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ORIGINAL RESEARCH PAPER

Pollution and environmental risk assessment of potentially toxic elements in surface sediments of Zayandeh-Rood River, Isfahan Province, Iran

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ABSTRACT

The Zayandeh-Rood River (Isfahan Province, Iran) is of vital importance as a water source for various purposes, but it is facing adverse effects from human activities. This study focused on the surface sediment of 21 stations along the river to assess the concentration of potentially toxic elements (PTEs) and their environmental risk using the Geoaccumulation Index (Igeo), Enrichment Factor (EF), Pollution Load Index (PLI), and Potential Ecological Risk Index (RI). The mean concentration of the PTEs (mg/kg) was ranked as follows: Cd (0.34)< As (9.73)< Pb (10.95)< Co (11.91)< Cu (31.14)< Ni (31.90)< Zn (61.33)< Cr (96.95)< V (125.09)< Mn (707.76). Positive correlation coefficients were found among all the PTEs, while their relationships with the sediment physicochemical characteristics varied considerably, indicating that various interacting factors might influence the deposition and mobility of PTEs in the river. The river was classified as having moderate to low contamination (Igeo index) and minimal-to-moderate enrichment (EF index) except for Cd and As which exhibited extremely high enrichment and strong pollution in the upstream zone, where agricultural activities dominate. Therefore, managing agricultural practices and reducing the excessive use of PTE-containing pesticides and insecticides should be a primary focus to protect the Zayandeh-Rood River from further contamination.

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1. Background

Rivers play a vital role as one of the most essential sources of drinking water for human societies, shaping the course of human civilization throughout history (Zhao et al., 2022). Their lengthy structure and continuous water flow ensure convenient and constant access to fresh water for a diverse range of human activities (Roviello et al., 2022). However, the rapid population growth in recent decades and the neglect of rivers' carrying capacity in development have placed these ecosystems at significant risk (Li et al., 2020). One of the most notable consequences of human pressure on rivers is water pollution, particularly with potentially toxic elements (PTEs) (also known as heavy metals) which adversely affected various organisms, including humans (Proshad et al., 2021). The contamination of many Asian rivers with PTEs began during the early 20th century due mostly to the expansion of industrial and agricultural activities (Putri et al., 2023; Zheng et al., 2021, Zhu et al., 2021). This alarming trend demands the urgent adoption of management approaches to monitor, preserve, and improve the health of river ecosystems (Ravan Nakhjavni and Fataei, 2015(Li et al., 2020, Xiao et al., 2021).

PTEs comprise a group of metallic elements with a density and atomic weight exceeding 5 grams per cubic centimeter (Shrestha et al., 2021). Although these elements occur naturally in the Earth's crust, they can accumulate in the environment through natural processes and human activities, such as industrial emissions, mining, and agricultural practices (Yang et al., 2020). While certain elements, like iron (Fe), zinc (Zn), and copper (Cu), serve crucial roles in essential biological processes within organisms' bodies, others lack any biological significance and can pose toxicity and hazards to living beings even at low concentrations. Lead (Pb), cadmium (Cd), and arsenic (As) stand out as some of the most significant elements in this category (Khatun et al., 2022). The consequences of exposure to these PTEs encompass a range of health issues, including neurological disorders like Parkinson's and Alzheimer's, kidney damage, cardiovascular complications, gastrointestinal problems, and carcinogenicity (Engwa et al., 2019, Haidar et al., 2023, Sahoo and Sharma, 2023).

The pollution of rivers with PTEs in dry and semi-arid regions, such as central areas of Iran, highlights immediate monitoring and assessment due to their vital role in supplying water for a significant portion of human activities (Shahradnia et al., 2022). In recent years, the rapid growth in Iran's population and the escalating demand for freshwater have put increased pressure on rivers, making them crucial for meeting water needs (Madani et al., 2016). However, human activities, particularly agriculture and industry near these rivers, have made them dumping grounds (sinks) for wastewater and runoff, resulting in severe pollution with PTEs. Rivers like Haraz (Nasrabadi et al., 2010), Gorganrood (Bagheri et al., 2011), Karun (Diagomanolin et al., 2004), and Chitgar (Sayadi et al., 2010) serve as examples of such pollution, where high concentrations of PTEs such as nickel (Ni), Pb, and Cd were detected.

Among the Iranian rivers, the Zayandeh-Rood River in Isfahan province is heavily impacted by human activities. The presence of large metal industries, extensive agricultural lands, and the discharge of wastewater from various cities, especially Isfahan (the third most populous city in Iran) pose a significant risk of contaminating the Zayandeh-Rood River with various PTEs (Karimian et al., 2020) Shahmorad Moghanlou and Fataei, 2015; Gazijahani et al., 2017; Hosseinzadeh et al., 2013; Sadeghi et al., 2022). Currently, researchers employ international standards, including permissible metal presence limits and pollution indices, to assess the severity of PTE pollution in various ecosystems such as river sediments (Shahradnia et al., 2022). These tools offer invaluable insights, enabling researchers to obtain a comprehensive understanding of the ecosystem's health status and its changes over time while facilitating meaningful comparisons with other ecosystems (Heidarogli et al.,2023; Jalalzadeh et al.,2022; Sadeghi et al., 2022; Talaei et al., 2022). Furthermore, these approaches are instrumental in identifying the sources of pollutants and understanding their relative impacts on causing pollution. This research delved into sediment pollution within the Zayandeh-Rood River, an immensely consequential waterway in Iran that has suffered considerable degradation due to a range of human activities. While prior investigations have examined the presence of potentially toxic elements in specific sections of the Zayandeh-Rood River, this study distinguishes itself by encompassing the entire stretch of the river from its source to its mouth. By considering a comprehensive array of elements, this study offers a holistic portrayal of the state of this invaluable ecosystem situated in the heart of Iran's central plateau.

2. Materials and Methods

Study area

Zayandeh-Rood River is located in the central region of Iran (Isfahan province) and is a crucial and significant source of freshwater. Spanning approximately 400 kilometers from west to east, this river plays a vital role in providing water for irrigation, drinking, and industrial purposes in the province (Dehkordi et al., 2021). During the release of water in the river, its average flow rate ranges from 30 to 40 cubic m/ sec. The river's width varies from 10 to 20 m in the upstream areas, expanding to a maximum of 800 m in its widest section, particularly within the city of Isfahan (Tashakkor et al., 2020). The construction of a dam on the Zayandeh-Rood River in 1970 facilitated managed water allocation to various sectors, leading to the growth of industries and the expansion of agricultural lands within the Zayandeh-Rood watershed (Asgarian et al., 2016).

Sediment collection, preparation and analysis

Considering the time and financial constraints of this study, sediment samples were collected in the summer of 2021, 3 months after the last rainfall from 21 stations, with three replicates at each station (totaling 63 samples),. Sampling stations were selected in areas surrounded by agricultural, industrial, and residential activities. The samples were carefully stored in polyethylene bags at a constant temperature of 20 °C until analysis. During the laboratory analyses, all materials used were kept in metal-free containers. Plastic and glass containers underwent a thorough soak in HNO3 (v:v, 1:3) for at least 24 h, followed by rinsing with deionized water (APHA, 2005). Additionally, during the testing process, blank samples were prepared alongside each group of samples, and the metal concentrations in these blank samples were measured and then subtracted from the values obtained for the actual samples. The recovery of results ranged from an impressive 96% to 100%.

Sediment samples were placed at room temperature (20°C) and then dried until a constant weight was achieved. To remove any excess moisture, soil samples were left at room temperature for 72 h. Subsequently, the samples were sieved through a 2 mm mesh to eliminate large particles and organic residues. For sample extraction, five ml of concentrated nitric acid (Merck) were added to one g of each sediment sample, and the resulting solution was heated on a heater at 95°C for 10 min. After a noticeable color change, the samples were allowed to cool. In two consecutive steps, five ml of concentrated nitric acid was added to the samples, and the resulting solution was heated at 95°C for 30 min. Then, two ml of distilled water and three ml of 30% hydrogen peroxide were added, and the contents were heated at 75°C for 5 min. Finally, 10 ml of concentrated hydrochloric acid was added, and the samples were passed through Whatman 42 filter paper. The resulting solutions were brought to a volume of 100 ml with distilled water. Ultimately, the concentration of PTEs was determined using an Inductively Coupled Plasma Mass Spectrometry (ICP-MS, Perkin 9000 DRCE) instrument. The amount of organic matter (OM) was determined using the method Walkley and Black (1934), and the sediment texture was classified as clay (<0.004 mm), silt (0.004 to 0.06 mm), and sand (0.06 to 2 mm). Additionally, ancillary data such as electrical conductivity (EC - dS m-1), total organic carbon (TOC %), and pH were measured to aid in interpreting the sedimentary availability of PTEs.

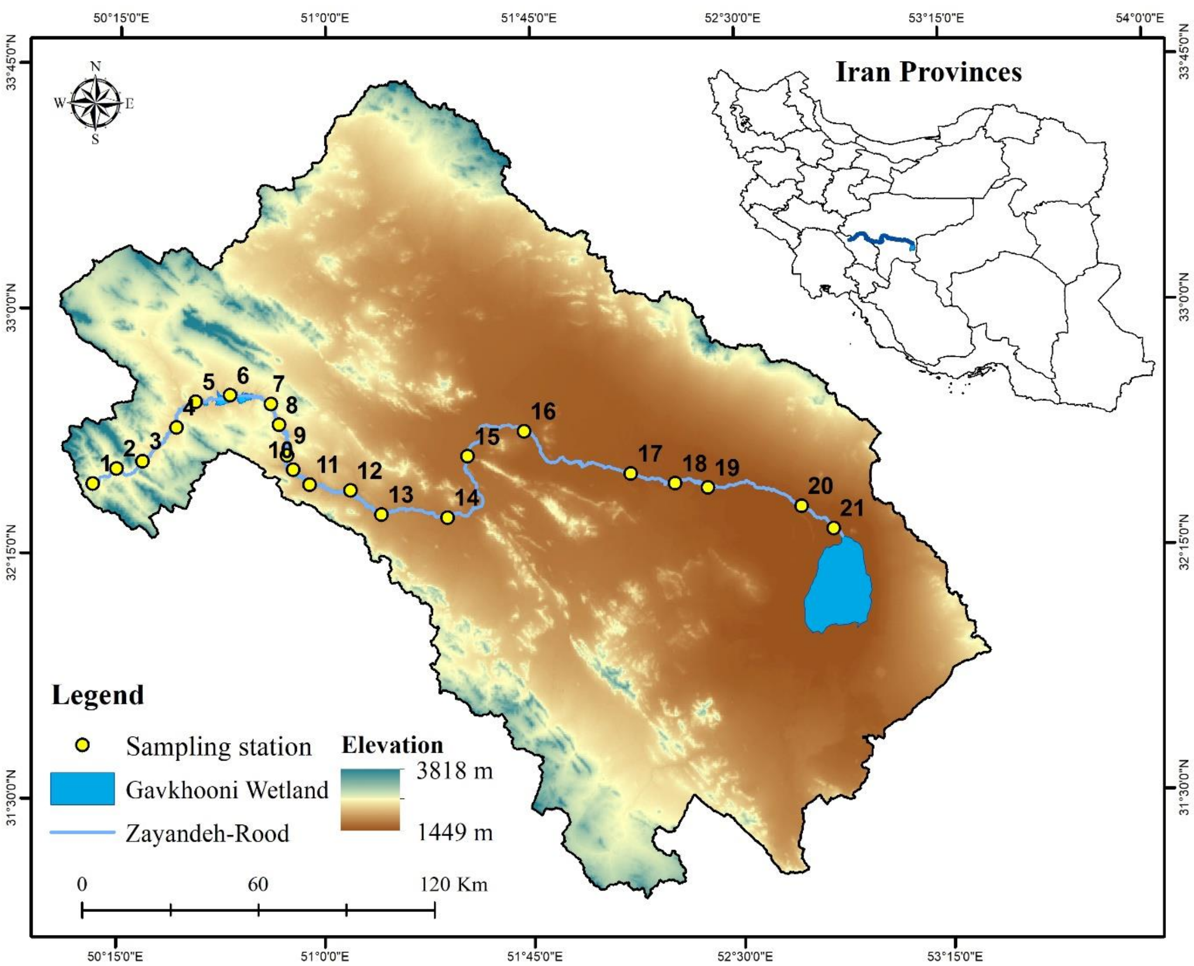

Fig 1. Distribution of sediment sampling points

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Measurement of pollution indices

To assess PTE pollution, we utilized the indices Geoaccumulation Index (Igeo), the Enrichment Factor (EF), the Pollution Load Index, and the Potential Ecological Risk Index (RI). Igeo is computed using Equation 1, where c_n represents the concentration of the element, and B_n denotes the geochemical background value of the PTE proposed by Muller (1979). The Igeo values are then divided into 5 or 7-grade levels, as per the classification suggested by Bowen (1979) from uncontaminated (Igeo < 0) to very strongly contaminated (Igeo > 5) (Table 1). EF is calculated using Equation 2, where C_M represents the total concentration of the PTE, and C_s represents the background level of the PTE, as proposed by Buat-Ménard (1979). EF values increase as the contribution of the PTE from anthropogenic sources rises from deficiency to minimal enrichment (EF < 2) to extremely high enrichment (EF > 40) (Table 1).

RI is determined by summing the result of dividing the concentration of each specific PTE (C_M) in the sample by that of the Earth's crust background value (C_s) multiplied by its corresponding toxic response factor (T_r^i) (Equation 3) (Hakanson, 1980). The T_r^i values were obtained from Ra et al. (2014), and based on the resulting values, the RI is classified into four risk classes ranging from low RI < 150) to high (RI > 600) potential ecological risk (Table 1). PLI is calculated using Equation 4 for a total of n PTEs and is classified into four classes from no pollution (PLI < 1) to extremely heavy pollution (PLI > 3) (Tomlinson et al., 1980). The mean crustal values were considered as follows: As = 1.8, Cd = 0.1, Cu = 55, Zn = 70, Ni = 20, Mn = 900, Cr = 100, Co = 10, Pb = 15, and V = 135 (mg/kg) (Kabata-Pendias, 2000) (Table 1).

Eq. 1 $$I_{geo} = \mathrm{Log}_2 \frac{c_n}{1.5B_n}$$

Eq. 2 $$EF = \left(\frac{C_M}{C_s}\right)_{Sample} \Big/ \left(\frac{C_M}{C_s}\right)_{Background}$$

Eq. 3 $$RI = \sum_{i=1}^{n} T_r^i \times (M_x^i / M_b^i)$$

Eq. 4 $$PLI = (P_1 * P_2 * \ldots * P_n)^{1/n}$$

Statistical analysis

To ensure the validity of the data, we conducted tests for normality and homogeneity of variance using the Shapiro-Wilk test and Levene's test, respectively. Based on the results, the data were found to be normally distributed and homogenous, allowing us to use Pearson correlation to explore the relationship between PTE concentrations and physicochemical parameters of the sediment. To assess any significant variations in PTE concentrations among different stations, we employed a one-way ANOVA followed by Duncan's post hoc test. Moreover, we conducted a one-sample t-test to investigate the significance of the relationship between the mean TPE concentrations and the corresponding standard values of sediment quality recommended by Canadian interim sediment quality guideline (ISQG) standards (CCME, 2001).

Table 1. Range and pollution/ enrichment status of Igeo, EF, PLI and RI values

Index range	Pollution status	Index range	Pollution status
Igeo < 0	Low	EF< 2	Minimal
0 < Igeo < 1	Low to moderate	2 < EF < 5	Moderate
1 < Igeo < 2	Moderate	5 < EF < 20	Significant
2 < Igeo < 3	Moderate to strong	20 < EF < 40	Very high
3 < Igeo < 4	Strong	EF> 40	Extremely high
4 < Igeo < 5	Strong to very strong	RI < 150	Low
Igeo > 5	Very strong	150 < RI < 300	Moderate
PLI < 1	Low	300 < RI < 600	Considerable
1 < PLI < 2	Moderate	RI > 600	Very high
2 < PLI < 3	Heavy		
PLI > 3	Extremely heavy		

3. Results

The mean concentration of PTEs in sediment samples was estimated using the ICP-MS method (Table 2). Cd exhibited the lowest mean concentration of 0.34 ± 0.31 mg/kg, while Mn showed the highest mean concentration of 707.76 ± 227.21 mg/kg. The trend of concentration change for the studied elements was as follows: Cd < As < Pb < Co < Cu < Ni < Zn < Cr < V < Mn. At S1, located upstream of the Zayandehrud River, the lowest concentrations of Cu (11 mg/kg), Zn (1 mg/kg), Mn (281 mg/kg), Cr (21 mg/kg), Co (4.5 mg/kg), Pb (3 mg/kg), and V (31 mg/kg) were observed. As for the highest concentrations of PTEs, S5 exhibited the highest levels of As (24.8 mg/kg), Ni (63 mg/kg), Cr (201 mg/kg), and Co (20.9 mg/kg), while S17 showed the highest levels of Cu (95 mg/kg), Zn (214 mg/kg), and Pb (23 mg/kg) among the studied stations. The results of the ANOVA test also demonstrated a significant difference ($P < 0.05$) in the mean concentrations of PTEs among different stations (Table 2). In Table 3, we compare the mean concentration of potentially toxic elements in

Table 2. Mean, maximum and minimum concentrations of PTEs measured from the sediments of Zayandeh-Rood River and their comparison using the ANOVA test

Metal	Mean ± SD (ppm)	Min (ppm)		Max (ppm)		ANOVA	
		Value	Station	Value	Station	F-value	P-value
As	9.73± 4.89	3.4	S11	24.8	S5	61.028	0.000
Cd	0.34± 0.31	0.1	S11	1.5	S2	138.273	0.000
Cu	31.14± 16.91	11	S1	95	S17	69.092	0.000
Zn	61.33± 49.75	1	S1	214	S17	121.343	0.000
Ni	31.90± 13.26	14	S21	63	S5	44.491	0.000
Mn	707.76± 227.21	281	S1	1168	S12	28.154	0.000
Cr	96.95± 41.11	21	S1	201	S5	46.053	0.000
Co	11.91± 3.72	4.5	S1	20.9	S5	26.807	0.000
Pb	10.95± 5.23	3	S1	23	S17	56.194	0.000
V	125.09± 83.79	31	S1	1427	S11	222.631	0.000

the sediments of the Zayandeh-Rood River with some international standards.

Correlation analysis (Table 4) indicated that there were no significant negative correlations between the PTEs; however, some showed significant positive correlation coefficients. Cr and Co had the highest correlation coefficient ($r = 0.93$, p-value < 0.01). Arsenic As and Cd did not show any significant correlation with other PTEs, whereas Cu showed a significant correlation with 6 other PTEs including Zn, Ni, Cr, Co, Pb, and V ($0.45 < r < 0.93$, p-value < 0.05).

The sediment pH was found to be alkaline and ranged between 7.47 and 8.33 (mean 7.89±0.23). The mean EC of the sediment samples was determined to be 8.56±17.8 ds/m. The levels of TOC and OM were within the ranges of 0.13-2.2% and 0.2-15.78%, respectively. Significant differences were observed in the texture of the sediment samples. For instance, there was an 80% difference in the silt content among them, and the sediment clay content varied by more than 50% among some stations (Table 4). The highest number of correlation coefficients with PTE concentrations was demonstrated by the clay content, which showed positive correlations for As, Zn, Ni, Cr, Co, and Pb ($0.28 < r < 0.70$, p-value < 0.05 and 0.01), and negative correlations for Mn and V ($r = -0.25$, p-value < 0.05). The OM% did not show any significant correlation with any of the PTEs concentrations, but the TOC% established significant positive correlations with Cu, Zn, and Pb ($0.46 < r < 0.56$, p-value < 0.01). With an increase in pH, there was a significant positive trend in the concentrations of Mn, Co, and V, while the concentration of Zn showed a significant decreasing trend. On the other hand, with an increase in EC, a significant decrease was found in the concentrations of Ni, Cr, and Co (Table 5).

Based on the Igeo Index (Figure 2), the concentrations of Cu, Zn, Ni, Mn, Cr, Co, and Pb were within the non-polluted range in all stations. As showed very strong pollution at S5 (3.19), moderate to high pollution levels at S3 (205), S6 (2.24), S9 (2.42), S18 (2.13), S19 (2.65), and S21 (2.01), and moderate pollution levels in other stations. For Cd, S2 showed high pollution levels (3.32), and S5 (2.00) and S14 (2.00) showed moderate to strong pollution levels, and other stations fall into lower pollution levels. According to the EF index (Figure 3), As showed extremely high enrichment at S1 (56.57) and significant enrichment at S19 (21.37) and S21 (24.57). For Cd, only S1 (78.33) and S2 (25.21) exhibited extremely high and very high enrichment, respectively, while other stations have lower enrichment levels. The Ni EF index showed significant enrichment at S1 (13.31)

Table 3. Comparison of the mean concentration of potentially toxic elements in the sediments of Zayandeh-Rood River with some international standards

	As	Cd	Cu	Zn	Ni	Mn	Cr	Co	Pb	V	References
This study	9.73	0.34	32.14	61.33	31.9	707.76	96.95	11.91	10.95	125.0 9	
ERL	8.2	1.2	34	150	20.9		81		47		(Long et al., 1995)
ERM	70	9.6	270	410	51.6		370		218		
ISQGs	5.9	0.6	35.7	123	16	-	37.3	-	35	-	(CCME, 2001)
PEL	17	3.5	197	315	75	-	90	-	91.3	-	
Shale standard	13	0.30	45	95	68	850	90	19	20	130	(Turekian and Wedepohl, 1961)
Crustal Average	1.8	0.1	55	70	20	900	100	10	15	135	(Taylor, 1964)

ISQG= Interim sediment quality guideline; PEL= Probable effect level; ERL= Environmental Research Laboratory; ERM= Environmental Research Management

Table 4. Correlation coefficients between the PTEs measured from the sediments of Zayandeh-Rood River

	As	Cd	Cu	Zn	Ni	Mn	Cr	Co	Pb	V
As										
Cd										
Cu				0.53*	0.45*		0.52*	0.53*		
Zn			0.53*						0.50*	
Ni			0.45*				0.79**	0.75**	0.49*	
Mn							0.48*	0.57**		0.73**
Cr			0.52*		0.79**	0.48*		0.93**		0.60**
Co			0.53*		0.75**	0.57**	0.93**			0.65**
Pb				0.50*	0.49*					
V			0.52*			0.73**	0.60**	0.65**		

* Correlation is significant at the 0.05 level (2-tailed) ** Correlation is significant at the 0.01 level (2-tailed)

Table 5. Physico-chemical characteristics of the sediment samples measured from the Zayandeh-Rood River and their correlation coefficients with the mean concentration of PTEs

		pH	EC (ds/m)	TOC (%)	OM (%)	Sand (%)	Clay (%)	Silt (%)
Mean± std		7.89± 0.23	8.56± 17.8	0.78± 0.57	1.92± 3.28	23.99± 11.64	22.65± 17.61	**54.63± 26.32**
Range		7.47-8.33	0.21-61.99	0.13-2.2	0.2-15.78	10.83-46.1	1.07-59.17	**5-85.56**
Correlation	As		0.28*			-0.29*	0.28*	**0.33****
	Cd							
	Cu			0.46**				
	Zn	-0.29*		0.56**		-0.44**	0.43**	**0.47****
	Ni		-0.36**			-0.55**	0.70**	**0.30***
	Mn	0.26**				0.29*	-0.25*	
	Cr		-0.41**				0.44**	
	CO	0.25*	-0.46**				0.37**	
	Pb			0.53**		-0.53**	0.58**	**0.35****
	V	0.45**					-0.25*	**-0.35****

* Correlation is significant at the 0.05 level (2-tailed) ** Correlation is significant at the 0.01 level (2-tailed)

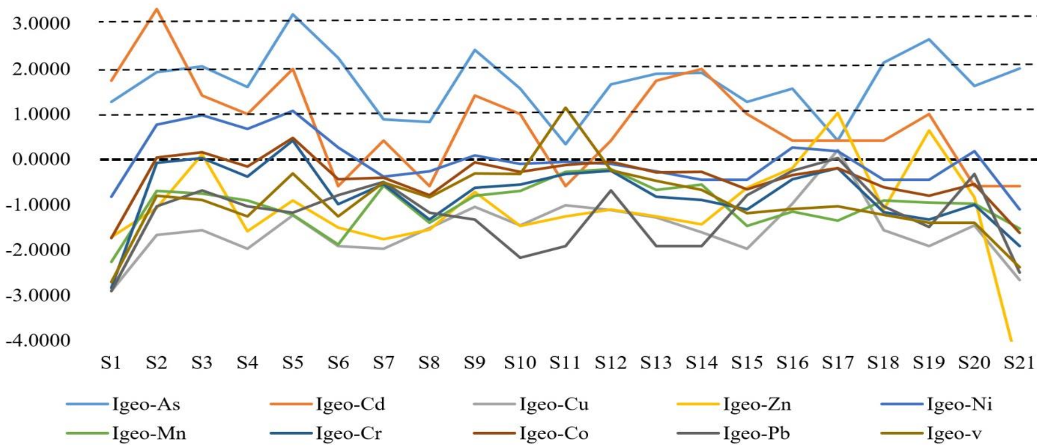

Fig 2. Values of the Igeo index measured from the concentration of PTEs in the sediments of the Zayandeh-Rood River

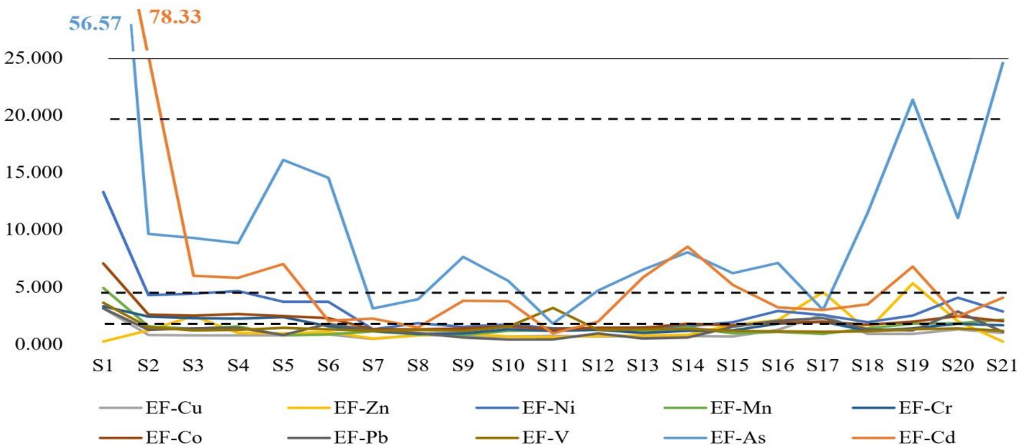

Fig 3. Values of EF index measured from the concentration of PTEs in the sediments of Zayandeh-Rood River

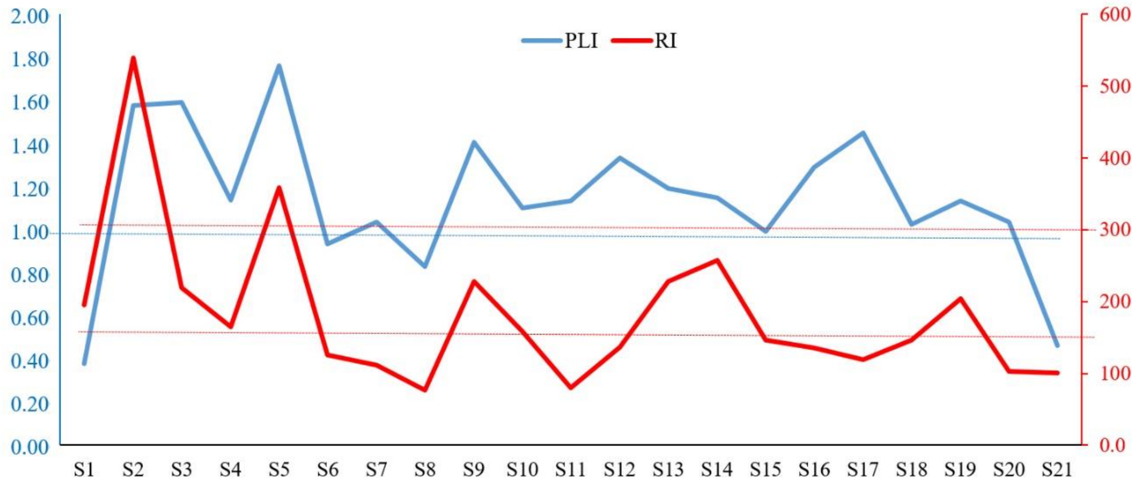

Fig 4. Values of PLI and RI indices measured from the concentration of PTEs in the sediments of Zayandeh-Rood River

and lower enrichment levels in other stations. The highest RI value was observed at S2 (539.90). Except for S2 and S5, which fall into Considerable, other stations were classified as having low to moderate ecological risk. The PLI index was less than 1 at S1 (0.37), S6 (0.93), S8 (0.82), and S21 (0.46), and the highest value is observed at S5 (1.76) (Figure 4).

4. Discussion

The Zayandeh-Rood River holds significant importance as a freshwater source in central Iran, crucial for both industrial and agricultural development. Consequently, PTE pollution in the river sediment is inevitable (Karimian et al., 2020). Research findings reveal that the uppermost station lacks industrial and agricultural activities, resulting in generally low concentrations of PTEs in the river sediment, conforming to the ISQG standards (CCME, 2001), except for As, which exceeds the limit with a concentration of 6.5 mg/kg. However, as human activities increase in the midstream and downstream regions, the concentration of the majority of PTEs showed notable rises. In particular, the mean concentration of As and Cr in the Zayandehrud River surpassed the permissible limit values of 5.9 mg/kg and 37.3 mg/kg set by ISQG, respectively. This increase can be attributed to agricultural practices and the use of fertilizers containing these metals in the upstream areas. Similar studies by Shahradnia et al. (2022) and Malvandi (2017) also demonstrated elevated concentrations of As and Cd in regions heavily influenced by agricultural activities, emphasizing the significant role of PTE-containing fertilizers, particularly As, in traditional agriculture practices in Iran (Shahradnia et al., 2022). In the transitional zones between the upstream and downstream of the river, agricultural runoff does not flow into the river due to the flat topographical characteristics of the area. However, the increasing number of cities and industries discharging wastewater directly into the river can be considered a major factor contributing to higher concentrations of As and Cr at stations like S9 and S14. Overall, the contamination of the river can be attributed to the presence of intensive agricultural activities in the upstream, industrial activities in the midstream region, and sewage discharge from cities along the entire course of the river.

The positive significant correlations observed between the majority of the PTEs in the river sediment samples, particularly between Pb, Ni, and Zn may indicate the existence of common sources that release these metals into the environment. These elements are often found together in certain mineral deposits (Rahman et al., 2014, Sutherland, 2002) and can be released into the environment through industrial activities, such as iron smelting, which is a prominent characteristic of industries in the region. Additionally, these metals display similar geochemical behaviors that can result from various factors such as river flow, sediment composition, acidity, and organic matter content, leading to their accumulation in sediment or presence in the dissolved phase in water. However, this study observed a range of correlations between the physical and chemical parameters of sediment and the concentrations of PTEs. One of the main reasons for this variability can be attributed to the interactions between different properties of the sediment as found by some previous studies such as Bartoli et al. (2012) and Miranda et al. (2021). For example, the increase in clay content positively impacts the accumulation of heavy metals in sediment, but it can be also influenced by factors such as acidity, oxidation-reduction potential and organic matter content in the sediment. Furthermore, changes in river flow at different points along the river can lead to variations in the effects of these parameters.

Based on the pollution indices, the Zayandeh-Rood River is classified as having moderate to low contamination (Igeo index) and minimal to moderate enrichment (EF index) for many of the studied PTEs. However, there are particular concerns regarding some PTEs like Cd and As. This is notably evident in the upstream areas with high agricultural activities and the downstream regions heavily affected by various wastewater discharges. In line with this research's findings, Karimian et al. (2020) also demonstrated that the Zayandeh-Rood River is severely polluted according to pollution indices, with one of the major contributing factors being the influx of wastewater from nearby cities such as Isfahan. According to RI and PLI indices, moreover, the upstream areas of the river have experienced higher levels of pollution. Overall, the Zayandeh-Rood River generally exhibits lower contamination levels for many PTEs, but specific areas, especially those influenced by agricultural activities and wastewater discharges, show concerning pollution levels. Hence, effective monitoring and pollution control measures are essential to address these issues and ensure the water quality and aquatic ecosystems of the river. In Table 5, we compare the mean concentration of potentially toxic elements in the sediments of Zayandeh-Rood River with the findings from other regions.

According to the results, prioritizing the management of agricultural activities and reducing the excessive use of PTE-containing pesticides and insecticides should be a primary focus for protecting the Zayandeh-Rood River. This conclusion is mostly because of the highest pollution levels observed in areas without industrial activities and major cities but with significant agricultural activities in the upstream regions. While the midstream section of the river currently experiences lower pollution levels, continuous industrial development and expanding residential areas may increase the risk of higher pollution levels in the future. To strengthen the results and interpretations made in this research, it is recommended to divide the river into sections based on topographical characteristics and various anthropogenic activities to conduct independent monitoring in each segment for proper PTE source apportioning. This approach will facilitate better management and conservation strategies for the Zayandeh-Rood River. In summary, prioritizing the control of agricultural activities and reducing the use of pesticides while implementing appropriate pollution control measures in the upstream regions are essential for preserving the water quality of the Zayandeh-Rood River. Additionally, adopting a segmented approach for monitoring and managing different parts of the river based on their unique characteristics and activities can further enhance conservation efforts and ensure more effective protection of the river in the future.

Table 6. Comparison of the mean concentration of potentially toxic elements in the sediments of Zayandeh-Rood River with the findings from other regions

Location	As	Cd	Cu	Zn	Ni	Mn	Cr	Co	Pb	V	Reference
Zayandeh-Rud river, Iran	9.73	0.34	31.14	61.33	31.90	707.76	96.95	11.91	10.95	186.29	This study
The Jinjiang River	6.2	0.51	26.04	104	24.47	787	58.66	11.6	23.81	93.8	(Liu et al., 2018)
The Mekong Delta	19.06	0.212	32.56	194.6	39.84	-	75.6	18.24	27.98	116.2	(Strady et al., 2017)
River Huaihe, China	-	-	-	-	-	7.84	-	21.03	-	-	(Wang et al., 2016)
The Mississippi River	-	0.175	21.31	144	-	1044	71.62	-	27.41	-	(Santschi et al., 2001)
Mangonbangon River, Philippines	-	-	116.36	213.45	61.14	261.97	89.45	15.31	-	-	(Pacle Decena et al., 2018)
The Yellow Sea	8.59	0.160	22.07	77.98	23.70	-	56.80	-	26.79	-	(Tian et al., 2020)
the Yangtze River, China	14.49	1.21	46.67	158	41.27	862	75.91	-	35.56	-	(Li et al., 2020)

5. Conclusion

In this research, the concentrations of As, Cd, Cu, Zn, Ni, Mn, Cr, Co, Pb, and V were measured in the surface sediments of the Zayandeh-Rood River. The results showed that human activities in the region had a significant impact on the accumulation of these PTEs. The river was classified as having moderate to low contamination (Igeo index) and minimal-to-moderate enrichment (EF index) except for Cd and As which exhibited extremely high enrichment and strong pollution in the upstream zone, where agricultural activities dominate. Given the non-biodegradable nature and harmful impacts of these elements on aquatic life, it is strongly recommended that rigorous management strategies be implemented for agricultural practices within the upper river region. In light of the limitations imposed by time and financial resources in this study, it is advisable to prioritize the implementation of comprehensive environmental monitoring protocols targeting a wide spectrum of organic and mineral pollutants in this specific area.

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