Sediment chemistry and the variation of three altiplano lakes to recent anthropogenic impacts in south-western China

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Abstract

The sediments of the lakes on the Yunnan-Guizhou Plateau have been subjected to the pressures of natural and catchment area activities. An analysis of these sediments therefore offers an important opportunity to assess the quality of lake water and aquatic ecosystems. In this study, the sediment chemistry of three altiplano lakes, Lake Dianchi, Lake Qilu, and Lake Qionghai, in south-western China, was analyzed to determine the effect of natural and recent anthropogenic activities. Pb and Cu were the focus of the analysis for the three lakes as they posed the highest ecological risks compared with other heavy metals. As phosphorus is the limiting factor for the eutrophication in the three lakes total phosphorus was also focused on in this study. The results showed that the thickest sediment was in Lake Qilu, followed by Lake Dianchi and Lake Qionghai. Among the three lakes, more anthropogenic activity has occurred in Lake Dianchi than in Lake Qilu, and much more than in Lake Qionghai. Accordingly, the amounts of heavy metals and organic matter in Lake Dianchi and Lake Qilu were much higher than the amounts in Lake Qionghai. The industrial production value of the Lake Qilu watershed was 10.54-fold higher in 2003 than in 1988 whereas the concentrations of Pb and Cu were 3.80- and 1.68-fold higher than those of the baseline year. Variations in the amounts of heavy metals in lake sediments thus serve as an important indicator of industrial pollution of a lake. There was an increase in the level of total phosphorus in the lakes, which indicated the aggravation of lake eutrophication due to anthropogenic impacts.

Keywords: lake sediment, anthropogenic impacts, altiplano lakes, Lake Dianchi, Lake Qionghai, Lake Qilu

Introduction

As a major part of catchment area landscapes, lakes have numerous important functions for humans and their environment. Over the past several decades, the deterioration of the water quality in China's lakes has become of great concern to national and local governments due to the impact on national/regional economic development and environmental safeguards. According to data on water quality issued by the State Environmental Protection Administration (SEPA) of China, of the 27 lakes that have been monitored, 59.2% cannot meet the basic demands of daily life and agricultural irrigation (SEPA, 2005). Thus, comprehensive analysis and assessment as well as ongoing monitoring of water pollution in Chinese lakes are essential in order to respond promptly to environmental stresses, effectively manage lake environments, and better protect aquatic ecosystems.

Lake sediments can receive and absorb pollutants in the water column resulting from natural weathering, erosion, and anthropogenic activities. Thus they are an important historical record of natural and artificial effects. Pollutants are released from sediments into the water column in response to certain pressures, such as wave-induced disturbances (Bailey and Hamilton, 1997; Agarwal et al., 2005). In recent years, the impact of anthropogenic activities on lake sediments has increased markedly compared to the effects of natural processes, with the sedimentation of heavy metals and nutrients being the most obvious examples (Song, 1999; Das, 2005). In turn, changes in the content and spatial distribution of nutrients and heavy metals in lake sediments reflect an improvement or a decline in the quality of lake water and aquatic ecosystems (Li et al., 1995; Wang et al., 2004). For this reason, lake sediment analyses are being increasingly used to determine the effects of anthropogenic activities on lake catchment areas (Kleeberg et al., 1999; Royall, 2000; Nelson and Booth, 2002; Ruiz-Fernandez et al., 2002; Kim, 2003; Tibby, 2003).

Several major lakes are found on the Yunnan-Guizhou Plateau in China (Yang et al., 2005). However, the complex topography, physiognomy, and climate of this region have made it difficult to identify the sources of variations in the natural sedimentation of a particular lake, while the effects of artificial influences vary substantially over different periods of time. Although numerous studies have been conducted on the lake sediments in this region, such as the sediment analyses of Lake Erhai (Jin, 1995; Li et al., 1995; Wan et al., 2003; Ji et al., 2005) and Lake Dianchi (Jin, 1995; Xia et al., 2002; Lu et al., 2005), they have focused mainly on a single lake and did not compare changes in the sediment quality of different lakes or examine the effects on lake sediments due to catchment area activities, especially those associated with the rapid anthropogenic and economic developments during the past 30 years. In the present study, the sediments found in three typical altiplano lakes, i.e. Lake Dianchi, Lake Qilu, and Lake Qionghai, in Yunnan-Guizhou Plateau, were analyzed. Lake Dianchi is under pressure due to industrial pollution and urbanization, Lake Qionghai is mainly affected by agricultural activities, and Lake Qilu is influenced by agricultural activities as well as urbanization. Our aim was to evaluate differences in the sediment qualities of the three lakes and the impact of recent anthropogenic activities on water quality.

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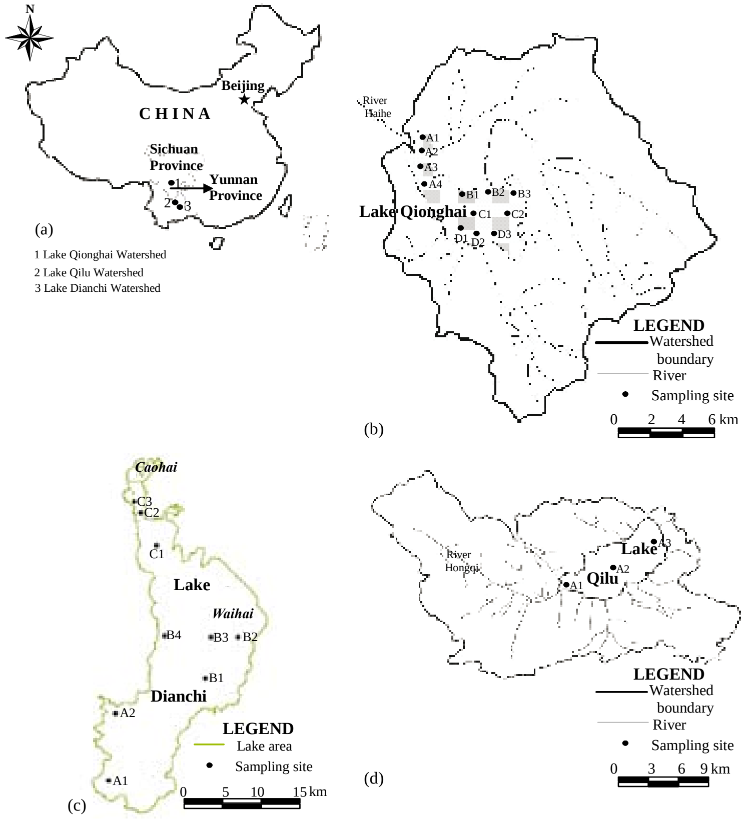

Figure 1
The location of the three lakes and the sediment sampling sites

Methods

The study area

Lake Dianchi, which comprises the lakes Caohai and Waihai, is located south of the city of Kunming (Fig. 1) at an altitude of 1 887.4 m. It is the 6th largest freshwater lake in China and has a surface area about 306.3 km^2 (Luo et al., 2004). The lake is the most important source of water for the surrounding watershed, which is located at latitude 24°28′ to 25°28′ N, longitude 102°30′ to 103°00′, has an area of approximately 2 920 km^2, and is characterized by a large human population and diversified industries. The rapid urbanization and industrial development of Kunming that began in the 1980s has led to a considerable deterioration in the water quality of Lake Dianchi. Industrial and urban contaminants have largely been released into Caohai, whereas mostly agricultural non-point pollution has contaminated Waihai. As a result, the water of Lake Dianchi is no longer suitable for daily life and agricultural activities. Moreover, the increasing deposition of contaminants and nutrients has led to extensive eutrophication, and in turn, the functional degeneration of the lake. Consequently, the socioeconomic development of the region and the health of its local residents have been greatly altered.

Lake Qilu is located in the city of Yuxi, Yunnan Province. It has a surface area of about 37.26 km^2 and a volume of about 1.676 × 10^8 m^3 at an altitude of 1 797.65 m (Fig. 1). The lake's watershed covers a much smaller region than that of Lake Dianchi – about 354.2 km^2 at latitude 24°4′ to 24°14′ N and longitude 102°33′ to 102°52′ E (Ma et al., 1999) – and is the site of intensive agricultural and industrial activities. Wastewater generated by industrial sources and urban living together with agricultural non-points contaminants are the main sources of pollution. In addition, Lake Qilu is surrounded by swampland and is of a long lake age. For these reasons, the quality of the water is such that it cannot satisfy the needs of the catchment area.

Lake Qionghai covers an area of 27.88 km^2 at a water-surface elevation of 1 509.8 m, a volume of 2.89 × 10^8 m^3 (Liu et al., 2006), and a drainage basin of 307.67 km^2. It is situated in the north-eastern portion of the city of Xichang, Sichuan Province, China (Fig. 1). Since Lake Qionghai is famous for its scenery, the environmental and ecological condition of its water is tied to the socioeconomic development of the region. In the catchment area, farming, forestry, and tourism have been the main causes of the degeneration in water quality that has occurred since the 1990s (Yong and Wang 2003). Soil erosion and the periodic flow of mud-rock amount to 9.35 × 10^5 m^3 bed-loads annually and bring large amounts of nutrients and heavy metals into the lake.

Sampling method

An XY100 drilling machine and vacuum suction were used for field sampling. The inner diameter of the sampling instrument was 110 mm, and the sampling depth was 3 m in normal sediments. All of the field samples were collected in 2003. Historical data were obtained from related references (Jin, 1995). The distributions of the sampling sites are shown in Fig. 1. The sediment samplings were prepared *in situ* and then transferred to the laboratory in airproof containers. Analytical methods strictly followed SEPA's recommended national standard GB3838-2002 (SEPA, 2003). Heavy metals are always inert in the sediment environment and were analyzed as the conservative pollutants (Wilcock, 1999). In addition, in the three lakes, Pb and Cu are the heavy metals with the highest ecological risks (Jin, 1995) and should therefore be the focus of the study. In addition, phosphorus is the limiting factor for the eutrophication in the three lakes (Ma et al., 1999; Luo et al., 2004; Liu et al., 2006). Thus we measured the thickness of the sediment layer and the concentrations of heavy metals and nutrients, such as Fe, total phosphorus (TP), total nitrogen (TN), organic substances, Cu, Zn, Pb, Cd, Cr, and As. In addition, as most of the development affecting the three catchment areas has taken place since the 1980s, we compared data obtained in 1988 and 2003, two periods that reflect the impact of human activities and lake deposition processes.

Results and discussion

Vertical distribution of lake sediments

Assessment of the vertical distribution of the lake sediments demonstrated the effects of changes in the catchment area of the lakes (Das, 2005). Those results were supported by analyses of the thickness, nutrient, and heavy metal content as well as the characteristics of the different sediment layers (Table 1).

We compared the thickness and characteristics of the contaminated silt layers of the three lakes and found that the contaminated silt layer of Lake Qilu was the thickest, and that of Lake Qionghai the thinnest. Lake Qilu, the lake with the longest age, showed the cumulative effects of agricultural,

TABLE 1 The sediment layers and the sediment characteristics for the three lakes			
Lake	**Sediment layer**	**Average thickness**	**Characteristics**
Lake Qionghai	①	0.10 m	nigrescent(taupe), fluid, with rotten plant debris, rancid
	②	0.15 m	lark, hypogenesis which is related to the generation and limited evolution of Lake Qionghai
	③	-	grey, with little plant debris, the geological substrate of the lake
Lake Qilu	①	0.26 m	taupe-black brown, fluid, peat soil
	②	0.57 m	taupe-black deepening with the depth, with plentiful plant roots in the top, with spiral shell in the middle, peat soil
	③	-	Grey-taupe, fluid, sludge
Lake Dianchi	①	0.20 m	black-atrous, fluid, rancid
	②	0.10 m	black-brown-filemot, with plentiful debris of underwater plant roots and caudex, loose
	③	-	filemot-yellow, marly and flour clay
Notes: ① Contaminated sullage layer; ② Transition layer; and ③ Natural sediment layer.			

TABLE 2 The vertical distribution of the nutrient and heavy metal of Lake Qilu sediments										
Sediment layer	**TN**	**TP**	**Pb**	**Cd**	**Cu**	**Zn**	**As**	**Hg**	**Organic matter (%)**	**Water content (%)**
	(%)	**(%)**	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**		
①	0.64	0.16	62	1.4	44.6	92.4	8.08	0.07	10.62	60.06
②	0.94	0.15	38.3	0.9	31	47.75	4.78	0.02	18.07	66.93
③	0.2	0.11	75.8	3.24	31.8	229.06	3.34	0.04	2.54	6.34

TABLE 3 The principal contaminants concentration of the surficial sediment in Lake Qionghai (2003)				
Sampling site	**TP(mg/kg)**	**TN(mg/kg)**	**Pb(mg/kg)**	**Organic matter (%)**
A1	1.077	37.16	1.564	1.94
A2	1.491	36.77	1.672	1.01
A3	1.491	34.83	1.589	0.57
A4	1.049	27.55	1.566	1.34
B1	0.69	43.17	1.624	1.7
B2	3.507	73.92	-	2.72
B3	1.684	37.93	1.507	0.29
B4	1.808	48.22	-	2.17
C1	1.339	29.59	1.753	2.38
C2	2.899	34.88	1.637	0.14
C3	0.69	45.31	1.699	0.98
D1	0.98	41.62	1.74	2.23
D2	1.546	35.99	2.003	0.76
Variance	0.672	134.2	0.018	0.718
Skewness	1.445	2.136	1.562	0.01
Kurtosis	1.888	5.964	3.34	-1.757

industrial, and municipal pollution, whereas the silt layers of Lake Dianchi (Waihai) were thinner because Lake Caohai takes up most of the industrial and municipal pollution. Lake Qionghai is, on average, the deepest of the three lakes, with a high ratio of catchment area to lake area. Little artificial disturbance has occurred and economic development in the watershed has been minimal.

The vertical distribution of the nutrient and heavy metal content of the three lakes was marked by distinct differences. In Lake Qilu, the concentrations of TN, TP, Cu, As, Hg, and organic matter in both the contaminated sullage layer and the transition layer were higher than in the natural sediment layer (Table 2). The high levels of nutrients, and especially heavy metals, reflect the large amount of artificial activity at Lake Qilu. Table 2 shows the levels of nutrients and heavy metals in the transition layers of the three lakes.

Heavy metals and nutrients in surficial sediment

The surficial substrate, including those layers contaminated with heavy metals and nutrients, might be resuspended by the combined actions of wind and waves, thereby generating new sources of pollution. The heavy metal and nutrient concentrations of the surficial sediment from Lake Qionghai, Lake Qionghai, and Lake Dianchi are shown in Tables 2, 3, and 4, respectively.

TABLE 4 The principal contaminants concentration of the surficial sediment in Lake Dianchi (2003)								
Sampling site	**As**	**Hg**	**Cr**	**Pb**	**Cd**	**Cu**	**Zn**	**TP**
A1	23.84	0.138	60.522	160.65	3.61	79.52	142.9	25.53
A2	31.52	0.106	57.469	144.18	4.22	78.5	119.24	21.59
B1	34.79	0.174	56.565	89.47	4.39	87.92	153.41	16.59
B2	28.71	0.065	43.535	101.43	3.23	82.33	158.05	15.89
B3	31.31	0.165	69.425	114.86	4.48	87.07	125.13	16.47
B4	37.67	0.151	68.056	129.88	4.52	76.53	156.71	18.46
C1	66.5	0.381	55.248	132.79	6.99	107.11	535.55	14.6
C2	97.5	0.65	71.706	295.86	50.17	233.45	344.69	28.71
C3	208.12	1.181	97.466	389.86	67.25	283.82	935.67	21.49
Variance	3549.8	0.134	228.6	10257.7	590.9	6063.9	76446.3	22.9
Skewness	2.251	1.918	1.198	1.652	1.744	1.676	1.914	0.824
Kurtosis	5.225	3.446	2.591	1.852	1.601	1.368	3.378	-0.355

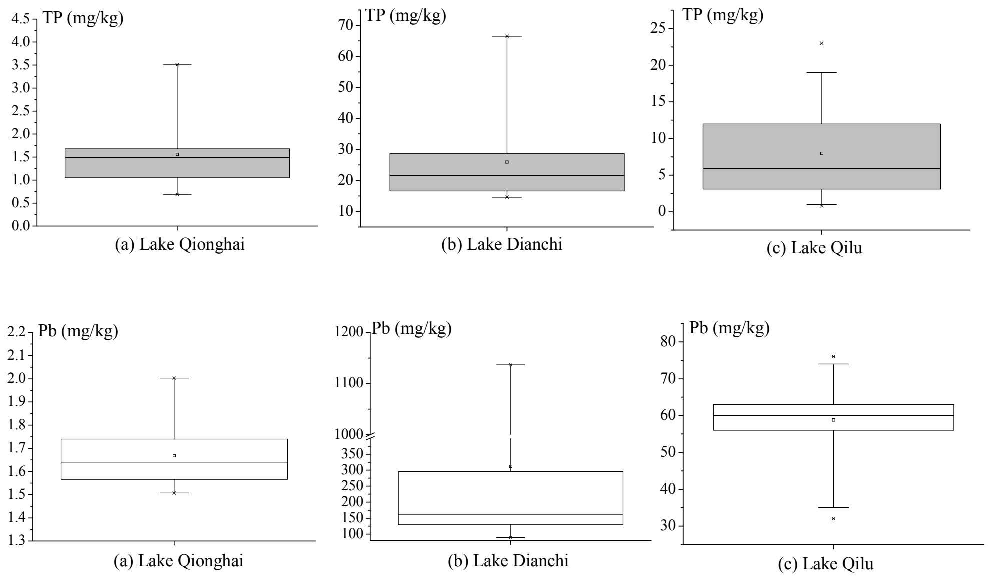

Figure 2
The comparative analysis of TP and Pb concentrations in the sediments of the three lakes

Figure 2 compares the TP and Pb concentrations of the three lakes. The heavy metal and nutrient concentrations of the surficial sediments of Lake Dianchi and Lake Qilu were much higher than those of Lake Qionghai. For example, the Pb concentrations in the surficial sediments of Lake Dianchi and Lake Qilu were, respectively, 221.04- and 41.58-fold higher than in the sediments of Lake Qionghai. The organic matter concentration in the surficial sediment of Lake Qilu was 7.43 times higher than that of Lake Qionghai. The TP concentration in the surficial sediment was 16.65 times higher in Lake Dianchi than in Lake Qionghai. The Pb and TP concentrations of different monitoring points in Lake Dianchi varied greatly, most likely due to frequent artificial disturbances in the catchment area. The population load (population per km^2) of the Dianchi catchment area was 1.16-fold higher that that of the Qilu catchment area and 273.45-fold higher than that of the Qionghai catchment area, and the industrial output load (10 000 yuan/km^2) of the Dianchi catchment area was 6.53-fold more than that of the Qilu catchment area and 65.32-fold more than that of the Qionghai catchment area.

The results showed that catchment area disturbances, caused by a large population and dense artificial activities, had the greatest impact on Lake Dianchi and the least effect on Lake Qionghai, which also had the smallest population and few artificial activities.

Horizontal distribution of lake sediments

Analysis of the thickness of the lake sediments and the concentration levels of heavy metals and nutrients improves our understanding of the temporal distribution of pollutants – and consequently, provides firsthand evidence regarding the need for internal pollution control and management. Monitoring of Lake Qilu's sediment (Table 2) showed that the distribution of sediment broadly included the entire lake; however, the concentrations of pollutants at the different sampling sites were not linear. The thickest sediments, 0.30, 0.23, and 0.27 m, respectively, were measured in the estuary of the Hongqihe River, the lake bay, and in the central lake (Fig. 1d). Little polluted sediment was detected in and near the outlet area of the lake. The relatively uniform distribution of Lake Qilu's sediment was due to its water level, which may be as low as 4.5 m. Therefore, the sediment is most likely resuspended by the wind.

The sediment distributions in Lake Qionghai can be classified into three sub-regions according to the sampling data (Table 3) and the cluster analysis of spatial distribution of pollutant concentrations (Fig. 3a): the north-western area (Part A in Fig. 1b), the northern area (Part B in Fig.1b), and the middle area (Part C in Fig. 1b). The north-western part of the lake is the

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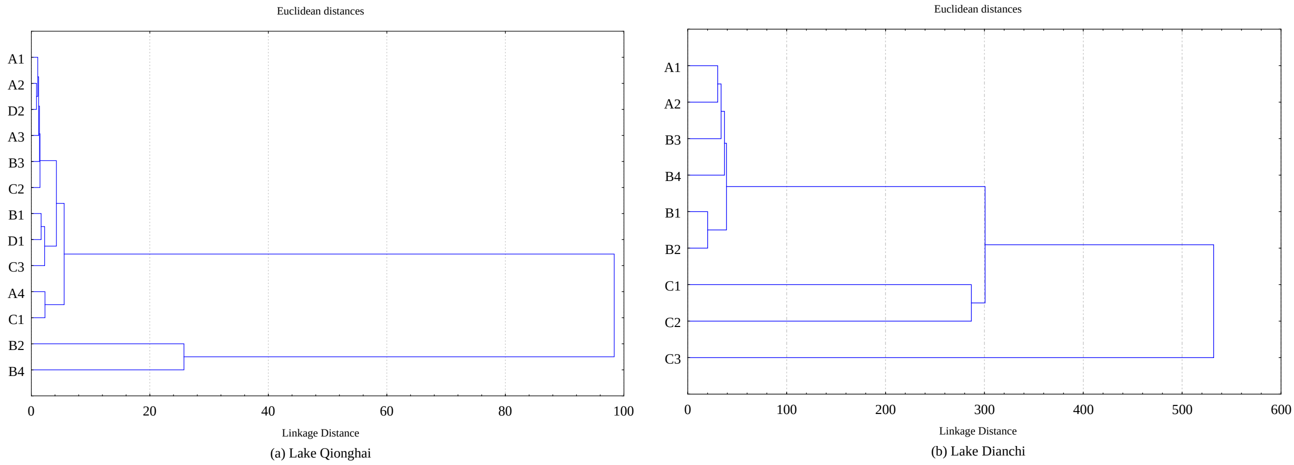

Figure 3
Dendrograms from spatial cluster analysis of pollutant concentration distributions for Lake Qionghai and Lake Dianchi
(a) Lake Qionghai
(b) Lake Dianchi

most severely silted and appears black or red-black without any aquatic plants. These properties may have resulted from the lake once having been flooded by the Haihe River. The northern area, which is less silted, is red or black with coarse granules in the sediment. Some organic components are evident but the levels of TN and TP are relatively high, most likely due to soil and water losses from the upper reaches. The middle area, which is the least silted due to the deep-water level, appears red or redblack and has fine granules.

The cluster analysis for the spatial distributions of pollutant concentrations in Lake Dianchi shows that the spatial distribution is not even, especially the sampling Site C3 (Fig. 3b). The following focus is concentrated on phosphorus (P) in the sediment for the simple reason that the critical eutrophic factor in Lake Dianchi is P (Jin, 1995). The distribution of P in the sediment of Lake Dianchi is shown in Table 4. Horizontally, the P level gradually descends from north to south in Caohai, while the reverse is true in Waihai. The highest P levels (≤5.80 mg/g) in Lake Dianchi were found in the deposits of Regions A1 and A2, due to fluvial phosphorite minerals in the southern part of Lake Dianchi, where weathering of the earth's surface and subsequent runoff result in the release of large amounts of phosphoric materials into the lake. In addition, pollutants from the Kunming Phosphorus Mineral Factory are directly released into the lake, but the hydropower of the southern part of Lake Dianchi is not strong enough to transfer the mud and sand to areas farther away. Thus, the alluvium steadily accumulates (Tian et al., 2002).

The TP levels in the sediments of Lake Dianchi during the high-water-level period of 2003 were higher than those of a similar period in 1988 at all monitoring sites. This difference was particularly noteworthy at sites near Lake Caohai, such as C1, C2, and C3 (Fig. 4). Based on the above observations, we concluded that the sediments of Lake Dianchi are undergoing a period of slowly increasing P levels.

Similarly, data from 2003 and 1988 were also compared for Lake Qilu. Little change had occurred in the levels of TN and TP, while those of the heavy metals Pb and Cu increased by as much as 3.80- and 1.68-fold, respectively. The data for Lake Qionghai showed an increase in the level of organics, as measured by changes in the amounts of TN and TP (Jin 1995). Lake sediments are easily influenced by the combined actions of natural movement and human activities. Organic and eutrophic matter

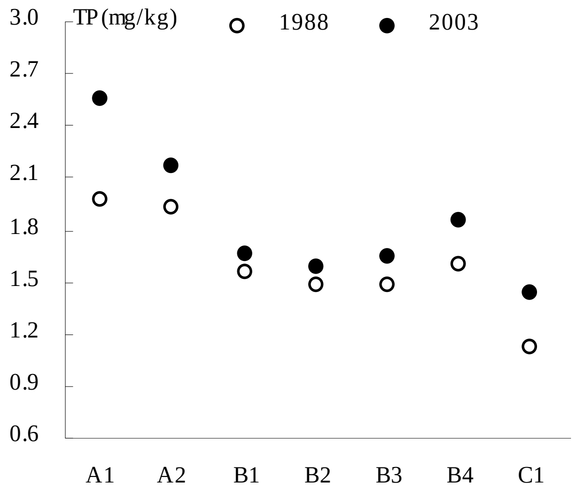

Figure 4
P distribution in sediments of Lake Dianchi in wet seasons of 1988 and 2003

is released by natural and anthropogenic contaminations, while heavy metals are contributed primarily by the latter. According to Wilcock (1999), the extent of heavy metal contamination serves as an indicator of industrial pollution in the catchment area. This argument can be easily validated in Lake Qilu, where from 1988 to 2003, the economic capacity, especially small-scale industry, developed rapidly in the catchment area, as reflected by the 10.54-fold increase. However, during that time, wastewater was imported into the lake without any treatment, such that the levels of heavy metals in the sediment increased significantly whereas those of organic matter (TN and TP) increased at a much slower pace. This difference is also influenced by the differential absorption and decomposition of organic-, nitrite-, and phosphorus-containing matter.

Conclusions

- In the three altiplano lakes, the depth of the sediment layer was greatest in Lake Qilu, followed by Lake Dianchi and Lake Qionghai. The different depths of the sediment layers are a product of both differences in the drainage areas of the lakes and their individual characteristics.

- Anthropogenic activities in Lake Dianchi are greater than in Lake Qilu, and much greater than in Lake Qionghai. Consequently, heavy metals and organic matter were much higher in the sediments of the former two lakes than in those of the latter one.
- The distributions of sediment pollutants are as follows: Lake Qilu has a relatively normal distribution due to its low water level. In Lake Qionghai, the water level is higher, and thus pollutants are mainly located in the river estuary. In Lake Dianchi, phosphorus levels increase from north to south as a result of the phosphorite mines on the southern side of the lake.
- Variations in the amounts of heavy metals in lake sediments serve as an important indicator of industrial pollution of a lake. The industrial production value in the drainage area of Lake Qilu was 10.54-fold higher in 2003 than in 1988 whereas the concentrations of Pb and Cu increased 3.80- and 1.68-fold compared to the baseline year.

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