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Characteristics of nutrients pollution and ecological risk assessment of heavy metal in sediments of Fenhe River, Taiyuan section, China

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ABSTRACT

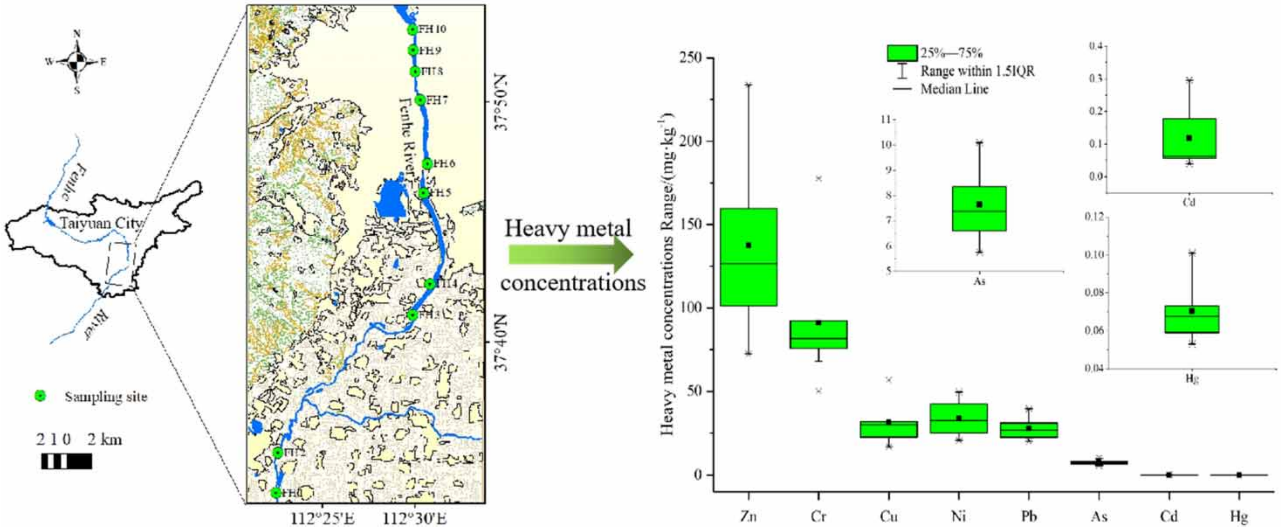
This study aimed to reveal the characteristics of nutrients and heavy metals associated with ecological risks in the sediments of Fenhe River, Taiyuan section. The concentrations of nutrients (total nitrogen, total phosphorus, total organic matter) and heavy metals (As, Cu, Zn, Pb, Cr, Ni, Hg, Cd) were investigated. Spatial distribution, correlation analysis and source identification were facilitated to indicate nutrient and heavy metal pollution characteristics. Evaluations of heavy metals' contamination degree were achieved by comprehensive ecological risk indexes including I_{geo}, I_{in}, C_f, pollution load index and risk index. The results showed that nutrients accumulated in the middle region and were mainly from embryophyte, zooplankton and phytoplankton or algae, based on C/*N* values. Large spatial variabilities existed in heavy metal distribution patterns; source identification for heavy metals revealed they were from natural sources and anthropogenic activities based on a principal component analysis model. Results of different ecological risk indexes showed that pollution associated with Hg was rated as a moderate ecological risk but was significant contamination, higher ecological risks mainly existed in the middle region.

Key words: ecological risk, Fenhe River, heavy metals, nutrients, sediment, source identification

HIGHLIGHTS

- The correlation analysis between nutrients and heavy metals.
- Comprehensive ecological risk assessment methods for heavy metals.
- The comprehensive understanding of pollution characteristics of heavy metals by detecting eight heavy metals (As, Cu, Zn, Pb, Cr, Ni, Hg, Cd).
- Focus was on the heavy metal contamination in the tributary of a large river, the Fenhe River.

GRAPHICAL ABSTRACT



1. INTRODUCTION

With rapid urbanization and industrial development, the accumulation of contaminants in rivers have posed problems to aquatic ecosystems (Kalnejais *et al.* 2010; Pan & Wang 2012; Islam *et al.* 2015; Yang *et al.* 2020). Sediments, as the indispensable ecological components of the water environment, play an important role in maintaining the stable ecosystem, which serves as both sources and sinks for contaminants (Chen *et al.* 2008; de Paula Filho *et al.* 2015; Bere *et al.* 2016; Zhu *et al.* 2018). Contaminants could be absorbed in sediment (Berg *et al.* 2001). Nevertheless, the release of contaminants from sediments into water would occur when external conditions change, resulting in aggravated contamination in aquatic ecosystems (Yi *et al.* 2011). If sufficiently large contaminants are loaded into the aquatic ecosystems, excessive quantities of contaminants may accumulate in the sediments and directly or indirectly destroy the ecosystem, thus leading to a significant deterioration in river water quality (Burton 2002; Bere *et al.* 2016; Dalu *et al.* 2018). Representative pollutants existing various forms in river sediments include nutrients (phosphorus, nitrogen, organic matter) and heavy metals (Förstner & Wittmann 1983; Yang *et al.* 2020). External inputs of nutrients mainly from human activities (industrial wastewater, urbanization and agricultural fertilizers) enter into the river then tend to be trapped in sediments by biochemical and physical reactions, excessive nutrient loading from the sediments accelerates eutrophication in the aquatic ecosystems (Zhu *et al.* 2013; Ra *et al.* 2014; Xu *et al.* 2017). In addition, heavy metals in aquatic environments originate from both natural sources (weathering soil and rock, erosion, forest fires and volcanic eruptions) and anthropogenic activities (industrial effluents, domestic sewage, smelting, mining, fossil fuel burning and agricultural fertilizers) (Karbassi *et al.* 2008; Malik *et al.* 2010; Davutluoglu *et al.* 2011). The existence of heavy metals in sediments poses a threat to the aquatic ecosystem, and heavy metals are regarded as the main contamination in aquatic environment due to their toxicity, persistence, bioaccumulation by organisms, non-biodegradation, ecological risk and adverse effects on animals, plants and human life through the food chain (Zheng *et al.* 2013; Zahra *et al.* 2014; Wei *et al.* 2016; Kang *et al.* 2020). Therefore, a better understanding of nutrient characteristics and heavy metal contamination will facilitate ecological risk assessments and provide more theoretical guidance of mitigation or remediation.

Fenhe River, as the mother river of Shanxi Province, China, has been developed into a tourist attraction in the Taiyuan section. Consequently, the quantity of natural precipitation replenishment for Fenhe River is extremely small except for a recharge from an upstream reservoir and the current water source mainly receives industrial wastewater and domestic sewage, changing Fenhe River into a drainage river. The nutrients and heavy metals from these contamination sources accumulate in the sediments, which have polluted the river for a long time. In addition, the nutrient pollution and ecological risk of heavy metals in the Fenhe River is a current issue of concern. Previous studies have focused on the spatial distribution, transport and transformation of contaminations for large rivers, lakes and estuaries, however, there have been few studies focusing on the ecological risk of heavy metals in tributaries of large rivers (such as the Fenhe River) (Yi *et al.* 2011; Liu *et al.* 2016; Bi *et al.* 2017; Xu *et al.* 2017; Kang *et al.* 2020; Xu *et al.* 2020; EI-Magd *et al.* 2021; Yang *et al.* 2021). It is of great practical significance to study the characteristics of nutrients and their distribution, related to potential ecological risks of heavy metals in the Fenhe River, Taiyuan section, with the aim to control the nutrients and heavy metal contamination and maintain a healthy river ecosystem.

In the present study, we aimed to (1) determine the concentrations and spatial distribution of nutrients (total nitrogen (TN), total phosphorus (TP), total organic matter (TOM)) in the sediments of the Fenhe River, Taiyuan section and reveal the correlations between nutrients and the source of nutrients; (2) investigate current sedimentary heavy metal concentrations (As, Cu, Zn, Pb, Cr, Ni, Hg, Cd) and corresponding spatial distributions; (3) reveal the correlation between heavy metal elements and identify the possible sources of heavy metals in sediments using principal component analysis (PCA); (4) evaluate the contamination degree and potential ecological risks of heavy metals using I_{geo}, I_{in}, C_f, pollution load index (PLI) and risk index (RI).

2. MATERIALS AND METHODS

2.1. Study area and sampling site

Fenhe River, as the second largest tributary of the Yellow River and the largest river in Shanxi Province, has a total length of 716 km and a basin area of 39,721 km^2 approximately occupying one-quarter of the total area of Shanxi Province. The climate in the basin is warm temperate continental monsoon climate, with an average annual temperature of 6.2 °C to 12.8 °C, which is characterized by hot summers, cold winters, and higher spring temperatures than autumn temperatures. The average annual precipitation is 434–528 mm, 70% of which is concentrated in June to September. The Fenhe River flows through Taiyuan City, the capital of Shanxi Province, from the north to the south. The length of the Fenhe River in Taiyuan section is about 30 km. It has been the main important source of drinking water in Taiyuan City. However, Taiyuan City used to be the national essential energy and heavy-chemical industrial base, and has leading heavy industries such as coal, chemical, mechanical manufacturing, smelting, and thermal power industries. The Fenhe River, has the important role of receiving pollution water, and has been seriously contaminated due to the backward process, and aging equipment of these heavy-chemical industries and domestic sewage.

Based on a field investigation, sampling sites were selected in the mainstream of Taiyuan section of the Fenhe River. The bridges in Fenhe River were regarded as the sampling cross-section, 10 sampling sites were arranged from the south to the north of Taiyuan City, marked with FH1 to FH10. The designations FH1 to FH10 represented Wennanshe Bridge, Erba Bridge, Yingbin Bridge, Jinyang Bridge, Tongda Bridge, Xiangyun Bridge, Nanzhonghuan Bridge, Nanneihuan Bridge, Yingze Bridge, Yifen Bridge and Shengli Bridge, respectively. The geographical positions of sampling sites were as shown in Figure 1. Among these sampling sites, FH1 and FH2, located in the southern part, were surrounded by villages and farmland, FH3 to FH6, located in the middle part, were in the surrounding environment of commercial activities and resident life, furthermore, most wastewater flowed into this middle part, FH7 to FH10, located in the north part, were the aggregated region of main heavy chemical industries.

2.2. Sampling and chemical analysis

Samples of surface sediments (top 10 cm) were collected in October 2020 using the box grab sampler. Three samples were collected in each site and mixed thoroughly, then transferred into polyethylene bags with the names of sampling sites. The samples were transported to the laboratory at 4 °C in a special container and air dried at room temperature (20–22 °C). After the removal of stones and plant or garbage residues, dry samples were ground into powder and passed through a 120 mesh sieve (Zhong *et al.* 2007). Fine particles were obtained for the latter nutrient (TN, TP, TOM) and heavy metal (As, Cu, Zn, Pb, Cr, Ni, Hg, Cd) analysis. The TOM, TP and TN were determined by potassium dichromate volumetric method, molybdenum blue spectrophotometry and semimicro-Kjeldahl method in Chinese national standards. Here, 1.000 g sediment powder samples for each site were digested with a concentrated acid mixture of HNO_3-HF-$HClO_4$ (1:3:1) in a Teflon digestion vessel at 115 °C for 24 h. The blank and reference material (the national standard sediments of GSD-10) were also characterised as the sediment sample. The concentrations of As and Hg were determined by atomic fluorescence spectrometry (AFS, SA 20; Jitian Ltd, China), the concentrations of Cu, Zn, Cr, Pb, Ni, Cd were detected by inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7700x; Agilent Ltd, USA). The detection limits were $\leq$10 ng/L and the recoveries ranged between 92 and 108%.

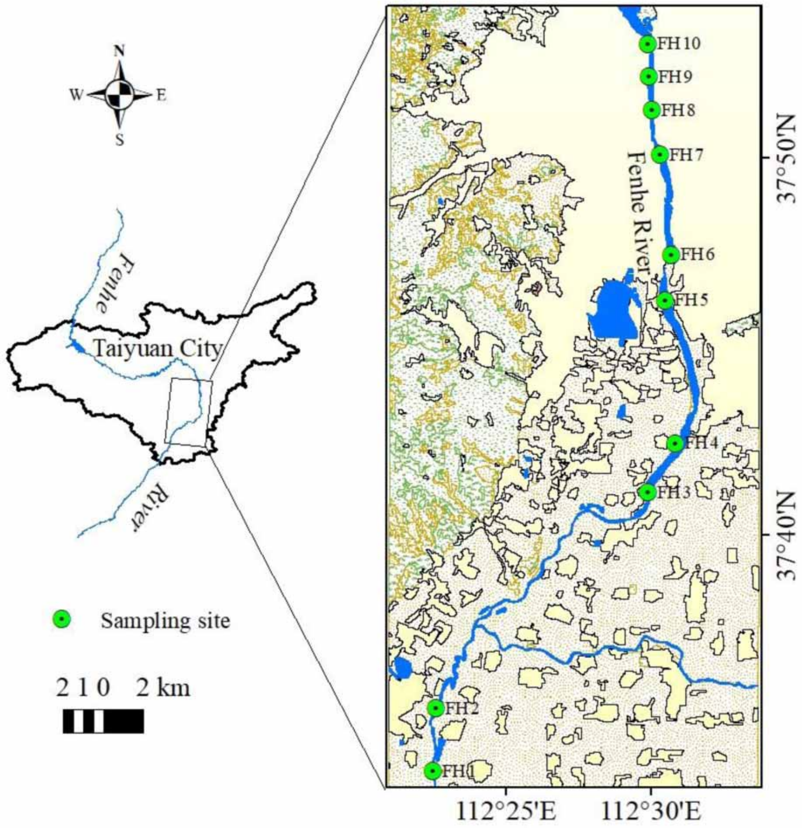


Figure 1 | Map of the sampling sites.

2.3. Statistic method

Standard descriptive statistics including mean, standard deviation (SD) and coefficient of variation (CV) were calculated to describe the different nutrients and heavy metal concentrations in the sediments using Microsoft Excel 2016 software. Pearon's correlation analysis was applied to reveal the relationships between nutrients and heavy metals in the sediments. PCA was performed to compress the multivariate data and extract a small number of latent factors from the eigenvalues and eigenvectors (Krzanowski 2000). Therefore, source identification of different heavy metals can be achieved with the method of PCA. Both Pearson's correlation analysis and the PCA model were conducted in SPSS.20 software.

2.4. Ecological risk assessment

2.4.1. Geoaccumulation index (I_{geo}) and Nemerow index (I_{in})

Geoaccumulation index was proposed by Müller in 1979. The relationship between the total content of heavy metals and corresponding geochemical background values was utilized to quantitatively evaluate the degree of heavy metal pollution in sediments (Müller 1969). The calculation formula is as follows:

$$I_{geo} = \log_2 [C_n/(k \times B_n)] \tag{1}$$

where C_n represents the measured concentration of heavy metal n in the sediment and B_n is the corresponding background value of heavy metal n. k is the factor due to the possible variation in the background which always equals 1.5.

The geoaccumulation index can be divided into seven categories according to different pollution levels, the classifications are shown in Table 1.

The geoaccumulation index only focuses on a single heavy metal's contamination level, in order to evaluate the contamination of all heavy metals in a study area, The Nemerow index was proposed by Nemerow and Sumitomo (Nemerow 1971) in

Table 1 | Geoaccumulation index (I_{geo}) to determine the contamination levels in sediments

I_{geo} class	I_{geo} value	Contamination level
0	$I_{geo} \leq 0$	Uncontaminated
1	$0 < I_{geo} < 1$	Uncontaminated/moderately contaminated
2	$1 < I_{geo} < 2$	Moderately contaminated
3	$2 < I_{geo} < 3$	Moderately/strongly contaminated
4	$3 < I_{geo} < 4$	Strongly contaminated
5	$4 < I_{geo} < 5$	Strongly/extremely contaminated
6	$5 < I_{geo}$	Extremely contaminated

the consideration of the maximum I_{geo} value and the arithmetic mean I_{geo} value for the sample, as follows:

$$I_{in} = \sqrt{(I^2_{geo\max} + I^2_{geoave})/2} \tag{2}$$

where I_{in}, I_{geomax} and I_{geoave} represent Nemerow index, the maximum value of I_{geo} and the arithmetic mean value of I_{geo} for the sample, respectively.

The classifications of Nemerow index are as listed in Table 2.

2.4.2. Contamination factor (C_f) and pollution load index (PLI)

Contamination factor (C_f) is the indicator for evaluating comprehensive heavy metal contamination, and it is the ratio of measured heavy metal concentration divided by the corresponding background value at the sampling site (Islam *et al.* 2015). The specific calculation formula is as follows:

$$C_{fi} = \frac{c_i}{c_0^i} \tag{3}$$

$$C_f = \sum_{i=1}^{n} C_{fi} \tag{4}$$

where C_{fi} is the contamination factor of the heavy metal i, c_i is the measured concentration of the heavy metal i and c_0^i is the geochemical background value of the heavy metal i, C_f is the degree of comprehensive heavy metal contamination.

The PLI based on the C_f^i values integrates all the determined metals and is calculated as the nth root of the product of n C_f^i, the formula as follows:

$$PLI = \sqrt[n]{C_{f1} \times C_{f2} \times C_{f3} \times \ldots . \times C_{fn}} \tag{5}$$

where n is the number of determined heavy metals.

Table 2 | Nemerow index class

I_{in} class	I_{in} value	Status
1	$I_{in} \leq 0.7$	Clean
2	$0.7 < I_{in} \leq 1$	Warning limit
3	$1 < I_{in} \leq 2$	Slight pollution
4	$2 < I_{in} \leq 3$	Moderate pollution
5	$I_{in} > 3$	Heavy pollution

Table 3 | Classification of C_{fi}, C_f and PLI

Class	C_{fi} value	C_f value	Level	PLI value	Level
1	$C_{fi} < 1$	$C_f < 8$	Low	$\text{PLI} \leq 1$	No pollution
2	$1 \leq C_{fi} < 3$	$8 \leq C_f < 16$	Moderate	$1 < \text{PLI} \leq 3$	Slight pollution
3	$3 \leq C_{fi} < 6$	$16 \leq C_f < 32$	Considerable	$3 < \text{PLI} \leq 6$	Moderate pollution
4	$C_{fi} \geq 6$	$C_f \geq 32$	Very high	$\text{PLI} > 6$	Heavy pollution

C_{fi}, C_f and PLI can be divided into four categories as shown in Table 3 (Hakanson 1980).

2.4.3. Potential ecological risk index (RI)

Potential ecological RI was proposed by Hakanson (1980). This method takes the measured concentrations of different heavy metals, their corresponding background values and biotoxicity coefficients as the evaluation indexes to comprehensively consider. It can not only reflect the influence of different single heavy metal pollutants in a specific environment, but also reflect the comprehensive influence of various heavy metal pollutants (Li *et al.* 2018; Liu *et al.* 2018a, 2018b; Wang *et al.* 2018; Yang *et al.* 2021). The calculation formula of RI is as follows:

$$E_r^i = T_i \times C_{fi} \tag{6}$$

$$RI = \sum_{i=1}^{n} E_r^i \tag{7}$$

where E_r^i, T_i and C_{fi} are the potential ecological risk factor, toxic response factor and contamination factor of the given heavy metal i. Potential ecological RI is the sum of various heavy metal E_r^i values. As studies suggested, T_i values for As, Cu, Zn, Pb, Cr, Ni, Hg and Cd were 10, 5, 1, 5, 2, 5, 40 and 30, respectively (Hakanson 1980; Li *et al.* 2018; Liu *et al.* 2018a, 2018b; Wang *et al.* 2018; Yang *et al.* 2021).

Based on the calculation results, potential ecological E_r^i and RI can be divided into five categories as listed in Table 4.

2.5. Environmental standard values

Background value (BV) is the composition and concentration of heavy metal elements which are not or less affected by human activities in the environment. BVs are the fundamental data for evaluating the ecological risk using different assessment methods. The use of environmental standards is the method which is different from and often complementary to geochemical background methods. Heavy metal concentration often indirectly indicates the degree of environmental pollution caused by heavy metals as different organisms have different demands or biotoxic effects for different heavy metals. This study used Chinese soil quality standards as a reference to determine whether heavy metals in sediments exceeded the standard value (Yuan *et al.* 2020). The BVs of heavy metals in Shanxi Province (Shi *et al.* 1994) and environment standards of soil quality are listed in Table 5.

Table 4 | Classification of E_r^i and RI

Class	E_r^i value	RI value	Level
1	$E_r^i < 40$	$RI < 150$	Low
2	$40 \leq E_r^i < 80$	$150 \leq RI < 300$	Moderate
3	$80 \leq E_r^i < 160$	$300 \leq RI < 600$	Considerable
4	$160 \leq E_r^i < 320$	$600 \leq RI < 1{,}200$	High
5	$E_r^i \geq 320$	$RI \geq 1{,}200$	Very high

Table 5 | The background value of heavy metal elements in Shanxi Province and Environment Quality Standard of Soil in China

Elements	Background value	Environment quantity standard of soil ($pH \leq 5.5$)
As	9.1	30
Cu	22.9	50
Zn	63.5	200
Pb	14.7	80
Cr	55.3	250
Ni	29.9	60
Hg	0.023	0.5
Cd	0.102	0.3

Table 6 | Descriptive statistics of nutrients in the sediment of Fenhe River ($n = 10$)

	Maximum	Minimum	Mean	Standard deviation	Coefficient of variation
TN	3.37	0.55	1.65	0.80	48.39%
TP	0.90	0.53	0.70	0.14	19.46%
TOM	76.08	12.23	41.57	20.20	48.60%
C/N	19.94	7.95	14.77	3.32	22.47%

3. RESULTS AND DISCUSSION

3.1. Spatial distribution characteristics and sources of nutrients

Table 6 summarizes the descriptive statistics of nutrients in the sediment of the Fenhe River. The TN concentrations varied from 0.55 g/kg to 3.37 g/kg, with the average concentrations of 1.65 g/kg, while the TP concentrations changed from 0.53 to 0.90 g/kg in a narrow range with the mean value 0.70 g/kg and the TOM concentrations ranged from 12.23 to 76.08 g/kg with the mean value 41.57 g/kg.

As Figure 2 demonstrated, the concentrations of TN, TP and TOM in FH6 were the highest of the 10 sampling sites. The TN and TOM concentrations showed the similar trends of rising first and then falling from north to south in spatial distribution, corresponding to the distribution of industrial and municipal wastewater mainly in the north and middle part. As opposed to the concentrations of TN and TOM, TP concentration in the south part was of relatively high values among all the concentrations, suggesting the industrial and domestic wastewater with high TP value discharge into the river in the south part.

As Table 7 indicated, TOM was significantly and positively correlated with TN, however, TP was less significantly correlated with TN and TOM, which demonstrated that TOM had similar sources with TN, yet TP had the different sources from TN and TOM. In addition, C/N of 10 sediment samples ranged from 7.95 to 19.94 with the average value of 14.77 (the calculation equation of $C/N = \text{organic carbon}/TN$, the calculation equation of $\text{organic carbon} = TOM/1.724$) (Zhang & Yu 2012). The C/N value in the sediment reflected the source of nutrients to some extent. C/N of different flora and fauna were 14–23 for embryophyte, 2.8–3.4 for aquatic life, 6–13 for zooplankton and phytoplankton and 5–14 for algae (Wang *et al.* 2004). Compared with these different C/N, 40% of sample C/N was in the range 7–14, and 60% varied from 14 to 23. Therefore, the sources of nutrients in the sediment were mainly from embryophyte, meanwhile zooplankton and phytoplankton or algae also took up a large part of the nutrient source.

3.2. Pollution characteristics of heavy metals in the sediment of Fenhe River

As shown in the Figure 3, the order of the average concentrations of these heavy metals was Zn ($137.51\ mg\cdot kg^{-1}$) > Cr ($91.04\ mg\cdot kg^{-1}$) > Ni ($33.71\ mg\cdot kg^{-1}$) > Cu ($31.63\ mg\cdot kg^{-1}$) > Pb ($27.68\ mg\cdot kg^{-1}$) > As ($7.64\ mg\cdot kg^{-1}$) > Cd ($0.07\ mg\cdot kg^{-1}$) > Hg ($0.12\ mg\cdot kg^{-1}$) in this study area and the concentrations of these heavy metals in sediments of the Fenhe River were in the range $5.76–10.1\ mg\cdot kg^{-1}$ (As), $16.9–56.8\ mg\cdot kg^{-1}$ (Cu), $72.3–233.6\ mg\cdot kg^{-1}$ (Zn), $20.3–39.6\ mg\cdot kg^{-1}$ (Pb), $50–177.7\ mg\cdot kg^{-1}$ (Cr), $20.7–49.6\ mg\cdot kg^{-1}$ (Ni), $0.053–0.101\ mg\cdot kg^{-1}$ (Hg), and $0.039–0.296\ mg\cdot kg^{-1}$ (Cd). The degree of variation

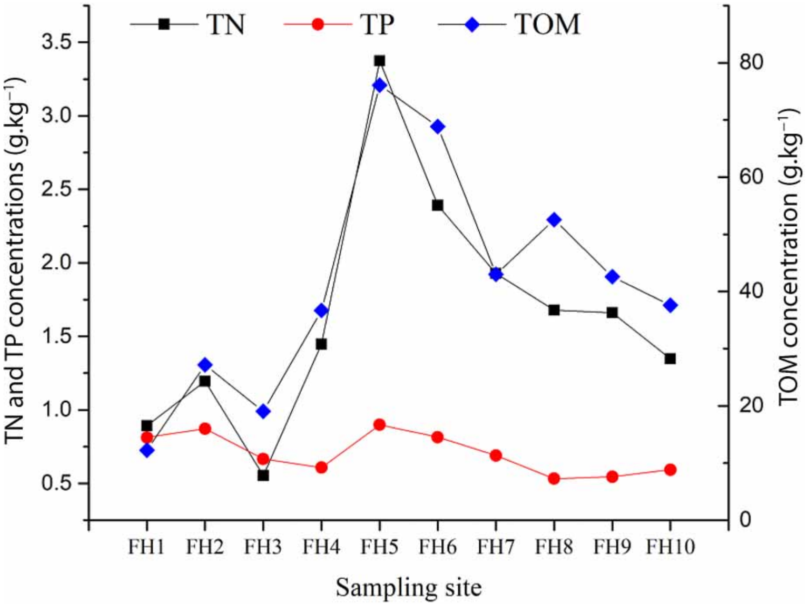


Figure 2 | The variety of nutrients concentrations in different sampling sites.

for the same heavy metal was different between different sampling sites, Cd varied greatly across the river, followed by the CVs of Cu, Cr, Zn, Hg and Pb, As had the smallest range of variation. The varied concentrations of heavy metals in the sediments suggested that the source may be different and were significantly affected by human activities (Lu *et al.* 2005). Only the average concentration of As was lower than its BV. The mean concentrations of other heavy metals (Cu, Zn, Pb, Cr, Ni, Hg and Cd) were approximately 38.12%, 116.55%, 88.30%, 64.63%, 12.74%, 206.52% and 15.20% higher than their BVs, respectively. Contrasting with the Environment Quality Standard of Soil in China ($pH \leq 5.5$, GB15618–2018), the average of all selected heavy metals was lower than the corresponding standard values of soil quality. The largest accumulated heavy metals were Hg, Zn, Pb and Cr. As investigated, most industrial effluent containing high concentrations of various heavy metals discharged wastewater into the Fenhe River, changing the nutrients, structure and function of the food chains in the aquatic ecosystems (Rinklebe *et al.* 2019).

Table 7 | Pearson's correlation coefficients of heavy metal and nutrients in the sediments of Fenhe River, Taiyuan section

	As	Cu	Zn	Pb	Cr	Ni	Hg	Cd	TN	TP	TOM
As	1										
Cu	0.889**	1									
Zn	0.692*	0.633*	1								
Pb	0.544	0.412	0.775**	1							
Cr	−0.175	−0.364	−0.286	−0.069	1						
Ni	0.052	−0.177	−0.18	0.214	0.507	1					
Hg	0.357	0.204	0.506	0.27	−0.181	0.113	1				
Cd	−0.356	−0.18	−0.305	−0.629	−0.408	−0.497	−0.334	1			
TN	0.793**	0.629	0.701*	0.606	−0.031	0.351	0.69*	−0.541	1		
TP	0.048	0.073	0.438	−0.009	−0.329	−0.408	0.761*	0.099	0.353	1	
TOM	0.765*	0.553	0.523	0.562	0.059	0.518	0.612	−0.526	0.939**	0.157	1

*Correlation is significant at the 0.05 level (two-tailed).

**Correlation is significant at the 0.01 level (two-tailed).

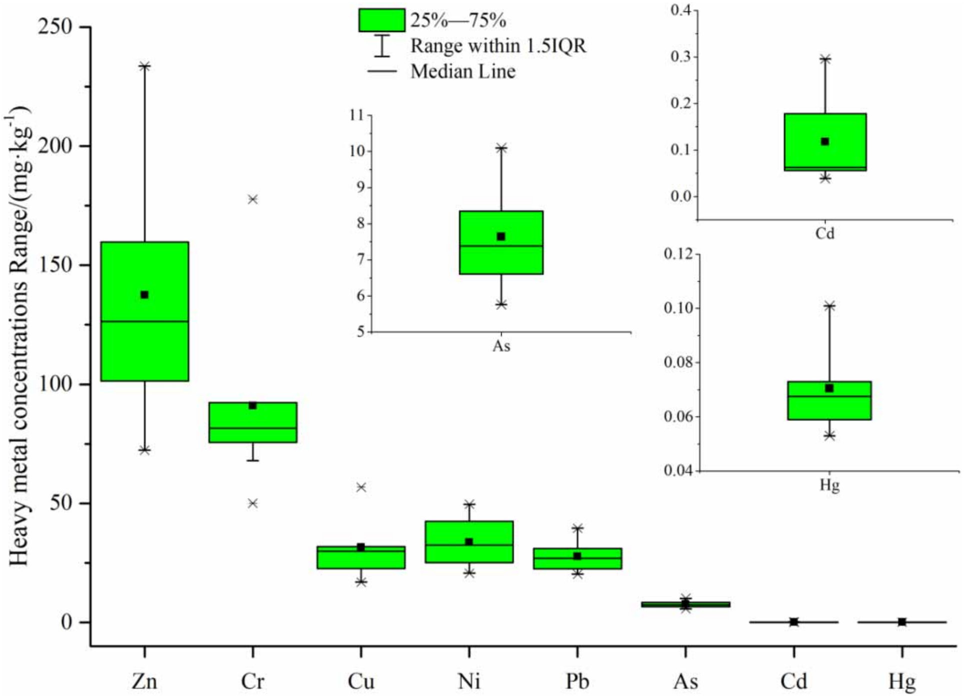


Figure 3 | Box-and-whisker plots for concentrations of heavy metals in the Fenhe River.

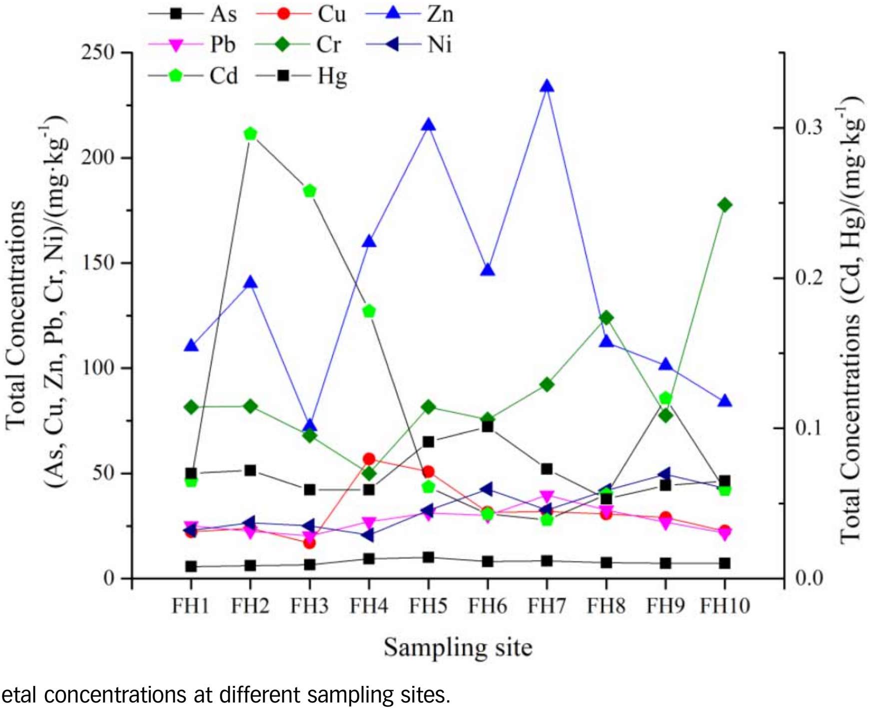


Figure 4 | The heavy metal concentrations at different sampling sites.

The spatial distribution of As, Cu, Zn, Pb and Hg in the riverways showed similar characteristics with the high concentrations observed in the midstream and low concentrations upstream and downstream, as Figure 4 shows, where the peak values of As, Cu, Zn, Pb and Hg appeared at FH6, FH4, FH8, FH9 and FH7 sampling sites with the maximum values of 10.1, 56.8, 233.6, 39.6 and 0.10 mg·kg^{-1}, respectively. Nevertheless, the concentrations of Cr, Ni and Cd had different spatial distributions from the other heavy metals. The similar distribution characteristics of Ni and Cd were with high concentrations

Table 8 | Comparison of heavy metal concentrations in sediments between this study and other selected rivers around world from references

Location	As	Cu	Zn	Pb	Cr	Ni	Hg	Cd	Reference
Fenhe River (China)	7.64	31.63	137.51	27.68	91.04	33.71	0.07	0.12	This study
Río Espíritu Santo estuary (USA)	–	122.00	76.33	12.33	48.00	21.33	–	0.18	Williams & Block (2015)
Laura River estuary (Brazil)	–	13.03	–	–	56.50	19.80	–	3.73	Lima *et al.* (2017)
Kelantan River (Malaysia)	–	21.66	57.78	52.01	59.32	24.62	–	0.07	Wang *et al.* (2017)
Han River (Korea)	–	25.90	150.40	31.60	60.50	26.10	–	0.21	Lai *et al.* (2013)
Salt-water River (Taiwan, China)	–	1,001.00	1,220.00	128.00	131.00	103.00	–	1.40	Lin *et al.* (2011)
Yangtze River Anqing section (China)	13.75	43.94	93.14	57.60	69.28	–	0.06	0.17	Liu *et al.* (2018a, 2018b)
Yellow River estuary (China)	10.98	34.35	74.30	23.29	83.45	31.59	–	83.45	Rao *et al.* (2018)
Xiashan Stream (China)	12.68	261.88	332.83	93.62	112.76	46.52	1.05	2.00	Li *et al.* (2020)
Heer River (China)	14.71	1,774.00	930.00	48.54	1,393.00	793.00	–	1.68	Zhu *et al.* (2018)

in the upstream then gradually decreased throughout the river flow downward. High concentrations of Cr were detected in downstream and low concentrations in upstream areas.

In order to understand the heavy metal pollution of the Fenhe River from a large spatial scale, results of selected heavy metal concentrations in previous studies conducted in domestic and foreign rivers are listed in Table 8. Compared with domestic rivers, the concentrations of As, Cd, Cu in the Fenhe River were the lowest, and the values of Ni, Pb concentrations were approximately equivalent to the corresponding values in the Yellow River estuary, lower than other domestic rivers. In addition, the concentrations (Zn, Cr) in the Fenhe River were only higher than the Yangtze River Anqing section and the Yellow River estuary and lower than other rivers. Hg pollution in the Fenhe River was not as significant as other rivers due to the value far below the Xiashan Stream. As for the comparison with foreign rivers, the highest values for Cr and Ni existed in the Fenhe River than other foreign rivers. The concentrations of Cu, Zn ranked second among these rivers. In addition, the pollution from Pb and Cd were at the moderate level. In general, the heavy metal contamination in the Fenhe River was in the moderate pollution range among these rivers, signifying that effective performance due to environmental protection measures had been implemented in the Fenhe River, Taiyuan section.

The correlations between these heavy metals and nutrients were analyzed using Pearson's correlation coefficients (Yi *et al.* 2011). The results are depicted in Table 7. The correlation matrix showed that Cd was negatively correlated with other metals. As, Cu, Zn were significantly and positively correlated with one another, the same significant correlation was found for Zn and Pb, indicating that both heavy metal groups may originate from a homologous source. Analyzing the correlations between heavy metals and nutrients, significant and positive correlation existed for As, Zn, Hg and TN, Hg and TP, As and TOM, indicating that nutrients may have a certain effect on the distribution of partial heavy metals such as As and Hg in sediments.

3.3. Source identification of heavy metals in the sediments of Fenhe River

PCA is an effective way to trace back the source of metals (Yongming *et al.* 2016; Xiao *et al.* 2019). Previous studies have identified that the sediment trace metals are derived either by anthropogenic pollution or natural geogenic sources. The sources of mentioned heavy metals in the sediments of the Fenhe River were identified with the assistance of a PCA model, as shown in Figure 5. The heavy metals can be grouped into two principal components (PC1 and PC2), cumulatively accounting for 69.86% of the total variance in the sediments: (1) PC1 was featured by the high loading of As, Cu, Zn, Pb and moderate loading of Hg, explaining 43.7% of the total variance. (2) PC2 was featured by the high loadings of Cr, Ni and moderate negative loading of Cd, explaining 26.2% of the total variance. Combined with the spatial distribution of different heavy metals and comparison with corresponding heavy metal's BVs, a better understanding of the sources from both PCs can be revealed. The high loadings of As, Cu, Zn, Pb indicated the dominance of weathering products from the land (Xu *et al.* 2016). In this study, the concentrations of As with moderate coefficient of variation and concentrations below background value supported the natural sources for As. In addition, the higher concentrations of Zn, Cu, Pb and Hg compared with the background values in some sampling sites demonstrated that anthropogenic sources had the influence in the surrounding environment, such as coal mining, smelting, chemical companies, wastewater, and transportation sources. Thus, PC1

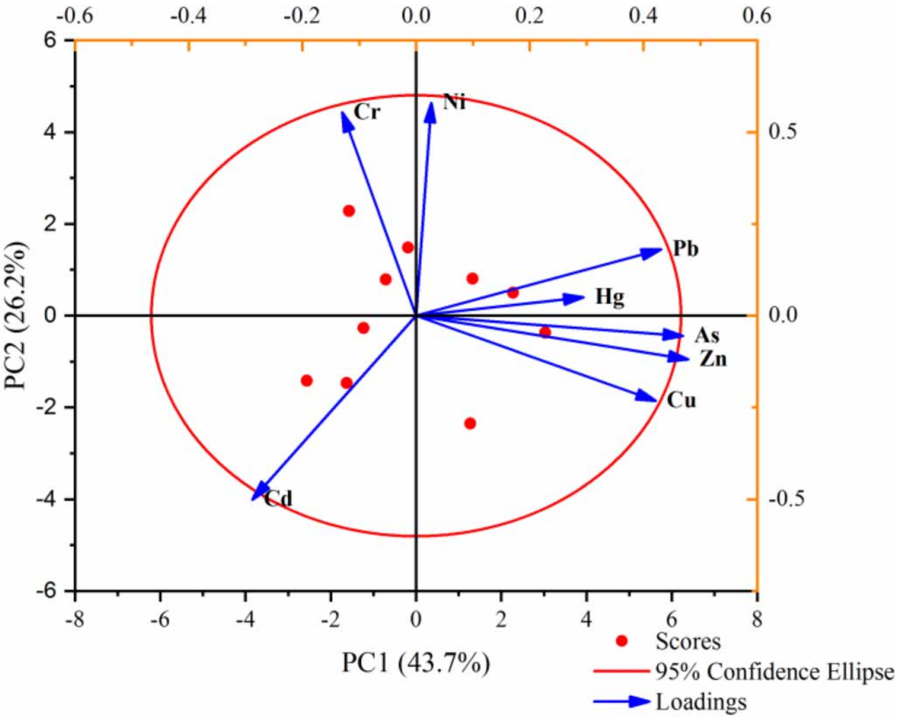


Figure 5 | Biplot of principal component analysis for heavy metals in sediments of the Fenhe River.

mainly came from the weathering and human activities' pollution in industry and daily life. Regarding PC2, the high values of Cr and Ni were mainly distributed in the north part with numerous industrial enterprises, consequently indicating that the sources of Cr, Ni were industrial wastewater. Prior studies have suggested that the distributions of Cd were closely related to the use of phosphate fertilizers in agriculture activities (Liu *et al.* 2016; Zhang *et al.* 2019; Tian *et al.* 2020), corresponding to the fact that peak values of Cd in the south part were mainly engaged in agricultural activities. As the results, PC2 was the source of industry wastewater and fertilization.

3.4. Risk assessment using geoaccumulation index and Nemerow index

The geoaccumulation index (I_{geo}) method was used to evaluate the contamination degree of heavy metals in the sediments of the Fenhe River, and the results are shown in Table 9. According to Table 1, the I_{geo} values revealed that the heavy metal

Table 9 | The calculated I_{geo} values and I_{in} values for different sampling sites in Fenhe River

	I_{geo} values										
Site	**As**	**Cu**	**Zn**	**Pb**	**Cr**	**Ni**	**Hg**	**Cd**	$I_{geo\ max}$	$I_{geo\ Ave}$	I_{in}
FH1	−1.24	−0.63	0.21	0.19	−0.02	−0.97	1.02	−1.24	1.02	−0.34	0.54
FH2	−1.15	−0.52	0.56	0.03	−0.02	−0.76	1.06	0.95	1.06	0.02	0.53
FH3	−1.05	−1.02	−0.40	−0.12	−0.29	−0.84	0.77	0.75	0.77	−0.27	0.41
FH4	−0.55	0.73	0.75	0.29	−0.73	−1.12	0.77	0.22	0.77	0.05	0.39
FH5	−0.43	0.56	1.18	0.50	−0.02	−0.47	1.40	−1.33	1.40	0.17	0.71
FH6	−0.75	−0.12	0.62	0.45	−0.13	−0.08	1.55	−1.83	1.55	−0.04	0.78
FH7	−0.71	−0.11	1.29	0.84	0.15	−0.46	1.08	−1.97	1.29	0.02	0.65
FH8	−0.86	−0.16	0.24	0.56	0.58	−0.10	0.62	−1.45	0.62	−0.07	0.31
FH9	−0.92	−0.24	0.09	0.28	−0.10	0.15	0.85	−0.35	0.85	−0.03	0.43
FH10	−0.91	−0.60	−0.18	−0.02	1.10	−0.06	0.91	−1.37	1.10	−0.14	0.55

pollution caused no effects or low impacts on sediments among the upstream and downstream areas. All the I_{geo} values for As were lower than 0, which demonstrated that the ecosystem was not contaminated by As pollution. In contrast, Hg pollution was mainly observed in which the average of Hg pollution ranged from slightly contaminated in the northern part to moderately contaminated in the middle and southern regions. Zn and Pb pollution were in the level of slight contamination, except individual sampling sites (FH3 and FH11) with no contamination. Cu and Cd caused slight contamination in the middle part and southern part, respectively, and Cr, Ni pollution led to slight contamination in the southern region. Considering all the heavy metals' effects, the Nemerow index (I_{in}) was calculated to reveal the contamination level among different sampling sites (Table 9). The results of I_{in} indicated that the contamination level was in the clean status in most regions except the warning limit status of contamination level for the middle region.

3.5. Risk assessment using contamination factor and pollution load index

In order to evaluate the contamination level of each heavy meal of the sediments in the Fenhe River, the C_{fi}, C_f and PLI values were calculated as shown in Table 10. The contamination level of As was the lowest among these heavy metals due to C_{fi} values of As below 1 at most sampling sites. The contamination with Cu, Ni, Cd, Pb, Cr was regarded as in the moderate level in most regions such as Cu, Ni mainly in the northern and middle parts and Cd collected in the south part. The pollution from Zn and Hg was placed in the considerable contamination level and very high contamination with Zn and Hg was confirmed in the middle part and in the middle and southern part, respectively. C_f values, aimed to evaluate the comprehensive heavy metal contamination level, indicated that the sediments were in the moderate contamination level (Table 10). As for PLI values observed in Table 10, the progressive deterioration of the sediment quality existed in all the sediments and the middle part was confronted with higher ecological risk.

3.6. Risk assessment using potential ecological RI

The potential ecological RI is the approach that considers ecological and environmental effects except the toxicology of heavy metals. The level of potential hazard directly was calculated using quantitative index and the aim of this index was to quantify the comprehensive effects of multiple heavy metals in the sediments (Fan *et al.* 2010; Chabukdhara & Nema 2012; Wang *et al.* 2013). The results of E_r^i and RI are listed in Table 11.

As shown in Table 11, E_r^i values demonstrated that the contamination levels of As, Cu, Zn, Pb, Cr, Ni were in the low-risk status in the Fenhe River. Cd had a wide variety of E_r^i values in the Fenhe River, the risk was in low status category in most study areas except the considerable risk posed at FH2 and moderate risk in FH3 and FH4. Hg was of considerable risk status in all Fenhe River areas as all E_r^i values were higher than 80 and lower than 160. According to the RI, the ecological risk was considerable for most sampling sites with the exception of moderate risk at the FH9 sampling site, in which Hg contributed most (63.7%) to the RI values. Areas with higher potential ecological risk were mainly distributed in the South-central

Table 10 | Contamination factor for each heavy metal and pollution load index for sediment heavy metals in the Fenhe River

	C_f^i									
Site	**As**	**Cu**	**Zn**	**Pb**	**Cr**	**Ni**	**Hg**	**Cd**	**C_f**	**PLI**
FH1	0.63	0.97	1.74	1.71	1.48	0.77	3.04	0.64	10.97	1.19
FH2	0.67	1.04	2.21	1.53	1.48	0.89	3.13	2.90	13.86	1.52
FH3	0.73	0.74	1.14	1.38	1.23	0.84	2.57	2.53	11.15	1.24
FH4	1.03	2.48	2.51	1.84	0.90	0.69	2.57	1.75	13.77	1.55
FH5	1.11	2.22	3.39	2.12	1.48	1.08	3.96	0.60	15.95	1.69
FH6	0.89	1.38	2.30	2.05	1.37	1.42	4.39	0.42	14.22	1.46
FH7	0.92	1.39	3.68	2.69	1.67	1.09	3.17	0.38	15.00	1.52
FH8	0.83	1.34	1.77	2.22	2.24	1.40	2.30	0.55	12.65	1.43
FH9	0.79	1.27	1.60	1.82	1.40	1.66	2.70	1.18	12.41	1.47
FH10	0.80	0.99	1.32	1.48	3.21	1.43	2.83	0.58	12.63	1.36

Table 11 | The factors of potential ecological risk for each heavy metal (E_r^i) and potential ecological RI in sediments of the Fenhe River

	E_r^i								
Sites	**As**	**Cu**	**Zn**	**Pb**	**Cr**	**Ni**	**Hg**	**Cd**	**RI**
FH1	6.33	4.85	1.74	8.54	2.95	3.83	121.74	19.12	169.09
FH2	6.74	5.22	2.21	7.65	2.97	4.43	125.22	87.06	241.49
FH3	7.26	3.69	1.14	6.90	2.46	4.20	102.61	75.88	204.14
FH4	10.26	12.40	2.51	9.18	1.81	3.46	102.61	52.35	194.60
FH5	11.10	11.09	3.39	10.58	2.95	5.42	158.26	17.94	220.73
FH6	8.93	6.88	2.30	10.24	2.73	7.11	175.65	12.65	226.50
FH7	9.18	6.97	3.68	13.47	3.34	5.45	126.96	11.47	180.51
FH8	8.26	6.70	1.77	11.09	4.49	7.01	92.17	16.47	147.96
FH9	7.90	6.33	1.60	9.12	2.80	8.29	107.83	35.29	179.16
FH10	7.96	4.93	1.32	7.38	6.43	7.17	113.04	17.35	165.59

Taiyuan region. Thus, more attention should be paid to these areas and necessary measures or strategies should be implemented to decrease the ecological and environmental effects of Hg pollution.

3.7. Comparison between different ecological risk assessments

There was a certain consistency between the evaluation results obtained by different ecological risk assessment methods in this study. From the single heavy metal contamination perspective, the order of heavy metal contamination level related to BVs and C_{fi} values was Hg > Zn > Pb > Cr > Cu > Cd > Ni > As. Due to the BVs' influence or elimination of extreme variations' effects for I_{geo} and the consideration of toxicological effects for E_f^i, the orders were different, which were Hg > Zn > Pb > Cr > Cu > Ni > Cd > As and Hg > Cu > Cd > Pb > As > Ni > Cr > Zn, respectively. All the evaluation results showed that Hg was the main pollutant in the sediments of the Fenhe River, however, As pollution had basically no effect on the surrounding environment. From the spatial distribution of a heavy metal perspective, the comprehensive contamination levels of heavy metals obtained from I_{in}, C_f, PLI and RI values demonstrated the main ecological risk mainly concentrated in the middle part and northern parts due to the accumulation of more industrial and municipal wastewater in these parts, leading to more heavy metals absorbed into the sediments.

The different evaluation results were due to the different emphasis of the evaluation methods, consequently generating the differences in the ranking of major heavy metal contamination in the same region. Overall, various methods can be applied to comprehensively evaluate the ecological risk status in the research of heavy metal contamination in sediments in order to acquire more accurate evaluation results for heavy metal contamination from different aspects.

4. CONCLUSION

The present study first investigated the nutrient concentrations (TN, TP, TOM) and their spatial distributions. The concentrations of TN, TP, TOM were found to be over a various range and the distribution of these nutrients showed a similar trend, which were high concentrations in the middle then lower concentrations in the northern and southern parts. In addition, a significant and positive correlation existed between TOM and TN but TP was less significantly correlated with TN and TOM. The sources of nutrients in the sediments were mainly from embryophyte, zooplankton and phytoplankton or algae according to C/N values. The concentrations of heavy metals showed large spatial variability with higher concentrations in the middle part for As, Cu, Zn, Pb Hg, in the upstream part for Cd, Ni and higher concentrations in the downstream part for Cr, respectively. The source identification suggested that As, Zn, Cu, Pb and Hg were mainly the product of natural weathering and anthropogenic activities while Cr, Ni mainly originated from industrial activities and Cd was closely related to agricultural fertilizers. Different ecological risk assessments indicated that the main contamination in sediments was from Hg pollution, whereas As was regarded as the least polluting contamination associated with lower concentrations. The indexes such as I_{in}, C_f, PLI and RI values suggested that the higher ecological risks mainly existed in the middle part.

In conclusion, the results obtained in this study could be helpful for local governments in the monitoring and treatment of aquatic environment in the Fenhe River, Taiyuan section. What is more, the dynamic monitoring of nutrients and heavy metals in sediments including factors such as seasonal changes should be implemented in the future, in order to aid more effective local management.

AUTHOR CONTRIBUTION

Haotian Ma: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Visualization and Writing – Original draft. **Zhilei Zhen:** Writing – Review & Editing, Supervision and Funding acquisition. **Meixia Mi:** Writing – Review & Editing and Supervision. **Qian Wang:** Data collection and Data curation.

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Not applicable.

CONSENT TO PARTICIPATE

Not applicable.

CONSENT TO PUBLISH

All authors have read and approved publications of the final manuscript.

CONFLICT OF INTEREST

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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