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RESEARCH ARTICLE

Spatial distribution, ecological risk, and human health assessment of heavy metals in lake surface sections — a case study of Qinghai Lake, China

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Abstract

Qinghai Lake is the largest inland saltwater lake in China, with a drainage area of 29,661 km^2. This study sought to conduct an ecological and human health risk assessment of metals and heavy metals, including copper, as well as investigate their concentration, distribution, and source distribution. In terms of seasonal variation, the increases in Fe, Cr, As, Pb, and Hg were relatively large, and the spatial distribution of metals presented a three-level stepped distribution trend, gradually increasing from east to west. By further exploring the source and migration path of pollutants, our study found that the source of metals in the sediments of Qinghai Lake is mainly controlled by five rivers entering the lake. Enrichment factor (EF) calculations indicated that the metal accumulation or enrichment capacity of the three central points in Qinghai Lake Basin was strong. Interestingly, the enrichment capacity of Cu and Zn was the strongest among all metals but occurred at low and medium concentration levels, respectively. The Igeo and E_r^i ecological risk assessment results indicated that the individual metals posed little to no ecological risks to the Qinghai Lake Basin. However, the multi-element environmental risk comprehensive index (RI) indicated that Hg (RI = 147.97) represented a slight ecological hazard, Mn (RI = 181.13) posed moderate ecological hazards, and Zn (RI = 386.66) posed strong ecological hazards. The human health risk assessment results showed that the heavy metals in the surface sediments of Qinghai Lake currently do not pose a threat to human health. This information may facilitate the implementation of more stringent monitoring programs in the aquatic ecosystem by the relevant regulatory authorities.

Keywords Qinghai Lake · Sediment heavy metal · Source distribution · Ecological risk · Human health

Highlights
- A comprehensive pollution and health risk assessment was conducted.
- The metal types with high enrichment capacity and priority control were determined.
- Children's risk of health hazards from heavy metals is 2–3 times that of adults.
- The content of heavy metals in lake sediments is affected by the rivers entering the lake.
- This data may help regulators adopt stringent aquatic ecosystem monitoring programs.

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Introduction

As an important part of the terrestrial hydrosphere, lakes have many functions, such as regulating regional climate, improving the regional environment, maintaining river runoff, maintaining regional balance, providing water for production activities, living, and agricultural irrigation, and breeding aquatic organisms (Guo et al. 2015; Ra et al. 2011; Hansen 2012). In recent decades, with the rapid development of China's industry, agriculture, and other socioeconomic activities, human activities have intensified (e.g., development of tourism resources, overgrazing, disorderly reclamation, road construction, and transportation) (Wang et al. 2014), and the discharge of solid waste, engineering waste, and sewage water has increased each year. This has resulted in an influx of metals and toxic substances into lakes through various channels, which in turn has led to the deterioration of aquatic environments (Nriagu and Pacyna 1988; Bergbäck et al. 2001; Förstner et al. 2004). Therefore, the Qinghai Lake Basin is currently facing huge ecological and environmental pressure. Among the contaminants that affect this basin, heavy metals have a wide range of sources, long residence times, and non-biodegradability (Dong et al. 2011; Li et al. 2014), and have thus become among the most important pollutants in aquatic environments (El-Sayed et al. 2015; Milenkovic et al. 2005; Mwamburi 2014; Hernández et al. 2020). However, few studies have assessed the level, source, and ecological risk of heavy metals in China's largest inland lake. In recent years, most studies on Qinghai Lake have focused on the impact of climate change on the lake area, dissolved organic matter (Li et al., 2021), and the source and distribution of microplastics (Xiong et al. 2018). Moreover, a few studies have characterized heavy metals in sediments but only consider small river sections. Therefore, these small-scale studies cannot meet the monitoring and evaluation requirements of the entire Qinghai Lake basin. In this study, Qinghai Lake, the largest inland saltwater lake in China, was selected as the research object. The basin is located in the transition zone of the northwest arid area, the eastern monsoon area, and the Qinghai Tibet high cold area in China. The basin is located in a sensitive global climate change area and is a typical example of a fragile ecosystem area (Lu et al. 2015). The environmental quality of the basin is directly related to the sustainable social and economic development of the region. Moreover, the basin has an important impact on the ecology of the region and the regional development of agriculture and animal husbandry (Jiang et al. 2015). Therefore, to protect the Qinghai Lake Basin, the levels of eight heavy metal elements (Cr, Mn, Fe, Hg, Cu, Zn, As, and Pb) were analyzed in the sediments of the study area. Specifically, this study evaluated the pollution degree, pollution characteristics, and ecological risk of heavy metals in the lakes in the study area. Moreover, we evaluated the source of the heavy metals and compared the rivers and lakes entering the lake in the basin to explore the impact of different types and intensities of human activities on heavy metal levels in lake sediments. Our findings will be of great significance for the sustainable socio-economic development in the region and provide a scientific basis for the effective control of heavy metal pollution in lakes, as well as for environmental governance.

Materials and methods

Study area and sampling design

Qinghai Lake is the largest inland saltwater lake in China and a representative plateau wetland inland lake. The basin is located in the northeast of Qinghai Tibet Plateau, with a drainage area of 29,661 km^2. The lake area spans from 97° 50′ E–101° 20′ E to 36° 15′ N–38° 20′ N (Zhang et al. 2021; Wang et al. 2010a, 2010b). Qinghai Lake is located at the intersection between the eastern monsoon region, the northwest arid region, and the southern Qinghai Tibet alpine region in China, and therefore exhibits unique regional climate characteristics (Chang et al. 2017). The annual average temperature in the Qinghai Lake area is −1.0–1.5 °C, the maximum monthly average temperature is 16.0–20.0 °C, and the absolute maximum temperature is 26 °C. The minimum monthly average temperature is −18.0 to −23.0 °C, and the absolute minimum temperature is −35.8 °C (Zhu et al. 2013). The average annual precipitation in the Qinghai Lake area is generally between 300 and 400 mm, but reaches up to 500 mm in some wet years. The Qinghai Lake area is a semi-arid area with frequent winds all year round. Therefore, the area exhibits a high evaporation capacity, with an average annual evaporation capacity of approximately 1300–2000 mm (Zhang et al. 2021; Chang et al. 2017; Zhu et al. 2013; Wang et al. 2010a, 2010b).

In this study, sampling was conducted in Qinghai Lake before the tourism season in July 2020 and in the frozen season in September to evaluate the impact of human factors on the region. A total of 25 sampling points (including 12 N1–N13 in the lake body, 7 R1–R8 in the river entering the lake, and 6 B1–B6 at the entrance of the lake) were set across Qinghai Lake and the five major rivers entering the lake (Fig. 1). The distribution pattern of heavy metals in the sediments of Qinghai Lake from 2020 to 2021 was analyzed, the sources of heavy metals were evaluated, and the pollution degree, pollution characteristics, and ecological risk of heavy metals in the lakes in the study area were assessed.

Sample collection, storage, and preservation

To prevent anthropogenic riverbed disturbances, the samples were collected from the middle of the river by wading (R1–R8) or from a sampling boat (N1–N13, B1–B6). Moreover, to minimize variations between samples, three parallel samples were collected at each point for mixing. The samples were collected using a mky-1 / 40 Peterson grab dredger, and the sample container was made of polyethylene. Before each use, the containers were soaked with (1+2) nitric acid for 2–3 days, cleaned with deionized water, and thoroughly dried before use. The mixed samples were packed in double polyethylene bags and placed in a portable refrigerator at −4 °C until required for downstream analyses. Before the test, the sample was ground with an agate mortar, passed through a 100-mesh nylon sieve, and transferred to a pre-numbered wide-mouth bottle until required for downstream analyses.

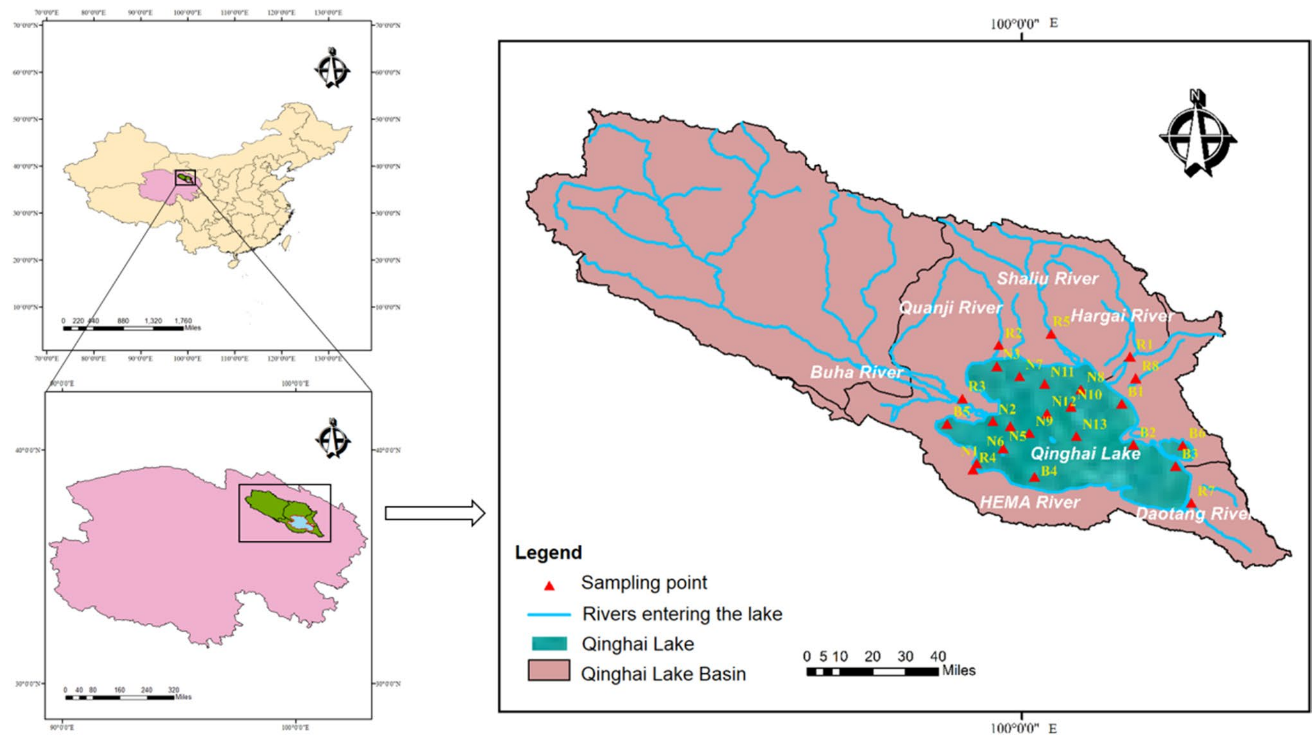

Fig. 1 Sampling sites in the Qinghai Lake basin

Sample laboratory analysis

The samples were further analyzed in the laboratory. Eight heavy metal elements (Cr, Mn, Fe, Hg, Ni, Cu, Zn, As, and Pb) in sediments were analyzed. These metals were selected because they are crustal metals (soil source) that are common in urban areas—Fe and Mn—and anthropogenic metals (from human activities): Cu, Zn, Pb, Cr, Hg, and As. For the extraction of total heavy metals in sediments, we followed the United States Environmental Protection Agency (US EPA) 3051 method (EPA., 2004) and used the acid digestion system of HNO_3+H_2O_2 for microwave digestion (microwave digester, ECM, USA). After digestion, the sample was filtered through a 0.45-μm mixed fiber membrane as described by the EPA (EPA., 2001). An Agilent 7800 inductively coupled plasma mass spectrometer (ICP-MS, Agilent, USA) was used to determine the content of heavy metals. During the analysis, all glass and polyethylene utensils were fully soaked in 10% HNO_3 for more than 24 h before use. In the process of sample pretreatment and analysis, all reagents were of superior purity to ensure the accuracy of the experimental data. In terms of quality assurance (QA) and quality control (QC), the national sediment standard GSD-7 (GBW-07366) was followed, and blank samples and parallel samples were used for quality control (QC). The total recovery rate of the standard material was 94–115%, and the detection limit of each metal element was 0.02–1.82 $\mu g \cdot L^{-1}$. The relative standard deviation (RSD) between the parallel samples was less than 5%, meaning that the accuracy and reproducibility of the analytical method were acceptable.

Statistical data analysis

SPSS 21.0, Python, and MATLAB were used for data analysis, using ArcGIS 10.2, Origin 2018, SigmaPlot 10.0, and other software for data visualization and graphing. Kriging interpolation and other geostatistical methods were used to analyze the spatial heterogeneity of the research area. Ecological risk assessment was conducted based on the Enrichment Factor (EF), geoaccumulation index (Igeo), and potential ecological hazard index (RI) (Müller 1979; Hakanson 1980; Brady et al. 2014; Gao et al. 2014; Knox et al. 2016). The US EPA health risk assessment model (US EPA 1996) was used to evaluate the carcinogenic risk of metal exposure in the study area.

Enrichment factor method

The enrichment factor method (EF) can be used to reflect the amount of heavy metal absorption, accumulation, or enrichment capacity in different environmental media. This method is often used to determine the accumulation capacity of metal elements in surface water sediments and coastal soils such as bays, lakes, and rivers (Zhang et al. 2016), and

Table 1 Håkanson reference value and toxicity coefficient of heavy metal elements

Project	Hg	Cr	Cu	Zn	As	Pb
C_n^i (mg/kg)	0.25	11.66	20.47	19.72	54.17	64.28
T_r^i	40	2	1	5	10	5

its calculation formula is as follows (Brady et al. 2014; Gao et al. 2014):

$$EF = \frac{\left(\frac{C_n}{C_{ref}}\right)\text{sample}}{\left(\frac{B_n}{B_{ref}}\right)\text{background}} \tag{1.1}$$

where EF represents the enrichment coefficient, C_n refers to the measured concentration value of the *n*th heavy metal in the sample, C_{ref} is the measured content value of the calibration element, B_n is the background value of each heavy metal element in the environmental medium, and B_{ref} is the background value of the calibration element in the environmental medium. Due to a lack of evidence from manmade sources, Fe was selected as the calibration element in this study. "Metal/Fe sample" is the sample's metal to Fe ratio and "Metal/Fe background" is the natural background value (Table 5). Fe was used as a normalizer to account for the lack of evidence of anthropogenic sources and compensate for the lack of information regarding the grain size of the sediments, as reported in several previous studies (Neto et al. 2000; Aloupi and Angelidis 2001; Mucha et al. 2003; Varol and Şen 2012; Silva et al. 2017b). Al, K, Sc, Ga, Zr, Cs, Be, Ti, Mn, and Si have also been used as normalizers in other previous studies (Middleton and Grant 1990; Xu et al. 2017b; Zhuang et al. 2018; Pavlović et al. 2019). The background values play an important role in interpreting geochemical data because they reflect the heavy metal concentration expected to occur naturally (Rubio et al. 2000; Turekian and Wedepohl 1961; Abrahim and Parker 2008; Silva et al. 2017a; Dung et al., 2013). The EF values were interpreted according to Xu et al. (2017a) as summarized in Table 2.

Ground accumulation index method

Igeo is widely used to evaluate sediment pollution. The following equation, proposed by Müller (1979) (Hanif et al. 2016), was used to quantify the degree of pollution in the sediments.

$$I_{geo} = \log_2\left(\frac{C_n}{KB_n}\right) \tag{1.2}$$

where C_n is the measured content of element *n*, in milligrams per kilogram; C_n is the background value of corresponding elements, in milligrams per kilogram; and the constant *K* is the natural fluctuation of the content of heavy metals during diagenesis, whose value is typically 1.5. A correction factor of 1.5 was employed to analyze the possible fluctuation of background values (BGV) due to the lithogenic phenomenon (Muller et al. 1981; Krishnakumar et al. 2017; Arisekar et al. 2021; Wei et al. 2019; Youssef et al. 2020; Magni et al. 2021). Based on the Muller (1981, 1969) classification, the Igeo values were classified into seven classes, as summarized in Table 2.

Table 2 Classification standard of ecological risk assessment methods

Method	Level	Status
EF	<2	Deficiency to minimal enrichment
	2 = EF < 5	Moderate enrichment
	5 = EF < 20	Significant enrichment
	20 = EF < 40	Very high enrichment
	EF ≥ 40	Extremely high enrichment
Igeo	≤0	Unpolluted
	0 < Igeo ≤1	Unpolluted to moderately polluted
	1 < Igeo ≤2	Moderately polluted
	2 < Igeo ≤3	Moderately to strongly polluted
	3 < Igeo ≤4	Strongly polluted
	4 < Igeo ≤5	Strongly to very strongly polluted
	≥6	Extremely/very strongly polluted
E_r^i	≤40	Slight ecological hazard
	40–79	Medium ecological hazard
	80–159	Strong ecological hazard
	160–320	Strong ecological hazard
	>320	Extremely strong ecological hazard
RI	≤150	Slight ecological hazard
	150–299	Medium ecological hazard
	300–600	Strong ecological hazard
	>600	Strong ecological hazard

Potential ecological hazard index

The potential ecological hazard index method, also known as the Håkanson method, is a way to evaluate heavy metal pollution and ecological damage based on the principle of sedimentology. This approach is mainly affected by the concentration, toxicity level, and type of heavy metals in surface sediments and the sensitivity of the water body to heavy metal pollution. Moreover, this method can evaluate the synergy of multiple heavy metal elements and consider the toxic pollution of a single metal (Hakanson 1980; Lin et al. 2019; Tang et al. 2017). The potential ecological risk index (E_r^i) of single heavy metals can be expressed as follows:

$$E_r^i = T_r^i \times C_f^i \tag{1.3}$$

$$C_f^i = C_s^i / C_n^i \tag{1.4}$$

where E_r^i is the environmental risk index of the *i*th heavy metal; C_f^i is the pollution coefficient of heavy metal *I* relative to the reference ratio; C_s^i is the measured concentration of heavy metal *I*; C_n^i is the evaluation reference ratio of heavy metal *I*; and T_r^i is the heavy metal *I* toxicity response coefficient, which mainly reflects the toxicity level of heavy metals and the sensitivity of the environment to heavy metal pollution. The multi-element comprehensive environmental risk index (RI) is expressed as follows (1.6):

$$RI = \sum_{i=1}^{n} E_r^i = \sum_{i=1}^{n} T_r^i \times C_f^i = \sum_{i=1}^{n} T_r^i \times \frac{C_s^i}{C_n^i} \tag{1.5}$$

In this study, the toxicity coefficient of heavy metals proposed by Håkanson (Table 1) was used as the reference ratio in the calculation formula of the potential ecological risk index. Due to the lack of data on the evaluation reference ratio and toxicity response coefficient of heavy metals, our study only assessed the ecological risk of six elements: Hg, Cr, Cu, Zn, As, and Pb. The calculation results of E_r^i and RI are shown in Table 5, and the classification is shown in Table 2 (Hakanson 1980; Lin et al. 2019; Tang et al. 2017; Wang et al. 2010a, 2010b; Li et al. 2020).

Human health risk assessment

US EPA Health Risk Assessment Model (US EPA 1996): We adopted the health risk model and recommended standards proposed by the US EPA to assess the human health risk of heavy metal pollution in lake surface sediments.

$$ADD_{\text{ing}} = \frac{C \times IngR \times EF \times ED}{BW \times AT} \times 10^{-6} \tag{1.6}$$

$$ADD_{\text{inh}} = \frac{C \times InhR \times EF \times ED}{PF \times BW \times AT} \times 10^{-6} \tag{1.7}$$

$$ADD_{\text{derm}} = \frac{C \times SA \times SD \times ABS \times EF \times ED}{BW \times AT} \times 10^{-6} \tag{1.8}$$

ADD_{ing}, ADD_{inh}, and ADD_{derm} are acceptable daily ingested, inhaled, and dermal intake doses in units of mg·(kg*day)$^{-1}$. *C* is the content of heavy metals in soil, in mg·kg^{-1}. The parameter in Formulas (1.7), (1.8), and (1.9) were selected from the data in Table 3, which in turn were obtained from previous literature (Wang et al. 2018).

Table 3 Health risk assessment model exposure parameters

Parameter	Units	Child	Adult	Meaning
IngR	mg/day	200	100	Ingested rate
InhR	m/day	5	20	Inhaled rate
EF	d/a	350	350	Exposure frequency
ED	A	6	24	Exposure duration
BW	kg	15	55.9	Body weight
AT	days	30 × 365 (non-carcinogenic)		Average time
		70 × 365 (carcinogenic)		
PF	m^3/kg	1.36 × 109	1.36 × 109	Particulate release factor
SA	cm^2	1800	5000	Skin exposure area
SD	mg/cm^{-2}	1	1	Skin adhesion degrees
ABS		0.001	0.001	Adsorption factor of skin

Table 4 RfD and SF values of different heavy metal exposure pathways

Heavy metals	RfD/(mg·(kg·day)$^{-1}$)			SF/(kg·day^{-1}·mg^{-1})		
	Ingested	Inhaled	Dermal	Ingested	Inhaled	Dermal
As	0.0003	0.000123	0.00301	1.5	0.00043	1.5
Cr	0.003	0.00286	0.00006	-	42	0.5
Hg	0.0003	0.0003	0.000024	-	-	-
Pb	0.0035	0.00352	0.0352	-	-	0.0085

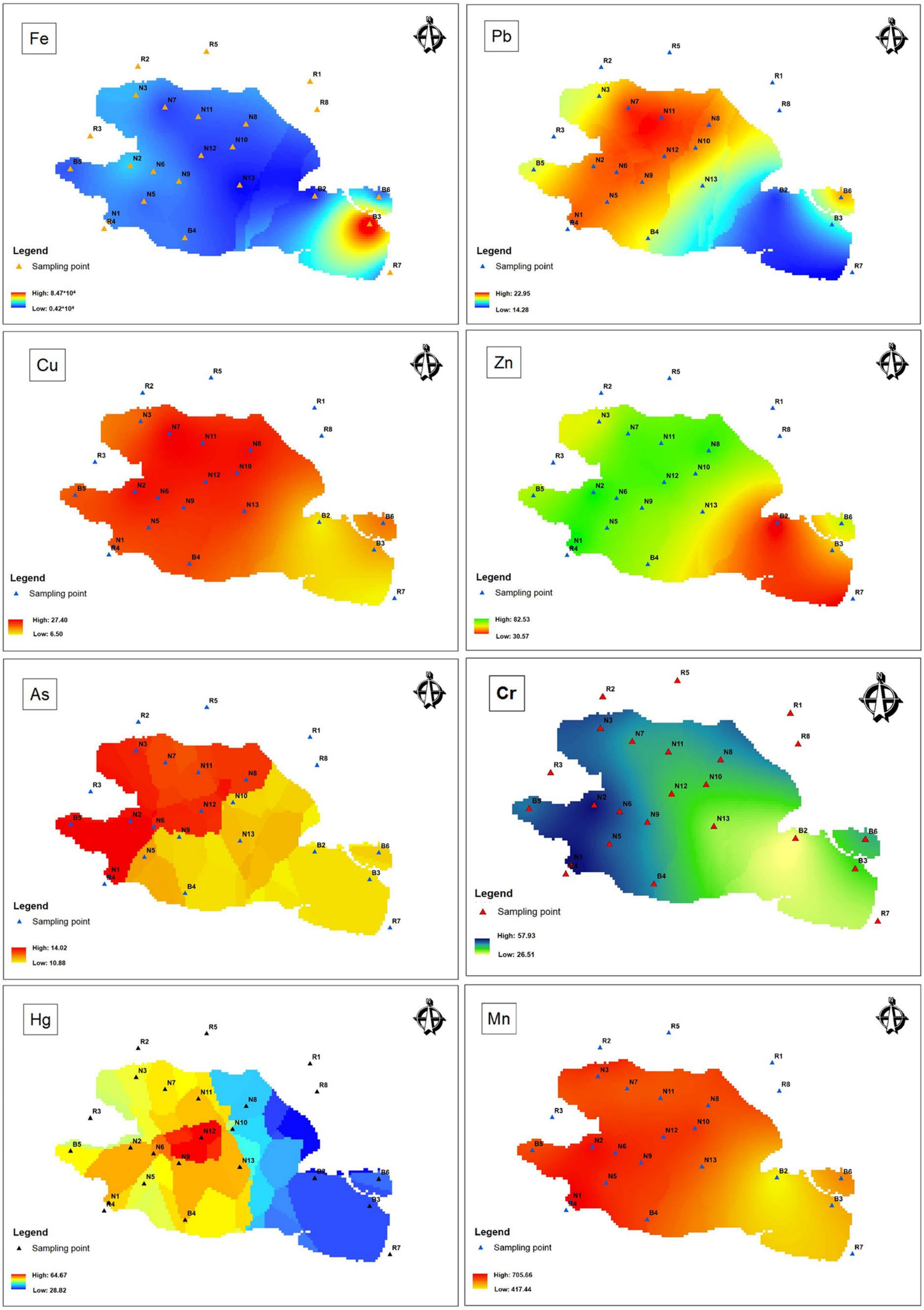

Fig. 2 Total metal loads in sediments in the Qinghai Lake Basin in July. Crustal metals — Fe, Mn; anthropogenic metals — Cu, Zn, Pb, Cr, Hg, As

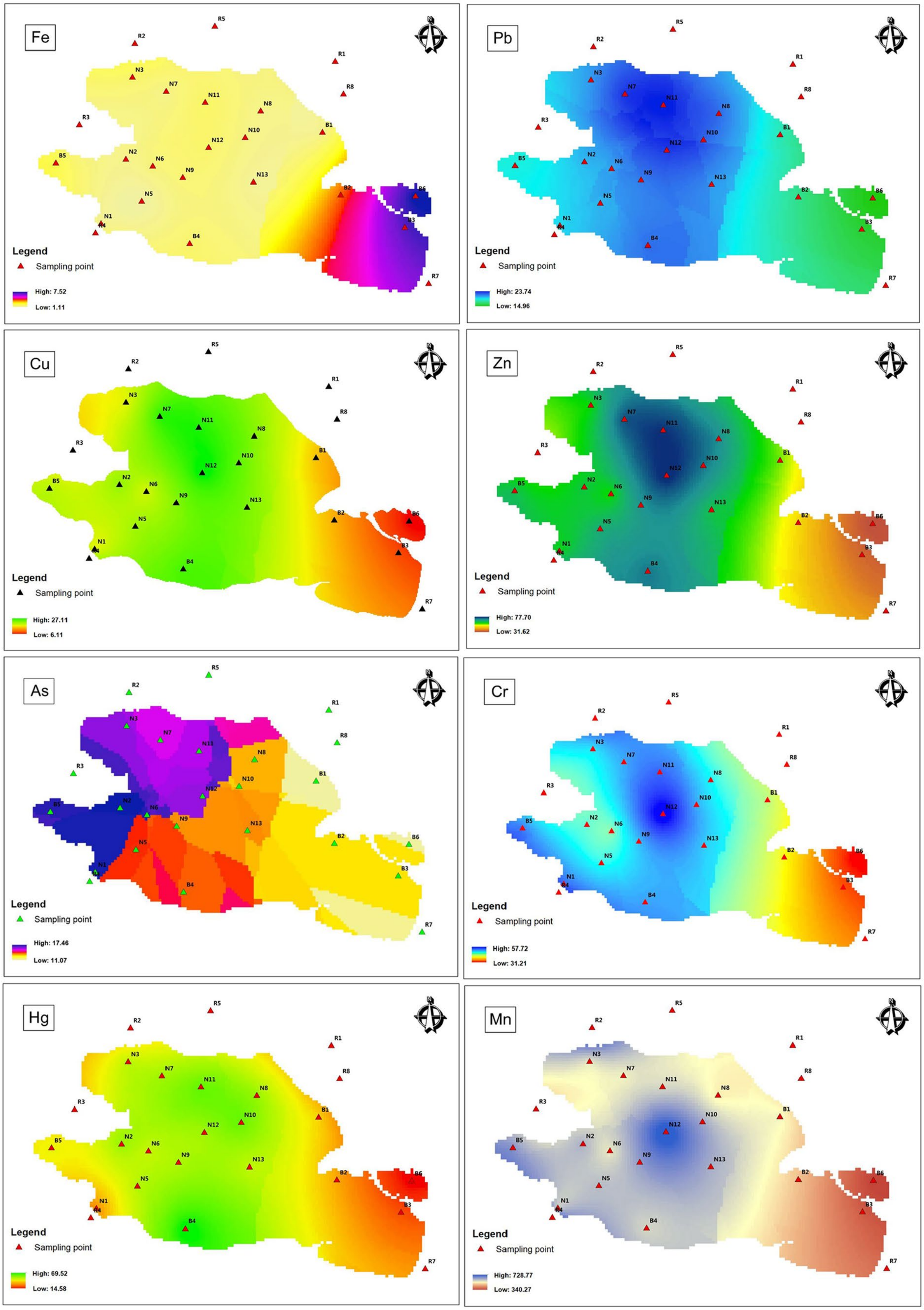

Fig. 3 Total metal loads in sediments in the Qinghai Lake Basin in September. Crustal metals — Fe, Mn; anthropogenic metals — Cu, Zn, Pb, Cr, Hg, As

Table 5 Summary of calculation results of ecological risk assessment

Method	Sample/element	Hg	Cr	Mn	Ni	Cu	Zn	As	Pb
EF	N1	-	0.81	1.23	0.91	1	1.36	0.58	1.02
	N2	-	0.63	0.86	0.81	0.93	0.87	0.57	0.62
	N3	-	0.52	0.8	0.64	0.68	0.63	1.63	0.51
	N5	-	0.75	1.29	1.12	1.33	1.3	0.92	1.01
	N7	-	1.02	1.84	2.01	2.72	2.19	1.18	1.88
	N8	-	0.88	1.43	1.52	1.86	1.71	0.83	1.32
	N9	-	0.68	1.09	0.92	1.1	1	0.51	0.8
	N10	-	0.9	1.88	1.61	2.02	1.69	0.9	1.36
	N11	-	0.83	1.42	1.63	1.8	1.54	0.9	1.24
	N12	-	0.93	2.11	1.92	2.26	2.23	1.33	1.56
	N13	-	1.53	4.01	3.69	4.65	3.56	2.58	2.78
	B2	-	0.65	1.67	0.93	0.63	0.89	1.5	0.83
	B3	-	0.99	1.59	1.25	1.29	1.39	1.4	1.11
	B4	-	0.76	1.19	1.07	1.21	1.1	0.9	0.77
	B5	-	0.89	1.5	1.36	1.5	1.44	1.31	1.03
	B6	-	0.72	1.07	0.82	1.03	1.08	0.8	1.19
	R1	-	0.58	0.82	0.77	0.77	0.77	0.58	0.52
	R2	-	0.64	1.01	0.91	0.72	0.75	0.42	0.59
	R3	-	0.63	0.89	0.73	0.69	0.75	0.6	0.56
	R4	-	0.79	1.11	0.82	0.79	0.8	0.59	0.61
	R5	-	0.41	0.62	0.5	0.43	0.55	0.35	0.35
	R7	-	0.58	1.34	0.59	0.38	0.66	0.51	0.66
	R8	-	0.64	0.89	0.8	0.89	0.83	0.68	0.61
	AVG	-	0.71	1.27	1.09	1.23	1.16	0.86	0.92
Igeo	N1	-	−0.44	−0.36	−0.42	−0.49	−0.01	−0.75	−0.13
	N2	-	−0.3	−0.37	−0.1	−0.11	−0.16	−0.28	−0.36
	N3	-	−0.79	−0.69	−0.64	−0.77	−0.84	1.01	−0.85
	N5	-	−0.88	−0.62	−0.47	−0.43	−0.42	−0.43	−0.48
	N7	-	−1.06	−0.72	−0.23	0	−0.27	−0.68	−0.19
	N8	-	−0.85	−0.68	−0.23	−0.14	−0.22	−0.78	−0.3
	N9	-	−0.7	−0.53	−0.42	−0.37	−0.46	−0.94	−0.48
	N10	-	−1.06	−0.51	−0.37	−0.25	−0.46	−0.9	−0.48
	N11	-	−0.92	−0.66	−0.1	−0.17	−0.34	−0.63	−0.36
	N12	-	−1.22	−0.54	−0.32	−0.3	−0.27	−0.53	−0.48
	N13	-	−1.54	−0.66	−0.42	−0.3	−0.64	−0.62	−0.69
	B2	-	−2.26	−1.42	−1.9	−2.68	−2.13	−0.9	−1.94
	B3	-	−1.1	−0.92	−0.9	−1.07	−0.92	−0.43	−0.94
	B4	-	−0.76	−0.64	−0.42	−0.46	−0.55	−0.36	−0.77
	B5	-	−0.88	−0.65	−0.42	−0.49	−0.5	−0.16	−0.69
	B6	-	−0.79	−0.74	−0.77	−0.65	−0.53	−0.48	−0.08
	R1	-	−0.54	−0.54	−0.27	−0.49	−0.44	−0.35	−0.69
	R2	-	−0.41	−0.27	−0.06	−0.61	−0.5	−0.85	−0.55
	R3	-	−0.76	−0.78	−0.7	−1	−0.84	−0.67	−0.94
	R4	-	−0.37	−0.39	−0.47	−0.73	−0.66	−0.62	−0.77
	R5	-	−0.7	−0.64	−0.58	−1	−0.61	−0.76	−0.94
	R7	-	−1.64	−0.96	−1.77	−2.62	−1.78	−1.67	−1.48
	R8	-	−0.39	−0.43	−0.23	−0.28	−0.32	−0.15	−0.48
	AVG	-	−0.81	−0.59	−0.49	−0.62	−0.55	−0.52	−0.6

Table 5 (continued)

Method	Sample/element	Hg	Cr	Mn	Ni	Cu	Zn	As	Pb
E_r^i	N1	3.3	10.29	-	-	1.03	24.34	1.92	2.18
	N2	30.72	11.32	-	-	1.34	21.81	2.66	1.87
	N3	15.73	8.06	-	-	0.85	13.69	6.52	1.32
	N5	7.07	7.55	-	-	1.07	18.26	2.4	1.71
	N7	8.22	6.69	-	-	1.44	20.28	2.01	2.1
	N8	9.22	7.72	-	-	1.31	21.04	1.88	1.94
	N9	6.1	8.58	-	-	1.12	17.75	1.68	1.71
	N10	6.8	6.69	-	-	1.21	17.75	1.74	1.71
	N11	9.17	7.38	-	-	1.28	19.27	2.09	1.87
	N12	5.78	6	-	-	1.18	20.28	2.23	1.71
	N13	4.78	4.8	-	-	1.18	15.72	2.1	1.48
	B2	1.2	2.92	-	-	0.22	5.58	1.74	0.62
	B3	3.81	6.52	-	-	0.69	12.93	2.4	1.24
	B4	17.28	8.23	-	-	1.05	16.73	2.51	1.4
	B5	4.3	7.55	-	-	1.03	17.24	2.9	1.48
	B6	2.74	8.06	-	-	0.92	16.99	2.31	2.26
	R1	3.04	9.61	-	-	1.03	18	2.53	1.48
	R2	1.47	10.46	-	-	0.95	17.24	1.79	1.63
	R3	1.01	8.23	-	-	0.72	13.69	2.03	1.24
	R4	1.02	10.81	-	-	0.87	15.47	2.1	1.4
	R5	2.51	8.58	-	-	0.72	15.97	1.9	1.24
	R7	0.32	4.46	-	-	0.23	7.1	1.02	0.86
	R8	2.38	10.63	-	-	1.19	19.52	2.92	1.71
	AVG	5.92	7.25	-	-	0.91	15.47	2.14	1.45
RI	Total RI	147.97	181.13	-	-	22.64	386.66	53.37	36.17

"-" means no point data

The formula for calculating the carcinogenic and non-carcinogenic effects of heavy metals on human health (Wang et al. 2018) is as follows:

$$HI = \sum HQ_i = \sum \frac{ADD_{ij}}{RfD_{if}} \tag{1.9}$$

HI is the non-carcinogenic risk index of multiple substances or multiple exposure modes of a substance, which has no dimension. HQ_i is a non-carcinogenic health risk index of non-carcinogenic heavy metal i, which has no dimension.

Table 6 Average individual annual risk of metal health hazards a/$^{-1}$

Crowd	As	Cr	Hg	Pb	HI
Child	0.10	0.12	0.05	0.31	0.58
Adult	0.03	0.06	0.01	0.09	0.19

ADD_{ij} and RfD_{ij} are the daily exposure and reference doses of non-carcinogenic heavy metal i in the j exposure pathway, respectively, in milligrams per kilogram. The RfD and SF reference values of each heavy metal are shown in Table 4 (He et al. 2020). When $HI \leq 1$, there is no risk of non-carcinogenic influence. When $HI > 1$, there is a risk of non-carcinogenic influence, and the likelihood of non-carcinogenic outcomes increases with the increase in the HI value.

Results and discussion

Analysis of spatial and temporal changes and pollution characteristics of heavy metals

In the context of environmental pollution, the origin of pollutants and their transport pathways are important for effective pollution mitigation. Understanding these factors allows decision-makers to determine whether to adopt a source-control or transport-control approach for the design of effective pollution mitigation strategies. Therefore, our study also sought to characterize the variations in crustal and anthropogenic metal load patterns and how these types of metals behave along the river.

The content of heavy metals in the surface sediments of Qinghai Lake presents a three-step distribution pattern in space, gradually increasing from east to west. The spatial distribution characteristics of the contents of As and Cr are similar, but different from the other 10 heavy metals. This indicates that the spatial fluctuation of As and Cr in Qinghai Lake is relatively large, and there may be pollution from point source discharge in these areas (Zhu et al. 2013). The first step (high value) takes N1, N6, N12, and N8 as the dividing interface to the west, and the second step (average content) in the third stage (low value) takes N1, N6, N12, and N8 as the dividing interface to the east, and gradually decreases with the B4 and N13 extension lines as the dividing line. Based on the results of a field investigation, the roads around Qinghai Lake are widely distributed and far-reaching (e.g., Qinghai Tibet railway, national highway 316, national highway 109, provincial roads, county and township roads), and the urbanization, construction, and tourism industry have also increased in recent 10 years. Therefore, traffic and transportation emissions have become one of the main sources of pollutants. The hukou of Buha River and the wharf of Jiangxi ditch may be directly related to human activities such as dense population, vehicle traffic, and scenic spot tourism around the sampling point. The level of pollution at the entrance of the Hema River and Bird Island may be related to pesticides, fertilizers, and farms. This is likely due to the rapid urban development and frequent vehicle traffic in the west of Qinghai Lake. The impact of agricultural non-point sources and human activities may result in high levels of Cu, Zn, Pb, Cr, and other metals nearby. Previous studies have shown that road sections with large traffic volume and frequent brake use such as intersections and turns exhibit high levels of Cu, Zn, Pb, and Cr accumulation in nearby sediments, which is consistent with the results of the present study (Zhu et al. 2013). Additionally, the contents of Cu, Zn, Pb, Cr, and As at points N2 (Buha River estuary), N7 (three rocks), and N5 (Quanji River Estuary and Qinghai Lake farm) were significantly higher than those at other points, which is thought to be related to natural factors and human impacts such as sediment accumulation at the entrance (Wang et al. 2010a, 2010b), increased tourism activities, and agricultural production (Zhu et al. 2013) (Figs. 2 and 3).

Relatively speaking, the other nine metal elements at B1 (Sand Island), B4 (Jiangxi ditch wharf), R7 (HEMA River), and B6 (Haiyan Bay) show low values except for the high values of the crustal metal Fe. The main external reasons are that the eastern part of the lake develops slowly, the population is small, the land use in the eastern part of the lake is mainly composed of natural reserves and biodiversity reserves, and human beings are less involved. The internal mechanism is that the sediments of the island and its adjacent waters are mainly sandy, and the sand particles are large and not easy to be enriched with metals (Chang et al. 2017). The source data is summarized in Supplementary Table S1.

Ecological risk assessment

EF can reflect the amount of heavy metal absorption, accumulation, or enrichment capacity in different environmental media. As summarized in Table 5, the metal accumulation or enrichment capacity of points N7, N10, N12, and N13 in Qinghai Lake Basin was strong. Interestingly, the enrichment capacity of Cu and Zn was the strongest among all metals, but they occurred at low and medium concentration enrichment, respectively. Therefore, our findings indicated that Cu and Zn had little impact on the ecological environment in the basin. Among the study points, N7 mainly enriches the metals Ni (EF = 2.10), Cu (EF = 2.72), and Zn (EF = 2.19); N10 enriches Cu (EF = 2.02); N12 enriches Cu (EF = 2.23); and N13 enriches Mn (EF = 4.01), Ni (EF = 3.69), Cu (EF = 4.65), Zn (EF = 3.56), As (EF = 2.58), and Pb (EF = 2.78). The Igeo calculation results (Table 5) show that the Igeo values of metals Cr, Mn, Ni, Cu, Zn, As, and Pb were less than 0, and therefore these metals do not pose an ecological risk to the Qinghai Lake Basin. The E_r^i calculation results indicated that the E_r^i values of Hg, Cr, Cu, Zn, As, and Pb were ≤ 40, and the average values were 5.92, 7.25, 0.91, 15.47, 2.14, and 1.45 respectively. The order from high to low is Zn > CR > Hg > As > Pb > Cu. Combined with the calculation results of Igeo, our findings indicated that the calculation results of Igeo and E_r^i were the same, and any given single metal posed little to no ecological risk to Qinghai Lake Basin. By further considering the toxicity level and types of heavy metals and the sensitivity of water bodies to heavy metal pollution, we calculated the multi-element environmental risk comprehensive index and found that Hg (RI = 147.97) posed a slight ecological risk, Mn (CE: Run-in header = 181.13) posed a moderate ecological risk, and Zn (CE: Run-in header = 386.66) posed a strong ecological risk. Therefore, Hg, Mn, Cu, and Zn should be listed as local priority pollution elements. Moreover, the interior of the study area and a small part of the northwest area are risk-prone areas and should thus be closely monitored.

Human health risk assessment

According to the health risk assessment model and model parameters, combined with the measured parameters of heavy metals, the average personal risk of adults and children that may be caused by the heavy metals As, Cr, Hg, and Pb in sediments can be calculated. The risk calculation is only based on the amount of food intake, without considering the carcinogenic risk of water consumption (i.e., the model assumes that the drinking water is clean). See Table 6 for the calculation results. Based on Table 6, the following conclusions were made: (1) at present, heavy metals in the surface sediments of Qinghai Lake do not pose a threat to the human health of the surrounding residents, because the HI values of metals As, Cr, Hg, and Pb are less than 1. When $HI > 1$, the metal pollution level poses a threat to human health. (2) The average personal risk of adults and children upon metal exposure exhibits the following order: Pb > CR > As > Hg. (3) A comprehensive comparison of HI between adults and children indicated that children are more vulnerable to the content of heavy metals in sediments than adults. Furthermore, the average risk coefficients of the four metals were greater in children than in adults. Specifically, the total health hazard risk for children is 2–3 times higher than that of adults.

Conclusion

The present watershed-scale study provides information about the widespread distribution, enrichment, ecological risk, and human health risk of heavy metals in the surface sediments of Qinghai Lake. The average concentration of heavy metals in surface sediments of Qinghai Lake does not exceed its geochemical background level. From the perspective of spatial distribution, the study site exhibited a three-level distribution pattern, gradually increasing from east to west, which may be caused by human activities (such as agriculture) around Qinghai Lake. Among the evaluated metals, the spatial distribution of As and Cr fluctuated greatly, suggesting that these heavy metals originate from point source emissions. The regional heavy metal enrichment was calculated using the EF model. Our findings indicated that the metal enrichment or enrichment capacity of points N7, N10, N12, and N13 in Qinghai Lake Basin was strong. Among the evaluated metals, Cu and Zn had the strongest enrichment capacity, but occurred at low and medium concentration enrichment. Therefore, these metals had little impact on the ecological environment of the basin. The comprehensive evaluation results of ecological risk level indicated that any single metal posed little to no ecological risk to the Qinghai Lake Basin. In other words, the metals in the surface sediments of Qinghai Lake are at a low risk level. However, the multi-element environmental risk comprehensive index (RI) shows that metal Hg ($RI = 147.97$) poses slight ecological risks, Mn ($RI = 181.13$) poses moderate ecological risks, and Zn ($RI = 386.66$) poses strong ecological risks. Relatively speaking, the metals Hg, Mn, Cu, and Zn in the study area should be listed as local priority pollution elements. Moreover, the interior of the study area and a small part of the northwest area are risk-prone areas and should thus be closely monitored. The human health risk assessment results indicated that the heavy metals in the surface sediments of Qinghai Lake do not currently pose a significant threat to the human health of the surrounding residents. It is also worth noting that after comprehensively comparing the HI results of adults and children, our findings indicated that children are more vulnerable to the content of heavy metals in sediments than adults, and the average risk coefficients of the four metals were greater in children than in adults. The total risk of health hazards for children was 2–3 times higher than that of adults. This study provides crucial insights into the pollution level of heavy metals in Qinghai Lake and provides a basis for the development and establishment of reasonable ecological protection measures. Nevertheless, there is still a lack of information on some pollutants and their toxicity. Therefore, future studies must fill these knowledge gaps to reveal the pollution level of metals in aquatic environments and improve the accuracy of ecological risk and human health risk calculation. Future studies should also consider metal conversion and response mechanisms from the perspective of pollutant synergy, and incorporate a wide range of metal toxicity data into ecological risk and health risk assessment methods to obtain more accurate estimations.

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Declarations

Ethics approval We the undersigned declare that this manuscript entitled "Spatial dynamics, ecological risk and human health assessment of heavy metals in lake surface sediments." However, the research content mainly includes the source analysis of heavy metal pollution, pollution path, and the methodological research of human exposure in natural basins of China, and does not involve the ethical and human experimental research.

Consent to participate We confirm that the manuscript has been read and approved by all named authors.

Consent for publication We confirm that the manuscript is approved by all authors for publication.

Competing interests The authors declare no competing interests.

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