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Original Research

Assessment of potential heavy metals in sediments of Arzhan Lake, Iran, using Kriging technique

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Abstract

This study investigates the concentrations, spatial distribution, and environmental impacts of potentially toxic elements (PTEs), including As, Cd, Cr, Cu, Ni, Pb, S, and Zn in the surface sediments of Arzhan Lake, Iran. Forty sediment samples were analyzed using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). Pollution indices, including the Contamination Factor (CF), Enrichment Factor (EF), Geo-accumulation Index (I_{geo}), Ecological Risk Index (ER), Toxicity Response Factor (TR), Integrated Pollution Index (IPI), and Nemerow Pollution Index ($PI_{Nemerow}$), were employed to assess contamination levels. Statistical analyses such as Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) facilitated geochemical interpretation, while Kriging interpolation was applied to map spatial distributions. Results indicated that the mean concentrations of all analyzed elements exceeded background values, based on local baselines, global averages, and Upper Continental Crust (UCC) levels to ensure contextual relevance. Cadmium (Cd) emerged as the most critical pollutant ($CF = 3.35$, $EF = 10.89$, $I_{geo} = 1.16$) and posed the greatest ecological risk ($Er = 100.50$). Arsenic (As), and S also showed elevated contamination levels. Spatial mapping of Arzhan Lake sediments using the Kriging method revealed hotspots of Cr and Ni in the northern part of the Lake, near agricultural areas, sulfur (S) and As in the central basin; and Cd in the southern part. These patterns highlight the roles of agricultural runoff, vehicular emissions, and natural depositional processes in controlling sediment contamination. The study's limitations include the use of seasonal sampling, which may not fully capture temporal variability, and the presence of potential unmeasured



pollutants. Additionally, the Kriging method assumes spatial stationarity, which may overlook micro-scale heterogeneity. Overall, sediments in Arzhan Lake exhibit moderate to considerable pollution and ecological risk (IPI = 1.86, RI = 144.36), underscoring the need for ongoing monitoring and targeted remediation.

Keywords: Pollution, Potentially toxic elements, Arzhan Lake, Iran, Ecological risk, Geostatistics

1. Introduction:

The increase in global population, industrial expansion (Han et al., 2002), and agricultural activities (Nagendran, 2011) have led to greater generation of polluted agricultural and industrial wastes which can enter in aquatic environments near these activities (Ganjali, 2016) which accumulate mostly in clay sediments due to their high surface adsorption capacity (Lamrani et al., 2025). Potentially toxic elements (PTEs) are of particular concern among other pollutants due to their persistence, resistance to biodegradation, environmental toxicity, and associated health hazards (He et al., 2012; Belhadj et al., 2017). They are generally defined as metallic and semi-metallic elements with a density greater than 5 g cm^{-3} (Ali, 2019) and exhibit toxicity even at low concentrations (Järup, 2011; Adani, 2015; Abd Elnabi et al., 2023). Their concentration in soils depends on total metal content (Abrahams, 2002), pH, cation exchange capacity, soil texture, organic material, metal oxides, and complexing ligands (Mourinha et al., 2022). These elements tend to have low mobility in sediments, accumulate in surface layers and can be absorbed by plants (Zhang et al., 2009), mollusks (Kabir Niloy, 2024), bivalves, fish (Ikem and Egiebor, 2005) and, finally, enter the food chain (Dehghani et al., 2016; Gribof et al., 2018; Sobhanardakani et al., 2020). Anthropogenic activities, such as mining, smelting, industrial development, waste disposal, and agricultural practices (Atafarz, 2010), (Wang et al., 2021), alongside natural processes like weathering and erosion (Wu et al, 2021), rainfall runoff (Zeng et al., 2023) etc., play the primary role in releasing these elements into the environment. Since PTEs do not easily degrade, they persist and can be remobilized, causing secondary pollution. Studies globally have documented heavy metal pollution in river sediments (Khan et al., 2025). For example, cadmium and lead enrichment in the Ganges (Pandi and Sin, 2017) and cadmium, lead, nickel, and zinc in the Pima River (Guan et al., 2018). Studies in Iran have indicated environmental pollution in rivers. Elevated levels of lead, cadmium, mercury, chromium, and copper in the Karun River (Jadari et al., 2025),



high enrichment of arsenic, cadmium, antimony, lead, and bismuth in the Zarshuran Aghdareh (Mousavi et al., 2018), elevated arsenic, zinc, copper, lead, and manganese in the Mahabad Dam sediments (Lahijani et al., 2020), emphasize the need for continuous monitoring and effective management strategies to safeguard environmental and public health. Lake Arzhan, within the Arzhan Biosphere Reserve, is a critical hydrological feature supporting the protected area. "The lake is important not only for its flora and fauna diversity but also for its connection with Lake Parishan. Contamination threatens biodiversity, food chain stability, public health (Islam et al., 2023), groundwater quality, agricultural productivity (Chai et al., 2021; Barahouei et al., 2025), and soil conditions in both Arzhan and Parishan Lake. No prior studies have assessed sediment contamination or PTE concentrations in Lake Arzhan, making this evaluation essential for environmental risk assessment and sustainable management (Sobhanardakani et al., 2018), aiming to protect the ecosystem, food safety, and human health.

2. Methods and Materials

Arzhan Lake (52°18'–52°27'E, 30°9'–30°18'N), a UNESCO Biosphere Reserve in southwestern Iran (Fig. 1), is ecologically significant and subject to seasonal hydrological fluctuations (Mohammadi et al., 2019). Agricultural well construction has exacerbated water level decline, leading to recent ecological changes. For determining the pollution levels and future protection management of the lake, surface sediment samples (n=40) were collected using the one km² gridded design (Hoppenbrock et al., 2021) (Fig. 2) using acid-washed plastic tools to prevent contamination. Samples were stored in polyethylene bags (Niu et al., 2024) at 4°C, air-dried, homogenized, and sieved through a 2 mm mesh (GILSON ISEO 565) (Unda-Calvo et al., 2019). Subsamples underwent microwave-assisted digestion with four acids, following USEPA 3051A, and were analyzed for potentially toxic elements (PTEs) using ICP-OES (E-733) (Phan-Thien et al., 2012) at the Geological Survey of Iran's Geochemistry Laboratory. QA/QC procedures followed Chinese national standards and protocols (e.g., Chen et al., 2018; Wang, 2021) to ensure data accuracy. To determine the contamination of the lake, the concentrations of PTEs were compared with standard values (Upper Continental Crust) and the regional background (Tshisikhawe, 2024) (uncontaminated soils, near Arzhan Lake) (Table 1). Additionally, the heavy metal concentrations in the surface sediments of Arzhan Lake were compared with those reported



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for other lakes, as shown in Table 2. Geochemical indices such as Geoaccumulation Index (I_{geo}) (Müller, 1969; Zhang et al., 2022), Pollution Index (PI) (Li et al., 2024), Potential Ecological Risk Index (RI) (Hakanson, 1980; Chen et al., 2018; Hosseini and Sobhanardakani, 2022; Siyahati Ardakani et al., 2023), Enrichment Factor (EF) (Sutherland, 2000), and the Nemerow Pollution Index (NPI) (Sanad et al., 2025) were calculated to highlight different aspects of contamination and ecological risks (Haris, 2013; Zhang et al., 2015). They facilitate the identification of priority pollutants and pollution severity (Tytła and Kostecki, 2019; Habibi et al., 2022) and can translate geochemical data into understandable metrics for environmental monitoring and management. Table 3 summarizes the formulas, components, and references for the geochemical indices used in this study, and the results of applying these indices in this study are presented in Table 4. Kriging, a geostatistical interpolation method, was employed to investigate the spatial distribution of heavy metals in the surface sediments of Arzhan Lake. This approach allowed the prediction of contaminant levels at unsampled locations, providing a comprehensive view of the lake quality.

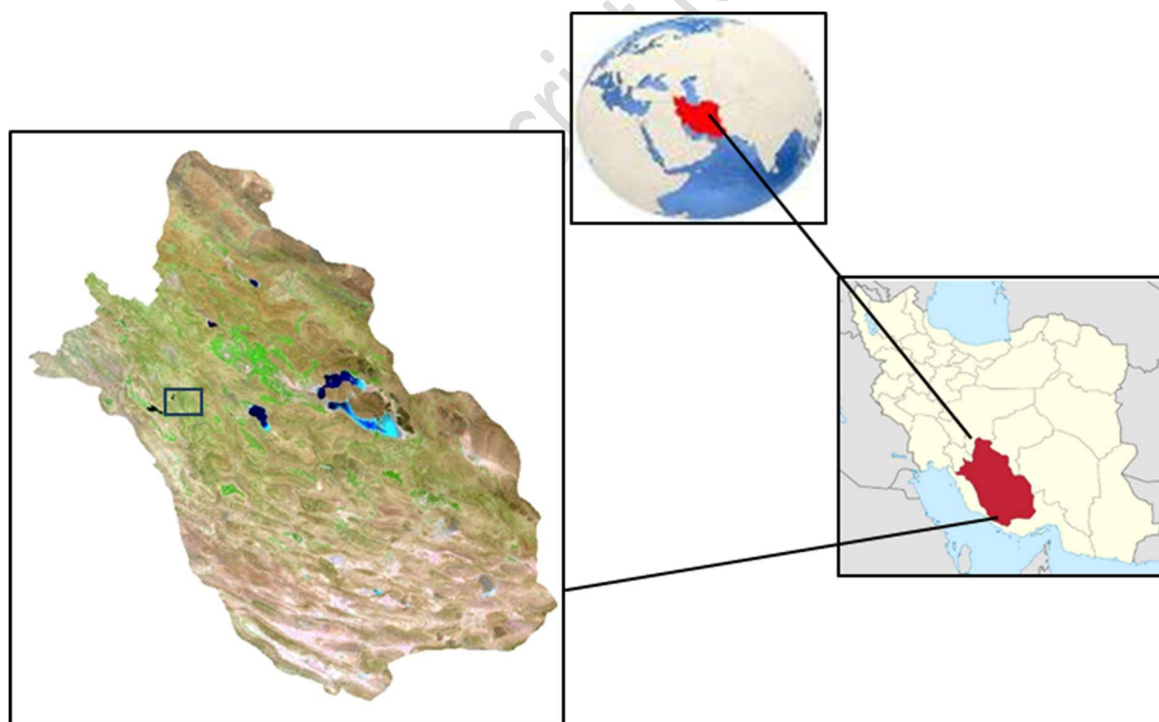


Figure 1. Geographic location of Arzhan Lake in the world, Iran and, Fars province.



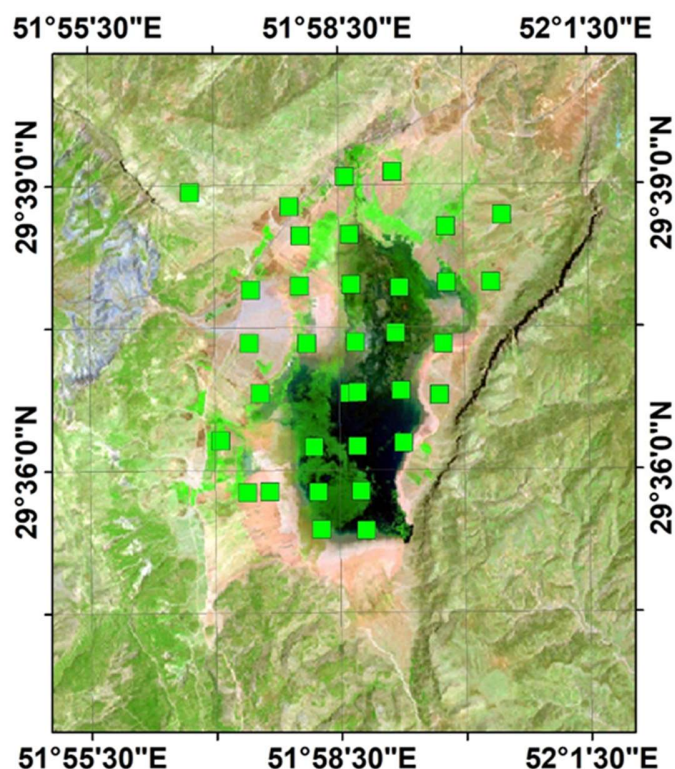


Figure 2. Surface sediment sampling locations within Arzhan Lake

Table 1. Statistical summary of the concentration (mg/kg) of 8 elements in 40 samples of Arzhan Lake. The last two rows show the concentrations of elements in the Upper Crust values (Kabata-Pendias and Mukherjee, 2007) and in the background.

Parameter	Values (All Elements)
Mean	As: 4.68, Cd: 0.67, Cr: 79.58, Cu: 18.84, Ni: 57.64, Pb: 12.07, S: 1417.21, Zn: 44.32
Std. Dev.	As: 2.51, Cd: 0.39, Cr: 23.17, Cu: 4.44, Ni: 17.04, Pb: 4.70, S: 1271.62, Zn: 13.67
Min	As: 0.90, Cd: 0.22, Cr: 27.67, Cu: 7.85, Ni: 21.07, Pb: 1.71, S: 339.36, Zn: 7.10
Max	As: 11.23, Cd: 2.03, Cr: 124.15, Cu: 26.61, Ni: 93.05, Pb: 24.14, S: 7152.23, Zn: 89.47
UCC	As: 1.80, Cd: 0.20, Cr: 100, Cu: 55, Ni: 75, Pb: 13, S: 260, Zn: 70
Background	As: 2.86, Cd: 0.23, Cr: 68.27, Cu: 19.55, Ni: 58.88, Pb: 11.89, S: 506.71, Zn: 45.92

3. Result and discussion

Table 1 presents a statistical summary of eight potentially toxic elements (PTEs) in surface sediments of Arzhan Lake. Mean concentrations of Cr (79.58 mg/kg), As (4.68 mg/kg), S (1417.21 mg/kg) and Ni (57.64 mg/kg) exceeded Threshold Effect Levels (TELs), suggesting potential ecological risks, while Zn (44.32 mg/kg) and Pb (12.07 mg/kg) were within acceptable limits. Although Cd concentrations were relatively low (0.67 mg/kg), its toxicity and bioaccumulation potential remain a concern. Compared to other lakes (Table 2), Arzhan Lake generally exhibited



lower PTE concentrations, likely due to lower population densities and less intensive anthropogenic activity in its vicinity. Geochemical indices (Table 4) indicated that Cd was the most polluting element ($I_{geo} = 1.16$, $CF = 3.35$, $EF = 10.89$, $Tr = 30$, $Er = 100.50$), classified as "very highly polluted." As ($I_{geo} = 0.79$, $CF = 2.60$, $EF = 8.45$, $Tr = 10$, $Er = 26.00$) and S ($I_{geo} = 1.86$, $CF = 5.45$, $EF = 17.72$, $Tr = 1$, $Er = 2.80$) also showed elevated levels, while Pb, Zn, and Cu exhibited low values indicative of unpolluted conditions. Ecological risk assessments confirmed the significance of Cd ($Er = 100.50$) and As ($Er = 26.00$), highlighting anthropogenic contributions. Other elements posed low ecological threats. The overall Ecological Risk Index ($RI = 144.36$) and Integrated Pollution Index ($IPI = 1.86$) indicated moderate to considerable ecological risk. Pearson correlation analysis revealed strong associations between Ni, Cr, and Cu, as well as between Zn and Ni, suggesting shared sources or geochemical behavior. Principal Component Analysis (PCA) (Fig. 3) and Hierarchical Cluster Analysis (HCA) identified distinct clusters of sampling stations with similar contamination profiles. Kriging maps (Fig. 4) of Arzhan Lake sediments revealed distinct hotspots for Cr and Ni in the northern part, primarily linked to agricultural runoff and human activities. This area receives irrigation return flows enriched with fertilizers, pesticides, and organic matter that contains trace metals, while the accumulation of fine-grained sediments and clay minerals further enhances the adsorption and retention of these elements. In contrast, elevated concentrations of sulfur (S) and arsenic (As) in the central part of the lake are controlled by a combination of geochemical and hydrological factors. The central basin, as a low-energy depositional zone, facilitates the accumulation of fine sediments and organic matter, creating reducing conditions that favor the formation of metal sulfides (e.g., As_2S_3) and the enrichment of sulfur. Runoff from surrounding agricultural areas transports sulfate- and arsenic-bearing compounds toward the lake center, where decreased water flow velocity promotes sedimentation. Moreover, groundwater inputs and diagenetic processes further contribute to the elevated concentrations of sulfur (S) and arsenic (As) in the central sediments. The elevated cadmium (Cd) levels in the southern part of Arzhan Lake are primarily influenced by nearby roads and traffic. Particles from vehicle wear, tire abrasion, and road dust, which are often enriched in Cd, are transported by surface runoff or wind and accumulate in the low-energy depositional zone of the southern sediments. Besides road traffic, elevated cadmium (Cd) in the southern sediments of Arzhan Lake is primarily attributed to agricultural runoff and local anthropogenic inputs, including fertilizers, pesticides, and small-scale discharges. Low-energy depositional conditions



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in this area further promote the accumulation and retention of Cd in fine-grained sediments. The combination of Kriging and statistical analyses can facilitate the identification of element sources, highlighting anthropogenic contributions for some PTEs and natural geological sources for others, which can inform targeted ecological risk management strategies. Limitations of this study include its single-season sampling, which does not account for seasonal changes or hydrological variability, and the potential presence of unmeasured pollutants. Additionally, the precision of Kriging interpolation depends on sample density and distribution, which should be considered in future research.

Table2. Concentration (mg/kg) of (PTEs) in surface sediments in Lakes around the world compared with this study.

Field / Location (Year, Reference)	Values (mg/kg)
Dongjiang Lake, China (2022, Zhao et al., 2019)	As: 80.8, Cd: 2.25, Cr: 67.58, Cu: 33.01, Pb: 47.4, Zn: 113.9
Kangryong, Korea (2021, Kim)	As: 14.3, Cd: 0.28, Cr: 53.9, Cu: 32.7, Pb: 30.9, Zn: 132.5
Hongze Lake, China (2021, Zi et al.)	As: 16.55, Cd: 0.23, Cr: 66.78, Cu: 24.35, Pb: 27.2, Zn: 74.77
East Dongting, China (2021, Tang)	As: ND, Cd: 5.5, Cr: 42.9, Cu: 42.6, Pb: 58.6, Zn: 88.8
Taihu Lake, China (2019, Zhang et al., 2019)	As: 13.34, Cd: 0.8, Cr: 102.46, Cu: 44.17, Pb: 37, Zn: 163.6
Persian Gulf, Iran (2021, Jahromi et al., 2021)	As: 5.92, Cd: 0.15, Cr: 59.22, Cu: 14.87, Pb: 7.42, Zn: 32.51
Lake Emerald, India (2020, Karthikeyan et al.)	As: ND, Cd: ND, Cr: 411.48, Cu: 611.32, Pb: 34.04, Zn: 174.4
Inle Lake, Myanmar (2019, Aung et al.)	As: 6.59, Cd: 0.05, Cr: 19.24, Cu: 7.92, Pb: 9.64, Zn: 18.8
Los Molinos Lake, Argentina (2018, Griboff et al., 2018)	As: 1.74, Cd: 0.06, Cr: 2.5, Cu: 4.67, Pb: 6.45, Zn: 9.8
Poyang Lake, China (2016, Xie et al.)	As: 11.34, Cd: 0.66, Cr: 81.39, Cu: 35.17, Pb: 32.63, Zn: 104.17
The present study	As: 4.68, Cd: 0.67, Cr: 79.58, Cu: 18.84, Pb: 11.5, Zn: 45.28

Table3. A summary table of the geochemical indices used in this study, along with their general specifications.

Index	Formula, Components and, Description
Enrichment Factor (EF)	Formula: $EF = (C_n/C_{ref})_{sample} \div (B_n/B_{ref})_{background}$ Components: C_n : concentration of target metal; C_{ref} : reference element in sample; B_n , B_{ref} : background concentrations (crustal values) Description: < 2: Deficiency to minimal enrichment (natural source); 2–5: Moderate enrichment; 5–20: Significant enrichment; 20–40: Very high enrichment; >40: Extremely high enrichment (anthropogenic source)
Contamination Factor (CF)	Formula: $CF = C_n / C_{background}$ Components: C_n : metal concentration in sample; $C_{background}$: background concentration Description: < 1: Low contamination; 1–3: Moderate contamination; 3–6: Considerable contamination; >6: Very high contamination
Geo-accumulation Index (I _{geo})	Formula: $I_{geo} = \log_2(C_n / (1.5 \times B_n))$ Components: C_n : concentration in sample; B_n : background concentration; 1.5: correction factor for natural variability Description: ≤ 0: Unpolluted; 0–1: Unpolluted to moderately polluted; 1–2: Moderately polluted; 2–3: Moderately to strongly polluted; 3–4: Strongly polluted; 4–5: Strongly to extremely polluted; >5: Extremely polluted
Ecological Risk Factor (Er)	Formula: $Er = Tr \times CF$ Components: Tr : toxic-response factor; CF : contamination factor Description: < 40: Low risk; 40–80: Moderate risk; 80–160: Considerable risk; 160–320: High risk; >320: Very high risk
Potential Ecological Risk Index (RI)	Formula: $RI = \sum ER$ Components: Sum of individual ER values for all metals Description: Indicates total ecological risk of all measured metals
Nemerow Pollution Index (PINemro)	Formula: $PINemro = \sqrt{[(P_{imean}^2 + P_{imax}^2)/2]}$ Components: P_{imean} : mean value of pollution indices; P_{imax} : maximum value among metals Description: < 0.7: Clean; 0.7–1: Warning line of pollution; 1–2: Low pollution; 2–3: Moderate pollution; >3: Heavy pollution
Toxicity Coefficient (Tr)	Formula: $Tr = \text{constant value per element}$ Represents element toxicity; used to calculate ER (Potential ecological risk factor); CF : Contamination factor, ratio of measured concentration to background



Table 4. The calculated geochemical indices in 40 samples of Arzhan Lake. (Müller 1979)

Element	Indices
As	CF: 2.60, EF: 8.45, I geo: 0.79, Tr: 10, Er: 26.00, IPI: 1.86, RI: 144.36
Cd	CF: 3.35, EF: 10.89, I geo: 1.16, Tr: 30, Er: 100.50, IPI: 1.86, RI: 144.36
Cr	CF: 0.80, EF: 2.59, I geo: -0.91, Tr: 2, Er: 1.59, IPI: 1.86, RI: 144.36
Cu	CF: 0.34, EF: 1.11, I geo: -2.13, Tr: 5, Er: 1.71, IPI: 1.86, RI: 144.36
Ni	CF: 0.77, EF: 2.50, I geo: -0.96, Tr: 5, Er: 3.84, IPI: 1.86, RI: 144.36
Pb	CF: 0.93, EF: 3.02, I geo: -0.69, Tr: 5, Er: 4.64, IPI: 1.86, RI: 144.36
S	CF: 5.45, EF: 17.72, I geo: 1.86, Tr: 1, Er: 2.80, IPI: 1.86, RI: 144.36
Zn	CF: 0.63, EF: 2.06, I geo: -1.24, Tr: 1, Er: 0.63, IPI: 1.86, RI: 144.36

Table 5. Pearson correlation coefficient of elements in Arzhan Lake sediments

Element	Correlation with other elements
As	As: 1.00, Cd: 0.74, Cr: -0.16, Cu: -0.31, Ni: 0.01, Pb: -0.73, S: -0.64, Zn: 0.21
Cd	Cd: 1.00, Cr: 0.37, Cu: 0.26, Ni: 0.41, Pb: -0.83, S: -0.35, Zn: 0.69
Cr	Cr: 1.00, Cu: 0.94, Ni: 0.93, Pb: 0.03, S: -0.06, Zn: 0.83
Cu	Cu: 1.00, Ni: 0.77, Pb: -0.03, S: 0.03, Zn: 0.64
Ni	Ni: 1.00, Pb: 0.08, S: -0.09, Zn: 0.84
Pb	Pb: 1.00, S: 0.34, Zn: -0.21
S	S: 1.00, Zn: -0.18
Zn	Zn: 1.00

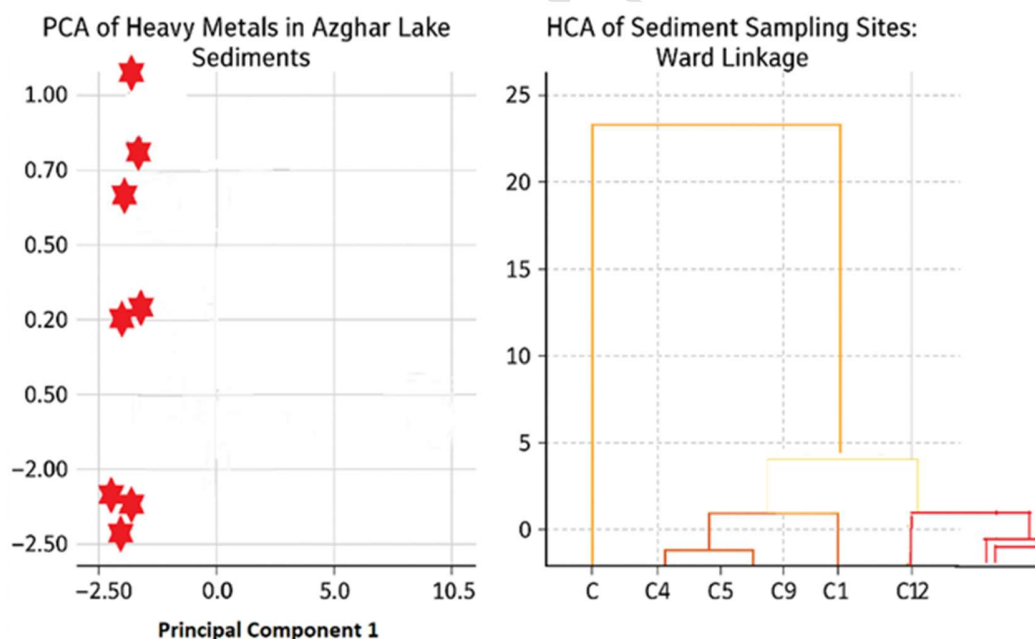


Figure 3. Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) of heavy metal concentrations in sediment samples from Arzhan Lake.



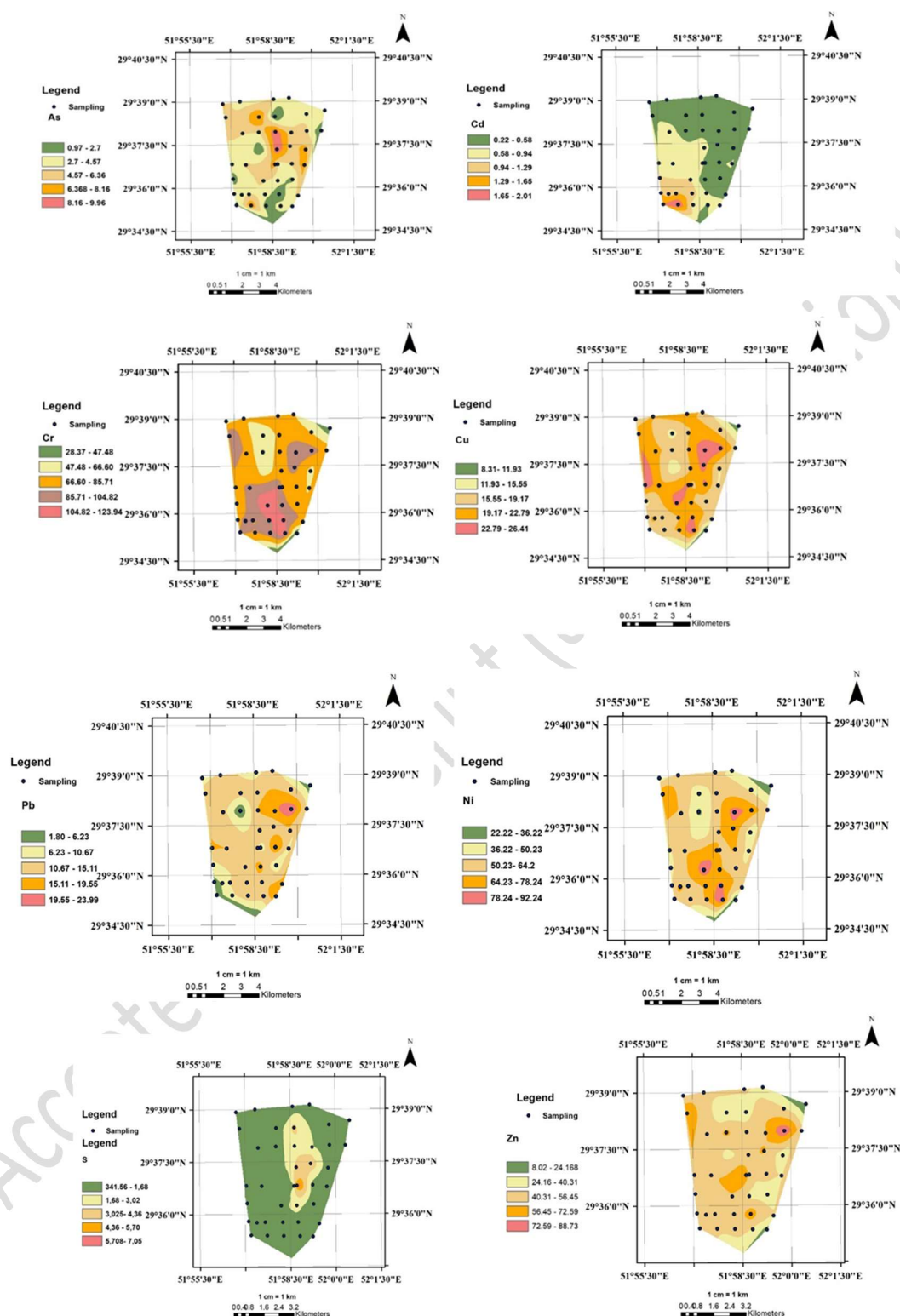


Figure 4. Spatial distribution map of potentially toxic elements in the sediments of the Arzhan Lake



4. Conclusion

The surface sediments of Arzhan Lake indicate potential ecological risks due to contamination from potentially toxic elements (PTEs). The average concentrations of chromium (Cr) (79.58 mg/kg) and nickel (Ni) (57.64 mg/kg) exceeded the Threshold Effect Levels (TELs). In contrast, zinc (Zn) (44.32 mg/kg) and lead (Pb) (12.07 mg/kg) were within acceptable limits. Although cadmium (Cd) is present at a low concentration (0.67 mg/kg), it remains a concern due to its high toxicity and tendency to bioaccumulate. When compared to other lakes, Arzhan Lake shows moderate levels of contamination. Geochemical indices revealed that Cd is "very highly polluted" (CF = 3.35, EF = 10.89, I_{geo} = 1.16, Tr = 30, Er = 100.50), followed by arsenic (As, CF = 2.60, EF = 8.45, I_{geo} = 0.79, Tr = 10, Er = 26.00), Ni (CF = 0.77, EF = 2.50, I_{geo} = -0.96, Tr = 5, Er = 3.84), and S (CF = 5.45, EF = 17.72, I_{geo} = 1.86, Tr = 1, Er = 2.80). Pb, Zn, and copper (Cu) exhibited low levels of pollution. Overall, the indices, including the Integrated Pollution Index (IPI = 1.86) and Risk Index (RI = 144.36), indicate a moderate to considerable level of pollution. Ecological risk assessments identified Cd and As as major contributors. Geochemical associations were noted among Ni, Cr, and Cu. Spatial mapping of Arzhan Lake sediments revealed distinct pollution patterns: Cr and Ni hotspots in the north are linked to agricultural runoff, S and As enrichment in the central basin result from geochemical and hydrological factors, and elevated Cd in the south is mainly driven by road traffic, with contributions from agriculture and local anthropogenic sources. Low-energy depositional zones and fine-grained sediments enhance the accumulation and retention of these elements. The results underscore the joint impact of anthropogenic and natural processes on sediment contamination, stressing the importance of targeted monitoring and management. Limitations of the study include seasonal sampling and the possibility of unmeasured pollutants. Future research should focus on the bioavailability, mobility, and ecotoxicological effects of these contaminants for a comprehensive risk assessment. These findings provide valuable data for environmental agencies and policymakers to support.

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