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Heavy metal distribution and bioaccumulation combined with ecological and human health risk evaluation in a typical urban plateau lake, Southwest China

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Abstract

Heavy metal contamination in lakes caused by the rapid industrialization and urbanization is a serious problem. In this study, 12 heavy metals were systematically surveyed in aquatic environment and organisms of Dianchi Lake. Results showed that heavy metals pollutions in surface water exhibited a decreasing order of Ba > Fe > Zn > Mn > As >Ni > Cr > Cu > Pb > Cd > Co, equipped a consistency in spatial distribution, seriously contaminating the northern and southern parts. The average concentration of sedimentary heavy metals appeared in an order of Fe > Mn > Zn > Ba > Cu > Pb > Cr > As > Ni > Co > Cd > Ag. The main existing fraction (51.9%–75.0%) of Cu, Pb, Cr, As, Fe, Co, Ni, Ag, and Ba in sediments was residual fraction, whereas the exchangeable fraction (40.9%–62.0%) was the dominant component for Cd, Zn, and Mn. Among the selected aquatic organisms, Cu, Pb, Zn, and Ag possessed a strong bioaccumulation effect, followed by Mn, Fe, Co, and Ni. Ecological risk assessment indicated that Cu, Cr, and Zn were the dominant heavy metal contaminants in surface water; Cd presented the disastrous risk and accounted for the considerable proportion of ecological risk in sediments. Human health risk evaluation showed that the selected aquatic products of Dianchi Lake were not absolutely safe, and As was the major contributor. This study systematically revealed heavy metal distributions in aquatic environments, which was conductive to environmental safety and human health.

Keywords: Dianchi Lake; Heavy metals; Bioaccumulation; Source identification; Risk assessment

Main findings of the work

This work revealed heavy metal distributions in a typical plateau lake, and comprehensively evaluated the ecological risk and human health risk.

1. Introduction

Heavy metal pollution in aquatic ecosystem has become a serious environmental problem in the world because of its potential toxicity and accumulation in organisms (Peng et al. 2009; Tang et al. 2010; Fu et al. 2013). These contaminants in aquatic environment not only generate direct toxic effects on aquatic organisms, but also bring potential threats to human health through the domestic water and food chain (Järup et al., 2003; Liu et al., 2018). In addition, heavy metals tend to accumulate in sediments and become the internal source of water pollution (Zhang et al., 2007; Bradl, 2004). After resuspension, heavy metals in sediments can be released into surface water again, thereby causing secondary pollution (Kelderman and Osman, 2007; Baran and Tarnawski, 2015). Therefore, systematically studying the distribution of heavy metals in surface water, sediments, and organisms is necessary for contamination control and environmental management. Moreover, identifying the pollution source will provide an important reference for ecosystem restoration and remediation (Wang et al., 2019).

The monitoring, risk assessment, and prevention of heavy metal pollution have been widely concerned for several decades (Kumar et al., 2019). Long-term heavy metal pollution is regarded to disrupt the aquatic ecological balance and cause serious adverse effects on aquatic ecosystem (Jaiswal et al. 2018). In freshwater ecosystem, numerous natural and anthropogenic sources contribute to the heavy metal pollution, including direct atmospheric precipitation, geological process, and discharge of abundant human activities (Saha and Paul, et al., 2018). For urban and suburban lakes, these environmental problems usually become more prominent because of the intensive human impact when compared with remote lakes (Cheng et al., 2015). With the rapid development of industrialization and urbanization in China, suburban and urban lakes have received considerable pollutants impacted by human activities and suffered ecological deterioration (Li et al., 2020; Qian et al., 2020). Previous literature indicated that the major rivers and lakes in China had been generally polluted by heavy metals at different levels, with the sedimentary pollution proportion over 80% (Wang et al., 2010). Hence, focusing on the pollution level and bioaccumulation of heavy metals in urban and suburban lakes is important to compare the contribution of rapid economic development to heavy metal pollution with remote plain lakes (Xia et al., 2011; Fu et al., 2014; Wei et al., 2012). Although heavy metal investigation and risk assessment in Chinese lakes have been reported, the comprehensive heavy metal evaluation of surface water, sediments, and organisms in a typical urban plateau lake is still limited (Fu et al., 2013; Tang et al., 2010; Cheng et al., 2015). When a large number of these contaminants are transported into the aquatic ecosystem, the bioaccumulation of metals and biomagnification of the food chain may cause a series of environmental problems, such as ecosystem degradation and public health risks (Altindag and Yigit, 2005; Xia et al., 2019). However, few research reports have focused on the bioaccumulation of heavy metals, their interaction with environmental parameters, and the transmission of metals from edible aquatic organisms to humans (Fu et al., 2014; Yi et al., 2011).

Dianchi Lake, located in the southwest of China near Kunming City, is the largest freshwater plateau lake in

China with an altitude of 1886.5 m above sea level (Fig. 1). In general, the lake provides water for agriculture, industry, drinking, and other activities (Wan et al., 2011). However, since the last century, rapid industrialization and urbanization in the watershed had contributed a serious eco-environmental problem in and around the lake (Guo et al., 2017). The lake receives numerous contaminants from its connected rivers and suffers from serious anthropogenic pollution, gradually evolving into a eutrophic lake (Wang et al., 2013; Wang et al., 2019). Reports indicated that the eutrophication of Dianchi Lake was closely correlated to human activities (Gao et al., 2016; Zhu et al., 2018). In recent years, the heavy metal evaluation in Dianchi Lake has also been carried out (Li et al., 2020). However, previous studies have only focused on the concentrations of heavy metals in sediments, and their pollution levels in multiple environmental media and source identifications are lacking, particularly for several trace elements such as Co, Ag, Ba, and Ni (Kumar et al., 2019; Qian et al., 2020). These less concerned heavy metals are also closely related to certain human health diseases (Li et al., 2014; Yi et al., 2011). Meanwhile, several aquatic species in Dianchi Lake are generally important food resources, and their human health risks must be considered. Chinese white prawn, *Macrobrachium nipponense*, *Hemisalanx prognathus* Regan, and *Rhinogobius giurinus* are four of the major commercial aquatic products consumed frequently by local residents. Although several studies had investigated heavy metals in fish community, only few of them addressed the transportation of metals in aquatic environments to the high trophic level and result in potential health risks through the food chain (Yang et al., 2017; Qian et al., 2020). Hence, comprehensive investigation of various heavy metals in Dianchi Lake ecosystem is of great significance for pollutant control and restoration. Furthermore, human health and ecological risk assessment of heavy metals in surface water and sediments, associating with bioaccumulation, will provide valuable basic information and important management strategies.

In the present study, distributions, risks, and source identifications of 12 heavy metals were focused on, including Cu, Cd, Cr, As, Pb, Zn, Mn, Fe, Co, Ag, Ba, and Ni. In particular, the species sensitivity distribution (SSD) model was used to evaluate the risk of heavy metal pollution in surface water; the geoaccumulation index (Igeo) and potential ecological risk index (RI) were selected to assess the sedimentary risk, and the bioaccumulation factor (BAF) was applied to illustrate the impact of heavy metals on organisms. The main purposes of this study included four aspects: 1) to systematically investigate the concentration of heavy metals in surface water, sediments, and organisms; 2) to identify the pollution source of heavy metals in Dianchi Lake; 3) to assess the ecological and human health risks of these contaminants in different media; and 4) to provide guidance for pollutant management and aquatic production consumption in Dianchi Lake.

2. Materials and methods

2.1. Study area and sample procedure

The Dianchi Lake (N24°40′-25°02′, E102°02′-102°47′), covering approximately 298 km^2 of water area and 2920 km^2 of watershed area, is the largest freshwater lake in the Yunnan–Guizhou Plateau of Southwest China. The lake is separated into two parts by artificial water conservancy facilities (Fig. 1). The northern part (Caohai) is adjacent to Kunming City, having only 3% of the total lake area and an average depth of 2.5 m. The southern part (Waihai) accounts for the most part of the lake area, having an average depth of 4.4 m. The climate of the Dianchi Lake is characterized by subtropical southwest monsoon, with an annual mean temperature of 14.4 °C and an average precipitation of 1000 mm (Wang et al., 2018). The hydraulic retention time of surface water in the Dianchi Lake is approximately 2.7 years, which limits the self-purification capacity of the lake (Li et al., 2020). Since the last century, rapid population and economic growth in this area have resulted in a serious eco-environmental problem, such as eutrophication and heavy metal pollution (Ma and Wang, 2015).

The locations of sampling samples in the lake were presented in Fig. 1 and Table S1. All samples were collected from the Dianchi Lake in July 2014. Organism samples, including shrimps (Chinese white prawn and *M. nipponense*) and fishes (*H. prognathus* Regan and *R. giurinus*), were stochastically obtained according to the actual situation (Table S8). Mixed water samples from three depths (~0.5, ~1.5, and ~2.5 m above the bottom) were collected. Surface sediment samples (0–10 cm) were obtained using a Peterson dredge. Organism samples were obtained by a trawl. The above-mentioned collected samples were stored in a −4 °C freezer until laboratory analysis.

Fig. 1

2.2. Laboratory analysis

Twelve heavy metals, including Cu, Cd, Cr, As, Pb, Zn, Mn, Fe, Co, Ag, Ba, and Ni, were measured in surface water, sediments, and organism samples. Four different forms of heavy metals in sediments were extracted, which were classified into residual, oxidizable, reducible, and exchangeable. The detailed sedimentary fractionation procedure was presented in Table S2. Before heavy metal analysis, sediment and organism samples were pretreated according to previous reports (Fu et al., 2013; Xing et al., 2013). All samples were treated using microwave digestion and analyzed by inductively coupled plasma mass spectrometry.

Electrical conductivity (EC), dissolved oxygen (DO), water temperature (WT), pH, suspended solid (SS), total dissolved solid (TDS), oxidation–reduction potential (ORP), and chlorophyll a (Chla) were determined in situ using EXO2 detector (YSI, USA). Other environmental parameters, including total nitrogen (TN), nitrate nitrogen (NO_3^--N), nitrite nitrogen (NO_2^--N), ammonium nitrogen (NH_4^+-N), activated phosphorous (PO_4^{3-}-P), total phosphorus (TP), and chemical oxygen demand (COD_{Mn}), were measured according to the standard methods in the laboratory (APHA, 1998). The moisture content of sediments was measured by drying at 105 °C, and sedimentary organic matter (SOM) was determined by calcination at 550 °C.

2.3. Data analysis

2.3.1. Multivariate statistical and geostatistical analysis

Pearson correlation analysis was performed to study the relationship among heavy metals. Principal component analysis (PCA) was used to identify the significant clusters and potential sources of heavy metals. A geostatistical approach called inverse distance weighting was applied to evaluate the distribution of heavy metals in unsampled areas and generate the spatial map. These statistical procedures for heavy metals in surface water and sediments were similar to our previous works (Wang et al., 2017; Liu et al., 2020). All data in this study were analyzed by SPSS 19.0, Origin 8.0, and ArcGIS 10.4.

2.3.2. Bioaccumulation factor (BAF)

The bioaccumulation factor (BAF) has been widely applied to quantify the bioaccumulation of environmental pollutants in previous studies (Hao et al., 2019). In this study, the BAF illustrated the impact of heavy metal concentrations in surface water on aquatic organisms (Ahmed et al., 2019). In general, BAF is the radio between heavy metal concentrations in the organisms and those in their main living environment (Qiu, 2015; Zhang et al., 2015). Therefore, BAFs for each freshwater organism sample and selected heavy metals were calculated with the following formula:

$$\mathrm{BAF} = \mathrm{C}_{\mathrm{organism}} / \mathrm{C}_{\mathrm{freshwater}},$$

where $C_{organism}$ is the heavy metal concentration in freshwater organisms (mg/Kg), and $C_{freshwater}$ is the concentration of heavy metals in a freshwater (μg/L) or sediment (mg/Kg) medium. BAF-freshwater can be categorized according to the following ranges: BAF < 1 indicates low probability of accumulation; 1 < BAF < 5 indicates moderate, and BAF > 5 indicates highly bio-accumulative (Arnot and Gobas, 2006). As for BAF-sediment, the calculated value > 1 indicates a potential accumulation of heavy metals, and the accumulative effect makes a significant difference when the BAF-sediment exceeds 100 (Zhang et al., 2015).

2.3.3. Species sensitivity distribution model (SSD)

The ecological risks of selected heavy metals in surface water were evaluated using SSD, which were introduced in detail in our previous study (Liu et al., 2018). In recent years, the SSD method has been widely used in risk assessment because of its simplicity and specific ecological significance (Xu et al., 2015). This risk assessment model has two important indicators: the potentially affected fraction (PAF) and concentration with 5% cumulative probability (HC5). The fundamental principle is illustrated in Fig. S1.

2.3.4. Sedimentary risk evaluation model

The RI, initially proposed by a Swedish scientist in 1980, has been proven to be an effective method and widely used to evaluate sedimentary pollution (Hakanson, 1980; Zhao et al., 2018). In this evaluation model, the toxicity characteristic, contaminant level, and background value of heavy metals were considered. The RI value was calculated using the following equations:

$$\mathrm{RI} = \sum_{i=1}^{n} E_r^i = \sum_{i=1}^{n} T_r^i \times \frac{C^i}{C_0^i}$$

where E_r^i is the individual potential risk factor; T_r^i is the toxicity factor for a selected metal (i.e., 30 for Cd, 5 for Ni, 5 for Cu, 5 for Pb, 2 for Cr, 1 for Zn, and 10 for As) (Hakanson, 1980). C_0 is the regional metal background value in the soil, and C_i represents the heavy metal concentration in sediments. In general, the potential ecological risk was classified into the following five levels (Wang et al., 2011; Hakanson, 1980): low risk (E_r^i < 30; RI < 100), moderate risk (30 < E_r^i < 50; 100 < RI < 150), considerable risk (50 < E_r^i < 100; 150 < RI < 200), very high risk (100 < E_r^i < 150; 200 < RI < 300), and disastrous risk (E_r^i > 150; RI > 300).

According to previous literature, the high heavy metal background value in this study area might overestimate the adverse effect of metals when using the RI and hazard quotient (HQ) models (Qian et al., 2020). Therefore, the Igeo was selected to assess the risks of heavy metals in sediments, whose calculation formula was as follows:

$$\mathrm{Igeo} = \log_2\left(\frac{C_n}{1.5B_n}\right)$$

where C_n is the measured concentration of each heavy metal in sediment samples; B_n is the geochemical background concentration of the corresponding metal in this study area. The soil evolvement and its influence on the eco-environment were important, representing the various geochemical processes in this area (Yuan et al., 2014). Therefore, the mean concentration of heavy metals in local soils was used as the background value (B_n) for sediments. According to the soil element background value investigation performed by China National Environmental Monitoring Center (1990), the B_n values were identified as 46.3 mg/kg for Cu, 0.218 mg/kg for Cd, 65.2 mg/kg for Cr, 18.4 mg/kg for As, 40.6 mg/kg for Pb, 89.7 mg/kg for Zn, 626 mg/kg for Mn, 52,200 mg/kg for Fe, 17.5 mg/kg for Co, 0.152 mg/kg for Ag, 346 mg/kg for Ba, and 42.5 mg/kg for Ni. Constant term 1.5 was the background matrix correction factor originated by lithospheric effects (Reddy et al., 2004). Based on the Igeo, the degree of risk is divided into seven levels: Igeo ≤ 0 (practically unpolluted), $0 <$ Igeo < 1 (unpolluted to moderately polluted), $1 <$ Igeo <2 (moderately polluted), $2 <$ Igeo <3 (moderately to heavily polluted), $3 <$ Igeo < 4 (heavily polluted), $4 <$ Igeo <5 (heavily to extremely polluted), and Igeo > 5 (extremely polluted; Bhuiyan et al., 2010).

2.3.5. Human health risk assessment

Human health risk assessment is the approach of estimating contaminant adverse effects on humans through aquatic products, and target hazard quotients (THQ) is regarded as an effective evaluation model (USEPA, 2014; Qian et al., 2020). Fishery and shrimp resources are important food resources for local residents around Dianchi Lake; therefore, evaluating the potential health risk related to their long-term consumptions is important (Guo et al., 2017; Wang et al., 2019). In general, no significant health risk is found if THQ is less than 1, but a potential health risk will occur if the index is greater than 1. The THQ value was obtained by the following formula (Yi et al., 2011; Qian et al., 2020):

$$\text{THQ} = \frac{EF_r \times ED_t \times FIR \times C_{factor} \times C}{RfDo \times BW_a \times AT_n} \times 10^{-3},$$

where THQ is the target hazard quotient; EF_r is the exposure frequency (365 days/year); ED_t is the exposure duration (70 years, average lifetime); FIR is the food ingestion rate (134 g/day, wet weight); C_{factor} is the conversion factor (0.085) that is used to convert fresh weight into dry weight; C is the heavy metal concentration in fish (mg/Kg); RfDo is the oral reference dose (mg/kg/day, Table S11); BW_a is the average adult body weight (60 kg); and ATn is the average exposure time for non-carcinogens (assuming 70 years). Total THQ (TTHQ) was calculated to estimate the additive effects of exposure to all the metals accumulated in fish:

$$\text{Total THQ} = THQ\ (toxicant\ 1) + THQ\ (toxicant\ 2) + \cdots + THQ\ (toxicant\ n)$$

3. Results and discussion

3.1. Descriptive statistics for physicochemical parameters in surface water and sediment

The surface waters were weakly alkaline, with mean pH of 9.3 (ranging from 7.9 to 10.0). During the sampling period, the average WT and DO were 23.9 °C and 9.77 mg/L, respectively. The EC, TDS, SS, and COD_{Mn} values ranged from 503 to 647 μS/cm (average 540 μS/cm), 331.5 to 435.5 mg/L (average 358.9 mg/L), 29 to 176 mg/L (average 84 mg/L), and 6.0 to 27.3 mg/L (average 15.8 mg/L), respectively. The mean concentrations of TN and TP were 4.62 and 0.21 mg/L, with the maximum of 9.56 and 0.56 mg/L, respectively. These typical water quality parameters suggested that the lake has suffered serious eutrophic pollution and algae bloom (Table S3; Qian et al., 2020). As shown in Table S4, the sediments in Dianchi Lake were reductive, with the mean pH and ORP values of 6.9 and −209.5 mV, respectively. The average SOM was 16.0%, ranging from 10.0% to 41.1%. Given the long-term eutrophication and weakly hydrodynamic processes of Dianchi Lake, a large number of nutrients had been enriched in sediments (Zhu et al., 2010). The mean concentration of sedimentary TN and TP was 5626 and 3584 mg/Kg, respectively. According to the U.S. Environmental Protection Agency, sediment was regarded as heavily polluted when sedimentary TN > 2000 mg/Kg and TP > 650 mg/Kg (USEPA, 2014). Important phosphorus industrial bases were found in China around Dianchi Lake, which might indicate the high phosphorus content in sediments (Zhu et al., 2010). However, the mean concentration of TN and TP in sediments of Taihu Lake (a eutrophic lake in China) was only 1110 and 930 mg/Kg, respectively (Fang et al., 2019). Therefore, based on the water and sediment quality characteristics of Dianchi Lake and previous literature, Taihu Lake was generally regarded as a typical hyper-eutrophic lake, which was suffering from the deterioration of the ecological environment (Huang et al., 2014; Cao et al., 2016).

3.2. Heavy metal distribution

3.2.1. Surface water

The pollution level of heavy metals in surface water exhibited a wide range, and the average concentration was arranged in a decreasing order: Ba (average 171.73 μg/L) > Fe (average 146.70 μg/L) > Zn (average 20.64 μg/L) > Mn (average 4.32 μg/L) > As (average 2.78 μg/L) > Ni (average 2.05 μg/L) > Cr (average 1.54 μg/L) > Cu (average 1.36 μg/L) > Pb (average 0.54 μg/L) > Cd (average 0.22 μg/L) > Co (average 0.13 μg/L, Figs. 2 and S3). Nearly all heavy metals equipped a great consistency in spatial distribution, seriously contaminated in the north and south part but less polluted in the middle part (Fig. 2). This differential spatial distribution might be due to the following reasons: the northern part was connected with Kunming City, and the southern part was densely distributed with residential communities. In general, the city and high-density population could remarkably contribute to the heavy metal pollution (Islam et al., 2015). By contrast, for example, the average Cu concentration in Dianchi Lake (1.4 μg/L) was lower than that in Poyang Lake (5.4 μg/L), Taihu Lake (2.9 μg/L), and Chaohu Lake (3.4 μg/L) but slightly higher than that in Liangzi Lake (1.1 μg/L). The Pb pollution level in this lake was lower than that in Poyang Lake, Taihu Lake, Chaohu Lake, and Liangzi Lake, whose average concentrations were 4.4, 3.8, 6.3, and 10.1 μg/L, respectively (Liu et al., 2018). The different metal pollution levels in various lakes of China were probably due to the different physical geography backgrounds and human activity impacts, thereby suggesting that the systematic investigation of metal pollution levels in different lakes was important.

Fig. 2

3.2.2. Sediment

The average concentration of sedimentary heavy metals appeared in a decreasing order: Fe (average 50720.35 mg/Kg) > Mn (average 813.03 mg/Kg) > Zn (average 496.80 mg/Kg) > Ba (average 273.35 mg/Kg) > Cu (average 146.19 mg/Kg) > Pb (average 108.83 mg/Kg) > Cr (average 74.78 mg/Kg) > As (average 61.95 mg/Kg) > Ni (average 45.81 mg/Kg) > Co (average 15.24 mg/Kg) > Cd (average 13.20 mg/Kg) > Ag (average 2.06 mg/Kg). Concentrations of Cu, Cd, Pb, Zn, As, Ni, and Ag in sediments had a similar spatial distribution. Remarkably, a decreasing trend was found from the northern (S1–S4) to the southern (S5–S12) part of Dianchi Lake ($P < 0.05$; Fig. 3). As for concentrations of Cr, Mn, Fe, Co, and Ba in sediments, their spatial distributions were basically consistent, varying within a limited range (Fig. 3). Fe was the most abundant metal in the sediment, exceeding the pollution level of other metals. According to previous literature and available data, several heavy metals were selected for comparison with published metal levels in Chinese lake sediments (Table S14). In this study, the mean concentration of heavy metals was consistent with the earlier report in Dianchi Lake (Yuan et al., 2014). Interestingly, contrary to that of surface water, the heavy metal concentration in sediments of Dianchi Lake was significantly higher than that of Chaohu Lake and Taihu Lake. For example, the concentrations of Cu and Pb in sediments of Dianchi Lake were about 8.5 times and 73.3 times higher than that of Chaohu Lake, respectively. This phenomenon was probably due to the following reasons. First, Dianchi Lake had higher density and biomass of algae compared with the other lakes, and the algae biomass could easily uptake or adsorb metals from water (De Philippis et al., 2011; Wang et al., 2019). Second, the average depth of Dianchi Lake (approximately 5.0 m) was deeper than that of Taihu Lake (approximately 1.8 m) and Chaohu Lake (approximately 3.0 m) (Zhang et al., 2019; Xu et al., 2010; Shang et al., 2007). The deeper water depth in Dianchi Lake could resist sediment re-suspension by wind wave, which could reduce the metal release from sediments (Gao et al., 2005; Bai et al., 2012).

Fig. 3

The characteristic of heavy metal fractions was important to reveal their potential mobility and toxicity (Maiz et al., 2000). The main existing fraction of Cu, Pb, Cr, As, Fe, Co, Ni, Ag, and Ba in sediments was residual fraction, with values of 60.95%, 57.06%, 66.56%, 61.98%, 75.03%, 39.36%, 51.90%, 91.94%, and 63.41%, respectively (Fig. 3 and Fig. S2). For Cd, Zn, and Mn, the exchangeable fraction was the dominant component, accounting for 62.05%, 49.08%, and 40.94%, respectively (Fig. 3 and Fig. S2). Based on the bioavailability of heavy metals, a decreasing order was found: exchangeable > oxidizable > reducible > residual (Li et al., 2000; Prasad et al., 2006). The exchangeable fraction was generally regarded as the most unstable sedimentary part, which exhibited a strong relationship with water environments (Alves et al., 2007). Therefore, the environmental mobility and risk of heavy metals showed a positive correlation with this fraction proportion. In this study, the exchangeable fraction of heavy metals was arranged in the following order: Cd (62.5%) > Zn (49.08%) > Mn (40.94%) > CO (21.82%) > Ni (20.52%) > Ba (5.35%) > Cr (4.27%) > Cu (3.51%) > As (3.40%) > Fe (3.30%) > Pb (2.05%) > Ag (0.09%), indicating their different interactions with environments. This result suggested that Cd, Zn, Mn, Co, and Ni had the strongest association with the aquatic ecosystem in Dianchi Lake and likely reflected highly potential risks.

3.2.3. Bioaccumulation of heavy metals

Chinese white prawn (CWP), *M. nipponense* (MBN), *H. prognathus* Regan (HPR), and *R. giurinus* (RGG) were selected to evaluate metal bioaccumulation because they were usually consumed by the local residents. Heavy metal levels in selected organisms showed great differences (Table S9), and the concentration of heavy metals in selected fish (*H. prognathus* Regan and *R. giurinus*) was significantly lower ($P < 0.05$) than that in surveyed shrimp (*C. prawn* and *M. nipponense*). These results indicated that the ability of benthic shrimp to accumulate heavy metals was stronger than that of fish, which was consistent with previous studies (De Mora et al., 2004; Yang et al., 2010). Firstly, benthic shrimps mainly live in the sediment-water interface, which probably straightly affected by the heavy metals in the sediment (2-3 orders of magnitude higher than that in the water body). Secondly, metal concentrations in organisms were also adjusted by their biological metabolisms (Markert, 1987).

In the present study, the BAF of organisms to heavy metal in surface water (BAF-water) was further explored (Fig. 4 and Table S10). Different organisms exhibited distinct bio-accumulative capacities in response to various heavy metals. In our study, a high accumulative possibility of Ag in *H. prognathus* Regan; Cu and Ag in Chinese prawn; Cu, Pb, Zn, and Ag in *M. nipponense*; and Pb, Zn, and Ag in *R. giurinus* was found. Notably, Cd, Cr, As, and Ba presented a low accumulative probability for all selected organisms. Moreover, Mn, Fe, Co, and Ni showed a moderate accumulative probability for at least one species. Hence, based on the probability heatmap between organisms and heavy metals (Fig. 4), we found that Cu, Pb, Zn, and Ag possessed a strong bioaccumulation effect, followed by Mn, Fe, Co, and Ni. In general, Cu and Zn were regarded as a crucial biological trace element and demanded for abundant enzymatic oxidation–reduction activities; however, excessive levels of these two metals could also cause high toxicity (Bonanno et al., 2010; Wang et al., 2017; Wei et al., 2020). Pb and Ag were immobile in aquatic environment, and they showed toxicity. When Pb and Ag were absorbed by organisms through the food chain, they would exist for a long period (Samecka et al., 2001).

Fig. 4

3.3. Principal component and correlation analysis (CA)

PCA and CA were applied to identify and explain the pollution source of heavy metals (Fig. 5 and Fig. S4). In surface water, two principal components were extracted, which accounted for 62% of the total variance in the data matrix. The first principal component (PCA1) in surface water generated 37% of the total variance, which was primarily characterized by heavy metals. Among the heavy metals, Ag, Zn, Co, Fe, Mn, Cr, Cu, Cd, and Pb were the most important, followed by Ni and As, and Ba was relatively small. The second principal component (PCA2) accounted for 25.36% of the total variance, which was heavily weighted by conventional water quality parameters. Our results indicated that the pollution sources of heavy metals and eutrophic elements in surface water were probably inconsistent because of three reasons. First, heavy metals were strictly controlled in the effluent of sewage treatment plant when compared with organic contaminants (Ignatowicz, 2017). Second, heavy metals induced by non-point source pollution tended to be precipitated under the long-distance water transport, whereas nutrients were gradually accumulated (Ouyang et al., 2016; Jeong et al., 2020). Lastly, heavy metals cannot be easily degraded, and the sedimentary resuspension would lead to their release, whereas the conventional pollutants were biodegradable (Baran and Tarnawski, 2015). In sediments, two principal components were extracted, which accounted for 69% of the total variance in the data matrix. The first principal component (PCA1), including Ag, Zn, Cd, Pb, Cu, As, and Ni, was primarily characterized by most heavy metals. However, the second principal component (PCA2) was completely dominated by Fe, Mn, and Ba, whereas Cr and Co remarkably contributed to both axes. In particular, PCA1 and PCA2 accounted for 47% and 22%, respectively. PCA1 probably originated from anthropogenic activities, as Cu and Pb were strongly associated with human activities (Audry et al., 2004). However, PCA2 was heavily weighted by Fe and Mn, which might be closely related to the surrounding mining areas (Zhao et al., 2018).

Fig. 5

3.4. Ecological and human health risk assessment

3.4.1. Potential ecological risk

In our previous study on the SSD model, five heavy metals were selected to evaluate their ecological risks in Dianchi Lake because of their occurrence and toxicity. These metals with HC5 values of 7.76 (Cd), 2.29 (Cr), 2.09 (Cu), 12.59 (Pb), and 31.62 (Zn) posed great toxicity to aquatic environments (Table S7; Liu et al., 2018). In general, these metals were considered to be at risks only when their concentrations exceeded individual HC5 values (Hose and Van den Brink, 2004). The maximum concentration of Cu, Cr, Cd, Pb, and Zn in Dianchi Lake was 4.06, 3.17, 0.71, 2.25, and 74.49 μg/L, respectively. Therefore, Cu, Cr, and Zn exhibited ecological risks with the maximum PAF of 14%, 8%, and 13%, respectively (Table S7). Therefore, about 14% of species in Dianchi Lake were probably adversely impacted by Cu, whereas 8% by Cr and 13% by Zn. Therefore, based on the SSD model, Cu, Cr, and Zn were the dominant heavy metal contaminants in surface water of Dianchi Lake. These heavy metals should be strictly controlled to ensure the health of aquatic organisms in Dianchi Lake.

The Igeo was applied to evaluate sedimentary metal contamination in Dianchi Lake, and the calculated result was presented in Fig. 6b. The mean values of Igeo for Cr, Mn, Fe, Co, Ni, and Ba were lower than 0, suggesting that no pollution was caused by these metals. However, the average of Cu, Pb, and As ranged from 0 to 1, indicating unpolluted to moderately polluted. Cd, Zn, and Ag showed heavily polluted (average Igeo 3.24), moderately polluted (average Igeo 1.08), and moderately to heavily polluted (average Igeo 2.81), respectively. Regarding the individual Igeo value, the pollution status in sediments followed the order of Cd > Ag > Zn > As > Cu > Pb > Mn > Cr > Ni > Fe > Co > Ba (Fig. 6b). The result of this methodology indicated that Cd, Zn, and Ag were the most polluted metals, which was consistent with previous literature in this area (Qian et al., 2020). Hence, the anthropogenic inputs of heavy metals in this area were Cd, Zn, and Ag, with Igeo > 1.

In addition, the calculated RI values of sedimentary metals were summarized in Fig. 6a and Table S13. The RI values from S1 to S4 (Caohai, closely related to Kunming city) were more than 900, indicating that these sediments in Caohai were heavily polluted, which showed more disastrous risks than other areas. In general, the RI value was clearly related to the degree of anthropogenic disturbance (Yi et al., 2011). About 45% of sediment samples (S1, S2, S3, S4, S6, S7, S8, S15, and S17) were disastrous risks (RI > 300), and the remaining 55% (S5, S9, S10, S11, S12, S13, S14, S16, S18, and S19) showed very high risks (200 < RI < 300). In particular, the contributions for individual metals were in the order of Cd (94.6%) > Cr (1.8%) = As (1.8%) > Cu (0.8%) > Pb (0.7%) > Zn (0.3%). Remarkably, Cd presented disastrous risks and accounted for the considerable proportion of ecological risks in sediments, whereas other metals (As, Zn, Cr, Cu, and Pb) showed low-to-moderate risks. Sediments in Dianchi Lake, particularly Northern Caohai, suffered from potential ecological risks caused by heavy metals, and Cd was the most important contaminant element. Based on the RI and Igeo, heavy metals in sediments of Dianchi Lake exhibited high ecological risks.

Fig. 6

3.4.2. Human health threat from edible organisms

Based on the bioaccumulation of heavy metals (Fig. 4), the investigated organisms in Dianchi Lake exhibited different accumulation effects on these contaminants. Long-term consumption of these polluted aquatic productions might cause human health risks (Kumar et al., 2019). Therefore, the human health threat from four common edible organisms was evaluated for residents around the lake. Given the absence of Fe and Co human chronic ingestion data, the remaining 10 heavy metals were used in human health risk assessment. The calculated THQ and total THQ

(TTHQ) values were presented in Table S12 and Fig. 7. Human health risks of selected aquatic products decreased in the order of *M. nipponense* (1.998) > *C. prawn* (1.450) > *R. giurinus* (1.213) > *H. prognathus* Regan (0.355), and THQ of As was the major contributor to TTHQ. This study was consistent with previous reports in Dianchi Lake, in which As in aquatic products showed the most significant health risk (Qian et al., 2020). Except for the THQ of As in Chinese white prawn (1.119) and *M. nipponense* (1.187), the THQ of other metals to each aquatic consumption was generally less than 1, indicating that residents would not experience significant health risks from the intake of individual metal through selected organisms (Table S12). Therefore, human health risks induced by As were found in the consumption of Chinese white prawn, *M. nipponense*, and *R. giurinus*. Considering the impact of heavy metal pollution on human health, this study revealed that *H. prognathus* Regan was a priority of healthy food resource in Dianchi Lake. The heavy metals in the environment had various chemical forms that exhibited different toxicity to human health, and the THQ > 1 might not suggest people who were experiencing direct adverse health effects (Yi et al., 2011; Jia et al., 2018). In our future work, evaluating human health risks of metals by considering chemical speciation was necessary.

Fig. 7

4. Conclusion

The distribution, ecological risk, and source identification of heavy metals in surface water, sediments, and organisms of Dianchi Lake had been systematically investigated. The pollution level of heavy metals exhibited a wide range in surface water, with a decreasing order of Ba > Fe > Zn > Mn > As >Ni > Cr > Cu > Pb > Cd > Co. Nearly all heavy metals in surface water equipped a great consistency in spatial distribution, seriously contaminating the northern and southern parts. We found that the residual and exchangeable fractions of heavy metals were primarily presented in sediments. The primary existing fraction of Cu, Pb, Cr, As, Fe, Co, Ni, Ag, and Ba was residual fraction, whereas the exchangeable fraction was the dominant component for Cd, Zn, and Mn, which suggested that Cd, Zn, Mn, Co, and Ni had the strongest association with the aquatic ecosystem in Dianchi Lake. Furthermore, the average concentration of sedimentary heavy metals appeared in a decreasing order: Fe > Mn > Zn > Ba > Cu > Pb > Cr > As > Ni > Co > Cd > Ag. We found that Cu, Pb, Zn, and Ag possessed a strong bioaccumulation effect, followed by Mn, Fe, Co, and Ni. Ecological risk assessment indicated that Cu, Cr, and Zn were the dominant heavy metal contaminants in surface water, whereas Cd and Ag were the most polluted metals in sediments. As in selected aquatic products had the most significant health risk, and *H. prognathus* Regan was a priority of healthy food resource for residents.

CRediT authorship contribution statement

Xi Liu: Software, Data analysis, Writing - original draft. **Junqian Zhang:** Investigation, Project administration, Writing - review & editing. **Xiaolong Huang:** Writing - review & editing. **Lu Zhang:** Software, Writing - review & editing. **Chao Yang**: Writing - review & editing. **Enhua Li:** Investigation, Funding acquisition, Writing - review & editing. **Zhi Wang:** Investigation, Project administration, Supervision, Funding acquisition, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declarations

- **Ethics approval and consent to participate:** Not applicable.
- **Consent for publication:** Not applicable.
- **Availability of data and materials:** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.
- **Competing interests:** The authors declare that they have no competing interests.
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Figure captions

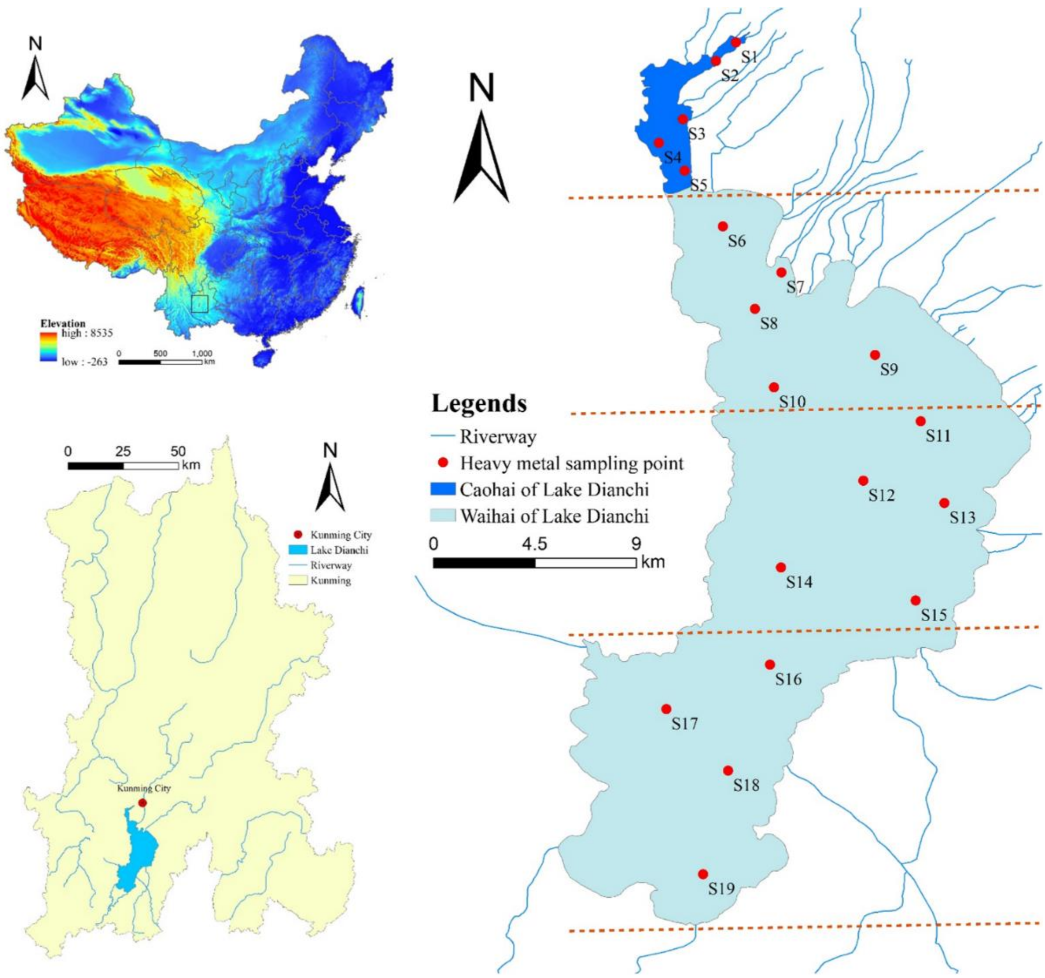

Fig. 1. Location of Lake Dianchi and sampling sites in the study area: S1–S5 in Caohai of Lake Dianchi, S6–S10 in Northern Waihai, S11–S15 in Central Waihai, and S16–S19 in Southern Waihai.

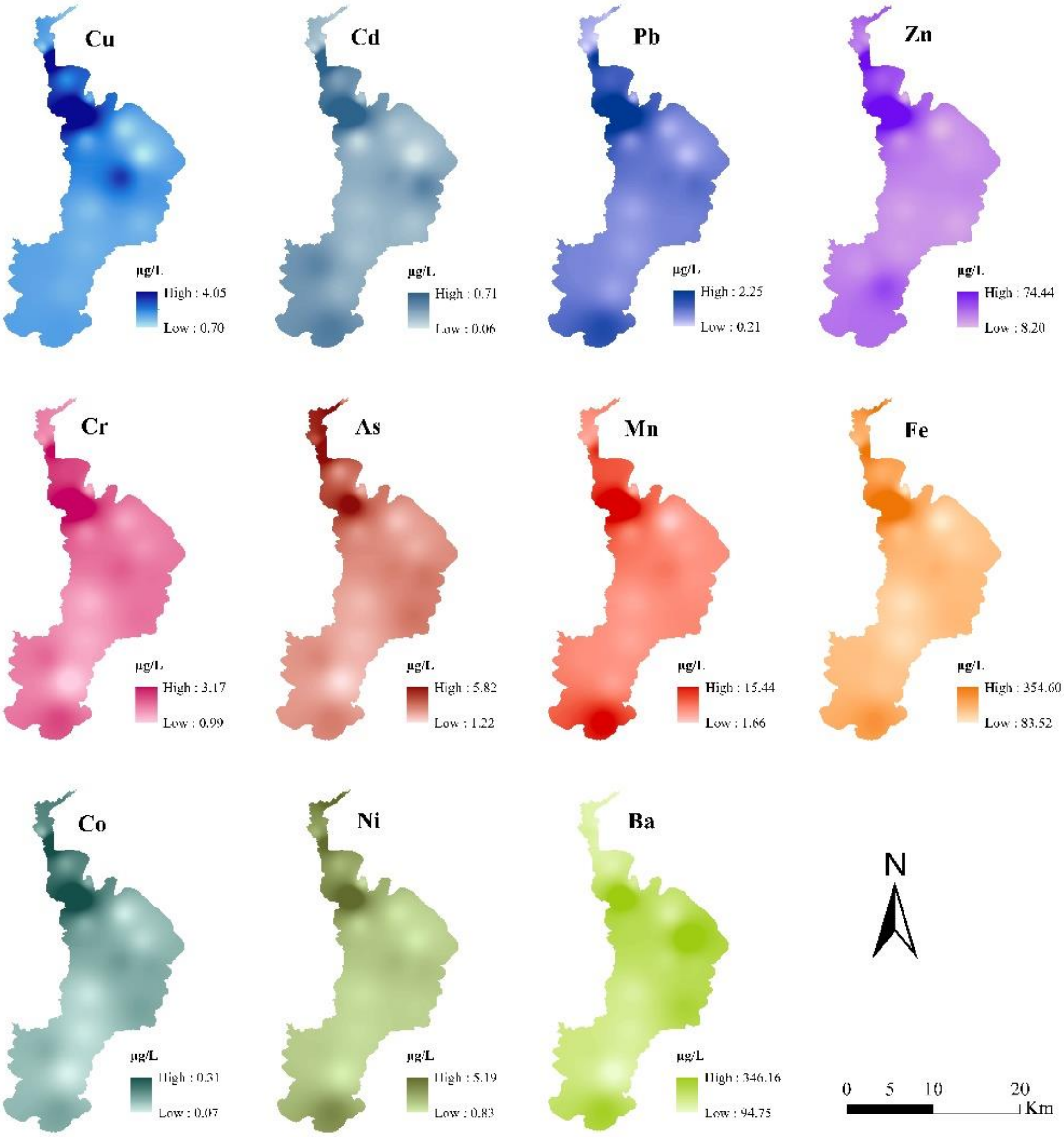

Fig. 2. Spatial variations of heavy metal concentration in surface water, including Cu, Cd, Pb, Zn, Cr, As, Mn, Fe, Co, Ni, and Ba. Ag was not presented because of its low concentration in surface water.

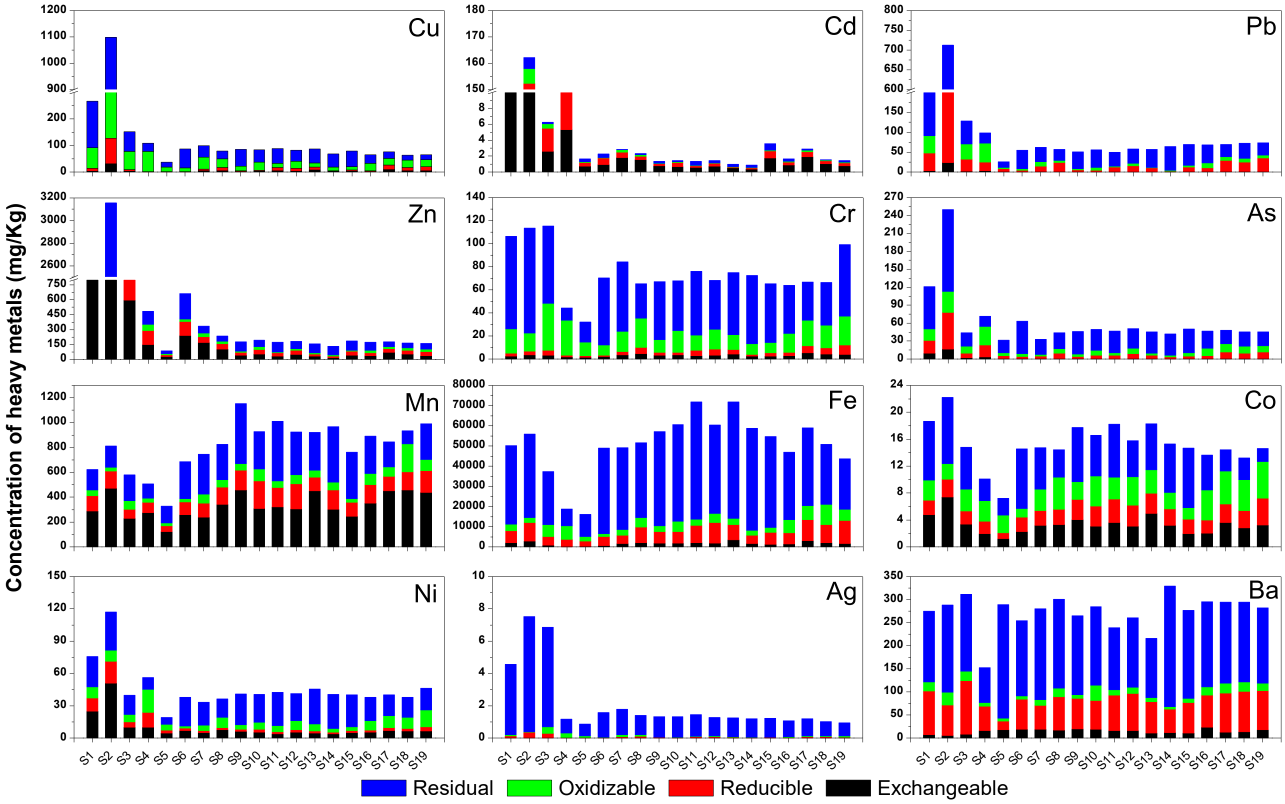

Fig. 3. Heavy metal concentrations in sediment samples. Blue: residual fraction; Green: oxidizable fraction; Red: reducible fraction; Black: exchangeable fraction.

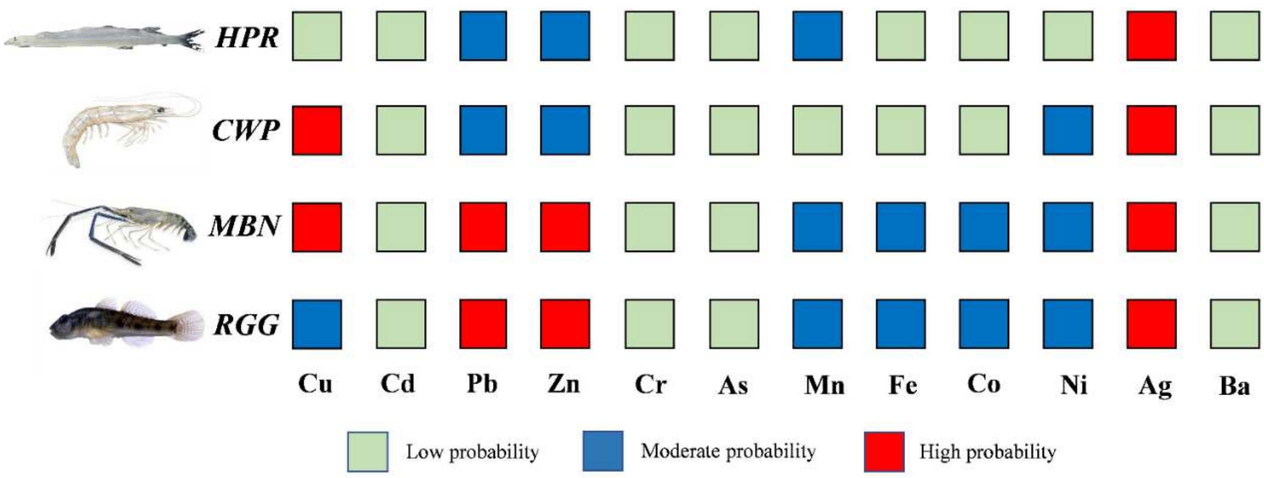

Fig. 4. Bioaccumulation factor of organisms to heavy metals in surface water (BAF-water). Green: low probability; Blue: moderate probability; Red: high probability.

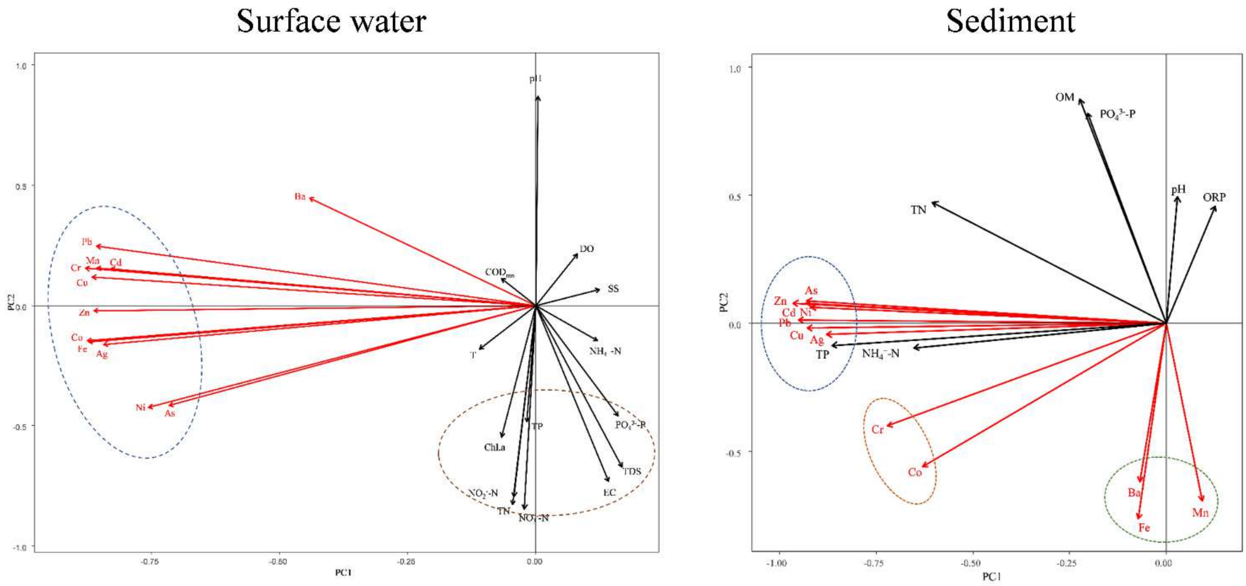

Fig. 5. Principal component analysis (PCA) of aquatic environmental parameters and heavy metals.

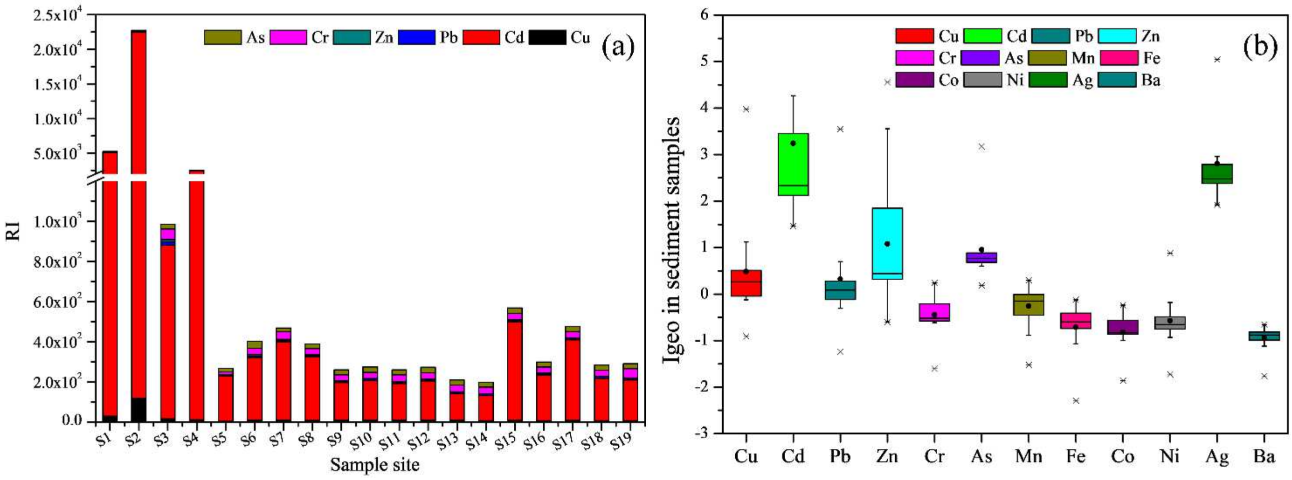

Fig. 6. Risk assessment for selected heavy metals in sediments: (a) RI of selected heavy metals in sediments. As: brownness; Cr: pink; Zn: green; Pb: blue; Cd: red; Cu: black. (b) Igeo of selected heavy metals in sediments. The box plots display the values from surface water samples (median, 25% and 75% quartiles [boxes], 10% and 90% percentiles [whiskers]).

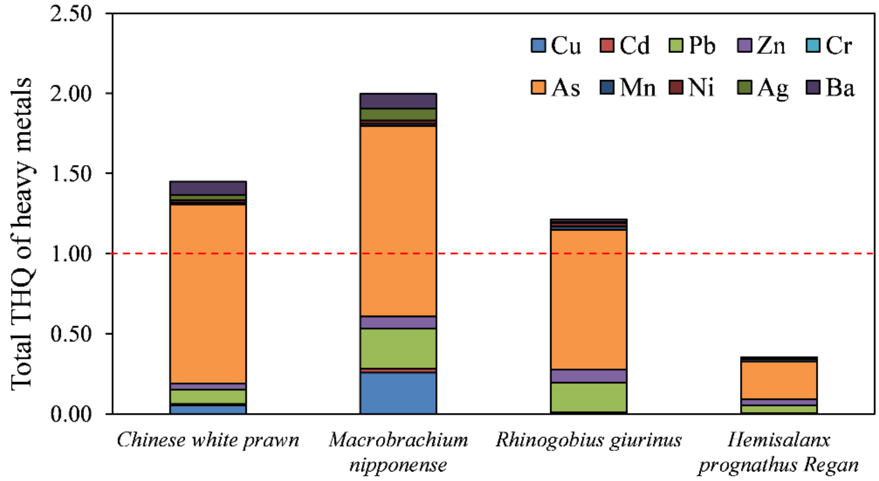

Fig. 7. Contributions of THQ to TTHQ for the 10 selected heavy metals via consumption of four aquatic species collected from Dianchi Lake. Red dash line indicated the acceptable total THQ threshold value (< 1).

Supplementary Files

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