TROPHIC STATUS OF TRIBUTARY BAY AGGREGATE AND THEIR RELATIONSHIPS WITH BASIN CHARACTERISTICS IN A LARGE, SUBTROPICAL DENDRITIC RESERVOIR, CHINA

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ABSTRACT

We surveyed the trophic status and its limiting factors of the Three-Gorges Reservoir (TGR) in China, including 153 sites in the mainstream of Yangtze River and 17 tributary bays quarterly for one year after the first full-capacity impoundment (175 m above sea level.) in 2010. Carlson-type trophic state indexes (TSI), including the trophic index of total phosphorus (TSI_{TP}), total nitrogen (TSI_{TN}), chlorophyll *a* (TSI_{CHL}), and Secchi depth (TSI_{SD}), were used to assess trophic status of TGR. Based on TSI_{CHL}, trophic status of the mainstream was oligotrophic in the four seasons; however most of tributary bays were in eutrophic status in spring and summer and oligotrophic states in autumn and winter. Judging from TSI_{SD}, the mainstream and tributary bays were in the status of mesotrophication in winter, but hypertrophication or eutrophication in the other seasons, TSI_{TP} showed that the mainstream was in the eutrophic or hypertrophic status; the tributary bays were in the eutrophic status in spring and summer, but in the mesotrophic status in autumn and winter. TSI_{TN} revealed that mainstream and tributary bays were characterized as eutrophic status in the four seasons. Using Carlson's two-dimensional graphical approach, the deviations of TSI_{SD}, TSI_{TP} and TSI_{TN} from TSI_{CHL} indicated that algal growth in the mainstream of TGR was limited by light other than nutrient in all year. For the tributary bays of TGR, light might be the factor limiting algal growth in autumn and winter. However, in spring and summer, nutrient and grazing became the limiting factors in some tributary bays. In addition, Basin characteristic had a significant influence on the trophic status and limiting factors in TGR. Our research provided fundamental information trophic status of the whole TGR water body and is helpfulness for water quality management of the reservoir.

KEYWORDS: Three-Gorges Reservoir; tributary bays; trophic status; basin characteristics; limiting factors

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1. INTRODUCTION

Water eutrophication is one of the most serious environmental problems in the world [1, 2]. Eutrophication will stimulate the primary productivity in aquatic ecosystem [3, 4], and pose serious risks for human health, fishery economy, and the water resources sustainability [5, 6]. Although the mechanisms of eutrophication are not fully discovered, the excessive nutrient (e.g. nitrogen, phosphorus) loading into the aquatic ecosystem has been long considered as the main reason causing eutrophication [7, 8]. The natural process of eutrophication is very slow, which need several centuries for a deep and oligotrophic lake shift to a shallow and eutrophic one [9]. However, in recent decades, the nutrient concentration of most water bodies has been increased dramatically, and eutrophication has become a worldwide environmental problem [10, 11].

The assessment of trophic status of water body and determining its limiting factors are key steps in pollution control and eutrophication management. In the past decades, limnologists have developed many methods to assess the trophic status, including the character method [12], parameter method, the biotic indices method [13], the phosphorus budget model method [14], and the trophic state index method [15-17]. Among these developed methods, Carlson's trophic state index (TSI) is one of the most widely accepted methods in evaluating the trophic status because that Carlson's TSI is a continuous number in assessing the trophic status, which can provide a more precise assessment of the trophic status than other conventional methods (e.g. parameter method), which only provide a rough typological trophic information [13, 15]. In addition, Carlson's TSI is easy to be implemented and analyzed the limiting factors of the trophic status [15, 18].

Since the impoundment of Three-Gorges Reservoir (TGR) in June 2003, the reduced water velocity and increased nutrient residence time have caused a serious eutrophication problem in TGR. Currently, ecological and environmental researches in TGR are main focusing on the phytoplankton blooms [19-22]. Trophic status and its limiting factors in the whole TGR area are still seldom addressed. Xu et al. [19] reported the trophic status and regulating factors of a small fraction of mainstream near the dam of TGR (about 50 of 600 km). Zhang et al. [23] compared trophic status before and after impoundment in Daning tributary of TGR. The previous eutrophication assessment emphasized the water body itself, but omitted the watershed and landscape factors (e.g. catchment area, hydrology etc.), which are also considered as important factors affect the eutrophication based on the published literatures [9, 24-26]. Therefore, the aims of this study are focusing on i) performing a systematic assessment of the trophic status of the whole TGR (including mainstream and tributaries); ii) identifying the potential limiting factors of eutrophication in the mainstream and tributary bays of TGR; iii) understanding trophic status and its relationships with basin characteristics. Our research can provide fundamental information in understanding the eutrophication of TGR water body and is helpfulness for carrying out specific environmental protection practices in the TGR.

2. MATERIALS AND METHODS

2.1. Design of sampling

TGR, located at 29°16’-31°25’N, 106°-111°10’E, is one of the largest reservoirs in the world, with a water area of 1080 km^2 and a capacity of 3.93 × 10^{10} m^3 at the water level of 175 m above sea level (a.s.l.) [27]. The impoundment of TGR was carried out with three different stages: the first impoundment stage was started in June 2003, with the water level of 135 m as the flood control water level and 139 m as the normal water level; the second impoundment stage was started in October 2006, the flood control and normal water level was increased into 145 and 156 m respectively; the final impoundment stage was started in October 2010, reaching a normal and flood control water level of 175 and 145 m [27, 28]. TGR is operated the way of ‘storing clear and releasing muddy’ every year. In other word, in flood seasons (summer and early autumn), the water level is maintained at the flood control limited level (145 m) accounts for releasing muddy water; while in dry seasons (autumn, winter and spring), the water level reaches to the maximum (175 m) in order to meet the demand for hydroelectric power generation accounts for storing clear water [27, 29].

We surveyed quarterly for one year in TGR after the first 175 m a.s.l. full-capacity impoundment in 2010. Along the 484 km-length (the flooded area at the water level of 156 m above sea level) mainstream of TGR, 14 transects (CJ01 ~ CJ02 and CJ04 ~ CJ15, thereinto CJ06, CJ11, CJ13 and CJ15 were only sampled in spring) were set up from the dam of TGR (CJ01) to its upstream (CJ15), and 17 main tributary bays of TGR were also surveyed to get a systematic understanding of the trophic status of the whole TGR (Fig. 1). In each tributary bay, several sampling sites were set up from the mouth to the end of backwater. In summary, a total of 47 sites in the mainstream of TGR and 106 sites in its tributary bays were sampled in this study.

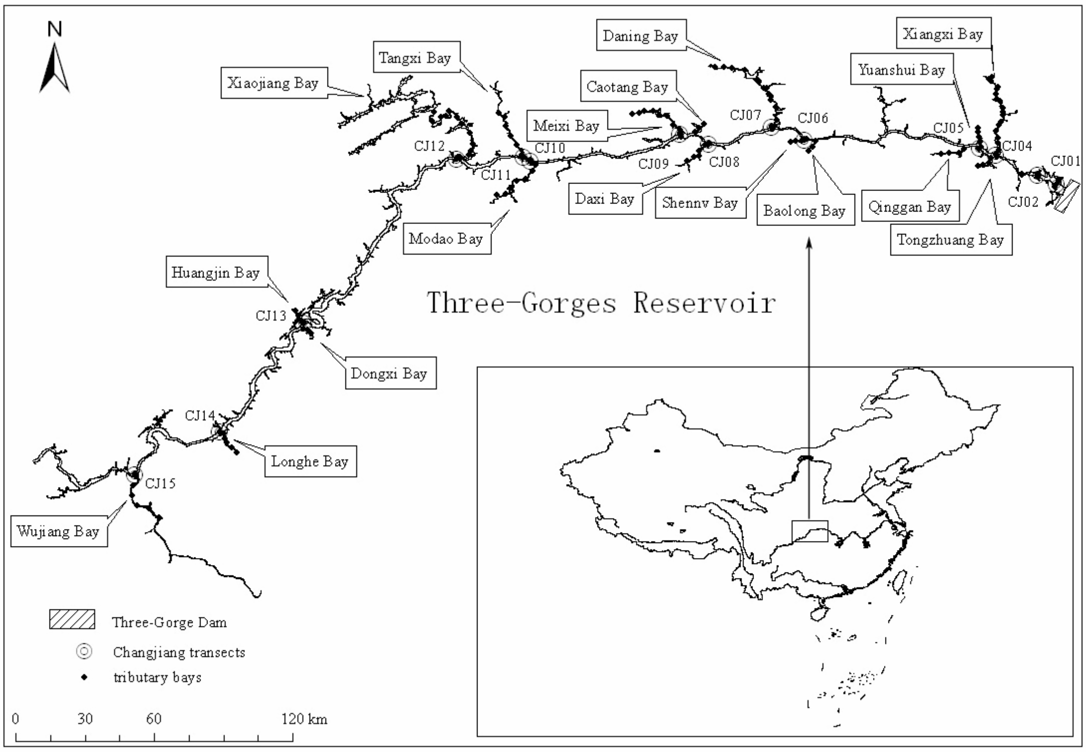

FIGURE 1 - Location of sampling sites in Three-Gorges Reservoir.

Sampling methods were referred to the Protocols for Standard Observation and Measurement of the Chinese Ecosystem Research Network (CERN) [30].

2.2. Sample collection and measurements

We measured the transparency (SD), the concentrations of total nitrogen (TN), total phosphorus (TP), and chlorophyll *a* (Chl. *a*) at each site. The transparency was *in situ* measured with a 20-cm Secchi disc. Water samples were collected at a depth of 0.5 m beneath the water surface using a 5-L Van Dorn sampler. Samples for TN and TP measurements were acidified with H_2SO_4 to pH < 2, and stored in a 500-mL plastic bottle for laboratory analysis. Phytoplankton cells were concentrated by filtering 1-L water through a microfilter (1.2 µm) for Chl. *a* determination. Water samples and filters were immediately placed in a dark cooler with ice until the laboratory analysis. The concentrations of TN and TP were analyzed according to the user manual of Skalar on a segmented flow analyzer (Skalar SAN^{++}, The Netherlands). The Chl. *a* concentration was measured on a spectrophotometer (Shimadzu UV-1800, Japan) according to the standard methods of APHA [30, 31].

2.3. Data analysis

By following the methods described by Carlson [15] and Kratzer and Brezonik [32], the concentrations of Chl. *a*, SD, TP and TN were transformed to a continuous TSI value ranging from 0 to 100 with the below equations:

$$TSI_{CHL} = 10\times(6 - (2.04 - 0.68 \ln (Chl.a, ig/L))/\ln2) \quad (1)$$

$$TSI_{SD} = 10\times(6 - \ln(SD, m)/\ln2) \quad (2)$$

$$TSI_{TP} = 10\times(6 - \ln(48/(TP, mg/L))/\ln2) \quad (3)$$

$$TSI_{TN} = 10\times(6 - \ln(1.47/(TN, mg/L))/\ln2) \quad (4)$$

With the calculated TSI values, the trophic status could be classified to oligotrophic (TSI < 40), mesotrophic (40 = TSI < 50), eutrophic (50 = TSI < 70), and hypertrophic (TSI = 70) according the TSI values [32].

Carlson's two-dimensional graphical approach was used to determine the limiting factors [18, 33]. In this approach, it was expected that a specific variable-based index would not correlate well with chlorophyll *a* in situations where the variable was not limiting algal growth; therefore, the deviations of the Chlorophyll *a* TSI (TSI_{CHL}) from the specific variable-based index (e.g. TSI_{TP}) could indicate this kind of situations [18]. Thus, based on deviations of TSI_{CHL} from $TSI_{TP(TN)}$ and TSI_{SD}, we could identify the possible limiting factors of algal growth with the two-dimensional graphical approach (TSI_{CHL}-TSI_{SD} as x-coordinate, and TSI_{CHL}-$TSI_{TP(TN)}$ as y-coordinate) proposed by Carlson [18]. Deviations located in the first quadrant and the second quadrant, in which TSI_{CHL}-$TSI_{TP(TN)}$ > 0, were inferred to be phosphorus (nitrogen) limited algal growth. If TSI_{CHL}-TSI_{TP} and TSI_{CHL}-TSI_{TN} both greater than 0, indicated phosphorus and nitrogen co-limitation (N + P co-limitation). Deviations located in the third quadrant, in which TSI_{CHL}-TSI_{SD} < 0 and TSI_{CHL}-$TSI_{TP(TN)}$ < 0, indicated that non-algal particles, color, water column stability [34] etc dominated light attenuation and limited algal growth. Deviations located in the fourth quadrant, in which TSI_{CHL}-TSI_{SD} > 0 and TSI_{CHL}-$TSI_{TP(TN)}$ < 0, indicated that algal growth was controlled by grazing [18, 33, 35].

In addition, the correlations between basin characteristics (data of catchment area, river length and discharge data from Huang et al. [27]) and TSI_{CHL}, TSI_{SD}, TSI_{TP}, TSI_{TN}, as well as their deviations from TSI_{CHL} were analyzed with linear regression models. Before fitting the models, the values of basin characteristics were $\log_{10}$ transformed to fit the requirement of normal distribution in linear model. The fitting of linear regression model was performed in the software of SPSS 16.0.

3. RESULTS AND DISCUSSION

3.1. Trophic status of Three-Gorges Reservoir

The statistical summaries of spatiotemporal variations of TSI in the mainstream and tributary bays of TGR are presented in Table 1. We found that there was a clear seasonal pattern of the trophic status in TGR (Table 1 and Fig. 2). Based on TSI_{CHL}, trophic status of the mainstream was oligotrophic in the four seasons; however most of tributary bays were characterized as eutrophic status in spring and summer and oligotrophic status in autumn and winter. Judging from TSI_{SD}, the mainstream was in the status of hypertrophication in summer, eutrophication in autumn and spring, and mesotrophication in winter; the trophic status of tributary bays was mesotrophic in winter, and eutrophic in the other seasons. The high TSI_{SD} value in the mainstream in summer is because that there is a large

TABLE 1 - Summary of TSI_{CHL}, TSI_{SD}, TSI_{TP} and TSI_{TN} in mainstream and tributary bays (SD presents standard deviation).

Variable	Area	Autumn (Oct.)		Winter (Jan.)		Spring (Apr.)		Summer (Jul.)		Inter-annual	
		Mean±SD	Range	Mean±SD	Range	Mean±SD	Range	Mean±SD	Range	Mean±SD	Range
TSI_{CHL}	Mainstream	29.59±8.47	19.03-48.67	26.99±7.33	18.61-43.15	39.67±10.49	20.06-53.76	33.72±12.70	17.38-53.98	33.15±10.91	17.38-53.98
	Tributary bay	34.20±6.56	26.31-45.57	37.41±11.82	22.91-55.98	52.43±10.78	26.27-67.79	56.55±9.65	37.56-67.61	46.02±13.47	22.91-67.79
TSI_{SD}	Mainstream	50.98±4.11	47.20-61.52	44.38±2.01	41.15-47.94	52.40±7.76	43.90-69.11	78.45±6.09	72.13-93.18	56.17±13.75	41.15-93.18
	Tributary bay	56.38±2.67	50.92-58.48	46.04±5.99	39.49-55.73	55.86±5.85	45.22-64.67	59.16±4.44	51.62-65.80	51.81±8.00	39.36-65.80
TSI_{TP}	Mainstream	65.88±3.26	62.53-70.73	73.82±3.09	66.98-78.60	81.85±2.55	74.51-85.71	70.11±6.44	62.49-83.18	73.73±7.33	62.49-85.71
	Tributary bay	48.26±3.43	42.58-51.80	46.23±3.53	41.43-53.67	55.15±5.63	46.26-64.60	66.74±7.06	59..96-82.67	54.22±9.12	41.34-82.67
TSI_{TN}	Mainstream	57.67±2.03	52.03-59.18	60.11±2.75	53.66-63.08	63.64±0.95	62.29-65.23	60.17±2.57	55.89-63.08	60.69±3.03	52.03-65.23
	Tributary bay	62.73±4.13	55.31-69.66	68.31±3.15	64.60-75.41	67.87±10.70	55.06-96.92	58.72±4.62	44.82-62.94	57.58±3.74	48.68-65.56

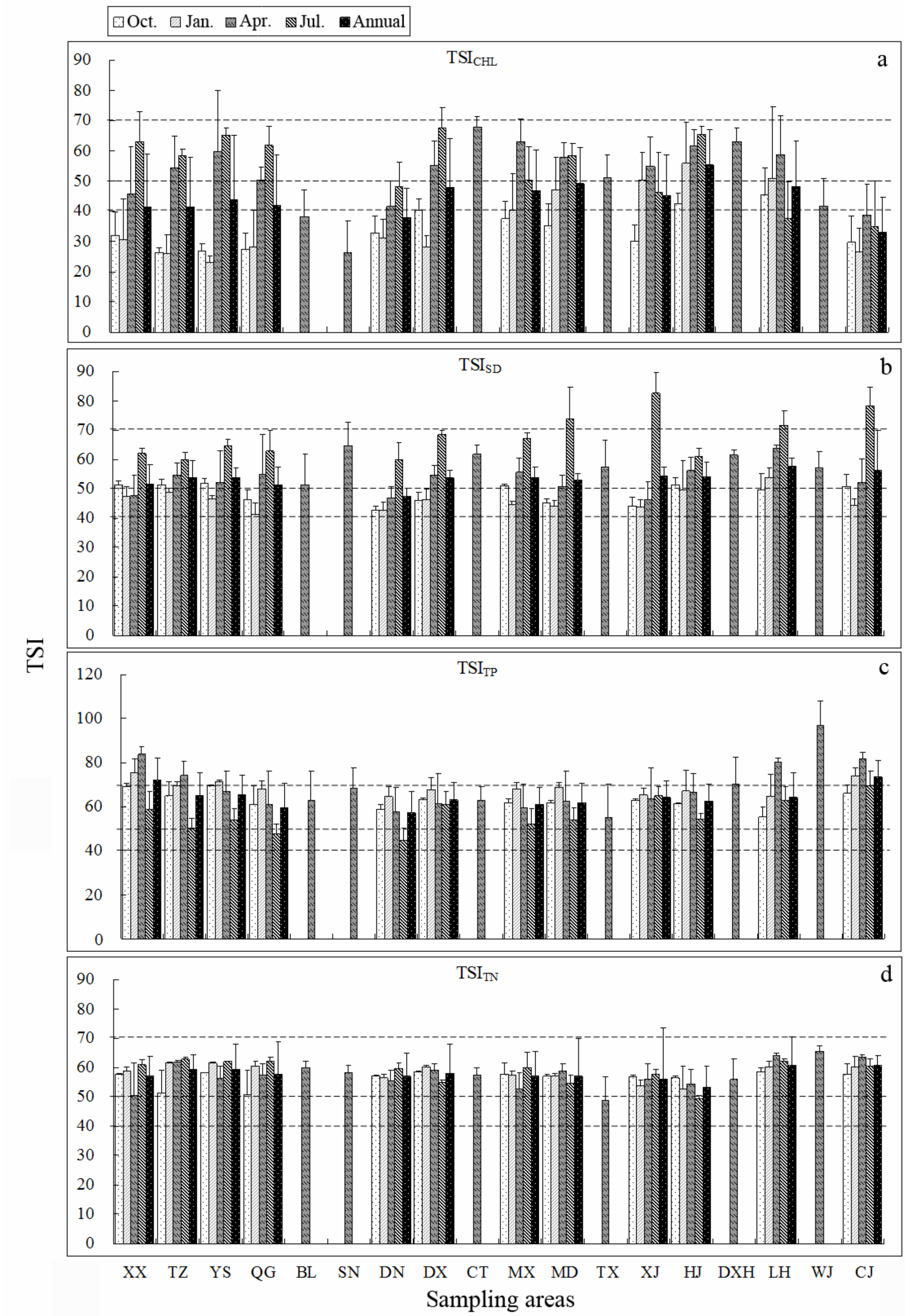

FIGURE 2 - Spatial and temporal pattern of TSI_{CHL} (a), TSI_{SD} (b), TSI_{TP} (c) and TSI_{TN} (d) in the Three Gorges Reservoir. The dashed lines represent the threshold of hypertrophic (70), eutrophic (50) and mesotrophic (40) status. (XX, TZ, YS, QG, BL, SN, DN, DX, CT, MX, MD, TX, XJ, HJ, DXH, LH and WJ are the abbreviation of Xiangxi Bay, Tongzhuang Bay, Yuanshui Bay, Qinggan Bay, Baolong Bay, Shennv Bay, Daning Bay, Daxi Bay, Caotang Bay, Meixi Bay, Modao Bay, Tangxi Bay, Xiaojiang Bay, Hangjin Bay, Dongxi Bay, Longhe Bay and Wujiang Bay respectively)

amount of sediments bring from the upstream of Yangtze into the reservoir in the floods seasons [19, 27, 29]. TSI_{TP} showed that the mainstream was in the eutrophic or hypertrophic status; the tributary bays were in eutrophic status in spring and summer, but in mesotrophic status in autumn and winter. Based on TSI_{TN}, the mainstream and tributary bays were characterized as eutrophic status in the four seasons. According to the seasonal dynamic of tropic status in TGR (Fig. 2), TSI_{CHL} values in spring and summer were greater than that in autumn and winter in mainstream and most of tributary bays. Highest TSI_{SD} value was observed in summer, and the lowest value was in the autumn and winter, while moderate value of TSI_{SD} was observed in spring. TSI_{TN} and TSI_{TP} had no significant seasonal patterns.

According to a previous study, the chlorophyll *a* concentration in the mainstream of TGR was very low after the impoundment of TGR [36]; however algal blooms were frequently observed in the tributary bays of TGR in spring and summer [19-22]. In this study, judging from TSI_{CHL}, trophic status in the mainstream of TGR was oligotrophic in the four seasons; most of tributary bays were characterized as oligotrophic status in autumn and winter, and eutrophic status in spring and summer. These results are coincident with the previous studies. Based on TSI_{TP} and TSI_{TN}, mainstream and most of tributary bays were in eutrophic status for the studied seasons, which suggests that the concentration of phosphorus and nitrogen are far exceeded the need for algal growth in TGR, which is in accordance with the former study carried out in the mainstream of TGR [19].

3.2. The limiting factor of trophic status

Based on Carlson's two-dimensional graphical approach [18], the deviations between TSI_{CHL}, $TSI_{TP(TN)}$ and TSI_{SD} of TGR in all seasons are presented in Figure 3 - 6. In autumn (Fig.3a, 3b), the plots of deviations indicated that light limited the algal growth for the whole mainstream and tributary bays of TGR. In winter (Fig.4a, 4b), the whole mainstream and most tributary bays were light limited except three nitrogen or grazing limited tributary bays (MD, XJ and HJ). In spring (Fig.5a, 5b), the limitation of algal growth in TGR showed a high diversity among mainstream and tributary bays. Most sites in the mainstream of TGR were light limited, excepted two grazing limited transects (CJ07 and CJ10). However for the tributary bays, the deviations between TSI_{CHL}, TSI_{TP} and TSI_{SD} of tributary bays showed light limitation in 9 tributary bays, grazing limitation in 6 tributary bays, and phosphorus limitation in 2 tributary bays (CT and MX) (Fig. 5a). In Fig. 5b, the deviations between TSI_{CHL}, TSI_{TN} and TSI_{SD} of tributary bays showed light limitation in 8 tributary bays, grazing limitation in 3 tributary bays and nitrogen limitation in 6 tributary bays. This phenomenon implied that grazing and nutrient might limit the algal growth in TGR with the increasing of algal biomass in the spring, and some tributary bays (e.g. CT Bay and MX Bay) might N + P co-limited. In summer (Fig.6a, 6b), all sites in the mainstream

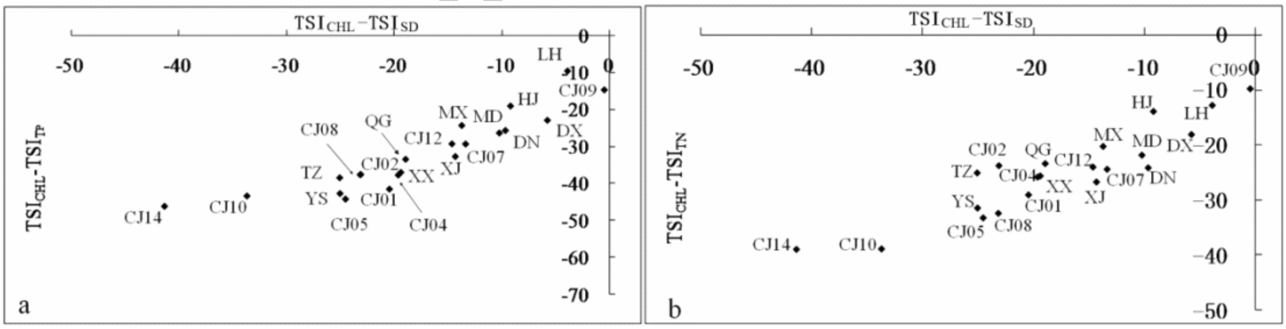

FIGURE 3 - The deviations between TSI_{CHL}, TSI_{TP} TSI_{TN} and TSI_{SD} in autumn—phosphorus limitation (a) and nitrogen limitation (b).

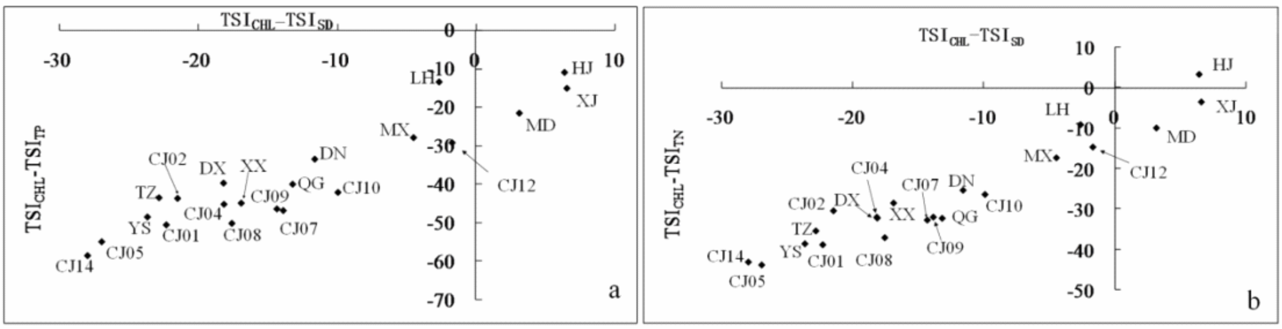

FIGURE 4 - The deviations between TSI_{CHL}, TSI_{TP} TSI_{TN} and TSI_{SD} in winter—phosphorus limitation (a) and nitrogen limitation (b).

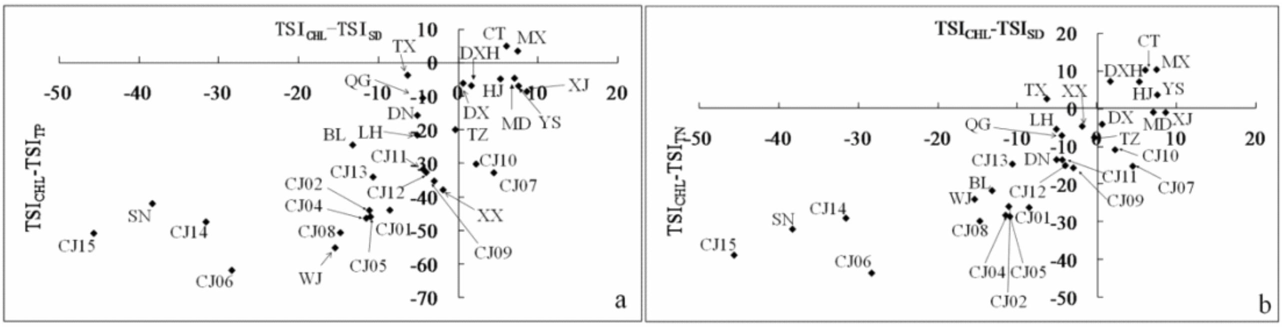

FIGURE 5 - The deviations between TSI_{CHL}, TSI_{TP} TSI_{TN} and TSI_{SD} in spring—phosphorus limitation (a) and nitrogen limitation (b).

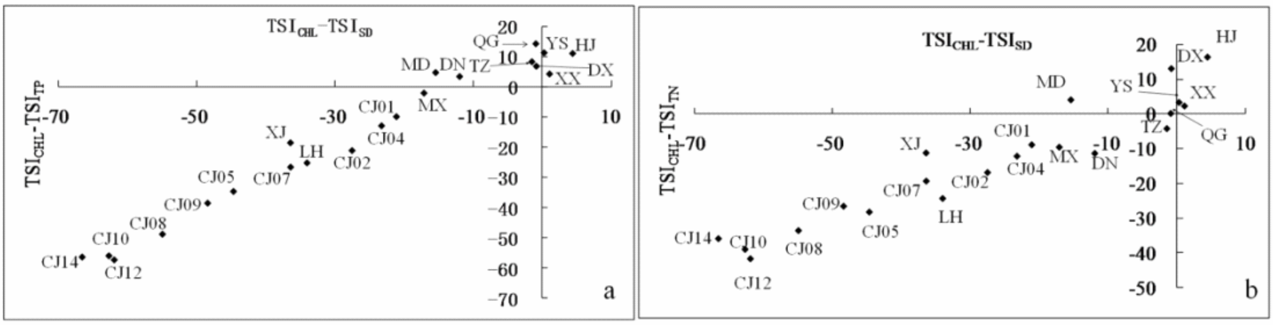

FIGURE 6 - The deviations between TSI_{CHL}, TSI_{TP} TSI_{TN} and TSI_{SD} in summer—phosphorus limitation (a) and nitrogen limitation (b).

of TGR were light limited; however most sites in tributary bays were nutrient limited. The deviations between TSI_{CHL}, TSI_{TP} and TSI_{SD} of tributary bays showed phosphorus limitation in most of tributary bays, and light limitation in 3 tributary bays (XJ, LH and MX) (Fig. 6a). The deviations between TSI_{CHL}, TSI_{TN} and TSI_{SD} of tributary bays showed light limitation in 6 tributary bays, and nitrogen limitation in 5 tributary bays (Fig. 6b). The deviations between TSI_{CHL}, $TSI_{TN(TP)}$ and TSI_{SD} of tributary bays showed N + P co-limitation in 5 tributary bays (Fig.6a, 6b).

Since the biology of the lake is of prime interest to the limnologists, managers, and user alike, the TSI_{CHL} has been considered as the most important index in assessing the trophic status [18]. And the potential limiting factors for TSI_{CHL} could be identifying by two-dimensional graphical approach [18], which has many successful applications in the previous studies [19, 33, 35]. For example, Xu et al. [19] studied on the mainstream of TGR, and found that algal growth (TSI_{CHL}) was limited by light attenuation causing by non-algal turbidity. Since our research sites have a wide geographic distribution in TGR (Fig. 1), the different hydrological conditions and watershed characteristics may cause different trophic status and limiting factors in the TGR. Even in the same tributary bay, trophic status and limiting factors may vary among different seasons because of the seasonal variations of light, heat, hydrological condition etc [19, 22]. Our study found that mainstream of TGR was characterized as light other than nitrogen or phosphorus limitation, which is in accordance with the reported study in the stage of low water level [19]. In most tributary bays the growths of phytoplankton was light limited in autumn and winter, but nutrient limited in spring and summer. The previous study in tributary bay of TGR showed that algal blooms in spring and summer were associated with the rapid decrease in mixing depth [37], and the rapid growth of algae will consume large amount of nutrient and the depletion of nutrients was observed [38], therefore, nutrient limitation might be observed in some sites in the tributary bays in spring and summer. Algal growth limited by zooplankton grazing had been seen in some bays (data supplied by Xiangxi River Ecosystem station, Chinese Academy of Sciences). Large zooplankton predation may result in lake appearing "clear water phase" in the spring [39].

3.3. The relationships between trophic status and basin characteristics

The linear regression analysis showed that averaged annual TSI_{CHL}, TSI_{SD}, TSI_{TN}, TSI_{TP} and the deviations of TSI had no significant correlation with basin characteristics including discharge, catchment area and river length (Table 2). Further analysis at the seasonal scales found some significant relationships between TSI, TSI deviations and basin characteristics (Table 2). TSI_{CHL} was negatively related to catchment area in summer ($p < 0.05$). TSI_{SD} was negatively related to discharge in spring and autumn ($p < 0.05$). TSI_{CHL-SD} was positively related to discharge and river length in autumn ($p < 0.05$) and catchment area

TABLE 2 - The linear regression relationships (y=ax+b) between TSI, TSI deviations and basin characteristics (log_{10} transformed)

Variable	Season	log_{10}(Catchment area)				log_{10}(River length)				log_{10}(discharge)			
		a	b	R^2	*p*	a	b	R^2	*p*	a	b	R^2	*p*
TSI_{CHL}	Autumn	0.02	2.38	0.05	0.5	0.01	1.46	0.2	0.16	0.02	0.75	0.11	0.33
	Winter	0.03	1.98	0.36	0.05	0.01	1.61	0.27	0.1	0.02	0.59	0.19	0.18
	Spring	0	2.97	0	0.95	0	1.62	0.02	0.58	0.00	1.30	0.00	0.98
	Summer	**-0.04**	**5.24**	**0.43**	**0.03**	-0.01	2.58	0.28	0.1	-0.03	3.16	0.36	0.05
	Inter-annual	0.00	3.11	0.00	0.98	0.00	1.76	0.01	0.78	-0.01	1.84	0.01	0.79
TSI_{SD}	Autumn	-0.06	5.99	0.13	0.27	-0.03	3.47	0.28	0.1	**-0.08**	**5.55**	**0.49**	**0.02**
	Winter	-0.02	3.99	0.02	0.71	-0.01	2.28	0.02	0.71	-0.03	2.58	0.07	0.44
	Spring	-0.04	5.23	0.19	0.09	-0.02	2.95	0.18	0.1	**-0.04**	**3.73**	**0.26**	**0.05**
	Summer	0.03	0.82	0.17	0.2	0.01	1.09	0.19	0.17	0.03	-0.54	0.33	0.07
	Inter-annual	-0.03	4.81	0.02	0.67	-0.01	2.56	0.02	0.68	-0.03	3.14	0.04	0.58
TSI_{TP}	Autumn	-0.05	6.43	0.15	0.24	-0.02	3.46	0.23	0.13	-0.05	4.45	0.22	0.14
	Winter	-0.05	6.34	0.07	0.43	-0.02	3.39	0.1	0.33	-0.05	4.82	0.17	0.21
	Spring	0	3.02	0	0.94	0	1.97	0	0.83	-0.01	1.97	0.03	0.55
	Summer	0.02	2.2	0.03	0.61	0.01	1.56	0.05	0.53	0.02	0.55	0.10	0.34
	Inter-annual	-0.01	3.60	0.00	0.87	-0.01	2.45	0.02	0.66	-0.02	2.57	0.02	0.64
TSI_{TN}	Autumn	0.07	-1.1	0.12	0.3	0.03	0.02	0.2	0.17	0.07	-2.59	0.21	0.15
	Winter	-0.11	9.68	0.35	0.05	-0.03	3.9	0.24	0.13	-0.06	4.94	0.22	0.15
	Spring	-0.05	5.58	0.11	0.21	-0.02	2.88	0.07	0.33	-0.03	3.01	0.06	0.38
	Summer	-0.01	3.59	0	0.84	-0.01	2.68	0.07	0.44	-0.01	2.28	0.01	0.77
	Inter-annual	-0.09	8.31	0.10	0.34	-0.03	3.44	0.06	0.46	-0.04	3.75	0.04	0.58
TSI_{CHL-SD}	Autumn	0.03	3.48	0.15	0.25	**0.02**	**2.21**	**0.43**	**0.03**	**0.04**	**1.97**	**0.39**	**0.04**
	Winter	**0.03**	**3.36**	**0.45**	**0.02**	0.01	2.04	0.34	0.06	0.02	1.33	0.29	0.09
	Spring	0.01	2.94	0.04	0.45	0.01	1.85	0.12	0.18	0.01	1.30	0.06	0.36
	Summer	**-0.03**	**2.8**	**0.42**	**0.03**	-0.01	1.86	0.33	0.07	**-0.02**	**1.50**	**0.48**	**0.02**
	Annual	0.01	3.16	0.01	0.81	0.01	2.03	0.04	0.53	0.00	1.51	0.00	0.97
TSI_{CHL-TP}	Autumn	0.02	3.61	0.11	0.33	0.01	2.26	0.27	0.1	0.02	1.99	0.18	0.19
	Winter	0.02	3.8	0.33	0.06	0.01	2.19	0.27	0.1	0.01	1.60	0.22	0.15
	Spring	0	2.92	0	0.99	0	1.87	0.02	0.57	0.00	1.33	0.01	0.74
	Summer	-0.03	3.1	0.35	0.06	-0.01	1.96	0.26	0.11	**-0.02**	**1.73**	**0.39**	**0.04**
	Inter-annual	0.00	3.11	0.00	0.93	0.01	2.05	0.03	0.62	0.00	1.53	0.00	0.93
TSI_{CHL-TN}	Autumn	0.01	3.3	0.01	0.76	0.01	2.21	0.1	0.34	0.01	1.74	0.03	0.63
	Winter	**0.03**	**3.58**	**0.39**	**0.04**	0.01	2.11	0.29	0.09	0.01	1.44	0.21	0.16
	Spring	0	2.93	0.01	0.72	0.01	1.85	0.05	0.39	0.00	1.29	0.01	0.78
	Summer	-0.02	3.01	0.26	0.11	-0.01	1.93	0.11	0.31	-0.02	1.67	0.21	0.16
	Inter-annual	0.01	3.18	0.01	0.77	0.01	2.01	0.03	0.64	0.00	1.49	0.00	0.98

in winter ($p < 0.05$), while negatively related to catchment area and discharge in summer ($p < 0.05$). TSI_{CHL-TP} was negatively related to catchment area and discharge in summer ($p < 0.05$). TSI_{CHL-TN} was positively related to catchment area in winter ($p < 0.05$).

Kosten et al. [25] sampled 83 shallow lakes along a latitudinal gradient in South America and pointed out that local characteristics (e.g. soil type and associated land use in the catchment) and hydrology had a stronger influence on nutrient limitation than climate. Nõges [26] sampled 1337 lakes in Europe, and found that the larger the catchment area was with respect to lake depth, area and volume, the lower was the water transparency and the higher were the concentrations of the nutrients and chlorophyll *a*. Geographical location catchment area, precipitation and surface runoff coefficient of tributaries of TGR were quite different, trophic status had significantly spatial and temporal differences (Fig. 2). In this study, although TSI_{TN} and TSI_{TP} had no significant correlation with basin characteristics, TSI_{CHL}-$TSI_{TP(TN)}$ was correlated significantly with basin characteristics in some season. TSI_{CHL} was inversely proportional to catchment area in summer, similar with the study of Cai and Hu [40], who found that the smaller the catchment area and average annual discharge, the higher chlorophyll *a* concentrations in low water level (156 m). Previous research suggested that subtropical monsoon and hydrological conditions etc have a significant impact on the seasonal pattern of trophic status [19, 24, 41]. In this study, we found that TSI_{CHL-SD} was positively related to river length and discharge, which indicated that the shorter river length and larger discharge, the weaker light limitation in autumn, and a positive correlation between TSI_{CHL-SD} and catchment area suggesting a larger catchment area has weaker light limitation in winter. In contrast, a negative correlation between TSI_{CHL-SD} and catchment area in summer was observed. This suggests that a larger catchment area has stronger light limitation in summer since larger catchment will receive higher sediment load in the rain season [42].

Finally, we should add a caveat that although Carlson's TSI has been proved as one of the most worldwide acceptable method for evaluating the eutrophication of aquatic ecosystem [19 33, 35, 43-48], it still has some limitations in determining the limiting factors of phytoplankton growth. Specifically, it uses the total nutrient, and Secchi depth to estimate the availability of nutrients or light for phytoplankton growth; therefore, the Carlson's TSI might bring some bias in determining the limiting factors of phytoplankton growth, especially in the situation that total nutrient has no correlation with dissolved nutrient, which phytoplankton could use. Fortunately, in our case, we found that there is a significant correlation between total nitrogen and dissolved inorganic nitrogen ($r = 0.962$, $p < 0.001$), as well as total phosphorus and dissolved phosphate ($r = 0.973$, $p < 0.001$). This suggests that the limiting factors of phytoplankton growth identified by Carlson's TSI in our study are reliable.

4. CONCLUSION

Judging from TSI_{CHL}, mainstream of TGR would be characterized as oligotrophic status in all seasons; however most of tributary bays were in eutrophic status in spring and summer. According to Carlson's two-dimensional graphical approach, algal growth in the mainstream of TGR was limited by light other than nitrogen or phosphorus. For the tributary bays of TGR, light might be the primary factor limiting algal growth in autumn and winter when the algal biomass was low. However, in spring and summer with higher algal biomass, nutrient and grazing would become the limiting factors in some tributary bays. In addition, the relationships between basin characteristics and trophic status and their deviations suggest that soil and conservation have great significance for reducing the trophic status of TGR. Our research present here provided fundamental trophic status information of TGR, identifying the potential limiting factors of eutrophication of TGR, and analyzing the trophic status and its relationships with basin characteristics, which may have important implication for further water resource management of TGR.

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