PRIMARY RESEARCH PAPER

Lake eutrophication associated with geographic location, lake morphology and climate in China

Wenzhi Liu · Quanfa Zhang · Guihua Liu

Abstract Lake eutrophication is influenced by both anthropogenic and natural factors. Few studies have examined relationships between eutrophication parameters and natural factors at a large spatial scale. This study explored these relationships using data from 103 lakes across China. Eutrophication parameters including total nitrogen (TN), total phosphorus (TP), TN:TP ratio, chemical oxygen demand (COD_{Mn}), chlorophyll-*a* (Chl-*a*), Secchi depth (SD), and trophic state index (TSI) were collected for the period 2001–2005. Sixteen natural factors included three of geographic location, five of lake morphology, and eight of climate variables. Pearson correlation analysis showed that TP and TSI were negatively related to elevation, lake depth, and lake volume, and positively related to longitude. All eutrophication parameters, except for COD_{Mn} and Chl-*a*, showed no significant correlation with climate variables. Multiple regression analyses indicated that natural factors together accounted for 13–58% of the variance in eutrophication parameters. When the 103 study lakes were classified into different groups based on longitude and elevation, regression analyses demonstrated that

natural factors explained more variance in TN, TP, COD_{Mn}, Chl-*a*, and TSI in western lakes than in eastern lakes. Lake depth, volume, elevation, and mean annual precipitation were the main predictors of eutrophication parameters for different lake groups. Although anthropogenic impacts such as point- and nonpoint-source pollution are considered as the main determinants of lake eutrophication, our results suggest that some natural factors that reflect lake buffer capacity to nutrient inputs can also play important roles in explaining the eutrophication status of Chinese lakes.

Keywords Human activity · Natural factor · Nitrogen · Phosphorus · Water quality

Introduction

China has a large number of lakes, 2300 of which with surface areas larger than 1 km^2. The total area of all the lakes is 70,988 km^2, accounting for about 0.8% of China's total land area (Jin, 2003). Unfortunately, as a result of natural and human influences, China's lakes have faced several environmental problems including eutrophication, salinization, and declines in surface area and submerged vegetation in recent decades (Xu et al., 1999; Jin et al., 2005; Wu et al., 2007; Liu et al., 2008). Eutrophication has been recognized as the most common and severe environmental hazard in lake ecosystems (Jin, 2003; Jin et al., 2005). As a global environmental issue, eutrophication is characterized by

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high nitrogen and phosphorus concentrations in water bodies, resulting in excessive growth of phytoplankton and other aquatic plants (Schindler et al., 2008).

Lake eutrophication is affected by a wide range of anthropogenic and natural factors (Müller et al., 1998; Hall et al., 1999). Relationships between anthropogenic factors such as land use, point-source pollution, water management, and eutrophication parameters have been studied frequently (Galbraith & Burns, 2007; Fraterrigo & Downing, 2008). By contrast, correlations of natural factors including geographic location, lake morphology, and climate variables with eutrophication parameters have been of less concern (Nõges et al., 2003; Nõges, 2009). According to Brylinsky & Mann (1973) and Nõges (2009), latitude and altitude can significantly affect the water quality and phytoplankton production of lakes. Lake morphology parameters (for instance, mean depth and volume) reflect buffer capacity to nutrient inputs and are considered important factors affecting water quality (Müller et al., 1998; Taranu & Gregory-Eaves, 2008). Relationships between climate variables, such as precipitation and temperature, and water quality have often been examined to forecast the effects of climate change on the water environment (Fukushima et al., 2000; Tibby & Tiller, 2007).

Few studies have focused on the influences of natural factors on the lake water quality at a large scale such as national or global level (Thierfelder, 1998; Nõges, 2009). In this study, we constructed relationships among seven eutrophication parameters and 16 natural factors of 103 Chinese lakes by collecting data from government environmental bulletins and published literatures for the period 2001–2005. The objectives of this study were (1) to explore eutrophication trend of Chinese lakes in recent decades; (2) to examine relationships between eutrophication parameters and geographic location, lake morphology, and climate; and (3) to identify which natural factors could significantly account for the spatial variability of eutrophication parameters in Chinese lakes.

Materials and methods

Data collection

Eutrophication data of natural lakes were collected from government environmental bulletins (http://www.stats.gov.cn/tjsj/qtsj/hjtjzl) and water quality

assessment studies (e.g., Xiong et al., 2003; Yang, 2004; Qian et al., 2007; Shi & Yan, 2007; Cheng et al., 2008). Water quality assessment studies were identified by searching the China National Knowledge Infrastructure (http://www.cnki.net) and ISI Web of Science (http://apps.isiknowledge.com) using combinations of titles such as lake, eutrophication, water quality, and nutrient. Each lake was surveyed at least twice (commonly in summer and winter, or high-flow and mean-flow period within a year) in 2–10 sampling sites based on surface area. A total of 103 Chinese lakes, including ten salty lakes were finally chosen as the database for subsequent analysis. As it was not feasible to collect eutrophication parameters for all the 103 lakes within the same year, we collected the eutrophication data for the period of 2001–2005; 75 of the 103 lakes had at least 2 years of data, and so we used their mean values to reduce among-year error. These lakes were located between the longitudes of 87°4′ and 132°33′ E and the latitudes of 22°48′ and 48°55′ N (Fig. 1). The total area of these lakes is 27,194 km^2, accounting for about 38.3% of China's total lake area.

Eutrophication parameters including total nitrogen (TN), total phosphorus (TP), TN:TP ratio, chemical oxygen demand (COD$_{Mn}$), chlorophyll-*a* (Chl-*a*), and Secchi depth (SD) in water bodies were directly obtained from government environmental bulletins and published literatures. The trophic state index (TSI) was calculated using the following equations (Carlson, 1977):

$$\text{TSI (SD)} = 10\left(6 - \frac{\ln \text{SD}}{\ln 2}\right)$$

$$\text{TSI (Chl-}a\text{)} = 10\left(6 - \frac{2.04 - 0.68 \ln \text{Chl-}a}{\ln 2}\right)$$

$$\text{TSI (TP)} = 10\left(6 - \frac{\ln\left(\frac{48}{\text{TP}}\right)}{\ln 2}\right)$$

where Chl-*a* and TP concentrations were expressed in mg/m^3, and SD in m. TSI used in this study was the average of TSI (SD), TSI (Chl-*a*), and TSI (TP). TSI values <40, 40–50, and >50 indicated oligotrophic, mesotrophic, and eutrophic status of lakes, respectively (Thomas et al., 2006).

For each lake, we recorded the longitude (°E) and latitude (°N) of the geographic midpoint from the China Lake Database (http://www.lake.csdb.cn/). Then, these longitudes and latitudes were imported
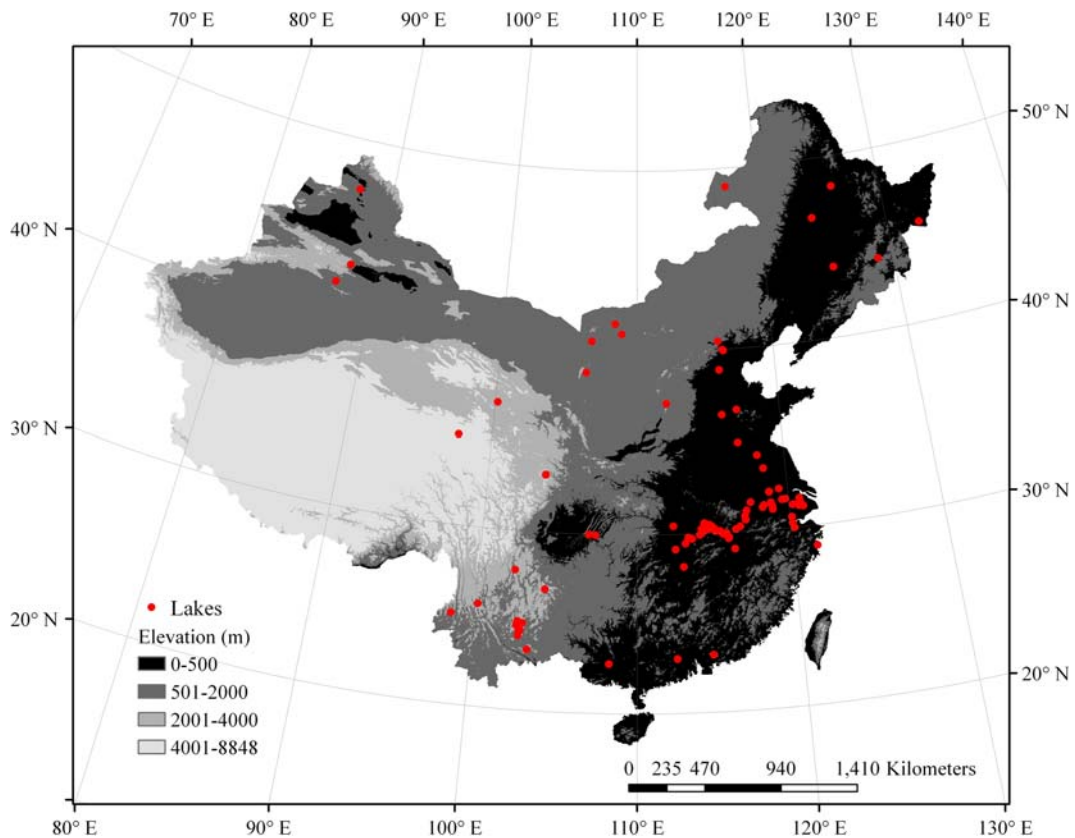
Fig. 1 Locations of the 103 Chinese lakes evaluated in this study. The background map shows the topography of China

into ArcGIS 9.1 (ESRI, California, USA) to extract elevation based on a digital elevation model at 1×1 km resolution. Lake morphology variables, including mean and maximum depth, surface area, volume, and length-to-width ratio, were obtained primarily from two monographs of Chinese lakes (Jin, 1995; Wang & Dou, 1998). Climate variables including mean annual precipitation, maximum, mean and minimum annual air temperatures, maximum and mean summer air temperatures, annual total radiation, and relative humidity for the period 1971–2000 were compiled from Chinese ecosystem research network dataset (http://www.cern.ac.cn/0index) at 1×1 km resolution in ArcGIS 9.1.

Statistical analyses

We used Statistica 8.0 for all statistical analyses. Table 1 summarizes the statistics of eutrophication parameters, geographic location, lake morphology, and climate variables. Before subsequent analyses, all eutrophication parameters, geographic location, and lake morphology variables (except for TSI and elevation) were Ln-transformed to satisfy the assumption of normality. Relationships among eutrophication parameters, geographic location, lake morphology, and climate variables were evaluated with Pearson correlation analysis. The step-up false discovery rate (FDR) approach was used to correct the P-values in correlation test (Benjamini & Hochberg, 1995; García, 2004). The 103 study lakes were grouped into the following categories based on longitude and elevation: eastern lakes (longitude $\geq 110°$ E, $n = 78$), western lakes (longitude $< 110°$ E, $n = 25$), mountain lakes (elevation ≥ 300 m, $n = 30$), and lowland lakes (elevation < 300 m, $n = 73$). Forward stepwise multiple regression analyses were used to determine which natural factors could best explain the spatial variability of eutrophication parameters.

Table 1 Summary for statistics of eutrophication parameters, geographic location, lake morphology, and climate variables used in this study

Variable	Abbr	N	Minimum	Maximum	Mean	SD
Eutrophication parameters						
Total nitrogen (mg/l)	TN	96	0.16	18.81	2.16	2.43
Total phosphorus (mg/l)	TP	99	0.01	0.85	0.14	0.17
TN:TP ratio	TN:TP	96	1.93	301.97	27.83	42.71
Chemical oxygen demand (mg/l)	COD_{Mn}	83	0.78	77.39	6.62	8.64
Chlorophyll-a (mg/m^3)	Chl-a	71	0.08	96.4	21.76	23.09
Secchi depth (m)	SD	70	0.17	3.76	0.84	0.56
Trophic state index	TSI	98	31.72	98.66	63.07	12.45
Geographic location						
Longitude (°E)	Long	103	87.07	132.55	113.63	7.9
Latitude (°N)	Lat	103	22.8	48.92	32.04	5.4
Elevation (m)	Elev	103	0.00	4257	429.29	834.07
Lake morphology						
Mean depth (m)	Z_{mean}	84	1	89.6	4.81	10.02
Maximum depth (m)	Z_{max}	72	1.3	155	10.07	19.58
Surface area (km^2)	SA	98	0.1	4340	277.49	685.31
Volume (10^8 m^3)	Vol	77	0.01	778	29.28	98.96
Length to width ratio	LWR	65	1.41	18.39	4.29	3.24
Climate variables						
Mean annual precipitation (mm)	P_{mean}	103	79.72	1521.7	939.02	358.56
Mean annual air temperatures (°C)	T_{mean}	103	−3.56	22.33	14.5	4.75
Mean summer air temperatures (°C)	ST_{mean}	103	6.46	28.20	24.47	3.79
Maximum annual air temperatures (°C)	T_{max}	103	4.23	26.35	19.49	3.84
Maximum summer air temperatures (°C)	ST_{max}	103	13.56	32.67	29.76	3.2
Minimum annual air temperatures (°C)	T_{min}	103	−9.62	19.32	10.46	5.59
Annual total radiation (kJ/cm^2)	ATR	103	286.18	516.77	409.6	40.45
Relative humidity (%)	RH	103	44.81	85.03	73.01	8.90

Results

The percentage of eutrophic lakes in China rapidly increased to 84.5% during the period of 2001–2005 from 41.2% in 1978–1980 and 51.2% in 1988–1992, while the oligotrophic lakes decreased to 2.9% from 11.8% and 7.6% in 1978–1980 and 1988–1992, respectively (Fig. 2).

Table 2 showed the Pearson correlations among the seven eutrophication parameters. Interestingly, Chl-a was positively and significantly related to TP, TN:TP, and COD_{Mn} ($r = 0.56$, $r = -0.35$, and $r = 0.65$, respectively, all $P < 0.01$), but not significantly related to TN.

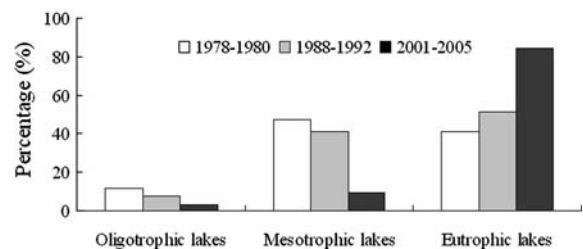Relationships among geographic location, lake morphology, and climate variables were significant

Fig. 2 Percentages of oligotrophic, mesotrophic, and eutrophic lakes during the periods 1978–1980, 1988–1992, and 2001–2005

(Table 3). Shallow lakes in China were generally located in the eastern region, such as the middle and lower reaches of Yangtze River, where annual precipitation, air temperatures, and humidity were relatively high and elevation was low (Table 3).

Table 2 Pearson correlation matrix of eutrophication parameters

	TN	TP	TN:TP	COD$_{Mn}$	Chl-a	SD	TSI
TN	1	0.62[b]	0.28[b]	0.56[b]	0.19	−0.65[b]	0.54[b]
TP		1	−0.58[b]	0.64[b]	0.56[b]	−0.71[b]	0.90[b]
TN:TP			1	−0.16	−0.35[b]	0.29[a]	−0.52[b]
COD$_{Mn}$				1	0.65[b]	−0.67[b]	0.70[b]
Chl-a					1	−0.48[b]	0.87[b]
SD						1	−0.83[b]
TSI							1

[a] Significant at the 0.05 level

[b] Significant at the 0.01 level

Pearson correlation analyses indicated that longitude was positively correlated with TP and TSI ($r = 0.31$ and $r = 0.30$, respectively, both $P < 0.05$) and negatively correlated with TN:TP ($r = −0.27$, $P < 0.05$), while latitude was only related to COD$_{Mn}$ ($r = 0.30$, $P < 0.05$). Elevation was found negatively related to TP, Chl-a, and TSI ($r = −0.26$, $P < 0.05$; $r = −0.42$, $P < 0.01$; $r = −0.30$, $P < 0.01$), and positively related to TN:TP ($r = 0.33$, $P < 0.01$) (Table 4).

Mean depth and maximum depth both had significant relationships with TN, TP, COD$_{Mn}$, Chl-a, and TSI. Mean depth was also positively related to Chl-a ($r = 0.32$, $P < 0.05$). Surface area only had a negative relationship with TN ($r = −0.37$, $P < 0.01$). Lake volume was negatively correlated with TN, TP, Chl-a, and TSI ($r = −0.45$, $r = −0.45$, $r = −0.52$, $r = −0.48$, respectively, all $P < 0.01$). Lake shape, represented by length to width ratio, showed no significant relationship with any eutrophication parameters (Table 4).

Among the eight climate variables, only mean annual precipitation, mean summer air temperatures, and maximum summer air temperatures had significant relationships with eutrophication parameters (Table 4). The former was negatively correlated with COD$_{Mn}$ ($r = −0.31$, $P < 0.05$), while the latter two were both positively related to Chl-a ($r = 0.34$, $P < 0.05$ and $r = 0.38$, $P < 0.01$).

Stepwise multiple regression analyses demonstrated that natural factors together accounted for 13.3–57.5% of the variance in eutrophication parameters (Table 5). TN was mainly determined by maximum depth, elevation, and length-to-width ratio, while TP was primarily determined by mean depth, longitude, and mean annual precipitation. Mean depth explained 13.3% of the variance in TSI while longitude, elevation, maximum depth, and volume were eliminated from the model. Mean annual precipitation was the strongest predictor of COD$_{Mn}$ and accounted for 25.6% of the variance (Table 5).

Natural factors explained more variance in most eutrophication parameters in western lakes than in eastern lakes. TN, TP, COD$_{Mn}$, and TSI in the eastern lakes were the most responsive to mean annual precipitation, while those in the western lakes were the most responsive to lake depth (Table 5). Mean depth was the strongest predictor of eutrophication parameters in mountain lakes, while maximum depth and mean annual precipitation were the most important natural variables controlling the eutrophication parameters in lowland lakes (Table 5).

Discussion

An early investigation of Chinese lakes in 1978–1980 concluded that 41.2% lakes were eutrophic (Jin, 2003). During the time period of 1988–1992, a nationwide water quality investigation on 131 lakes demonstrated that 51.2% of these lakes had undergone eutrophication (Wang & Dou, 1998). Our study indicates that the percentage of eutrophic lakes rapidly increased to 84.5% in 2001–2005. Evidently, water quality of Chinese lakes has deteriorated considerably in recent decades due to increasing nutrient inputs and decreasing buffer capacity. In this study, Chl-a was found to be positively and significantly related to TP, but not to TN. This result supports the view that phosphorus but not nitrogen

Table 3 Pearson correlation matrix of geographic location, lake morphology, and climate variables

	Long	Lat	Elev	Z_{mean}	Z_{max}	SA	Vol	LWR	P_{mean}	T_{mean}	ST_{mean}	T_{max}	ST_{max}	T_{min}	ATR	RH
Long	1	0.07	−0.69[b]	−0.47[b]	−0.42[b]	−0.07	−0.19	0.03	0.40[b]	0.28[b]	0.51[b]	0.16	0.47[b]	0.32[b]	−0.41[b]	0.43[b]
Lat		1	−0.02	−0.01	−0.09	0.12	0.24	−0.18	−0.73[b]	−0.77[b]	−0.30[b]	−0.81[b]	−0.14	−0.76[b]	0.31[b]	−0.68[b]
Elev			1	0.55[b]	0.55[b]	0.02	0.31[b]	0.01	−0.49[b]	−0.59[b]	−0.91[b]	−0.47[b]	−0.92[b]	−0.61[b]	0.52[b]	−0.49[b]
Z_{mean}				1	0.90[b]	0.37[b]	0.55[b]	0.15	−0.23[a]	−0.34[b]	−0.52[b]	−0.28[a]	−0.55[b]	−0.35[b]	0.17	−0.20
Z_{max}					1	0.25[a]	0.58[b]	0.26[a]	−0.18	−0.32[a]	−0.55[b]	−0.24[a]	−0.57[b]	−0.34[b]	0.28[a]	−0.18
SA						1	0.92[b]	0.05	−0.11	−0.12	−0.05	−0.12	−0.05	−0.11	0.16	−0.04
Vol							1	0.04	−0.28[a]	−0.41[b]	−0.37[b]	−0.39[b]	−0.38[b]	−0.41[b]	0.35[a]	−0.27[a]
LWR								1	0.06	0.11	0.03	0.12	−0.02	0.10	−0.09	0.08
P_{mean}									1	0.83[b]	0.66[b]	0.76[b]	0.52[b]	0.86[b]	−0.64[b]	0.89[b]
T_{mean}										1	0.83[b]	0.98[b]	0.73[b]	0.99[b]	−0.54[b]	0.76[b]
ST_{mean}											1	0.75[b]	0.97[b]	0.84[b]	−0.56[b]	0.59[b]
T_{max}												1	0.66[b]	0.96[b]	−0.43[b]	0.69[b]
ST_{max}													1	0.73[b]	−0.51[b]	0.46[b]
T_{min}														1	−0.59[b]	0.79[b]
ATR															1	−0.78[b]
RH																1

Abbreviations are given in Table 1

[a] Significant at the 0.05 level

[b] Significant at the 0.01 level

Table 4 Pearson correlation coefficients of eutrophication parameters with geographic location, lake morphology, and climate variables

Natural factors	TN	TP	TN:TP	COD$_{Mn}$	Chl-a	SD	TSI
Long	0.12	0.31[a]	−0.27[a]	0.15	0.22	−0.26	0.30[a]
Lat	0.02	0.15	−0.14	0.30[a]	−0.01	−0.28	0.09
Elev	−0.01	−0.26[a]	0.33[b]	−0.21	−0.42[b]	0.17	−0.30[b]
Z_{mean}	−0.48[b]	−0.52[b]	0.13	−0.39[b]	−0.51[b]	0.32[a]	−0.49[b]
Z_{max}	−0.46[b]	−0.54[b]	0.16	−0.32[a]	−0.48[b]	0.28	−0.45[b]
SA	−0.37[b]	−0.22	−0.11	−0.23	−0.20	0.24	−0.23
Vol	−0.45[b]	−0.45[b]	0.05	−0.21	−0.52[b]	0.16	−0.48[b]
LWR	0.12	−0.01	0.14	−0.08	−0.21	0.01	−0.04
P_{mean}	−0.10	−0.07	−0.06	−0.31[a]	−0.01	0.18	−0.03
T_{mean}	−0.01	0.01	−0.02	−0.18	0.23	0.20	0.06
ST_{mean}	−0.01	0.16	−0.20	0.06	0.34[a]	0.01	0.19
T_{max}	0.01	−0.06	0.06	−0.20	0.22	0.25	0.02
ST_{max}	0.03	0.16	−0.18	0.12	0.38[b]	−0.02	0.19
T_{min}	−0.01	0.03	−0.03	−0.19	0.21	0.19	0.07
ATR	−0.01	−0.14	0.15	0.23	0.05	−0.06	−0.05
RH	−0.06	0.04	−0.13	−0.20	0.08	0.17	0.04

Abbreviations are given in Table 1

[a] Significant at the 0.05 level

[b] Significant at the 0.01 level

control is critical to mitigating lake eutrophication (Carpenter, 2008; Schindler et al., 2008; Wang et al., 2008).

Lake eutrophication is influenced by both natural and anthropogenic factors (Müller et al., 1998). Anthropogenic factors, including point- and non-point-source pollutions, land use patterns, urbanization, aquaculture, and hydrological regulation have been frequently studied to explore their influences on water quality variables including eutrophication parameters in different types of water bodies (Hall et al., 1999; Arbuckle & Dowing, 2001; Buck et al., 2004; Fraterrigo & Downing, 2008). By contrast, relationships between natural factors and eutrophication parameters in lakes have been rarely studied, especially at the larger scales (Thierfelder, 1998). Understanding these relationships is essential to recognize the influences of natural drivers on lake eutrophication process in the background of increasing human activities in China.

Relatively few studies have explored the correlations between geographic location and nutrient content and phytoplankton biomass in lakes (Kalff, 1991; Cobelas & Rojo, 1994; Nõges, 2009). According to

Brylinsky & Mann (1973), 56% of the variability in global phytoplankton production can be explained by latitude alone. However, other global-scale studies have shown that there is no significant correlation between latitude and phytoplankton biomass and partly attributed to the paucity of data from tropical lakes (Schindler, 1978; Cobelas & Rojo, 1994). A similar result was also observed in our study at a national scale. This might be because 56% of the study lakes were located in the Yangtze floodplain between 29 and 32° N, where eutrophication was more common and severe than other regions in China (Zhou & Zheng, 2008). This study found an eastward increase in TP and TSI but no trend in TN and Chl-a. Longitude in China is a compound factor reflecting both elevation and economy. In higher longitude regions, such as the middle and lower reaches of the Yangtze Basin, topography is mainly plain and the majority of the area lies below 50 m. As such, industry and agriculture are more developed in comparison to lower longitude regions. Positive relationship between elevation and TN:TP ratio in this study can be partly attributed to nitrogen deposition. Atmospheric nitrogen deposition was probably higher in the lakes located in higher

Table 5 Determinants of eutrophication parameters analyzed by stepwise multiple regression analyses

Eutrophication parameters	Regression equations	R^2	P value
All lakes ($N = 103$)			
LnTN	$0.566 - 0.688 \, LnZ_{max} + 0.001 \, Elev + 0.522 \, LnLWR$	0.363	<0.001
LnTP	$-21.438 - 0.478 \, LnZ_{mean} + 4.28 \, LnLong - 0.001 \, P_{mean}$	0.371	<0.001
LnTN:TP	$-2.803 + 0.001 \, Elev + 0.173 \, ST_{max}$	0.286	<0.001
LnCOD$_{Mn}$	$-13.646 - 0.001 \, P_{mean} - 0.316 \, LnZ_{max} + 3.47 \, LnLong + 0.001 \, Elev$	0.575	<0.001
LnChl-a	$3.553 - 0.938 \, LnZ_{max}$	0.261	0.001
LnSD	$8.359 - 2.503 \, LnLat$	0.219	0.002
TSI	$69.365 - 6.134 \, LnZ_{mean}$	0.133	0.005
Eastern lakes ($N = 78$)			
LnTN	$22.109 - 0.454 \, LnZ_{max} + 0.503 \, LnLWR - 0.003 \, P_{mean} - 5.413 \, LnLat$	0.517	<0.001
LnTP	$-0.508 - 0.002 \, P_{mean} - 0.141 \, LnVol$	0.406	<0.001
LnTN:TP	$43.651 - 9.685 \, LnLong + 0.084 \, RH - 0.001 \, P_{mean}$	0.376	<0.001
LnCOD$_{Mn}$	$2.953 - 0.001 \, P_{mean} - 0.09 \, LnVol$	0.551	<0.001
LnChl-a	$3.448 - 0.899 \, LnZ_{max}$	0.255	0.001
LnSD	$-2.637 + 0.115 \, T_{max}$	0.156	0.015
TSI	$-368.647 - 0.015 \, P_{mean} - 1.911 \, LnVol + 94.373 \, LnLong$	0.433	<0.001
Western lakes ($N = 25$)			
LnTN	$0.459 - 0.892 \, LnZ_{mean} + 0.001 \, Elev$	0.582	0.008
LnTP	$-1.467 - 0.885 \, LnZ_{mean}$	0.532	0.003
LnCOD$_{Mn}$	$3.270 - 0.847 \, LnZ_{max} + 0.164 \, LnVol$	0.914	0.001
LnChl-a	$11.854 + 2.773 \, LnVol - 0.515 \, ST_{mean}$	0.905	<0.001
TSI	$79.852 - 11.850 \, LnZ_{mean}$	0.462	0.008
Mountain lakes ($N = 30$)			
LnTN	$21.438 - 0.478 \, LnZ_{mean}$	0.327	0.021
LnTP	$-1.517 - 0.754 \, LnZ_{mean}$	0.379	0.011
LnTN:TP	$2.286 + 0.001 \, Elev - 0.001 \, P_{mean}$	0.511	0.01
LnCOD$_{Mn}$	$3.91 - 0.545 \, LnZ_{mean} - 0.072 \, T_{max}$	0.690	0.009
TSI	$78.609 - 9.99 \, LnZ_{mean}$	0.338	0.018
Lowland lakes ($N = 73$)			
LnTN	$-44.396 - 0.449 \, LnZ_{max} + 0.543 \, LnLWR - 0.003 \, P_{mean} + 9.351 \, LnLong$	0.604	<0.001
LnTP	$0.617 - 0.002 \, P_{mean} - 0.165 \, LnSA$	0.434	<0.001
LnTN:TP	$-0.714 + 0.164 \, T_{max}$	0.285	<0.001
LnCOD$_{Mn}$	$-34.998 - 0.002 \, P_{mean} - 0.08 \, LnVol + 7.778 \, LnLong + 0.107 \, T_{min}$	0.606	<0.001
LnChl-a	$3.44 - 0.889 \, LnZ_{max}$	0.246	0.002
TSI	$102.291 - 0.027 \, P_{mean} - 2.064 \, LnSA$	0.379	<0.001

Abbreviations are given in Table 1. The eutrophication parameters without regression models are not listed

altitude due to elevated orographic precipitation and the amount of horizontal deposition (Kopácek et al., 2000). Elevation was found negatively related to Chl-a in these 103 lakes. Lakes located in higher elevation region including Yunnan–Guizhou Plateau, Inner Mongolia–Xinjiang Plateau, and Qinghai–Tibetan Plateau suffered relatively little industrial pollution and thus partly resulted in a negative relationship between elevation and TSI.

Some morphological features of lakes, such as depth and lake volume, have been proved significantly related to nutrient concentration or eutrophication status (Hamilton et al., 2001; Taranu & Gregory-Eaves, 2008). Vollenweider (1968) recognized that

mean depth was a synthetic variable for lake morphology and water residence time. Owing to differences in geological formation and topography, lakes with mean depths above 5 m in China were mainly located in Yunnan–Guizhou Plateau, Inner Mongolia–Xinjiang Plateau, and Qinghai–Tibetan Plateau, while almost all other lakes located in Eastern Plain were shallow water lakes, except the Poyang Lake and Dongting Lake (Zhou & Zheng, 2008). In this study, mean depth was negatively related to TN, TP, COD_{Mn}, Chl-*a*, and TSI, and positively related to SD. Deep lakes have relatively strong buffer capacity for wastewater runoff. Phosphorus nutrient can deposit into sediment in both deep and shallow lakes. However, sediment phosphorus in shallow lakes would strongly resuspend and release into overlying water due to wind wave or fishes disturbance. Therefore, although vast efforts have been used to control eutrophication in different lake depths worldwide, almost all successful cases came from deep lakes.

Relationships between climate and water quality have gained an increasing attention in the background of global climate change (Tibby & Tiller, 2007; Wagner & Adrian, 2009). However, studies conducted in different scales may result in inconsistent conclusion (Brylinsky & Mann, 1973; Quirós, 1988; Hamilton et al., 2001). In this study, we show that at a national scale, only the mean and the maximum summer air temperatures and mean annual precipitation are significantly related to eutrophication parameters. In order to test these relationships at a regional scale, we chose a subset of 78 eastern lakes (data not showed). Surprisingly, in addition to mean and maximum summer air temperatures and mean annual precipitation, minimum, mean, and maximum annual air temperatures, and relative humidity had significant relationships with two or more eutrophication parameters. Furthermore, the trends were not completely comparable to those observed at the national scale. For instance, a significant and positive correlation was found between mean summer air temperatures and Chl-*a* at the national scale, while a weakly negative relationship was noted at the regional scale. Consistent with results from correlation analyses, multiple regression analyses also indicated that TP, SD, and TSI in eastern lakes were most responsive to annual precipitation and maximum annual air temperatures, while those in all study lakes were most responsive to lake depth and latitude.

Other natural factors related to water quality such as bedrock geology in lake catchments were not considered in this study, because this factor mainly affected the cations including Ca^{2+}, Mg^{2+}, Na^+, and K^+ (Nilsson & Hakanson, 1992). Although anthropogenic influences such as land-use changes, point- and nonpoint-source pollutions have been generally considered as the main determinants of eutrophication process in the background of increasing human activities, results from this study suggest that lake depth, volume, and geographic location can also play an important role in explaining the eutrophication status of Chinese lakes.

Conclusion

1. Water quality of Chinese lakes has deteriorated rapidly in recent decades. The percentage of eutrophic lakes increased from 41.2% in 1978–1980, when China's economy was just recovering, to 84.5% in 2001–2005.

2. Chl-*a* was significantly related to TP, but not to TN. This supports the view that phosphorus control is critical to mitigating lake eutrophication.

3. Longitude and elevation were found to be significantly related to TP, TN:TP, and TSI. Lake longitude and elevation could reflect both the degree of industrial and agriculture pollution in China.

4. Among lake morphology factors, such as maximum depth, mean depth, and lake volume were negatively related to TSI. This suggests that large, deep lakes have stronger buffer capacity to nutrient inputs.

5. Although these 103 lakes were located from the tropics to the North Frigid Zone, climate variables were found to have weak correlations with eutrophication parameters at the national scale.

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