

Eutrophication in the Yunnan Plateau lakes: the influence of lake morphology, watershed land use, and socioeconomic factors

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Abstract

Introduction Lakes play an important role in socioeconomic development and ecological balance in China, but their water quality has deteriorated considerably in recent decades. In this study, we investigated the spatial–temporal variations of eutrophication parameters (secchi depth, total nitrogen, total phosphorus, chemical oxygen demand, chlorophyll-*a*, trophic level index, and trophic state index) and their relationships with lake morphology, watershed land use, and socioeconomic factors in the Yunnan Plateau lakes.

Discussion Results indicated that about 77.8% of lakes were eutrophic according to trophic state index. The plateau lakes showed spatial variations in water quality and could be classified into high-nutrient and low-nutrient groups. However, because watersheds were dominated by vegetation, all eutrophication parameters except chlorophyll-*a* showed no significant differences between the wet and dry seasons. Lake depth, water residence time, volume, and percentage of built-up land were significantly related to several eutrophication parameters. Agricultural land use

and social–economic factors had no significant correlation with all eutrophication parameters. Stepwise regression analyses demonstrated that lake depth and water residence time accounted for 73.8% to 87.6% of the spatial variation of single water quality variables, respectively. Redundancy analyses indicated that lake morphology, watershed land use, and socioeconomic factors together explained 74.3% of the spatial variation in overall water quality. The results imply that water quality degradation in the plateau lakes may be mainly due to the domestic and industrial wastewaters. This study will improve our understanding of the determinants of lake water quality and help to design efficient strategies for controlling eutrophication in the plateau region.

Keywords Cropland · Land use · Trophic state index · Water depth · Water quality

1 Introduction

Deteriorating water quality is of major concern at a time when freshwater supply is facing rapidly increasing demand in many developing countries, especially in China (Jin 2003; James et al. 2009). Eutrophication, characterized by high nitrogen and phosphorus concentrations in water body and excessive growth of phytoplankton and other aquatic plant, is a common consequence of water quality degradation in lakes, ponds, and other aquatic ecosystems (Wang and Dou 1998; Abell et al. 2011). Although eutrophication is generally recognized as a natural process in the aging of lakes, human activities (e.g., urban runoff, over-application of inorganic fertilizers, and sewage discharges) can greatly accelerate the process by increasing the rate at which nutrients enter

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the aquatic environments from their surrounding watersheds (Kiage and Walker 2009; Ansari et al. 2010).

Lake water quality is affected by a large number of anthropogenic and natural factors at both the lake and watershed scales (Müller et al. 1998; Kopáček et al. 2000; Parker et al. 2008; Nöges 2009; Abell et al. 2011). Relationships between water quality and anthropogenic factors, including land use, landscape structure, water management, gross domestic product, and population density, have been studied frequently (Uuemaa et al. 2005; Galbraith and Burns 2007; Li et al. 2008). Some studies find that land uses, especially agricultural land use in watershed, play a critical role in determining the water nutrient concentrations in many regions (Müller et al. 1998; Morrice et al. 2008). By contrast, correlations of natural factors such as lake morphology, hydrological processes, topography, and climate variables with water quality parameters have been received relatively less attention, although some studies have pointed out that some natural factors can also influence the lake water quality significantly (Nöges 2009; Liu et al. 2010a, b).

China has a large number of lakes and 2,300 of them with an area larger than 1 km² (Wang and Dou 1998). The total area of all the lakes is 70,988 km², accounting for about 0.8% of the total land area of China (Jin 2003). Chinese lakes mainly distribute in five physiographic regions. The Qinghai–Tibet Plateau and Eastern Plains (e.g., the Yangtze floodplain), which contain 1,091 and 696 lakes with an area larger than 1 km², respectively, are the two largest lake regions (Wang and Dou 1998). As a result of rapid economic development in their respective watersheds, Chinese lakes have faced several serious environmental problems including eutrophication, trace element pollution, salinization, and declines in surface area and submerged vegetation in recent decades (Wang and Dou 1998; Li et al. 2007; Chen et al. 2008; Liu et al. 2010a, b). A recent investigation on 67 main Chinese lakes has indicated that nearly 75% of them are eutrophic (Li 2006).

The Yunnan Plateau, located in the southwest of China, is the smallest one among the five lake regions in China. There are only nine lakes with an area greater than 30 km² (Wang and Dou 1998). These large lakes play a very important role in providing freshwater resources for adjacent urban and rural areas and developing aquaculture, but their water quality has deteriorated considerably in recent decades and shows strong spatial variations (Li et al. 2007). The mean depth of these lakes varies between 2.4 and 89.6 m, while maximum depth ranges from 6.2 to 155 m (Wang and Dou 1998). Based on previous findings that lake depth is negatively related to surface water quality at larger scales (Taranu and Gregory-Eaves 2008; Nöges 2009; Liu et al. 2010a, b; Abell et al. 2011), we proposed a hypothesis that lake depth could play a key role in

explaining the spatial variation of water quality in these plateau lakes at a regional scale (hypothesis 1).

Agricultural activities (e.g., fertilizer applications) in watersheds may produce large quantities of nutrients during rainfall events and are thus generally considered as a main factor affecting the lake water quality in the Yunnan Plateau (Li et al. 2007). However, compare with lakes in floodplain (e.g., Taihu Lake and Chaohu Lake) in China, Yunnan Plateau lakes have relatively low percentages of paddy field and high percentage of vegetation cover in their watersheds (Wang and Dou 1998). Studies demonstrated that river water quality in wet season is worse than that in dry season in agriculture-dominated watersheds because of the input of agricultural pollutants (Steege et al. 2001; Pan et al. 2004); we therefore assumed that there were no significant statistical differences between wet and dry seasons in nutrient concentrations in the Yunnan Plateau lakes whose watersheds were dominated by vegetation (hypothesis 2).

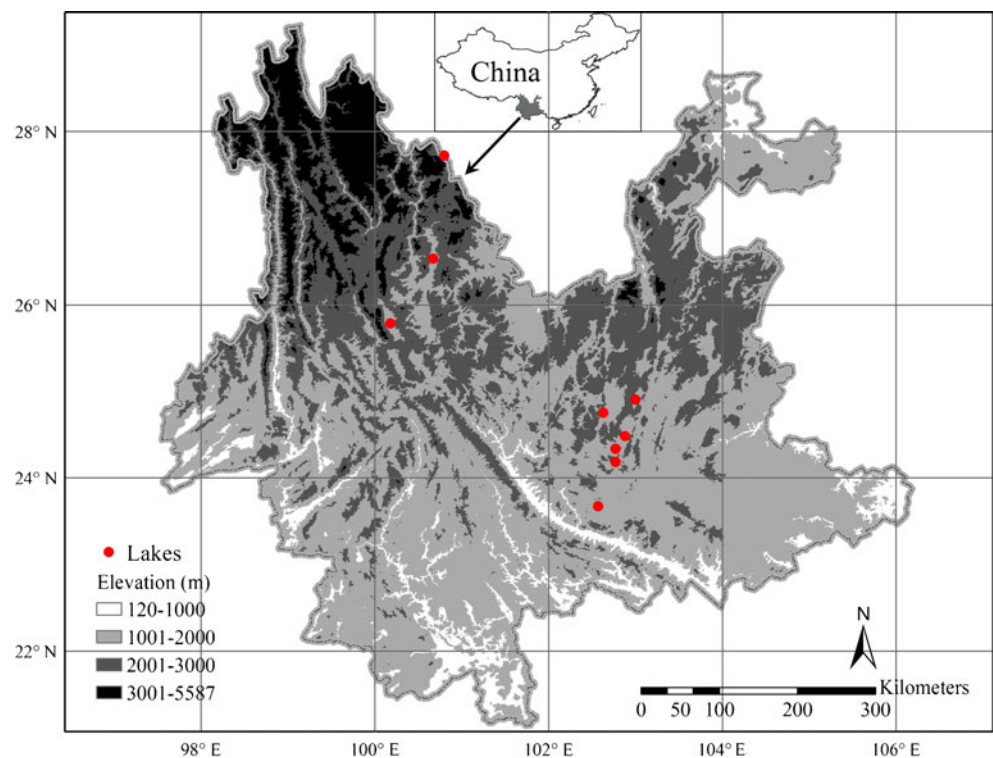
In the present study, we investigated the relationships between water quality variables and lake morphology, land use, and social–economic factors at both the lake and watershed scales for the Yunnan Plateau lakes. The main objectives of this study were (1) to first assess the status of water eutrophication in the Yunnan Plateau lakes, (2) to identify the spatial and temporal pattern of water quality parameters and verify the second hypothesis, and (3) to explore the capacities of lake morphology, land use, and social–economic factors in explaining the spatial variation in lake water quality and test the first hypothesis.

2 Materials and methods

2.1 Study sites

The Yunnan Plateau (i.e., Yunnan Province) is located in southwest China and covers an area of 394,000 km² (Fig. 1). This plateau is the middle tier on the eastern slope of the Himalayas and has intensive neotectonic movement since late Pliocene time. The Yunnan Plateau experiences distinct wet season (from May to October) and dry season (from November to next April). Central Yunnan Plateau receives 800–1,200 mm of precipitation annually, over 85% of which falls between May and October under the influence of a strong southwesterly monsoon that emanates from the Bay of Bengal (Fig. S1 in supporting information). Over 60% of the Yunnan Plateau area is covered by forest and grassland. Croplands comprise 21.8% of the plateau area, and more than 78.2% of croplands are planted with maize, wheat, soybeans, and tobacco with the rest in rice paddies. Built-up lands (e.g., urban areas, rural settlements, and industrial areas) only occupy 1.42% of the plateau area. The percentages of cropland and built-up land in this

Fig. 1 Locations of the nine lakes in the Yunnan plateau, China



plateau are lower than those in the Eastern Plains of China. For example, croplands and built-up lands account, respectively, for 42.6% and 9.0% of the total area of Anhui Province.

There are nine lakes (i.e., Chenghai Lake, Dianchi Lake, Erhai Lake, Fuxianhu Lake, Lugu Lake, Qilu Lake, Xingyunhu Lake, Yangzonghai Lake, and Yilonghu Lake) with an area greater than 30 km² in the Yunnan Plateau (Wang and Dou 1998). These nine lakes are distributed at elevations from 1,412 to 2,691 m above sea level. The Yunnan lakes have been described as “The pearls on the plateau” because of their importance for water resources and economic development (Whitmore et al. 1997). Most of these lakes are tectonic in origin and generally deep. The largest lake is Dianchi Lake with an area of 297.9 km², while the deepest one is Fuxianhu Lake with a mean depth of 89.6 m. The geographic location and morphology characteristics of the nine plateau lakes are listed in Table S1 in supporting information.

2.2 Water quality data

Water quality of the nine plateau lakes was available for 10 months during 2009–2011 (Table 1). We classified months into wet season (from May to October) and dry season (from November to March) according to monthly precipitation of the Yunnan Plateau. Each lake had three to 12 sampling sites based on its surface area. The sampling sites, which were selected by the Environmental Monitoring Center of Yunnan Province, at least included the entrance, exit, and center of a lake. More detailed information about the sampling method was presented in Li et al. (2007).

Water quality parameters, including temperature (*T*), pH, dissolved oxygen (DO), and secchi depth (SD) were measured on site. Total nitrogen (TN), Total phosphorus (TP), chemical oxygen demand (COD_{Mn}), and chlorophyll-*a* (Chl-*a*) were analyzed in laboratory using standard testing procedures as recommended by the

Table 1 Months of water quality data available from 2009 to 2011

	Dry season			Wet season					Dry season			
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2009	■									■		
2010		■	■	■			■		■	■		■
2011	■	■	■									

Ministry of Environmental Protection of China. Trophic level index (TLI), an index recommended by the Ministry of Environmental Protection of China for evaluating eutrophication, was calculated using the following equations (Zhang et al. 2006):

$$TLI(SD) = 10(5.118 - 1.94 \ln SD) \tag{1}$$

$$TLI(TN) = 10(5.453 + 1.694 \ln TN) \tag{2}$$

$$TLI(TP) = 10(9.436 + 1.624 \ln TP) \tag{3}$$

$$TLI(COD_{Mn}) = 10(0.109 + 2.661 \ln COD_{Mn}) \tag{4}$$

$$TLI(Chl-a) = 10(2.5 + 1.086 \ln Chl-a) \tag{5}$$

$$TLI = 0.183TLI(SD) + 0.179TLI(TN) + 0.188TLI(TP) + 0.183TLI(COD_{Mn}) + 0.266TLI(Chl-a) \tag{6}$$

where TN, TP, and COD_{Mn} were expressed in milligrams per liter, Chl-*a* in milligrams per cubic meter, and SD in meters. TLI values <30, 30–50, and >50 indicated oligotrophic, mesotrophic, and eutrophic status of lakes, respectively (Zhang et al. 2006).

The trophic state index (TSI) was universally used and could be calculated using the following equations (Carlson 1977):

$$TSI(SD) = 10 \left(6 - \frac{\ln SD}{\ln 2} \right) \tag{7}$$

$$TSI(Chl-a) = 10 \left(6 - \frac{2.04 - 0.68 \ln Chl-a}{\ln 2} \right) \tag{8}$$

$$TSI(TP) = 10 \left(6 - \frac{\ln \left(\frac{48}{TP} \right)}{\ln 2} \right) \tag{9}$$

where Chl-*a* and TP concentrations were expressed in milligrams per cubic meter and SD in meters. TSI used in the present 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 (Bott et al. 2006).

Among the ten water quality variables, SD, TN, TP, COD_{Mn} , Chl-*a*, TLI, and TSI were regarded as eutrophica-

tion parameters. SD, TN, TP, and COD_{Mn} concentrations of the nine plateau lakes during 1988–1992 were obtained from a monograph of Chinese lakes (Wang and Dou 1998).

2.3 Lake morphology, land use, and socioeconomic data

Lake morphology characteristics including area, volume, mean depth (Z_{mean}), and water residence time (WRT) of the nine plateau lakes were obtained primarily from a monograph of Chinese lakes (Wang and Dou 1998).

After delineating the watershed boundaries of the nine plateau lakes using a DEM with a resolution of 1 km, land use map of each watershed was extracted from a 1-km resolution national land cover data interpreted from 2000’s Landsat TM images in ArcGIS Desktop software by using overlay functions on watershed boundary and land use data layers. The original land use classes were further grouped into four main categories: (1) vegetation, including forest and grassland; (2) cropland, including dry land and paddy field; (3) built-up land, including urban area, rural settlements, and others such as industrial areas, airports, and roads; and (4) water body, including rivers, lakes, reservoirs, and ponds (Liu et al. 2003). Percentages of vegetation, cropland, built-up land, and water body in watershed were abbreviated as PV, PC, PB, and PW, respectively.

Socioeconomic factors, including gross domestic product (GDP), gross domestic product per capita (GDP_{pc}), human population (HP), human population density (HP_d), total grain yield (GY), and total meat yield (MY) in each watershed were derived from the Yunnan Statistical Yearbook 2010 compiled by the Statistical Bureau of Yunnan Province and Survey Office of the National Bureau of Statistics in Yunnan Province (SBYP and NBSYP 2010). Table 2 summarized the statistics of lake morphology, land use, and socioeconomic factors, and Figure S2 in supporting information presented detailed information on the land use composition in each watershed.

2.4 Statistical analyses

We tested the data for normality using the Shapiro–Wilk test before the statistical analyses. *T*, pH, DO, TLI, TSI, PV, PC, and PW were normally distributed and other variables were natural logarithm (ln) transformed to satisfy normality assumptions. Hierarchical cluster analysis was performed to group the nine plateau lakes into clusters by the similarity of water quality characteristics. Principal components analysis (PCA) was undertaken to identify major gradients and principal patterns in the water quality data between wet and dry seasons. Comparison between spatial clusters and seasons in the water quality variables was conducted using independent sample *t* test.

Table 2 Mean, maximum, and minimum of the lake morphology, land use, and socioeconomic factors for nine Yunnan Plateau lakes

	Abbreviation	Unit	Mean±SD	Max	Min
Lake morphology					
Area		km ²	113.87±107.18	297.9	31.68
Volume		10 ⁸ m ³	30.66±60.06	189	1.05
Mean depth	Z _{mean}	m	22.38±28.19	89.6	2.4
Water residence time	WRT	year	8.92±12.33	37.57	0.73
Land use					
Percentages of vegetation	PV	%	57.99±9.83	74.94	45.90
Percentages of cropland	PC	%	25.51±8.14	40.58	15.52
Percentages of built-up land	PB	%	2.96±3.36	11.01	0.32
Percentages of water body	PW	%	13.24±6.27	20.39	2.71
Socioeconomic factors					
Gross domestic product	GDP	10 ⁸ Chinese yuan	155.03±372.41	1,138.82	0.22
Gross domestic product per capita	GDP _{pc}	10 ⁴ Chinese yuan	1.59±1.13	4.14	0.48
Human population	HP	10 ⁴ persons	46.4±88.96	275.3	0.46
Human population density	HP _d	persons/km ²	301.28±271.19	942.81	42.99
Total grain yield	GY	10 ⁴ t	5.30±7.52	22.46	0.13
Total meat yield	MY	10 ⁴ t	2.16±2.75	8.17	0.02

Relationships between the water quality variables and lake morphology, land use, and socioeconomic factors were explored using Pearson correlation test, multiple regression analyses, and redundancy analyses (RDA). Forward stepwise multiple regression analyses were executed to determine which environmental or socioeconomic factors (independent) could best explain the spatial variability of single water quality variables (dependent). In order to avoid multicollinearity among independent variables, all predictors in the final models had a variance inflation factor <10 (Myers 1990). Unlike regression analysis, RDA allowed us to examine the influences of environmental factors on overall water quality, not only on single water quality variables (Johnson et al. 1997; Sliva and Williams 2001). Gradient length of detrended correspondence analysis was used to check whether the RDA was the appropriate ordination form. RDA axes were evaluated statistically with a Monte Carlo permutation test. Statistical analyses were performed using SPSS version 13.0 and CANOCO version 4.5.

3 Results

3.1 Water quality status

According to TLI values, the Dianchi Lake, Qiluhu Lake, Xingyunhu Lake, and Yilonghu Lake were eutrophic. However, based on TSI values, the Chenghai Lake, Erhai Lake, and Yangzonghai Lake could also be regarded as

eutrophic (Fig. 2). The SD for the nine lakes varied from 0.23 to 10.94 m and COD_{Mn} concentration from 1.07 to 25.18 mg/l (Fig. 3). The highest TN and TP concentrations were found, respectively, in Yilonghu Lake (5.53 mg/l) and Xingyunhu Lake (0.36 mg/l).

Water quality of some eutrophic lakes deteriorated rapidly in recent two decades (Fig. 3). For instance, during 1988–1992, TN, TP, and COD_{Mn} in Dianchi Lake, the largest (297.9 km²) freshwater lake in the Yunnan Plateau, were 1.44, 0.11, and 7.91 mg/l and then rose to 2.61, 0.18, and 10.21 mg/l in 2009–2011, respectively. Interestingly, nutrient and organic matter concentrations in two oligotrophic lakes (i.e., Fuxianhu Lake and Luguhu Lake) did not

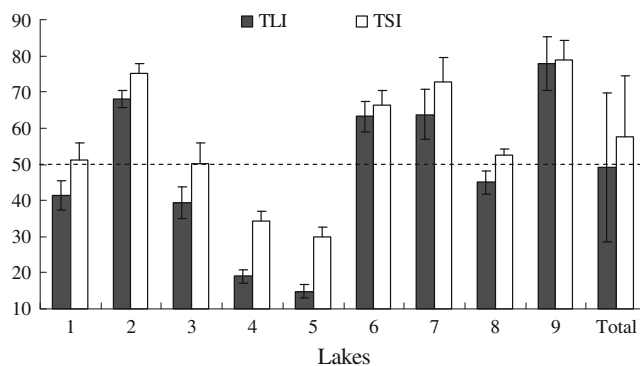
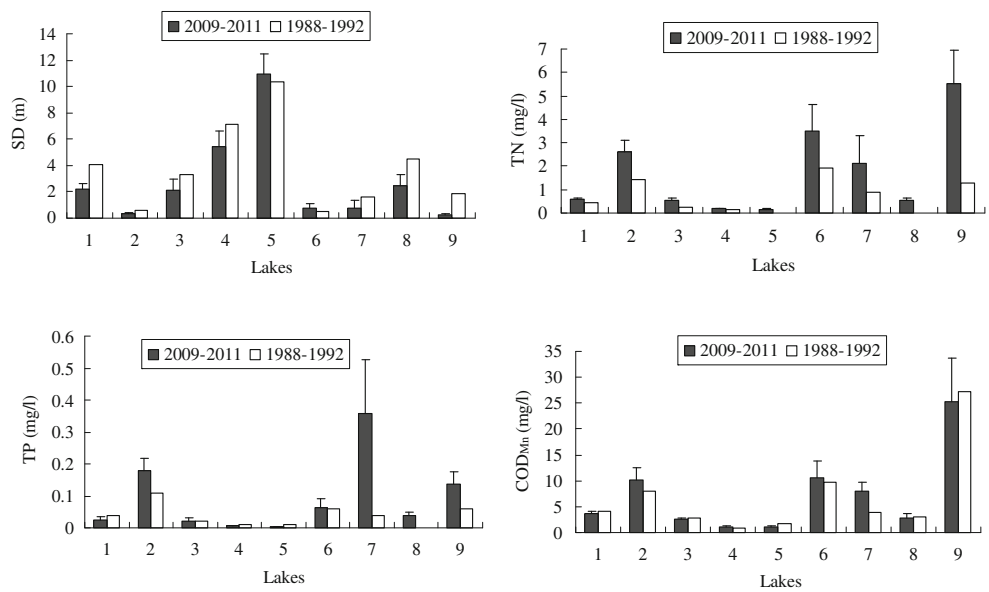


Fig. 2 Trophic state index (TSI) and trophic level index (TLI) of the nine lakes in the Yunnan plateau, China. The error bars represent standard deviations. The name of each lake corresponding to each number is shown in Table 3

Fig. 3 Comparison of selected eutrophication variables between 2009–2011 and 1988–1992. The error bars represent standard deviations. The name of each lake corresponding to each number is shown in Table 3



rise after 20 years of economic development in their respective watersheds (Fig. 3).

3.2 Spatial and temporal variations in water quality

Based on the eutrophication variables, hierarchical cluster analysis classified the nine lakes into two distinct clusters (Fig. 4). Cluster 1 (Chenghai Lake, Erhai Lake, Yangzonghai Lake, Fuxianhu Lake, and Lugu Lake) and cluster 2 (Dianchi Lake, Xingyunhu Lake, Qiluhu Lake, and Yilonghu Lake) corresponded to low- and high-nutrient lakes, respectively. All eutrophication variables except SD in cluster 2 were significantly higher than those in cluster 1 (Table 3).

The mean nutrient and organic matter concentrations for nine plateau lakes rose remarkably in July or September 2010 and then decreased in the next months (Fig. 5). However, only *T*, pH, and Chl-*a* had significant

differences between wet and dry seasons, although the values of eutrophication parameters (except SD) were relatively high in wet season (Table 3). For single lake, only Chenghai Lake and Erhai Lake had significant differences between wet and dry seasons in TN or TP concentrations (Table 3).

Three significant factors (i.e., eigenvalue >1) were extracted by PCA based on wet-season water quality data, which explained 80.21% of the total variances (Table 4). The first factor accounted for 35.043% of the total variance and had strong positive loadings to TN, COD_{Mn}, Chl-*a*, TLI, and TSI. PCA analysis of dry-season water quality data showed that the eigenvalues for two significant factors were 5.496 and 1.497, respectively, accounting for 69.93% of the total variances. Factor 1 accounted for 54.96% of the total variance and was positively correlated with TN, TP, COD_{Mn}, Chl-*a*, TLI, and TSI and negatively related to SD (Table 4).

3.3 Water quality related to environmental, social, and economic factors

Correlation analyses indicated that lake depth, WRT, and volume had significant relationships with all eutrophication parameters (Table 5). PB was positively related to TN ($r=0.71, p<0.05$) and TP ($r=0.67, p<0.05$), while PW was negatively correlated with COD_{Mn} ($r=-0.70, p<0.05$), Chl-*a* ($r=-0.71, p<0.05$), and TLI ($r=-0.69, p<0.05$). Water quality parameters had no significant relationships with any socioeconomic factors (Table 5).

Stepwise multiple regression analyses demonstrated that lake morphology accounted for 73.8% to 87.6% of the variance in eutrophication parameters (Table 6). Lake depth was the main predictor of SD, TLI, TSI, TN, Chl-*a*, and

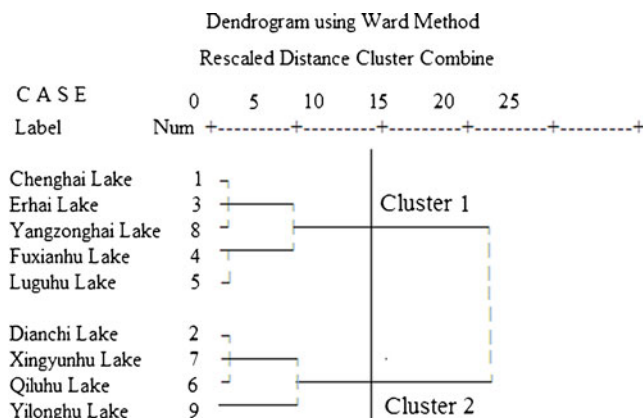


Fig. 4 Dendrogram from cluster analysis based on seven eutrophication variables for Yunnan Plateau lakes

Table 3 Water quality differences between dry and wet seasons and between cluster 1 and cluster 2

		<i>T</i> (°C)	pH	DO (mg/L)	SD (m)	TN (mg/L)	TP (mg/L)	COD _{Mn} (mg/L)	Chl- <i>a</i> (mg/m ³)	TLI	TSI
Chenghai Lake	Dry season	15.25 ±3.40	9.31±0.09	7.52±0.79	2.20±0.50	0.58±0.10	0.03 ±0.01	3.72±0.31	18.83±11.57	42.98±2.15	53.22±1.90
	Wet season	22.67 ±2.08	9.39±0.07	7.25±1.16	2.23±0.24	0.58±0.05	0.02 ±0.01	3.75±0.26	11.75±8.58	39.03±5.21	47.91±6.21
Dianchi Lake	Dry season	13.00 ±1.20	8.82 ±0.47	6.93±0.72	0.36±0.03	2.80±0.54	0.17±0.03	9.65±2.52	55.83 ±32.27	67.05±2.16	73.88±2.58
	Wet season	21.05 ±1.80	9.60 ±0.26	7.00±1.38	0.36±0.07	2.32±0.29	0.19±0.06	11.05±1.71	99.75 ±18.63	69.75±2.11	76.67±2.53
Erhai Lake	Dry season	11.87 ±1.60	8.59±0.08	6.40 ±0.53	2.58 ±0.85	0.52 ±0.06	0.01 ±0.00	2.50±0.14	7.33 ±2.94	36.68 ±3.34	46.35 ±3.30
	Wet season	21.08 ±1.47	8.68±0.06	5.43 ±0.26	1.41 ±0.14	0.61 ±0.01	0.03 ±0.00	2.65±0.13	19.25 ±5.50	43.58 ±1.57	55.98 ±1.75
Fuxianhu Lake	Dry season	14.72 ±1.14	8.56 ±0.08	7.52±0.56	5.92±1.17	0.17±0.02	0.01±0.00	1.00 ±0.00	3.00±1.79	18.92±2.16	34.49±3.05
	Wet season	21.60 ±0.86	8.73 ±0.12	7.53±0.79	4.87±1.24	0.18±0.01	0.01±0.00	1.15 ±0.06	2.00±0.82	19.05±1.58	33.86±2.41
Luguhu Lake	Dry season	7.5 ±0.71	8.41±0.12	7.78±0.49	10.58±2.00	0.14±0.07	0.01±0.00	0.88 ±0.15	2.00±2.16	13.85±1.72	29.91±3.12
	Wet season	16.5 ±2.12	8.61±0.18	7.07±0.12	11.43±0.81	0.13±0.06	0.01±0.00	1.33 ±0.12	2.33±1.15	16.13±1.17	30.00±2.27
Qiluhu Lake	Dry season	12.50 ±2.12	9.25±0.38	7.97±1.20	0.71±0.32	3.22±0.68	0.07±0.03	9.05±1.22	48.00±24.58	61.60±4.42	65.46±4.76
	Wet season	21.80 ±1.81	9.45±0.33	8.15±0.48	0.49±0.12	3.82±1.56	0.06±0.04	13.2±4.97	63.50±10.02	65.68±2.62	67.88±2.80
Xingyunhu Lake	Dry season	13.13 ±1.66	9.27±0.38	7.60±0.76	1.14 ±0.56	1.52±0.32	0.32±0.17	6.98±0.49	23.17 ±5.71	59.50 ±3.04	68.75 ±4.23
	Wet season	21.85 ±2.21	9.31±0.35	7.85±1.25	0.45 ±0.20	3.01±1.65	0.48±0.14	8.95±2.08	70.75 ±49.28	70.00 ±6.29	78.74 ±4.94
Yangzonghai Lake	Dry season	14.27 ±1.01	8.24±0.45	7.98±0.71	2.87±0.83	0.56±0.14	0.04±0.01	2.75±0.68	11.33±3.50	43.85±3.71	52.29±2.05
	Wet season	23.10 ±1.01	8.74±0.24	6.88±0.85	1.92±0.41	0.46±0.08	0.03±0.01	3.13±0.77	11.25±2.22	46.80±1.34	53.03±1.28
Yilonghu Lake	Dry season	15.12 ±4.29	8.70 ±0.21	6.80±1.20	0.27±0.09	5.00±1.64	0.13±0.04	22.37±9.78	89.17 ±45.21	75.20±8.53	76.72±5.97
	Wet season	23.38 ±1.03	9.10 ±0.10	7.53±2.17	0.17±0.05	6.32±0.66	0.15±0.02	29.40±4.71	244.75 ±26.47	82.20±2.23	82.28±2.05
All lakes	Dry season	13.41 ±2.66	8.81 ±0.47	7.37±0.92	2.67±2.96	1.67±1.73	0.09±0.12	6.76±7.23	29.79 ±34.30	47.89±19.80	56.66±15.81
	Wet season	21.71 ±2.10	9.08 ±0.41	7.19±1.25	2.34±3.20	1.99±2.16	0.11±0.15	8.49±8.98	59.97 ±77.33	51.22±22.01	59.30±18.23
Cluster 1	Cluster 1	16.71±4.76	8.72 ±0.40	7.17±0.95	4.27 ±3.27	0.41 ±0.21	0.02 ±0.01	2.34 ±1.11	9.28 ±8.02	33.03 ±12.61	44.49 ±9.96
	Cluster 2	16.87±4.84	9.15 ±0.42	7.45±1.18	0.52 ±0.39	3.43 ±1.71	0.19 ±0.15	13.47 ±8.37	80.30 ±66.11	68.27 ±8.08	73.28 ±6.63

Bold denotes significance at the 0.05 level

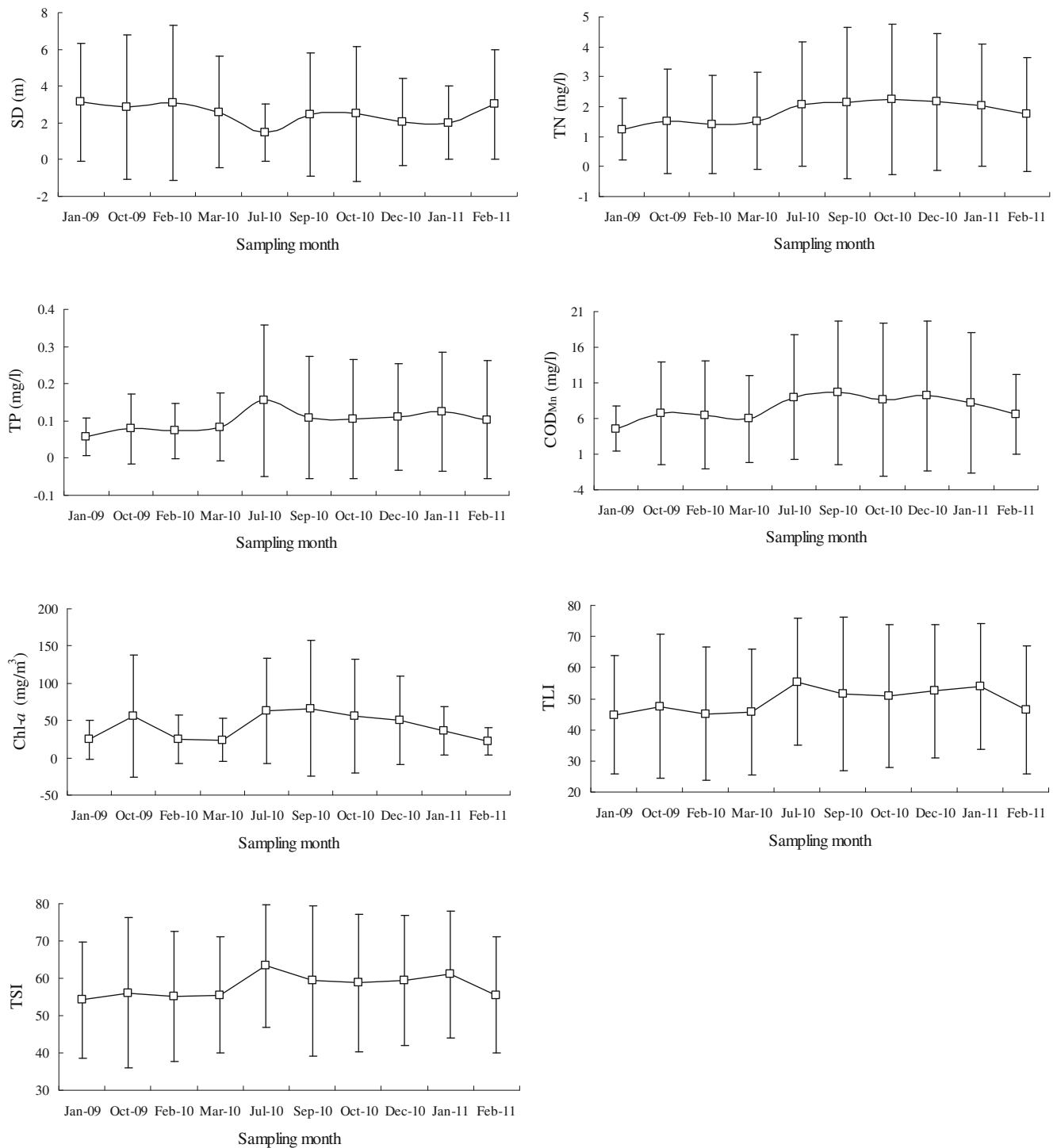


Fig. 5 Temporal variation of seven eutrophication variables in the nine Yunnan Plateau lakes, China. The *error bars* represent standard deviations

COD_{Mn} concentrations, while WRT was a good predictor of TP concentration (Table 6).

RDA of overall water quality as dependent variables showed that volume, Z_{mean} , WRT, PB, and PW could alone explain 18.6–63.1% of the spatial variation and lake morphology, land use, and social–economic factors together explained 74.3% of the variation in overall water quality

(Table 7). Ordination diagram of overall water quality and lake morphology, land use, and social–economic factors indicated that the first RDA axis mainly represented a self-purifying capacity gradient of lakes (Fig. 6) and accounted for 70.9% of the variance in water quality (Table 8). The second RDA axis was related to HP_d and only explained 2.2% of the variance (Table 8).

Table 4 Rotated component matrix of PCA on date sets during wet-season and dry-season, respectively

Variables	Wet season			Dry season	
	PC1	PC2	PC3	PC1	PC2
T	0.224	0.238	0.577	0.298	-0.507
pH	0.118	0.675	0.386	0.375	0.625
DO	0.072	0.058	0.938	-0.098	0.691
SD	-0.340	-0.770	-0.088	-0.844	-0.106
TN	0.842	0.350	0.260	0.920	-0.133
TP	0.122	0.761	0.110	0.550	0.515
COD _{Mn}	0.952	0.183	0.110	0.894	-0.192
Chl- <i>a</i>	0.942	0.238	0.151	0.868	-0.083
TLI	0.659	0.717	0.123	0.967	0.086
TSI	0.607	0.772	0.078	0.953	0.161
Eigenvalues	3.504	3.011	1.506	5.496	1.497
Percentage of variance	35.043	30.113	15.058	54.958	14.971
Cumulative percentage of variance	35.043	65.157	80.214	54.958	69.930

4 Discussion

Extensive runoffs from agricultural activities might have resulted in significantly lower water quality in wet season than dry season in vegetation dominated watersheds (Chen et al. 2002; Ngoye and Machiwa 2004). However, the present study does not concur this finding, and Hong et al. (2008) have also demonstrated that TN and TP concentrations in wet season are not significantly different from those in dry season in the Xingfengjiang Reservoir watershed where forests are dominant land use. The contrasting results could be partly due to the difference among watersheds in terms of agricultural practices including intensity and types which also influence the outputs of nutrients and other pollutants. Mean percentage of cropland in the watersheds of the studied lakes was only

25.51%, and approximately 80% of croplands were planted with maize, wheat, soybeans, and tobacco and the rest are paddy fields. Furthermore, utilization efficiencies of nitrogen fertilizers and phosphorus fertilizers by the crop in dry lands were relatively higher than those in paddy fields, generally 30–50% for nitrogen and 5–15% for phosphorus in China (Dong et al. 2009). Wang et al. (2009) have found that TN and TP concentrations in agricultural streams in wet season are generally higher than those in dry season in the Dianchi Lake watershed. However, they have also found that TN, TP, and NH₄⁺ concentrations in urban and forest streams in wet season are substantially lower than those in dry season due to dilution effects (Wang et al. 2009).

Many studies have indicated that some water quality parameters (e.g., TN and TP) are mainly determined by

Table 5 Pearson correlation matrix between water quality parameters and lake morphology, land use, and socioeconomic factors

	Area	Z _{mean}	Volume	WRT	PV	PC	PB	PW	GDP	GDP _{pc}	HP	HP _d	GY	MY
T	-0.06	-0.19	-0.17	-0.10	0.07	0.20	0.11	-0.23	0.22	0.27	0.23	0.22	0.32	0.37
pH	-0.10	-0.51	-0.43	-0.52	-0.35	0.29	0.30	0.01	0.12	0.04	0.17	0.28	0.07	0.13
DO	-0.64	0.12	-0.28	0.15	-0.57	0.49	-0.12	0.33	-0.41	-0.31	-0.42	-0.10	-0.60	-0.45
SD	0.09	0.92 ^a	0.72 ^b	0.83 ^a	-0.06	-0.28	-0.66	0.69 ^b	-0.41	-0.35	-0.43	-0.50	-0.34	-0.48
TN	-0.08	-0.93 ^a	-0.73 ^b	-0.87 ^a	-0.05	0.30	0.71 ^b	-0.62	0.43	0.36	0.45	0.55	0.30	0.44
TP	-0.16	-0.87 ^a	-0.72 ^b	-0.88 ^a	-0.12	0.30	0.67 ^b	-0.47	0.42	0.37	0.43	0.58	0.28	0.40
COD _{Mn}	-0.29	-0.93 ^a	-0.84 ^a	-0.82 ^a	0.13	0.25	0.52	-0.70 ^b	0.21	0.15	0.22	0.33	0.13	0.29
Chl- <i>a</i>	-0.21	-0.94 ^a	-0.80 ^a	-0.83 ^a	0.16	0.21	0.55	-0.71 ^b	0.27	0.21	0.29	0.37	0.21	0.35
TLI	-0.24	-0.94 ^a	-0.82 ^a	-0.87 ^a	0.05	0.31	0.62	-0.69 ^b	0.34	0.29	0.34	0.47	0.24	0.40
TSI	-0.19	-0.94 ^a	-0.79 ^a	-0.88 ^a	0.02	0.30	0.65	-0.64	0.37	0.32	0.39	0.50	0.28	0.42

Abbreviations are given in Table 2

^a Significant at the 0.01 level

^b Significant at the 0.05 level

Table 6 Determinants of water quality parameters analyzed by stepwise multiple regression analyses

Water quality parameters	Regression equations	R ²	Adjusted R ²	p value
SD	-2.070+0.985Z _{mean}	0.850	0.829	<0.001
TN	1.266-0.504Z _{mean}	0.870	0.852	<0.001
TP	-0.820-0.415WRT	0.771	0.738	0.002
COD _{Mn}	1.565-0.370Z _{mean}	0.872	0.854	<0.001
Chl- <i>a</i>	-0.891-1.215Z _{mean}	0.884	0.868	<0.001
TLI	91.655-17.508Z _{mean}	0.891	0.876	<0.001
TSI	91.635-13.997Z _{mean}	0.881	0.864	<0.001

Abbreviations are given in Table 2. The water quality parameters without regression models are not listed

agricultural land use in watershed in many parts of the world (Müller et al. 1998; Taranu and Gregory-Eaves 2008; Morrice et al. 2008). Agricultural runoff has been recognized as important drivers of water quality degradation in this plateau (Li et al. 2007). Non-point-source pollution, mainly from agricultural sources, contributes approximately 21% and 32% of the annual total nitrogen and phosphorus loads in the Dianchi Lake, respectively (KEPB 2006). To control the eutrophication of the Yunnan Plateau lakes, the government has proposed several strategies, including external nutrient loading control, internal source pollution control, and ecosystem restoration. However, this study found that agricultural development variables (e.g., agricultural land use and grain yield) in watersheds played a small role in explaining the spatial variation of the lake water quality in the Yunnan Plateau. Watersheds of these plateau

lakes have low percentage of cropland (Table 2), especially paddy fields. Vegetated buffers adjacent to croplands can greatly mitigate nutrients and other contaminants from agricultural runoff through the processes of deposition, absorption, and denitrification. Moreover, small and scattered agricultural patches in watershed may have a lesser impact on lake water quality than large and clustered ones (Liu et al., online). These reasons can explain why lake water quality has no significant correlation with percentage of cropland in watershed in this plateau. We thus suggest that more attention should be paid to the industrial wastewater and domestic sewage control in industrial areas, urban areas, and rural settlements.

Built-up lands including urban, industrial areas, and large rural settlements are the leading source of point-source pollution. Our study found that percentage of built-up land in watersheds was positively related to TN and TP contents of lakes. These results suggest that

Table 7 RDA results showing the percentage variance of overall water quality explained by single and all explanatory variables

Explanatory variables	% variance explained	p value
Lake morphology		
Area	6.6	0.61
Volume	50.6	0.002
Z _{mean}	63.1	0.002
WRT	50.3	0.002
Land use		
PV	3	0.516
PC	1.5	0.708
PB	18.6	0.002
PW	30	0.002
Social-economic factors		
GDP	3	0.386
GDP _{pc}	1.7	0.474
HP	3.2	0.418
HP _d	7.7	0.034
GY	1.1	0.878
MY	4.1	0.272
Lake morphology+land use+social-economic factors	74.3	0.002

Abbreviations are given in Table 2

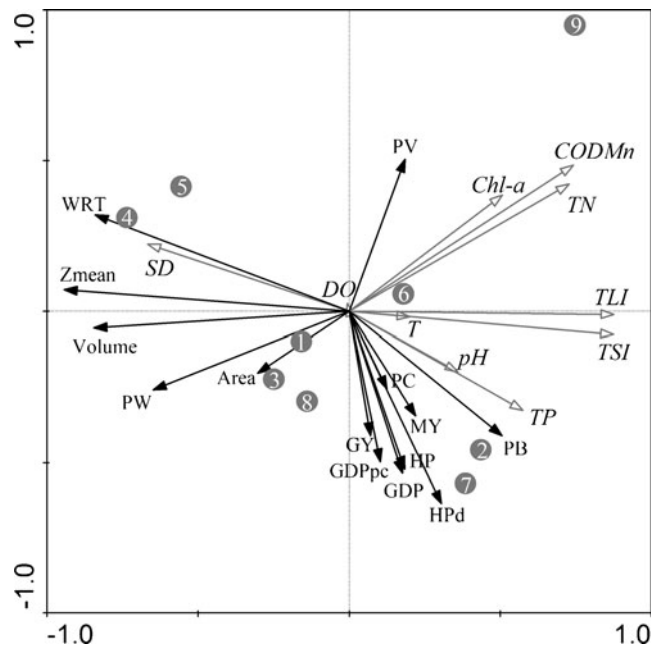


Fig. 6 Biplots of RDA analysis between water quality variables and lake morphology, land use, and social-economic factors (1–9 represent the studied lakes). The name of each lake corresponding to each number is shown in Table 3

Table 8 Eigenvalues and percentage variance of overall water quality explained by the first two RDA axes and all RDA axes

	Axis 1	Axis 2	All axes
Eigenvalues	0.709	0.022	0.743
Percentage variance of water quality explained	70.9	2.2	74.3
Dominant environmental factors	Z_{mean} (-0.8291) Volume (-0.7423) WRT (-0.7393) PW (-0.5698) PB (0.4445)	HP_d (-0.5311)	

Abbreviations are given in Table 2. Number in parentheses indicates the canonical coefficients of environmental factors with the first two RDA axes

point-source pollution control is important for improving lake water quality in the Yunnan Plateau. Some lakes in the plateau are located near urban areas. For example, Dianchi Lake is one of the most eutrophic lakes in China, and about 240 million m³ of wastewater was discharged into the lake from its watershed. Kunming City, which is the largest city in the Yunnan plateau and located in the Dianchi Lake watershed, had contributed 75% of the total wastewater discharges (KEPB 2001). Over half of the municipal domestic wastewaters and almost all domestic wastewaters in rural settlements of the Yunnan plateau are not treated before they are released into the environment. Besides producing pollution, impervious surface associated with urbanization decreases the volume of water that percolates into the ground and results in increase of volume and decrease of surface water quality (Rose and Peters 2001).

This study found that lake depth and WRT played key roles in explaining the spatial pattern of water quality in the Yunnan Plateau lakes. Mean depth of these plateau lakes showed a large variation from a minimum of 2.4 m in the Yilonghu Lake to a maximum of 89.6 m in the Fuxianhu Lake. Deeper lakes are generally associated with better water quality than shallow lakes in the plateau, most probably because deeper lakes are more likely to undergo thermal stratification with numerous nutrients and other pollutants settling out of the epilimnion (Omernik et al. 1991; Ekholm et al. 1997). Nutrient exchange between sediment and overlying water in deep lakes mainly depends on diffusion-related processes. By contrast, overlying water in shallow lakes can mix daily and sediment resuspension may occur easily during wind events which increase the interaction between the sediment and the overlying water (Newman and Reddy 1992; Taranu and Gregory-Eaves 2008). Moreover, deep lakes have a higher ratio of water volume to sediment surface and thus have a higher nutrient dilution potential than shallow lakes.

Although few socioeconomic factors such as GDP and population density have been proved to have significant effects on water environment (Ahearn et al. 2005; Morrice et al. 2008), our study has not found any association between

water quality parameters and socioeconomic factors in the Yunnan Plateau lakes. Morrice et al. (2008) have found that human population is the second strongest predictor of TP and chloride contents in water bodies and also a significant factor affecting several other water chemistry variables such as TN and Chl-*a*. There is no doubt that social and economic development in watersheds would increase the production of point and non-point-source pollution. However, considering the important roles of wastewater treatment efficiency and buffer capacity of deep lakes, it is not necessary that higher production of pollutants in watersheds will definitely lead to poor water quality in lakes. For instance, although watershed of the Fuxianhu Lake has the third largest GDP (36.53×10^8 Chinese yuan) among the nine lake watersheds, the Fuxianhu Lake remains oligotrophic due to its water depth (89.6 m) and high treatment efficiency of industrial and domestic wastewaters (YEPB 2006). The common developing way “pollution first, treatment later” in China is not the only mode of economic development in these plateau watersheds.

5 Conclusion

This study indicated that seven of the nine Yunnan Plateau lakes were eutrophic according to trophic state index. Most of the water quality parameters showed strong spatial variability, but no significant differences between the wet and dry seasons. Although agricultural development in watersheds would lead to the increased production of nutrients and other contaminants, this study found that the degradation of water quality in the Yunnan Plateau lakes could not be mainly attributed to the agricultural activities in watersheds. Correlation analysis revealed that pollution control in the urban, industrial areas, and rural settlements was important for these plateau lakes, although all eutrophication parameters were well explained by the lake morphology characteristics in the multiple regression and redundancy analyses. This study would improve our understanding of the determinants of lake water quality and help design efficient strategies for controlling lake eutrophication in the plateau region.

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