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

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Received: 3 November 2021 / Accepted: 27 April 2022 / Published online: 31 May 2022
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Abstract
Salt lakes considerably affect the regional climate, environment, and ecology of semi-arid regions characterized by low rainfall and high evaporation. However, under the stresses of global change and human disturbance, anthropogenic pollution is the primary factor threatening the lake’s 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) due to the presence of Na2SO4, whereas those of Chaigannaoer and Hongjiannao were strongly alkaline (pH > 9) due to the presence of Na2CO3. The concentration range of Cr, Ni, Cu, Zn, As, Cd, and Pb in the sediment samples collected from the salt lakes in the Ordos Plateau followed the order of Cr > Zn > Ni > Pb > Cu > As > Cd. The Cr concentration values were higher in Chaigannaoer and Hongjiannao; however, the Ni, Cu, and Zn values were higher in Beida Pond and Gouchi Pond. The geoaccumulation index (Igeo) 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 Chaigannaoer or Hongjiannao. However, the ecological risk index and potential ecological risk value indicated that these heavy metals posed low risks to the environment. The risk assessment code (RAC) revealed that Pb and Cr exhibited no mobility and had low potential bioavailability risk. Meanwhile, Zn, Ni, and As were categorized as medium risk. Cu had the highest mobility and was categorized as high risk. Principal component analysis for the four salt lakes revealed that the source of Ni, Cu, Zn, and Cd might be associated with water-soluble elements associated with aqueous migration, while the source of Cr, Pb, and As might be the lithospheric minerals carried by dust storms. Pearson’s correlation analysis indicated that clay minerals were the primary adsorbers of Ni, Cu, Zn, and Cd. Moreover, pH was identified as the main environmental factor controlling the distribution of heavy metals in the salt lakes.

Keywords Heavy metals · Sediments · Salt lakes · Pollution assessment · Sources · Ordos Plateau

Introduction
As important sinks of surface runoff, lakes considerably affect the regional climate, environment, and ecology of semi-arid regions characterized by the climate of drought with little rainfall (Chen et al. 2020b, 2021; Crootof et al. 2015; Fang et al. 2018). Lakes serve as a link between regional ecosystems and provide a habitat for animals, water, and food for human beings; they significantly affect the local climate as well (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 activities (for example, agriculture and resources exploitation, chemical industries), the ecological environment of the lakes deteriorates
due 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 in sediments mainly exist in the form of clay mineral adsorption or coprecipitation. When the solid–liquid interface conditions change (such as pH, oxidation reduction potential), heavy metals are released into the water, threatening the surrounding biological community and food chain (Wang et al. 2017; Wen et al. 2018; Zhan et al. 2020; Zhang et al. 2016; Zhang and Gao 2015). Generally, the bioavailability, toxicity, and mobility of heavy metals in sediment and water depend on the pH, organic matter content, cation substitution amount, and physical clay content (Abu El-Magd et al. 2021; Li et al. 2021; Popovicheva et al. 2021; Wu et al. 2021).

The Ordos Plateau comprises a loess plateau in the south and a desert plateau in the north, which includes the Mu Us Desert and the Kubuqi Desert (Xu et al. 2010, Zhang and Wang 2020). Many lakes are distributed throughout the Ordos Plateau, all of which are inland lakes with low water levels. Groundwater and spring water are the main water sources of salt lakes in this area. In particular, these lakes are mainly saline-alkali water bodies because of the high evaporation/precipitation ratio (Chen et al. 2020b; Fang et al. 2018). The Ordos Plateau is an arid/semiarid steppe-desert area with plenty 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, 2020c; Qi et al. 2020). The heavy metal elements released by industrial development pose a serious threat to saline lakes. Therefore, the distribution, source, and pollution assessment of heavy metals in lake sediments are of great significance.

Moreover, because of the differences in the chemical compositions of soil and rock in runoff areas (the loess, desert, and sandstone) (Shi and Huang 2021; Sun et al. 2021; Xu et al. 2010), the lakes of the Ordos Plateau clearly differ in chemical composition. The salt lake water is rich in sulfate ions in the southwest plateau (Yanchi county of Ningxia province and Dingbian county of Shannxi province) and carbonate in the northeastern part (Ordos city of Inner Mongolia). 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, herein, we investigated the metals in the surface sediments of 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.

Materials and methods

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 the Inner Mongolia Autonomous Region, Jingbian and Dingbian county in Shannxi province, and Yanchi County in the Ningxia Hui Autonomous Region. The plateau covers a total area of more than 120,000 km², with an average annual temperature of 6–8 °C and average annual precipitation of 150–500 mm (Xu et al. 2010). There are more than 50 salt lakes in the Ordos Plateau. Beida Pond and Gouchi Pond are mainly supplied by groundwater, whereas Chagannaoer and Hongjiannao are mainly supplied by the surrounding rivers.

Sampling and analysis methods

In August 2020, 34 surface sediment samples (0–10 cm) were selected as sampling sites in the Ordos Plateau, including samples from 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 the samples were wrapped in aluminum foil and stored at −20 °C until analysis.

Prior to measurement, the stored samples were freeze-dried and passed through a 200-mesh sieve. Electrical conductivity (EC), pH, TDS (total dissolved solids), and ion concentration (of K⁺, Na⁺, Ca²⁺, Mg²⁺, F⁻, Cl⁻, NO₃ −, 3, and SO₂ − 4 ions) were determined from the measurement of a 1:2.5 sediment:water suspension using conductivity, pH meters (Metller Toledo FE20, Switzerland), and an ion chromatograph (Metrohm 883, Switzerland), respectively. The contents of CO₃ − 2 and HCO₃ − were determined using a double indicator neutralization titration method (Kai et al. 2020).

The particle sizes of the sediments were measured using a laser particle size analyzer. A sample of 1 g was taken and treated with 10% H₂O₂ and 0.5 mol/L HCl for 24 h to remove the organic matter and carbonates. The samples were dispersed evenly by ultrasonic shock for 30 s before the instrument test. The particle sizes of the clay minerals, mud, and sand were less than 4 μm, 4–63 μm, and greater than 63 μm, respectively. The relative error of the repeated samples was less than 3% (n = 4).

The clay mineral content was analyzed using a Rigaku Ultima IV X-ray diffractometer, and the data were processed using the PDXL analysis software. The mineral
content was determined using the K-value method. The test conditions were as follows. The X-ray source was Cu-Kα ($\lambda = 1.54$ Å); the operating voltage was 40 kV; the current was 40 mA; the scanning speed was 4°/min; the step size was $2\theta = 0.02°$; and the scanning range was 2°–55°.

The samples were dried in an oven at 105 °C for 2 h for major element analysis and then ground to less than 200 mesh. After that, 4-g powder samples were weighed and placed in a mold. After leveling, boric acid was used as the edge padding, and the samples were placed in an X-ray fluorescence special automatic powder tablet press (under 10 MPa) for tablet forming. The prepared discs were determined using a Panalytical Magix PW2403 XRF spectrometer.

For the metal analysis, the prepared samples were weighed, and 20 mg of each sample was digested in an oven with a mixture of 10 mL HNO$_3$, 5 mL HF, and 5 mL HClO$_4$. The concentration of heavy metals was determined using inductively coupled plasma-mass spectrometry (ICP-MS, 7850 Agilent). Table S1 shows ICP-MS instrumental optimizing conditions. During the digestion and test procedures, standard reference samples (GSS-1), blank samples, parallel samples, and study samples were analyzed similarly to control the quality of the
Assessment of sediment pollution

Geoaccumulation index

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

$$I_{geo} = \log_2 \left[ \frac{C_m}{(1.5B_m)} \right]$$  

(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 identify as lithospheric effects. The $I_{geo}$ parameter divides the heavy metal contamination degree from nonpollution to extremely strong pollution (Table 1) (Muller 1969).

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 calculated using the following equation.

$$EF = \left[ \frac{(C_E/C_R)_{sample}}{(C_E/C_R)_{Background}} \right]$$  

(2)

where $(C_E/C_R)_{Sample}$ represents the ratio between the level of the examined element and the level of a normalized element in the surface sediment and $(C_E/C_R)_{Background}$ is the ratio of two elements in the Ordos Plateau (Centre 1990). Al was used as the standardized element for geochemical normalization.

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 sediments. The PER was calculated using the following equations.

$$C_i^f = C_i^f / C_n$$  

(3)

$$E_i^r = E_i^r \times T_i^r$$  

(4)

$$RI = (E_1^r + E_2^r + E_3^r + E_4^r + \cdots + E_n^r)$$  

(5)

where $C_i^f$ is the contamination factor of heavy metal $i$, $C^f_i$ is the measured concentration of heavy metal $i$, and $C_n^f$ 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. The toxicity coefficients of Cr, Ni, Cu, Zn, As, Cd, and Pb are 2, 5, 5, 1, 10, 30, and 5, respectively (Hakanson 1980). $E_i^r$ is the single potential ecological risk index of heavy metal $i$ in sediments, and RI is the sum of the potential of all $E_i^r$ in the sampling site.

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 $RAC_i$ 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.

Statistical analysis

Statistical analyses were performed using the SPSS 19.0 software (IBM, NYC, USA). One-way ANOVA was used.
to test the difference of the four lakes in the general properties and heavy metal concentrations. The sampling site map (Fig. 1) was drawn using ArcGIS10.2.

Results and discussion

General properties of the surface sediments

The EC, TDS, pH, and ion concentrations (of K⁺, Na⁺, Ca²⁺, Mg²⁺, F⁻, Cl⁻, NO−3, and SO₂−4) in the sediment samples collected from these salt lakes are shown in Table S3. For Beida Pond, the conductivity of surface sediment is in the range of 2.45–29.4 mS/cm, averaging 10.66 mS/cm; the TDS is in the range of 1.7 to 20.5 g/L, averaging 7.44 g/L, and the pH is in the range of 8.49–8.88. For Gouchi Pond, the EC present in the surface sediment ranged from 1.91 to 10.6 mS/cm, with an average of 6.89 mS/cm, and the ranges of TDS and pH were 1.35–7.36 g/L and 8.25–8.88, respectively. For Chagannaoer, the EC and TDS ranged from 0.45 to 17.2 mS/cm and from 0.31 to 12.2 g/L, respectively. The pH ranged from 10.19 to 10.94, with an average of 10.49. For Hongjiannao, the ranges of EC and TDS were 0.11–0.86 mS/cm and 0.07–0.60 g/L, respectively. The average pH was 9.48, with a range of 9.05–9.77. 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 Ca²⁺, while the main anions were Cl⁻ and SO₂−4. The K⁺, Na⁺, Ca²⁺, and Mg²⁺ concentrations ranged from 12.71 to 71.38, 32.16 to 6268.75, 55.07 to 672.89, and 23.43 to 472.22 mg/kg, respectively; the Cl⁻, SO₂−4, and HCO₃− concentrations ranged from 5.32 to 5485.35, 1146.42 to 8165.87, and 66.37 to 2448.42 mg/kg, respectively. The cation in the surface sediment soluble salts from Gouchi Pond were Na⁺, Ca²⁺, and Mg²⁺, and the main anions were Cl⁻ and SO₂−4. The K⁺, Na⁺, Ca²⁺, and Mg²⁺ concentrations ranged from 4.56 to 33.56, 320.11 to 1465.92, 19.34 to 663.8, and 38.13 to 417.38 mg/kg, respectively; the Cl⁻, SO₂−4, and HCO₃− concentrations ranged from 4.15 to 2168.54, 10.00 to 481.35, and 66.37 to 2448.42 mg/kg, respectively. The cations in the soluble salts of Chagannaoer surface sediments were Na⁺, and the anions were Cl⁻, SO₂−4, and CO₂−3. The K⁺, Na⁺, Ca²⁺, and Mg²⁺ concentrations ranged from 33.14 to 5485.35, 112.51 to 4548.57, 10.01 to 110.71, and 10.10 to 74.48 mg/kg, respectively; and the Cl⁻, SO₂−4, and HCO₃− concentrations ranged from 4.15 to 2168.54, 10.00 to 481.35, and 66.37 to 2448.42 mg/kg, respectively. The cations in the surface sediment soluble salts of Hongjiannao was Na⁺, and the anions were Cl⁻, SO₂−4, and HCO₃−. The K⁺, Na⁺, Ca²⁺, and Mg²⁺ concentrations ranged from 4.58 to 11.51, 10.02 to 156.87, 5.68 to 10.92, and 2.97 to 8.93 mg/kg, respectively, and the Cl⁻, SO₂−4, CO₂−3, and HCO₃− concentrations ranged from 1.89 to 94.77, 9.78 to 96.02, 5.04 to 21.60, and 35.14 to 166.92 mg/kg, respectively.

Concentrations of metals in the surface sediments

The concentrations of heavy metals in the sediment samples are presented in Table S5. 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 2). 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 Beida Pond: Cr > Zn > Pb > Cu > As > Cd. The means that the 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) and followed a similar pattern to those in 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 was significantly higher than that in Beida Pond and Gouchi Pond. The Pb concentrations in Beida Pond, Gouchi Pond, Chagannaoer, and Hongjiannao were 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.

One-way ANOVA

The difference between the four lakes in terms of the above general properties and heavy metal concentrations was tested using statistical methods such as one-way ANOVA. The EC, salinity, pH, the concentrations of K⁺, Na⁺, Ca²⁺, Mg²⁺, Cl⁻, SO₂−4, CO₂−3, HCO₃−, SiO₂, K₂O, Cr, Ni, Cu, Zn, Cd, Pb, and median size were tested to show significant differences.

Major elements, clay contents, and grain size

Although we analyzed all the major elements, clay minerals, and nonclay minerals, this study only showed the total amount of clay minerals and the contents of Al₂O₃, SiO₂, and K₂O, which indirectly reflect illite–montmorillonite, quartz, and potassium feldspar, respectively. The contents of Al₂O₃, SiO₂, and K₂O in the surface sediments ranged from 28.61 to 65.68%, 5.62 to 12.69%, and 1.11 to 3.8%, respectively (Table S4). The range of the total amount of clay minerals was 4.9–12.9%, and the order was Beida Pond > Gouchi Pond > Hongjiannaoer > Chagannaoer. The median particle sizes were selected to represent the sediment grain sizes. The median particle sizes of the Beida Pond and Gouchi Pond sediments ranged from 12 to 114 μm, with an average median particle size of 86 μm. Meanwhile, the median particle sizes of the Hongjiannaoer and Chagannaoer sediments ranged from 79 to 299 μm, with an average median particle size of 212 μm.

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in the four salt lakes. Conversely, \( \text{Al}_2\text{O}_3, \text{As}, \) and clay content showed no significant differences (Table S5).

### Risk assessment

#### Geoaccumulation index

The geoaccumulation index \( (I_{\text{geo}}) \) values of heavy metals detected in the sediments of the salt lakes in the Ordos Plateau are shown in Table S6. The \( I_{\text{geo}} \) value ranges of Cr in Beida Pond, Gouchi Pond, Chagannaoer, and Hongjiannao suggested moderate contamination by Cr in the four salt lakes. The \( I_{\text{geo}} \) value of Ni indicated 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. The \( I_{\text{geo}} \) values of As, Cd, and Pb were \(<0\) in the four salt lakes. Based on the \( I_{\text{geo}} \) values of these 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), indicating the surrounding soil of the four salt lakes have a limited pollution. Conversely, the \( I_{\text{geo}} \) values of Cr (in the 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.

#### Enrichment factor

The EF is commonly used to determine the degree of anthropogenic heavy metal pollution (Li et al. 2020). Generally, an EF of \( <1.5 \) suggests that an element is entirely controlled by natural processes while \( 1.5<\text{EF}<3 \), \( 3<\text{EF}<5 \), and \( 5<\text{EF}<10 \) are interpreted as minor, moderate, severe sediment contamination, respectively (Xu et al. 2010). 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 (Table S7).

In Beida Pond, the average EF values of Cr, Ni, and Zn were \( >1.5 \), and those of Cu, Pb, Cd, and As were \(<1.5 \). In Gouchi Pond, the average EF values of Cr, Ni, Zn, and Cu were \( >1.5 \), and those of Pb, Cd, and As were \(<1.5 \). In Chagannaoer and Hongjiannao, the average EF values of all the tested heavy metals were \( >1.5 \), except for Cr. 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 of As, Cd, and Pb in the four salt lakes in the Ordos Plateau; a moderate anthropogenic impact of Ni and Zn in Beida Pond and Cr, Ni, Cu, and Zn in Gouchi Pond and a severe anthropogenic impact of Cr in Chagannaoer and Hongjiannao.

#### Potential ecological risk index

The ecological risk index (Er) was calculated to determine the potential ecological risk (RI) associated with heavy metals in the sediments of the salt lakes in the Ordos. The standard level of the potential risk of heavy metals is presented in Table S8, indicating the various risk levels based on the values of the index. The comprehensive RI values of individual heavy metals, individual sampling sites, and group sites were calculated and are presented in Table S8. The Cr, Ni, Cu, Zn, As, Cd, and Pb pose a low risk. 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.
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 risks to the environment (Ma et al. 2016; Rosado et al. 2016). The values were categorized using the RAC classifications (Martley et al. 2004). RAC values < 1% indicated no risk, whereas metals with RAC values of 1–10%, 11–30%, 31–50%, and 50–75% were classified as low risk, medium risk, high risk, and very high risk, respectively. Cr, Ni, Cu, Zn, As, Cd, and Pb were mainly present as residual fractions (Table 3, Fig. 2, and Fig. S9). This indicated that these metals were associated strongly with crystalline mineral structures; they 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 low content Cu, Zn, and Ni were mainly present in fraction F2. Moreover, Cd mainly occurred in fractions F1, F2, F3, and F4.

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 to the environment. Overall, the heavy metals in sediments posed the greatest ecological risk to Chagannaoer, followed by Gouchi Pond, Beida Pond, and Hongjianao.

Herein, inconsistent results were obtained from the above evaluation methods for the ecological risk of heavy metals. $I_{geo}$ and EF values showed that Cr posed the largest potential ecological risk in all the salt lakes. The Ni, Cu, and Zn pollution in Beida Pond and Gouchi Pond was more serious than that in Chagannaoer and Hongjianao. Both Er and RI values show that the environmental risk of these heavy metals is low in all the salt lakes, with the overall order of Gouchi Pond > Beida Pond > Hongjianao > Chagannaoer. However, RACs indicate that the ecological risk of Cu, Ni, and Zn was higher than that of Cr, with the order of Chagannaoer > Gouchi Pond > Beida Pond > Hongjianao. These inconsistencies may be due to the different assessment objectives of the methods. $I_{geo}$, EF, Er, and RI values were calculated by comparing the metal concentrations of pollutants with natural background levels. Meanwhile, RAC was calculated using metals from F1 and F2 to indicate metal mobility and bioavailability in sediments. Therefore, employing various methods and multipurpose assessments of heavy metal levels is necessary for fully and accurately understanding the ecological risks of heavy metals to sediments. Considering that the RACs values of Cr are less than 16% and most are less than 10%, we believe that Cr has no ecological risk in the surface sediments of the four lakes. However, the RACs values of Ni, Cu, and Zn all exceed 20%, with the maximum value being 63.55%. Thus, they have potential activation and migration capacities but low ecological risk because of their low biological toxicity.

Source identification and influence factors

Principal component analysis (PCA) was performed to analyze the potential sources and influencing factors of heavy metals in the sediments of the four lakes. 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, major elements, pH, salinity, clay minerals, and median size (MD) in these sediments. The first principal component (PC1) and the second principal component (PC2) of the lakes that explained the variance accounted for 52.29% and 22.46% of the total variance, respectively.

PC1 was explained 52.29% of the total variance, was positively loaded with salinity (0.49), Ni (0.94), Cu (0.91), Zn (0.89), Cd (0.92), clay (0.63) and negatively loaded with pH (−0.84), SiO2 (−0.62), K2O (−0.68), and MD (−0.88). The correlation analysis coefficients showed that there were

| 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 |
| RSD % | 4.13 | 3.37 | 4.57 | 1.83 | 2.67 | 4.42 | 1.78 |
significant correlations among salinity, MD, clay, and metals, including Ni, Cu, Zn, and Cd, suggesting that these heavy metals may come from the same source (Table 4). Given that salt (K\textsuperscript{+}, Na\textsuperscript{+}, etc.) and clay are mobile elements present in nature and that the high-RAC values of Ni, Cu, and Zn are found in the sediments, it can be concluded that PC1 represents the sources associated with soluble salts and fine-grained sediments, which are discharged during agricultural irrigation and industrial production (Kharazi et al. 2021; Wang et al. 2021).

PC2 was positively loaded with SiO\textsubscript{2} (0.67), K\textsubscript{2}O (0.64), Cr (0.34), Pb (0.89), and As (0.68). There were positive correlations among SiO\textsubscript{2}, K\textsubscript{2}O, Cr, Pb, and As; these heavy metals had low RAC values (Table 4), which indicated that they may be stably adsorbed or fixed between the lattices of silicate minerals. PC2 probably represents the source of the minerals (particularly potassium feldspar, K\textsubscript{2}O·Al\textsubscript{2}O\textsubscript{3}·6SiO\textsubscript{2}) carried by dust storms from the Mu Us desert (Oliveira et al. 2011; Zhang and Wang 2020). With the small loading of clay, Cr, Ni, Cu, Zn, and Cd, the small amount of coarse-grained minerals, including these heavy metals, comes from flash flooding from the surrounding lakes (Chen et al. 2020a; Zhang and Wang 2020). Herein, fine-grained loess is more abundant around the Gouchi Pond and Beidu Pond, whereas coarse-grained desert sand dominates around Chagannaoer and Hongjiannaoer. The pH and median particle size showed a significant positive correlation ($R^2 = 0.807$), which confirmed the difference in the provenance area results with the different physical and chemical properties of the two salt lakes.

Generally, the bioavailability, toxicity, and mobility of heavy metals were affected by pH, organic matter, cation substitution amount, and clay content in sediment/water. Ni, Cu, Cd, and Pb had significantly positive correlations with MD and clay content, which reflects the adsorption of fine minerals to metal under hydrodynamic separation (Qiao et al. 2015; Sutherland et al. 2007). Furthermore, Pearson correlation analysis showed that metal element content was significantly negatively correlated with pH (Table 4). pH can indirectly or directly affect the solubility, adsorption, retention, and movement of metals in the solid–liquid interface (Kashem and Singh 2001; Ma et al. 2016). It has been reported that increasing the pH value can increase the possibility of the conversion of heavy metal components into oxidizable and residual states (Zhang et al. 2014). Therefore, the pH in the sediments of these lakes has a significant negative correlation with heavy metal concentration, possibly because high pH reduces the activity of heavy metals in water from the source to sink, leading to low heavy metal content in water and sediment.
Table 4 The correlations between the concentration of heavy metals and influencing factors according to Pearson's correlation analysis

|         | Salinity  | pH       | SiO₂  | K₂O   | Cr     | Ni     | Cu     | Zn     | As     | Cd     | Pb     | Clay    | MD      |
|---------|-----------|----------|-------|-------|--------|--------|--------|--------|--------|--------|--------|---------|---------|
| Salinity| 1         |          |       |       |        |        |        |        |        |        |        |         |         |
| pH      | 0.167     | 1        |       |       |        |        |        |        |        |        |        | 0.500   | 0.096   |
| SiO₂    | 0.167     | 1        |       |       |        |        |        |        |        |        |        | 0.500   | 0.096   |
| K₂O     | 0.588***  | 0.467*** | 1     |       |        |        |        |        |        |        |        |         |         |
| Cr      | 0.324     | 0.474*** | 0.508** | 1     |        |        |        |        |        |        |        |         |         |
| Ni      | 0.312     | 0.471*** | 0.508** | 0.535** | 1      |        |        |        |        |        |        |         |         |
| Cu      | 0.324     | 0.474*** | 0.508** | 0.535** | 0.535** | 1      |        |        |        |        |        |         |         |
| Zn      | 0.324     | 0.474*** | 0.508** | 0.535** | 0.535** | 0.535** | 1      |        |        |        |        |         |         |
| As      | 0.324     | 0.474*** | 0.508** | 0.535** | 0.535** | 0.535** | 0.535** | 1      |        |        |        |         |         |
| Cd      | 0.324     | 0.474*** | 0.508** | 0.535** | 0.535** | 0.535** | 0.535** | 0.535** | 1      |        |        |         |         |
| Pb      | 0.324     | 0.474*** | 0.508** | 0.535** | 0.535** | 0.535** | 0.535** | 0.535** | 0.535** | 1      |        |         |         |
| Clay    | 0.324     | 0.474*** | 0.508** | 0.535** | 0.535** | 0.535** | 0.535** | 0.535** | 0.535** | 0.535** | 1      |         |         |
| MD      | 0.324     | 0.474*** | 0.508** | 0.535** | 0.535** | 0.535** | 0.535** | 0.535** | 0.535** | 0.535** | 0.535** | 1      |         |

**Correlation is significant at 0.01 level (bilateral).**
*Correlation is significant at 0.05 level (bilateral).

Conclusions

(1) Surface sediment samples were collected from the four salt lakes in the Ordos Plateau 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) due to the presence of Na₂SO₄, whereas those of Chaigannaoer and Hongjianao were strongly alkaline (pH > 9) owing to the presence of Na₂CO₃.

(2) The Igeo 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 Chaigannaoer and Hongjianao. However, Er and RI values indicated that these heavy metals posed a low risk to the environment. RAC values revealed that Pb and Cr exhibited no mobility and had low potential bioavailability risk, while Zn, Ni, and As were categorized as medium risk. Cu had the highest mobility and was categorized as high risk.

(3) PCA revealed that the source of Ni, Cu, Zn, Cd, and Pb might be associated with water-soluble elements associated with aqueous migration. The source of Cr, Pb, and As may be lithospheric minerals carried by wind sand. Pearson’s correlation analysis indicated that clay minerals were the main adsorbers of Ni, Cu, Zn, and Cd. Moreover, pH was identified as the main environmental factor controlling the distribution of heavy metals in the salt lakes.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-022-20557-8.

Acknowledgements We thank the editor and the reviewers for their insightful and valuable suggestions, which greatly improved the quality of this manuscript.

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

Funding This study was financially supported by the National Natural Science Foundation of China (Grant Nos. 41503048, 41872145, 42002174) and the Guangxi Natural Science Foundation, China (2019GXNSFAA245016).

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

Declarations

Competing interests The authors declare no competing interests.
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