water quality index assessment under climate change. Journal of Water Resource and Protection 6(6), 533-542. http://hdl.handle.net/123456789/324

Fu, B. J., Wu, B. F., Lu, Y. H., Xu, Z. H., Cao, J. H., Niu, D., Gui, S. Y., Yue, M. Z. 2010. Three gorges project: efforts and challenges for the environment. Progress in Physical Geography 34(6), 741-754. https://doi.org/10.1177/0309133310370286

Gao, Q., Li, Y., Cheng, Q., Yu, M., Hu, B., Wang, Z., Yu, Z. 2016. Analysis and assessment of the nutrients, biochemical indexes and heavy metals in the Three Gorges Reservoir, China, from 2008 to 2013. Water Research 92, 262-274. https://doi.org/10.1016/j.watres.2015.12.055

Hamed, K. H., Rao, A. R. 1998. A modified Mann-Kendall trend test for autocorrelated data. Journal of hydrology 204(1-4), 182-196. https://doi.org/10.1016/S0022-1694(97)00125-X

He, Q., Peng, S., Zhai, J., Xiao, H. 2011. Development and application of a water pollution emergency response system for the Three Gorges Reservoir in the Yangtze River, Journal of Environmental Sciences 23(4), 595-600. https://doi.org/10.1016/S1001-0742(10)60424-X

Henson, S. A. 2007. Water column stability and spring bloom dynamics in the Gulf of Alaska. Journal of Marine Research 65(6), 715-736. https://doi/10.1357/002224007784219002

Huang, Z., Han, L., Zeng, L., Xiao, W., Tian, Y. 2016. Effects of land use patterns on stream water quality: a case study of a small-scale watershed in the Three Gorges Reservoir Area, China. Environmental Science and Pollution Research 23(4), 3943-3955. https://doi.org/10.1007/s11356-015-5874-8

Hülya, B. 2010. Utilization of the water quality index method as a classification tool. Environmental Monitoring and Assessment 167(1-4), 115-124. https://doi.org/10.1007/s10661-009-1035-1

Hurley, T., Sadiq, R., Mazumder, A. 2012. Adaptation and evaluation of the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) for use as an effective tool to characterize drinking source water quality. Water Research 46(11), 3544-3552. https://doi.org/10.1016/j.watres.2012.03.061

Khan, A. A., Paterson, R., Khan, H. 2003. "Modification and Application of the CCME WQI for the Communication of Drinking Water Quality Data in Newfoundland and Labrador", Proceedings of the 38th Central Symposium on Water Quality Research, Canadian Association on Water Quality, Burlington, Canada.

Li, Z., Ma, J., Guo, J., Paerl, H. W., Brookes, J. D., Xiao, Y., Fang, F., Ouyang, W., Lunhui, L. 2019. Water quality trends in the Three Gorges Reservoir region before and after impoundment (1992–2016). Ecohydrology & Hydrobiology 19(3), 317-327. https://doi.org/10.1016/j.ecohyd.2018.08.005

Liu, J. G., Mason, P. J., Clerici, N., Chen, S., Davis, A., Miao, F., Deng, H., Liang, L. 2004. Landslide hazard assessment in the three gorges area of the Yangtze river using ASTER imagery: Zigui-Badong. Geomorphology 61(1-2), 171-187. https://doi.org/10.1016/j.geomorph.2003.12.004

Liu, L., Liu, D., Johnson, D. M., Yi, Z., Huang, Y. 2012. Effects of vertical mixing on phytoplankton blooms in Xiangxi Bay of Three Gorges Reservoir: implications for management. Water research 46(7), 2121-2130. https://doi.org/10.1016/j.watres.2012.01.029

Luo, F. 2004. Research on the eutrophication trend in the tributary of Three Gorge Region. Doctoral dissertation, Chongqing University. (in Chinese)

Luo, G., Bu, F., Xu, X., Cao, J., Shu, W. 2011. Seasonal variations of dissolved inorganic nutrients transported to the Linjiang Bay of the Three Gorges Reservoir, China. Environmental monitoring and assessment 173(1-4), 55-64. https://doi.org/10.1007/s10661-010-1370-2

Ma, J., Liu, D., Wells, S. A., Tang, H., Ji, D., Yang, Z. 2015. Modeling density currents in a typical tributary of the three gorges reservoir, china. Ecological Modelling 296, 113-125. https://doi.org/10.1016/j.ecolmodel.2014.10.030

Ma, X., Li, Y., Li, B., Han, W., Liu, D., Gan, X. 2016. Nitrogen and phosphorus losses by runoff erosion: Field data monitored under natural rainfall in Three Gorges Reservoir Area, China. Catena 147, 797-808. https://doi.org/10.1016/j.catena.2016.09.004

MEP (Ministry of Environmental Protection P.R. China). http://www.mee.gov.cn/

MEP (Ministry of Environmental Protection P.R. China), 2002. Environmental Quality Standards for Surface Water (GB 3838-2002). (in Chinese)

MEP (Ministry of Environmental Protection P.R. China). 2002 – 2017. Bulletin on the Ecological and Environmental Monitoring Results of the Three Gorges Project. (in Chinese)

Mustapha, A. 2013. Detecting surface water quality trends using Mann-Kendall tests and Sen's slope estimates. International Journal of Agriculture Innovations and Research 1, 108-114.

Nusch, E. A. 1980 Comparison of different methods for chlorophyll and pheopigment determination. Arch Hydrobiol Beiheft Ergebn Limnol 14, 14-36.

Peng, Y. 2005. Eutrophication investigation on the backwater reach of the branch river of the three gorge reservior. Doctoral dissertation, Chongqing University. (in Chinese)

R Core Development Team. 2019. R: a language and environment for statistical computing. R foundation for statistical computing, Vienna, Austria. https://www.Rproject.org/

Ran, X., Bouwman, L., Yu, Z., Beusen, A., Chen, H., Yao, Q. 2017. Nitrogen transport, transformation, and retention in the Three Gorges Reservoir: A mass balance approach. Limnology and Oceanography 62(5), 2323-2337. https://doi.org/10.1002/lno.10568

Ran, X., Yu, Z., Yao, Q., Chen, H., Mi, T. 2010. Major ion geochemistry and nutrient behaviour in the mixing zone of the changjiang (yangtze) river and its tributaries in the three gorges reservoir. Hydrological Processes 24(17), 2481-2495. https://doi.org/10.1002/hyp.7684

Ren, C., Wang, L., Zheng, B., Holbach, A. 2015. Total nitrogen sources of the Three Gorges Reservoir—a spatio-temporal approach. PloS One 10(10). https://doi.org/10.1371/journal.pone.0141458

Secchi, P. A. 1864. Relazione delle esperienze fatte a bordo della pontificia pirocorvetta Imacolata Concezione per determinare la trasparenza del mare. Memoria del PA Secchi. Il Nuovo Cimento Giornale de Fisica, Chimica e Storia Naturale 20, 205-237.

Sinha, E., Michalak, A. M., Balaji, V. 2017. Eutrophication will increase during the 21st century as a result of precipitation changes. Science 357(6349), 405-408.

https://doi.org/10.1126/science.aan2409

Stone, R. 2011. The legacy of the Three Gorges Dam. Science 333:817. https://doi.org/10.1126/science.333.6044.817

Strskraba, M., Tundisi, J. G. 1999. Guidelines of lake management volume 9. reservoir water quality management. International Lake Environment Committee 1-60.

Tang, J., Wang, T., Zhu, B., Zhao, P., Xiao, Y., Wang, R. 2015. Tempo-spatial analysis of water quality in tributary bays of the Three Gorges Reservoir region (China). Environmental Science and Pollution Research 22(21), 16709-16720. https://doi.org/10.1007/s11356-015-4805-z

Tang, Q., Bao, Y., He, X., Zhou, H., Zhang, X. 2014. Sedimentation and associated trace metal enrichment in the riparian zone of the Three Gorges Reservoir, China. Science of The Total Environment 479-480(1), 258-266. https://doi.org/10.1016/j.scitotenv.2014.01.122

Tong, J., Qiang, Z., Deming, Z., Yijin, W. 2006. Yangtze floods and droughts (China) and teleconnections with ENSO activities (1470–2003). Quaternary International 144(1), 29-37. https://doi.org/10.1016/j.quaint.2005.05.010

Tranmer, A. W., Weigel, D., Marti, C. L., Vidergar, D., Benjankar, R., Tonina, D., Goodwin, P., Imberger, J. 2020. Coupled reservoir-river systems: lessons from an integrated aquatic ecosystem assessment. Journal of Environmental Management 260, 1-14. https://doi.org/10.1016/j.jenvman.2020.110107

Wang, L., Cai, Q., Tan, L., Kong, L. 2011. Phytoplankton development and ecological status during a cyanobacterial bloom in a tributary bay of the Three Gorges Reservoir, China. Science of the Total Environment 409(19), 3820-3828.

https://doi.org/10.1016/j.scitotenv.2011.06.041

Wang, L. L., Zhang, B., Li, Y., Yan, C. M. 2013b. Preliminary study on aquatic ecoregion in Three Gorges Area. Environmental Science & Technology 36(5), 193-196. https://doi.org/10.3969/j.issn.1003-6504.2013.05.038

Wang, X., Chen, Y., Song, L., Chen, X., Xie, H., Liu, L. 2013a. Analysis of lengths, water areas and volumes of the three gorges reservoir at different water levels using landsat images and srtm dem data. Quaternary International 304, 115-125. https://doi.org/10.1016/j.quaint.2013.03.041

Wei, O., Hao, F., Song, K., Zhang, X. 2011. Cascade dam-induced hydrological disturbance and environmental impact in the upper stream of the Yellow River. Water Resources Management 25(3), 913-927. https://doi.org/10.1007/s11269-010-9733-6

Xia, J., Xu, G., Guo, P., Peng, H., Zhang, X., Wang, Y., Zhang, W. 2018. Tempo-spatial analysis of water quality in the Three Gorges Reservoir, china, after its 175-m experimental impoundment. Water Resources Management 32(9), 2937-2954. https://doi.org/10.1007/s11269-018-1918-4

Xia, Z. Q. 2014. Study of temporal-spatial distribution of the water quality and phytoplankton of the Three Goeges area in algal blooms sensitve season. Southwest University. (in Chinese)

Xiao, L., Zhu, B., Nsenga Kumwimba, M., Jiang, S. 2017. Plant soaking decomposition as well as nitrogen and phosphorous release in the water-level fluctuation zone of the three gorges reservoir. Science of the Total Environment 592, 527-534. https://doi.org/10.1016/j.scitotenv.2017.03.104

Xiao, Y., Li, Z., Guo, J., Fang, F., Smith, V. H. 2016. Succession of phytoplankton assemblages in response to large-scale reservoir operation: a case study in a tributary of the Three Gorges Reservoir, China. Environmental monitoring and assessment 188(3), 153. https://doi.org/10.1007/s10661-016-5132-7

Xiang, R., Wang, L. J., Li, H., Tian, Z. B., Zheng, B. H. 2021. Temporal and spatial variation in water quality in the Three Gorges Reservoir from 1998 to 2018. Science of the Total Environment 768. https://doi.org/10.1016/j.scitotenv.2020.144866

Xie, H., Shen, Z., Chen, L., Qiu, J., Dong, J. 2017. Time-varying sensitivity analysis of hydrologic and sediment parameters at multiple timescales: implications for conservation practices. Science of The Total Environment 598, 353-364. https://doi.org/10.1016/j.scitotenv.2017.04.074

Xu, X., Tan, Y., Yang, G. 2013. Environmental impact assessments of the Three Gorges Project in China: Issues and interventions. Earth-Science Reviews 124, 115-125. https://doi.org/10.1016/j.earscirev.2013.05.007

Xu, X., Tan, Y., Yang, G., Li, H., Su, W. 2011b. Soil erosion in the Three Gorges Reservoir area. Soil Research 49(3), 212-222. https://doi.org/10.1071/SR10191

Xu, Y., Zhang, M., Wang, L., Kong, L., Cai, Q. 2011a. Changes in water types under the regulated mode of water level in three gorges reservoir, China. Quaternary International 244(2), 272-279. https://doi.org/10.1016/j.quaint.2011.01.019

Xu, Y., Cai, Q., Ye, L., Shao, M. 2011c. Asynchrony of spring phytoplankton response to temperature driver within a spatial heterogeneity bay of Three-Gorges Reservoir, China. Limnologica 41(3), 174-180. https://doi.org/10.1016/j.limno.2010.10.004

Yang, Z., Liu, D., Ji, D., Xiao, S. 2010. Influence of the impounding process of the Three

Gorges Reservoir up to water level 172.5 m on water eutrophication in the Xiangxi Bay. Science China Technological Sciences 53(4), 1114-1125. https://doi.org/10.1007/s11431-009-0387-7

Yang, Z. J., Liu, D. F., Ji, D. B., Xiao, S. B., Huang, Y. L., Ma, J. 2013. An eco-environmental friendly operation: an effective method to mitigate the harmful blooms in the tributary bays of three gorges reservoir. Science China Technological Sciences 56(006), 1458-1470. https://doi.org/10.1007/s11431-013-5190-9

Yang, Z. J., Zhang, J. L. 2014. Factors to affect the eutrophication and phytoplankton blooms in the three Gorges reservoir. In Advanced Materials Research. Trans Tech Publications Ltd 1010, 1104-1109. https://doi.org/10.4028/www.scientific.net/AMR.1010-1012.1104

Yu, Z. Z., Wang, L. L. 2011. Factors influencing thermal structure in a tributary bay of three gorges reservoir. Journal of Hydrodynamics Ser B 23(4), 407-415. https://doi.org/10.1016/S1001-6058(10)60130-8

Zhang, J., Li, S., Dong, R., Jiang, C., Ni, M. 2019. Influences of land use metrics at multi-spatial scales on seasonal water quality: A case study of river systems in the Three Gorges Reservoir Area, China. Journal of cleaner production 206, 76-85. https://doi.org/10.1016/j.jclepro.2018.09.179

Zhang, M., Xu, Y., Shao, M., Cai, Q. 2012b. Sedimentary nutrients in the mainstream and its five tributary bays of a large subtropical reservoir (Three Gorges Reservoir, China). Quaternary international, 282, 171-177. https://doi.org/10.1016/j.quaint.2012.02.054

Zhang, Q. F., Lou, Z. P., 2011. The environmental changes and mitigation actions in the Three Gorges Reservoir region, China. Environmental Science & Policy 14, 1132-1138.

https://doi.org/10.1016/j.envsci.2011.07.008

Zhang, S. 2012a. Eutrophication of the Three Gorges Reservoir after its first filling. In Tropical and Sub-Tropical Reservoir Limnology in China. Springer, Dordrecht. 91, 293-309. https://doi.org/10.1007/978-94-007-2007-7_17

Zhao, P., Tang, X., Tang, J., Wang, C. 2013. Assessing water quality of Three Gorges Reservoir, China, over a five-year period from 2006 to 2011. Water Resources Management 27(13), 4545-4558. https://doi.org/10.1007/s11269-013-0425-x

Zhao, Y., Qin, Y., Zhang, L., Zheng, B., Ma, Y. 2016. Water quality analysis for the Three Gorges Reservoir, China, from 2010 to 2013. Environmental Earth Sciences 75(17), 1225. https://doi.org/10.1007/s12665-016-5954-1

Zhao, Y., Zheng, B., Wang, L., Qin, Y., Li, H., Cao, W. 2015. Characterization of mixing processes in the confluence zone between the three gorges reservoir mainstream and the daning river using stable isotope analysis. Environmental ence & Technology 9907. https://doi.org/10.1021/acs.est.5b01132

Zheng, B., Zhao, Y., Qin, Y., Ma, Y., Han, C. 2016. Input characteristics and sources identification of nitrogen in the three main tributaries of the Three Gorges Reservoir, China. Environmental Earth Sciences 75(17), 1219. https://doi.org/10.1007/s12665-016-6028-0

Zheng, T., Mao, J., Dai, H., Liu, D. 2011. Impacts of water release operations on algal blooms in a tributary bay of Three Gorges Reservoir. Science China Technological Sciences 54(6), 1588-1598. https://doi.org/10.1007/s11431-011-4371-7

Graphical Abstract