Distribution characteristics, source identification, and risk assessment of heavy metals in surface sediments of the salt lakes in the Ordos Plateau, China

Shengyin Zhang
Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences
Shuncun Zhang
Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences
Yongxin Chen (chenyongxin@lzb.ac.cn)
Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences
Bo Chen
Tianzhu Lei
Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences

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Abstract

Salt lakes have a significant effect on the regional climate, environment, and ecology in semi-arid regions characterized by lower rainfall and high evaporation. However, under the stresses of global change and human disturbance, anthropogenic pollution is the main factor threatening the lake ecological environment. Surface sediment samples collected from four salt lakes in the Ordos Plateau were used to investigate the salinity, concentration, pollution status, potential sources of heavy metals, and influencing factors. The surface sediments of Beida Pond and Gouchi Pond were weakly alkaline (pH < 9) owing to Na_2SO_4, whereas those of Chaigannaoer and Hongjiannao were strongly alkaline (pH > 9) owing to Na_2CO_3. The concentration range of Cr, Ni, Cu, Zn, As, Cd, and Pb in the sediment samples collected from the salt lake in the Ordos followed the order of Cr > Zn > Ni > Pb > Cu > As > Cd. The Cr values were higher in Chagannaoer and Hongjiannao, but the Ni, Cu, and Zn values were higher in Beida Pond and Gouchi Pond. The geoaccumulation index (I_{geo}) and enrichment factor (EF) consistently indicated that Cr posed the greatest potential ecological risk and that Ni, Cu, and Zn pollution was more severe in Beida Pond and Gouchi Pond than in Chagannaoer or Hongjiannao. However, Er and RI indicated these heavy metals were a low risk to the environment. Risk assessment code (RAC) revealed that Pb and Cr exhibited no mobility and had low potential bioavailability risk, although Zn, Ni, and As were categorized as medium risk. Cu had the highest mobility and high risk. Principal component analysis for Beida Pond and Gouchi Pond revealed that the source of Ni, Cu, Zn, Cd, and Pb might be associated with water - soluble elements in aqueous migration. For Cr, Pb, and As, it was indicated that the source of these heavy metals might be lithospheric minerals carried by dust storms. Ni, Cu, Zn, Cd, Cr, and Pb in Chagannaoer and Hongjiannao may be derived from surface runoff, and chemicals from these sources may eventually accumulate in sediments. Pearson's correlation analysis indicated that pH was the main environmental factor controlling the distribution of heavy metals in Chagannaoer and Hongjiannao.

1. Introduction

As an important sink of surface runoff, lakes have a significant effect on the regional climate, environment, and ecology in semi-arid regions characterized by lower rainless and high evaporation(Chen et al. 2020b, Chen et al. 2021, Crootof et al. 2015, Fang et al. 2018). These lakes serve not only as a link between regional ecosystems but also provides habitat for animals, adjusts local climate, and provides water and food for human beings(Bullerjahn et al. 2020, Kong et al. 2016, Liu et al. 2021, Xie et al. 2021). However, under the stresses of global change and human disturbance (for example, agriculture and resources exploitation, chemical industry), the ecological environment of the lake deteriorates owing to anthropogenic pollution, restricting the sustainable development of the regional economy(Abu El-Magd et al. 2021, Li et al. 2021, Popovicheva et al. 2021, Wu et al. 2021). Heavy metals are deposited in the sediment by adsorption, hydrolysis, and co-precipitation processes and can also be released from sediments back into the water when environmental conditions change, posing a potential threat to aquatic biota and human health(Wang et al. 2017, Wen et al. 2018, Zhan et al. 2020, Zhang et al. 2016, Zhang &Gao 2015). When environmental conditions (e.g., redox potential, pH, bioturbation, and organic matter) change, heavy metals may be released from river sediments into water(Abu El-Magd et al. 2021, Li et al. 2021, Popovicheva et al. 2021, Wu et al. 2021), and this can affect water environment safety and allow heavy metals to enter the food chain, posing a health risk to living organisms.

The Ordos Plateau consists of a loess plateau in the south and a desert plateau in the north, which contains the Mu us Desert and the Kubuqi Desert(Xu et al. 2010, Zhang &Wang 2020). There are many lakes distributed throughout the Ordos Plateau, all of which are inland lakes with lower water level. Shallow diving and spring water are the water sources of salt lakes in this area. In particular, these lakes are mainly saline-alkali water bodies because of the high ratio of evaporation/ precipitation (Chen et al. 2020b, Fang et al. 2018). The ecological geography of the Ordos Plateau is arid/semi-arid steppe - desert area, with lots of wind and sand and little precipitation. Therefore, saline lakes are an important water resource in this region, maintaining the regional ecosystem security of the Ordos Plateau, which is an important base for the production of raw coal, petroleum, trusone, and other chemicals in China(Chen et al. 2020a, Chen et al. 2020c, Qi et al. 2020). Heavy metal elements released by industrial development pose a serious threat to saline lake. Therefore, the distribution, source, and pollution assessment of heavy metals in lake sediments are of great significance.

Moreover, because of the difference in the chemical composition of soil and rock in runoff areas (the loess, desert and sandstone)(Shi &Huang 2021, Sun et al. 2021, Xu et al. 2010), the lakes of the Ordos Plateau clearly differ in chemical composition. The water of salt lakes are rich in sulfate ions in the southwest plateau (Yanchi county of Ningxia province and Dingbian county of Shanxi province), and the northeastern Ordos Plateau (Ordos city of Inner Mongolia) contains more carbonate rich lakes. Detailed knowledge about the changes in heavy metals in contaminated lake sediments is required for a better understanding of the mobilization and immobilization of metals and the associated controlling processes. Therefore, in this study, we investigated the metals in the surface sediments in these salt lakes and aimed to: (1) determine the heavy metals in the surface sediment of the salt lakes in the Ordos Plateau; (2) assess the level of ecological risk posed by each of the heavy metals in the sediment; and (3) identify the potential sources and factors controlling the distribution of these metals in the sediment.

2. Materials And Methods

2.1 Geographic setting

The Ordos Plateau is located in the south of the Inner Mongolia Autonomous Region and the east of the Ningxia Autonomous Region (north latitude, 37°20'–40°50'; east longitude, 106°24'–111°28'). The north and east areas are surrounded by the Yellow River, and the southeast is bounded by the ancient Great Wall and the Northern Shaanxi Loess Plateau. The administrative divisions include Ordos City in Inner Mongolia Autonomous Region, Jingbian and Dingbian county in Shaanxi province, and Yanchi County in Ningxia Hui Autonomous Region. The plateau covers a total area of more than 120,000 square kilometers, with an average annual temperature of 6°C–8°C and an average annual precipitation of 150–500 mm(Xu et al. 2010).There are more than 50 salt lakes in the Ordos Plateau, and Beida Pond and

Gouchi Pond is are mainly supplied by groundwater, Chagannaoer, and Hongjiannao are mainly supplied by rivers surrounding these lakes.

2.2 Sampling and analysis methods

In August 2020, 34 surface sediment samples (0–10 cm) were selected as sampling sites in the Ordos Plateau, including Beida Pond, Gouchi Pond, Chagannaoer, and Hongjiannao (Fig. 1). These 34 sampling sites were designated as follows: BP1–BP9; CP1–CP9; Ch1–Ch9; and HJ–D7, respectively (Fig. 1). All samples were wrapped in aluminum foil and stored at −20°C until analysis.

Prior to measurement, the stored samples were freeze-dried, passed through a 200 mesh sieve. EC, pH, and ion concentration (of K^+, Na^+, Ca^{2+}, Mg^{2+}, F^-, Cl^-, NO- 3, and SO2- 4 ions) were determined from the measurement of a 1:2.5 sediment: water suspension using conductivity, pH meters (Mettler Toledo FE20, Switzerland), and an ion chromatograph (Metrohm 883, Switzerland), respectively. The contents of $CO_3{}^{2-}$ and $HCO_3{}^-$ were determined using a double indicator neutralization titration method(Kai et al. 2020).

For the metal analysis, the prepared samples were weighed, and 20 mg of each sample was digested in an oven by a mixture of 10 mL HNO_3, 5 mL HF, and 5 mL $HClO_4$. The concentration of heavy metals was determined by inductively coupled plasma-mass spectrometry (ICP-MS, 7850 Agilent). During the digestion and test procedures, standard reference samples (GSS-1), blank samples, parallel samples, and the study samples were analyzed in the same way to control the quality of the entire analytical procedure and ensure comparable detection results(Wu et al. 2014).

The sequential extraction procedure described by (Tessier et al. 1979) was performed to determine which metals were present in the exchangeable fraction (F1, 1 M $MgCl_2$, pH 7.0), carbonate-bound fraction (F2, 1 M NaOAc, pH 5.0), Fe\Mn oxide-bound fraction (F3, 0.04 M $NH_2OH{\cdot}HCl$ in 25% HOAc, pH 2.0), organic matter-bound fraction (F4, 0.02 M HNO_3 in 30% H_2O_2; 3.2 M NH_4OAc in 20% HNO_3, pH 2.0), and residual fraction (F5, digested with HF-HNO_3-$HClO_4$) of sediments (Liang et al., 2017). The concentrations of Cd, Cu, Ni, Pb, Zn, Cr, Cu, Be, and V were determined using ICP-MS. The recovery rates of five sequential extractions for all heavy metals were determined to be between 89% and 101%.

2.3. Assessment of sediment pollution

2.3.1. Geoaccumulation index

The geoaccumulation index (I_{geo}) proposed was used to quantify metal contamination caused by both natural geological and geographical processes and human activities(Muller 1969). I_{geo} is calculated from the following formula:

$I_{geo} = \log_2[C_m/(1.5B_m)]$ (1)

where C_m is the concentration of metals in the examined samples and B_m is the regional background level of the evaluated metal(Centre) 1990). A factor of 1.5 was used to adjust for lithospheric effects. The

I_{geo} parameter divides heavy metal contamination into seven levels (Muller, 1981): Class 0, practically no pollution ($I_{geo} \leq 0$); Class 1, no pollution to moderate pollution ($0 < I_{geo} < 1$); Class 2, moderate pollution ($1 < I_{geo} < 2$); Class 3, heavy pollution ($2 < I_{geo} < 3$); Class 4, heavy pollution ($3 < I_{geo} < 4$); Class 5, heavy to extremely heavy pollution ($4 < I_{geo} < 5$); and Class 6, extremely heavy pollution ($I_{geo} > 5$).

2.3.2. Enrichment factor

The enrichment factor (EF) is commonly used to determine the degree of anthropogenic heavy metal pollution (Caeiro et al. 2005). The EF is computed from the following equation:

$EF=[(C_E/C_R)_{Sample}]/[(C_E/C_R)_{Background}]$ (2)

where $(C_E/C_R)_{Sample}$ represents the ratio between the level of the examined element and the level of a reference element in the river sediment and $(C_E/C_R)_{Background}$ is the ratio of two elements in the Tibetan Plateau topsoil (Li et al., 2009). Al was used as the reference element for geochemical normalization.

2.3.3 Hakanson potential ecological risk assessment

The Hakanson potential ecological risk (PER) assessment was proposed by (Hakanson 1980) for the assessment of the risk of heavy metal pollution in sediment. The PER was calculated using the following equations:

$C^i_f = C^i / C^i_n$ (3)

$E^i_r = C^i_f \times T^i_r$ (4)

$RI = (E^1_r + E^2_r + E^3_r + E^4_r + \ldots + E^n_r)$ (5)

where C_f^i is the contamination factor of heavy metal i, Ci is the measured concentration of heavy metal i, and C^i_n is the geochemical background value of heavy metal i. E^i_r and T^i_r are the ecological risk index and the toxicity coefficient of heavy metal i, respectively. According to the recommendation, the toxicity coefficients of Cr, Ni, Cu, Zn, As, Cd, and Pb are 2, 5, 5, 1, 10, 30, and 5, respectively (Hakanson 1980). RI is the potential ecological risk index, which is the sum of all ecological risk indices for multiple heavy metals in the sediments at a single site.

2.3.4. Risk assessment code

The degree of heavy metal mobility and bioaccessibility can be assessed quantitatively using the risk assessment code (RAC) method by analyzing the total metal concentration and the chemical fraction. Given that the acid-extractable fraction, which comprises the exchangeable fraction (F1) and the carbonate fraction (F2), has a higher bioaccessibility level, the total acid-extractable fraction was used to assess the bioaccessibility of metals in the sediment using the RAC method.

$RAC_i = C^i_F / C^i_T$ (6)

where RACi is the RAC index of heavy metals in the sediment, C^i_F is the concentration of the acid-extractable fraction in the sediment (F1 + F2), and C^i_T is the actual measured concentration of the heavy metal in the sediment. The values were categorized using the RAC classifications (Martley et al. 2004) : RAC < 1%, no risk; and metals with RAC values of 1–10%, 11–30%, 31–50%, and N75% were classified as low risk, medium risk, high risk, and very high risk, respectively.

2.3 Statistical analysis

Statistical analyses were performed using SPSS 19.0 software (IBM, NYC, USA). Pearson's correlation analysis was performed to identify EFs that were significantly associated with each metal in the sediment samples. Multiple regression analyses were performed to quantify the relative importance of EFs among the nine heavy metals examined. To determine the relative similarity of the EF distribution patterns, cluster analysis of data was performed using the Ward method and the squared Euclidean distance based on the similarity within groups and the dissimilarity between different groups. The sampling site map (Fig. 1) was drawn using ArcGIS10.2; all other figures were drawn using Origin 9.0.

3. Results And Discussion

3.1 General properties of the surface sediments

The mean conductivity, pH, and ion concentrations (K^+, Na^+, Ca^{2+}, Mg^{2+}, F^-, Cl^-, NO- 3, SO2- 4) in the sediment samples collected from these salt lakes are shown in Table S1. For Beida Pond, the surface sediment ranged from 2.45 mS/cm to 29.4 mS/cm (average, 10.66 mS/cm), the salt content (TDS) ranged from 1.7 to 20.5 g/L (average, 7.44 g/L), and the pH ranged from 8.49 to 8.88 (average, 8.66). For Gouchi Pond, the surface sediment EC ranged from 1.91 to 10.6 mS/cm (average, 6.89 mS/cm), the TDS ranged from 1.35 to 7.36 g/L (average, 4.81 g/L), and the pH ranged from 8.25 to 8.88 (average, 8.52). For Chagannaoer, the surface sediment EC ranged from 0.45 to 17.2 mS/cm (average, 6.78 mS/cm), the TDS ranged from 0.31 to 12.2 g/L (average, 4.76 g/L), and the pH ranged from 10.19 to 10.94 (average, 10.49). For Hongjiannao, the EC of surface sediments ranged from 0.11 to 0.86 mS/cm (average, 0.36 mS/cm), the TDS ranged from 0.07 to 0.60 g/L (average, 0.25 g/L), and the pH ranged from 9.05 to 9.77 (average, 9.48). In conclusion, Beida Pond and Gouchi Pond have weakly alkaline salt deposits, whereas Chagannaoer and Hongjiannao have strongly alkaline salt deposits.

The main cations in the surface sediment soluble salts of Beida Pond were Na^+ and Ca^{2+}, and the main anions were Cl^- and SO_2^{4-}. The K^+, Na^+, Ca^{2+}, and Mg^{2+} concentrations ranged from 12.71–71.38, 32.16–6268.75, 55.07–672.89, and 23.43–472.22 ppm, respectively; the Cl^-, SO_2^{4-}, and HCO^{3-} concentrations ranged from 5.32–5485.35, 1146.42–8165.87, and 7.32–43.93 ppm, respectively. The main cations in the surface sediment soluble salts from Gouchi Pond were Na^+, Ca^{2+}, and Mg^{2+}, and the main anions were Cl^- and SO_2^{4-}. The K^+, Na^+, Ca^{2+}, and Mg^{2+} concentrations ranged from 4.36–33.56, 320.11–1465.92, 19.34–663.8, and 38.13–417.38 ppm, respectively, and the Cl^-, SO_2^{4-}, and HCO^{3-}

concentrations ranged from 261.6–2219.07, 387.23–3558.07, 36.61–213.32 ppm, respectively. The cations in the soluble salts of Chagannaoer surface sediments were Na^+, and the anions were Cl^-, $SO_2{}^{4-}$, and $CO_2{}^{3-}$. The K^+, Na^+, Ca^{2+}, and Mg^{2+} concentrations ranged from 33.14–436.44, 112.51–4548.57, 1.01–110.71, and 10.10–74.48 ppm, respectively, and the Cl^-, $SO_2{}^{4-}$, and $CO_2{}^{3-}$ concentrations ranged from 4.15–2168.54, 10.00–481.35, and 66.37–2448.42 ppm, respectively. The cation in the surface sediment soluble salts of Hongjiannao was Na^+, and the anions were Cl^-, $SO_2{}^{4-}$, and HCO^{3-}. The K^+, Na^+, Ca^{2+}, and Mg^{2+} concentrations ranged from 4.58–11.51, 10.02–156.87, 5.68–10.92, and 2.97–8.93 ppm, respectively, and the Cl^-, $SO_2{}^{4-}$, $CO_2{}^{3-}$, and HCO^{3-} concentrations ranged from 1.89–94.77, 9.78–96.02, 5.04–21.60, and 35.14–166.92 ppm, respectively.

3.2 Concentrations of metals in the surface sediments

The concentrations of heavy metals in the sediment samples are presented in Table S1. The ranges of Cr, Ni, Cu, Zn, As, Cd, and Pb in the salt lakes of the Ordos were 50.84–261.73, 6.05–36.94, 3.59–24.33, 12.57–66.38, 0.04–1.24, 0.01–0.04, and 8.77–22.38 μg/g, respectively (Table.1). The mean heavy metal concentration in pond sediments was 75.49, 18.08, 9.91, 29.75, 0.37, 0.02, and 13.71, respectively. The concentration of heavy metals in Gouchi Pond followed a similar pattern to that of Gouchi Pond: Cr > Zn > Ni > Pb > Cu > As > Cd. The median heavy metal contents in Chagannaoer sediments were 142.66 (Cr), 9.21 (Ni), 5.85 (Cu), 19.46 (Zn), 0.63 (As), 0.01 (Cd), and 15.08 (Pb), respectively, and followed a similar pattern to those of Hongjiannao sediments: Cr>Zn>Pb>Ni>Cu>As>Cd. In comparison, the Ni, Cu, and Zn concentrations in Beida Pond and Gouchi Pond were higher than those in Chagannaoer and Hongjiannao. The Cr concentration in Chagannaoer and Hongjiannao was significantly higher than that in Beida Pond and Gouchi Pond. The Pb concentration in the four salt lakes was similar, at 13.71, 15.15, 15.08, and 16.66, respectively. The concentrations of As and Cd in all the salt lake sediments were lower than the background values, within the ranges of 0.04–1.24 and 0.01–0.04, respectively.

Table.1 Heavy metal concentrations (based on dry weight basis) and background values (mg•kg−1) in the surface sediment of the salt lake in Ordos, China

Salt lake	Cr	Ni	Cu	Zn	As	Cd	Pb
Beida pond (mean)	50.84-130.89 (75.49)	14.75-26.73 (18.08)	7.72-19.51 (9.91)	23.94-50.15 (29.75)	0.07-1.08 (0.37)	0.02-0.03 (0.02)	8.77-17.10 (13.71)
Gouchi pond	65.79-89.22 (73.79)	17.86-36.94 (23.89)	10.70-24.33 (13.95)	30.41-66.38 (40.51)	0.36-0.92 (0.62)	0.02-0.04 (0.03)	14.04-22.38 (15.15)
Chaigannaoer	85.66-165.16 (142.66)	7.54-16.57 (9.21)	3.91-9.86 (5.85)	14.25-31.94 (19.46)	0.27-1.24 (0.63)	0.01-0.02 (0.01)	13.16-16.13 (15.08)
Hongjiannao	77.74-261.73 (130.12)	6.05-13.60 (9.20)	3.59-8.10 (5.33)	12.57-29.03 (19.00)	0.04-1.05 (0.83)	0.01-0.02 (0.02)	15.88-16.92 (16.66)
Background	24.8	11.5	8.8	23.5	4.3	0.044	13.8

3.3 Risk assessment

3.3.1 Geoaccumulation index

The geoaccumulation index (I_{geo}) values of heavy metals detected in the sediments of the salt lake in the Ordos are shown in Fig. 2, and the details are presented in Table S1. The index values of Cr ranged from 0.51–1.81 (average, 0.93) in Beida Pond, 0.82–1.26 (average, 0.98) in Gouchi Pond, 1.20–2.15 (average, 1.84) in Chagannaoer, and 1.06–2.81 (average, 1.87) in Hongjiannao. This suggested moderate contamination by Cr in the four salt lakes. The index values of Ni in Chagannaoer and Hongjiannao were <0, and ranged from −0.22–0.63 (average, 0.13) and 0.05–1.10 (average, 0.48) in Beida Pond and Gouchi Pond, respectively, suggesting no contamination in Chagannaoer and Hongjiannao, but moderate contamination in Beida Pond and Gouchi Pond. The index values of Cu and Zn were <0 in the four salt lakes, except Gouchi Pond (average Cu, 0.12; average Zn, 0.22). The I_{geo} values of As, Cd, and Pb were < in the four salt lakes. Based on the I_{geo} values of different heavy metals, their pollution potential can be ranked as Cr>Ni>Zn>Cu>Pb>Cd>As in Beida Pond and Gouchi Pond, and Cr>Pb>Zn>Ni>Cu>Cd>As in Chagannaoer and Hongjiannao. The negative values of Ni (in Chagannaoer and Hongjiannao), Cu (in Beida Pond, Chagannaoer, and Hongjiannao), Zn (in Beida Pond, Chagannaoer, and Hongjiannao), and As, Cd, and Pb in the four lakes correspond to the uncontaminated level based on the Muller scale(Muller 1969) and have the potential to cause limited pollution to the salt lakes in the Ordos and the surroundings. In contrast, the I_{geo} values of Cr (in four lakes), Ni (in Beida Pond and Gouchi Pond), Cu (in Gouchi Pond), and Zn (in Gouchi Pond) suggested moderate contamination in the study area.

3.3.2 Enrichment factor

The EF is commonly used to determine the degree of anthropogenic heavy metal pollution (Li et al. 2020) (Atiemo et al., 2012). Generally, an EF of <1.5 suggests that an element is entirely controlled by natural processes, and 1.5 < EF < 3, 3 < EF < 5, and 5 < EF < 10 are interpreted as minor, moderate, severe, and very severe sediment contamination, respectively (Loska and Wiechula, 2003; Sutherland, 2000; Xu et al., 2017b). The average EF values of the heavy metals tested in this study followed the order Cr > Ni > Zn > Cu > Pb > Cd > As in Beida Pond and Gouchi Pond, and Cr > Pb > Zn > Ni > Cu > Cd > As in Chagannaoer and Hongjiannao (Fig. 3).

In Beida Pond, the average EF values of Cr (3.35), Ni (1.97), and Zn (1.55) were >1.5, and for Cu (1.47), Pb (1.06), Cd (0.64), and As (0.13) were <1.5. In Gouchi Pond, the average EF values of Cr (2.95), Ni (2.08), Zn (1.74), and Cu (1.63) were >1.5, and for Pb (1.13), Cd (0.65), and As (0.14) were <1.5. In Chagannaoer and Hongjiannao, the average EF values of all tested heavy metals were > 1.5, except for Cr, which was 5.43 and 5.52, respectively. These data indicated that the sediments in Beida Pond were moderately polluted by Ni and Zn, and severely polluted by Cr. The sediments in Gouchi Pond were moderately polluted by Cr, Ni, Cu, and Zn. The sediments in Chagannaoer and Hongjiannao were only very severely polluted by Cr. Thus, the results suggested that there was a minor anthropogenic impact from As, Cd, and Pb in the four salt lakes in the Ordos, a moderate anthropogenic impact from Ni and Zn in Beida Pond, and Cr, Ni, Cu, and Zn in Gouchi Pond, and a severe anthropogenic impact from Cr in Chagannaoer and Hongjiannao.

3.3.3 Potential ecological risk index

The ecological risk index (Er) was calculated to determine the potential ecological risk (RI) associated with heavy metals in sediments of the salt lakes in the Ordos. The standard level of the potential risk of heavy metals is presented in Table S1, indicating the various risk levels based on values of the index. The comprehensive RI values of individual heavy metals, individual sampling sites, and among the group sites were calculated and are presented in Table S2. The calculated mean Er for Cr, Ni, Cu, Zn, As, Cd, and Pb was 6.68 (4.10–21.11), 6.67 (2.63–16.06), 4.67 (2.04–13.83), 1.17 (0.53–2.82), 1.44 (0.10–2.88), 13.85 (7.24–30.54), and 5.60 (3.18–8.11), respectively. The seven heavy metals pose a low risk (Table 2). The RI values of sediments ranged from 28.50 to 79.45, and with a mean value of 41.94. The average RI for polluted habitats decreased in the following order Gouchi pond > Beidachi pond > Hongjiannao > Chagannaoer, demonstrating that the contaminated sediments in the sampling area pose a low ecological risk.

3.3.4 The risk assessment code (RAC)

Heavy metal analysis was performed using Tessier's sequential extraction procedure to identify the potential bioavailability and mobility of heavy metals and their risk to the environment (Ma et al. 2016, Rosado et al. 2016). Cr, Ni, Cu, Zn, As, Cd, and Pb were mainly present in residual fractions, accounting for 51.14–68.45%, 43.35–54.52%, 33.02–66.11%, 54.65–65.78%, 44.32–61.38%, 9.52–45.55%, and 91.10–98.49% of the total, respectively (Table 2 and Table S2). This indicated that these metals were associated strongly with crystalline mineral structures, were stable under natural conditions, and had low transferability (Ma et al. 2016, Rosado et al. 2016, Xia et al. 2020). With the exception of Cu at the Ch-7 and Ch-8 sites of Chagannaoer, the proportion of these elements in fraction F1 was relatively low. Cu, Zn, and Ni were mainly present in fraction F2, accounting for 23.41–28.07%, and 19.35–31.76% of the total amount, respectively. Moreover, Cd mainly occurred in fractions F1, F2, F3, and F4, with proportions of 1.07–13.62%, 5.05–13.85%, 10.49–45.33%, and 19.75–50.15% of the total metal content, respectively.

Table 2
RACs of heavy metals from surface sediments in the salt lakes

Sites	Cr	Ni	Cu	Zn	As	Cd	Pb
BP-6	10.61	29.67	49.64	32.07	25.05	11.02	0.33
BP-7	9.30	24.75	42.22	28.74	13.38	12.61	0.34
GP-7	6.41	29.82	45.77	30.84	28.68	14.47	0.23
GP-8	6.18	28.57	43.68	26.94	21.99	15.80	0.69
Ch-7	10.76	32.72	48.32	31.23	14.75	19.32	3.85
Ch-8	15.39	36.90	63.55	38.98	22.94	18.67	7.67
HJ-5	7.23	25.80	29.15	21.14	10.88	13.11	1.24
HJ-4	6.36	25.65	25.56	22.17	11.04	8.90	0.95

Assessment of the risk posed by heavy metals in sediments at the sampling area using RAC revealed that Pb and Cr exhibited no mobility and had low potential bioavailability risk and that Zn, Ni, and As were categorized as medium risk (Fig. 3). Cu had the highest mobility, with a high risk. Based on the average RAC values, the environmental risk of the bioavailability fraction of these metals decreased in the order Cu (43.49) > Ni (29.23) > Zn (29.01) > As (18.59) > Cd (14.24) > Cr (9.03) > Pb (1.91). These RAC values indicated that Cu, Ni, and Zn posed the greatest ecological risk in this environment. Overall, heavy metals in sediments posed the greatest ecological risk at Chagannaoer, followed by Gouchi Pond, Beida Pond, and Hongjiannao.

In this study, the I_{geo} and EF values consistently indicated that Cr posed the greatest potential ecological risk and that Ni, Cu, and Zn pollution was more severe in Beida Pond and Gouchi Pond than in Chagannaoer and Hongjiannao. However, the results of the seven heavy metals were inconsistent when assessed by different methods. For example, both Er and RI indicated that these heavy metals were a low risk to the environment, whereas I_{geo}, EF, and RAC showed the opposite result. These inconsistencies may be a result of the different assessment objectives of the methods. I_{geo} and EF are calculated by comparing the metal concentration of the contaminant with the natural background level; however, RAC uses the F1 fraction of metals to indicate metal mobility and bioavailability in sediments. Therefore, we suggested that it is essential to assess heavy metal levels using multiple methods to gain a comprehensive and accurate picture of the ecological risks posed by heavy metal for sediments.

3.4 Source identification and influence factors

The lakes in the study area were divided into two groups based on the pH of soluble salts in the sediments: The first group was Beida Pond and Gouchi Pond (pH < 9), the second group was Chagannaoer and Hongjiannao (pH > 9). Principal component analysis (PCA) was performed to analyze the potential sources and influence factors of heavy metals in the two types of lake sediment. The PCA results passed the Bartlett sphericity tests ($P < 0.001$), indicating that the application of PCA was appropriate for the assessment of heavy metals, pH, anions, and cations in these salt lake sediments. The principal components of the first and second types of lakes that explained the variance accounted for 72.19% and 70.16% of the total variance, respectively (Fig. 4 and Fig. 5).

For Beida Pond and Gouchi Pond, the first principal component (PC1), which explained 49.73% of the total variance, was positively loaded with K^+ (0.94), Na^+ (0.85), Cl^- (0.85), SO_2^{4-} (0.80), Ni (0.72), Cu (0.95), Zn (0.96), Cd (0.76), and Pb (0.78). The correlation analysis coefficients showed that there were significant positive correlations between K^+ and these metals, including Ni, Cu, Zn, Cd, and Pb, suggesting that these heavy metals may come from the same source (Table S4). Given that K^+ and Na^+ are mobile elements present in nature, it can be concluded that PC1 represents the sources associated with water - soluble elements, which are discharged by agricultural industries (Kharazi et al. 2021, Wang et al. 2021), resulting in heavy metal pollution. The second principal component (PC2) explained 22.50% of the total variance, and was positively loaded with SiO_2 (0.916), Al_2O_3 (0.78), Cr (0.61), Pb (0.62), and As (0.43). There were positive correlations between SiO_2, Al_2O_3 and Cr, Pb, and As, indicating that these heavy metals arose from the same source of lithospheric minerals carried by dust storms (Oliveira et al. 2011, Zhang &Wang 2020).

For Chagannaoer and Hongjiannao, PC1 was loaded by Al_2O_3 (0.92), Ni (0.99), Cu (0.99), Zn (0.99), Cd (0.78), Pb (0.91), and moderately by Cr (0.54), and this component accounted for 42.8% of the total variance. The correlation analysis coefficients indicated that Ni, Cu, Zn, Cd, Cr, and Pb might be derived from similar sources (Table S5). Cu, Cd, and Pb had significantly positive correlations with Al_2O_3, which was the essential element of the clay mineral (illite and montmorillonite) in sediment (Qiao et al. 2015, Sutherland et al. 2007); therefore, we suggested that PC1 may represent heavy metals via surface runoff and that chemicals from these sources may eventually accumulate in sediments. Moreover, As had a relatively smaller loading in PC1 and did not show a correlation with other metals, and this may also be derived from the dissolution and release of minerals. PC2, which explains 27.3% of the total variance, was mainly characterized by the positive loading of Na^+ (0.92), Cl^- (0.77), and SO_2^{4-} (0.73), suggesting that these ions migrate in surface water and the groundwater surrounding lakes(Chen et al. 2020a, Zhang &Wang 2020).

Pearson's correlation analysis indicated that metals in the second group (pH > 9) were mainly significantly associated with pH (Table S5). Multiple regression analyses were also performed to quantify the relative importance of these factors among these metals. As shown in PCA, the concentration levels of Ni, Cu, Zn, and Cd were affected by a combination of the pH. Physical chemistry plays a leading role in determining the concentration levels of these heavy metals in sediments. Among the environmental parameters studied, pH was identified as the main environmental factor controlling the distribution of heavy metals. pH can indirectly or directly affect the solubility, adsorption, retention, movement, and distribution of metals in surface sediments (Kashem &Singh 2001, Ma et al. 2016) and is a key factor determining the speciation of heavy metals in sediments. A previous study has shown that increasing the pH can increase the likelihood of the F5 fraction of heavy metals being transformed to oxidizable and residual states (Zhang et al. 2014). There is a significant negatively correlation between pH and heavy metal concentration in sediment, which may be because the high pH reduces the heavy metals activity in rivers, leading to a decrease in heavy metal content in lakes.

4. Conclusions

Surface sediment samples were collected from the salt lakes in the Ordos and assessed to determine the concentrations of heavy metals, including Cr, Ni, Cu, Zn, As, Cd, and Pb. The surface sediments of Beida Pond and Gouchi Pond were weakly alkaline (pH < 9) owing to Na_2SO_4, whereas those of Chaigannaoer and Hongjiannao were strongly alkaline (pH > 9) owing to Na_2CO_3. The concentrations ranges of Cr, Ni, Cu, Zn, As, Cd, and Pb in the sediment samples collected from the salt lakes in the Ordos were 50.84–261.73, 6.05–36.94, 3.59–24.33, 12.57–66.38, 0.04–1.24, 0.01–0.04, and 8.77–22.38 μg/g, respectively. The I_{geo} and EF consistently indicated that Cr posed the greatest potential ecological risk and that Ni, Cu, and Zn pollution was more severe in Beida Pond and Gouchi Pond than in Chagannaoer and Hongjiannao. However, Er and RI indicated these heavy metals were a low risk to the environment. RAC revealed that Pb and Cr exhibited no mobility and had low potential bioavailability risk, and Zn, Ni, and As were categorized as medium risk. Cu had the highest mobility, with a high risk. PCA for Beida Pond and Gouchi Pond revealed that the source of Ni, Cu, Zn, Cd, and Pb might be associated with water - soluble elements in aqueous migration. For Cr, Pb, and As, the source of these heavy metals may be lithospheric minerals carried by wind sand. However, the PAC for Ni, Cu, Zn, Cd, Cr, and Pb in Chagannaoer and Hongjiannao may be derived from surface runoff, and chemicals from these sources may eventually accumulate in sediments. Pearson's correlation analysis indicated that clay minerals were the main adsorbers for Ni, Cu, Zn, Cd, and Pb in Beida Pond and Gouchi Pond, whereas pH was identified as the main environmental factor controlling the distribution of heavy metals in Chagannaoer and Hongjiannao.

Declarations

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Author contribution Yongxin Chen: conceptualization and writing. Shengyin Zhang: original draft preparation, methodology. Shuncun Zhang: experiment and software. Bo Chen: data curation and editing. Tianzhu Lei: data curation and investigation.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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Figures

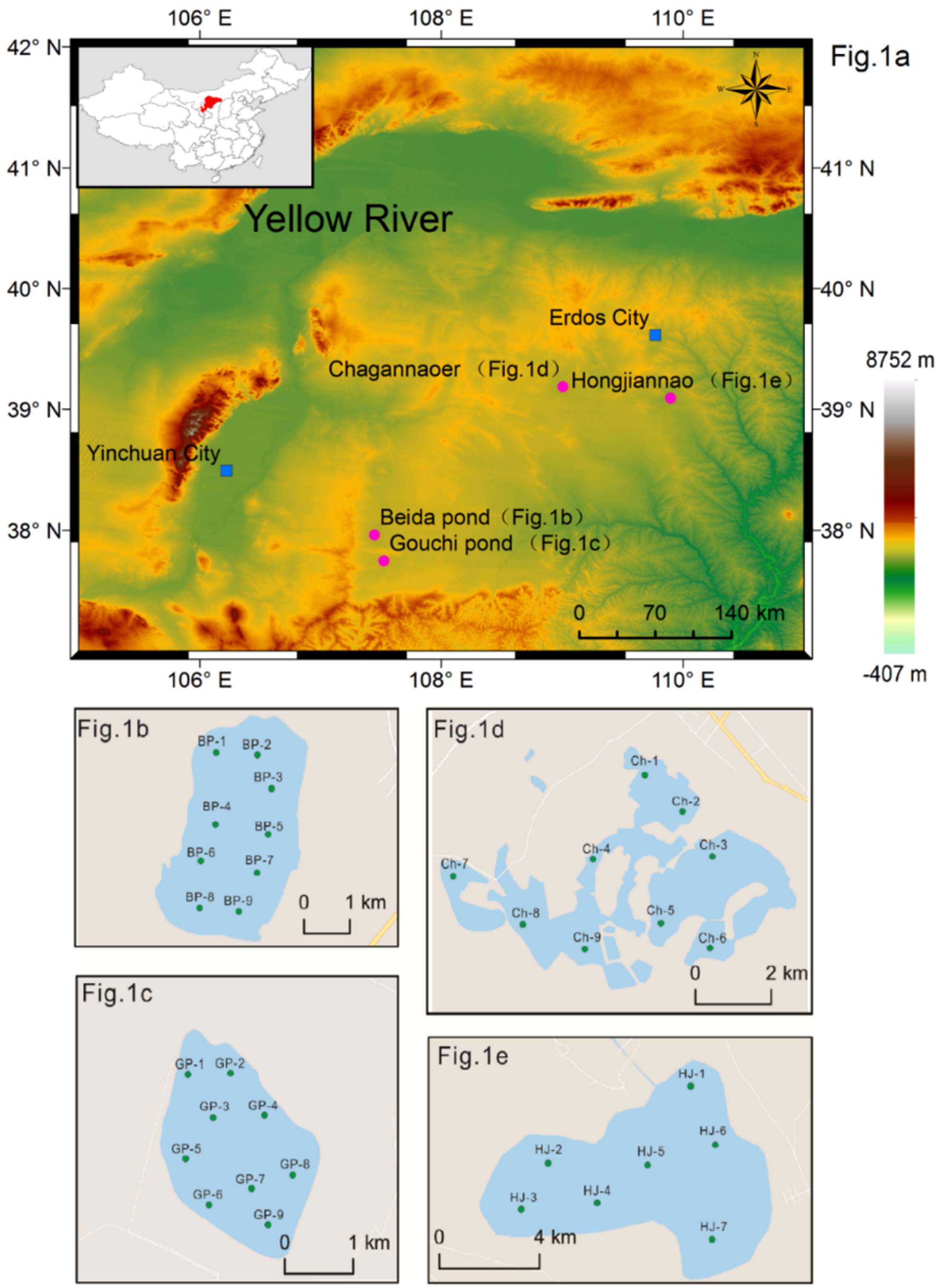

Figure 1

Location of the sampling sites in the Ordos Plateau, China

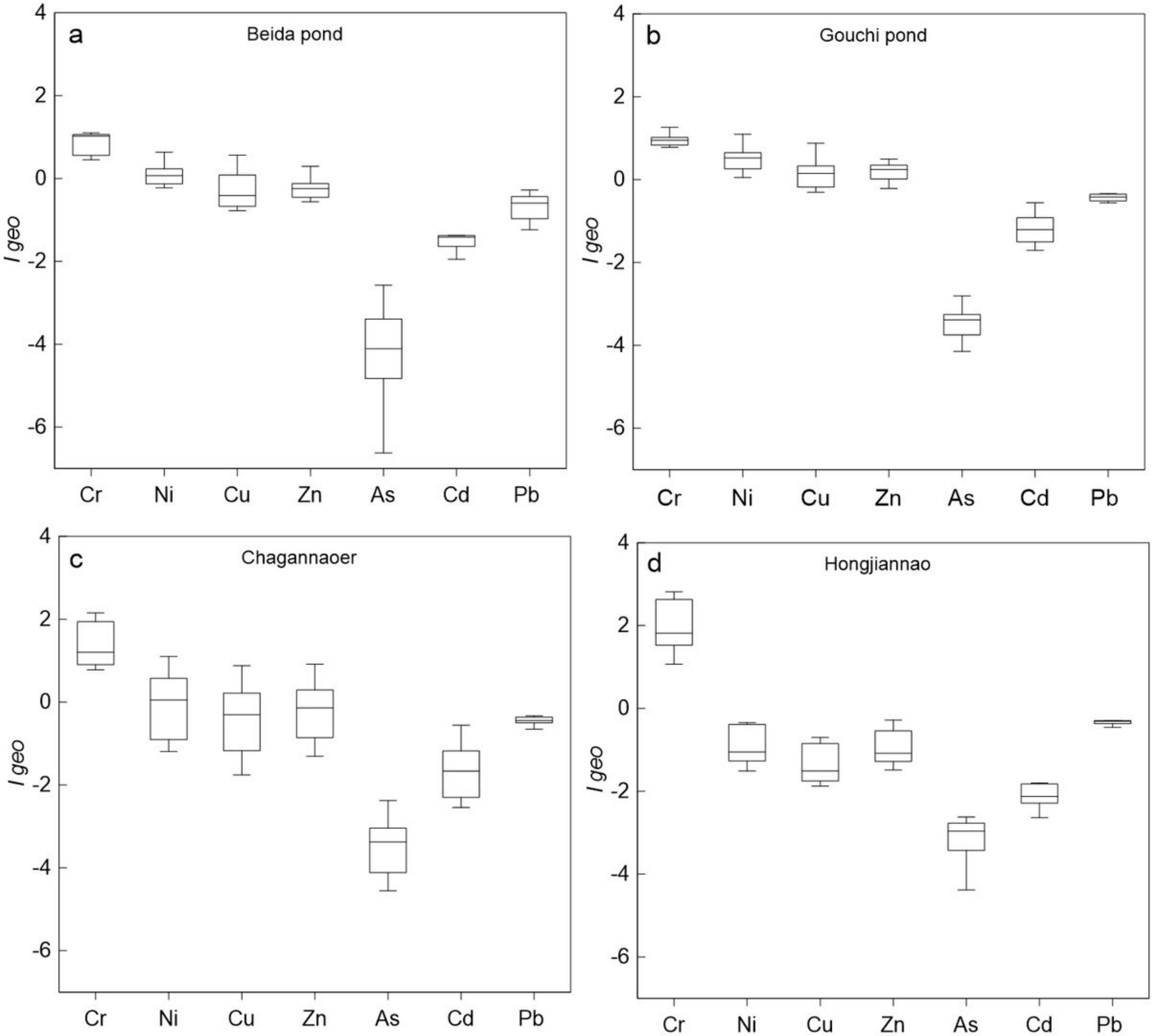

Figure 2

Geoaccumulation indices of various heavy metals present in sediments at sampling sites in Beida Pond (a), Gouchi Pond (b), Chagannaoer (c), and Hongjiannao (d).

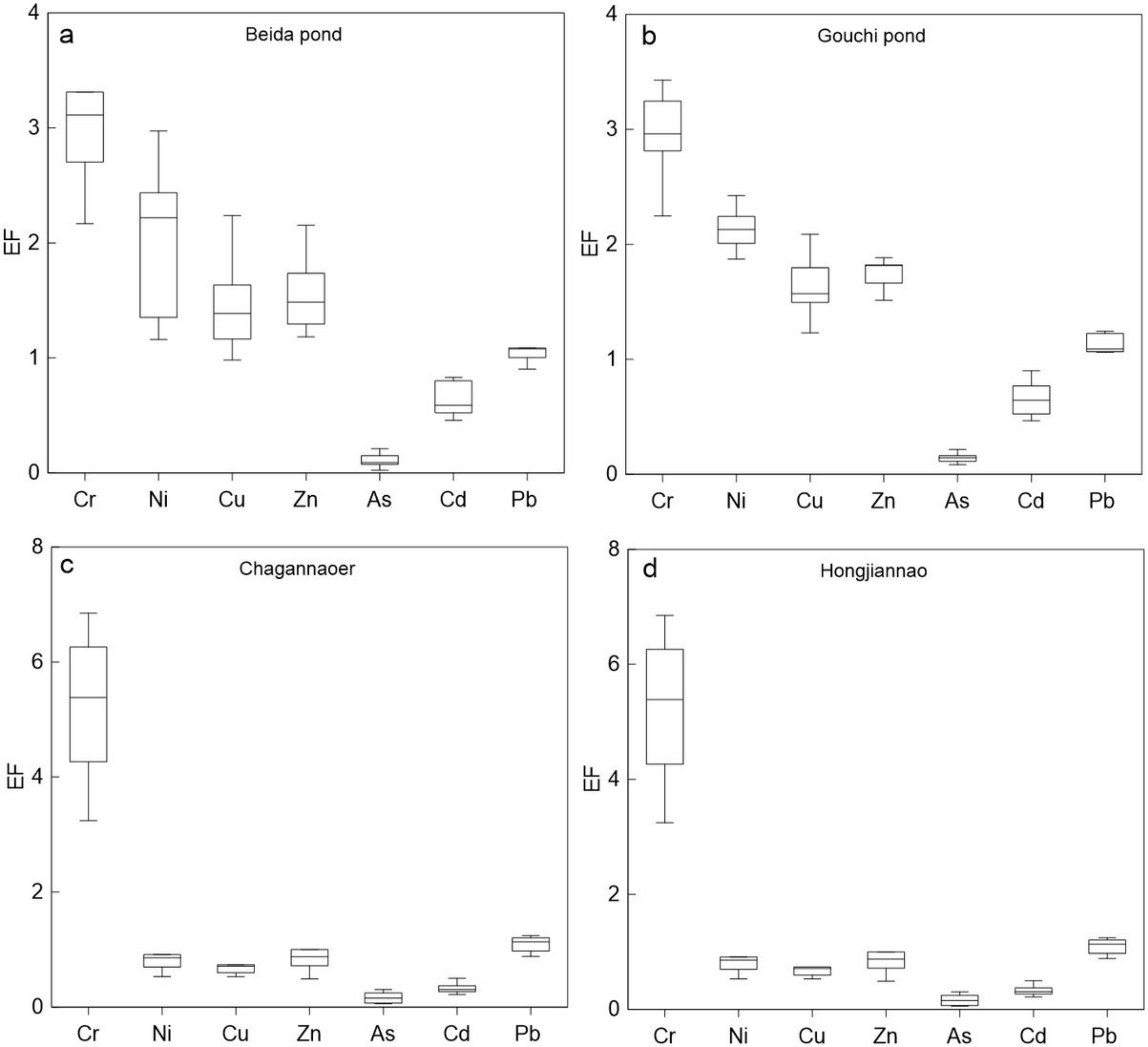

Figure 3

Enrichment factor of heavy metals in surface sediments from Beida Pond (a), Gouchi Pond (b), Chagannaoer (c), and Hongjiannao (d).

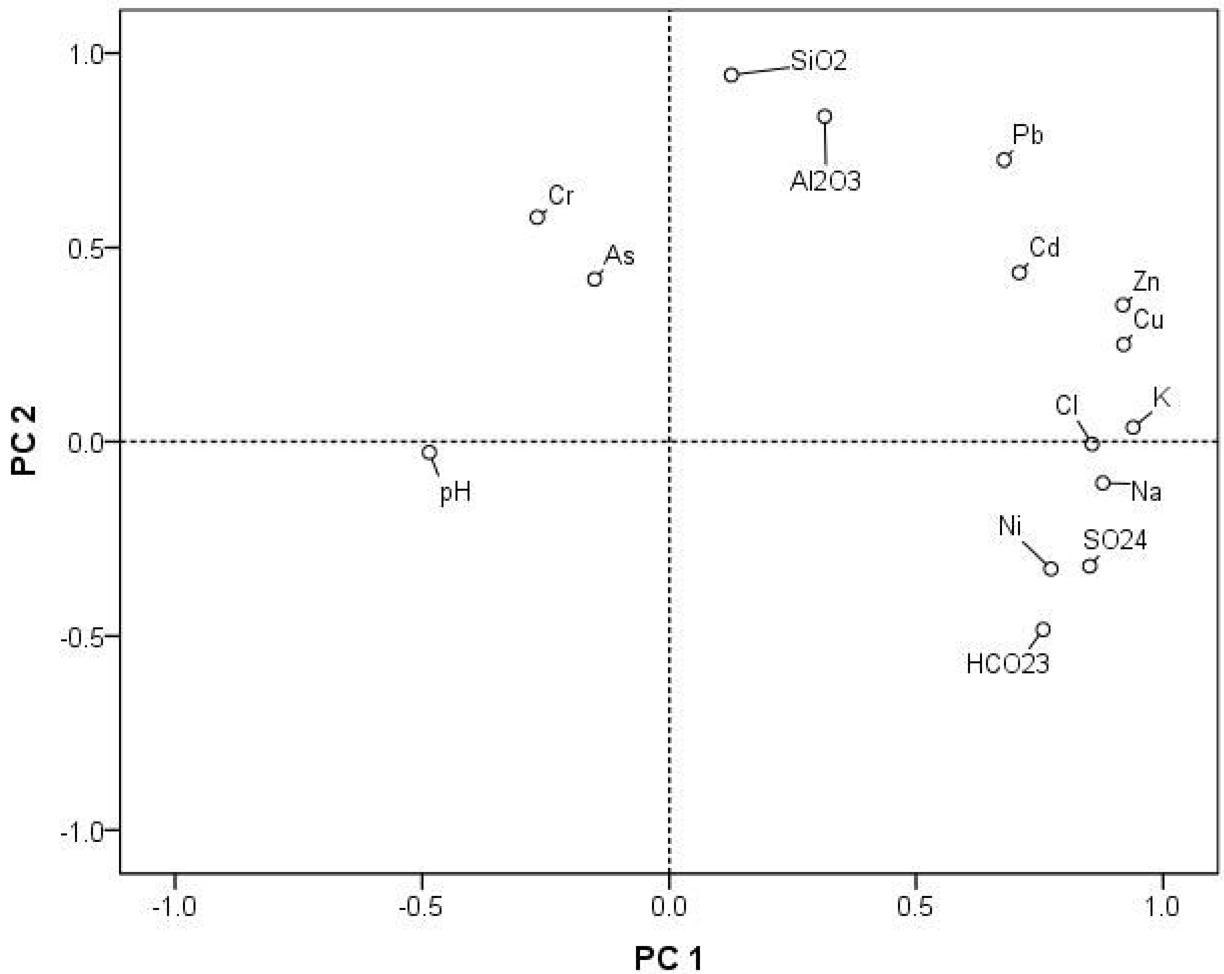

Figure 4

Loading plot showing loading of the two principal components in the principal component analysis for Beida Pond and Gouchi Pond.

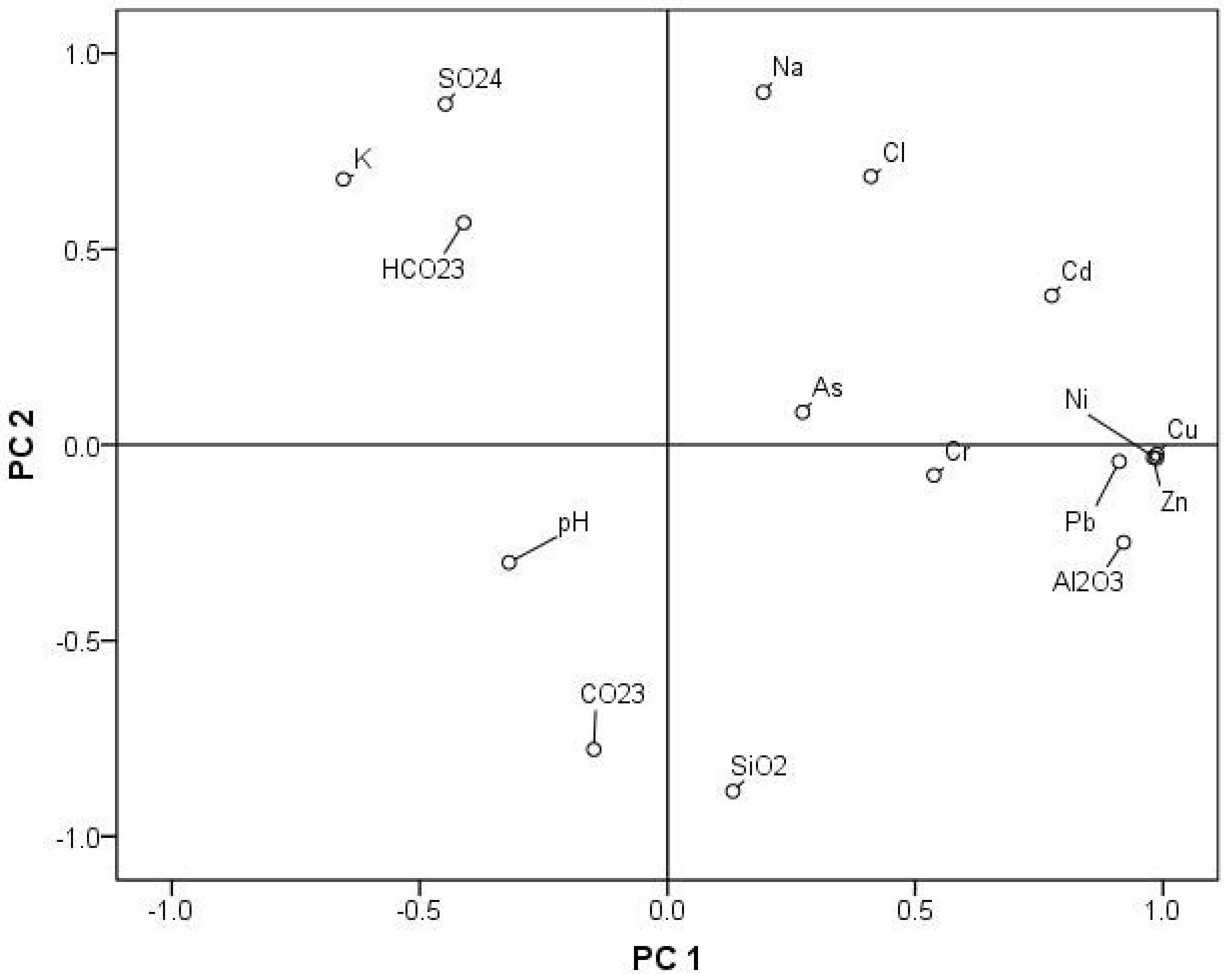

Figure 5

Plot showing the loading of the two principal components in the principal component analysis for Chagannaoer and Hongjiannao.

Supplementary Files

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- Supplementarytable.docx