

Water and Sediment Quality in Lakes along the Middle and Lower Reaches of the Yangtze River, China

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Abstract Water and sediment samples were collected from 45 lakes along the middle-lower Yangtze River, China. Each lake was sampled seasonally, over a period of one year. Water quality variables and metals in sediments were measured. Lakes along the lowest part of the river, within the Yangtze River Delta, had highest nutrient concentrations and were eutrophic or hypereutrophic. Lakes displayed a gradient in many water chemistry variables, from the middle to the lower Yangtze River. Lakes of the Delta region had the highest conductivity, sulfate, turbidity, and Chl-a values, and the lowest dissolved oxygen concentrations. A number of lakes near urban areas in the study region also displayed similar conditions. Lakes polluted by heavy metals were found in the upper part of the lower Yangtze River and had high Cu, Cr, and Co concentrations in sediments. The mean I_{geo} (index of geoaccumulation) values for Cu, Cr, and Co classes ranged from 0 to 4, indicating moderate to heavy contamination, contributed mainly from untreated industrial waste water produced within the lake catchments. Lakes of the middle Yangtze River are generally in relatively better condition, except for those around urban zones, which experience higher nutrient and heavy metal loading. The spatial distribution of lake conditions in the area can be related to the policy of regional economic development. The Delta region in China is developed and includes such cities as Shanghai and Suzhou. Heavy industries have moved into the interior region of China too, and development of modern cities is now occurring under some level of environmental protection. Nevertheless, lakes in the central part are becoming seriously polluted with both heavy metals and nutrients because local authorities promote industrialization and urbanization to improve economic conditions, while often ignoring

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environmental protection. Pollution is increasingly occurring in upstream reaches, a tendency that will bring more environmental problems. Interior lakes of China require immediate attention to prevent further declines in water quality.

Keywords Water quality, Heavy metal pollution, Lake status, Yangtze River · China

1 Introduction

Water is vital to all organisms and its availability and quality are important issues, especially in light of global warming and human population growth (Hanjra and Qureshi 2010; Franchini et al. 2011). Water scarcity is already a critical concern in parts of the world (Schindler 1974; Fedoroff et al. 2010) and there are growing public concerns (Postel et al. 1996; Franczyk and Chang 2009; Khan and Hanjra 2009; Khan et al. 2009a,b). Anthropogenic water eutrophication and pollution, in association with industrialization and agricultural activities such as mining, metallurgy, fuel combustion, waste disposal, fertilizer application, have exacerbated water resource scarcity. Nutrient enrichment seriously degrades aquatic ecosystems, impairing the use of water for drinking, industry, agriculture, recreation and other purposes (Carpenter et al. 1998). Heavy metal residues may accumulate in aquatic ecosystem, which, in turn, may enter the human food chain and cause health problems (Deniseger et al. 1990; Sin et al. 2001). Sediments may act as sinks for contaminants, but are also potential sources of contaminants in aquatic systems (Smol 2002; Battarbee et al. 2005). Therefore, analysis of river and lake sediments is a useful method to study metal and nutrient pollution in an area. Many studies have been carried out worldwide to assess nutrient and heavy metal contamination in surface water and/or sediments, with the objective of improving local water quality (e.g. Galan et al. 2003; Loska et al. 2004; Rose et al. 2004; Alexakis 2010) and thereby mitigating the issue of limited water resources. China is facing increasingly severe water scarcity. Overexploitation of water resources has led to serious environmental consequences, such as ground subsidence, salinity intrusion, and ecosystem deterioration (Liu and Yu 2001; Qin 2002; Han 2003; Foster et al. 2004; Liu and Xia 2004; Fan et al. 2006; Cai and Ringler 2007; Xia et al. 2007; Jiang 2009). Poor water quality caused by pollution is now observed in both areas where water is scarce and in areas where water is abundant (Zhu et al. 2001; Liu and Diamond 2005). Water shortages and poor water quality interact to threaten China's food security, economic development, and quality of life. Environmental scientists, citizens and governments must face this serious problem (Kuang et al. 2004; Khan and Ansari 2005; James et al. 2008; Shao 2010).

The Yangtze River, the longest river in China, is located in Southeast Asia and discharges into the western Pacific Ocean. The river plays an important role in regional economic and social development and is used for shipping and irrigation, as well as for domestic and industrial water supply. Historical processes along the river have given rise to numerous lakes that store great volumes of fresh water. These waterbodies play a vital role in the lives of local inhabitants and have stimulated regional economic development (Wang and Dou 1999). Many of these lakes, however, experience cyanobacterial blooms in the warm season because of high nutrient levels (Chen et al. 2002; Qin 2002; Cheng and Li 2006). Most of the lakes in the middle and lower reaches of the Yangtze River region are mesotrophic or eutrophic as a consequence of excessive agricultural fertilizer use and discharge of municipal sewage, associated with large-scale cultivation and high-density populations in their watersheds, respectively. These waterbodies constitute the main eutrophic lake region in China, and their condition now affects the economic development of this region. Lake eutrophication and pollution in this region have become serious concerns (Qin 2002).

We present results of water and sediment analyses from a limnologically diverse group of lakes along the middle-lower Yangtze River. Many of these waterbodies were previously unstudied. We characterize the physical and chemical limnology of these lakes and address the effects of river regulation and human influences on water quality. In addition to examining the current status of lake water quality in this region, this study provides information that future studies can use to evaluate further changes in water quality. Our analysis can be used to develop a scientific basis for environmental protection in the region and a policy for rational water utilization.

2 Materials and Methods

2.1 Study Area

The Yangtze River is 6300 km long and has a catchment area of 1.8 million km², which is equivalent to ~20 % of the total land area of China. The river can be divided by topographic and hydrologic characteristics. The upper stream runs from the source to Yichang in Hubei Province, a distance of 4510 km. The famous “Three Gorges” stretch is located in this section of the river and is 209 km long. From Yichang to Hukou, in Jiangxi Province, the river enters the middle reaches, which are 940 km long. From Hukou to the lower reaches is a distance of 850 km (Fig. 1).

The middle and lower reaches of the Yangtze River cross the central and eastern parts of China and lie in the most important economic area of the country. They are located in the subtropical monsoon zone. The seasonal climate is warm and wet in summer, and cold and dry in winter. The basin has a mean annual temperature of between 15 °C and 20 °C and receives more than 1,000 mm of precipitation annually, 40–60 % of which falls between June and August under the influence of a strong monsoon that originates in the Pacific Ocean. Evaporation approximates or slightly exceeds rainfall in the basin during an average year (Wang and Dou 1999; Chen et al. 2001; Shi et al. 2007; Xu et al. 2010).

The middle and lower Yangtze River crosses the Dongting and Poyang lacustrine plains, and receives inflows from the Dongting and Poyang lake systems and the large Han River tributary, forming a flatland river reach with a wide channel and slow flow. Downstream, the channel is wider and lacks large tributary inflows. On the Anhui-Jiangsu plain the river is a flatland-tidal reach as a consequence of tidal backwater flow. Topographic and climate characteristics, combined with evolutionary processes in the Yangtze, have contributed to formation of three lake groups along the middle and lower reaches of the river, the Tongting-Jiangnan lake group, the Poyang-Huayang lake group and Taihu-Yangtze Delta lake group. There are more than 600 lakes >1 km² in this region, including many large lakes such as Dongting, Poyang, Caohu and Taihu, which cover a combined area of 18,400 km² and represent 25 % of lake surface area in China (Wang and Dou 1999). The 45 shallow lakes in this study belong, for the most part, to the three lake groups and are scattered across six provinces (Hubei, Hunan, Jiangxi, Anhui, Jiangsu and Shanghai) along the middle and lower reaches of the Yangtze River (Fig. 1) (Table 1). Most of these lakes are eutrophic or hypereutrophic.

2.2 Sampling, Sample Preparation and Analysis

Two or three sites were sampled in each lake to account for spatial heterogeneity and the large area of the lakes. Sampling positions were recorded using a GPS system. Every lake

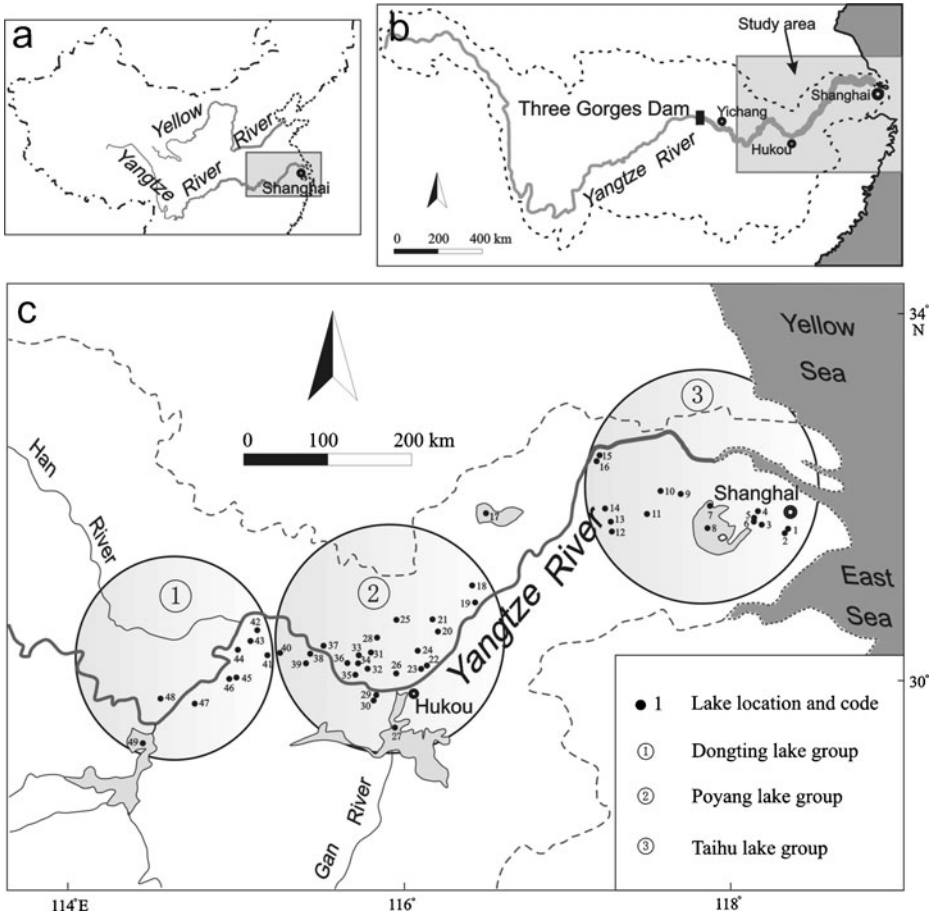


Fig. 1 Location of the study region in southeast China (a and b) and sampled lakes along the middle and lower Yangtze River (c)

was sampled over one year during each of the four seasons. Sampling of all lakes required two years (2003 and 2004) to complete because of the wide geographic distribution of the sampled water bodies (Yang et al. 2005).

Water samples for analysis of total nitrogen (TN), total phosphorus (TP), NO_3^- , NO_2^- and chlorophyll *a* (Chl-*a*) were collected using Tygon tubing fitted with a one-way valve. A sediment sample was taken from the topmost (0–1 cm) mud in the lake bottom at each site. Samples were refrigerated under dark conditions until laboratory analysis. Lake water was filtered through a 0.45- μ -membrane filter for analysis of NO_3^- , NH_4^+ and NO_2^- . TN was determined by the alkaline potassium persulphate digestion-UV spectrophotometric method. TP was determined by the ammonium molybdate method after potassium persulphate digestion. Ammonium (NH_4^+ -N) was measured by the Nessler method, nitrite by the *o*-naphthylamine method and nitrate by the UV spectrophotometry method (Eaton et al. 1995). Chl-*a* was measured spectrophotometrically (Zhang et al. 1991). Mean water temperature was measured *in situ* using a thermometer and Secchi depth (SD) was recorded at one central site.

All samples for $\delta^{18}\text{O}$ were stored in 25-ml glass bottles free of headspace and refrigerated at 4°C before analysis. The $\delta^{18}\text{O}$ analysis involved the CO_2 - H_2O equilibration technique

Table 1 Lake location (lake name, latitude, longitude), surface area, mean depth and lake elevation

Lake code	Lake name	Location		Area (km ²)	Mean depth (m)	Lake elevation (m.a.s.l.)
		N	E			
1	Dingshan Lake	31.0506	120.5435	64	2.5	2.5
2	Yuandang Lake	31.043	120.5351	13	1.4	2.6
3	Cheng Lake	31.1308	120.5045	45	1.8	2.7
4	Yangcheng Lake	31.2322	120.4609	119	1.4	2.8
5	Jinji Lake	31.1828	120.4124	7	1.3	2.8
6	Dushu Lake	31.165	120.4124	10	1.7	2.7
7	Meiliang Lake	31.2829	120.1131	129	2	3.1
8	Tai Lake	31.2033	120.1045	2425	2.1	3.1
9	Ge Lake	31.3222	119.4636	147	1.2	3.2
10	Changdang Lake	31.3636	119.3234	88	1.1	3.4
11	Tianmu Lake	31.183	119.2613	12	9.0	20
12	Nanyi Lake	31.0936	118.5909	148	2.3	9.4
13	Gucheng Lake	31.1654	118.5511	25	1.6	8.0
14	Shijiu Lake	31.2624	118.5404	210	4.1	9.3
15	Xuanwu Lake	32.0438	118.4709	4	1.5	10
16	Mochou Lake	32.0212	118.4522	0.3	1.0	10
17	Cao Lake	31.4108	117.2037	77	2.7	8.4
18	Shitang Lake	30.3747	117.0555	23	1.5	11.0
19	Caizi Lake	30.5009	117.0207	172	1.7	11.0
20	Wuchang Lake	31.1549	116.4233	101	3.4	13.8
21	Matang Lake	30.2502	116.371	3	2.0	17
22	Huang Lake	30.0114	116.2437	12	2.8	10.5
23	Daguan Lake	30.0108	116.2251	133	2.0	13
24	Bo Lake	30.1018	116.2229	180	4.4	15
25	Hualiangting Reservoir	30.2813	116.1422	53	20.0	90
26	Longgan Lake	29.5721	116.1144	316	3.8	15
27	Poyang Lake	29.2148	116.033	2993	5.1	21.7
29	Gantang Lake	29.4319	115.5849	0.8	1.4	17.5
30	Bali Lake	29.4113	115.5634	13	1.8	16.5
32	Taibai Lake	29.5804	115.4928	25	3.2	16.0
35	Wushan Lake	29.5321	115.3622	16	2.2	15
36	Cedong Lake	30.054	115.2255	27	3.5	19.5
37	Ce Lake	30.1517	115.842	12	2.1	18.0
38	Ci Lake	30.1302	115.0325	10	1.5	18.0
39	Daye Lake	30.0539	114.5932	69	2.3	18
40	Baoan Lake	30.1717	114.4313	48	3.4	20.0
41	Liangzi Lake	30.1413	114.3713	304	4.2	20.0
42	Dong Lake	30.3318	114.233	34	2.8	19.8
43	Tangsun Lake	30.2502	114.2248	37	1.9	18.8
44	Lu Lake	30.1408	114.1102	40	2.7	21.0
45	Futou Lake	29.5853	114.1011	115	2.9	22.0
46	Xiliang Lake	29.5609	114.0725	72	1.9	22.0
47	Huanggai Lake	29.4516	113.334	86	4.2	28.0
48	Hong Lake	29.4553	113.2237	344	1.9	25.0
49	Dongting Lake	29.2206	113.0215	2432	6.4	33.0

and used a GAS Bench II (Finnigan MAT) connected to a Delta plus mass spectrometer (Finnigan MAT) (Laudon et al. 2007). $\delta^{18}\text{O}$ values were determined by analysis relative to an internal standard that was calibrated to the SMOW standard and data are reported in standard δ -‰ notation. Analytical reproducibility was better than 0.2%.

Sediment samples were oven-dried at 40 °C, ground in a mortar and pestle to <74 μm grain size, and then dried again at 105 °C prior to laboratory analyses. An accurately weighed sediment sample (~125 mg) was placed in a Teflon nitrification tank, 6.0 ml HNO_3 , 0.5 ml HCl, and 3.0 ml HF were added. The sealed tank was then placed in a microwave oven (Berghof MWS-3 Digester) and nitrified at 180 ± 5 °C for 15 min. The residue from the tank was then transferred into a Teflon breaker and dissolved with 0.5 ml HClO_4 in a heating block at about 200 °C and diluted to 25 ml with double-distilled de-ionized water. The solution was then analyzed for elements by inductively coupled plasma-atomic emission spectrometry (ICP-AES). Standard EPA method 3052 was used for the determination of element concentrations (USEPA 1996). The accuracy of the analytical determination was established using the reference material GSD-9, supplied by the Chinese Academy of Geological Sciences. The analytical results for all elements were found to be in agreement with the certified values, with measurement errors <10 % (Zeng and Wu 2009). The degree of anthropogenic enrichment was estimated with the index of geoaccumulation (I_{geo}) (Loska et al. 2004), which was calculated as follows:

$$I_{\text{geo}} = \log_2(\text{Cn}/1.5\text{Bn})$$

Where Cn is the measured concentration of element n in the sediment and Bn is the background concentration of element n. The factor 1.5 is introduced to allow for possible differences in background values as a consequence of lithologic variability (Müller 1969). I_{geo} assesses the degree of metal pollution, defining seven classes of sediment quality. Class 0 (practically unpolluted): $I_{\text{geo}} \leq 0$; Class 1 (unpolluted to moderately polluted): $0 < I_{\text{geo}} < 1$; Class 2 (moderately polluted): $1 < I_{\text{geo}} < 2$; Class 3 (moderately to heavily polluted): $2 < I_{\text{geo}} < 3$; Class 4 (heavily polluted): $3 < I_{\text{geo}} < 4$; Class 5 (heavily to extremely polluted): $4 < I_{\text{geo}} < 5$; Class 6 (extremely polluted): $5 < I_{\text{geo}}$ (Bhuiyan et al. 2010). For this study, we considered the geographic location of each lake and used the soil background values of Jiangsu, Anhui, Jiangxi, Hubei, and Hunan Provinces (Table 2), as proposed by China National Environmental Monitoring Center (1990), as the reference values to calculate the geoaccumulation index.

STATISTIC for Windows statistical software (version 6.0) was used for all statistical analyses, including means, correlations, and cluster analyses. Cluster analyses were performed using euclidean distances and the average clustering methods (Krzysztof and Danuta 2003).

Table 2 The background values of heavy metals (mg kg^{-1}) in each Province in the study area

Province	Cr	Cu	Pb	Zn	Co	Ni	Cd
Jiangsu	77.8	22.3	24.9	62.6	13.6	26.7	0.126
Anhui	66.5	20.4	26.9	62.0	16.3	29.8	0.097
Jiangxi	45.9	20.3	30.4	69.4	11.5	18.9	0.108
Hubei	86.0	30.7	27.1	83.6	15.4	37.3	0.172
Hunan	71.4	27.3	29.6	94.4	14.6	31.9	0.126

3 Results

3.1 Physical and Chemical Characteristics of the Lake Water

Physical and chemical characteristics of the 45 lakes are given in Table 3. Concentration ranges for cations were 0.03–0.30 meq/L for K^+ , 0.21–2.76 meq/L for Na^+ , 0.38–3.16 meq/L for Ca^{2+} and 0.19–0.83 meq/L for Mg^{2+} . For anions, the concentration range was 0.13–2.04 meq/L for Cl^- , 0.12–1.47 meq/L for SO_4^{2-} , 0.00–0.18 meq/L for CO_3^{2-} and 0.66–2.54 meq/L for HCO_3^- . Nutrient concentration ranges were 0.02–0.73 mg/L for TP, 0.21–3.54 mg/L for TN, 2.14–93.50 $\mu g/L$ for Chl-*a* and 1.25–8.99 mg/L for chemical oxygen demand (COD). The pH values ranged from 7.6 to 8.9 and Secchi depth (SD) varied between 0.3 and 3.4 m. The $\delta^{18}O$ values ranged from -8.0% to -4.2% (Table 3).

Lakes in this region are diverse with respect to nutrient status and ion composition. Concentrations of TP, TN, Chl-*a*, COD and SD depth vary widely. The major ions in the lake water are Ca^{2+} , Mg^{2+} , $Na^+ + K^+$, Cl^- , SO_4^{2-} , CO_3^{2-} , and HCO_3^- . HCO_3^- represents 36.4 %–83.2 % of anions in all the lakes. $Na^+ + K^+$ represent 44.1 %–52.9 % of cations in lakes with codes 1 to 8, whereas Ca^{2+} represents 39.2 %–77.4 % of cations in the lakes of codes 9 to 49. The total ion concentrations of the lake waters of the lower region were higher than those of the upper and middle regions. Moreover, the concentration of K^+ , Na^+ , Ca^{2+} , Mg^{2+} , Cl^- and SO_4^{2-} in lake water increased toward Shanghai (Table 3).

3.2 Trace Element Concentrations in Sediments

Trace metal concentrations in sediments from the sampled lakes are shown in Table 4. The concentration range was 51.0–104.0 mg/g for Al, 2.4–164.0 mg/g for Ca, 26.2–84.6 mg/g for Fe, 10.3–25.6 mg/g for K, 4.0–18.6 mg/g for Mg, 0.9–14.0 mg/g for Na, 2.3–6.8 mg/g for Ti, 291–805 mg/kg for Ba, 1.4–3.5 mg/kg for Be, 5–52 mg/kg for Co, 50–159 mg/kg for Cr, 21–1462 mg/kg for Cu, 508–2365 mg/kg for Mn, 20.4–81.0 mg/kg for Ni, 24–116 mg/kg for Pb, 41–658 mg/kg for Sr, 62–185 mg/kg for V and 78–1182 mg/kg for Zn (Table 4).

Mean concentrations of trace elements are in the order $Al > Fe > K > Ca > Mg > Na > Ti > Mn > Ba > Zn > V > Sr > Cr > Cu > Pb > Ni > Be$. Skewness and K-S tests indicate that Al, Ba, Be, Co, Cr, Fe, K, Mg, Mn, Na, Ni, Ti and V approach a normal distribution. On the other hand, elements Ca, Cu, Pb, Sr and Zn are positively skewed toward lower concentrations. This is confirmed by the fact that the median concentration for each of the elements in this latter group is much lower than the mean concentration. The variability coefficients (VCs) of the concentrations of the trace elements can be used to classify them into three groups: Al, Ba, Be, Co, Cr, Fe, K, Mg, Mn, Ni, Na, Ti and V with VCs $< 50\%$; Pb and Sr with VCs between 50 % and 100 %; Cu and Zn with VCs $> 100\%$. Elements dominated by natural sources usually have low VCs, whereas elements affected by anthropogenic sources are associated with high VCs (Huang et al. 2009). Results of skewness, K-S test and VCs calculations indicate that some elements in the sediments of lakes in the study area exhibit great spatial variability and are affected by anthropogenic sources.

4 Discussion

4.1 Classification

Cluster analysis of lakes, using mean annual water quality variables, produced three clusters (Fig. 2). All water quality variables were used in this analysis. Cluster A consists of nine

Table 3 Mean values of surface water quality parameters of the 45 lakes sampled in this study

Lake Code	K ⁺ meq/L	Na ⁺ meq/L	Cd ²⁺ meq/L	Mg ²⁺ meq/L	Cl ⁻ meq/L	SO ₄ ²⁻ meq/L	CO ₃ ²⁻ meq/L	HCO ₃ ⁻ meq/L	SC* meq/L	SA* meq/L	δ ¹⁸ O ‰	pH	Cond μS/cm	SD m	TP mg/L	TN mg/L	COD mg/L	Chla μg/L
1	0.19	2.25	1.65	0.77	1.54	1.44	0.08	1.81	4.86	4.86	-4.9	8.3	502	0.5	0.17	2.94	7.55	33
2	0.16	2.14	1.66	0.74	1.49	1.34	0.01	1.88	4.70	4.72	-4.7	8.3	497	0.4	0.15	2.44	6.83	24
3	0.20	2.59	1.87	0.70	1.85	1.46	0.10	1.96	5.36	5.38	-5.5	8.8	548	0.5	0.29	2.84	7.29	58
4	0.16	2.23	1.68	0.73	1.42	1.31	0.05	2.02	4.79	4.80	-4.9	8.4	525	1.1	0.09	0.75	5.52	7
5	0.18	2.76	2.02	0.73	2.04	1.33	0.05	2.27	5.70	5.69	-5.7	8.5	605	0.5	0.23	3.53	8.58	77
6	0.19	2.61	2.02	0.74	1.87	1.37	0.04	2.32	5.56	5.60	-5.6	8.5	581	0.4	0.29	3.54	8.76	72
7	0.14	2.03	1.78	0.67	1.31	1.29	0.08	2.00	4.62	4.67	-5.9	8.6	472	0.5	0.17	2.65	7.99	17
8	0.14	1.76	1.75	0.67	1.16	1.16	0.05	1.94	4.31	4.30	-5.3	8.3	425	0.6	0.11	1.77	5.12	8
9	0.14	0.99	1.53	0.78	0.93	0.75	0.05	1.70	3.44	3.42	-6.0	8.3	335	1.1	0.06	1.05	5.95	6
10	0.11	0.92	1.87	0.74	0.76	0.71	0.04	2.12	3.63	3.63	-6.5	8.3	369	0.5	0.12	2.28	6.00	26
11	0.06	0.37	1.10	0.41	0.22	0.39	0.06	1.28	1.94	1.95	-5.7	8.5	178	1.4	0.07	0.89	3.79	11
12	0.10	0.64	0.89	0.36	0.52	0.55	0.00	0.93	1.99	2.01	-5.6	7.8	187	0.8	0.09	2.34	5.45	10
13	0.09	0.41	0.95	0.53	0.33	0.45	0.10	1.13	1.99	2.02	-5.1	8.9	186	2.8	0.05	0.62	4.12	4
14	0.10	0.35	0.90	0.33	0.26	0.18	0.13	1.12	1.68	1.69	-5.7	8.7	164	1.6	0.05	0.61	3.83	5
15	0.09	1.00	1.49	0.61	0.49	0.54	0.07	2.11	3.18	3.21	-6.6	8.6	248	0.5	0.16	1.85	7.05	94
16	0.30	2.03	1.50	0.72	1.51	0.84	0.18	2.08	4.56	4.62	-4.2	8.4	408	0.4	0.73	2.00	8.99	88
17	0.10	0.95	1.05	0.51	0.74	0.57	0.03	1.31	2.62	2.65	-5.6	8.2	248	0.3	0.12	2.21	4.95	11
18	0.10	0.63	1.43	0.49	0.48	0.53	0.03	1.61	2.65	2.64	-5.0	8.2	226	0.5	0.03	1.09	5.61	9
19	0.07	0.42	0.66	0.39	0.29	0.31	0.03	0.93	1.54	1.56	-5.7	8.1	127	0.8	0.06	0.76	3.76	18
20	0.07	0.28	0.61	0.33	0.24	0.21	0.06	0.80	1.29	1.31	-4.5	8.3	109	0.9	0.05	0.32	5.12	6
21	0.05	0.30	0.48	0.28	0.26	0.17	0.00	0.72	1.11	1.15	-4.7	8.1	91	1.6	0.02	0.32	3.80	3
22	0.08	0.45	1.26	0.44	0.37	0.34	0.03	1.52	2.23	2.25	-4.5	8.3	195	1.0	0.04	0.65	3.94	3
23	0.09	0.51	1.24	0.54	0.40	0.35	0.03	1.58	2.37	2.36	-4.6	8.2	199	1.0	0.04	0.66	3.84	4
24	0.10	0.31	0.57	0.25	0.25	0.17	0.03	0.78	1.23	1.23	-5.2	8.0	103	0.9	0.05	0.45	3.43	3
25	0.03	0.28	0.38	0.27	0.16	0.12	0.03	0.68	0.97	0.99	-6.9	7.9	75	3.4	0.03	0.21	2.84	10
26	0.11	0.50	1.19	0.53	0.36	0.38	0.03	1.55	2.33	2.32	-5.2	8.2	223	0.8	0.04	0.67	3.92	5
27	0.06	0.23	0.45	0.19	0.14	0.12	0.00	0.66	0.93	0.92	-7.6	7.7	77	1.5	0.05	0.62	1.25	3

Table 3 (continued)

Lake Code	K ⁺ meq/L	Na ⁺ meq/L	Ca ²⁺ meq/L	Mg ²⁺ meq/L	Cl ⁻ meq/L	SO ₄ ²⁻ meq/L	CO ₃ ²⁻ meq/L	HCO ₃ ⁻ meq/L	SC* meq/L	SA* meq/L	δ ¹⁸ O ‰	pH	Cond μS/cm	SD m	TP mg/L	TN mg/L	COD mg/L	Chla μg/L
29	0.15	0.84	1.65	0.50	0.53	0.60	0.00	2.04	3.15	3.16	-6.9	7.8	267	0.4	0.08	1.69	4.73	17
30	0.09	0.32	0.85	0.29	0.18	0.23	0.00	1.16	1.55	1.57	-6.9	7.6	135	0.6	0.07	1.06	3.82	12
32	0.10	0.44	0.97	0.43	0.41	0.32	0.01	1.23	1.94	1.96	-5.6	7.8	174	0.7	0.06	1.28	3.86	11
35	0.17	0.79	1.69	0.61	0.54	0.64	0.00	2.10	3.26	3.27	-6.2	7.8	271	0.5	0.15	2.29	6.94	25
36	0.10	0.42	0.88	0.44	0.28	0.29	0.05	1.25	1.84	1.87	-5.2	8.4	144	0.6	0.07	0.76	3.71	17
37	0.12	0.36	1.32	0.64	0.39	0.29	0.05	1.75	2.43	2.48	-5.3	8.0	221	0.9	0.04	1.00	3.15	3
38	0.19	0.89	2.56	0.72	0.76	1.38	0.07	2.09	4.36	4.31	-6.7	8.6	405	0.5	0.14	1.87	4.32	59
39	0.12	0.45	3.16	0.83	0.47	1.47	0.00	2.54	4.56	4.48	-6.7	7.8	425	0.6	0.07	1.71	2.69	7
40	0.07	0.22	2.00	0.59	0.28	1.14	0.05	1.45	2.88	2.92	-5.3	8.1	293	1.5	0.04	0.35	2.20	6
41	0.08	0.36	1.16	0.30	0.22	0.18	0.01	1.50	1.89	1.90	-6.5	8.2	155	1.4	0.04	0.49	2.44	6
42	0.19	1.01	1.85	0.65	0.81	0.45	0.13	2.31	3.70	3.69	-5.9	8.7	332	0.9	0.17	1.87	5.06	49
43	0.14	0.55	0.89	0.42	0.41	0.29	0.03	1.28	2.00	2.01	-5.6	7.9	177	0.9	0.04	1.45	2.14	6
44	0.09	0.29	1.03	0.34	0.27	0.20	0.03	1.26	1.74	1.76	-5.0	8.1	157	0.8	0.05	0.60	2.33	10
45	0.09	0.30	1.11	0.33	0.21	0.26	0.03	1.34	1.83	1.84	-5.6	8.2	147	1.0	0.04	0.53	2.70	4
46	0.06	0.25	1.95	0.26	0.15	0.25	0.03	2.13	2.52	2.56	-6.9	8.1	213	1.5	0.03	0.44	1.69	2
47	0.05	0.21	0.71	0.32	0.13	0.20	0.01	0.95	1.28	1.30	-6.1	8.0	97	0.7	0.05	1.14	4.49	15
48	0.14	0.54	2.05	0.77	0.47	0.44	0.13	2.48	3.49	3.52	-4.9	8.6	277	1.2	0.06	1.30	4.60	31
49	0.06	0.37	1.36	0.41	0.22	0.24	0.00	1.76	2.20	2.22	-8.0	8.0	189	0.5	0.04	1.09	2.04	4
Min	0.03	0.21	0.38	0.19	0.13	0.12	0.00	0.66	0.81	0.90	-8.0	7.6	75	0.3	0.02	0.21	1.25	2
Max	0.30	2.76	3.16	0.83	2.04	1.47	0.18	2.54	7.05	6.23	-4.2	8.9	605	3.4	0.73	3.54	8.99	94
Mean	0.12	0.86	1.36	0.52	0.62	0.60	0.04	1.59	2.85	2.86	-5.7	8.2	266	0.9	0.10	1.35	4.63	20
Std	0.05	0.76	0.58	0.18	0.53	0.45	0.04	0.53	1.58	1.55	0.86	0.3	148	0.6	0.12	0.89	1.97	24
MDL*	0.05	0.05	0.05	0.05	0.02	0.02	0.1	0.1	-	-	-	0	0.1	0.05	0.01	0.1	0.5	0.1

SC the sum of cation charges; SA the sum of anion charges; MDL method detection limit (unit: mg/L for cation and anion)

Table 4 Major and trace element contents of lake sediments of the study area

Lake Code	Al mg/g	Ca	Fe	K	Mg	Na	Ti	Ba mg/kg	Be	Co	Cd	Cr	Cu	Mn	Ni	Pb	Sr	V	Zn
1	60.9	5.4	35.4	16.7	7.0	9.4	5.1	452	1.9	15	<1	110	26	1225	41.5	24	91	97	100
2	72.0	6.9	38.2	18.2	6.3	10.9	5.5	484	2.5	18	<1	82	26	1339	43.5	28	105	111	99
3	61.6	8.4	36.0	18.8	9.3	11.0	5.1	467	2.3	19	<1	111	29	1063	48.4	33	97	110	113
4	86.7	26.1	47.5	19.6	7.9	6.2	5.2	589	2.9	24	<1	101	38	1289	59.1	42	123	138	138
5	70.0	7.2	43.4	14.8	6.0	8.0	4.8	452	2.2	18	2.6	148	370	1443	81.0	109	94	97	431
6	60.9	9.3	34.5	17.0	9.2	10.5	4.7	468	1.9	14	<1	81	45	1128	46.5	31	105	84	208
7	68.3	10.8	35.8	15.9	6.1	9.7	5.7	504	2.1	15	<1	75	32	929	41.6	31	112	89	104
8	61.3	5.3	31.9	15.0	5.6	10.1	5.8	459	1.9	14	<1	74	26	905	31.8	31	98	86	85
9	51.8	44.2	26.2	12.9	5.7	9.2	4.4	394	1.8	12	<1	107	31	594	30.2	37	145	82	83
10	60.6	53.1	38.1	15.1	8.2	9.3	4.3	423	2.2	17	<1	107	30	590	39.2	32	157	101	99
11	85.9	7.4	38.0	20.3	5.7	5.6	4.2	533	2.9	17	<1	58	26	1224	24.6	40	79	97	91
12	58.2	4.4	34.3	16.4	4.4	6.8	4.6	461	2.5	15	<1	50	22	2332	22.7	24	73	76	79
13	80.0	19.5	41.3	17.7	6.1	5.8	4.6	666	2.7	17	<1	80	35	508	39.2	45	103	127	111
14	76.0	14.9	43.4	17.5	6.2	6.0	5.2	629	2.7	19	<1	75	43	576	39.8	51	97	124	119
15	87.9	27.9	48.5	19.4	8.5	5.8	4.8	598	3.1	22	<1	146	91	684	69.3	63	129	143	558
16	79.8	11.7	46.6	21.4	9.5	6.9	5.2	531	2.8	21	<1	88	70	1199	45.0	69	114	123	196
17	74.3	5.3	45.9	18.5	8.4	7.1	5.7	545	2.8	26	1.7	155	42	1281	55.0	97	86	127	350
18	92.0	5.1	48.0	20.8	7.5	6.7	6.1	540	3.1	19	1.6	81	33	1243	39.3	43	96	120	135
19	78.4	4.9	55.6	17.8	9.8	7.3	6.4	614	3.0	32	<1	153	32	1740	50.3	44	100	151	115
20	71.1	4.6	54.5	20.3	8.3	4.2	5.7	511	2.6	22	<1	132	43	1354	47.9	34	65	145	109
21	104	3.9	54.0	21.8	6.5	4.3	5.7	746	2.8	25	2.0	79	33	1799	38.0	40	85	126	111
22	90.5	9.2	58.2	23.6	10.5	5.5	6.8	587	3.3	29	<1	110	47	1574	57.9	47	89	170	124
23	79.3	12.2	52.2	21.1	12.2	5.6	6.4	549	2.6	20	<1	95	44	1175	43.9	32	89	133	103
24	91.8	2.8	54.8	15.7	5.9	2.9	6.0	537	2.4	23	<1	83	30	1216	37.1	37	68	126	89
25	100	4.2	74.2	11.2	6.6	6.1	5.0	586	3.0	27	<1	80	48	1743	46.2	48	71	166	172
26	84.7	7.9	54.4	21.6	8.6	6.7	6.6	584	3.2	27	<1	98	43	2365	54.4	49	89	160	118

Table 4 (continued)

Lake Code	Al mg/g	Ca	Fe	K	Mg	Na	Ti	Ba mg/kg	Be	Co	Cd	Cr	Cu	Mn	Ni	Pb	Sr	V	Zn
27	51.0	2.4	30.0	20.6	4.0	4.5	4.5	380	3.0	12	<1	87	21	781	20.4	30	41	71	84
29	104	9.4	61.6	25.6	10.5	4.0	5.7	570	3.5	30	<1	121	79	970	69.7	96	87	185	222
30	90.4	5.6	58.4	22.9	7.8	3.9	5.9	573	3.3	26	<1	112	274	1593	57.8	46	71	165	152
32	99.1	5.8	56.0	17.4	7.2	4.8	6.4	609	3.3	26	<1	96	37	2239	46.5	43	97	141	116
35	92.1	7.6	58.9	20.2	9.0	5.3	6.6	534	3.1	29	1.6	131	69	958	74.3	48	102	180	179
36	92.8	12.1	59.6	20.1	16.2	14.0	5.4	805	2.7	31	<1	146	49	1490	54.6	39	217	144	126
37	89.4	16.6	59.8	24.4	17.0	4.3	5.7	572	2.9	29	1.5	150	59	1422	58.0	49	101	169	143
38	81.3	77.9	45.9	18.0	10.3	2.8	4.3	543	2.4	16	1.7	133	92	1161	38.9	111	658	107	280
39	74.1	35.2	84.6	14.0	18.6	2.9	3.8	392	2.2	52	80	69	1462	1415	41.6	166	143	102	1182
40	78.5	7.0	55.1	19.6	8.9	3.3	5.1	428	2.6	19	1.5	103	84	1961	44.9	50	92	131	132
41	101	5.9	57.6	20.5	9.1	2.5	4.9	531	2.6	22	<1	99	47	1800	45.2	43	74	138	124
42	70.8	11.2	57.6	22.0	12.1	3.6	4.9	453	2.9	26	<1	159	56	1244	56.5	56	71	167	143
43	82.8	3.5	55.8	16.5	5.9	3.0	5.9	462	2.5	22	<1	101	40	1090	43.5	41	61	133	109
44	92.8	7.7	57.8	23.0	11.8	4.0	5.8	542	2.8	22	<1	105	45	1294	49.5	35	74	143	126
45	71.1	12.7	50.6	19.7	10.3	3.7	4.7	420	2.6	22	1.6	142	44	854	49.9	58	64	151	130
46	55.1	164	33.5	10.3	5.7	0.9	2.3	291	1.4	5	<1	51	21	1127	23.9	27	272	62	78
47	96.4	13.2	56.6	24.3	9.7	4.8	5.6	562	3.2	28	1.6	101	49	1789	58.1	56	85	169	143
48	61.1	68.3	42.3	17.6	14.8	4.6	4.3	506	1.7	13	<1	96	35	1805	32.9	45	197	97	105
49	63.8	17.8	39.7	20.6	12.2	5.9	5.3	457	2.6	16	3.3	77	43	1138	35.3	55	87	102	185
Min	51	2.4	26.2	10.3	4	0.9	2.3	291	1.4	5		50	21	508	20.4	24	41	62	78
Max	104	164	84.6	25.6	18.6	14	6.8	805	3.5	52		159	1462	2365	81	166	658	185	1182
Mean	78.6	17.9	48.7	18.8	8.8	6	5.3	523	2.6	22		103	88	1303	46.1	50	115	126	173
S.D	14.7	27.8	11.8	3.4	3.3	2.7	0.9	94	0.5	8		29	218	450	13.1	27	93	31	179
VC	18.7	155.3	24.2	18.1	37.5	45.0	17.0	18	19.2	36.4		28.2	248	34.5	28.4	54.0	81	25	103
MDL	0.02	0.01	0.01	0.03	0.01	0.02	2	1	0.1	1	1	1	1	0.5	1	2	0.5	2	1

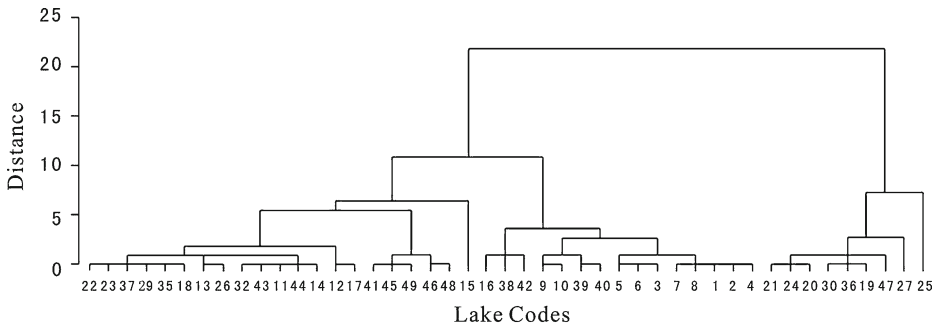


Fig. 2 Dendrograms produced by hierarchical clustering of water quality variables from selected lakes. Lake codes and parameters of lake water quality are indicated in Table 2. Cluster A: group of nine lakes 25, 27, 47, 19, 36, 30, 20, 24, 21; Cluster B: group of 15 lakes 4, 2, 1, 8, 7, 3, 6, 5, 40, 39, 10, 9, 42, 38, 16; Cluster C: group of 21 lakes 15, 48, 46, 49, 45, 41, 17, 12, 14, 44, 11, 43, 32, 26, 13, 18, 35, 29, 37, 23, 22

lakes in the Huayan-Poyan lake group (Fig. 1). Lake Hualiang (25), a man-made reservoir, is strongly differentiated from the other lakes in the cluster because of its low K^+ , Na^+ , Ca^{2+} , conductivity, and TP and TN values. Lake Poyang (27), a section of the Han River, is connected with the Yangtze River seasonally, and is differentiated from other lakes by virtue of its low Ca^{2+} and SO_4^{2-} concentrations. Cluster B is composed of 15 lakes, including all the lakes in the Taihu Delta and some lakes in the Dongting-Honghu lake group, i.e. lakes along the middle Yangtze River. Lakes 38 (Lake Ci), 39 (Lake Daye), 40 (Lake Baoan), and 42 (Lake Dong) are located in the middle Yangtze River where lake water is greatly affected by sewage, e.g. Lake Dong by Wuhan City and Lake Daye by Huangshi, etc. Lake Mochou (16) is situated in Nanjing City. All these lakes have high Ca^{2+} and SO_4^{2-} concentrations and receive high nutrient loads. Cluster C consists of 21 lakes with median values of water quality variables distributed across the whole study region, except the Taihu Delta. Most of the lakes in this cluster are affected by the Yangtze River seasonally or by temporary flooding. Lake Xuanwu (15) is an urban lake in Nanjing that is differentiated from the other lakes by its high Ca^{2+} and SO_4^{2-} concentrations. Values are, however, lower than those of another waterbody in Nanjing City, Lake Mucou, which belongs to cluster B. This is because Lake Xuanwu was inundated by water from the Yangtze River just before samples were collected.

4.2 Water Quality

Lakes of cluster A have the lowest trophic state, inferred from the lowest mean values of TP, TN, Chl-*a*, and COD in the water column (Fig. 3). Cluster B lakes have the highest values of TP, TN, Chl-*a*, and COD, indicating the highest trophic states. Cluster C is of intermediate status. Generally, lakes in cluster B are eutrophic to hypereutrophic, judging from their TP, TN, Chl-*a*, and COD values. Lake Taihu (7), for example, has cyanobacteria blooms in summer, indicating poor water quality (Chen et al. 2002). Likewise, Lake Donghu (42) experiences such blue-green blooms. Lakes in cluster A, with the lowest average TP, TN, Chl-*a*, and COD, range from oligotrophic to mesotrophic. These lakes are located farther upstream and receive more precipitation from drainage of the mountain region. Lower $\delta^{18}O$ values in the water column of these lakes are probably indicative of their relatively short residence times. For instance, Lake Hua (25) is situated at the base of mountains and yielded a $\delta^{18}O$ value of -6.9‰ . Lake Poyang (27), with a $\delta^{18}O$ value of -7.6‰ receives a large

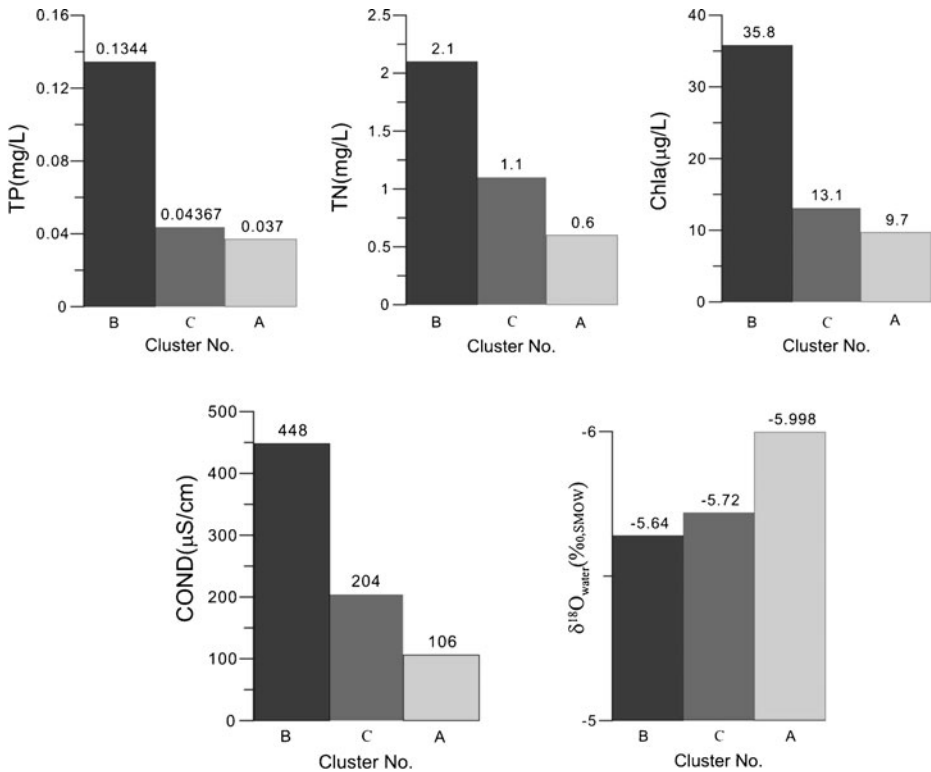


Fig. 3 Water quality variables among lake clusters A, B, and C. The value above each bar indicates the mean value for the variable in lakes of the cluster

amount of water from the Han River, the largest tributary of the Yangtze River, which originates in a nearby mountain region.

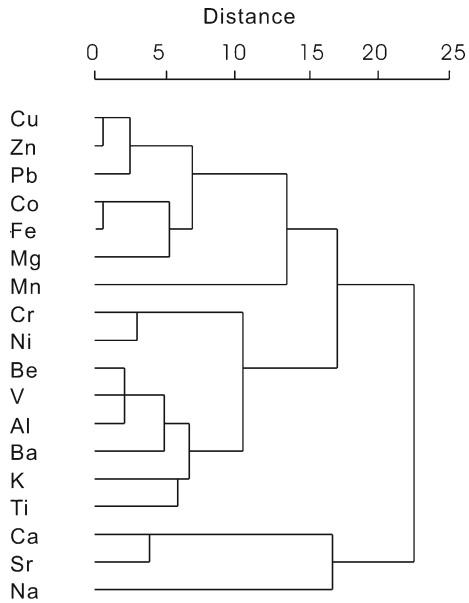
Cluster C contains the largest number of lakes studied. They mostly range in trophic state from mesotrophic to eutrophic. Topographically, they are located nearer the Yangtze River and have a connection with the river, especially during the flood season. For example, Lake Dongting (49) is part of the Yangtze River and has a $\delta^{18}\text{O}$ value of -8.0% . Lake Longgan (26) often receives river water during the flood season. In this cluster, some lakes stand out. For example, Lake Tianmu (11) lies far from the river and receives much of its hydrologic input from direct precipitation. Nevertheless, tourism activities have influenced this relatively pristine lake, and it now displays mesotrophic conditions.

Generally, nutrient status increases from the middle Yangtze River to the Delta region, reflecting the impact of cities and economic development. Upstream lakes in the central part, however, show signs of rapid eutrophication in recent years (Cheng and Li 2006).

4.3 Heavy Metals

Cluster analysis of lakes, using concentrations of metals in the sediments, produced three clusters (Fig. 4). Cluster A contained Cu, Zn, Pb, Co, Fe, Mg and Mn. These elements probably are attributed to anthropogenic sources in the lake basins, and reflect heavy metal pollution. Cluster B contained Cr, Ni, Be, V, Al, Ba, K and Ti. The elements may originate

Fig. 4 Dendrograms produced by hierarchical clustering of trace metals in the sediments from selected lakes. Lake codes and concentrations of trace metals are shown in Table 3. Cluster A contains metals Cu, Zn, Pb, Co, Fe, Mg, and Mn. Cluster B contains metals Cr, Ni, Be, V, Al, Ba, K and Ti. Cluster C possesses metals Ca, Sr and Na



from natural parent materials in watershed rocks and soils. Cluster C contained Ca, Sr and Na.

Heavy metal elements Cu, Zn, Pb, Co, Fe, Mg and Mn were used in a cluster analysis that yielded three lake groups (Fig. 5) and Fig. 6 shows the distribution of each heavy metal Igeo values in the different lake groups. Metal pollution displays a sequence, with group 1 > group 2 > group 3. Group 1 consists of three lakes, 5, 39 and 30. The lake sediments in the group can be characterized as moderately polluted with Pb and Zn ($1 \leq \text{mean Igeo} \leq 2$), strongly polluted with Cu ($3 \leq \text{mean Igeo} \leq 4$), and unpolluted to moderately polluted with Co, Cr and Ni ($0 \leq \text{Igeo} \leq 1$). Lake Jinji (5), with higher Igeo

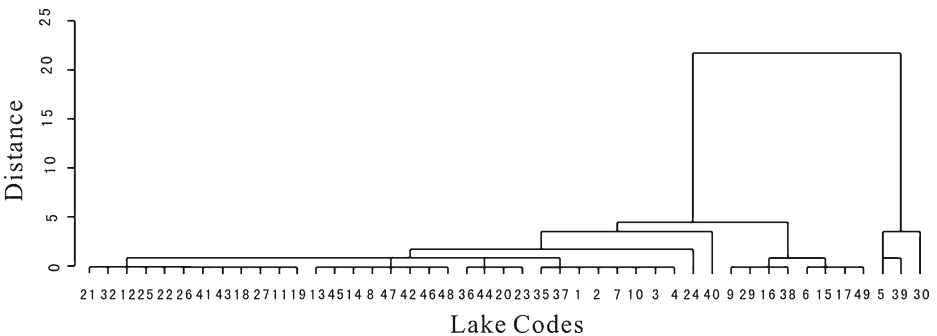
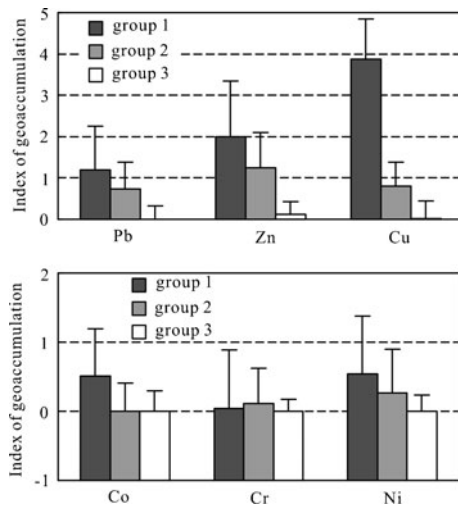


Fig. 5 Dendrograms produced by hierarchical clustering of trace metals Cu, Zn, Pb, Co, Fe, Mg, Mn from selected lakes. Lake codes and parameters of lake water quality are indicated in Table 2. Cluster A: group of three lakes—5, 39, 30; Cluster B: group of eight lakes—9, 29, 16, 38, 6, 15, 17, 49; Cluster C: group of 34 lakes—40, 24, 4, 3, 10, 7, 2, 1, 37, 35, 23, 20, 44, 36, 48, 46, 42, 47, 8, 14, 45, 13, 19, 11, 27, 18, 43, 41, 26, 22, 25, 12, 32, 21

Fig. 6 Distribution of index of geoaccumulation of heavy metals in the sediments of the study. The lines extending from the top of each column mark the standard deviation



values for Cd, Cu, Zn and Pb of 3.78, 3.47, 2.2, 1.55, respectively, is located in a special industrial zone in Suzhou City that is surrounded by factories from which it receives waste water. Lake Daye (39) displays the highest I_{geo} values for these metals, among all the lake sediments. The I_{geo} values for Cd, Pb, Cu and Zn from Daye Lake sediment are 8.28, 2.03, 3.24, 4.99, respectively, reflecting moderate to extreme pollution by the different heavy metals. Lake Bali (30) has high Cu content, with an I_{geo} value 3.17. The I_{geo} values for other metals were <1 in the sediment of Lake Bali, which generally fell into the “unpolluted to moderately polluted” class. Group 2 contains eight lakes: 9, 29, 16, 38, 6, 15, 17 and 49, which receive pollutants from urban runoff. For example, lakes 15 and 16 are located in Nanjing City, lake 17 is near Hefei City, the capital of Anhui Province, and Lake 49 is affected by Yueyang City. The lake sediments from the group can be categorized as unpolluted to moderately polluted with Pb, Cu, Cr, Ni and Co ($0 \leq \text{mean } I_{geo} \leq 1$), and as moderately polluted with Zn ($1 \leq \text{mean } I_{geo} \leq 2$). The other lakes belong to group 3, which is characterized by normal heavy metal concentrations. Lakes in the group are distributed across the whole study area, including near cities. The lake sediments from the group are unpolluted with Co, Cr, Ni and Pb, and are unpolluted to moderately polluted with Cu and Zn ($0 \leq \text{mean } I_{geo} \leq 1$). In this group, a few lakes display exceptional heavy metal content. Lake Wushan (35) has high Cd, with an I_{geo} value of 2.66, a consequence of chemical and medical industries.

Geographically, lakes polluted by heavy metals are mainly concentrated along the upper part of the lower Yangtze River, in Anhui and Hubei Provinces, in the centre of China. Lake Daye is polluted by mining activity near the city of Huangshi and Lake Wushan is affected by factories along the lake shore (Deng and Xie 1995). Lakes along the middle of the Yangtze River are unpolluted to moderately polluted with metals, except for those near urban areas. For example, Lake 49 is affected by a yacht dock, a famous tourist destination near Yueyang City. Lakes in the Taihu Delta or within urban areas are polluted mainly from municipal drainage or industries that discharge waste with relatively high heavy metal concentrations (Lin and Wu 2008). For example, lakes 15 and 16 are located in Nanjing City, lake 17 is at Hefei City, the capital of Anhui Province and Lake 5 is at Suzhou City.

5 Conclusions

Nutrient pollution in lakes of the Yangtze River region, China, is marked by high TP, TN, COD, and Chl-*a* in the water column, and is associated with high $\delta^{18}\text{O}$ of lake waters. High $\delta^{18}\text{O}$ values in the lake water indicate the effect of evaporation and hence the relatively long residence time of water in the basin. Urbanization is the main source of nutrient loads. Industries also contribute to pollution. Lakes with heavy metal pollution display high concentrations of Cu, Zn, Pb, Co, Fe, Mg and Mn in their sediment. Such lakes receive untreated waste water from industries in their catchments. Other anthropogenic activities in urban areas can also serve as heavy metal sources. Water residence time has a greater impact on nutrient pollution than it does on heavy metal pollution of lake sediments, e.g. Lake Tongtin. Whereas increased water exchange can improve water quality by lowering nutrient concentrations, it has little impact on heavy metal accumulation in lake sediments.

Lakes affected by the Yangtze River are in relatively good condition. Most of them, such as Lakes Taibai and Longgan are mesotrophic. Most of these lakes are found in the interior part of China, in the upper portion of the lower Yangtze River. Lakes in this region, however, are polluted by heavy metals. The pollution is caused by industries that discharge untreated waste water into the rivers and lakes. Most of the lakes serve as temporary holding basins for water that then flows into the Yangtze River. Over time, these lake sediments accumulate a great amount of pollutants. High heavy metal concentrations in lake sediments are a serious threat to these lakes. Because these lakes exchange water seasonally with the Yangtze River, nutrient concentrations do not reach high levels, but heavy metals accumulate in the sediments.

Lakes in the Delta area or urban regions display the highest nutrient levels. In recent years, as a result of changing industrial practices and more environmental protection from local authorities, these lakes have not been polluted by heavy metals. Nutrient pollution, however, is a serious problem for lakes in these areas as a consequence of development of modern cities and industries. Lakes in the middle reach of the river or upstream have large freshwater supplies, with low nutrient levels and heavy metal concentrations. Only a few of the lakes, however, belong to this group, and even some of them are starting to show evidence of anthropogenic impacts, for instance the effect of tourism on Lake Tianmu.

Current lake status in the middle and lower reaches of the Yangtze River is related to the policy of regional economic development. The Delta region of China is developed and includes the cities of Shanghai, Suzhou, and others. Heavy industries have recently moved into the interior region of China, accompanied by the development of modern cities. Despite environmental protection efforts, lakes in the central region are faced with high nutrient loading from industry. This has occurred as a consequence of efforts to improve the economic conditions of citizens, sometimes at the expense of environmental quality. Lakes in the central part of China require immediate attention and efforts should be made to implement management plans to prevent further degradation of water quality in these lakes. If such steps are not taken in these upstream aquatic ecosystems, there may also be adverse impacts on the downstream water bodies.

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References

- Alexakis D (2010) Diagnosis of stream sediment quality and assessment of toxic element contamination sources in East Attica, Greece. *Environ Earth Sci* 63:1369–1383
- Battarbee RW, Anderson NJ, Jeppesen E, Leavitt PR (2005) Combining palaeolimnological and limnological approaches in assessing lake ecosystem response to nutrient reduction. *Freshwater Biol* 50:1772–1780
- Bhuiyan MAH, Parvez L, Islam MA, Dampare SB, Suzuki S (2010) Heavy metal pollution of coal mine-affected agricultural soils in the northern part of Bangladesh. *J Hazard Mater* 173:384–392
- Cai XM, Ringler C (2007) Balancing agriculture and environmental water needs in China: alternative scenarios and policy options. *Water Policy* 9:95–108
- Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN, Smith VH (1998) Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol Appl* 8:559–568
- Chen Z, Li J, Shen H, Wang Z (2001) Yangtze River of China: historical analysis of discharge variability and sediment flux. *Geomorphology* 41:77–91
- Chen L, Xu Y, Xu X, Hu F, Yu Z (2002) Surface water pollution in the Yangtze River Delta: patterns and countermeasures. *Pedosphere* 12:111–120
- Cheng XY, Li SJ (2006) An analysis on the evolution processes of lake eutrophication and their characteristics of the typical lakes in the middle and lower reaches of Yangtze River. *Chin Sci Bull* 51:1603–1613
- China National Environmental Monitoring Center (1990) The Background Values of Chinese Soils. Chinese Environmental Science Press, Beijing (in Chinese)
- Deng Z, Xie L (1995) A Preliminary analysis of the influences on piscatorial economics from water body contamination of Daye Lake. *J Cent China Norm Univ* 29:387–390 (in Chinese with English abstract)
- Deniseger J, Erickson J, Austin A, Roch M, Clark MJR (1990) The effects of decreasing heavy metal concentrations on the biota of Buttle Lake. *Water Res* 24:403–416
- Eaton AD, Clesceri LS, Greenberg AE (1995) Standard methods for the examination of water and wastewater, 19th edn. American Public Health Association, Washington
- Fan H, Huang H, Zeng T (2006) Impacts of anthropogenic activity on the recent evolution of the Huang (Yellow) River Delta. *J Coast Res* 22:919–929
- Fedoroff NV, Battisti DS, Beachy RN, Cooper PJM, Fischhoff DA, Hodges CN, Knauf VC, Lobell D, Mazur BJ, Molden D, Reynolds MP, Ronald PC, Rosegrant MW, Sanchez PA, Vonshak A, Zhu JK (2010) Radically rethinking agriculture for the 21st century. *Science* 327:833–834
- Foster S, Garduno H, Evans R, Olson D, Tian Y, Zhang W, Han Z (2004) Quaternary aquifer of the North China Plain assessing and achieving groundwater resource sustainability. *Hydrogeol J* 12:81–93
- Franchini M, Ventaglio E, Bonoli A (2011) A procedure for evaluating the compatibility of surface water resources with environmental and human requirements. *Water Resour Manage* 25:3613–3634
- Franczyk J, Chang H (2009) Spatial analysis of water use in Oregon, USA, 1985–2005. *Water Resour Manage* 23:755–774
- Galan E, Gomez-Ariza JL, Gonzalez I, Fernandez-Caliani JC, Morales E, Giraldez I (2003) Heavy metal partitioning in river sediments severely polluted by acid mine drainage in the Iberian Pyrite Belt. *Appl Geochem* 18:409–421
- Han ZS (2003) Groundwater resources protection and aquifer recovery in China. *Environ Geol* 44:106–111
- Hanjra MA, Qureshi ME (2010) Global water crisis and future food security in an era of climate change. *Food Policy* 35:365–377
- Huang SS, Tu J, Liu HY, Hua M, Liao QL, Feng JS, Weng ZH, Huang GM (2009) Multivariate analysis of trace element concentrations in atmospheric deposition in the Yangtze River Delta, East China. *Atmos Environ* 43:5781–5790
- James N, Galloway JN, Townsend AR, Erisman JW, Bekunda M, Cai Z, Freney JR, Martinelli LA, Seitzinger SP, Sutton MA (2008) Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. *Science* 320:889–892
- Jiang Y (2009) China's water scarcity. *J Environ Manage* 90:3185–3196
- Khan F, Ansari A (2005) Eutrophication: an ecological vision. *Bot Rev* 71:449–482
- Khan S, Hanjra MA (2009) Footprints of water and energy inputs in food production-global perspectives. *Food Policy* 34:130–140

- Khan S, Hanjra MA, Mu J (2009a) Water management and crop production for food security in China: a review. *Agr Water Manage* 96:349–360
- Khan S, Khan MA, Mu J (2009b) Pathways to reduce the environmental footprints of water and energy inputs in food production. *Food Policy* 34:141–149
- Krzysztof L, Danuta W (2003) Application of principal component analysis for the estimation of source of heavy metal contamination in surface sediments from the Rybnik Reservoir. *Chemosphere* 51:723–733
- Kuang Q, Bi Y, Xia Y, Hu Z (2004) Phytoplankton community and algal growth potential in Taipinghu Reservoir, Anhui Province, China. *Lakes Reserve Res Manage* 9:119–124
- Laudon H, Sjöblom V, Buffam I, Seibert J, Mörth M (2007) The role of catchment scale and landscape characteristics for runoff generation of boreal streams. *J Hydrol* 344:198–209
- Lin L, Wu J (2008) Application of multivariate statistical analysis to elemental geochemical records of Lacustrine sediment of Meiliang Bay in Lake Taihu. *J Lake Sci* 20:76–82 (in Chinese with English abstract)
- Liu J, Diamond J (2005) China's environment in a globalizing world. *Nature* 435:1179–1186
- Liu CM, Xia J (2004) Water problems and hydrological research in the Yellow River and the Huai and Hai River Basins of China. *Hydrol Process* 18:2197–2210
- Liu CM, Yu JJ (2001) Groundwater exploitation and its impact on the environment in the North China Plain. *Water Int* 26:265–272
- Loska K, Wiechula D, Korus I (2004) Metal contamination of farming soils affected by industry. *Environ Int* 30:159–165
- Müller G (1969) Index of geoaccumulation in sediments of the Rhine River. *Geo J* 2:108–118
- Postel SL, Daily GC, Ehrlich PR (1996) Human appropriation of renewable freshwater. *Science* 271:785–788
- Qin BQ (2002) Approaches to mechanisms and control of eutrophication of shallow lakes in the middle and lower reaches of the Yangtze River. *J Lake Sci* 14:193–202 (in Chinese with English abstract)
- Rose NL, Boyle JF, Du Y, Yi C, Dai X, Appleby PG, Bennion H, Cai S, Yu L (2004) Sedimentary evidence for changes in the pollution status of Taihu in the Jiangsu region of eastern China. *J Paleolimnol* 32:41–51
- Schindler DW (1974) Eutrophication and recovery in experimental lakes: implication for lake management. *Science* 184:897–899
- Shao W (2010) Effectiveness of water protection policy in China: a case study of Jiaying. *Sci Total Environ* 408:690–701
- Shi Y, Zhang Q, Chen Z, Jiang T, Wu J (2007) Channel morphology and its impact on flood passage, the Tianjiazhen reach of the middle Yangtze River. *Geomorphology* 85:176–184
- Sin SN, Chua H, Lo W, Ng LM (2001) Assessment of heavy metal cations in sediments of Shing Mun River, Hong Kong. *Environ Int* 26:297–301
- Smol JP (2002) Pollution of lakes and rivers: a paleoenvironmental perspective. Arnold, London
- USEPA (1996) Method 3052: microwave assisted acid digestion of siliceous and organically based matrices. United States Environmental Protection Agency, Washington, DC, CD-ROM
- Wang SM, Dou HS (1999) Memoirs of lakes in China. Science Press, Beijing (in Chinese)
- Xia J, Zhang L, Liu CM, Yu JJ (2007) Towards better water security in North China. *Water Resour Manage* 21:233–247
- Xu K, John D, Xu H (2010) Temporal trend of precipitation and runoff in major Chinese Rivers since 1951. *Global Planet Change* 73:219–232
- Yang XD, Dong XH, Gao G, Pan HX, Wu JL (2005) Relationship between surface sediment diatoms and summer water quality in shallow lakes of the middle and lower reaches of the Yangtze River. *J Integr Plant Biol* 47:153–164
- Zeng HA, Wu JL (2009) Sedimentary records of heavy metal pollution in Fuxian Lake, Yunnan, China: the intensity, history and source. *Pedosphere* 19:562–569
- Zhang JY, Huang JY, Shen YR, Chen CT, Wu BC (1991) Picosecond optical parametric amplification in lithium triborate. *Appl Phys Lett* 58:213–215
- Zhu ZY, Zhou HY, Ouyang TP, Deng QL, Kuang YQ, Huang NS (2001) Water shortage: a serious problem in sustainable development of China. *Int J Sust Dev World* 8:233–237