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Occurrence, spatial distribution, sources, and risks of polychlorinated biphenyls and heavy metals in surface sediments from a large eutrophic Chinese lake (Lake Chaohu)

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Abstract Surface sediment from large and eutrophic Lake Chaohu was investigated to determine the occurrence, spatial distribution, sources, and risks of polychlorinated biphenyls (PCBs) and heavy metals in one of the five biggest freshwater lakes in China. Total concentration of PCBs (Σ_{34}PCBs) in Lake Chaohu was 672 pg g^{-1} dry weight (dw), with a range of 7 to 3999 pg g^{-1} dw, which was lower than other water bodies worldwide. The majority of heavy metals were detected at all sampling locations, except for Sr, B, and In. Concentrations of Al, Fe, Ca, Mn, Sr, Co, Zn, Cd, Pb, and Hg were similar to that reported for other lakes globally. Concentrations of K, Mg, Na, Li, Ga, and Ag were greater than the average, whereas those of Cr, Ni, and Cu were lower. Cluster analysis (CA) and positive matrix factorization (PMF) yielded accordant results for the source apportionment of PCBs. The technical PCBs and microbial degradation accounted for 34.2 % and 65.8 % of total PCBs using PMF, and PMF revealed that natural and anthropogenic sources of heavy metals accounted for 38.1 % and 61.8 %, respectively.

CA indicated that some toxic heavy metals (e.g., Cd, In, Tl, and Hg) were associated with Ca–Na–Mg minerals rather than Fe–Mn minerals. The uncorrelated results between organic matter revealed by pyrolysis technology and heavy metals might be caused by the existence of competitive adsorption between organic matter and minerals. PCBs and heavy metals were coupling discharge without organochlorine pesticides (OCPs), but with polycyclic aromatic hydrocarbons (PAHs) and polybrominated diphenyl ethers (PBDEs). No sediment sample exceeded the toxic threshold for dioxin-like PCBs (dl-PCBs) set at 20 pg toxicity equivalency quantity (TEQ) g^{-1}, (max dl-PCBs, 10.9 pg TEQ g^{-1}). However, concentrations of Ag, Cd, and Hg were at levels of environmental concern. The sediment in the drinking water source area (DWSA) was threatened by heavy metals from other areas, and some fundamental solutions were proposed to protect the DWSA.

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Introduction

In the aquatic ecosystem, polychlorinated biphenyls (PCBs) and heavy metals (including metalloids such as arsenic) are ubiquitous persistent-toxicant organic and inorganic contaminants, respectively, which pose potential ecological and human health risks (Al-Taani et al. 2015; Brown et al. 2013; Caeiro et al. 2005). The estimated half-lives of PCBs are >10 years in the sediments of the Great Lakes, with estimates of 179 years in Lake Michigan (Li et al. 2009). The degradation of PCBs is the combined effect of microorganisms, nutrients, biphenyls, and oxygen (Hakanson 1980). Heavy metals in inorganic form cannot be degraded; however, their valence states, which decide

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their toxicity, are easily changed under specific circumstances (Gadd and Griffiths 1977). Most heavy metals (10^{-6}–10^{-2}) are more abundant than PCBs (10^{-12}–10^{-6}) due to their natural sources in parent rocks (Bai et al. 2011). Moreover, human activities such as mining, smelting, industrial sewage, agriculture, and traffic emissions will significantly increase the abundance of heavy metals in sediments (Besser et al. 2008; Dauvalter 1994; Li et al. 2013; Odhiambo et al. 2013). The only fundamental sources of PCBs are industrial production and usage of plasticizers, insulating oil, and flame retardants (Iozza et al. 2008; Ok et al. 2013). However, PCBs have the ability to be transported long distance due to their semi-volatility, whereas heavy metals are generally associated with particles, whose ability to be transported long distance is much weaker (Clozel et al. 2006; Qi et al. 1997). Although PCBs have lower occurrence than heavy metals, their toxicity to organisms in sediments is much larger (Tsakovski et al. 2009). The toxicity parameters of PCBs range from 0.12 to 3.1 mg kg^{-1} while for most heavy metals the toxicity parameters are >10 mg kg^{-1} (Tsakovski et al. 2009). Moreover, unlike the bio-dilution effect of most heavy metals (Aktumsek and Gezgin 2011), PCBs exhibit trophic magnification with values (TMF) of 1.23–1.42 and biomagnification factors (BMF) of 5.5–8.6 (Allen-Gil et al. 1997; Helm et al. 2008). PCBs in sediments may renter the food chain through ingestion by benthic organisms and bioaccumulate in higher trophic species posing a risk to consumers (Finley et al. 1997). Furthermore, the 12 dioxin-like PCBs might cause reproductive and developmental problems, damage the immune system, disrupt the endocrine system, and even cause cancer (Van den Berg et al. 2006). Because both PCBs (higher toxicity but lower amount) and heavy metals (greater amount but lower toxicity) have their own characteristics in the sediment, it is suggested that their risk to human health and wildlife may be considered similar in sediment quality management.

Multivariate statistical analysis, including principal component analysis (PCA) and cluster analysis, is generally employed to identify the sources of contamination (He et al. 2013a). PCA has been successfully used for source apportionment of both PCBs and heavy metals (Cacela et al. 2002; Ikem and Adisa 2011; Li et al. 2013). However, these methods require significant levels of additional information but still have uncertainty (Qin et al. 2014). The US EPA recommended a novel multivariate analysis, namely positive matrix factorization (PMF), used first to identify the sources of PCBs in the sediment (Bzdusek et al. 2006a). Recently, PMF has also been used in the source apportionment of heavy metals (Wang et al. 2015). Tsakovski et al. (2009) employed a self-organization map (SOM) to construct the visible linkage among sampling sites and connections among PCBs and heavy metals, which offered valuable information to explain the sources. PMF and PCA both have advantages and disadvantages, so combining usage of those methods is proposed by Wang et al. (2015).

To evaluate the risks of the contaminants in sediment, two major strategies are widely employed. One is to compare the environmental concentration to the pre-industrial or background concentrations, including degree of contamination (Hakanson 1980) and geo-accumulation index (Loska et al. 1997). The other is to compare the environmental concentration to the toxicity parameters, including Hakanson's risk index (Hakanson 1980), the sediment quality guideline (SQG) method (MacDonald et al. 2000), and the mean probable effect concentration (PEC) quotient method (Niu et al. 2009). In practice, two or more risk assessment methods are used to increase the accuracy and decrease the uncertainty (Al-Taani et al. 2015; Hou et al. 2013; Niu et al. 2009).

Lake Chaohu is one of the largest eutrophic lakes in China. It is located in the Yangtze River Delta Economic Zone, one of the most developed areas of China (Qin et al. 2014). The lake has been confronting serious nutrient contamination due to the significant increase in human activities during the last 35 years (Xu et al. 1999). Due to the levels of contaminants in the western end of the lake, the waterworks was closed in "date" (He et al. 2013b). Drinking water is still sourced from the eastern end of the lake where the water is less contaminated; however, sediment from the west of the lake may be transported to the east. The emission of pollutants caused by resuspension of sediment potentially threatens organisms and drinking water (He et al. 2013a). Therefore, persistent organic contaminants, including polybrominated diphenyl ethers (PBDEs), organochlorine pesticides (OCPs), and polycyclic aromatic hydrocarbons (PAHs), in the sediment of the lake have been investigated (Gao et al. 2013; He et al. 2013a; Qin et al. 2014). We further investigated the PCBs and heavy metals in the present study. The aims of this study are (1) investigation of the occurrence, distribution, and composition of PCBs and heavy metals in the sediment, (2) source apportionment of the PCBs and heavy metals using multiple methods, (3) correlation with organic matter and pollutants, and (4) risk assessment of the PCBs and heavy metals.

Materials and methods

Sampling and pretreatment

The sampling location and methods were illustrated in previous studies (He et al. 2013a; Qin et al. 2014). In brief, 14 sediment samples cover the drinking water source area (DWSA; A6, B2, B3, B4, and B5), the buffer area (BA, A1-A4) in the west of the water source, potential pollutant-discharging rivers (PDR, B6, C1, C2, and C4), and the western part of Lake Chaohu (D1) (Fig. S1). Most riverine samples were located at the estuary to monitor the pollution discharge by rivers, but C2, near a thermal power station and an important pollution sources, were collected in the midstream of

Xiaozhegaohe River. In August, 2009, the surface sediment (<15 cm based on the angle of that system) samples were collected using a stainless steel Ponar grab sampler as other studies did (Omwoma et al. 2015; van Drooge et al. 2013; Yun et al. 2015; Zhang et al. 2014), freeze-dried, ground using an agate mortar, and sifted through a 70-mesh sieve. To minimize the sampling error caused by that tool, a composite sampling, which was mixed thoroughly with the sub-sample, was prepared for extraction.

Reagents and materials

A standard mixture stock of 36 PCBs (PCB-18, PCB-37, PCB-44, PCB-49, PCB-52, PCB-70, PCB-74, PCB-77, PCB-81, PCB-87, PCB-99, PCB-101, PCB-105, PCB-114, PCB-118, PCB-119, PCB-123, PCB-126, PCB-128, PCB-138, PCB-151, PCB-153, PCB-156, PCB-157, PCB-158, PCB-167, PCB-168, PCB-169, PCB-170, PCB-177, PCB-180, PCB-183, PCB-187, PCB-189, PCB-194, and PCB-199) was obtained from AccuStandard Inc., NY, USA. The surrogate standard (SS) and internal standard (IS) for PCBs were PCB-141 ($^{13}C_{12}$, 99 %) and PCB-208 ($^{13}C_{12}$, 99 %), respectively, which were purchased from Cambridge Isotope Laboratories, Inc., USA. A standard mixture stock of 23 heavy metals (AccuStandard Inc., NY, USA) includes silver (Ag), Al, boron (B), barium (Ba), bismuth (Bi), Cd, calcium (Ca), Cr, cobalt (Co), Cu, Fe, gallium (Ga), indium (In), potassium (K), Li, magnesium (Mg), Mn, sodium (Na), nickel (Ni), Pb, strontium (Sr), thallium (Tl), and zinc (Zn). The mercury (Hg) standard solution was obtained from the National Research Center for Certified Reference Materials of China. Acetone (ACE), *n*-hexane (HEX), and dichloromethane (DCM; analytical grade, Sinopharm Chemical Reagent Co., Ltd, Shanghai, China), were purified by distillation. Analytical grade granular anhydrous sodium sulfate, alumina (100–200 mesh), silica gel (200–300 mesh), sodium hydroxide (NaOH), and concentrated sulfuric acid (H_2SO_4, 98 %) were purchased from Sinopharm Chemical Reagent Co., Ltd, China. Guaranteed reagent concentrated hydrochloric acid (HCl; 37 %), nitric acid (HNO_3; 65 %), hydrofluoric acid (HF; 40 %), and perchloric acid ($HClO_4$; 70~72 %) were also obtained from Sinopharm Chemical Reagent Co., Ltd, China. Granular anhydrous sodium sulfate was baked at 650 °C for 6 h and stored in a sealed desiccator before use. Alumina and silica gel were baked at 450 °C for 6 h and maintained at 130 °C for 16 h. After allowing the baked silica gel and alumina to cool to ambient temperature, 3 g of ultrapure water was added into 100 g of silica gel or alumina to form neutral silica gel (NSG) and alumina (NAl), and 33 g of 1 mol/L NaOH and 44 g of H_2SO_4 (99 %) were added to 100 g of silica gel to form alkaline silica gel (AcSG) and acidic silica gel (AkSG), respectively. The silica gel and alumina were shaken to a powder and then soaked in HEX overnight. All glass or Teflon wares for PCBs analysis were cleaned in an ultrasonic cleaner (KQ-500B, Kunshan Ultrasonic Instrument, China) and baked at 450 °C for 6 h. All glass and Teflon wares for metal determination were cleaned and soaked with 5 % HCl-HNO_3 washing liquor for 24 h. The acid was washed away using ultrapure water, and the wares were dried at ambient temperature.

Extraction and cleanup

PCBs

Eight grams of homogenized sediment was added into a Teflon microware extract tank with 25 mL of HEX:ACE (1:1, *v/v*) and 50 ng SS for PCB extraction. The tank was placed in the microwave-assisted extraction (MAE) system MARS 5 (CEM Corp., Matthews, NC, USA) with the following instrument conditions: working power 1,200 W, temperature increase to 100 °C within 10 min, hold at 100 °C for 10 min, and decrease to ambient temperature within 30 min. The extracted solution was concentrated to approximately 1 mL on a rotary evaporator at 35 °C and transferred to the top of a glass column that was packed with 1 cm of anhydrous sodium sulfate (baked for 6 hours at 650 °C), 6 cm of concentrated-H_2SO_4-acidic silica gel, 2 cm of neutral silica gel (NSG), 5 cm of 1-mol L^{-1}-NaOH-alkaline silica gel, 2 cm of NSG, 6 cm of neutral alumina and pre-extracted absorbent cotton from top to bottom. Both silica gel and alumina were baked at 450 °C for 6 h and activated at 130 °C for 18 h until use. An aliquot of 70 mL of the solvent mixture HEX/DCM (1:1, *v/v*) was used to elute the target chemicals. The eluate was concentrated to 1 mL, and 50 ng IS was added. The eluate was further concentrated to approximately 50 μL in a marked vial under a gentle stream of nitrogen and stored at −18 °C until GC-MS determination.

Metals

For metal analysis, 100 mg homogenized sediment samples were added into a 50-mL Teflon digestion tank with 3 mL HCl (37 %) and 2 mL HNO_3 (65 %). The Teflon tank was inserted into the graphite cuvette of the digestion system (EHD36, LabTech, China) and system was sealed using a graphite cap. The temperature was increased and held at 110 °C for 1 h. Then, 3 mL HF (40 %) and 1 mL $HClO_4$ (70 %~72 %) were added, and the temperature was maintained for 6 h. After removing the cap, the temperature was increased and held at 130 °C for 2 h to evaporate the HF, and the temperature was further increased and held at 150 °C to evaporate the $HClO_4$. After digestion, 1 mL aqua regia (HCl/HNO_3, 3:1, *v/v*) was added, and the samples were transferred into a 25-mL volumetric flask, diluted with 5 % HNO_3 to volume, mixed, and stored at 4 °C until inductively coupled plasma optical

emission spectroscopy (ICP-OES) and inductively coupled plasma optical mass spectrometry (ICP-MS) determination.

Instrumental analysis

PCBs were analyzed using a Varian CP3800-320MS GC-MSD/MSD with EI source and a DB-5MS column (30 m × 0.25 mm internal diameter; 0.25 μm film thickness). The oven temperature was programmed to an initial temperature of 100 °C for 2 min, increased at a rate of 5 °C min^{-1} to 200 °C, and then increased at a rate of 3 °C min^{-1} to 270 °C, where the temperature was maintained for 5 min. Then, the temperature was increased at a rate of 10 °C min^{-1} to 300 °C, where the temperature was maintained for 5 min. Helium was used as the carrier (1 mL min^{-1}). The temperatures of the inlet and ion sources were 220 and 230 °C, respectively. The quantitative ion fragments, with limits of detection (LOD) and method limits of detection (MLD), are reported in Table S1. Quantitation was performed using the internal calibration method based on a 6-point calibration curve for individual PCBs. The order of the PCB congeners in the rest of the study followed the eluting sequence in the GC column.

The major elements (Al, Ba, Ca, Fe, K, Mg, Na, Mn, and Sr) were determined by ICP-OES (Prodigy, Leeman Labs, USA); the minor elements (Li, B, Cr, Co, Ni, Cu, Zn, Ga, Ag, Cd, In, Tl, Pb, and Bi) were measured by ICP-MS (Elan DRC-e, PerkinElmer Inc., USA); Hg was analyzed by a RA-915 mercury vapor analyzer (Lumex, Canada).

Total organic carbon (TOC) in the sediment was analyzed by TOC 5000A coupled with an SSM-5000A sampler (Shimadzu Corp., Japan). Rock-Eval 6 pyrolysis (Vinci Technologies, Rueil-Malmaison, France) was employed to investigate the organic carbon in bulk sediment regarding the thermal evolution of hydrocarbons, free and volatile hydrocarbons (S1), kerogen-derived hydrocarbon (S2), and refractory residual organic carbon (RC). The thermally less stable macromolecular organic matter (S2a) and high molecular weight kerogens (S2b) were further evaluated from the S2 spectrum (Carrie et al. 2009; Wu et al. 2012).

QA/QC

Spiked extracted sediments with 50 ng PCBs and extracted sediment without PCBs were processed in triplicate to determine the recovery and precision of the sediment analysis. The average recovery percentages were 76.8–126.3 %, and the relative standard deviation ranged from 1.2 % to 25.3 %. A 50-ng SS was added to 20 % of microware extract before extracting to evaluate procedural recoveries. The average recoveries were 99.8 ± 17.4 %. The LOD (3 signal/noise) of individual PCBs were 3–16 pg g^{-1} dry weight (dw) for 8 g of sediment (Table S1). Three procedural blank samples were analyzed for solvent and glassware contamination to correct the samples'

data. Samples for PCBs were extracted and analyzed in triplicate. The sediment samples spiked with heavy metal standard mixture solution were processed in duplicate to determine the recovery, which ranged from 72.8 % to 116.5 %. The LOD and MLD are shown in Table S2. The standard reference material (IFP 160000, VINCI Parc d) was analyzed as an unknown sample, and one out of five samples had been determined by Rock-Eval 6. The errors in the nominal of the standard were within 5 %.

Data handling

Statistical analysis, including normal or logarithm normal distribution tests, correlation analysis, and CA were carried out using SPSS v. 20. A significant value was assigned as 0.05. The CA was used to show the similarities and differences among contaminants, which would indicate the potential sources. To meet the requirements of the CA, non-detected data were assigned as 1/2 MLD, and the data were log-transformed to obey a normal distribution. The similarity coefficient was set as the classification criterion. PMF v. 5.0 was also used to identify sources of PCBs and heavy metals.

To assess the risks of both PCBs and heavy metals, Hakanson's degree of contamination in Eq. (1) and consensus-based SQG were employed (Hakanson 1980; MacDonald et al. 2000).

$$C_d = \sum_{i-1}^{n} C_f^i = \sum_{i-1}^{n} {C_0^i}\Big/{C_b^i} \tag{1}$$

where C_d is the degree of contamination; C_f^i is the contamination factor for each contaminant (i); C_0^i is the concentration of the sample for a specific contaminant; C_b^i is the background concentration of a specific contaminant in the sediment, which is shown in Table S3; and n is the number of the contaminants. The description of the low, moderate, considerable, and very high degree of contamination is based on $C_d < n$, $n \le C_d < 2n$, $2n \le C_d < 4n$, and $C_d \ge 4n$, respectively (Hakanson 1980).

Employing only one SQG might cause uncertainty. SQGs of some contaminants such as As and Ni were found to be lower than background values, and SQGs varied among different nations (Chapman et al. 1999). It was suggested that consensus-based SQGs be employed (MacDonald et al. 2000). The recommended SQGs of selected heavy metals and total PCBs, including the threshold effect concentration (TEC), the midpoint effect concentration (MEC), and the PEC, are summarized in Table S4 on the basis of reports by MacDonald et al. (2000), Persaud et al. (1993), and MacDonald and MacFarlane (1999).

Results and discussion

Occurrence and composition

PCBs

The occurrence of PCBs in each sampling site is shown in Table S5 and summarized in Table 1. The total concentration of 34 PCBs (Σ_{34}PCBs) in Lake Chaohu was 672 ± 1,

293 pg g^{-1} dw with a range of 7 to 3999 pg g^{-1} dw. The greatest level of Σ_{34}PCBs was observed in the upstream of the Xiaozhegaohe River, where a coal-fired power station was located (Qin et al. 2014). Σ_{34}PCBs in sediment from most river sites (B6, C1, and C3) and the outlet of the lake (A6) were typically greater than in other places. Those sites were closer to the coast and dense urbanization (Hong et al. 2012).

Most PCB congeners had low frequency of detection (<50 %) except for PCB-18 (79 %), PCB-153/157 (100 %),

Table 1 Occurrence of PCBs and heavy metals in the sediment from Lake Chaohu (CH), drinking water sources area (DWSA), buffer area (BA), pollutant-discharging rivers (PDR), and the western part of Lake Chaohu (D1)

	CH (DR, %)	CH (AM ± SD)	CH (Min)	CH (Max)	DWSA (AM ± SD)	BA (AM ± SD)	PDR (AM ± SD)	WL (D1)
PCBs (pg g^{-1} dw)								
TriCB	79	6 ± 2	ND	9	5 ± 1	7 ± 1	6 ± 3	3
TetraCB	79	619 ± 1,230	ND	3327	69 ± 57	23 ± 22	1640 ± 1586	20
PentaCB	57	50 ± 85	ND	272	146 ± 126	15 ± 22	29	18
HexaCB	100	32 ± 78	1	307	65 ± 121	8 ± 7	17 ± 26	20
HeptaCB	57	182 ± 306	ND	856	271 ± 259	7 ± 2	291 ± 399	24
OctaCB	79	21 ± 32	ND	118	34 ± 43	9 ± 3	16 ± 3	ND
Σ_{34}PCBs	100	672 ± 1293	7	3999	297 ± 532	66 ± 47	1893 ± 1836	85
dl-PCBs (fg g^{-1})		893 ± 2824	<1	10,980	2197 ± 4392	376 ± 650	5 ± 9	1
Heavy metals (dw)								
Al (‰)	100	57.38 ± 6.47	42.75	67.12	53.74 ± 6.62	60.10 ± 3.44	61.61 ± 3.84	47.74
Fe (‰)	100	28.94 ± 4.77	19.31	38.18	27.17 ± 4.38	31.50 ± 2.57	28.25 ± 6.15	30.32
K (‰)	100	14.86 ± 1.87	10.59	17.15	14.66 ± 1.16	16.08 ± 0.69	14.13 ± 2.78	13.82
Ca (‰)	100	9.69 ± 13.10	1.80	46.23	3.87 ± 0.96	2.22 ± 0.34	25.01 ± 16.29	7.44
Mg (‰)	100	6.58 ± 1.29	4.80	9.68	6.15 ± 0.83	6.15 ± 0.57	7.77 ± 1.60	5.65
Na (‰)	100	3.94 ± 1.39	1.52	6.72	4.30 ± 1.01	5.06 ± 1.10	2.46 ± 0.82	3.56
Mn (‰)	100	0.79 ± 0.24	0.42	1.31	0.65 ± 0.14	1.00 ± 0.03	0.76 ± 0.33	0.74
Ba (‰)	100	0.51 ± 0.08	0.36	0.673	0.50 ± 0.04	0.58 ± 0.02	0.47 ± 0.12	0.51
Sr (mg kg^{-1})	79	20.62 ± 33.37	ND	119.09	7.20 ± 7.57	3.71 ± 1.83	47.61 ± 43.19	<0.75
Li (mg kg^{-1})	100	29.59 ± 4.39	18.63	36.70	28.78 ± 5.62	31.84 ± 2.96	29.11 ± 3.31	26.56
B (mg kg^{-1})	57	10.05 ± 8.51	ND	24.10	4.50 ± 3.47	22.80 ± 1.30	2.30 ± 0.00	14.50
Cr (mg kg^{-1})	100	11.89 ± 5.22	3.23	21.18	9.59 ± 3.89	16.44 ± 2.76	11.16 ± 6.11	8.08
Co (mg kg^{-1})	100	10.67 ± 1.55	7.45	13.23	10.36 ± 1.60	11.63 ± 0.79	10.13 ± 1.81	10.53
Ni (mg kg^{-1})	100	14.96 ± 3.80	5.82	22.21	13.85 ± 4.42	15.97 ± 2.78	15.59 ± 3.88	13.95
Cu (mg kg^{-1})	100	8.93 ± 7.15	1.71	30.86	7.41 ± 4.43	4.19 ± 2.24	10.10 ± 1.48	30.86
Zn (mg kg^{-1})	100	103.26 ± 33.37	59.37	213.12	87.71 ± 15.90	103.51 ± 8.60	122.54 ± 53.23	102.83
Ga (mg kg^{-1})	100	11.54 ± 2.14	7.44	15.55	11.01 ± 1.99	12.99 ± 1.04	11.03 ± 2.63	10.36
Ag (mg kg^{-1})	100	3.31 ± 4.35	0.37	17.72	1.47 ± 1.99	1.59 ± 1.12	3.73 ± 0.91	17.72
Cd (mg kg^{-1})	100	0.63 ± 0.46	0.07	1.78	0.39 ± 0.25	0.66 ± 0.47	0.97 ± 0.48	0.36
In (mg kg^{-1})	43	0.65 ± 0.30	ND	0.92	0.92 ± 0.00	ND	0.60 ± 0.34	0.60
Tl (mg kg^{-1})	100	0.65 ± 0.11	0.41	0.86	0.59 ± 0.11	0.67 ± 0.06	0.72 ± 0.12	0.65
Pb (mg kg^{-1})	100	26.77 ± 10.84	9.80	58.60	21.70 ± 6.89	30.12 ± 2.85	29.49 ± 17.11	27.89
Bi (mg kg^{-1})	100	0.44 ± 0.32	0.03	1.41	0.27 ± 0.16	0.51 ± 0.07	0.53 ± 0.51	0.61
Hg (mg kg^{-1})	100	0.23 ± 0.35	0.03	1.34	0.07 ± 0.02	0.08 ± 0.01	0.57 ± 0.51	0.25

Notes: *DR* detection ratio, *AM* arithmetic mean, *SD* standard deviance, *ND* not detected, *TriCB* PCB-18, *TetraCB* PCB-37, PCB-44, PCB-49, PCB-52, PCB-70, PCB-74, PCB-77, PCB-81, *PentaCB* PCB-97, PCB-99, PCB-101, PCB-105, PCB-114, PCB-118, PCB-119, PCB-123, PCB-126, *HexaCB* PCB-128/158, PCB-138, PCB-151, PCB-153/157, PCB-156, PCB-167, PCB-168, PCB-169, *HeptaCB* PCB-170, PCB-177, PCB-180, PCB-183, PCB-187, PCB-189, *OctaCB* PCB-194, PCB-199, *dl-PCBs* total dioxin-like PCBs concentration using updated WHO toxic equivalency factors

and PCB-194 (64 %). In the sediment from the outlet of the lakes (A6), 31 of 34 PCB congeners were detected. A shipping lock at A6 may affect the transport of PCBs across the lake allowing sediments to settle and concentrating PCBs at this bottleneck. Vessels gathered to pass through the lock at A6 may be an additional source (Odhiambo et al. 2013; Vanier et al. 1996). The congener profiles of PCBs in the sediment from Lake Chaohu are shown in Fig. 1. The PCBs with lower degrees of chlorination (3–4 Cl) dominated the PCBs in sediment from Lake Chaohu, which was also similar to other water bodies such as the Three Gorges Reservoir (Zhao et al. 2013), Lake Dianchi (Wan et al. 2011), and East Lake

(Yun et al. 2015). Yun et al. (2015) has emphasized that industry such as steel manufacturing might contribute to the lower chlorinated PCBs in these sediments. Microbial dechlorination is also an important pathway (Bzdusek et al. 2006a). Eight-chlorinated PCBs dominated the PCBs in sediment from DWSA, and a relatively high concentration of eight-chlorinated PCBs was also observed in BA. However, no eight-chlorinated PCBs were found in PDR or WL. Eight-chlorinated PCBs have low mobility and greater partitioning to particles than the lower chlorinated PCBs so we suspect a local source possibly from ships. These PCBs are also subject to greater rates of degradation than lower chlorinated
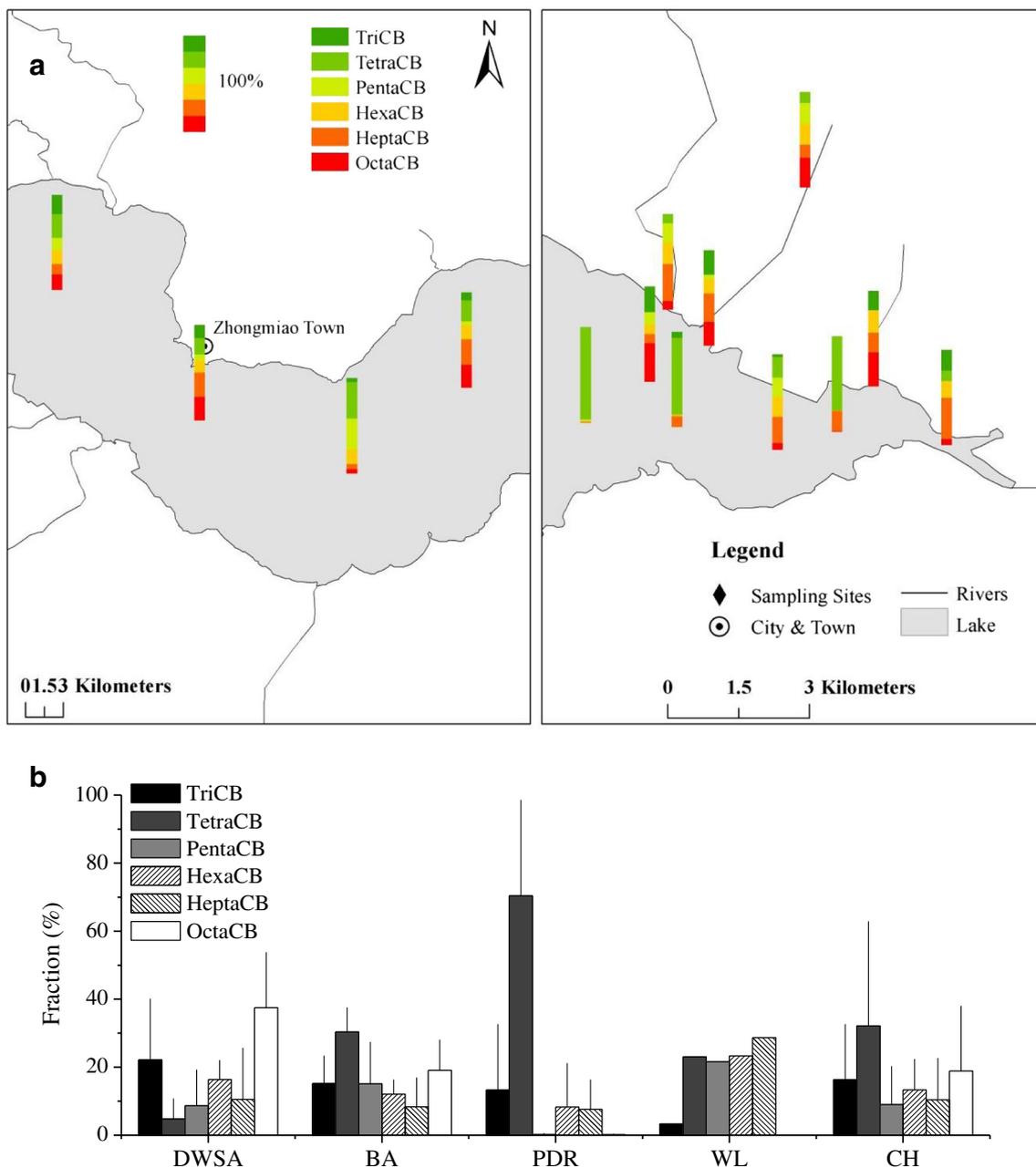

Fig. 1 Congener profiles of PCBs in the sediment from sampling sites (a) and various areas (b) in Lake Chaohu

congeners so their presence may be from a more recent source (Brown et al. 1987). Similar to Kisumu of Winam Gulf in Lake Victoria, whose PCBs was up to 4850 pg g^{-1} dw (Omwoma et al. 2015), discharge rivers B6 (Σ_{34}PCBs = 3436 pg g^{-1}) and C2 (Σ_{34}PCBs = 3999 pg g^{-1}) through Chaohu City also carried sediment with large amount of PCBs into DWSA. The dioxin-like PCBs (dl-PCBs) in Lake Chaohu accounted for 21.9 % of total PCBs, which is also similar to that (20.1 %) in Lake Victoria (Omwoma et al. 2015). Although sediment in DWSA confronted a threat from PDR, the occurrence of PCBs was lower than other water bodies worldwide (Feng et al. 1998; Hong et al. 2012; Samara et al. 2006; van Drooge et al. 2013; Vanier et al. 1996) (Fig. S2).

Heavy metals

Most heavy metals were detected in all sampling sites except for Sr, B, and In (Table 1). The sediment of rivers (PDR) had greatest average concentrations of Ca (25.01 ± 16.29 ‰), Mg (7.77 ± 1.60 ‰), Sr (48 ± 43 mg kg^{-1}), Zn (122.5 ± 53.2 mg kg^{-1}), Cd (0.966 ± 0.481 mg kg^{-1}), Tl (0.721 ± 0.116 mg kg^{-1}), and Hg (0.570 ± 0.510 mg kg^{-1}), whereas the greatest concentrations of Cu (30.9 mg kg^{-1}) and Ag (157.590 mg kg^{-1}) were found in the west of the lake (WL). Only In was found to have the highest concentration in the sediment from DWSA, and most heavy metals were found to be less than other areas.

After comparison with heavy metal concentrations of sediments from rivers and lakes worldwide (Dauvalter 1994; Ikem and Adisa 2011; Yang et al. 2009; Yu et al. 2011; Zaharescu et al. 2009; Zhao et al. 2012) (Fig. 2), it was easy to observe which metals were comparatively high or low in concentration in sediment from Lake Chaohu. Concentrations of Al, Fe, Ca, Mn, Sr, Co, Zn, Cd, Pb, and Hg were close to the median of the literature values, those of K, Mg, Na, Li, Ga, and Ag were higher than the median levels of the literature values, and those of Cr, Ni, and Cu were lower than the median level of the literature values.
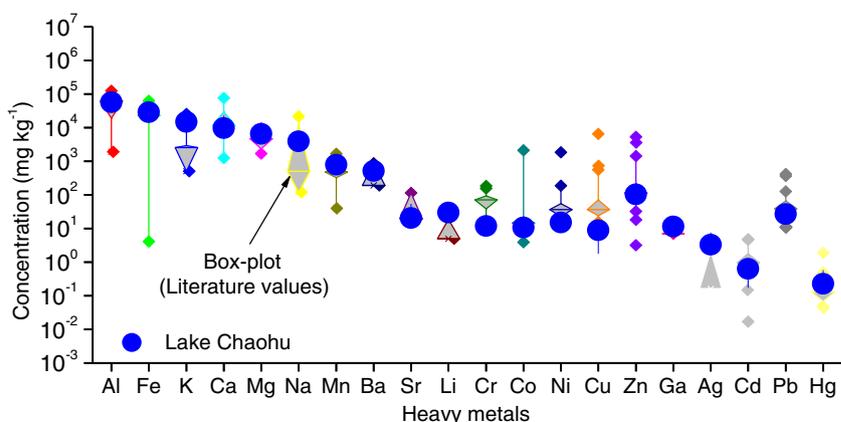
Source apportionment

PCBs

The PCA associated 85.3 % of total variance with the first two axes (53.9 % and 31.4 %, respectively) (Fig. 3a). The PCBs with higher chlorination (5–8 Cl) were associated with component 1, whereas the lower chlorinated PCBs (3–4 Cl) were associated with component 2. However, the negative loading of triCB compared with tetraCB indicated their different sources. The presence of triCB can be attributed to technical PCBs such as Aroclor 1016 and 1242, which were dominated by three-chlorinated PCBs (Frame et al. 1996). The presence of tetraCB can be attributed to degradation from five-chlorinated technical PCBs such as Aroclor 1248 and 1254 (Bzdusek et al. 2006b). The source of higher-chlorinated PCBs was similar and was attributed to ships along the navigation channel in the lake and suspended particulate matter (SPM) (Young et al. 1976). The less soluble higher-chlorinated PCBs generally had affinity with SPM (Ferreira et al. 2003). Therefore, PCBs in SPM, carried from discharge rivers in the east of Lake Chaohu, would settle in the east of the shallow lake and caused the greater concentrations of higher-chlorinated PCBs in sediment. These phenomena have been found for PBDEs in sediment from the same sampling locations (He et al. 2013a).

As shown in Fig. 3b, most sampling sites were weakly affected by the higher-chlorinated PCB source (component 1) but influenced by TriCB (negative direction of component 2). However, A6, B6, and C2 were much different than other samples, indicating their different sources. In detail, A6 was significantly affected by the higher-chlorinated PCB source, probably the waiting large vessels. B6 and C2 were affected by tetraCB (positive direction of component 2), which might be caused by microbial degradation of higher-chlorinated PCBs and urbanization (Hong et al. 2012; Vanier et al. 1996).

The major sources of PCBs were also identified by the PMF model, and the factor profiles and coefficients of determination were shown in Table 2. Three factors were extracted because of the lower factors with better simulation (Bzdusek

Fig. 2 Comparison of heavy metal concentrations of sediments from rivers and lakes worldwide. The boxplot (including 5th, 25th, 50th, 75th, and 95th percentiles and outliers) was drawn using literature values, which are summarized from references in Table S7

Fig. 3 PCA plot (loading and score) of PCBs and heavy metals in the sediments from Lake Chaohu. **a** PC1/PC2 axes for PCB congeners, **b** PC1/PC2 axes for sampling sites based on PCBs data, **c** PC1/PC2 axes for specific heavy metals, **d** PC1/PC2 axes for sampling sites based on heavy metal data, **e** PC1/PC3 axes for specific heavy metals, and **f** PC1/PC3 axes for sampling sites based on heavy metal data
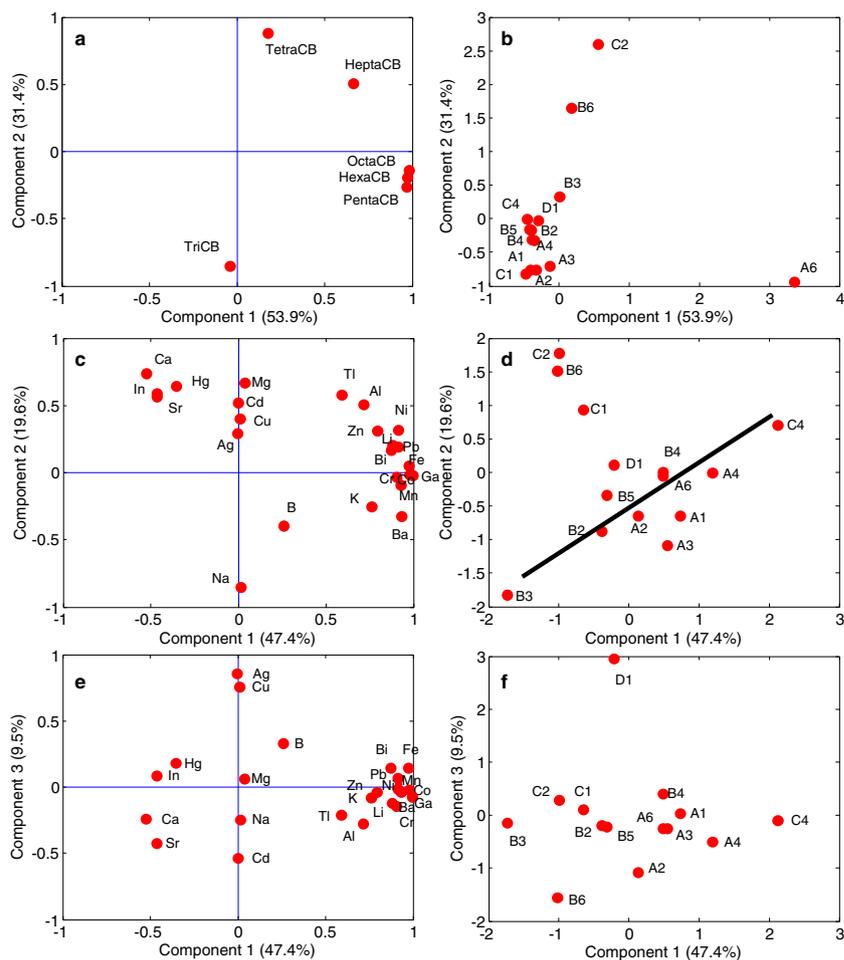
et al. 2006b; Qin et al. 2014). Factor 1 was weighted by heptaCB, which might be a source of the technical PCBs Aroclor 1260 and 1262 (Frame et al. 1996). Factor 2 was predominately composed of tetraCB, which was identified as microbial degradation of higher-chlorinated PCBs (Vanier et al. 1996). Factor 3 had higher loading values of the remaining PCB congeners, which originated from many technical PCBs (Du et al. 2008; Frame et al. 1996). The above three sources of PCBs accounted for 20.7, 65.8, and 13.5 % of the total PCBs.

Heavy metals

The PCA associated 76.5 % of the total variance with the first three axes (47.4, 19.6, and 9.5 %, respectively) (Table S8). According to PCA in Fig. 3c, e, Ga, Co, Cr, Mn, Fe, Pb, Bi, Li, Ni, Zn, K, and Ba exhibited high positive loading of the first component, indicating that those heavy metals might have similar sources. Those heavy metals were found together with Fe and Mn, indicating that the trace elements are of geogenic origin in association with Fe–Mn minerals (Zaharescu et al. 2009). In addition, high-toxicity and low-residual Cd, In, Tl,

and Hg were associated with natural Ca, Mg, Sr, and Na in the second component, indicating their geogenic origin in association with Ca–Na–Mg minerals (Iqbal et al. 2013). Cu and Ag had relatively high positive loadings of the third component, indicating possible urban discharge and nonpoint agricultural sources (Feng et al. 1998; Li et al. 2013).

As shown in Fig. 3d, the scores of component 1 for most sampling sites were significantly correlated with component 2 ($p < 0.01$) after excluding some river sampling sites (C1, C2, and B6), indicating that Fe–Mn minerals and Ca–Na–Mg minerals were coupled for most samples in the lake. However, heavy metals in sediment from the river were more affected by Fe–Mn minerals than Ca–Na–Mg minerals. As shown in Fig. 3f, most sampling sites, except D1, were at low levels of Ag–Cu pollution, although their Fe–Mn mineral associations were different. The high occurrence of Ag and Cu in D1 were caused by possible urban discharge and nonpoint agricultural sources in the west of the lake because of high industrial pressure in Hefei, the capital of Anhui Province, and large areas of agricultural land (He et al. 2013b).

According to PMF source apportionment in Table 2 and metals' sources identification by investigating literatures

Table 2 Factor profiles of PCBs and heavy metals (fractional contribution to the sum of PCBs, % of species sum) in the sediment using PMF

	Factors					R^2
	F1	F2	F3	F4	F5	
PCBs						
TriCB	4.8	1.9	*93.3*			0.01
TetraCB	10.2	*89.8*	0.0			1.00
PentaCB	2.2	0.0	*97.8*			0.99
HexaCB	0.0	9.1	*90.9*			0.99
HeptaCB	*83.7*	0.7	15.6			1.00
OctaCB	15.6	0.5	*83.9*			0.94
Σ_{34}PCBs	20.7	*65.8*	13.5			1.00
Heavy metals						
Al	*34.3*	9.7	25.0	10.3	20.7	0.87
Fe	*34.0*	6.7	27.1	13.3	18.9	0.93
K	*39.1*	7.1	23.5	11.8	18.6	0.57
Ca	14.5	*49.8*	6.4	11.8	17.6	0.33
Mg	*33.7*	14.6	21.0	10.4	20.3	0.83
Na	*56.8*	2.4	18.8	13.6	8.4	0.46
Mn	*34.7*	6.1	*39.7*	13.0	6.4	0.84
Ba	*36.6*	5.4	29.1	13.0	15.8	0.92
Sr	18.8	*63.4*	17.8	0.0	0.0	0.07
Li	*34.1*	7.6	22.0	10.3	26.0	1.00
B	16.5	0.0	0.0	*72.6*	10.9	0.07
Cr	21.9	5.6	*38.2*	7.0	27.4	0.59
Co	*34.8*	6.2	24.4	12.1	22.5	0.99
Ni	26.5	5.9	*29.3*	10.8	27.5	0.88
Cu	0.0	10.3	0.0	*40.9*	*48.8*	1.00
Zn	17.7	5.5	*48.2*	13.4	15.3	1.00
Ga	*32.8*	6.2	27.5	10.9	22.6	0.95
Ag	0.5	15.8	9.2	*73.2*	1.3	0.95
Cd	6.4	11.8	27.2	4.3	*50.2*	0.21
In	0.0	*42.9*	0.0	*57.1*	0.0	0.24
Tl	*31.3*	7.9	24.9	12.4	23.4	0.56
Pb	19.2	5.7	*48.6*	13.5	13.0	0.89
Bi	0.0	0.0	*77.3*	20.5	2.2	0.85
Hg	10.4	*62.4*	6.8	11.6	8.8	1.00
Average	23.1	15.0	24.7	19.5	17.8	

Notes: Three factors and five factors were extracted for PCBs and heavy metals, respectively. The values in italics denote the significant factors. R^2 is the coefficient of determination between observed and predicted concentrations

worldwide, factor 1 was associated with Al, Fe, K, Mg, Na, Mn, Ba, Li, Co, Ga, and Tl, indicating that it represents natural geogenic sources (Iqbal et al. 2013; Zaharescu et al. 2009). Factor 2 was predominately composed of Ca, Hg, In, and Sr, also suggesting mineral sources (Iqbal et al. 2013). Factor 3 was dominated by Mn, Cr, Ni, Zn, Pb, and Bi, indicating that its source was smelters, industrial sewage, and traffic pollution

(Bai et al. 2011; Dauvalter 1994; Zhang et al. 2014). Factor 4 mainly consisted of B, Cu, Ag, and In, which were thought to be from urban discharge and nonpoint agricultural sources (Feng et al. 1998; Li et al. 2013). Factor 5 was weighted by Cr, Co, Ni, Cu, and Cd, which were all originating from industry, such as atmospheric emissions from smelters (Dauvalter 1994). To summarize, factors 1 and 2 had natural sources, whereas factors 3–5 had anthropogenic sources. The two sources accounted for 38.1 and 61.9 % of heavy metals in the sediment, respectively.

Influencing factors and association with other contaminants

Effect of organic matter

Most contaminants did not have significant correlation with the TOC, except for PCBs (e.g., tetraCB and heptaCB), K, Ca, and Hg. The correlation between TOC and PCBs was also reported by Chevreuil et al. (1998). However, Gao et al. (2013) found that TOC and grain size did not correlate with PCBs. Therefore, the effect of organic matter on the distribution of PCBs might be site dependent. Although there might be a good correlation between TOC and heavy metals due to the organic complexes with heavy metals (Selvam et al. 2012), not all heavy metals correlated with organic matter in our studies, which was in accordance with other studies (Kukrer et al. 2014; Swarnalatha et al. 2013). To our knowledge, both organic matter and minerals can serve as absorbents of heavy metals (Davis 1984; Hochella et al. 2005). The competitive adsorption might exist between the two components in the sediment. According to Table S8, many heavy metals correlated with Al, Fe, K, Ca, Mn, Ba, and Li, which were major components of the minerals in the sediment. Although the trace metals (e.g., Sr, Cd, In, Tl) were not associated with TOC, they correlated with some components of the organic matter. There was a significantly positive correlation between Sr/In and all organic carbon species separated by pyrolysis. Ca was associated with volatile hydrocarbons (S1) and kerogen-derived hydrocarbon (S2), whereas Tl was only associated with S2 and high molecular weight kerogens.

Correlation between PCBs and metals

Generally, the correlation between PCBs and metals not only indicated their interactions such as the adsorption but also revealed their potential similar or different sources. The fairly positive correlation between PCBs and mineral element Ca, and negative correlations between PCBs and mineral element K and Ba indicated that the PCBs might be absorbed on Ca minerals rather than K–Ba minerals (Table S9). Chaohu and Hefei cities near Lake Chaohu belonged to developing cites in China, where many factories were transported from developed

cites in the east of China. Furthermore, both PCBs and heavy metals were not strictly controlled like developed countries or developed cites in China. The significantly positive correlation between PCBs and some trace heavy metals (e.g., Cd and Hg) revealed that they might have similar sources such as discharge of municipal wastewater from rivers through Hefei City (Feng et al. 1998).

Coupling discharge with other pollutants

The correlation between present contaminants (PCBs and heavy metals) and other investigated contaminants (PAHs, OCPs, and PBDEs) was analyzed in Table 3 (Gao et al.

2013; He et al. 2013a; Qin et al. 2014). None of the present contaminants correlated with OCPs, indicating that PCBs and heavy metals were not coupling discharge with OCPs. PCBs were found to be positively associated with PAHs and PBDEs, suggesting that they might have similar sources such as leachate from electronic waste (He et al. 2013a). Only Cd was positively correlated with PAHs, indicating potentially similar sources or coupled discharge. The reason might be that both PAHs and heavy metals were derived from the same sources (coal and petroleum combustion) and are first deposited together in soils, but heavy metals are less easily leached than PAHs and are transported to lower portions of the soil (Müller et al. 1977).

Table 3 Correlation between present contaminants (PCBs and heavy metals) and organic matter (TOC and organic carbon indicators using Rock-Eval 6 pyrolysis) as well as other investigated contaminants (PAHs, OCPs, and PBDEs)

	Organic matter						Other contaminants		
	TOCs	S1	S2	S2a	S2b	RC	PAHs	OCPs	PBDEs
TriCB	−0.456	−0.513	−0.502	−0.433	−0.559	−0.436	−0.627*	0.111	−0.062
TetraCB	0.766**	0.940**	0.871**	0.847**	0.884**	0.806**	0.982**	−0.368	0.500
PentaCB	0.013	0.215	0.276	0.298	0.254	0.270	−0.004	0.119	0.509
HexaCB	0.052	0.323	0.392	0.403	0.379	0.391	0.093	0.108	0.485
HeptaCB	0.824**	0.154	0.241	0.253	0.227	0.253	0.484	−0.106	0.674**
OctaCB	0.103	0.224	0.296	0.311	0.281	0.310	0.030	0.114	0.464
PCBs	0.827**	0.966**	0.926**	0.909**	0.933**	0.867**	0.948**	−0.323	0.630*
Al	0.228	−0.064	0.078	0.068	0.087	0.066	0.104	−0.340	0.393
Fe	−0.258	−0.580	−0.398	−0.400	−0.392	−0.383	−0.406	0.012	−0.003
K	−0.651*	−0.643	−0.514	−0.498	−0.523	−0.466	−0.706**	0.000	−0.181
Ca	0.554*	0.933**	0.865**	0.841**	0.880**	0.809**	0.912**	−0.456	0.335
Mg	0.521	−0.201	−0.020	−0.041	0.000	0.019	0.256	−0.485	0.310
Na	−0.461	−0.270	−0.418	−0.354	−0.471	−0.432	−0.418	0.173	−0.050
Mn	−0.194	−0.635	−0.506	−0.486	−0.519	−0.532	−0.436	0.057	0.040
Ba	−0.419	−0.622	−0.478	−0.468	−0.484	−0.501	−0.509	0.223	−0.076
Sr	0.291	0.932**	0.862**	0.838**	0.876**	0.801**	0.827**	−0.439	0.252
Li	0.072	−0.319	−0.174	−0.182	−0.165	−0.133	−0.120	−0.045	0.332
B	−0.063	−0.156	−0.136	−0.072	−0.192	−0.102	−0.238	0.341	0.226
Cr	0.061	−0.501	−0.368	−0.360	−0.372	−0.363	−0.203	0.100	0.438
Co	−0.186	−0.506	−0.338	−0.338	−0.334	−0.326	−0.315	0.061	0.113
Ni	−0.027	−0.295	−0.107	−0.134	−0.083	−0.106	−0.130	−0.123	0.191
Cu	0.253	0.094	0.145	0.143	0.145	0.142	0.273	−0.007	0.042
Zn	−0.031	−0.150	0.016	−0.021	0.048	−0.096	0.024	−0.016	0.064
Ga	−0.129	−0.539	−0.387	−0.386	−0.386	−0.388	−0.335	0.039	0.188
Ag	0.205	−0.048	0.012	0.016	0.007	0.043	0.152	0.046	−0.166
Cd	0.279	0.721*	0.704*	0.705*	0.697*	0.602	0.628*	−0.259	0.379
In	0.210	0.757*	0.718*	0.701*	0.726*	0.672*	0.503	−0.479	−0.114
Tl	0.215	0.600	0.685*	0.657	0.703*	0.605	0.469	−0.284	0.427
Pb	0.035	−0.430	−0.251	−0.272	−0.231	−0.323	−0.112	0.072	0.124
Bi	−0.130	−0.377	−0.211	−0.235	−0.188	−0.296	−0.155	0.034	0.002
Hg	0.730**	0.294	0.306	0.307	0.302	0.322	0.496	−0.350	0.370

Notes: **<0.01, significance; *<0.05, significance

Risk assessment

Toxicity equivalency quantity of dioxin-like PCB

Twelve PCB congeners (non-*ortho*-substituted PCBs: PCB-77, PCB-81, PCB-126, and PCB-169; mono-*ortho*-substituted PCBs: PCB-105, PCB-114, PCB-118, PCB-123, PCB-156, PCB-157, PCB-167, and PCB-189) are considered as dioxins-like compounds by the WHO (Van den Berg et al. 2006). The total dioxin-like PCBs concentration using updated WHO toxic equivalency factors ranged from 0.1 to 10, 980 fg toxicity equivalency quantity (TEQ) g^{-1} (Table 1), which was much lower than the toxic threshold (20 pg TEQ g^{-1}) (Eljarrat et al. 2001). PCB-126 and PCB-169 were the main dl-PCB, and together they contributed 99.8 % of the TEQs. In A6, all of the dl-PCB congeners were detected, and the TEQ was 11.0 pg TEQ g^{-1}, which was greater than the interim sediment quality guideline of 0.85 pg TEQ g^{-1} recommended by the Canadian Council of Ministers of the Environment (Ssebugere et al. 2013).

Risk assessment of PCBs and heavy metals

According to Hakanason's degree of contamination (C_d) in Fig. 4a, sampling sites covered all four contamination degrees. The pollution of the DWSA by PCBs and heavy metals was low-to-considerable. The BA contamination was low to moderate, whereas the contamination degree of PDR was considerable to very high. The west of the lake (D1) had the highest pollution among all of the sampling sites. The distribution of contamination factors (C_f) for PCBs, and heavy metals was shown in a boxplot graphic (Fig. 4b). The degrees of contamination by PCBs, as well as some heavy metals such as Al, Fe, K, Ca, Mg, Na, Mn, Sr, Li, B, Cr, Co, Ni, Cu, Ga, and In, were found to be low for most sampling sites. Contamination by Ba, Zn, Tl, Pb, and Bi was low to moderate. However,

contamination with those heavy metals was up to considerable in the Dazhegaohe River (C4). Pollution by Ag, Cd, and Hg was considerable to very high in Lake Chaohu, whose highest sampling sites were D1 (seriously affected by the city of Hefei, the capital of Anhui Province), B6 (harbor of fishing boats), and C2 (the location of a coal-fired power station, where substantial amounts of mercury might be produced (Wang et al. 2000)).

The risk based on the toxicity parameters was assessed in Fig. 5. The ecotoxicity risk of PCBs, Cr, Ni, Cu, Zn, Cd, Pb, and Hg for most sampling sites (>79 %) was below TEC. A TEC-to-PEC level of risk of Fe and Mn was found for most sampling sites (Fe, 93 %; Mn, 79 %). The risks of Mn, Ag, and Hg for some sampling sites were larger than PEC, indicating that these heavy metals posed potential ecological risks to the benthic organisms in Lake Chaohu.

Implication for the drinking water sources

On the basis of the risk assessment of PCBs and heavy metals in sediment described above, the drinking water source area (low-to-considerable risk) was found to be less polluted than PDR (considerable-to-very high risk). The risk pattern that the DWSA was threatened by PDR was similar with other pollutants like PBDEs in previous studies (He et al. 2013a). Many studies suggested that the anthrophonic activities such as fishing boats' discharge, coal-fired power station, traffic emissions, industrial sewage, and daily plastic discharge, were comprehensively causing the contamination of sediment in DWSA (Besser et al. 2008; He et al. 2013b; Li et al. 2013; Odhiambo et al. 2013). Some other natural factors such as water circulation patterns, depth, and bathymetry might potentially influence the deposition of pollutants into sediment. Furthermore, resuspension of sediment might increase the pollutants' concentration in the surface water (He et al.

Fig. 4 Hakanson's degree of contamination (C_d) for each sampling site (**a**) and boxplot (**b**) of the contamination factors (C_f) for each contaminant on the basis of data from fourteen sampling sites in Lake Chaohu
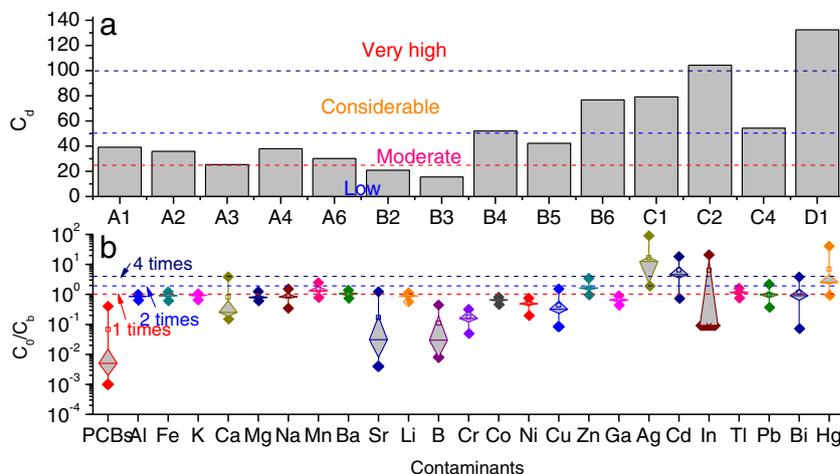
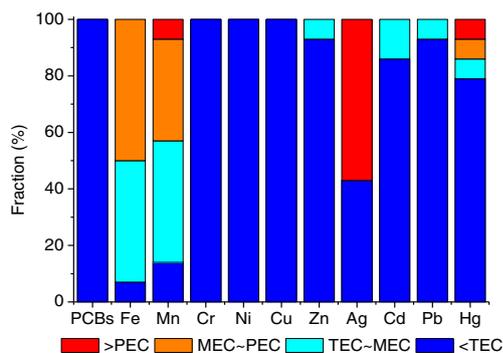**Fig. 5** The fraction (%) of samples below TEC, between TEC and MEC, between MEC and PEC, and above PEC on the basis of consensus-based SQG

the toxic threshold for dl-PCBs set at 20 pg TEQ g^{-1}, (max dl-PCBs, 10.9 pg TEQ g^{-1}), However, concentrations of Ag, Cd, and Hg were at levels of environmental concern.

2013a). To reduce the threats from sediment, the DWSA was desilted periodically. However, the fundamental solution is to reduce the discharge of contaminants such as heavy metals, to reduce the depletion of coal in the power station, and to treat the wastewater carefully before discharging into the lake.

Conclusions

The total concentration of 34 PCBs (Σ_{34}PCBs) in Lake Chaohu was 672 pg g^{-1} dw with a range of 7 to 3999 pg g^{-1} dw. The PCBs with lower degrees of chlorination (3–4 Cl) dominated the PCBs in sediment from Lake Chaohu. Although sediment in DWSA confronted a threat from PDR, the occurrence of PCBs was much lower than in other water bodies worldwide. The majority of heavy metals were detected in all sampling locations, except for Sr, B, and In. Concentrations of Al, Fe, Ca, Mn, Sr, Co, Zn, Cd, Pb, and Hg were similar to that reported for other lakes globally, and those of K, Mg, Na, Li, Ga, and Ag were greater than the average, whereas those of Cr, Ni, and Cu were lower. The sediments in DWSA were threatened by heavy metals from other areas. CA and PMF yielded accordant results for the source apportionment of PCBs. The technical PCBs and microbial degradation accounted for 34.2 % and 65.8 % of total PCBs in Lake Chaohu using PMF, whereas PMF revealed that natural and anthropogenic sources of heavy metals accounted for 38.1 % and 61.8 %, respectively. CA indicated that some toxic heavy metals (e.g., Cd, In, Tl, and Hg) were associated with Ca–Na–Mg minerals rather than Fe–Mn minerals. The uncorrelated results between TOC and heavy metals might be caused by the existence of competitive adsorption between organic matter and minerals. PCBs and heavy metals coexisted in discharge without OCPs, but with PAHs and PBDEs. No sediment sample exceeded

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