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Response of Eutrophication Development to Variations in Nutrients and Hydrological Regime: A Case Study in the Changjiang River (Yangtze) Basin

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Abstract: Data and literature related to water quality as well as nutrient loads were used to evaluate the Changjiang River (also Yangtze or Yangzi) Basin with respect to its hydrological regime, sediment transport, and eutrophication status. Waterbodies exhibited different eutrophic degrees following the ranking order of river < reservoir < lake. Most of the eutrophic lakes and reservoirs distributed in the upstream Sichuan Basin and Jianghan Plain are located in the middle main stream reaches. During the past decade, the water surface area proportion of moderately eutrophic lakes to total evaluated lakes continually increased from 31.3% in 2009 to 42.7% in 2018, and the trophic level of reservoirs rapidly developed from mesotrophic to slightly eutrophic. Construction and operation of numerous gates and dams changed the natural transportation rhythm of runoff, suspended solids (SS), and nutrients, and reduced flow velocity, resulting in decreased discharge runoff, slow water exchange, and decreased connectivity between rivers and lakes as well as accumulated nutrient and SS, which are the main driving forces of eutrophication. To mitigate eutrophication, jointly controlling and monitoring nutrient concentrations and flux at key sections, strengthening water quality management for irrigation backwater and aquaculture wastewater, and balancing transportation among runoff, SS, and nutrients is recommended.

Keywords: eutrophication; phosphorus; suspended sediment; reservoir; regulation; water resources' management

1. Introduction

Eutrophication is the process by which a body of water becomes enriched in dissolved nutrients (such as phosphorus), which stimulate the growth of aquatic plant life usually resulting in the depletion of dissolved oxygen. As natural water bodies become eutrophic, the proliferation of harmful algae can accelerate the deterioration of water quality and then lead to detrimental impacts on the aquatic ecosystem. This phenomenon is often referred to as algal blooming [1]. Eutrophication occurs around the world, and the following four factors can stimulate the eutrophication process: (1) Sufficient supply of nutrients (nitrogen and phosphorus) and organic matter [2], (2) suitable meteorological conditions in terms of temperature and light [3], (3) hydrodynamic processes such as slow water flow and long hydraulic retention time [4], and (4) loss of control of algal growth through the aquatic food web, algae biomass exceeded the prey capacity for algophagous zooplankton and fish [5]. Hydrology, sediment, and nutrients are key factors that affect eutrophication. Runoff and sediment are the main carriers of nutrients [4]. Retention and regulation of runoff and sediment by dams or gates cause slow water flow, declining runoff, and the accumulation of nutrients, which subsequently trigger the development of water eutrophication.

The Changjiang River is the largest one in China. This river contains one-third of China's total freshwater resources, three-fifths of the hydropower resource reserves, abundant biological resources, and considerable navigational potential. The Changjiang River system has a well-developed water network. The Bulletin of First National Census for Water indicated that this network consists of 10,741 rivers with a catchment area larger than 50 km^2, 805 lakes with a perennial water surface area of at least 1 km^2, and 51,600 reservoirs that account for 52.65% of the total reservoirs in China [6]. Since the 1980s, the Changjiang River Basin has experienced large-scale, high-intensity development and construction, altering the hydrological regime, sediment transport, and nutrient distribution through anthropogenic activity and climate change [4,7]. Tensive relationships between water resources, water quality, and river ecology as well as overloaded pollutant discharge are threatening the health of the Changjiang River [8]. Moreover, rapidly developing eutrophication has led to frequent and serious algal blooms in the basin, which can damage the aquatic ecosystem and interfere with drinking water supply.

For the Changjiang River Basin, algal blooms have already occurred in some large lakes (e.g., Taihu Lake and Chaohu Lake), primary tributaries such as the Hanjiang River, and large reservoirs including the Three Gorges Reservoir ((TGR) mainly for bays and tributary estuaries) in the 1970s, 1990s, and the early 21st century [1]. Furthermore, the latest Water Resources Bulletin of the Changjiang River Basin and Southwest Rivers indicated eutrophication as the most serious problem in the basin [9]. Eutrophication monitoring, assessment, and control for downstream shallow lakes (e.g., Taihu Lake and Chaohu Lake), upstream plateau lakes (e.g., Dianchi Lake), the TGR, and Hanjiang River have provided useful outcomes related to eutrophic mechanisms, influential factors, and countermeasures for the aforementioned single-type water bodies [10–12]. However, the Changjiang River Basin covers a catchment area of more than 2,000,000 km^2, with great variability in hydrological regimes, sediment transportation processes, hydrodynamic characteristics, and nutrient loads among rivers, lakes, and reservoirs, which result in differences in eutrophication formation and mechanism development. This study compares the eutrophic similarities and differences of rivers, lakes, and reservoirs at the basin level to provide guidance on how to approach and mitigate the eutrophication challenges linked to the Changjiang River.

This study examines authoritative monitoring and assessment data and published literature regarding runoff, sediment, nutrients (mainly for nitrogen and phosphorus), wastewater discharge, fertilizer application, aquaculture, algal density, and water quality from the previous decade to (1) evaluate the status and trends of eutrophication in rivers, lakes, and reservoirs; (2) reveal the main driving forces for eutrophication in representative rivers, lakes, and reservoirs; and (3) propose countermeasures to alleviate eutrophication development, and thus provide scientific means of nutrient management and eutrophication control in the basin. The outcome of this study will provide management advice and prioritization of actions for basin protection and management of the Changjiang River as well as other similar rivers.

2. Methods and Materials

Data for water quality and trophic level for rivers, lakes, and reservoirs as well as wastewater discharge volumes were collected from the Water Resources Bulletin of the Changjiang River Basin and Southwest Rivers (2006–2018), which was annually issued by the Changjiang River Water Resources Commission (CWRC). The Environmental Quality Standard for Surface Water (GB 3838-2002) was used to assess the water quality and nutrient loads in rivers, lakes, and reservoirs (Table S1). Between 2016 and 2017, eutrophic lake and reservoir distributions in the main stream flowing through 11 provinces (municipalities), namely Yunnan, Sichuan, Guizhou, Chongqing, Hubei, Hunan, Anhui, Jiangxi, Jiangsu, Zhejiang, and Shanghai, were obtained from water resources bulletins, which were issued by corresponding provincial departments of water resources. According to the technological regulation for surface water resources quality assessments SL 395-2007, rivers, lakes, and reservoirs are classified as oligotrophic, mesotrophic, slightly eutrophic, moderately eutrophic, or hypertrophic, corresponding to an eutrophication index (EI) of <20, 20–50, 50–60, 60–80, and >80 (Table 1). Based on the measurement of Secchi disc transparency (SD), total phosphorus (TP), total nitrogen (TN), permanganate index (COD_{Mn}), and algal biomass in the form of chlorophyll-a (Chl-a), the EI can be calculated with Equation (1):

$$\mathrm{EI} = \sum_{n=1}^{n} \frac{E_n}{n} \tag{1}$$

where E_n is the score of the nth indicator, n is the number of the indicator, and chlorophyll-a is the essential evaluation indicator.

Table 1. Evaluation standard and classification method of lake (reservoir) trophic status (SL 395-2007).

Class	E_n	TP (mg/L)	TN (mg/L)	Chl-a (mg/L)	COD_{Mn} (mg/L)	SD (m)
Oligotrophic $0 \le EI \le 20$	10	0.001	0.020	0.0005	0.15	10
	20	0.004	0.050	0.0010	0.4	5.0
Mesotrophic $20 < EI \le 50$	30	0.010	0.10	0.0020	1.0	3.0
	40	0.025	0.30	0.0040	2.0	1.5
	50	0.050	0.50	0.010	4.0	1.0
Slight eutrophic $50 < EI \le 60$	60	0.10	1.0	0.026	8.0	0.5
Moderate eutrophic $60 < EI \le 80$	70	0.20	2.0	0.064	10	0.4
	80	0.60	6.0	0.16	25	0.3
Hypereutrophic $80 < EI \le 100$	90	0.90	9.0	0.40	40	0.2
	100	1.3	16.0	1.0	60	0.12

EI, eutrophication index; E_n, score of the nth eutrophication indicator; TP, total phosphorus; TN, total nitrogen; Chl-a, chlorophyll-a; COD_{Mn}, permanganate index; SD, Secchi disc transparency.

Data of chemical fertilizer application and aquaculture production in 11 provinces (municipalities) between 1998 and 2018 were collected from statistical yearbooks, and data of aquaculture areas for rivers, lakes, and reservoirs in Hubei Province were obtained from the provincial statistical yearbook.

Hydrology and water quality monitoring data from Taihu Lake were received from the Taihu Basin Authority of the Ministry of Water Resources. Main stream runoff, sediment grain size, and SS concentration on controlled sections of Hankou and Datong were obtained from the Changjiang River sediment bulletins that were issued by CWRC. Monthly averaged runoff, SS, and TP concentrations on the Datong section were obtained from the Bureau of Changjiang Hydrology. There are numerous studies on the nutrient distribution in the main stream of the Changjiang River but only few monitoring data at the same period and locations. The TP and soluble reactive phosphorus (SRP) concentrations along the main stream sections in 2006 and 2014 were received from previous studies [13,14], and these data were comparable given the same sampling period (April), sampling sections, and monitoring methods. Moreover, algal characteristics, algae density, and hydrodynamic conditions including flow velocity and flow rate for Taihu Lake, Chaohu Lake, and Daning River in the TGR and Hanjiang River were obtained from numerous documents provided by Wanfang Data and Science Direct databases.

Only the key documents are referenced in this article. Average sediment TN and TP content in rivers, lakes, and reservoirs in the Changjiang River Basin were estimated. A distribution map for eutrophic lakes and reservoirs was generated using Arc Map (Environment System Research Institute) and other figures were prepared with Origin 8.0 (OriginLab Corp).

3. Results and Discussions

3.1. Trophic Status and Developed Trends

3.1.1. Basin Nutrient Loads

Water quality reflects the level of nutrients within water bodies. The total length of assessed rivers increased from 38,679 km in 2006 to 85,842 km in 2018, and the maximum proportion of the river length that reached a water quality standard of Grades I–III (meet the requirements for drinking water sources) of the GB 3838-2002 was 88.2% (Figure 1a). Proportions of the river length with a water quality standard of Grades IV, V, or worse than V of the GB 3838-2002 continued to decline since 2006. Until 2018, approximately 5% of the total assessed river length with a water quality lower than Grade IV of the GB 3838-2002 was recorded.

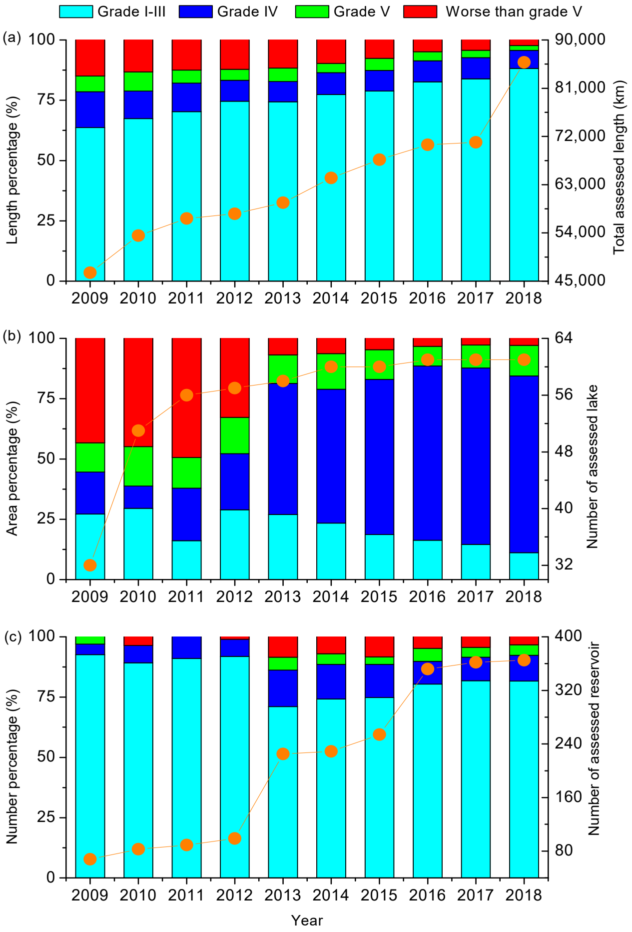

Figure 1. Variation in water quality for basin-assessed (**a**) rivers, (**b**) lakes, and (**c**) reservoirs between 2009 and 2018.

The water quality of lakes was bad in general. Water surface area proportions for lakes with water quality of Grades I-III and worse than Grade V of the GB 3838-2002 declined from 33.4% to 9.8% and from 43.3% to 2.9% between 2009 and 2018, respectively (Figure 1b). Lake water with Grade IV of the GB 3838-2002 had the greatest proportion of surface area, reaching 73.3% in 2018 (Figure 1b).

The tendency of lake water quality indicated that some lakes with good water quality failed to be protected, and part of the lakes with deteriorated water quality were efficiently restored.

The water quality of reservoirs was better than that of lakes, and most evaluated reservoirs had a water quality higher than Grade III of the GB 3838-2002 (Figure 1c). The proportion of reservoirs with a water quality of Grades I-III of the GB 3838-2002 had the highest level at 83.2%. Due to the sharp increase in the number of monitored water bodies, the water quality of the reservoirs seems to have improved after 2013, and the proportion of reservoirs with a water quality of Grades I-III of the GB 3838-2002 increased from 71.1% in 2013 to 81.6% in 2018. The proportion of reservoirs with a water quality of Grade IV and worse than Grade V of the GB 3838-2002 decreased from 15.1% and 8.5% in 2013 to 10.7% and 3.3% in 2018 (Figure 1c), correspondingly.

Nutrients (particularly phosphorus) are the primary determinants of the trophic level of water bodies. Lack of municipal wastewater treatment facilities and massive poultry and livestock farming contributed to the majority of the phosphorus discharge flowing to the Minjiang River and Tuojiang River. Waste produced in the phosphorus industry including tailing pond leakage, ore mining, and wastewater discharge are the major sources of phosphorus input to the Wujiang River. Moreover, phosphorus-containing chemical industrial wastewater discharge and unsound municipal domestic sewage collection networks have resulted in high levels of phosphorus in Hanjiang River [15]. The TP concentration in the Wujiang main stream reached its maximum of 0.674 mg/L in 2011, which was 2.37 times that of Grade III of the GB 3838-2002 [15].

The TP concentrations tended to decrease downstream of the Yichang section, whereas the SRP concentration distribution exhibited an increasing trend (Figure 2). Phosphorus transportation in the river mainly occurred through particulate phosphorus (PP), and more than 95% of phosphorus flowing into the sea is PP from the Changjiang River [16]. Due to upstream large-scale water and soil conservation as well as the construction and operation of 196 large dams, SS output flux in the Changjiang River Basin sharply decreased from 198.7 t km^{-2} year^{-1} between 1986 and 2002 to 81.0 t km^{-2} year^{-1} between 2003 and 2015 [17]. The PP content is mainly adsorbed into fine SS and can be effectively retained by dams, and the TGR can intercept more than 75% of the upstream PP input through SS retention [4]. Declining SS discharge led to the reduction of PP transportation to downstream areas and thus resulted in an increase in the ratio of SRP to TP. The average ratio of SRP to TP increased from 27.6% in 2006 to 36.5% in 2014 (Figure 2).

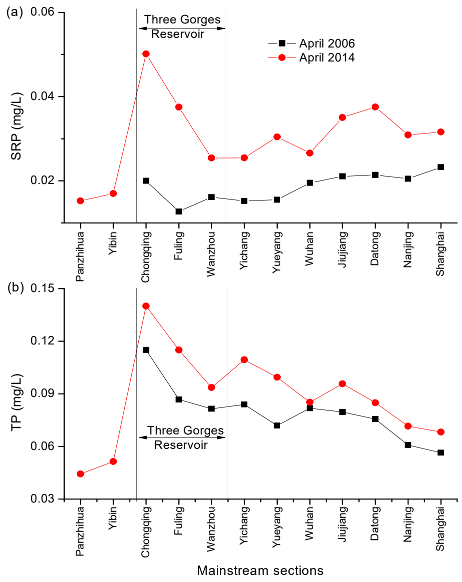

Figure 2. (**a**) Total phosphorus (TP) and (**b**) soluble reactive phosphorus (SRP) concentrations along the main stream sections in 2006 [13] and 2014 [14].

3.1.2. Eutrophic Trends for Various Water Bodies

For about 6000 km of the main stream of the Changjiang River eutrophication monitoring and assessment was carried out. The water quality reached Grade I-II of the GB 3838-2002 (Supplementary Material Table S1). The primary productivity was achieved at low levels of eutrophication [18]. Lu et al. [19] studied the spatiotemporal characteristics of water quality and trophic status, and observed that the main stream maintained a moderate eutrophic level between June 2012 and December 2017.

High flushing volumes reduce the conditions that can cause algal blooms in the main stream of the Changjiang River. However, sufficient water column nutrients and suitable hydrodynamic conditions encourage diatom-dominated algal blooms in the Hanjiang River with durations of at least 30 days/year (Table 2). Algal blooms have appeared in the middle and lower reaches of Hanjiang River since the early 1990s, and the outburst period is between early February and the beginning of March. Sufficient nutrients, slow water flow of less than 0.225 m/s, and discharge of less than 500 m^3/s were reported to be the main reasons for algal propagation [20].

Eutrophic levels for lakes and reservoirs in the basin exhibit clear differences in spatial distribution. Moderately eutrophic to hypertrophic lakes and reservoirs are located in the Sichuan Basin and Jianghan Plain (Figure 3). Moreover, the ratio of eutrophic reservoirs in the Minjiang River, Jialingjiang River, and Hanjiang River corresponded to total assessed reservoirs reaching 70%, 52%, and 38%, respectively (Figure 3).

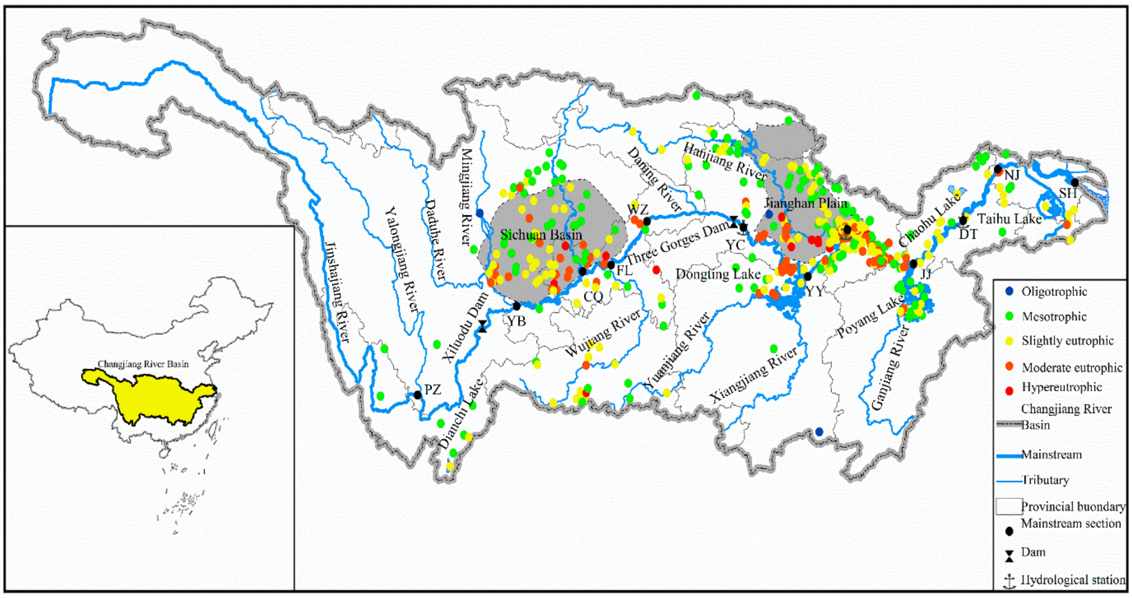

Figure 3. Distribution of eutrophic lakes and reservoirs in the Changjiang River Basin. The trophic levels were determined according to the eutrophic index assessment regulations of SL 395-2007. PZ, YB, CQ, FL, WZ, YC, YY, WH, JJ, DT, NJ, and SH signify Panzhihua, Yibin, Chongqing, Fuling, Wanzhou, Yichang, Yueyang, Wuhan, Jiujiang, Datong, Nanjing, and Shanghai, respectively.

Table 2. Characteristics of algae blooms occurring in representative reservoirs, lakes, and rivers in the Changjiang River Basin.

Water Bodies	**Dominating Algae Species**	**First Outburst**	**Frequent Outburst Period**	**Duration and Scope**	**Major Driving Forces**
Three Gorges Reservoir [21]	Cyanobacteria (*Aphanizomenon flos-aquae* and *Dolichospermum*), Chlorophyta (*Coelastrum*) and Dinoflagellate	2003	Spring and autumn	Approximately 30 days per year in nearly 10 km of river reaches	Sufficient nutrient supply and slow water flow of 0.1–0.3 m/s
Taihu Lake [22]	Cyanobacteria (*Microcystis aeruginosa*)	1950s	Spring, autumn and winter	75–320 days per year with a water surface area of 67–1150 km^2	Sufficient nutrient supply (0.064–0.111 mg/L of TP and 1.80–2.04 mg/L of TN), wind wave–promoted sediment nutrient release and algae aggregation
Chaohu Lake [23]	Cyanobacteria (*Anabaena* in spring and *Microcystis aeruginosa* in summer and autumn)	1980s	April–November, peaking in September	34–318 days per year with a maximal water surface area of 500 km^2	Sufficient nutrient supply (0.088–0.109 mg/L of TP and 1.55–3.14 mg/L of TN), wind wave–promoted sediment nutrient release and algae aggregation
Hanjiang River [24]	Bacillariophyta (*Cyclotella* and *Stephanodiscus ehrenberg*)	1992	Early February to beginning of March	6–30 days with a maximal river reach of 200 km	Sufficient nutrient supply (0.07–0.17 mg/L of TP and 1.09–2.40 mg/L of TN) and flow velocity and runoff under critical minimum values of 0.225 m/s and 500 m^3/s, respectively

TP, total phosphorus; and TN, total nitrogen.

The majority of freshwater lakes in the middle and lower reaches of the Changjiang River are characterized as plain shallow lakes. During the past 40 years, reclamation, aquaculture, and pollutant discharge have resulted in sharp declines of water surface area, connectivity between rivers and lakes, and water exchange as well as nutrient accumulation. Algae replaced aquatic macrophytes and became dominant [25]. The number of lakes that have undergone eutrophic assessments increased from 10 in 2008 to 61 in 2018 (Figure 4a), and trophic levels have gradually changed from oligotrophic and mesotrophic to slightly eutrophic. Moreover, lake eutrophication was not effectively controlled, and the proportion of moderately eutrophic lakes increased from 31.3% in 2009 to 42.7% in 2018 (Figure 4a).

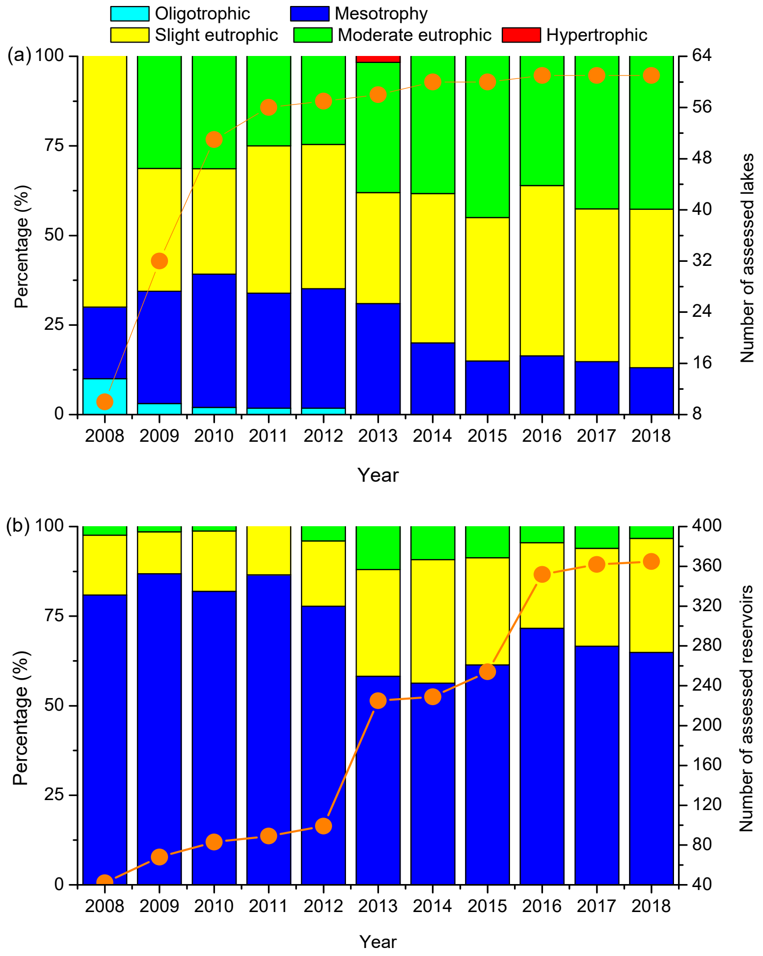

Figure 4. Trophic levels for (**a**) lakes and (**b**) reservoirs between 2008 and 2018. The trophic levels were determined according to the eutrophic index assessment regulations of SL 395-2007.

Compared with lakes, the majority of reservoirs have short hydraulic retention times and good hydrodynamic conditions [1]. The water quality for most reservoirs in the basin is good. However, extensively developed fisheries and high-density duck raising accelerated the eutrophication process for the majority of small and rural reservoirs [26].

Statistical results indicated that the number of large- and medium-sized reservoirs that underwent eutrophic assessment increased from 42 in 2008 to 365 in 2018 (Figure 4b). About 95% of the total assessed reservoirs are mesotrophic and slightly eutrophic, and no hypertrophic reservoir was observed. In general, the eutrophic degree of reservoirs was lower than that of lakes. However, the trophic level of reservoirs has been developing from mesotrophic to slightly eutrophic (Figure 4b).

Compared with rivers, slow water flow facilitated the eutrophication of lakes and reservoirs. Sufficient nutrient input has led to cyanobacteria-dominated algal bloom outbursts in Taihu Lake and Chaohu Lake since the 1950s and 1980s, respectively. The outburst duration and water surface area exceeded 300 days/year and 500 km^2 (Table 2). Wind-induced waves stimulated sediment nutrient release and algae aggregation, and thus promoted cyanobacterial blooms [22,23]. The TGR is a channel reservoir. Slow water flow favored cyanobacteria blooms have appeared there since the first impoundment in 2003 with durations of up to 30 days [21].

3.2. Nutrient Discharge Dynamics in the Basin

3.2.1. Wastewater Discharge

The total wastewater discharge volume slowly increased from 30,600,000,000 t in 2006 to 35,200,000,000 t in 2017 (Supplementary Material Figure S1). Industrial wastewater discharge volume markedly decreased because of technological development improvement. The domestic wastewater discharge volume continually increased, because of the increasing urban population and wastewater collection rate. The proportion of domestic to total wastewater discharge volume correspondingly increased from 31.9% in 2006 to 47.7% in 2017 (Supplementary Material Figure S1). The majority of phosphorus within industrial wastewater originates from phosphate ore mining and the phosphorus chemical industry [15]. In 2015, one-third of phosphorus mining enterprises discharged effluent with TP concentrations exceeding the Grade I emission limit of 0.5 mg/L specified by the Integrated Water Discharge Standard (GB 8978-1996, Supplementary Material Table S1), and 25.8% of the phosphate fertilizer enterprises discharged wastewater exceeding the TP emission concentration limit of 15 mg/L required by the Discharge Standards of Water Pollutants for the Phosphate Fertilizer Industry (GB 15580-2011, Supplementary Material Table S1). For domestic wastewater, sewage treatment facilities discharged TP with a basin average concentration of 0.68 mg/L, which is substantially higher than the 0.40 mg/L limit for Grade V of the GB 3838-2002. Moreover, most sewage collection networks remain unsound, and phosphorus removal is not enhanced in the upstream and middle reaches of the Changjiang River Basin. In the Minjiang River Basin, for example, 69.5% of sewage treatment plants implement the Class A discharge criterion within the TP limit of 0.50 mg/L required by the Discharge Standard of Pollutants for Municipal Wastewater Treatment Plants (GB 18918-2002, Supplementary Material Table S1), and 23.9% of sewage treatment plants implement the Class B discharge criterion within the TP limit of 1.0 mg/L [15].

3.2.2. Chemical Fertilizer Loss

Farmland fertilizer application was the most crucial source of nitrogen input in spring and autumn [27]. During 2012–2016, non-point sources contributed to 36% and 63% of the nitrogen and phosphorus flux into the sea, respectively, and its contributions tended to increase from upstream to downstream [28]. The Changjiang River Basin is the main rice-cropping area, and fertilization during the rice tillering stage (June) always takes place during the Meiyu period (June and July), which is the main reason for the high rate of chemical fertilizer loss [29,30].

Agricultural non-point source pollution was mainly distributed in the Jinshajiang River Basin and Jialingjiang River Basin (upstream of the Changjiang River) and Hanjiang River Basin (middle reaches of the Changjiang River), where the key Chinese commodity grain base is located. The China Statistical Yearbook indicated that fertilizer application in the Changjiang River Basin continued to increase to maximal level of 21,790,000 t in 2014 (Supplementary Material Figure S2) before slowly decreasing. From 1998 to 2015, nitrogen fertilizer application tended to decline, phosphorus fertilizer application fluctuated between 2,850,000 and 3,220,000 t, and compound fertilizer application considerably increased from 3,040,000 t to 6,940,000 t (Supplementary Material Figure S2). In China, chemical fertilizers contributed to 40% of grain production growth, but the average application rate of 21.9 kg/mu (1 mu ≈ 667 m^2) exceeded the global level of 8.0 kg/mu (1 mu ≈ 667 m^2) [31]. Moreover, the utilization efficiency of phosphorus fertilizer gradually decreased with increases in application rate [32], and a 78% decline in crop phosphorus utilization efficiency was observed in China between 1949 and 2012, which resulted in 41 kg P ha^{-1} year^{-1} phosphorus accumulation in farmland soil [33]. Chemical fertilizer loss contributing to phosphorus flux increased from 509.9 kg P km^{-2} year^{-1} in 1980 to 1346.7 kg P km^{-2} year^{-1}, which accounted for 56–67% of the total non-point source phosphorus input [34].

3.2.3. Aquaculture

Aquaculture is another key non-point source of phosphorus pollution. The Changjiang River Basin is the principal production region for freshwater aquaculture in China, and its fisheries account for 60% of the national total fishery yield [35]. As illustrated in Figure S3 of the Supplementary Material, freshwater aquaculture yields increased from 10,540,000 t in 1998 to 23,200,000 t in 2016. Hubei Province is located in the Jianghan Plain, which has the greatest freshwater fish yields in China. For Hubei Province, ponds, lakes, and reservoirs consistently dominated aquaculture water bodies between 1995 and 2017, although a recent decrease in lake and reservoir culture areas was recorded. Until 2017, lakes and reservoirs accounted for more than 35% of the total culture area in Hubei Province (Supplementary Material Figure S3). However, the feed utilization rate is low for aquaculture; 13–15 kg of feed may be directly lost within the waterbody when 100 kg of feed is used [36] and 20–30% of feed intake by fish is discharged into the water through feces [37]. Therefore, TN and TP concentrations were 219% and 150%, respectively, higher in culture areas than in non-culture ones [38]. Due to the massive aquaculture pollution and agricultural nutrient loss, most lakes and reservoirs in the Jianghan Plain of the Hanjiang River Basin exhibited moderate eutrophic and hypertrophic conditions (Figure 3).

3.2.4. Internal Sediment Nutrient Accumulation

Table 3 lists the sediment TN and TP content in rivers, lakes, and reservoirs of the Changjiang River Basin. The average sediment TP content in the basin ranged between 738 and 914 mg/kg, which is slightly higher than the national average level of 733 mg/kg [39]. The average sediment TN content of 1114–3700 mg/kg was apparently higher than the national average value of 1070 mg/kg [39]. TN and TP content in lake sediment is higher than that in river sediment (Table 3), and the nitrogen and phosphorus released from sediment are crucial nutrient sources for promoting eutrophication in Taihu Lake and Chaohu Lake [22,23] (Table 2). Furthermore, tributaries such as Wujiang River and Hanjiang River flow through regions with a geologically high phosphorus level. Thus, the sediment of reservoirs located in these sub-basins has a relatively high average TP content of 4719 mg/kg, which is six times higher than the national average (Table 3), indicating a high phosphorus-releasing potential and associated eutrophic risk.

Table 3. Sediment nutrient content of eutrophic water bodies in the Changjiang River Basin.

Water Bodies	TP (mg/kg)	TN (mg/kg)
Rivers (22)	245–1145 (738 ± 273)	789–1616 (1114 ± 266)
Reservoirs (35)	490–1220 (743 ± 189)	1340–4950 (3017 ± 934)
Reservoirs * (10)	2657–8133 (4719 ± 2534)	3100–4200 (3700 ± 497)
Lakes (18)	457–2608 (914 ± 510)	533–12390 (2346 ± 2473)

* Reservoirs located in the region with a high phosphorus geological background. Sample numbers are in parentheses for each type of water body. Sediment TN and TP content are given as a range and mean value ± standard deviation in parentheses.

3.3. Response of Eutrophication to Hydrologic Regime Variation

3.3.1. Flow Velocity

Formation of algal blooms is easier in lentic (stagnant or still) waters than in flowing waters. The TGR is an example of the response of eutrophication to flow velocity. Since the first impoundment in

2003, main stream average water flow decreased from 3–5 m/s in natural river channels to 0.07–2.43 m/s in the newly formed reservoir [4]. The elevation of water level and reduction of flow velocity caused an increase in water transparency and the proportion of soluble nutrients, which facilitated nutrient uptake by phytoplankton [4]. Moreover, when the reservoir operates at a high water level, the main stream jacking effect promoted nutrient accumulation and subsequent algae propagation in the estuaries [2]. Nutrient (in particular, phosphorus) availability is already sufficient in the TGR and the hydrodynamic conditions such as flow velocity were the main driving forces for eutrophication [4,40]. Lower flow velocity resulted in higher algal density. Algal blooms frequently occurred in the tributary of the Daninghe River, and chlorophyll-a decreased from 29.8 to 2.7 mg/L, whereas the flow velocity increased from 0.025 to 0.87 m/s [41]. The chlorophyll-a concentration was negatively and exponentially fitted with flow velocity, resulting in a correlation coefficient of 0.89 (Figure 5). Moreover, augmentation of impoundment water level and declining main stream flow velocity greatly promoted eutrophication, and the number of tributaries in which algal blooms occurred increased from 5 to more than 20 when the impoundment water level increased from 135 to 175 m. Nearly two-thirds of the tributaries of the TGR have experienced algal blooms [4].

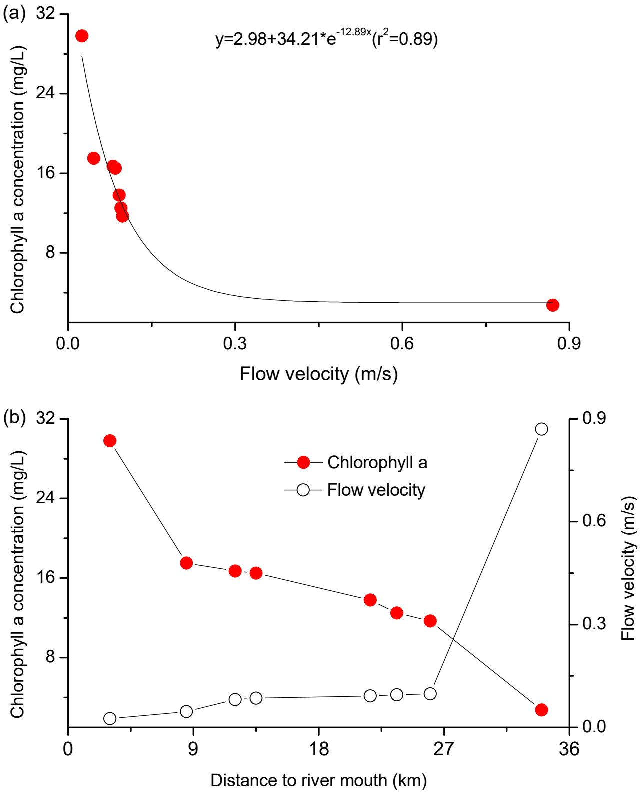

Figure 5. Relationship between chlorophyll-a concentration and (**a**) flow velocity and (**b**) distance to river mouth for the Daning River of the Three Gorges Reservoir and flow velocity (adapted from [41]).

3.3.2. Flow Rate

Because of reduced inflow and upstream water flow diversion, the middle and lower reaches of the Hanjiang River are relatively dry, and outbursts of diatom blooms have been observed since 1992. *Stephanodiscus* is the dominant algal genus, and accounts for more than 95% of total phytoplankton biomass [42]. Nitrogen, phosphorus, and water temperature are not limiting factors for algal blooms in the Hanjiang River, but flow rate and flow velocity may determine eutrophication development [10]. About 70 % of algal blooms occurred with a seven-day minimum flow of 600 m^3/s between 1992 and 2012 [43]. Field monitoring for diatom blooms in the early spring of 2018 found that algal blooms occurred in flow rates lower than 700 m^3/s and regressed with flow rates higher than 1000 m^3/s [44].

As displayed in Figure 6, the diatom density exhibited a negative and linear fit to flow rate with a correlation coefficient of 0.73 ($p < 0.01$). Calculation results indicated that a minimum flow rate of 1200 m^3/s was required to control diatom density to less than 10^6 cell/L, and to avoid outbursts of diatom blooms without nutrient reduction (Figure 6).

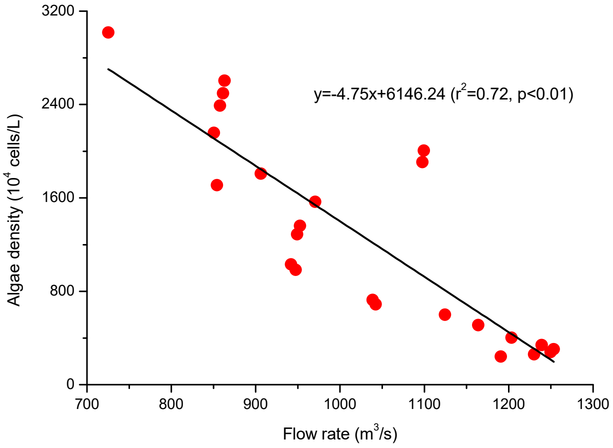

Figure 6. Relationship between algae density and flow rate for the middle and lower reaches of Hanjiang River (adapted from [43,44]).

3.3.3. Water Network Connectivity

The construction of gates and dams favors water resource allocation and utilization, but simultaneously blocks the hydraulic connectivity between lakes and the main stream of the Changjiang River. As a result of the disconnection between Taihu Lake and the Changjiang River, a negligible exchange of runoff and accumulation of pollutants caused overloading of nutrients in both water and sediment in the Taihu Lake. This is a shallow lake with an average water depth less than two meters. Nutrients transfer between the water column and sediment encouraging algal growth and triggering water blooms [45]. To mitigate water quality deterioration, water diversion from the Changjiang River to Taihu Lake was conducted in 2005. After then, the water exchange period of Taihu Lake decreased from 300 to 250 days, and the resulting enhanced water flow improved the water-dissolved oxygen content and self-purification capacity. Moreover, shortened water residence time accelerated the water column pollutant dilution [28]. Restoring water connectivity generally improved water quality in Taihu Lake. Permanganate (COD_{Mn}), TN, and TP concentrations decreased from 5.90, 2.85, and 0.097 mg/L to 4.27, 1.55, and 0.079 mg/L. The corresponding ratio of TN to TP decreased from 29.5 to 19.6 (Figure 7). For Taihu Lake, phosphorus was the limiting element for eutrophication [46], and the reductions concerning COD_{Mn} and TN were quicker than TP. Nevertheless, nitrogen and phosphorus concentrations remained high and provided sufficient support to algal blooms [22]. Therefore, the eutrophication index slightly decreased from 63 in 2006 to 61 in 2018 (Figure 7).

3.3.4. Sediment Transport

Sediment is the storage medium and transportation carrier for phosphorus, and plays a key role in determining turbidity and the distribution of phosphorus. Since the 1990s, sediment transport in the middle and lower reaches of the Changjiang River changed considerably, because of upstream large-scale water and soil conservation and application of massive cascade dams. The annual average SS concentration monitored at the Hankou Hydrologic Station located at the middle reaches and downstream Datong Hydrologic Station decreased from 0.573 and 0.486 kg/m^3 between 1954 and 2000 to 0.145 and 0.154 kg/m^3 between 2003 and 2018 (Table 4). The corresponding percentage decreases were 74.7% and 68.3%, correspondingly. Moreover, the sediment grain size observed at the Hankou and Datong hydrological stations decreased from 0.010 and 0.015 mm to 0.009 and 0.011 mm during the same period (Table 4). The SS in the middle and lower reaches of the Changjiang River tended to decrease in content and fineness of grain size. Sediment in the main stream of the Changjiang River was mainly composed of chlorite, illite, and quartz [47]. Small proportions of clay resulted in a phosphorus adsorption capacity of less than 135 mg/kg [48]. The retention of SS by dams increased the accumulation of sediment and phosphorus. Total sediment deposition volumes increased from 100,000,000 t in 2004 to 1,420,000,000 t in 2014 in the TGR. However, sediment TP content stabilized at 800 mg/kg after the impoundment, because of low water column TP concentration (<0.12 mg/L) and weak phosphorus adsorption to sediment [47]. Bioavailable phosphorus accounted for up to 10% of the sediment TP content [49]. Sediment-released phosphorus only accounted for 0.013% of total dissolved phosphorus loads in the water column [47]. Sediment retention and deposition led to an increase in the concentration of soluble phosphorus in the reservoir, but decreased downstream PP and SS discharge [50].

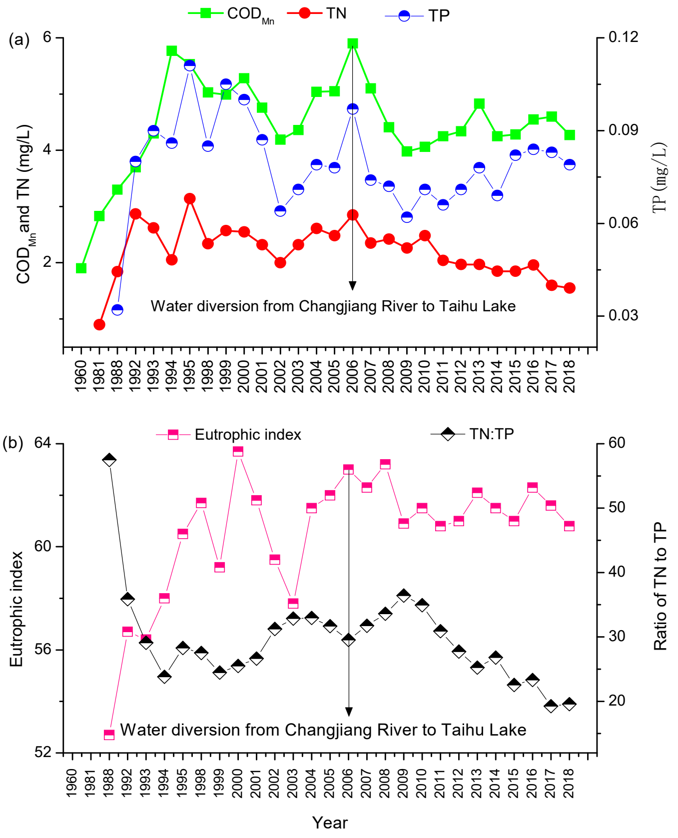

Figure 7. Variations in (**a**) nutrient concentration and (**b**) the eutrophic index between 1960 and 2018.

Table 4. Annual average suspended solids' (SS) concentration and grain size before and after TGR impoundment.

Period	SS Concentration (kg/m^3)		SS Grain Size (mm)	
	Hankou	Datong	Hankou	Datong
Pre-TGR (1954–2000)	0.573	0.486	0.01	0.009
Post-TGR (2003–2018)	0.145	0.154	0.015	0.011

TGR, Three Gorges Reservoir.

3.4. Other Factors Related to Eutrophication Development

3.4.1. Atmospheric Deposition

The contribution of atmospheric deposition to nutrient input at the basin level cannot be ignored, and the proportion of atmospheric nitrogen deposition to the basin net anthropogenic nitrogen input considerably increased from 3.2% in 1980 to 23.5% in 2015 due to increased industrial emissions and agricultural chemical fertilizer loss [51]. The proportion of atmospheric phosphorus deposition in relation to the basin net anthropogenic phosphorus input moderately increased from 3.7% in 1980 to 5.7% in 2015 [34]. Therefore, atmospheric precipitation increases the nutrient load of rivers, lakes, and reservoirs, thus accelerating eutrophication.

3.4.2. Meteorological Conditions

In the Changjiang River Basin, relatively warm atmospheric temperatures in spring and winter result in more outbursts of algal blooms in plateau lakes such as Dianchi Lake than in plain lakes including Taihu Lake and Chaohu Lake. Moreover, algal blooms occurred earlier and lasted much longer in plateau lakes than in plain lakes [24]. For Taihu Lake, atmospheric temperature dominated outbursts of cyanobacteria blooms. The most crucial atmospheric temperature factor was the annual average temperature, followed by seasonal average temperatures during spring and winter [52]. Precipitation variations induced by climate change caused 19±14% augmentation of inland river TN loads and aggregated water eutrophication in India, China, and Southeast Asia [53].

3.4.3. Environmental Management Policy

Due to the full implementation of river chief policies, pollutant discharge decreased in more than 40 cities along the Changjiang River Economic Belt between 2004 and 2015. Much effort has been undertaken to reduce phosphorus loads, which caused the water column TP to decline considerably faster than that of TN. Consequently, the ratio of TN to TP in the estuary of the Changjiang River continually increased from 8 in 1900 to 35 in 2010 [30]. Therefore, management agencies and decision makers should note the rapid and large-scale changes of the nutrient stoichiometry [54], and employ adaptable countermeasures to prevent associated ecological risks such as the decline in nitrogen fixation by, for example, hydrophytes.

4. Countermeasures for Basin Eutrophication Control

4.1. Nutrient Management at the Basin Level

Chemical fertilizer loss, aquaculture, wastewater discharge, and atmospheric precipitation are major sources of phosphorus input to rivers, lakes, and reservoirs. Accompanied by rapid urbanization, the proportion of wastewater-discharged phosphorus in relation to the basin's total received phosphorus increased from 14% in 2000 [55] to 37% in 2017 [56]. This ratio can be further reduced to less than 20%, if the effluent water quality of all sewage treatment facilities can be improved from Class B standard (1.0 mg/L of TP) to Class A standard (0.5 mg/L of TP) of the GB 18918-2002. For chemical fertilizer loss and aquaculture, determining discharge limits for nutrients such as nitrogen and phosphorus for irrigation backwater and aquaculture wastewater based on the major function of the receiving water bodies is necessary.

Water column phosphorus concentrations also relate to runoff conditions. Phosphorus concentrations may exceed the management standard because of inadequate flow, although all wastewater is treated to match its discharge standard [57]. Monitoring phosphorus concentrations cannot fully reflect actual phosphorus input from upstream regions. Simultaneously monitoring phosphorus concentration and flux at controlled sections and then determining phosphorus flux limits for river reaches and associated regions is recommended. Once joint control for concentration and flux at monitoring stations is adopted, scientifically upgrading wastewater discharge standards and reducing chemical fertilizer loss is beneficial.

4.2. Harmonize the Transportation of Runoff, Sediment, and Nutrients

Numerous gates and dams have transformed the Changjiang River into an artificially controlled channel. Water resources' management and sediment regulation altered the transportation of runoff, SS, and nutrients. Taking Datong section as an example, runoff, SS, and nutrients are simultaneously transported before the impoundment of upstream, large reservoirs such as the TGR. The monthly average distribution of runoff, SS, and TP nearly overlapped during the flood seasons between 1981 and 2002, with their maximal values observed in July (Figure 8). Higher runoff and SS concentrations result in higher TP concentrations. However, during the post-TGR period, the monthly average SS concentration considerably decreased from 0.414 kg/m^3 between 1987 and 2002 to 0.150 kg/m^3 between 2006 and 2014, with a decreasing amplitude of 64%. The TP concentration reduced from 0.136 to 0.126 mg/L during the same periods. Most critically, runoff, SS, and nutrient transport exhibited inconsistencies. Runoff and SS displayed similar distribution trends, but the TP concentration curve tended to be attenuated in one hydrological year (Figure 8). The TP concentrations are evenly distributed from January to December, but with the minimum value occurring in July. This phenomenon can be regarded as the dilution effect, with more runoff resulting in relatively low TP concentrations. The SS-associated PP was the main component of TP [4], and retention of PP in upstream large reservoirs resulted in the selective and unbalanced transportation of runoff, SS, and phosphorus at the basin level.

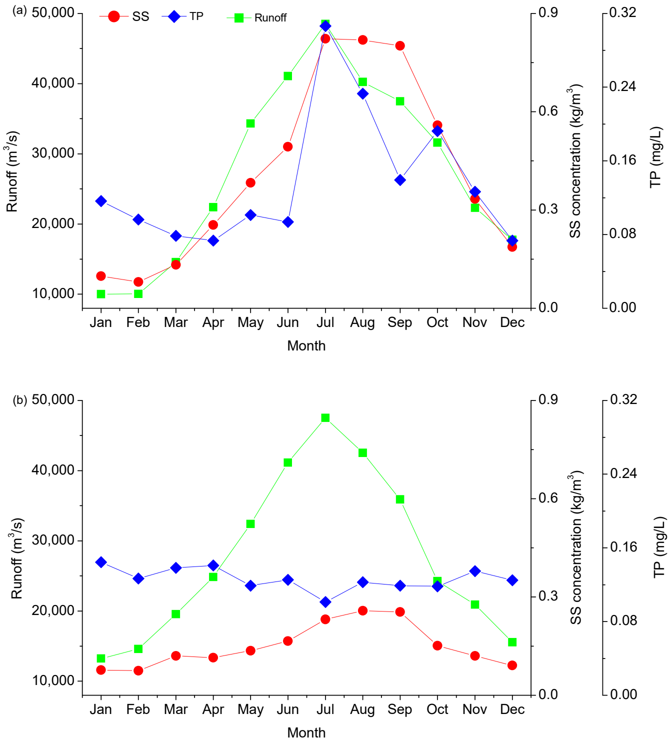

Figure 8. Monthly average runoff, suspended solids (SS), and total phosphorous (TP) distribution (**a**) between 1987 and 2002 and (**b**) between 2006 and 2014 at the Datong section of the main stream.

To alleviate the negative effect resulting from the operation of the water conservancy project, ecological regulation experiments were conducted for the TGR for seven consecutive years since 2011. Moreover, emergency water regulation to restrain diatom blooms in the Hanjiang River and experimental stratified water intake in the Xiluodu Reservoir were also implemented in the Changjiang River [58,59]. The regulation of water temperature and runoff may meet some requirements for *Acipenser sinensis* (Chinese sturgeon) and the spawning of four major Chinese carp species, but negligibly contribute to the alleviation of unbalanced transportation of runoff, SS, and nutrients. To mitigate eutrophication, comprehensively considering the regulatory needs of flood prevention, sediment deposition control, and pollution reduction, activities include water level manipulations during the flood season for the huge reservoirs to increase the SS and PP discharge, which may help to restore the continual and balanced transport of SS.

4.3. Coordinated Governance between Region and Basin

Since 2016, the visual appearance of rivers, lakes, and reservoirs has been improving through effective measures such as closures or improvements of wastewater outfall operations, elimination of black-odor water bodies, water surface cleaning, and the banning of cage culture [60]. Because the river chief policies are characterized as local management and regional governance, the "one river, one solution" strategy was applied for each provincial reach of the main stream in the Changjiang River Basin, thus unavoidably resulting in "one river, multiple solutions" or "one reach, one solution" due to differences among provinces in terms of regional environmental concerns, technological and economic levels, and law and regulation enforcement strengths. Eutrophication is a common problem for the whole basin because of the disharmonic transportation of runoff, SS, and nutrients, which requires coordination between upstream and downstream agencies. Therefore, formulating a true "one river, one solution" for the whole Changjiang River at the basin scale rather than regional scale and jointly promoting nutrient reduction, runoff and sediment regulation, and algal bloom control are necessary.

Coordinated promotion of river chief policy and basin water resource management should involve integrating basin management with regional governance. Basin management agencies such as the CWRC should draft an overall plan for water resources use, water quality improvement, and operation regulations of dams and gates. Additionally, the CWRC should monitor and evaluate controlled and transprovincial sections, implement ecological regulations, guide practices for pollution control and ecological restoration, and organize joint law enforcement. The provincial government should appoint financial and human resources to fulfil these tasks and objectives and adhere to the evaluation index allocated by CWRC to ensure implementation of the "one river, one solution" in their regions.

5. Concluding Remarks and Further Research Needs

By 2018, 85,482 km of river reaches, 61 lakes and 365 reservoirs had undergone eutrophic assessment, and the eutrophication degree followed the ranking order of lake > reservoir > river. Trophic levels for lakes and reservoirs exhibited spatial variability, and moderately eutrophic and hypertrophic lakes and reservoirs were mainly located in the Sichuan Basin and Jianghan Plain. The water surface proportion of moderately eutrophic lakes in relation to the total assessed lakes consistently increased from 31.3% in 2009 to 42.7% in 2018, and the trophic level for reservoirs rapidly developed from mesotrophic to slightly eutrophic.

Continual increase in municipal sewage discharge accounted for 47.7% of the basin total wastewater discharge in 2018. The construction and operation of numerous gates and dams has altered the natural transportation regime among runoff, SS, and nutrients. Slow water exchange, lost hydraulic connectivity between rivers and lakes, and nutrient enrichment are the main driving forces for basin eutrophication. Moreover, algae growth was exponentially and linearly fitted with the flow velocity and flow rate for TGR and the Hanjiang River, respectively.

Retention of SS and particulate nutrients has caused changes in the transport of runoff, SS, and nutrients in the middle and lower main stream reaches. During the post-TGR era, runoff and SS had similar transport characteristics, but the TP concentration distribution curve exhibited a flattening tendency in the Datong section. To efficiently reduce nutrient loads in the basin and hinder the development of eutrophication, jointly controlling and monitoring nutrient concentrations and flux at key sections, strengthening discharge water quality management for irrigation backwater and aquaculture wastewater, and harmonizing runoff, SS and nutrient transportation through coupled regulation of dams and gates are recommended approaches.

Supplementary Materials: The following information is available online at http://www.mdpi.com/2073-4441/12/6/1634/s1. Figure S1: Variation in basin domestic and industrial wastewater discharge between 2006 and 2017. Figure S2: Variation in basin chemical fertilizer application between 1998 and 2016. Figure S3: Variation in (a) total aquaculture production in China and (b) culture areas of Hubei Province. Table S1: TP concentration comparison among water quality standards issued by the Ministry of Environmental Protection of China.

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