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RESEARCH ARTICLE

Heavy metals in the surface sediments of lakes on the Tibetan Plateau, China

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Abstract Heavy metal contamination has affected many regions in the world, particularly the developing countries of Asia. We investigated 8 heavy metals (Cu, Zn, Cd, Pb, Cr, Co, Ni, and As) in the surface sediments of 18 lakes on the Tibetan Plateau. It was found that the distributions of the heavy metals showed no clear spatial pattern on the plateau. The results indicated that the mean concentrations of these metals in the sediment samples diminished as follows: Cr > As > Zn > Ni > Pb > Cu > Co > Cd. The results of geoaccumulation index (I_{geo}) and potential ecological risk factor (E^i_r) assessments showed that the sediments were moderately polluted by Cd and As, which posed much higher risks than the other metals. The values of the potential ecological risk index (RI) showed that lake Bieruoze Co has been severely polluted by heavy metals. Principal component analysis, hierarchical cluster analysis, and Pearson correlation analysis results indicated that the 8 heavy metals in the lake surface sediments of the Tibetan Plateau could be classified into four groups. Group 1 included Cu, Zn, Pb, Co, and Ni which were mainly derived from both natural and traffic sources. Group 2 included Cd which mainly originated from anthropogenic sources like alloying, electroplating, and dyeing industries and was transported to the Tibetan Plateau by atmospheric circulation. Group 3 included Cr and it might mainly generate from parent rocks of watersheds. The last Group (As) was mainly from manufacturing, living, and the striking deterioration of atmospheric environment of the West, Central Asia, and South Asia.

Keywords Sediments · Heavy metal · Ecological risk · Contamination indices · Source

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Introduction

Industrialization and agricultural processes have led to increasing levels of heavy metal pollution in the aquatic phase through atmospheric deposition, waste water discharge, water and soil erosion and rain-wash (Uluturhan and Kucuksezgin 2007; Zhu et al. 2010). Therefore, significant quantities of heavy metals are discharged into lakes. The increasing levels of contamination result in sublethal environmental hazards for humans and the ecological environment due to being non-biodegradable in the environment and their ability to easily enter into the food chain (Almeida et al. 2002; Jones et al. 2001; McGeer et al. 2000; Yi et al. 2011). Heavy metals have become a special group of contaminants in water systems (Loska and Wiechuła 2003).

Lake sediments can absorb and receive heavy metals through co-precipitation, hydrolysis, and adsorption processes (Singh et al. 2005; Wang et al. 2010; Suresh et al. 2015).

Sediments are sensitive indicators for monitoring contaminants and not only act as carriers of heavy metals but also potential secondary sources of heavy metals in aquatic systems (Vandecasteele et al. 2004; Fatoki and Mathabatha 2004). After sedimentary deposition, heavy metals can be released into an overlying water source in response to both chemical and biological factors and certain disturbances, thereby resulting in sublethal effects or death in humans (Hill et al. 2013; Jia et al. 2013). Thus, understanding the properties of heavy metals in lake sediments is very useful for evaluating the pollution status in an aquatic environment (Bai et al. 2011, Pekey 2006).

To date, serious environmental status issues have caused widespread concern from the public and government at different levels, and a great amount of studies have been focused on heavy metals in sediments. Wang et al. (2010) reported that human activities strongly affected these chemicals in Qinghai Lake through an analysis of heavy metals in the sediments. However, heavy metals in the Yarlung Tsangbo (YT) river sediments were derived fundamentally from the parent rocks of the YT river basin (Li et al. 2011). Although combinations of different sources of heavy metals have been previously studied, limited research has been focused on the ecological risk assessment of heavy metal contamination in the lake sediments of the Tibetan Plateau.

The Tibetan Plateau contains more than 1055 plateau inland lakes, which are mainly supplied by surface runoff, precipitation, and glaciers (Wan et al. 2014). Rock weathering, climate change, glacier melting, and human activities in the watershed all influence the chemical characteristics of lakes on the Tibetan Plateau (Zhu et al. 2010; Wang et al. 2012). Although the Tibetan Plateau used to be far from industrialized areas and lightly populated, it is adjacent to South Asia, which has experienced a recent boom in industry. In addition, the Tibetan Plateau is the water source for rivers that feed approximately one-third of the global population (Xie et al. 2014). Heavy metal pollution in the aquatic ecosystem will directly affect human health and the stability of the vulnerable highland ecosystem (Xie et al. 2014).

Therefore, this study selected 18 lakes on the Tibetan Plateau to investigate the sources of heavy metals in the lake sediments and their hazards on human life and the ecological environment. The results provide a basis for the comprehensive evaluation of the environmental quality and heavy metal pollution in the Tibetan Plateau.

Materials and methods

Study area

The Tibetan Plateau and its surrounding mountains are called the Third Pole of the World (Yan et al. 2013a). It is the largest and highest plateau in the world with an average altitude of 4500 m above sea level. The Tibetan Plateau contains the majority of the world's largest and highest saline and alkaline lakes (Zhang et al. 2012). The total area of the lakes on the Tibetan Plateau is approximately 3.7×10^4 km^2, which equals 51% of China's total lake area (Zhang et al. 2012; Shi et al. 2014). The Tibetan Plateau also represents one of the largest ice masses beside the polar regions and includes more than 1×10^5 km^2 of glaciers (Zhang et al. 2015). The climate of the Tibetan Plateau is cold and dry with low annual precipitation and strong evaporation. Therefore, glacier melt water is one of the major sources that supply the plateau lakes (Lu 2005).

Sampling

In this study, 18 lakes on the Tibetan Plateau were investigated (28°34′33.347″~34°36′40.804″N, 78°57′30.553″~96°45′E, Fig. 1), including the Songmuxi Co (SMXC), the Longmo Co (LMC), the Bangong Co (BGC), the Lubu Co (LBC), the Kunzhong Co (KZC), the Rebang Co (RBC), the Aiyong Co (AYC), the Awong Co (AWC), the Gongzhu Co (GZC), the Zhacangcha Ka (ZCCK), the Bieruoze Co (BRZC), the Darebu Co (DRBC), the Lang Co (LC), the Dong Co (DC), the Yangzhoyong Co (YZYC), the Pumoyo Co (PMYC), the Daze Co (DZC), and the Ranwu Co (RWC) lakes (Table S1). The altitudes and areas of the 18 lakes range from 3850 (RWC)-5010 (PMYC) m above sea level and 12.1 (LC)-638 (YZYC) km^2. The Tibetan Plateau supports a wide diversity of ecosystems due to its unique geographic position and its strong climate gradients and variety of vegetations across the whole plateau. The summer and winter monsoons of Asia contribute to the development of wetter climates in the southern and eastern Tibetan Plateau and drier climates in the northern and western Tibetan Plateau (Kutzbach et al. 1993). There are obvious regional patterns of vegetation growth across the plateau. The southeastern region is mostly subtropical evergreen broad-leaved forest, the central Tibetan Plateau is mainly dominated by alpine meadow and alpine grassland, and the western area is alpine desert steppe. These regional gradients exert effects on the lakes of the Tibetan Plateau. Therefore, our 18 studied lakes are distributed across different regions throughout the entire plateau. The 18 lakes, which exhibit salinities that vary from 0.3 to 47.1 g L^{-1}, are divided into freshwater lakes, brackish water lakes, and saline lakes according to Wang and Dou (1998). Accordingly, SMXC, RWC, PMYC, and BGC are freshwater lakes; LC, GZC, DC, and YZYC are brackish water lakes; and LMC, AYC, RBC, AWC, ZCCK, BRZC, and DZC are saline lakes. In 2007, we used an Ekman Grab to get surface sediment (approximately 10 cm) samples from the centers of the 18 lakes and the sample size is a cube about 20 cm × 30 cm × 8 cm. All sediment samples sealed on site with whirl packs and then transferred to and frozen in the lab at − 20 °C until
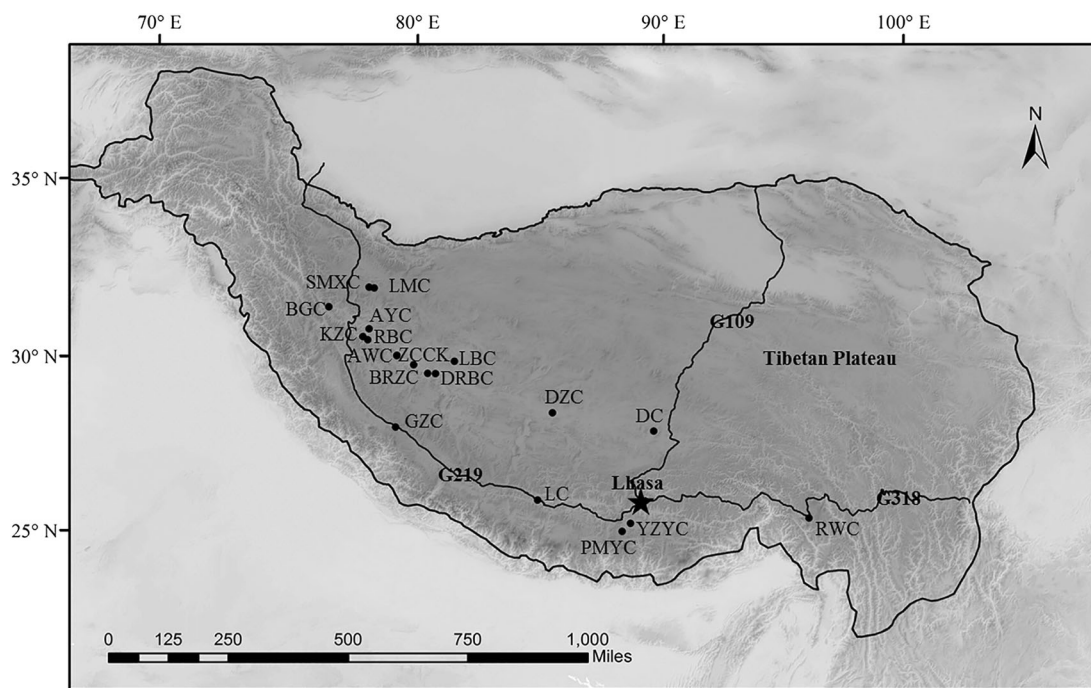
Fig. 1 Site location map of 18 sampling lakes in the Tibetan Plateau

further analyses were conducted. We collected about 200 g sediment of each sampling site in the field and used 20–25 g to measure in the lab. We collected one surface sample from RWC, LC, GZC, BGC, SMXC, LMC, AYC, RBC, AWC, BRZC, DRBC, DC, DZC, PMYC, and YZYC, 2 samples from LBC and KZC, and 3 samples from ZCCK.

Data extraction

We extracted the lake areas using lake data from a paper entitled "Lakes' state and abundance across the Tibetan Plateau" by Zhang et al. (2014) (Zhang et al. 2014). The catchment areas were provided through a suite of drainage and water flow data known as HydroSHEDS (hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales) (Lehner et al. 2006). Glacier melt water is one of the most important sources for the lakes on the Tibetan Plateau. Based on the data from the Second Glacier Inventory of China, we obtained the glacier areas in each of the 18 lake catchments. We also collected the lake water electrical conductivities and pH values from previous studies (Wang and Dou 1998).

Chemical analysis

The sediment samples were air-dried at room temperature in the lab and were crushed and sieved through a 100-mesh nylon sieve for further study. For the heavy metal element analysis, approximately 20–25 mg of finely ground sediment sample material was weighed and placed into a PTFE beaker and moistened with water. Reference samples (e.g., AGV-2 and GSS-9) were used to control the quality of the total analytical procedure. One milliliter of 16 mol L^{-1} HNO$_3$ (electronic grade purity, Duksan Co., Korea) and 1 ml of 22 mol L^{-1} HF (BV-III grade, Chemical Reagent Research Institute of Beijing, China) were added into the beaker sequentially. After closing the beaker and placing it into an ultrasonic bath for approximately 30 min, the sample was placed on a hot plate at 155 °C and evaporated until nearly dry. Another 1 ml of 16 mol L^{-1} HNO$_3$ and 1 ml of 22 mol L^{-1} HF were added to the beaker, and the beaker was again placed into the ultrasonic bath for 30 min. The beaker was closed and placed into a pressure-resistant steel can before being heating within an oven at 190 °C for 24 h. The beaker was opened and heated until nearly dry at 155 °C. Then, 1 ml of 16 mol L^{-1} HNO3 was added, and the beaker was heated until nearly dry twice. Two milliliters of 16 mol L^{-1} HNO$_3$ and 3 ml of ultrapure water were added to the beaker before closing and heating it at 150 °C for another 24 h. The solution was then transferred to a polypropylene bottle, and ultrapure water was added with a weight that was approximately 2000 times that of the sample. The concentrations of the heavy metals were measured using an inductively coupled plasma mass spectrometer (ICP-MS, X-7 Series) with relative standard deviation values (i.e., an analytical precision) of less than 5%. In order to run samples at sufficiently high signal intensity, the operating parameters like sensitivity, background, oxide, dual charge, and stability of equipment installation standards of ICP-MS were defined by the tuning optimization. The main operating parameters of the instrument were as follows: RF power 1300 W, cooling

gas 14.0 L min^{-1}, auxiliary gas 0.95 L min^{-1}, Nebuliser gas 0.88 L min^{-1}, oxide ion yield < 2%, and double charge ion yield < 3%. The recovery rates of AGV-2 for Cu, Zn, Pb, Cr, Co, and Ni were 100.30, 104.02, 103.30, 103.29, 101.63, and 100.00%, respectively. The recovery rates of GSS-9 for Cu, Zn, Cd, Pb, Cr, Co, Ni, and As was 107.72, 91.18, 77, 91.56, 100.87, 96.57, 106.12, and 101.30%, respectively.

Statistical analyses

The multivariate statistical analyses, namely, principal component analysis (PCA), hierarchical cluster analysis (HCA), Pearson correlation analysis, and data standardization, were performed using the SPSS Statistics 22 software for Windows. PCA was used to reveal the various origins of the heavy metals. The validity of the PCA was examined using the Kaiser-Meyer-Olkin (KMO) and Bartlett sphericity tests. A varimax rotation was applied, and the PCs with eigenvalues above 1 and cumulative variances above 70% were retained (Liu et al. 2003; Lee et al. 2006; Li and Zhang 2010; Huang et al. 2013). The purpose of the HCA was to classify the heavy metals and lakes into categories or clusters based on their similarities. The HCA was conducted based on the Ward method and the squared Euclidean distance (Jiang et al. 2013; Zhu et al. 2013; Tang et al. 2014). The Pearson correlation analysis was applied to statistically characterize the relationships between the heavy metal concentrations with other factors. Data standardization, which equalizes the effects of the different variables, was carried out based on the mean values of the Z-punctuations.

Risk assessment methods of heavy metals in 18 lake sediments

Geoaccumulation index method

The geoaccumulation index (I_{geo}) is a classical assessment model that enables an evaluation of the considered changes in background concentrations caused by both natural geological processes and anthropogenic effects (Muller 1969; Zhang et al. 2016). This index compares the heavy metal pollution levels found in a system with their pre-industrial levels (Dahms et al. 2017). Mathematically, the I_{geo} is expressed as

$$I_{geo} = \log_2 \left[\frac{C_n}{1.5 B_n} \right] \tag{1}$$

where C_n is the concentration of the metal n in the sediment and B_n is the geochemical metal background concentration (Cheng and Tian 1993). A value of 1.5 is used for the background matrix correction coefficient. The I_{geo} values of the heavy metals are categorized according to seven levels, as shown in Table S2.

Evaluating potential ecological risks

To evaluate the potential ecological risks associated with the toxicities of the heavy metals and the organism response to the environment, the Hakanson potential ecological risk index method was used in this study (Hakanson 1980). It can not only assess the contamination degrees of heavy metals but also reveal the biological risk in the study region (Yan et al. 2013a; Yan et al. 2013b). The index is calculated by Eq. (2):

$$RI = \sum E^i_r; E^i_{r=} T^i_r \times C^i_{f;} \ C^i_f = C^i_s / C^i_n \tag{2}$$

where RI is the potential ecological risk index for a given region, E^i_r is the potential ecological risk factor of a given substance i, T^i_r is the toxic-response factor of a single pollution element i, C^i_f is the pollution coefficient of a heavy metal i, C^i_s is the concentration of a metal i in the sediment, and C^i_n is a reference value for a given metal i. The degree of the potential ecological risk index (RI) of a given region is divided into 4 grades, and the degree of the ecological risk index (E^i_r) of a given substance is divided into 5 grades, as shown in Table S2 (Hakanson 1980).

Results and discussion

Basic statistics and concentration comparisons

The concentrations of the 8 heavy metals varied among the different lakes (Table 1). The Cu concentration ranged from 9.2 to 74.1 mg kg^{-1} with the highest value in lake LC and the lowest in lake LMC. The Zn concentration varied from 31.2 to 156 mg kg^{-1}; lake SMXC had the highest value of Zn and lake DRBC had the lowest. The concentration of Cd varied within a range of 0–0.8 mg kg^{-1}, where the highest Cd concentration was in lake RBC and the lowest was in lake DRBC. The Pb concentration ranged from 13.1 mg kg^{-1} in lake DRBC to 76.7 mg kg^{-1} in lake RWC. The concentration of Cr varied between 26.5 and 262 mg kg^{-1}, an extremely high Cr concentration was found in lake GZC. The Co concentration varied from 0.1 mg kg^{-1} in lake DRBC to 23.2 mg kg^{-1} in lake LC. The concentration of Ni ranged from 11 mg kg^{-1} in lake DRBC to 95.2 mg kg^{-1} in lake RBC. The concentration of As varied from 11.1 mg kg^{-1} in lake LBC to 216 mg kg^{-1} in lake GZC. The mean concentrations of these metals in the sediment samples followed the order of Cr > As > Zn > Ni > Pb > Cu > Co > Cd. The distributions of the 8 heavy metals are shown in Fig. 2.

Many researches have studied the sources of heavy metals in lake sediments and the results are different. Comparing to the heavily industrialized lake—Taihu Lake, the concentrations of Cu, Zn, Pb, Cr, and Ni were all significantly higher than in the Tibetan Plateau sediments (Tao et al. 2012).

Table 1 Concentrations of 8 heavy metals in lake sediments

Lake ID	Concentrations (mg kg^{-1})							
	Cu	Zn	Cd	Pb	Cr	Co	Ni	As
RWC	43.9	144	0.2	76.7	55.9	15.5	31.5	36.5
LC	74.1	123	0.3	27.2	110	23.2	69.1	28.0
GZC	41.4	53.9	0	13.2	262	0.9	44.5	216.0
BGC	32.9	109	0.1	20.4	164	9.5	38.5	14.5
SMXC	28.9	156	0.3	53.7	56.5	15.1	34.9	34.8
LMC	9.2	46.8	0.1	22.8	11.9	4.5	11.2	11.1
AYC	12.7	53.2	0	12.2	35.7	7	35.6	65.8
LBC	14.8	47.3	0.3	22	78.9	2.7	21.4	12.8
KZC	32.5	64.7	0.3	17.3	102.3	7.8	45.6	16.2
RBC	21.6	64.4	0.8	40.7	72.7	11.1	95.2	53.3
AWC	17.5	49	0.3	20.3	40.8	9.8	58.7	29.1
ZCCK	11.7	42.8	0.2	16.9	29.5	3.4	12.1	153.8
BRZC	12.9	47.1	0.7	16	38.7	4.7	20.9	463
DRBC	14.3	31.2	0	13.1	100	0.1	11.0	31.8
DC	9.8	42.6	0.3	26.2	26.5	5.6	22.8	53.1
DZC	19	65.8	0.6	18.5	63.8	8.5	33.2	27.1
PMYC	42.3	142.1	0.1	47.7	73.7	14.8	32.1	–
YZYC	31.5	62.5	0.1	21.7	67.4	13.1	35.3	48.3
Average	26.2	74.7	0.3	27.0	77.2	8.7	36.3	76.2
S.D.	16.7	40.4	0.2	17.1	58.8	6.0	21.4	113.2
Background value	21.9	73.7	0.1	28.9	77.4	11.6	32.1	18.7

– no value

According to the analysis of Tao et al. (2012), anthropogenic activities had a significant impact on heavy metals in Taihu Lake. Taihu locates at one of the most densely populated and economically developed regions of China where water quality has been deterioration by increased anthropogenic inputs (Qu et al. 2001; Tao et al. 2012). Since the Tibetan Plateau is less affected by anthropogenic activities than Taihu Lake, heavy metal concentrations were much lower in our studied lakes. Comparing to the other studies of the Tibetan Plateau, it is interesting to notice that the concentrations of Cu, Zn, Cd, Pb, Cr, Co, and Ni were at the same level with the metals found by Wang et al. (2010) in Qinghai Lake while As was about 7 times higher in our studied lakes (Wang et al. 2010). As was likely from the atmospheric inputs of anthropogenic sources in Qinghai Lake which located on the Tibetan Plateau (Wang et al. 2010). Since the concentrations of As in our studied lakes was much higher, and most of our studied lakes locate in the south part of the Tibetan Plateau adjacent to South Asia where atmospheric pollution is serious, we suggested that As in our lakes could be affected by anthropogenic activities (Lelieveld et al. 2001; Cong et al. 2007). The Yarlung Tsangbo is a large river that runs across southern Tibet, the upper reaches of the Brahmaputra River (Hren et al. 2007). Compared to Yarlung Tsangbo, the

concentrations of Cu, Zn, Pb, Cr, Co, and Ni were little lower in our studied lakes (Li et al. 2011). According to Li et al. (2011), most heavy metals in the Yarlung Tsangbo sediments indicated almost no anthropogenic impact. Also, the concentrations of Cu, Zn, Cd, Pb, Cr, Co, and Ni were at the same level with the background values of the Tibetan Plateau soil (Cheng and Tian 1993). Although As and Cd were higher in our studied lakes than in the Yarlung Tsangbo sediments, we indicated that most heavy metals in our studied lakes were majoritively from natural sources. Comparing with other remote areas like Arctic region, most heavy metals in our studied lakes were lower while As was about 11 times higher than the Arctic lake. According to the study, As in the Arctic lake came from human activities like non-ferrous metal industry (Evenset et al. 2007). Since non-ferrous metals are one of the large point sources which contributed to PM2.5 emitted in India and heavy metals can transported by aerosol (Reddy and Venkataraman 2002), the higher As concentration in our studied lakes might come from anthropogenic processes of India. According to the above discussion, we speculated that heavy metals in the lake sediments on the Tibetan Plateau might be affected by both anthropogenic and natural processes.

Spatially, these heavy metal concentrations showed no clear distribution pattern from east to west on the Tibetan Plateau according to Fig. 2. The accumulation and distribution of heavy metal elements depend mostly on the characteristics of the geological material such as mineral species and grain sizes (Taylor 2007). The geological structure of the Tibetan Plateau is complex (Qiao et al. 2009). The mineralization of the Tibetan Plateau which runs through the collisional orogeny process of the Indo-Asian continent has developed different types of regional mineralization in different orogenic stages and form a unique combination of mineral deposits over the Tibetan Plateau (Chen et al. 2009). The rivers which run into the lakes on the Tibetan Plateau not only transport particles to lake sediments but also transport nutrients and pollutants from different regions of the watersheds (Schauble 1999). Therefore, there could be a lot of different sources of the heavy metals in lake sediments on the Tibetan Plateau. In addition, increasing intensity of human activities has reshaped many parts of the plateau (Chen et al. 2013). Different human activities affect different parts which may cause the accumulations of diverse heavy metals. The different distributions of the 8 heavy metals in 18 lakes might indicate their different sources and mechanisms to control the patterns.

Risk assessment

According to the results, the calculated I_{geo} values of Zn, Pb, Co, and Ni fluctuated from practically unpolluted to unpolluted to moderately polluted (Table 2). The I_{geo} values of Cu and Cr fluctuated from practically unpolluted to moderately
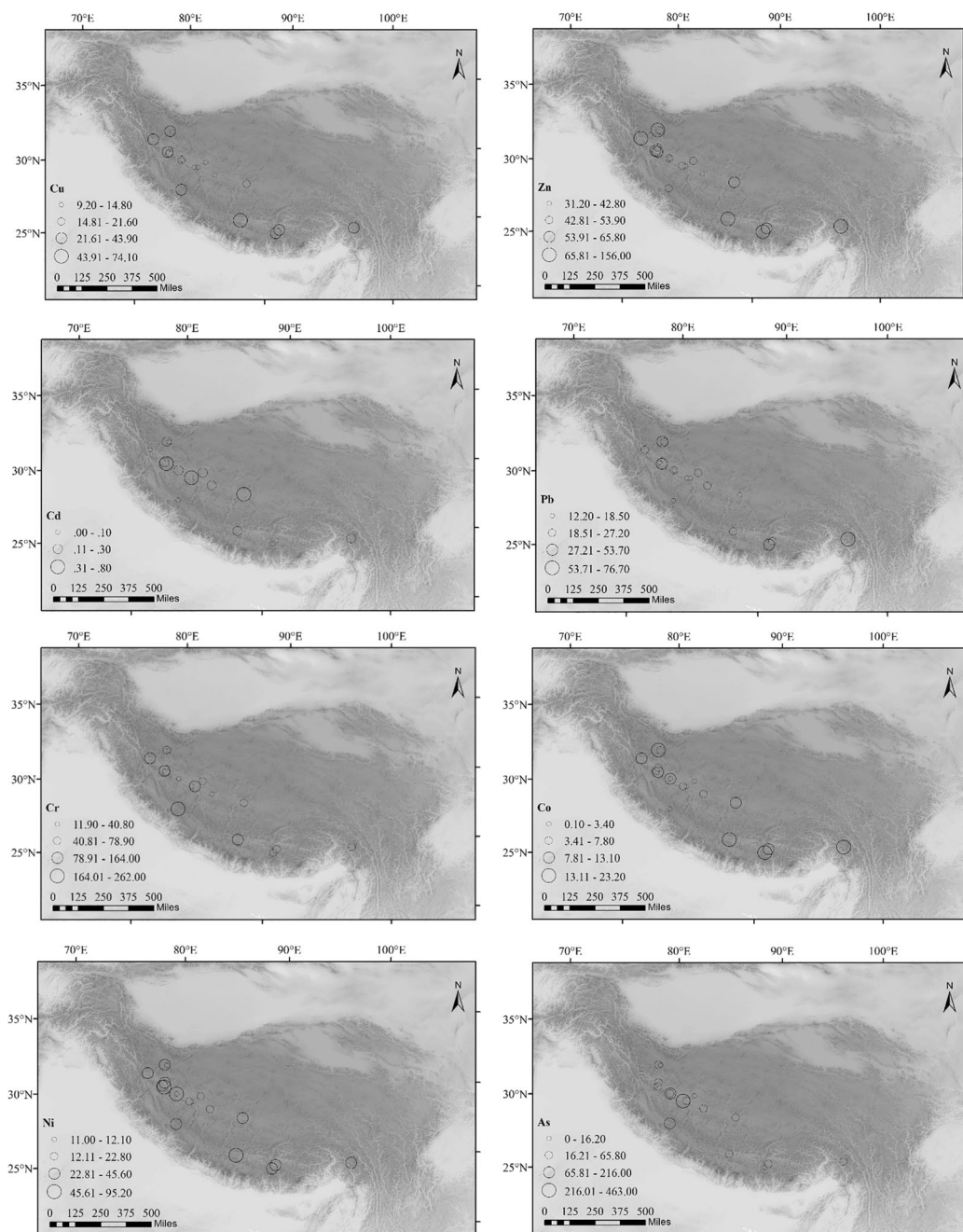
Fig. 2 Concentrations (mg kg^{-1}) of Cu, Zn, Cd, Pb, Cr, Co, Ni, and As in 18 lakes on the Tibetan Plateau

polluted. The I_{geo} values of Cd ranged from practically unpolluted to moderately polluted to heavily polluted. The I_{geo} values of As ranged from − 1.34 to 4.04, which indicate practically unpolluted to extremely polluted conditions. The mean I_{geo} values for Cu, Zn, Pb, Cr, Co, and Ni in each of the examined samples fell into class 0, indicating a lack of Cu, Zn, Pb, Cr, Co, and Ni pollution. The I_{geo} values of Cd and As fell into class 1, indicating that the 18 studied lakes on the Tibetan Plateau were moderately polluted by Cd and As.

The E^i_r values of the 8 heavy metals in the 18 study lakes ranged from 0 to 2437 (Table 3). The E^i_r values of Cu, Zn, Pb, Cr, Co, and Ni were all below 40; these results indicate that the potential ecological risk indices of these heavy metals were at a safe level. It was determined that only two metals in the lake sediments (i.e., Cd and As) might pose a potential risk within the lakes. The E^i_r values of Cd were low in lakes GZC, BGC, AYC, and DRBC; moderate in lakes LMC, PMYC, and YZYC; considerable in lakes RWC, LC, SMXC, KZC, DC,

Table 2 I_{geo} assessment data of heavy metals in lake sediments

Lake ID	I_{geo}							
	Cu	Zn	Cd	Pb	Cr	Co	Ni	As
RWC	0.42	0.38	0.42	0.82	− 1.05	− 0.17	− 0.61	0.38
LC	1.17	0.15	1.00	− 0.67	− 0.08	0.42	0.52	0.00
GZC	0.33	− 1.04	− 1.91	− 1.72	1.17	− 4.27	− 0.11	2.94
BGC	0.00	− 0.02	− 0.58	− 1.09	0.50	− 0.87	− 0.32	− 0.95
SMXC	− 0.18	0.50	1.00	0.31	− 1.04	− 0.20	− 0.46	0.31
LMC	− 1.84	− 1.24	− 0.58	− 0.93	− 3.29	− 1.95	− 2.10	− 1.34
AYC	− 1.37	− 1.06	− 2.91	− 1.83	− 1.70	− 1.31	− 0.44	1.23
LBC	− 1.15	− 1.22	1.00	− 0.98	− 0.56	− 2.69	− 1.17	− 1.13
KZC	− 0.02	− 0.77	1.00	− 1.33	− 0.18	− 1.16	− 0.08	− 0.79
RBC	− 0.60	− 0.78	2.42	− 0.09	− 0.68	− 0.65	0.98	0.93
AWC	− 0.91	− 1.17	1.00	− 1.09	− 1.51	− 0.83	0.29	0.05
ZCCK	− 1.49	− 1.37	0.42	− 1.36	− 1.98	− 2.36	− 1.99	2.45
BRZC	− 1.35	− 1.23	2.22	− 1.44	− 1.58	− 1.89	− 1.20	4.04
DRBC	− 1.20	− 1.83	− 2.32	− 1.73	− 0.22	− 7.44	− 2.13	0.18
DC	− 1.75	− 1.38	1.00	− 0.73	− 2.13	− 1.64	− 1.08	0.92
DZC	− 0.79	− 0.75	2.00	− 1.23	− 0.86	− 1.03	− 0.54	− 0.05
PMYC	0.36	0.36	− 0.58	0.14	− 0.66	− 0.23	− 0.58	–
YZYC	− 0.06	− 0.82	− 0.58	− 1.00	− 0.78	− 0.41	− 0.45	0.78
Mean	− 0.58	− 0.74	0.22	− 0.88	− 0.92	− 1.59	− 0.64	0.59
Level	0.00	0.00	1.00	0.00	0.00	0.00	0.00	1.00

"–" means no value

and ZCCK; high in lakes LBC and AWC; and very high in lakes RBC, BRZC, and DZC. The potential ecological risk indices detected for As were mostly even higher and were moderate in lakes BGC, LMC, and LBC; considerable in lakes LC, KZC, AWC, and DZC; high in lakes RWC, SMXC, RBC, DRBC, DC, and YZYC; and very high in lakes GZC, AYC, ZCCK, and BRZC. The risk value of As was especially high in lake BRZC (2437). Overall, the heavy metals in the sediments from the lakes in the Tibetan Plateau were found to pose light ecological risks. Much higher risks were found to be posed by Cd and As than by the other metals; thus, Cd and As should be included within the list of priority pollutants for the studied lakes. This finding is in perfect agreement with the results from the I_{geo}.

The RI values of the 18 study lakes ranged from 105 to 2837 with an average of 551, representing very high eco-risks (Table 3). The RIs of PMYC, LMC, and BGC were below 150, indicating a low potential ecological risk level. The RIs of LBC, KZC, and DRBC were at a moderate potential ecological risk level. The RIs of RWC, LC, SMXC, AYC, AWC, DC, DZC, and YZYC were between 300~600, indicating a considerable potential ecological risk level. For lakes GZC, RBC, ZCCK, and BRZC, the values of the RI were higher than 600, indicating a high-risk level. Particularly, the RI value of lake BRZC was as high as 2837, which suggested that BRZC had been severely polluted by heavy metals. None of the lakes with high potential ecological risk levels (i.e., GZC, RBC, ZCCK, and BRZC) are

freshwater lakes. Overall, the mean potential risk index for the 8 heavy metals in the surface sediments of the 18 lakes on the Tibetan Plateau was classified as considerably polluted.

The potential ecological risk assessments of the heavy metals in lake sediments of the Tibetan Plateau showed that lakes PMYC, LMC, and BGC were at low potential ecological risks. The result for lake PMYC was similar with that of another study (Xie et al. 2014). Data from Pumoyum Co studied by Xie et al. indicated that metals in the sediments from that lake represented low concentration levels, and sediment quality guidelines and potential ecological risk indices suggested that the lake could be ranked with a low potential ecological risk (Xie et al. 2014). The climate in the watershed of lake LMC is extremely cold and dry with an annual average temperature of − 8 °C and an annual precipitation of 75–100 mm (Wang and Dou 1998). The waters of the lake are mainly sourced from groundwater, and there is no surface runoff (Wang and Dou 1998). Thus, less amounts of heavy metals could be transported via road runoff or atmospheric deposition to the lake sediments. Lake Bangong Co is located in the western Tibetan Plateau within a cold desert that is located in the rain shadow of the Kunlun and Karakorum ranges with a mean annual air temperature ranging from − 4 to − 2 °C (Liu et al. 2014). Because of the lack of direct anthropogenic influences, Bangong Co showed a low ecological risk. Heavy metals of GZC, RBC, ZCCK, and BRZC showed a high-

Table 3 Potential ecological risk indices of heavy metals in lake sediments

Lake ID	E_r^i								RI
	Cu	Zn	Cd	Pb	Cr	Co	Ni	As	
RWC	5.78	1.67	126	19.18	1.77	2.42	2.76	192.11	351.69
LC	9.75	1.43	156	6.8	3.492	3.63	6.06	147.37	334.53
GZC	5.45	0.63	24	3.3	8.32	0.14	3.9	1136.84	1182.57
BGC	4.33	1.27	36	5.1	5.21	1.48	3.38	76.32	133.07
SMXC	3.80	1.81	156	13.43	1.79	2.36	3.06	183.16	365.41
LMC	1.21	0.54	60	5.7	0.38	0.70	0.98	58.42	127.93
AYC	1.67	0.62	12	3.05	1.13	1.09	3.12	346.32	369
LBC	1.94	0.55	192	5.49	2.5	0.43	1.88	67.11	271.89
KZC	4.28	0.75	150	4.31	3.25	1.22	4	85.26	253.07
RBC	2.84	0.75	498	10.18	2.31	1.73	8.35	280.53	804.69
AWC	2.30	0.57	162	5.08	1.30	1.53	5.15	153.16	331.08
ZCCK	1.54	0.50	146	4.23	0.94	0.53	1.06	809.30	964.09
BRZC	1.70	0.55	390	4	1.23	0.73	1.83	2436.84	2836.88
DRBC	1.88	0.36	18	3.28	3.17	0.02	0.96	167.37	195.04
DC	1.29	0.50	156	6.55	0.84	0.88	2	279.47	447.53
DZC	2.49	0.77	360	4.63	2.04	1.32	2.91	142.63	516.77
PMYC	5.57	1.65	78	11.92	2.34	2.31	2.81	–	104.60
YZYC	4.14	0.73	48	5.43	2.14	2.04	3.09	254	319.57
Mean	3.44	0.87	153.78	6.76	2.45	1.36	3.18	400.95	550.52

"–" means no value

risk level. ZCCK locates in the western part of the Tibetan Plateau where the continental climate is with dry, little precipitation and high evaporation (Zheng 1982). The annual precipitation of ZCCK is about 151 mm and the evaporation is about 2302 mm (Wang and Dou 1998). The high rates of evaporation may cause more heavy metals accumulated in the lake water and therefor increase the heavy metals deposition in the sediments (Dixit and Tiwari 2008). GZC locates in the southwestern part of the Tibetan Plateau where the climate is semiarid (Wang and Dou 1998). There is a national road near the northern part of the lake GZC and the high potential ecological risk index could be caused by increasing tourism and traffic. RBC locates in the western part of the Tibetan Plateau where climate is arid (Wang and Dou 1998). Like lake ZCCK, maybe the low-precipitation and high-evaporation rates in arid climate areas drive the increasing deposition of heavy metals in the lake sediment which causes the high threat to the aquatic ecosystem. The RI value of lake BRZC was the highest (2837), indicating that it could be a threat to lake sediments and aquatic organisms and should be especially monitored. According to our study, As was the most prominent heavy metal that contributed to the risk in lake BRZC. The distribution of As in the environment is caused mainly by different anthropogenic activities in recent years such as industrial activities, emissions from the burning of fossil fuels, wide use of pigments, and pesticides (O'Neill 1990; Tsai et al. 2003). Moreover, there has been a research which reported that some gasoline contain 30–120 ng g^{-1} of As (Nakamoto 2000).

Since there is a traffic road near the southeast of the lake BRZC, the high concentration of As may be contributed to traffic. As can be accumulated by phytoplankton and organoarsenic compounds can be bioaccumulated by aquatic animals through their food (Wängberg et al. 1991; Neff 1997). The high As concentration in the surface sediment of BRZC which interface with water may change phytoplankton species and accumulated in invertebrates (Neff 1997). Thus, the potential for significant impact on trace element capture by benthic organisms increased and could change the food chain (Langston 1980).

Source and influencing factors

Various multivariate techniques such as the PCA and Pearson correlation analysis which have been used as tools to distinguish sources of heavy metal elements in previous researches were conducted in our studied systems (Zhou et al. 2008; Fu et al. 2014). Based on the results of the PCA, Pearson correlation analysis, we also performed hierarchical cluster analysis (CA) on the standardized data. According to the statistical analysis, we clustered the 8 heavy metals to 4 groups according to their similar sources.

Group 1 included Cu, Zn, Pb, Co, and Ni. PCA was performed based on the concentrations of all of the heavy metals with a varimax rotation (Table 4). The results provided three PCs with eigenvalues > 1 that explained 81.001% of the total variance. The first component (PC1) explained 42.706% of the

Table 4 Results of principle component analysis (PCA) for the environment variables of the sediments

Component	Rotated component matrix		
	1	2	3
Cu	*0.808*	− 0.421	0.245
Zn	*0.887*	− 0.047	− 0.227
Cd	0.205	*0.797*	0.512
Pb	*0.716*	0.329	−0.370
Cr	0.156	*− 0.790*	0.497
Co	*0.934*	0.155	− 0.046
Ni	*0.632*	0.087	0.542
As	− 0.355	0.263	*0.603*
% of variance	42.706	20.589	17.705
Cumulative (%)	42.706	63.295	81.001

total variance, which was positively loaded with respect to Cu, Zn, Pb, Co, and Ni. Cu, Zn, Pb, Co, and Ni might have certain degrees of similarity with regard to their source and distribution processes. The Pearson correlation analysis was also used to predict the mean common sources and 7 potential influencing factors of the 8 heavy metal elements in the lake sediments (Table 5). Positive correlations ($P < 0.01$) were found between several element pairs: Cu-Zn (0.689), Cu-Co (0.742), Zn-Pb (0. 784), Zn-Co (0.797), and Pb-Co (0.603). The correlation coefficients of Cu-Ni (0.486) and Co-Ni (0.582) were larger than 0. 4 at the $P < 0.05$ level. These results showed that the heavy metals demonstrated identical transport behaviors, similar pollution levels, and common sources (Qu and Kelderman 2001,

Suresh et al. 2011, Zeng and Wu 2013). The positive correlation of Pb and Zn showed that Pb shared similar sources with Zn. The less positive relationship between Ni-Cu and Ni-Co indicated that the Ni have similar origin with Cu and Co to some extent. Cu, Zn, and Co were significantly associated with each other, and thus, they might have a common pollution source. Thus, Cu, Zn, Pb, Co, and Ni might have similar sources. In addition, Cu, Zn, and Co had significant negative correlations with the distance between the lake and a major road ($r = − 0.610$, $P < 0.01$; $r = − 0.497$, $P < 0.05$; $r = − 0.521$, $P < 0.05$), which suggested that Cu, Zn, and Co could be influenced by traffic. Cu could be derived from brake wear and the mineral filler materials in asphalt road surfaces. Zn originates from brake and tire wear, and Co is sourced from fossil fuel combustion (Winther and Slentø 2010). The fragile natural environment of the Tibetan Plateau is sensitive to environmental changes (Zhen and Zhang 2009). In recent years, coincident with the development of the Chinese economy and the associated booming tourism, the Tibetan Plateau has attracted more and more tourists. Some of the sampling sites in this study were located near major roads (Fig. 1). Thus, although traffic is a source of heavy metals in the soils along the roads, due to the correlation between the lakes and major roads, Cu, Zn, and Co might be affected by traffic activity, which could generate a partial contribution to the heavy metal concentrations in the sediments. Other than anthropogenic influence, Cu and Zn were also negatively correlated with the electrical conductivity ($r = −0.602$, $P < 0.01$; $r = −0.550$, $P < 0.05$), indicating that the concentrations of these two heavy metals were also affected by aqueous complexation (García-Gil et al. 2016). Based on the results of the Pearson correlation analysis and the comparison between

Table 5 Correlation coefficient between metals and major environmental elements of 18 lake sediments ($n = 14$ for salinity and $n = 18$ for other elements)

	Cu	Zn	Cd	Pb	Cr	Co	Ni	As
Cu	1							
Zn	*0.689**	1						
Cd	− 0.140	− 0.057	1					
Pb	0.372	*0.784**	0.115	1				
Cr	0.504*	0.104	− 0.284	− 0.187	1			
Co	*0.742**	*0.797**	0.145	*0.603**	− 0.102	1		
Ni	*0.468*	0.231	0.428	0.174	0.264	*0.528*	1	
As	− 0.147	− 0.253	0.304	− 0.234	0.073	− 0.312	− 0.174	1
Glacier area in catchment	0.254	0.565*	− 0.198	0.453	0.184	0.295	− 0.021	− 0.203
Roadside distance	*− 0.610**	*− 0.497*	0.329	− 0.395	− 0.288	*− 0.521*	− 0.389	0.148
Lake area	0.113	0.166	− 0.193	− 0.107	0.206	0.168	− 0.034	− 0.167
Catchment area	0.023	0.140	−0.038	−0.153	0.278	0.045	0.005	−0.171
Conductivity	*− 0.602**	*− 0.550*	0.006	− 0.419	*− 0.530*	− 0.364	− 0.253	0.241
pH	0.029	− 0.243	0.020	− 0.369	0.004	0.017	0.084	0.291
Salinity	− 0.353	− 0.442	0.402	− 0.326	− 0.257	− 0.258	0.069	0.146

**Correlation is significant at the 0.01 level,*correlation is significant at the 0.05 level

concentrations of heavy metals in studied lakes and published results (Qinghai Lake and the background values of the Tibetan Plateau soil), we suggested that the Cu, Zn, and Co could come from both rock material and traffic (Cheng and Tian 1993). The hierarchical cluster analysis clustered Zn, Co, Cu, and Pb as Cluster 1, which also indicated same sources (Fig. 3).

Group 2 included Cd. The results of PCA showed the second principal component (PC2) accounted for 20.589% of the total variance and was mainly characterized by the high positive loading of Cd. The concentrations of Cd were not significantly correlated with any of the other heavy metals and influencing factors. Previous researches confirmed that heavy metals can reach remote alpine regions by atmospheric transport (Zechmeister 1995; Schilling and Lehman 2002; Yang et al. 2002). Atmospheric pollution is serious in South Asia due to significant developing industries, fossil fuel burning, vehicle exhaust emission, and so on (Lelieveld et al. 2001; Cong et al. 2007). High concentrations of toxic heavy metals such as Cd were found in PM10 in Calcutta, India, which could be transported to the Tibetan Plateau by monsoon air masses. Cd was widely used in alloying, electroplating, and dyeing industries (Yuan et al. 2014). Thus, Cd might be majoritively generated from anthropogenic sources. The hierarchical cluster analysis showed Cluster 2 included Cd and Ni. Based on the low Ni loading (PC1, 0.632) in PCA analysis and hierarchical cluster analysis, we could suggest that Ni may also slightly influenced by atmospheric deposition.

Group 3 included Cr. PCA results showed that Cr was the only element with a negative loading in the PC loading plot, suggesting that the source of Cr in the sediments was different from those of the other heavy metals. The results of the Pearson correlation analysis indicated Cr was negatively correlated with the electrical conductivity ($r = -0.530$, $P < 0.01$), indicating that the electrical conductivity might be the main potential factor affecting the Cr concentration in the lake sediments of the Tibetan Plateau. The hierarchical cluster analysis showed Cluster 3 included Cr. Due to the lower concentrations than the background values of soil in the Tibetan Plateau, we indicated that Cr could originate from natural processes such as weathering of parent rocks in watersheds.

Group 4 included As, which was the most polluted heavy metal in our studied lakes. PCA analysis showed the last component (PC3) explained 17.705% of the total variance and consisted only of As with a high positive loading. The concentration of As was not significantly correlated with any of the other heavy metals and influencing factors. The results of hierarchical cluster analysis showed Cluster 4 included As. According to Yuan et al. (2014), Ximen Co lake which is on the eastern Tibetan Plateau showed obvious increasing As concentration which reflected the development of manufacturing, living, and the striking deterioration of atmospheric environment of the West, Central Asia, and South Asia regions. Based on the statistical results and comparison with previous studies, As might reflect the control of anthropogenic activities.

Conclusions

Due to its unique geographical position, the environment of the Tibetan Plateau is affected by both special lake properties and anthropogenic interference. In this study, 18 lakes in the Tibetan Plateau were investigated. The concentrations of 8 heavy metals (Cu, Zn, Cd, Pb, Cr,

Fig. 3 Hierarchical dendrogram for the heavy metals in sediment samples from the lakes on the Tibetan Plateau, produced using average linkages between groups and the Pearson correlation coefficients as measured intervals
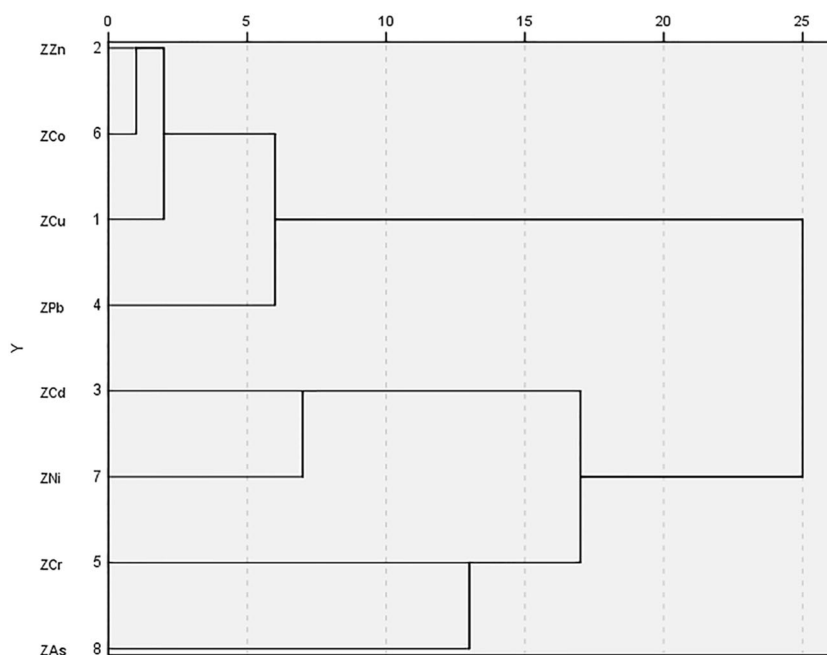
Co, Ni, and As) in the sediments from the 18 lakes on the Tibetan Plateau were analyzed to determine their sources, influencing factors and potential ecological risks. The results showed that the mean concentrations of these metals had no clear spatial pattern throughout the Tibetan Plateau and followed the order of Cr > As > Zn > Ni > Pb > Cu > Co > Cd. According to a comparison with other regions, the lake sediments of the Tibetan Plateau were less impacted by human activities compared to natural factors. To further investigate the potential ecological risks of the heavy metals, two assessment methods (the I_{geo} and the potential ecological risk index) were introduced. The results of the I_{geo} assessment showed that the sediments were moderately polluted by Cd and As, which posed much higher risks than did the other metals. The values of the E^i_r demonstrated similar results. The values of the RI showed that lake BRZC had been severely polluted by heavy metals. Cd and As were the main priority pollutants in our studied lakes. The PCA, HCA, and Pearson correlation analyses results indicated that Cu, Zn, Pb, Co, and Ni mainly originated from both natural and traffic sources. Ni could also be mildly influenced by aerosols. Cd originated from anthropogenic activates like alloying, electroplating, and dyeing industries which transported South Asia from to the Tibetan Plateau by atmospheric circulation. Cr might be generated from natural sources like parent rocks of watersheds. As might originate mainly from anthropogenic activities such as manufacturing, living, and the striking deterioration of atmospheric environment of the West, Central Asia, and South Asia. These results will help to provide quality guidelines for the government and to study potential ecological problems regarding the lakes on the Tibetan Plateau.

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