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A two-year field study and evaluation of water quality and trophic state of a large shallow drinking water reservoir in Shanghai, China

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ABSTRACT

Reservoirs have been widely constructed all over the world in recent years to alleviate the shortage of water resources. Nevertheless, the assessment method of water quality and its trophic status needs to be developed. In this study, water quality parameters of a newly constructed shallow reservoir were regularly monitored for a period of two years, which is used as a major drinking water source of Shanghai, China. Furthermore, the trophic state indices of the reservoir were investigated based on literature and evaluated with the two-year field data. The results indicated that the studied reservoir is reaching the mesotrophic–eutrophic boundary, where further nutrient enrichment could cause water quality degradation; total phosphorus is the limiting nutrient for algal growth in the studied reservoir. Results of the study can help operators understand change and status of water quality of the reservoir and provide valuable data demonstrating variation of water quality indicators and trophic characteristics in shallow reservoirs or lakes.

Keywords: Water supply; Drinking water; Water quality; Trophic state index; Shallow reservoir

1. Introduction

Water is one of the essential resources in life. Due to the continuous growth of water demand for anthropogenic activities and the increase of water pollution episodes, constructed reservoirs are becoming critical water sources, especially for urban cities; reservoirs have been widely constructed all over the world for decades with many located in China [1–3].

Urbanization has been growing so fast in China for the past decades that some of the metropolises have been suffering from insufficient drinking water supply. Shanghai, for example, will be short of 2.58 million m^3/d of drinking water in 2020 if no new water source is developed, as its current drinking water sources, mainly the Huangpu River and the Chenhang Reservoir, are running to their limiting capacities. Under these circumstances, a new drinking water reservoir named Qingcaosha was constructed and has been in operation since December 2010, storing fresh water from the Yangtze River during "non-salt-water" days. The total capacity of the reservoir is 524 million m^3 with the effective volume of 435 million m^3. At full operation, the reservoir is meant to provide 7.19 million m^3 of drinking water a day and serve more than 10 million residents.

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Nevertheless, it is still a great challenge to evaluate trophic states of the reservoirs in a scientific and efficient way [2,3]. Ortiz proposed a model to determine the trophic state boundaries in tropical lakes and reservoirs in the Latin American region by using General Purpose Simulation System [4]; fuzzy index model, mass-balance mode, and Landsat TM images have also been developed [5–7].

Total phosphorus (TP), chlorophyll-a (Chla), total nitrogen (TN), chemical oxygen demand in manganese (COD_{Mn}), and transparency (SD) are parameters frequently used in water quality and trophic evaluation models [8]. Carlson firstly proposed the trophic state indices (TSI) to determine eutrophication level of lakes using TP, Chla, TN, $COD_{Mn,}$ and SD as major parameters [9]; subsequently, TSI have been widely used in lakes and reservoirs [10–16]. Cunha further developed a method, proposing the modification of the Carlson's index to evaluate tropical/subtropical reservoirs [17]. An index for water quality evaluation has also been established using Chla, SD, TP, and dissolved oxygen (DO) as important parameters [10]. Other parameters such as conductivity, pH, total hardness, dissolved silica, nitrite, nitrate, ammonium, orthophosphate, and heterotrophic bacteria have also been used in the management of water bodies [18,19]. Still more emerging substances and biological indictors are used to evaluate water quality and/or trophic state of reservoirs. Algal toxins, taste and odor causing compounds, for example, are currently two challenging substances in the drinking water industry; algal toxins such as microcystin-LR, microcystin-RR and taste & odor causing compounds such as geosmin and 2-methylisoborneol are frequently used as critical water quality indicators in lakes and reservoirs [20–23]. Meanwhile, trophic analysis based on zooplankton, phytoplankton, and diatoms were also elaborated [24,25]. Nutrient indicators such as TP and TN are important components for nearly all the water quality and/or trophic evaluation models mentioned above.

Phosphorus (P) and nitrogen (N) used to be considered as the major limiting nutrients in aquatic systems [9,18,19]; P seems to be the main limiting factor for phytoplankton growth rather than N in many water bodies [26,27]. The TN/TP ratios are also advised as the major water quality indicator in the literature [10]. Researchers classified TN/TP ratios into several ranks and pointed out that, in different TN/TP ratios, P or N should be the limiting factor and/or co-limitation factors [28,29]. Redfield N/P ratio was even considered as a judging parameter to identify the balance of phytoplankton growth [30]. Wang proposed that TN/TP ratios are not suitable to decide whether P or N is the limiting factor in an aquatic system since many components of TN and TP are not bio-available [26]; instead the ratio of dissolved inorganic nitrogen and dissolved inorganic phosphorus might be a better alternative [24,31].

In order to help operators understand the changes and status of water quality of the newly constructed reservoir (Qingcaosha), the temporal and spatial variation of water quality parameters were regularly monitored for two years. Furthermore, the trophic status of the reservoir was evaluated with the two-year field data in the present study, which can help to determine whether it is fulfilling the requirements for drinking water sources.

2. Materials and methods

2.1. Study area

The studied reservoir is located in Shanghai, China. It has a surface area of approximately 70 km^2, a mean depth of 2.7 m, and a hydraulic retention time (at normal annual precipitation levels) of approximately 25 d. The initial inlet water was kept in the reservoir from April 2009 to September 2010 during construction period. After the trial operation period from October 2010 to December 2010, the studied reservoir has been running to supply raw water for the city so far to date. The studied period for this work was from April 2009 to May 2011. Sampling stations were selected in the main channel of the studied reservoir to cover the whole water body area, which are divided into three regions, namely, the riverine zone (S1–4), the transition zone (S5–7), and the lacustrine zone (S8–10) (as seen in Fig. 1).

2.2. Sampling procedure

Water samples of the studied reservoir were collected once or twice a month from 15th April 2009 to 14th May 2011. The samples were either examined on site or stored immediately with ice and/or chemicals for subsequent examination according to standard methods described in Section 2.3. All the samples were collected between 8 am and 2 pm from the 10 stations (Table 1). Vertically, 1–3 samples were taken at each station according to water depth. The specific sampling scheme in vertical direction for each site was as follows: the sampling point is chosen at 0.5 m from the surface when the water depth is less than 5 m (S1–3, S5 and S7); the sampling points are chosen at 0.5 m from the surface and 0.5 m from the bottom, respectively, when the water depth is greater than 5 m but less than 10 m (S4, S8 and S10); the sampling points are chosen at 0.5 m from the surface, middle of

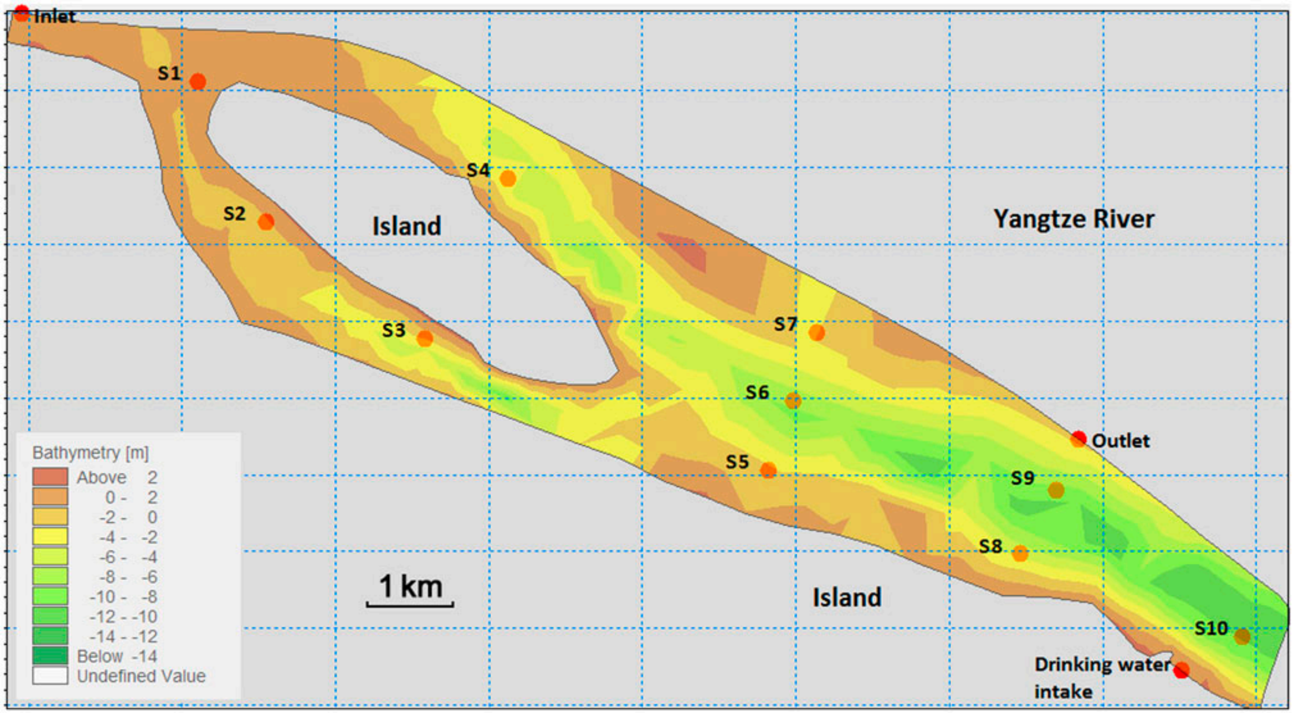

Fig. 1. The studied reservoir and sampling stations.

Table 1
Names, geographic coordinates (longitude and latitude), water depth (m), and sampling layer of the 10 stations

Station	Longitude E	Latitude N	Water depth (m)	Sampling layer
S1	E 121.570423	N 31.4838308	1.5	Surface layer
S2	E 121.57989	N 31.4675914	3.8	Surface layer
S3	E 121.601982	N 31.4540519	2.7	Surface layer
S4	E 121.613046	N 31.4729895	5.8	Surface and bottom layer
S5	E 121.649318	N 31.4391362	2.5	Surface layer
S6	E 121.652484	N 31.4472522	11.0	Surface, middle and bottom layer
S7	E 121.655651	N 31.4553681	3.6	Surface layer
S8	E 121.684024	N 31.42963	7.2	Surface and bottom layer
S9	E 121.68877	N 31.4372021	13.1	Surface, middle and bottom layer
S10	E 121.709256	N 31.4201271	10.0	Surface and bottom layer

water depth and 0.5 m from the bottom, respectively, when the water depth is greater than 10 m (S6 and S9).

2.3. Analytical methods

Water parameters are determined by the standard methods listed in Table 2. TP was determined with a UV spectrophotometer (UV-2501); total organic carbon (TOC) was determined by a TOC analyzer (TOC-5000A); TN was determined by a UV spectrophotometer (UV-2501); the COD_{Mn} was determined by an automatic titrator (50 mL); while Chla was determined by a UV spectrophotometer (UV-2501).

2.4. Data analysis

The Carlson's TSI (Chla) and TSI (TP) were calculated using the following equations:

$$\text{TSI (Chla)} = 10 \times [6 - (2.04 - 0.68 \times \ln \text{Chla}) / \ln 2] \quad (1)$$

Table 2
The list of analytical methods

Monitoring indicator	Standard	Equipment	Type
DO	GB/T 11913-1989	DO meter	YSI-58
Temperature	GB/T 13195-1991	Surface thermometer	F-0014
TP	GB/T 11893-1989	UV spectrophotometer	UV-2501
TOC	HJ 501-2009	TOC analyzer	TOC-5000A
TN	GB/T 11894-1989	UV spectrophotometer	UV-2501
pH	GB/T 6920-1986	Acidity meter	PHS-3C
CODMn	GB/T11892-1989	Automatic titrator	50 mL
Chlorophyll-a	SL 88-2012	UV spectrophotometer	UV-2501

$$TSI\ (TP) = 10 \times [6 - \ln(48/TP)/\ln\ 2] \quad (2)$$

The Cunha's trophic state index TSI_{tsr} was calculated using the following equations:

$$TSI_{tsr} = [TSI\ (TP)_{tsr} + TSI\ (Chla)_{tsr}]/2 \quad (3)$$

where

$$TSI\ (TP)_{tsr} = 10 \times [6 - (1.329766 - 0.27637 \times \ln TP)/\ln 2] \quad (4)$$

$$TSI\ (Chla)_{tsr} = 10 \times [6 - (0.842257 - 0.2512 \times \ln\ Chla)/\ln\ 2] \quad (5)$$

Results showed that concentrations of major water parameters such as Chla and TP were similar for stations within the same region. To make the analysis concise and brief, we used S2, S6, and S9 to represent the riverine zone, the transition zone, and the lacustrine zone, respectively.

3. Results

3.1. Variation of water quality parameters

Water quality parameters of the reservoir during the study period are shown in Table 3 using S2, S6, and S9 as representative stations for the riverine zone, the transition zone, and the lacustrine zone, respectively.

Normally, DO concentration in the studied reservoir displayed annual variation with concentrations between 6.25 mg/L and the saturation level (7.50–14.62 mg/L). It was found that DO concentration was higher than the saturation level in several points (Fig. 2(A)), which might be related to the big wave derived from strong winds. The highest DO concentrations during the construction period occurred in January 2010 and in January 2011 during the trial operation/full operational period. Throughout the course of the study, the studied reservoir showed alkaline waters, with pH values ranging from 8.13 to 9.08 (Fig. 2(B)); pH of the studied reservoir was relatively higher in the summer season. Variation of water temperature followed a strong seasonal pattern ranging from 3.1 to 32.9 ℃ (Fig. 2(C)).

Concentration of Chla showed a decreasing trend from the construction period to the trial operation/full operational period (Fig. 2(D)). During the early construction period of June 2009–February 2010, concentration of Chla accumulated (>10 μg/L); while during the trial operation/full operational period, it declined to be less than 4 μg/L, which is exactly the threshold value for the oligotrophic state according to Cunha et al. [17]. Concentration of COD_{Mn} for the studied reservoir water varied from 1.48 to 5.69 mg/L with an average value of 2.5 mg/L (Fig. 2(E)). Concentration of TOC varied from 1.44 to 5.55 mg/L throughout the study period (Fig. 2(F)), with the relatively higher values occurred in the summer season.

Distribution of TN concentration in the studied reservoir was demonstrated in Fig. 3(A). TN concentration decreased from ca. 1.8 to 0.5 mg/L during the construction period and then increased to ca. 1.5 mg/L at the end of the study. The highest value (3.17 mg/L) was observed in August 2010. TP concentration showed a significant spatial difference (Fig. 3(B)). During the early construction period (June 2009–February 2010), the TP concentrations for S6 and S9 (below 0.06 mg/L) were normally lower than that for S2 (ranging from 0.06 to 0.12 mg/L). TN/TP ratio in the studied reservoir varied from 1.6 to 62.6 during the construction period and from 8.75 to 114.2 during the trial operation/full operational period (Fig. 3(C)). Water quality results for the middle and bottom layers of S6 and S9 were close to the surface as demonstrated in Sup. 1–3.

Table 3
Water quality in S2, S6, and S9

Indicator	S2			S6			S9		
	N	AVG	SD	N	AVG	SD	N	AVG	SD
DO (mg/L)	30	9.80	2.63	30	9.55	2.13	30	9.33	2.42
pH	30	8.47	0.20	30	8.45	0.21	30	8.42	0.20
Temperature (℃)	30	19.9	8.8	30	19.5	8.9	30	19.6	8.9
Chlorophyll-a (μg/L)	27	8.32	7.90	27	8.76	8.65	27	8.24	7.55
COD (mg/L)	29	2.67	0.65	29	2.66	0.63	29	2.61	0.73
TOC (mg/L)	29	3.57	0.80	30	3.30	0.73	30	3.21	0.81
TN (mg/L)	30	0.76	0.55	29	0.70	0.45	30	0.79	0.64
TP (mg/L)	27	0.058	0.030	29	0.041	0.022	27	0.040	0.021

Notes: N: total number of available data; AVG: average values; SD: standard deviation.

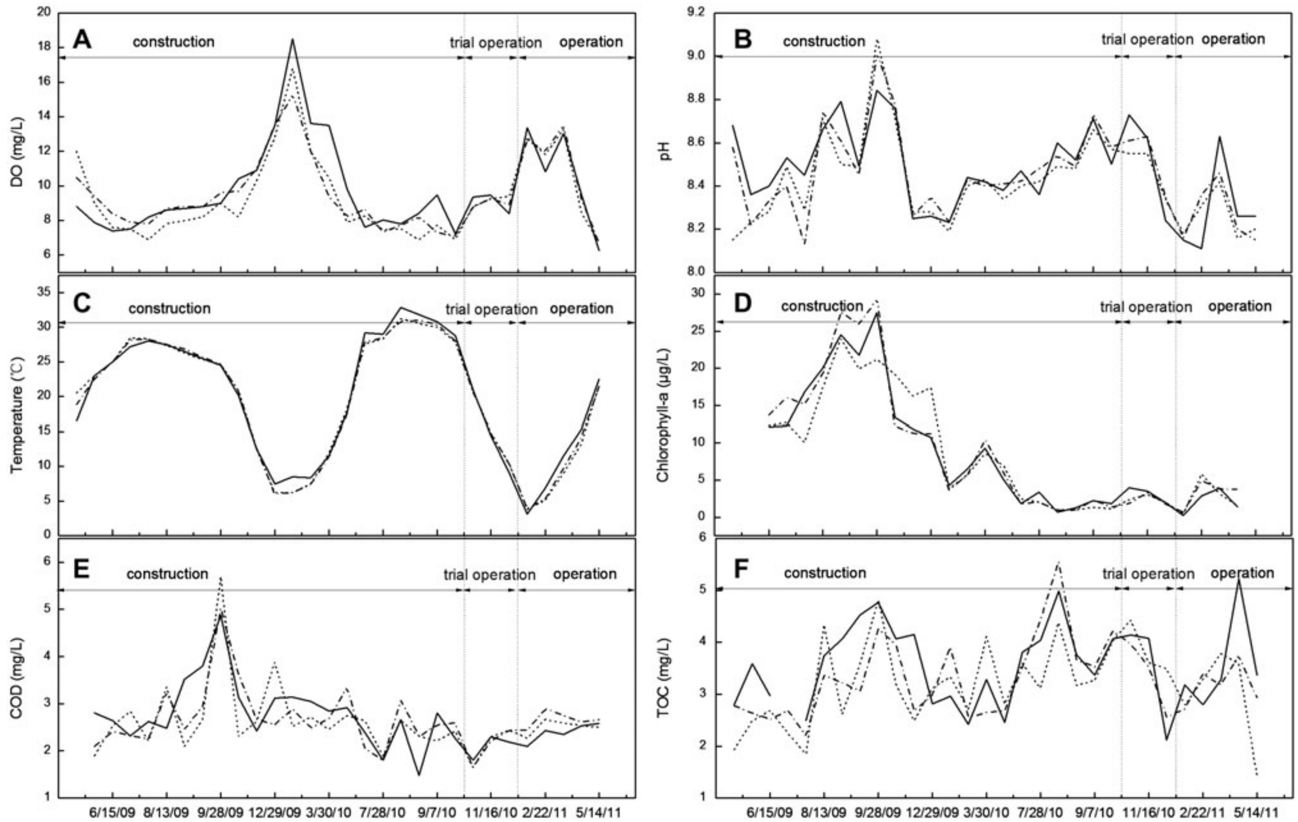

Fig. 2. Variation of DO (A), pH (B), temperature (C), Chla (D), COD_{Mn} (E), and TOC (F) in representative stations of the reservoir; solid line represents S2, dash dot represents S6, and short dash represents S9.

3.2. Trophic status of the reservoir

Temporal and spatial changes of TSI in the studied reservoir were shown in Fig. 4, where TSI (Chla) and TSI (TP) were calculated according to Carlson [9], and TSI_{tsr} was calculated according to Cunha et al. [17]. Boundaries for TP, Chla, and TSI values in literature are also shown in Table 4. The TSI scale shown in Table 4 ranges from 0 (ultraoligotrophic) to 100 (hypereutrophic), where higher and/or increasing TSI values indicate an exacerbation in eutrophic conditions.

Calculated TSI (Chla) varied between 14.3 and 63.7 (Fig. 4(A)). Its value stayed at a level as high as 50–60 from June 2009 to May 2010, which can be classified

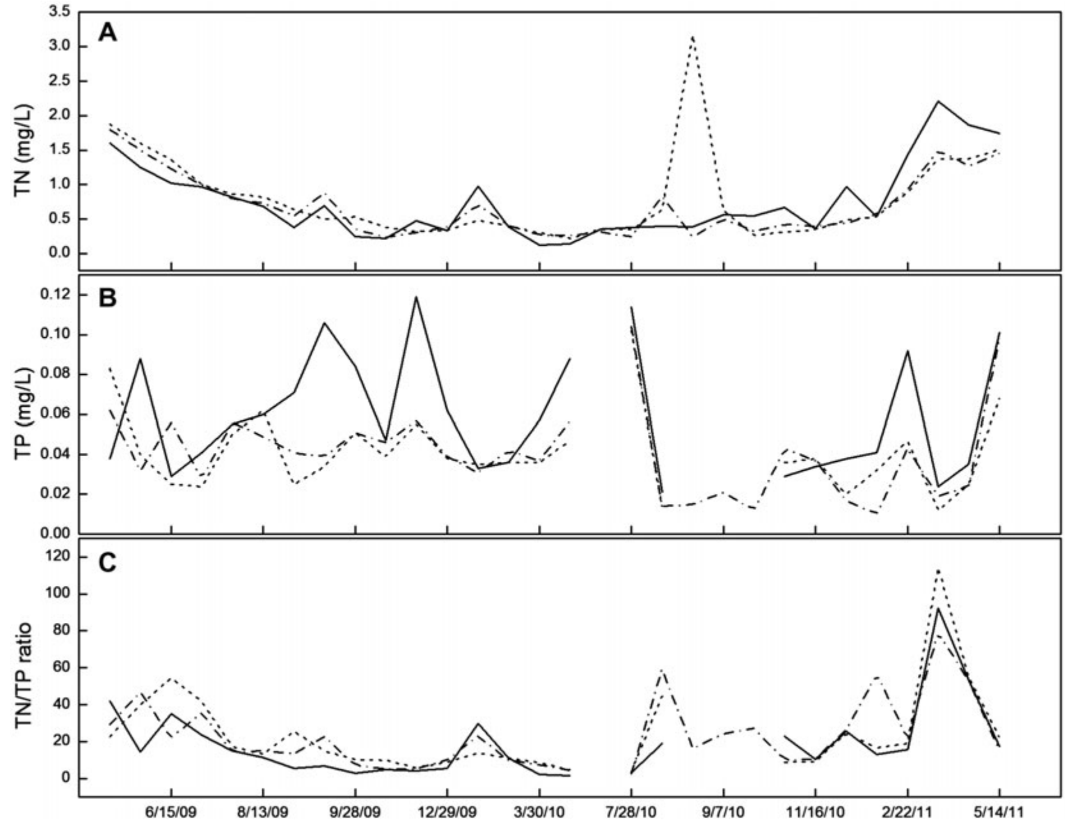

Fig. 3. Variation of TN, TP and calculated TN/TP ratios; solid line represents S2, dash dot represents S6, and short dash represents S9: annual variation of total nitrogen (A), total phosphorus (B) and calculated TN/TP ratios (C).

into the mesoeutrophic and the eutrophic states, respectively. During the trial operation/full operational period, TSI (Chla) reached higher levels in November, 2010, February, 2011, and March, 2011, respectively; while TSI (Chla) occurred on 6 January 2011 with a relatively lower value below 25.

Calculated TSI (TP) varied from 37 to 73 (Fig. 4(B)). The TSI (TP) for S6 and S9 were normally lower than for S2 during the early construction period (June 2009–February 2010). TSI_{tsr} varied from 48 to 55 during the trial operation/full operational period; variation of calculated TSI_{tsr} displayed similar trends as TSI (Chla) and TSI (TP) (Fig. 5) during the whole study period.

4. Discussions

4.1. Distribution of water quality parameters in the reservoir

DO and pH are two important parameters which are helpful to describe the status of a natural surface water body [32]. DO concentration in the studied reservoir presented higher values in winter and lower values in summer; similar trends have been shown in a French reservoir [33]. The results of the present study are different from the Raipur reservoir in India, where the higher values of DO concentration occurred in summer [34]. Sometimes the DO is incredibly higher than its saturation level but not due to excessive algae growth according to Chla level in the reservoir; the occurrence of incredible high DO events often accompanied a higher wind speed higher than 5 m/s after checking the meteorology data, which caused vortex and re-oxygenation in the water. The pH value reflects the acidity or alkalinity of a water body, which depends on the composition of chemical compounds and the occurrence of biochemical processes in the water body. The pH value in the studied reservoir had an annual average value of 8.45. The alkalinity pH is an indication of eutrophication that consumes carbon dioxide (CO_2) in the water body. Similar observations have been reported covering water bodies in India [34], China [35], and Portugal [3,36]. The changes of water temperature and temperature stratification dynamics can have a profound effect on aquatic, biological, and chemical processes; the

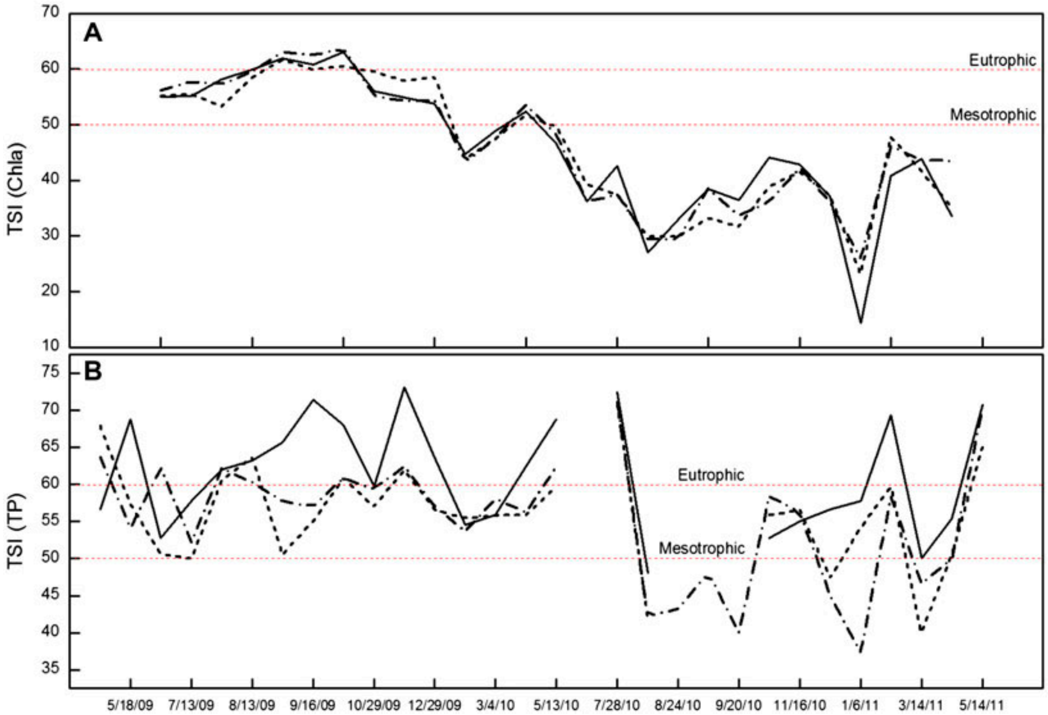

Fig. 4. Calculated TSI according to Carlson; solid line represents S2; dash dot represents S6, and short dash represents S9: calculated TSI according to Carlson by chlorophyll-a (A) and total phosphorus (B).

Table 4
Proposed trophic state threshold values for TP (μg/L) and Chla (μg/L) in literature

		Total phosphorus (μg/L)		
TSI (by Carlson)	Trophic state category	Carlson	Vollenwelder	Cunha
–[a]	Ultraoligotrophic	–	≤4	≤15.9
–	Oligotrophic	≤12.0	4–10	16.0–23.8
40–60	Mesotrophic	12–24	10–35	23.9–36.7
≥60	Eutrophic	24–96	35–100	36.8–63.7
–	Supereutrophic	–	–	63.8–77.6
–	Hypereutrophic	≥96	≥100	≥77.7
TSI_{tsr} (by Cunha)	Trophic state category	Chlorophyll-a (μg/L)		
≤51.1	Ultraoligotrophic	–	≤1	≤2.0
51.2–53.1	Oligotrophic	≤2.6	≤2.5	2.1–3.9
53.2–55.7	Mesotrophic	2.6–20	2.5–8	4.0–10.0
55.8–58.1	Eutrophic	20–56	8–25	10.1–20.2
58.2–59.0	Supereutrophic	–	–	20.3–27.1
≥59.1	Hypereutrophic	≥56	≥25	≥27.2

[a]Not applicable.

temperature in the studied reservoir had an annual average value of 19.7°C.

Chla is regarded as an important hydrological factor for aquatic ecosystems and is frequently used to estimate phytoplankton biomass in short-term bioassays [27,37]. Chla concentration in the studied reservoir decreased dramatically from the construction period to the trial operation/operation period; similar phenomenon was also observed in other reservoirs [38]. Average concentration of Chla for the trial operation/full operational period was 2.66 μg/L. The COD value of a water body depends mainly on the content

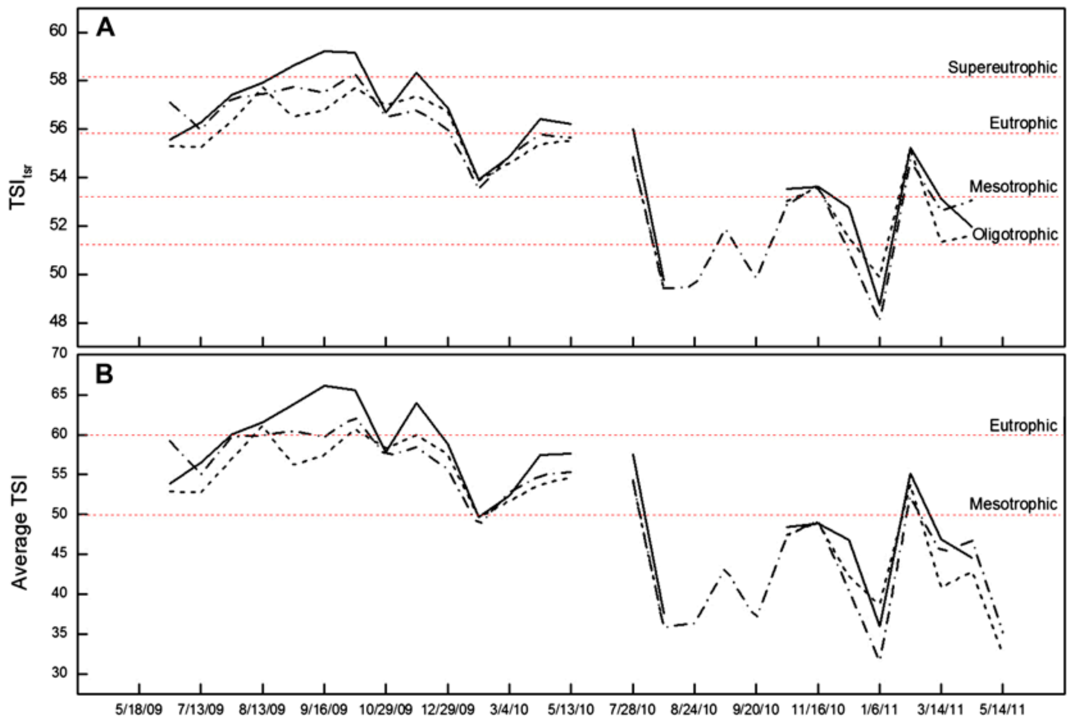

Fig. 5. Calculated TSI_{tsr} according to Cunha (A) and the average TSI (Chla) and TSI (TP) (B); solid line for S2; dash dot for S6, and short dash for S9.

of organic matters [34]; the higher DO concentration during the trial operation/full operational period can also expedite the decrease of organic matters in the reservoir [16]. Either COD_{Mn} or TOC in the studied reservoir showed a strong seasonal variation, similar to a Swedish catchment [39].

Even today researchers are not certain about the limiting nutrient mechanism in a water body [28]; however, they tend to assume that P limitation is more reasonable in most water systems over N [2,8,28]. TN and TP concentrations in the studied reservoir were 749 and 46 μg/L, respectively, similar to those in the Itupararanga Reservoir [28]. However, TN and TP concentrations in the studied reservoir were 1–3 times higher than the reference concentrations proposed by Lamparelli, who presented baseline TP concentration for São Paulo state (Brazil) reservoirs as 15–30 μg/L and TN as 810–840 μg/L [40]. TN/TP ratios in the studied reservoir were much higher than the Redfield ratio with an obvious increase during the full operational period [30] mainly due to the following reasons: (1) The asynchronization in magnitude of TN and TP concentration leads to an increasing TN/TP ratios; (2) the consumption proportion of TP by phytoplankton is much larger than TN. In this case, the nutrient limitation factor for the studied reservoir should be P.

4.2. Temporal and spatial change of TSI

In present study, the trophic state of investigated reservoir was evaluated by TSI (Chla), TSI (TP), and TSI_{tsr}. The calculated TSI (Chla) and TSI (TP) showed an obvious declining from the construction period to the trial operation/full operational period. The average values for TSI (Chla) and TSI (TP) were 49 and 58, respectively, during the construction period and 38 and 55 during the trial operation/full operational period, while the average values for TSI_{tsr} were 56 and 52 during the construction period and the trial operation/full operational period, respectively. TSI_{tsr} is more stable than TSI (Chla) and TSI (TP) due to its comprehensive property by using several water quality parameters. However, results of TSI (Chla) and TSI (TP) values indicated that trophic state of the reservoir is more sensitive in Chla than TP.

The TSI value is a reflection of the magnitude of nutrients in a water body; the change of trophic state reveals the variation of nutrients. Because of the massive discharge of industrial effluents and municipal sewage, the Yangtze River has been suffering severe pollution in recent years. During the construction period, the rich nutrients in inlet Yangtze led to higher TSI values in the reservoir; while after more than a year of treatment and management, there has been a great improvement in water quality of the reservoir. Fig. 5 indicated that, trophic state of the reservoir changed from the eutrophic state during the construction period to the mesotrophic state during the trial operation/full operational period.

5. Conclusions

DO concentration in the studied reservoir displayed annual variation between 6.25 mg/L and the saturation level. pH of the studied reservoir ranged from 8.13 to 9.08 with relatively higher values in the summer. The concentrations of Chla and TN showed a decreasing trend from the construction period to the trial operation/full operational period; while TP concentration showed a significant spatial difference.

The increasing TN/TP ratios suggest that the reservoir is phosphorus limited. Trophic state of the reservoir changed from the eutrophic state during the construction period to the mesotrophic state during the trial operation/full operational period. Nevertheless, pollutants coming from the Yangtze River are still risky. Further increase of nutrient loading in inlet could cause water quality degradation and measurements must be taken in order to avoid the deterioration.

Acknowledgements

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Nomenclature

GPSS	—	general purpose simulation system
TP	—	total phosphorus
Chla	—	chlorophyll-a
TN	—	total nitrogen
COD_{Mn}	—	chemical oxygen demand in manganese
SD	—	transparency
TSI	—	trophic state indices
P	—	phosphorus
N	—	nitrogen
DIN	—	dissolved inorganic nitrogen
DIP	—	dissolved inorganic phosphorus
TOC	—	total organic carbon
CO_2	—	carbon dioxide

Supplementary material

The supplementary material for this paper is available online at http://dx.doi.10.1080/19443994.2015.1059370.

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