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Factors regulating trophic status in a large subtropical reservoir, China

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Abstract We evaluated a 4-year data set (July 2003 to June 2007) to assess the trophic state and its limiting factors of Three-Gorges Reservoir (TGR), China, a large subtropical reservoir. Based on Carlson-type trophic state index $(TSI)_{CHL}$, the trophic state of the system was oligotrophic ($TSI_S < 40$) in most months after the reservoir became operational, although both TSI_{TP} and TSI_{TN} were higher than the critical value of eutrophic state ($TSI_S > 50$). Using Carlson's (1991) two-dimensional approach, deviations of the TSI_S indicated that factors other than phosphorus and nitrogen limited algal growth and that nonalgal particles affected light attenuation. These findings were further supported by the significant correlation among the values of $TSI_{CHL} - TSI_{SD}$ and nonvolatile suspended solids and water residence time. The logarithmic model showed that an equivalent TSI_{CHL} and TSI_{SD} could be found at $\tau = 54$ days in the TGR (Fig. 7). Accordingly, nonalgal particulates dominated light attenuation and limited algal biomass of the reservoir when $\tau < 54$ days.

Keywords Trophic state · Hydrological factors · Three-Gorges Reservoir · Empirical models

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Introduction

Lake eutrophication has been a major water quality problem for decades (Carpenter et al. 1998; Portielje and Molen 1999; Genkai-Kato and Carpenter 2005; Kagalou et al. 2008). It can result in a shift in lake status from a macrophyte-dominated and clear water state to a phytoplankton-dominated and turbid state, imposing detrimental effects on the ecosystem (Portielje and Molen 1999). Trophic state, an indicator of biotic productivity, is often used to classify aquatic ecosystems. As a fundamental property of ecosystem, this concept was first applied to aquatic ecosystems by Naumann in the early twentieth century, who proposed the terms "oligotrophic" and "eutrophic" (Dodds and Cole 2007). With the increase in the research of eutrophication process, ecologists made the greatest efforts to define trophic state (Schindler 2006). Carlson (1977) introduced a set of lake trophic state indices (TSIs) based on measurements of total phosphorus (TSI_{TP}), chlorophyll (TSI_{CHL}), and Secchi depth (TSI_{SD}). Kratzer and Brezonik (1981) developed an index (TSI_{TN}) based on total nitrogen concentration. Furthermore, Carlson (1991) expanded the concept of TSI differences by providing a two-dimensional graphical approach for assessing lake ecosystems. The deviations of TSI_{SD}, TSI_{TP}, and TSI_{TN} from TSI_{CHL} were used to describe abiotic and biotic relationships, gain insight about lake trophic structure, and infer additional information about the functioning of the lake (Osgood 1982; Havens 2000; Matthews et al. 2002; An and Park 2003). Therefore, the TSIs and their deviations can be employed to access the state of lake ecosystems.

There are many factors regulating the change of lake ecosystems (Kagalou et al. 2008). Generally, lake eutrophication processes are regarded as a response to increased nutrient loading (Verspagen et al. 2006; Brett and Benjamin 2008). Responding to a period of globally intensive eutrophication, an increasing interest in freshwater restoration has taken place over the last two or three decades, and the reduction of nutrient loading is usually considered to be the first step in the recovery of lake ecosystems (Carpenter et al. 1999; Smith et al. 1999; Howarth and Roxanne 2006; Verspagen et al. 2006; Brett and Benjamin 2008). In recent years, the response mechanisms of lake ecosystems have been extensively studied and the importance of hydrological conditions was gradually recognized. For example, Jones and Elliott (2007) modeled the responses of abundance and composition of phytoplankton species to the change of retention time in a small lake. Burford et al. (2007) argued that watershed inputs, particularly nutrients, were not the only driver of algal growth, and hydrological factors such as residence time also affected algal growth in subtropical reservoirs. Ferris and Lehman (2007) demonstrated that hydrologic conditions strongly controlled spring diatom dynamics in an urban impoundment, and they made use of this control to alter the phytoplankton community through the whole lake manipulation. Lehman et al. (2007) showed that hydrological factors play an important role in the development of a vernal clear water phase in an urban impoundment. The relative importance and interplay of factors controlling ecosystems vary greatly among different waters, so that the larger the diversity of systems investigated, the more the information available to understand the interaction of these factors.

Generally, damming of rivers has the potential to induce cultural eutrophication, as well as dramatic changes in the hydrology and ecology (Ha et al. 2003). Upon its planned completion in 2009, Three-Gorges Reservoir (TGR) located in the mainstream of the Yangtze River (China) will be one of the largest man-made lakes in the world, with capacity of 3.93×10^{10} m^3, water level of 175 m, and surface area of 1,080 km^2 (Wang et al. 1997; Huang et al. 2006). The eutrophication processes of TGR have drawn much attention and been a hot topic in freshwater ecology (Cai and Hu 2006). A large part of the Yangtze River Basin has a subtropical monsoon climate, and the summer monsoon starts to influence the TGR in May and generally retreats in October (Gemmer et al. 2008). Consequently, the inflow discharges of TGR mostly concentrated from June to September (the flood season), accounting for 61% of annual total (Huang et al. 2006). In addition, seasonal changes in suspended particles and its seasonal flooding account for the operational pattern of the TGR, i.e., storing clear water after the flood season and releasing muddy water by lowering the water level of the reservoir during the flood season (Shao et al. 2008). Presumably, the eutrophication process and ecosystem dynamics may be closely related to the hydrological regime of the Yangtze River regulated by monsoon activities and seasonal motion of subtropical highs. Here, we present the changes in Carlson-type trophic state index during a 4-year period (July 2003 to June 2007) after the reservoir became operational. The main objective is to determine the key factor regulating ecosystem dynamics in this large subtropical reservoir.

Investigation area, data, and methods

According to the operational pattern of the TGR, after the first impoundment in June 2003, the water level of the reservoir remained at about 135 m a.s.l. in the flood season and about 139 m a.s.l. in the rest of a year; after the second impoundment in October 2006, the water level of the reservoir remained at about 145 m a.s.l. in the flood season and about 156 m a.s.l. in the rest of a year. During the sampling period, the data for the inflow discharge and the water level of the reservoir were downloaded from the website of China Three Gorges Project Corporation. The reservoir capacity in the given water level was mainly taken from Huang et al. (2006). The estimated residence time is generally calculated by relating the annual amount of water passing through the reservoir to the volume of the whole basin. Here, the residence time for each day of a year was calculated as George and Hurley (2003):

$$\tau = \frac{V_T}{Q_T},$$

where τ is water residence time (days) for each day, V_T is the daily volume (cubic meter) of the reservoir for $T = 1,\ldots,365$, and Q_T is the daily inflow discharge (cubic meter per day). To obtain the monthly residence time, the daily residence time was averaged over the days in the month.

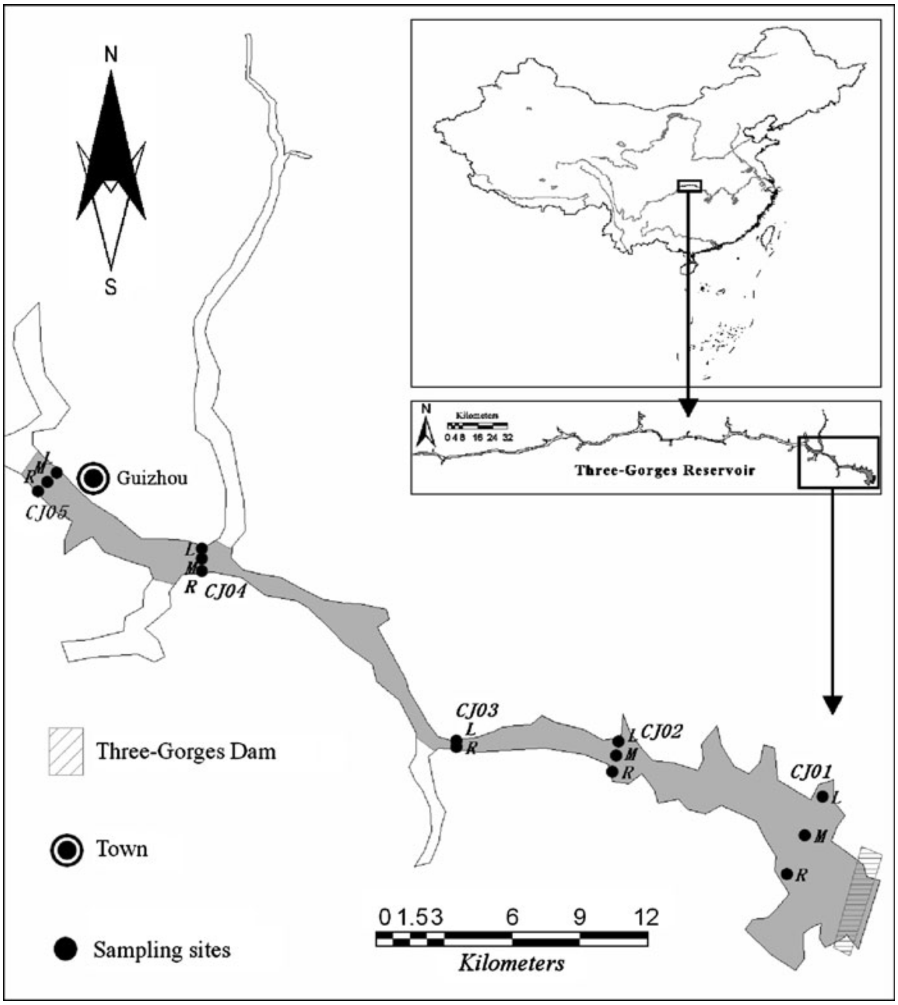


Fig. 1 The map showing location of five sampling transects (CJ01–CJ05) in Three-Gorges Reservoir

Five transverse transects (CJ01–CJ05) were set up along the mainstream of the TGR, over a distance of ca. 40 km (Fig. 1). CJ01 was just upstream from the dam, and CJ05 was upstream from the mouth of the Xiangxi Bay. Three sites, located in the left, middle, and right part of the channel, respectively, were set up in each transect, except CJ03 (only two sites) due to the narrow channel. We monitored transparency (SD), concentrations of total nitrogen (TN), total phosphorus (TP), and chlorophyll *a* (chl. *a*) monthly from July 2003 to June 2007. Twelve surveys for suspended solids were performed monthly from August 2005 to July 2006. Transparency was in situ determined with a 20-cm Secchi disc (Huang et al. 2000). Water samples for TN and TP measurements were collected, acidified with H_2SO_4 to pH < 2, and stored in a 500-mL precleaned plastic bottle. Phytoplankton cells were concentrated by filtering a known volume of water through a microfilter (0.8 μm) for chl. *a* determination. From the third year, an additional known volume of water was filtered through a weighed pre-ignited glass fiber filter (Whatman type GF/F) for suspended solid measurements. All water samples and filters were immediately placed in a dark cooler and packed in ice until the laboratory analysis.

The chl. *a* concentrations were determined on a spectrophotometer (Shimadzu UV-1601, Japan) according to the standard methods of APHA (1989). The concentrations of TN and TP were analyzed according to the user manual of Skalar on a segmented flow analyzer (Skalar SAN++, The Netherlands). Total suspended solids (TSS) and its nonvolatile suspended solids (NVSS) were measured according to a Standard Operating Procedure for Total Suspended Solids Analysis (EPA 1997).

TSI_S of the reservoir were calculated using the methods described by Carlson (1977) and Kratzer and Brezonik (1981). Deviations between TSI_S were calculated by subtracting the mean of TSI_{TP}, TSI_{TN}, or TSI_{SD} from TSI_{CHL} (Carlson 1991; Matthews et al. 2002; An and Park 2003). The equations are as follows:

$$TSI_{SD} = 60 - 14.42 \ln (SD, m)$$

$$TSI_{TN} = 54.45 + 14.43 \ln \left(TN, mg/L\right)$$

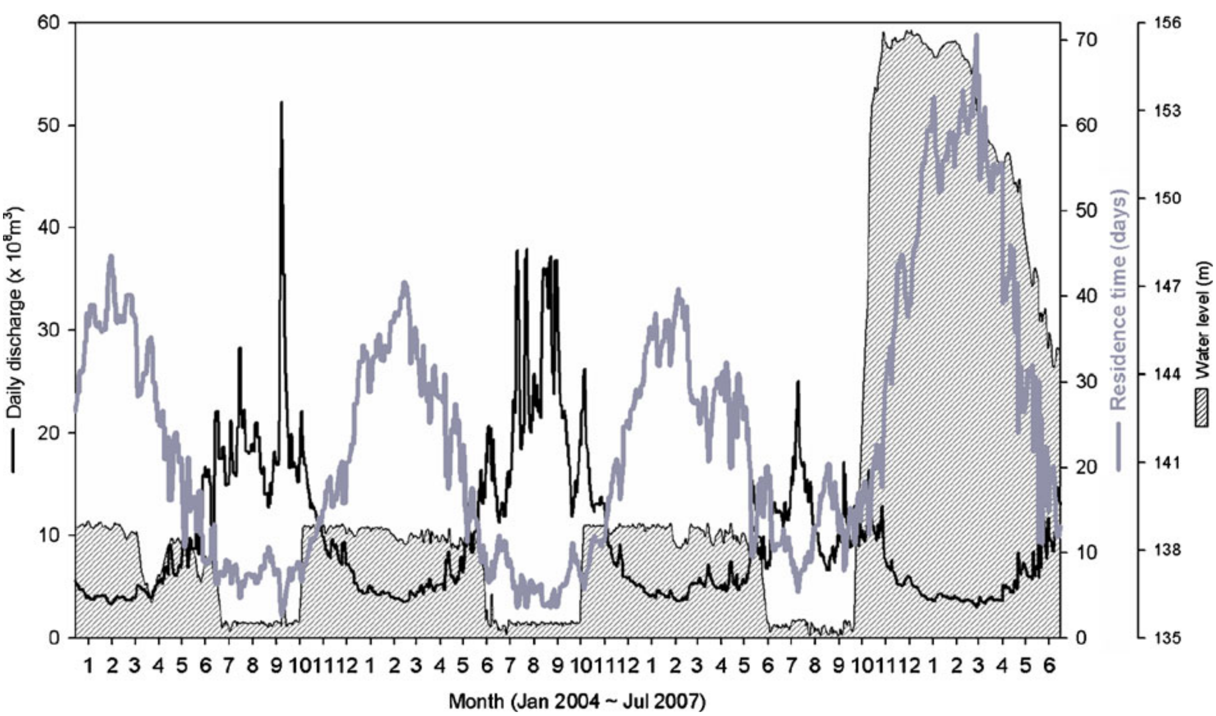


Fig. 2 The daily inflow discharge, water level, and water residence time of TGR during the survey

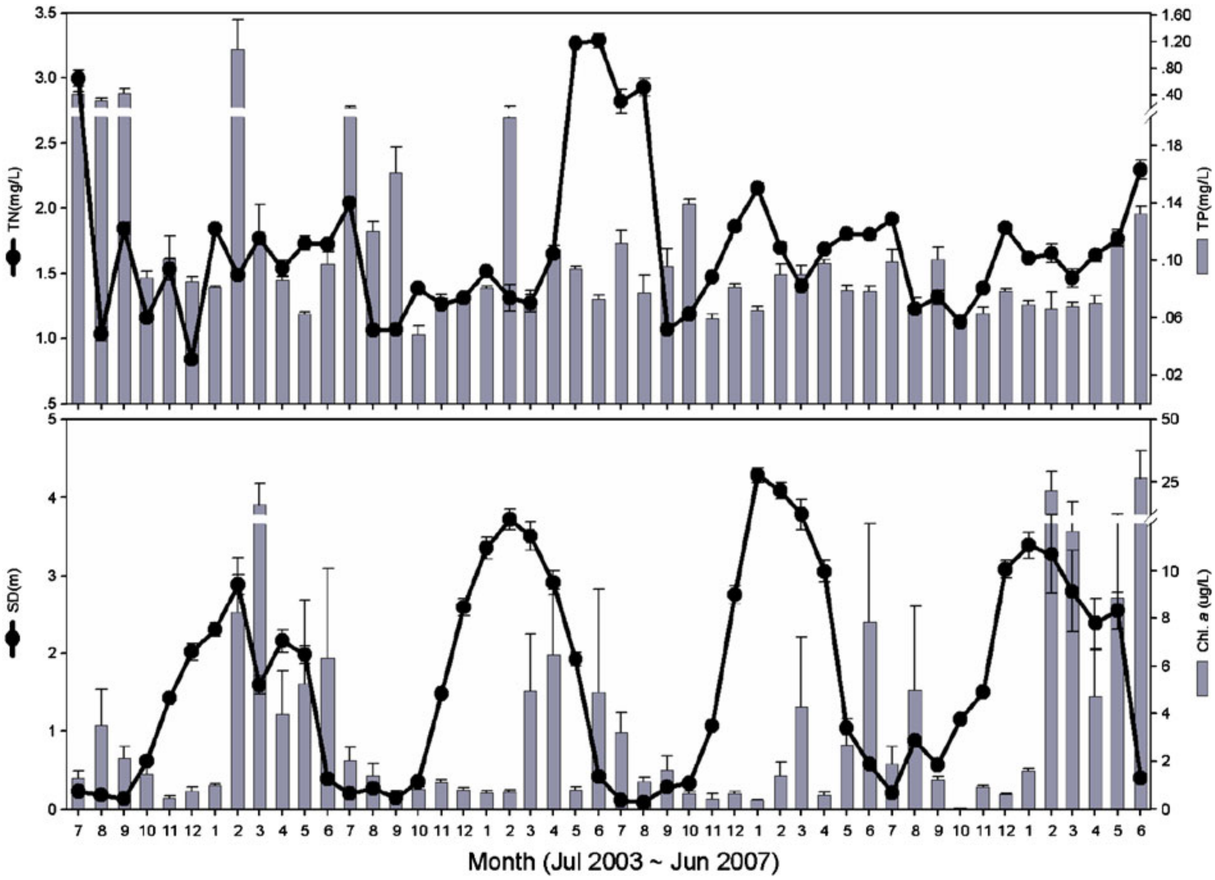


Fig. 3 Monthly mean value of chl. *a*, SD, TP, and TN for all TGR sites during the survey

$$\mathrm{TSI_{TP}} = 14.42 \ln\left(\mathrm{TP}, \mu\mathrm{g/L}\right) + 4.15$$

$$\mathrm{TSI_{CHL}} = 9.81 \ln\left(\mathrm{CHL}, \mu\mathrm{g/L}\right) + 30.6.$$

Nonparametric correlation analysis and regression model were all performed in the software SPSS 13.5.

Results

The daily discharge showed an apparent seasonal pattern (Fig. 2). Major inflows occurred from June to September and accounted for 48–64% of annual total. The seasonal patterns of the daily water level were opposite to that of the daily discharge (Fig. 2). Calculated residence time showed a striking variation during the study period, ranging from a few days (ca. 2 days) in the flood season up to 63 days in the dry season. Following the classification of Straškraba and Tundisi (1999), a reservoir with the residence time less than 20 days

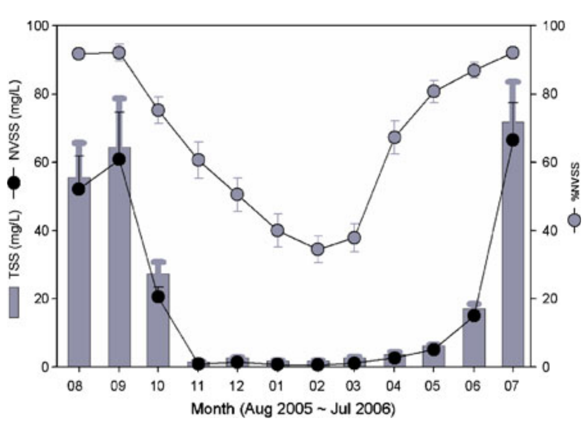


Fig. 4 Monthly mean value of TSS, NVSS, and %NVSS for all TGR sites during the third year of the survey

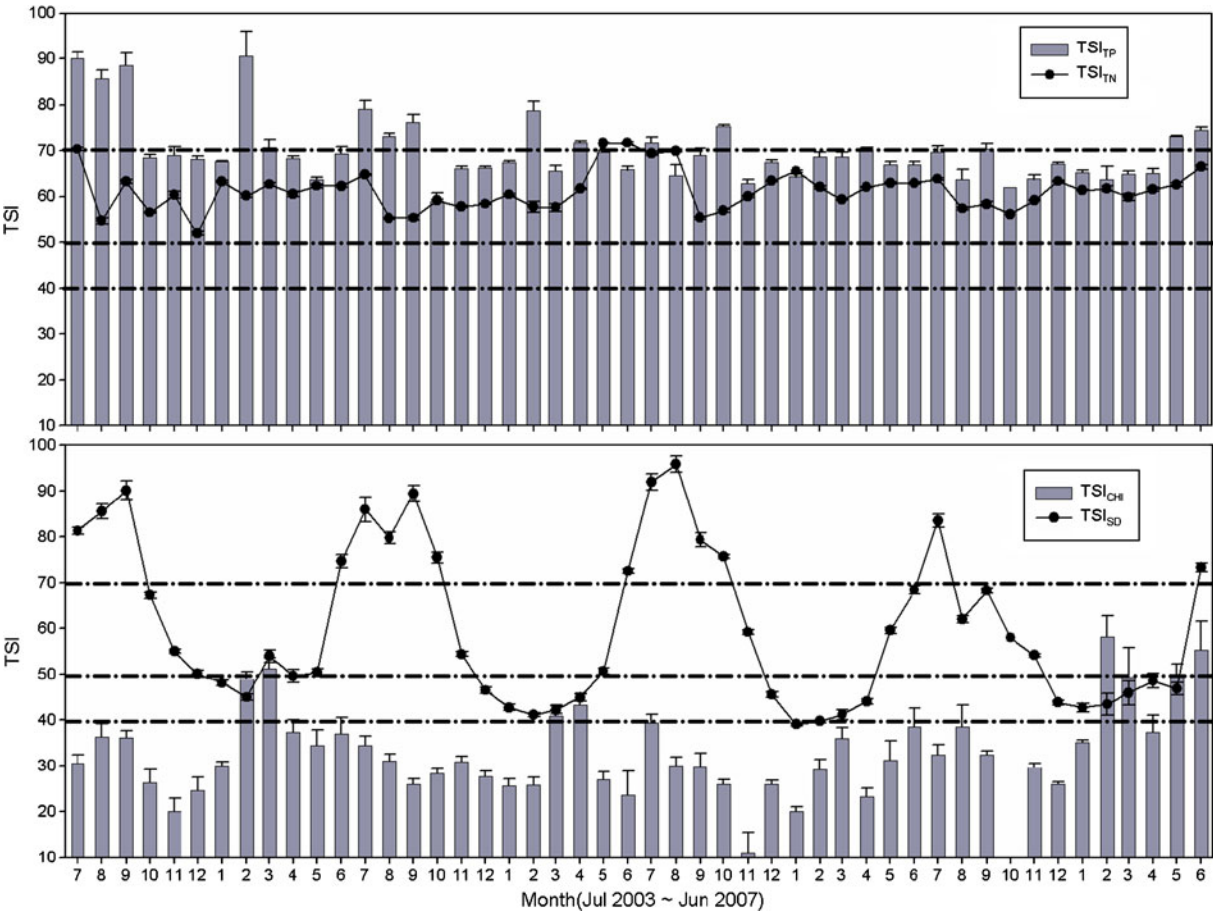


Fig. 5 Monthly mean value of TSI_{TN}, TSI_{TP}, TSI_{CHL}, and TSI_{SD} for all TGR sites during the survey

can be distinguished into class A, i.e., a fully mixed system, and a reservoir with the residence time ranging between 20 and 300 days should be grouped into class B, i.e., an intermediate stratified system. If the residence time is longer than 300 days, the reservoir will be characterized by well-developed stratification and belongs to class C. According to this criterion, class A was the most common in the flood season, while class B was often observed in the dry season (Fig. 2).

The concentrations of chl. *a*, TN and TP varied substantially among months, with mean monthly concentrations ranging from 0.07 to 26.44 μg L^{-1}, 0.84 to 3.29 mg L^{-1}, and 0.05 to 1.09 mg L^{-1}, respectively. None of the three parameters showed a consistently seasonal trend (Fig. 3). The mean monthly transparency ranged from 0.09 to 4.29 m and displayed a clear seasonal trend, with the lowest value during the flood season (Fig. 3). Mean monthly concentrations of TSS and NVSS ranged from 1.46 to 71.81 and 0.68 to 66.46 mg L^{-1}, respectively. NVSS was the dominant fraction of TSS, especially during the flood season (>85%; Fig. 4). The seasonal patterns for TSS and NVSS were contrary to that for

Table 1 Spearman's rank correlations between hydrological parameters and Carlson-type TSI_S

Variable	TSI_{CHL} ($n = 42$)	TSI_{SD} ($n = 42$)	TSI_{TP} ($n = 42$)	TSI_{TN} ($n = 42$)
ID	−0.086	0.869[a]	0.125	0.116
τ	0.08	−0.874[a]	−0.243	−0.063
TSI_{CHL}	–	0.016	0.174	0.110

ID monthly inflow discharge

[a]Correlation is significant at the 0.01 level (two-tailed)

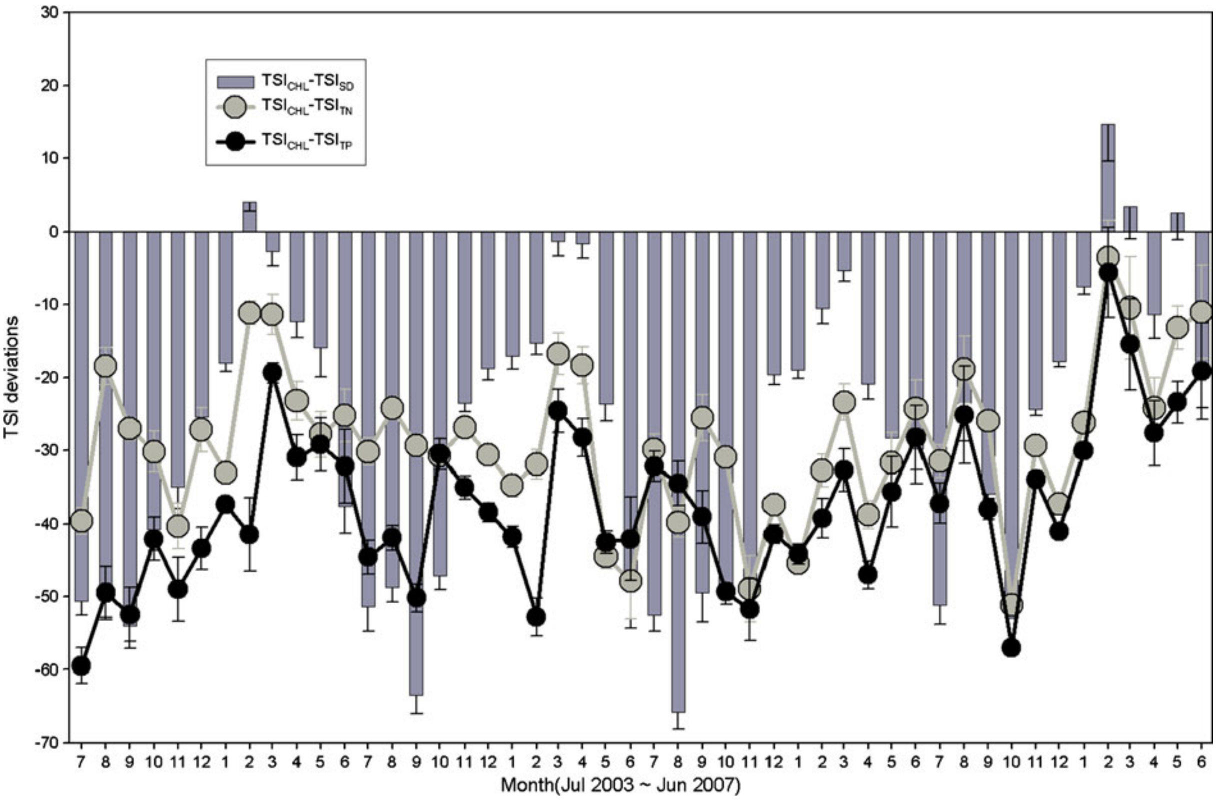


Fig. 6 Monthly mean value of TSI_S deviation for all TGR sites during the survey. The *dashed line* indicates the threshold value of trophic state

transparency (Fig. 3 vs. Fig. 4), and there were significant relationships (Spearman's rank correlation) between transparency and TSS ($r = -0.857$, $n = 153$, $p < 0.001$) and NVSS ($r = -0.875$, $n = 153$, $p < 0.001$).

The trophic state index displayed much variation among months (Fig. 5). The monthly values of TSI_{TP}, TSI_{TN}, TSI_{SD}, and TSI_{CHL} ranged from 58.9 to 98.5, 51.9 to 71.6, 39.1 to 95.8 and 5.0 to 58.1, respectively. TSI_{SD} was the only index exhibiting a typical seasonal pattern and significantly correlated with monthly inflow discharge and residence time (Table 1). Following the trophic state gradient (Kratzer and Brezonik 1981), the waters with TSI_S less than 40 should be grouped into oligotrophic state, and the waters with TSI_S ranging from 40 to 50 can be distinguished into mesotrophic state. If the TSI_S values range from 50 to 70, the waters belong to eutrophic state. The value of TSI_S is higher than 70, suggesting hypertrophic state. Based on TSI_{TP} and TSI_{TN}, the TGR was always characterized by eutrophic state in all months. Assessments based on TSI_{SD} showed that the reservoir ranged from mesotrophic state in the dry season to hypereutrophic state in the flood season. Based on TSI_{CHL}, the system was oligotrophic state in most months.

During the study period, TSI_{CHL} did not significantly correlate with TSI_{TN}, TSI_{TP}, or TSI_{SD}

Table 2 Spearman's rank correlations between suspend solids and the deviations value of Carlson-type TSI_S

Variable	TSI_{CHL} – TSI_{SD} ($n = 42$)	TSI_{CHL} – TSI_{TN} ($n = 42$)	TSI_{CHL} – TSI_{TP} ($n = 42$)
TSS	−0.720[a]	0.517	0.441
NVSS	−0.825[a]	0.399	0.329
%NVSS	−0.853[a]	0.238	0.294

[a]Correlation is significant at the 0.01 level (two-tailed)

Table 3 Spearman's rank correlations between hydrological parameters and the deviations value of Carlson-type TSI_S

Variable	$TSI_{CHL} - TSI_{SD}$ ($n = 42$)	$TSI_{CHL} - TSI_{TN}$ ($n = 42$)	$TSI_{CHL} - TSI_{TP}$ ($n = 42$)
ID	−0.812[a]	−0.164	−0.117
τ	0.803[a]	0.134	0.175

ID monthly inflow discharge

[a]Correlation is significant at the 0.01 level (two-tailed)

(Table 1), and monthly TSI_{CHL} value was almost always lower than the latter three (Fig. 5). The deviation values ($TSI_{CHL} - TSI_{TN}$ or $TSI_{CHL} - TSI_{TP}$) were always less than zero (Fig. 6). According to the concept of TSI_S differences (Carlson 1991; Matthews et al. 2002), it indicated that nutrient inputs exceeded the actual nutrient availability for algal production and factors other than nutrient limited algal biomass of the TGR. The values of $TSI_{CHL} - TSI_{SD}$ exhibited a clear seasonal variation and were also less than zero in most months, suggesting that algal productivity of the TGR may be influenced by nonalgal turbidity (Fig. 6). Further, the values of $TSI_{CHL} - TSI_{SD}$ related to TSS and NVSS (Table 2), which suggested that nonalgal turbidity was a key factor limiting algal biomass of the TGR. The hydrological parameters had no closely relationship with the $TSI_{CHL} - TSI_{TN}$ and $TSI_{CHL} - TSI_{TP}$ value (Table 3). However, they significantly correlated with the $TSI_{CHL} - TSI_{SD}$ value, and these relationships could be well modeled by logarithmic regression (Fig. 7). The logarithmic model showed that an equivalent TSI_{CHL} and TSI_{SD} could be found at $\tau = 54$ days in the TGR (Fig. 7). Accordingly, nonalgal particulates dominate light attenuation and limit algal biomass of the reservoir when $\tau < 54$ days.

Discussion

Lake trophic state may be influenced by a variety of factors, including nutrients, light, disturbance, and food web structure. Nutrient bioassays are commonly employed to estimate the importance of nutrients in primary production, and the TSI_S differences can be used to assess the degree and type of nutrient limitation in lakes (Carlson 1991; Matthews et al. 2002). The results obtained from TSI_S differences in the present study showed that nutrients (TN or TP) should not be considered as the primary factors limiting primary production in the TGR, consistently with An and Park (2003) who also observed that factors other than

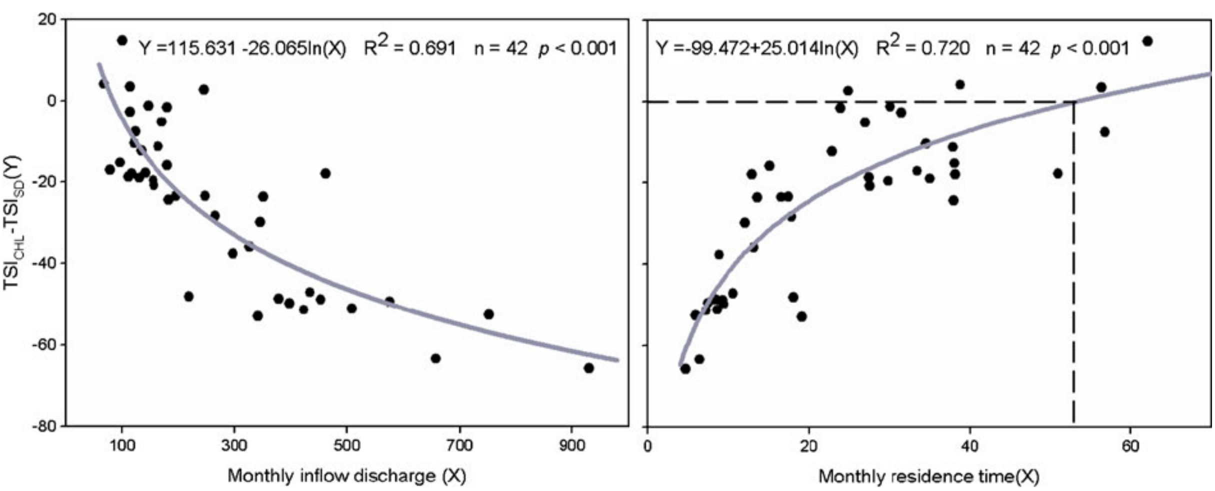


Fig. 7 Logistic regression between inflow discharge, residence time, and $TSI_{CHL} - TSI_{SD}$. The *dashed line* indicates an equivalent TSI_{CHL} and TSI_{SD}

phosphorus limited algal growth, and that nonalgal particles affect light attenuation during intensive monsoon in an Asian reservoir, but did not occur during weak monsoon.

When there are no nutrient limitations, top-down control (planktivorous fish or zooplankton grazing) is often regarded as an important factor regulating phytoplankton biomass (Kasai et al. 1997). Top-down effects can be indicated when $TSI_{CHL} > TSI_{SD}$ and $TSI_{CHL} < TSI_{TP}$ and TSI_{TN}, whereas nonalgal turbidity limitation is indicated when $TSI_{CHL} < TSI_{SD}$ and $TSI_{CHL} < TSI_{TP}$ and TSI_{TN} (Matthews et al. 2002). According to this criterion, top-down control did not influence trophic state of the TGR. Low zooplankton density further supported that zooplankton grazing is not the important factor controlling the primary producers in the TGR. For example, a maximum density of cladocerans was less than 20 ind. L^{-1} in the study area (data supplied by Xiangxi River Ecosystem Station, CAS). Several studies in rivers, riverine systems, and reservoirs have shown that washout effects regulate zooplankton biomass, and zooplankton density is usually lower in the fully mixed system than in the system of well-developed stratification (Lehman et al. 2007). Thus, the low density of zooplankton in the reservoir mainly resulted from the hydrological characteristic of the reservoir—the TGR was never a well-stratified system as demonstrated above. Presumably, zooplankton grazing would be incapable of limiting trophic state of the TGR, due to the short residence time of the reservoir.

Generally, damming of rivers evokes increases in residence time and reduction in nonalgal turbidity (Friedl and Wüest 2002). However, the situation in the TGR may be different to some extent. Despite of the increased residence time, the TGR was still a fully mixed system in the flood season and an intermediate stratified system in the dry season as mentioned above. Simultaneously, the relatively short residence time (especially in the flood season) and seasonal high sediment loadings from the drainage basin, which are usually induced by subtropical monsoon (Chen et al. 2007), resulted in seasonal high nonalgal turbidity in the TGR (Fig. 4). This pattern can be further supported by the significant relationships between nonalgal turbidity [measured as NVSS and %NVSS] and hydrological parameters, as shown by the power model (Figs. 8 and 9). Therefore, algal productivity of the TGR was still mainly influenced by nonalgal turbidity throughout most months, suggesting that trophic state of the TGR was still determined by exogenous influences (hydrological factors and sediment loadings).

After the planned last impoundment of the TGR in 2009, the water level will fluctuate between 145 m a.s.l. (flood seasons) and 175 m a.s.l. (dry seasons; Fig. 10; Huang et al. 2006). Based

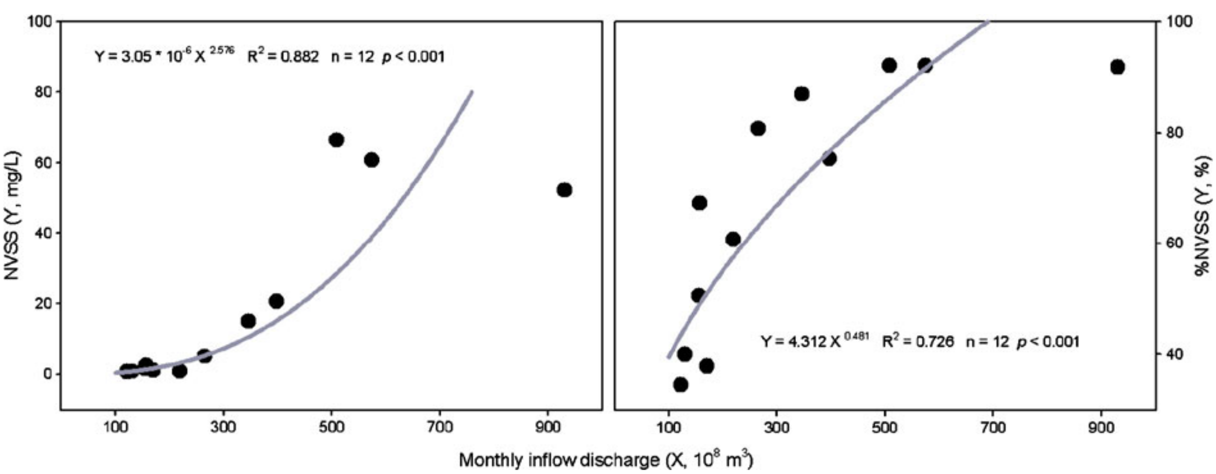


Fig. 8 Power regression between NVSS, %NVSS, and inflow discharge

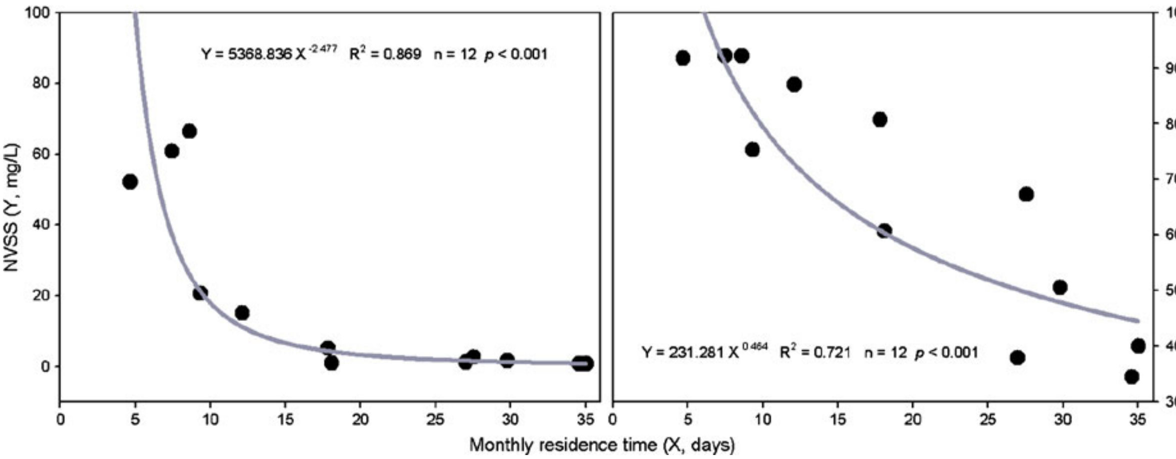


Fig. 9 Power regression between NVSS, %NVSS, and residence time

Fig. 10 Monthly inflow discharge based on long-term averages, operational pattern of water level, and estimated residence time in TGR after the last impoundment. The *dashed line* indicates the threshold value ($\tau =$ 20 days) for the classification of class A and class B

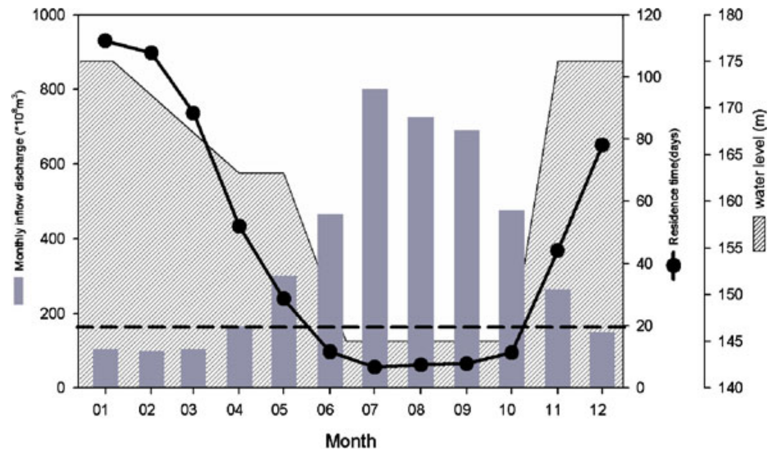
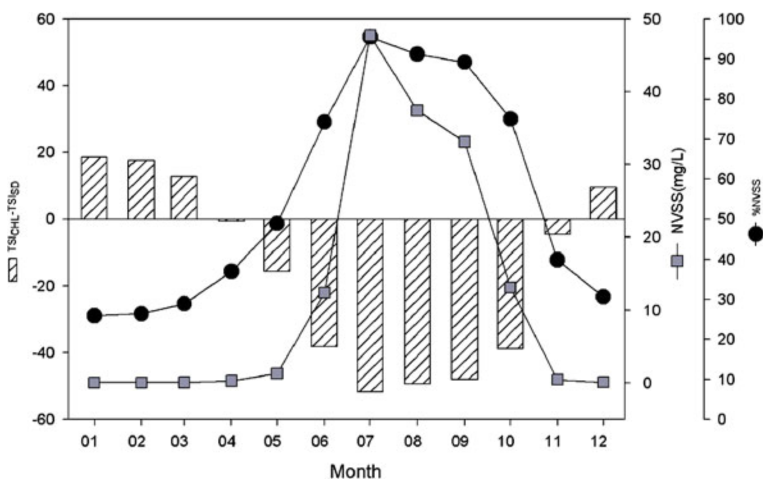


Fig. 11 The predicted value of $TSI_{CHL} - TSI_{SD}$, NVSS, and %NVSS in TGR after the last impoundment



on long-term averages, the monthly estimated residence time will range from 7 to 112 days, with an annual mean of 45 days (Fig. 10). The stratified characteristic of the TGR will not substantially change, and the system will also never be a well-stratified reservoir. According to the estimated residence time, the empirical models (Figs. 7 and 9) can be used to predict the seasonal variations of nonalgal turbidity and $TSI_{CHL} - TSI_{SD}$ values (Fig. 11). The predicted results showed that nonalgal turbidity will still limit trophic status of the TGR from April to November, but it will not during other months.

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