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Spatial distribution, sources, ecological risk assessment of heavy metals in surface sediments of Wular lake, Kashmir, India-a Ramsar site

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Introduction: Wular Lake, one of the largest freshwater lakes in South Asia and a Ramsar-designated site, sustains biodiversity, fisheries, and livelihoods in the Kashmir Valley. However, increasing anthropogenic activities have raised concerns about heavy metal (HM) contamination in its sediments due to their persistence and ecological risks.

Methods: A total of 32 surface sediment samples were collected from Wular Lake to determine the levels, distribution, and potential sources of HMs including Co, Cu, Fe, Mn, Ni, Pb, Zn, and Cr. Grain size composition, concentration analysis, and pollution indices such as contamination factor (CF), geoaccumulation index (Igeo), enrichment factor (EF), pollution load index (PLI), and potential ecological risk index (PERI) were applied. Multivariate statistics, including correlation, factor, and cluster analyses, were used to identify pollution sources.

Results: Sediments predominantly comprised silt (5.8%–88.8%). Average HM concentrations were Co (34.26 mg/kg), Cu (53.2 mg/kg), Mn (1,478 mg/kg), Ni (78.85 mg/kg), Zn (113 mg/kg), and Cr (96.08 mg/kg), all exceeding natural background levels, suggesting anthropogenic enrichment. Risk assessment indicated moderate contamination (PLI = 1.17; PERI = 19.20), with site-specific hotspots of elevated pollution. Strong correlations were observed among Co, Ni, Fe and among Cu, Pb, Zn. Factor analysis attributed 77.1% of the variance to industrial, urban, and agricultural activities, while cluster analysis segregated sites according to pollution intensity.

Discussion: The findings indicate that Wular Lake sediments are moderately contaminated by heavy metals, primarily due to industrial discharge, agricultural practices, and urban runoff. Although the overall ecological risk was low to moderate, localized hotspots warrant urgent monitoring and management. Strengthening pollution mitigation measures is essential to safeguard the ecological health of this Ramsar site.

KEYWORDS

heavy metals, Wular lake, Ramsar site, sediment contamination, ecological risk assessment, anthropogenic pollution

1 Introduction

Heavy metals (HMs) are pollutants of great environmental concern due to their persistence in the environment, toxicity to living organisms, and tendency to bioaccumulate through food webs (Edo et al., 2024; Muhammad, 2023; Mohammad et al., 2024a; Saidon et al., 2024). Unlike organic pollutants that may degrade over time, heavy metals remain in the ecosystem for long periods and can accumulate in the tissues of organisms, leading to adverse ecological and human health effects (Mishra et al., 2019; Bharti and Sharma, 2022). The primary sources of heavy metal contamination are both natural and anthropogenic. Natural sources include processes like weathering of bedrock, volcanic eruptions, and erosion (Masindi et al., 2021; Wu et al., 2022a). On the other hand, anthropogenic activities such as mining, industrial production, coal burning, urbanization, and agricultural runoff are major contributors to heavy metal pollution, especially in aquatic environments (Daripa et al., 2023; Ali and Muhammad, 2023; Jadaa and Mohammed, 2023). While the relative contribution of natural and human activities to heavy metal concentrations varies by region, human-induced sources are increasingly dominant in many parts of the world (Akhtar et al., 2021; Teschke, 2024). The distribution and concentration of heavy metals in aquatic environments, particularly in lake sediments, are influenced by several factors, including local land use, climate, and hydrological conditions (Miranda et al., 2022; Muhammad et al., 2024b; Fu et al., 2025). Sediments, which consist of particulate matter settling at the bottom of water bodies, are considered both a sink and a source of pollution (Taylor and Owens, 2009). They act as a reservoir for contaminants, including heavy metals, which can accumulate over time due to adsorption onto organic matter, minerals, and other sediment components (Gupta et al., 2013). Over time, these metals can become concentrated in sediments, especially in areas with low water movement or where there is a high influx of pollutants from external sources (Debnath et al., 2021). One of the key characteristics of lake sediments is their capacity to adsorb heavy metal ions, particularly due to the presence of organic matter, iron and manganese oxides, and secondary clay minerals (Darricau et al., 2021; Jurkovic et al., 2021). This adsorption plays a significant role in trapping pollutants, preventing their immediate release into the water column. However, changes in environmental conditions, such as fluctuations in temperature, pH, dissolved oxygen, and organic matter content, can alter the physical and chemical properties of the sediments, potentially leading to the re-release of these heavy metals into the water (Li et al., 2023; Yan and Li, 2023). This phenomenon, reminiscent of secondary pollution can have serious consequences, particularly when it leads to the mobilization of metals into the food web, threatening aquatic organisms and, by extension, human populations reliant on the lake for water or food resources (Borgå et al., 2022; Babaniyi et al., 2025). Moreover, the study of heavy metal contamination in lake sediments is a critical component of environmental monitoring and management (Muhammad and Ullah, 2023; Sojka et al., 2022; Haq et al., 2024; Nazir et al., 2024). This type of research is particularly important in regions where lakes serve as vital water resources or support diverse ecosystems (Sterner et al., 2020; Heino et al., 2021). In many parts of the world, lakes are subject to increasing anthropogenic pressures, leading to heightened concerns about their long-term environmental health (Brown et al., 2021; Huang et al., 2022; Muhammad and Ullah, 2022).

Wular Lake, located in the Bandipora district of Jammu and Kashmir, India, is a Ramsar wetland site of international importance (Bhat and Pandit, 2014). It is one of the largest freshwater lakes in the Indian subcontinent, playing a crucial role in regional water supply, fisheries, and biodiversity (Geelani et al., 2018). The lake is surrounded by agricultural lands and settlements, and pollution from these areas enters the lake through surface runoff, wastewater discharge, and industrial effluents (Kour et al., 2024). Despite its ecological significance, Wular Lake has been under-researched in terms of sediment geochemistry, particularly regarding heavy metal contamination. While several studies have addressed the impacts of various pollutants on lake water quality and biodiversity, comprehensive investigations into the distribution, sources, and ecological risks of heavy metals in the lake's sediments remain sparse. This study seeks to fill this gap by evaluating the spatial distribution, sources, and ecological risks of heavy metals in the surface sediments of Wular Lake. The lake's proximity to agricultural lands and settlements makes it an ideal case study for understanding the effects of anthropogenic activities on sediment contamination. This research will employ environmental risk assessment methods, including Geoaccumulation indices (Igeo), enrichment factors (EF), contamination factors (CF), and pollution load index (PLI), to assess the pollution levels in the lake. Additionally, multivariate statistical techniques, such as Pearson correlation analysis and principal component analysis (PCA), will be used to identify the relationship between heavy metal concentrations and potential pollution sources. The findings of this study will contribute to a better understanding of the environmental risks posed by heavy metal contamination in Wular Lake, supporting local authorities in their efforts to develop effective management strategies and safeguard the health of the ecosystem and the communities relying on the lake. By assessing the sources, distribution, and ecological risks of heavy metals, this study will provide valuable data to guide future environmental policies and help mitigate the adverse effects of pollution on both aquatic life and human health in the region.

2 Materials and methods

2.1 Study area

Wular Lake, a significant freshwater lake in Asia, is situated in the northwestern area of the Kashmir Himalayas, India, with coordinates 34°16′–34°32′N latitude and 74°28′–74°48′E longitude (Jamal et al., 2022). Located around 55 km from Srinagar at an altitude of 1,580 m above sea level, the lake occupies a significant geographical and biological position (Figure 1). Designated as a Wetland of International Importance under the Ramsar Convention since 1990, Wular Lake is vital to area ecology, hydrology, and socio-economic activity (Roy et al., 2022). The lake sustains a complex environment, functioning as a crucial habitat for migrating waterfowl, including ducks, shorebirds, geese, and cranes. Furthermore, it supports substantial fisheries, including endemic

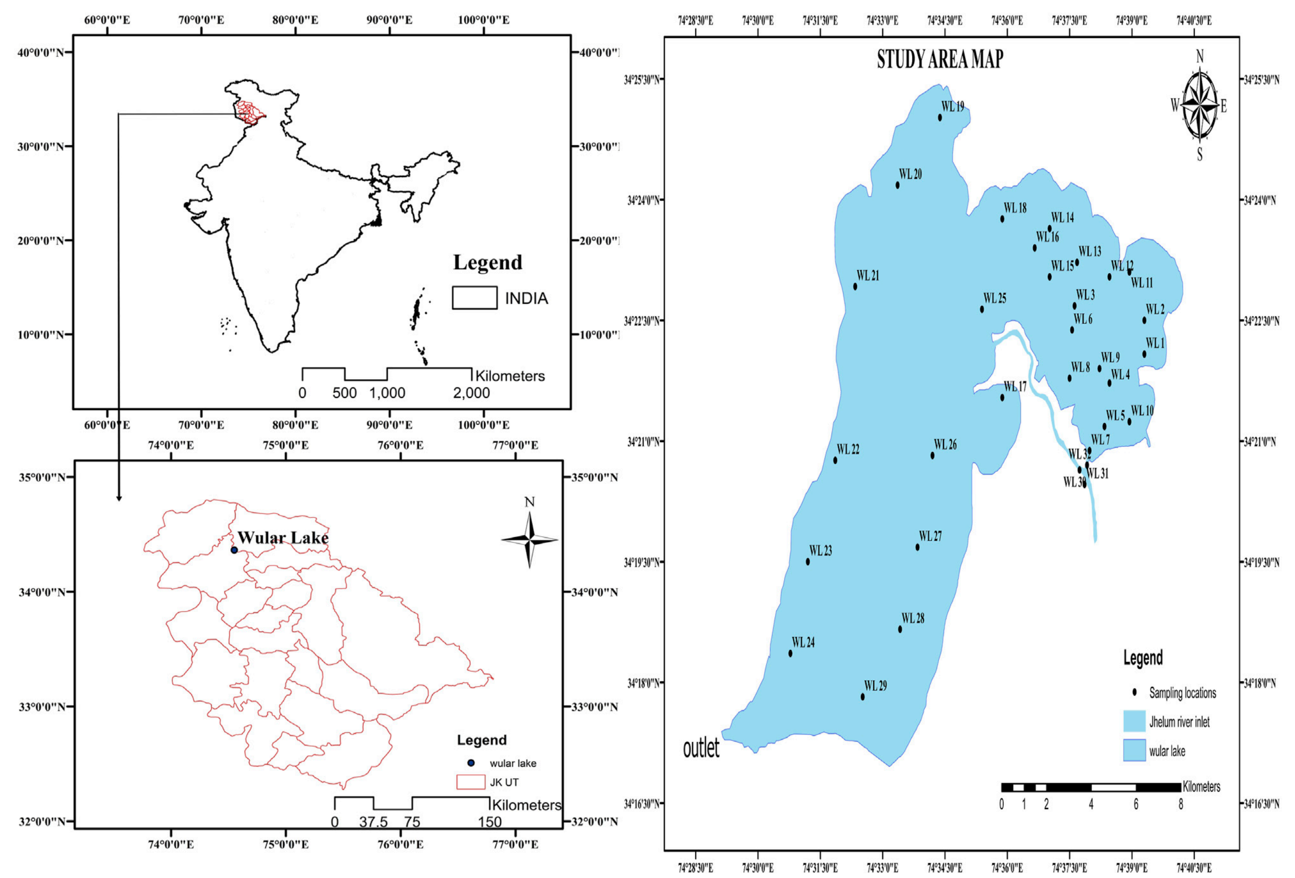

FIGURE 1
Study area map of Wular Lake with sampling locations.

and commercially important species such as *Schizothorax niger*, *Triplophysa marmorata*, and *Triplophysa kashmirensis* (Atufa et al., 2023). The lake supports aquatic flora, particularly the water chestnut (*Trapa* sp.) and lotus root (*Nelumbo nucifera*), which are essential to the local economy and traditional winter meals in the Kashmir Valley. Wular Lake is crucial in flood mitigation and water control. It constitutes a segment of the Jhelum River basin, receiving significant inflows from the Jhelum, Madhumati, and Erin rivers, and discharging into the Jhelum River at Sopore in the southwest. The lake's extensive wetland ecosystem sustains significant biodiversity, accommodating migratory and resident avifauna, ichthyofauna, and aquatic vegetation (Mushtaq et al., 2024; Qadir et al., 2024).

2.2 Sampling and data collection

We gathered 32 surface sediment samples from various lake sites using a Van Veen grab sampler. These samples were stored in pre-sterilized, durable polyethylene containers to ensure their preservation for subsequent geochemical analysis. Prior to the analysis, the sediments were air-dried at 60 °C to eliminate any remaining moisture. Once dried, the samples were finely ground using an agate mortar and pestle to achieve uniform consistency. The primary objective of the geochemical analysis was to determine the calcium carbonate ($CaCO_3$) content and the concentration of several heavy metals, following the procedures outlined by Loring and Rantala (1992). The sediments were carefully assessed for their sand, silt, and clay composition using the pipette method described by Krumbein and Pettijohn (1938). A pre-treatment process was employed to enhance the accuracy of the analysis, consisting of a mixture of 30% hydrogen peroxide (H_2O_2) and 10% acetic acid. This was aimed at reducing the interference of organic matter and carbonates in the analytical results. The organic carbon (OC) content of the sediments was determined using a conventional method, which involved exothermic oxidation with potassium dichromate and sulfuric acid, followed by titration with 0.5 N ferrous ammonium sulfate (Gaudette et al., 1974).

For the analysis of heavy metals such as Fe, Mn, Pb, Zn, Cu, Cr, and Ni, the sediment samples were first ground into a fine powder and passed through a 63-μm sieve. After preparation, a comprehensive digestion process was carried out using Aqua Regia in a Teflon bomb, as described by Yang et al. (2012). After digestion, the solution was centrifuged and appropriately diluted for further analysis. The concentrations of these metals were determined at the Department of Geology, University of Madras, India, using a Graphite Furnace Atomic Absorption Spectrophotometer (Perkin Elmer-PinAAcle 900AA). The reliability of the analytical method was validated with standard reference material (SRM, MESS-2), with heavy metal recovery rates ranging from 96.2% to 99.57% (Pradhap et al., 2020). To evaluate the spatial distribution of the measured metals, the inverse distance weighted (IDW) method was applied in ArcGIS 10.3 software. This geostatistical technique enabled the visualization of concentration gradients at the sampling locations, providing valuable insights into the distribution and accumulation patterns of heavy metals within the sediment.

2.3 Environmental pollution indices

Several contamination indices and ecological risk assessment methods were utilized to assess the presence of toxic metal contamination in the surface sediments of Wular Lake. These included the contamination factor (Cf), degree of contamination (Dc), enrichment factor (Ef), geo-accumulation index (Igeo), pollution load index (PLI), risk index (ERi), and potential ecological risk index (PERI).

2.3.1 Contamination Factor and Degree of Contamination

The evaluation of sediment contamination, specifically through the Contamination Factor (Cf) and Degree of Contamination (Dc), follows the methodology outlined by Hakanson (1980). This method plays a vital role in assessing metal concentrations in sediment samples and is a fundamental tool for monitoring sediment contamination. The Contamination Factor (Cf) is calculated by determining the ratio of each metal's concentration in the sediment to its corresponding background concentration (Equation 1). In addition, the Degree of Contamination (Dc) is obtained by summing the Contamination Factors (Cf) for all metals analyzed at a specific site (Equation 2). This approach provides a quantitative assessment of metal contamination in the sediment, offering valuable insights into the environmental condition and potential pollution sources in the study area (Barik et al., 2018).

$$Cf = \frac{M_x}{M_b} \tag{1}$$

$$Dc = \sum_{i=1}^{i=n} Cf \tag{2}$$

In this context, Mx represents the concentration of a specific metal in the sediment under analysis, while Mb refers to the reference or geochemical background value. The variable n indicates the number of elements analyzed within the sediment sample. Given the lack of local background values, this study utilized the geochemical background values for shales as proposed by Turekian and Wedepohl (1961).

2.3.2 Enrichment factor (Ef)

The enrichment factors of metals were calculated (Equation 3) to assess the impact of human activities or natural metal-processing processes on the lake sediments. Iron (Fe) was selected as the normalisation element for this study, as it provides a dependable baseline for identifying unusual metal concentrations. Consequently, the enrichment factor (Ef) can be expressed as follows:

$$EF = \frac{(Cn/CFe)\, sample}{(Cn/CFe)\, background} \tag{3}$$

In Equation 3, Cn (sample) and CFe (sample) signify the concentrations of the target metal and the reference element (Fe) in the sediment samples, respectively, while Cn (crust) and CFe (crust) indicate the concentrations of these elements at the reference location. The numerator indicates the ratio of the concentration of the element of interest to that of Fe in the sediment sample, while the denominator signifies the natural background concentration of Fe. Different categories for the enrichment factor are shown in Supplementary Table 1.

2.3.3 Geo-accumulation index (Igeo)

The Geo-Accumulation Index (Igeo) is widely employed to assess elemental contamination in sediments (Feng et al., 2019). Muller (1969) proposed the following equation (Equation 4) for calculating Igeo, which is expressed as:

$$I_{geo} = log_2\left(\frac{C_n}{1.5Bn}\right) \tag{4}$$

In this equation, Cn represents the observed concentration of the heavy metal in the sediment, while Bn is the geochemical background concentration of the element. The factor 1.5 is applied to account for any variations in the background data due to lithological influences. The different classification categories for Igeo are detailed in Supplementary Table 1.

2.3.4 Pollution load index (PLI)

As a cumulative measure of the total heavy metal contamination in a sample, the Pollution Load Index (PLI) provides a very effective way for measuring sediment contamination levels (Muller, 1969). To determine PLI for every location of sediment sample, Tomlinson et al. (1980) proposed the following equation (Equation 5).

$$PLI = (Cf_1 \times Cf_2 \times Cf_3 \times ...Cf_n)^{\frac{1}{n}} \tag{5}$$

Here, n stands for the number of metals examined in each sample, and Cf is the contamination factor for the metals found in the sediment samples. After tallying the PLI values from each sediment-sampling location, the *n*th root of the product was used to get the PLI for Wular Lake Equation 6. The sediments are grouped into two groups based on the PLI values, which are shown in Supplementary Table 1: unpolluted (PLI < 1) and contaminated (PLI > 1).

$$PLI = (PLI_1 \times PLI_2 \times PLI_3 \times ...PLI_n)^{\frac{1}{n}} \tag{6}$$

2.3.5 Potential ecological risk index and ecological risk

For the purpose of evaluating the dangers that heavy metals in sediments bring to the ecosystem, Hakanson (1980) developed the Ecological Risk Index (Ri), which can be seen in Equation 7. By taking into account the sensitivity of different populations to harmful substances, the RI calculates the ecological risk of heavy metals in sediment.

$$R_i = TR_i \times Cf^i \tag{7}$$

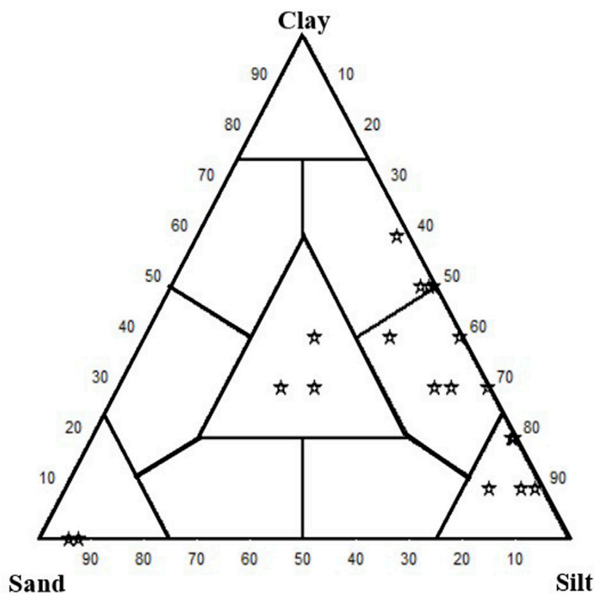

FIGURE 2
Ternary plot of Shepard's sediment classification based on sand, silt, and clay proportions in Wular Lake sediments.

Toxic response factor for metal i, TRi, is given by Equation 7. The values of 1, 2, 5, 6, and 1 for the toxic response factors for Zn, Cr, Cu, Pb, Ni, and Fe were taken from Hakanson (1980). Additional information may be found in Supplementary Table 1, which shows the four levels of ecological risk. Using the method given in Equation 8 by Hakanson (1980), the Potential Ecological Risk Index (PERI) was computed to assess the cumulative harmful effect of the studied heavy metals (HMs) on aquatic life. Also, as shown in Supplementary Table 1, the PERI was ranked from low to high into four distinct groups.

$$PERI = \sum_{i=1}^{n} R_i \tag{8}$$

2.4 Multivariate data analysis

In this study, Pearson's correlation coefficients (r) were employed to evaluate the linear relationships between sediment characteristics and heavy metal concentrations (Liu et al., 2003). These coefficients are crucial for determining both the strength and direction of the correlations among the variables being studied. To further investigate the interactions between sediment properties and heavy metal levels, cluster analysis (CA) was conducted. This method grouped the variables based on their similarities, helping to identify patterns in the data (Ma et al., 2016; Lone et al., 2018). Additionally, Principal Component Analysis (PCA), a common technique for data reduction, was used to reveal underlying patterns and to differentiate between similarities and differences within the dataset (Liu et al., 2023). By simplifying the data, PCA condenses it into principal components that capture a significant portion of the variability. The outcomes of the CA were displayed in a dendrogram, which visually organized the clusters, offering insights into potential sources of heavy metals in the sediments. A second dendrogram, generated using Ward's method, further highlighted the similarity between various sampling locations, which is useful for identifying sites with comparable contamination profiles. All statistical analyses were performed using IBM SPSS software (version 21) and Origin Pro 2024.

3 Results

3.1 Sediment texture characteristics

The grain size analysis across the 32 sampling locations revealed a diverse range of sediment textures as shown in (Figure 2; Supplementary Table 1). The sand content varied significantly, ranging from a minimum of 0.2% at site WL 10 to a maximum of 94.2% at WL 31. Silt emerged as the predominant grain size fraction at most sites, with values spanning from 5.8% at WL 31 to as high as 88.8% at WL 1. Clay content also showed substantial variability, ranging from 0% at WL 9%–60% at both WL 18 and WL 19. Only four sites were classified as sandy sediments, where sand comprised more than 50% of the sample: WL 7 (92.4% sand), WL 9 (92.4% sand), WL 31 (94.2% sand), and WL 32 (92.4% sand). Conversely, six sites were characterized by high clay content, exceeding 30%: WL 11 (50% clay), WL 14 (30% clay), WL 16 (30% clay), WL 18 (60% clay), WL 19 (60% clay), and WL 27and WL 28 (40% clay). The remaining 22 sites predominantly consisted of silt-sized particles, with silt content surpassing 60% of the total sample (Supplementary Table 1). The spatial distribution of sediment textures revealed distinct trends across the study area (Figure 3). Sand-rich sediments were primarily concentrated in the central and south western regions, as observed at sites WL 9, WL 24, WL 29, and WL 32. In contrast, clay-dominated sediments (>30% clay) were predominantly found in the eastern region, particularly at WL 18, WL 19, WL 20, and WL 27. Silt-rich sediments (>60% silt) were more widely dispersed throughout the study area, with a higher concentration in the northern and eastern extremities, exemplified by WL 1, WL 2, WL 3, WL 23, and WL 26 (all containing over 75% silt).

3.2 Geochemical properties analysis

The calcium carbonate ($CaCO_3$) content of the sediments varied across the 32 sampling locations, ranging from 1.15% to 5.98% (Supplementary Table 1). The lowest $CaCO_3$ percentage was observed at site WL 23 (1.15%), while the highest value of 5.98% was recorded at WL 31. Spatially, higher $CaCO_3$ concentrations (>4%) were generally found in the southern and eastern regions, particularly at sites WL 12, WL 29, WL 30, WL 31, In contrast, the western and central sites, such as WL 21, WL 22, WL 23, and WL 24, exhibited relatively lower $CaCO_3$ levels, typically below 3% (Figure 4). The organic matter (OM) content of the sediments ranged from 1.14% to 14.89%, with an average of 7.69% across all sites (Supplementary Table 1). The highest OM percentage of 14.89% was found at WL 18, and WL 19 while the lowest value of 1.42% occurred at WL 31. Unlike the $CaCO_3$ distribution, no clear

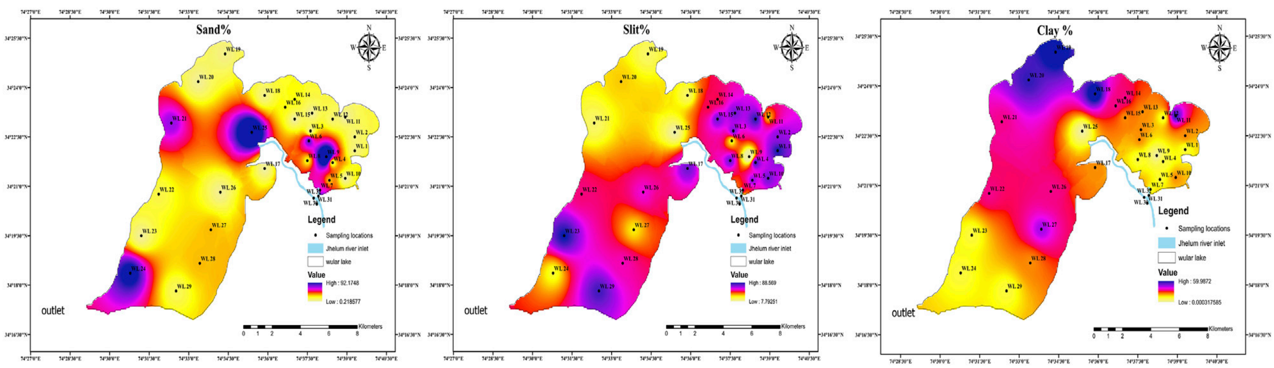

FIGURE 3
Interpolation diagrams depicting the spatial distribution of Sand **(a)**, Slit **(b)** and Clay **(c)** percentages in the surface sediments of Wular Lake.

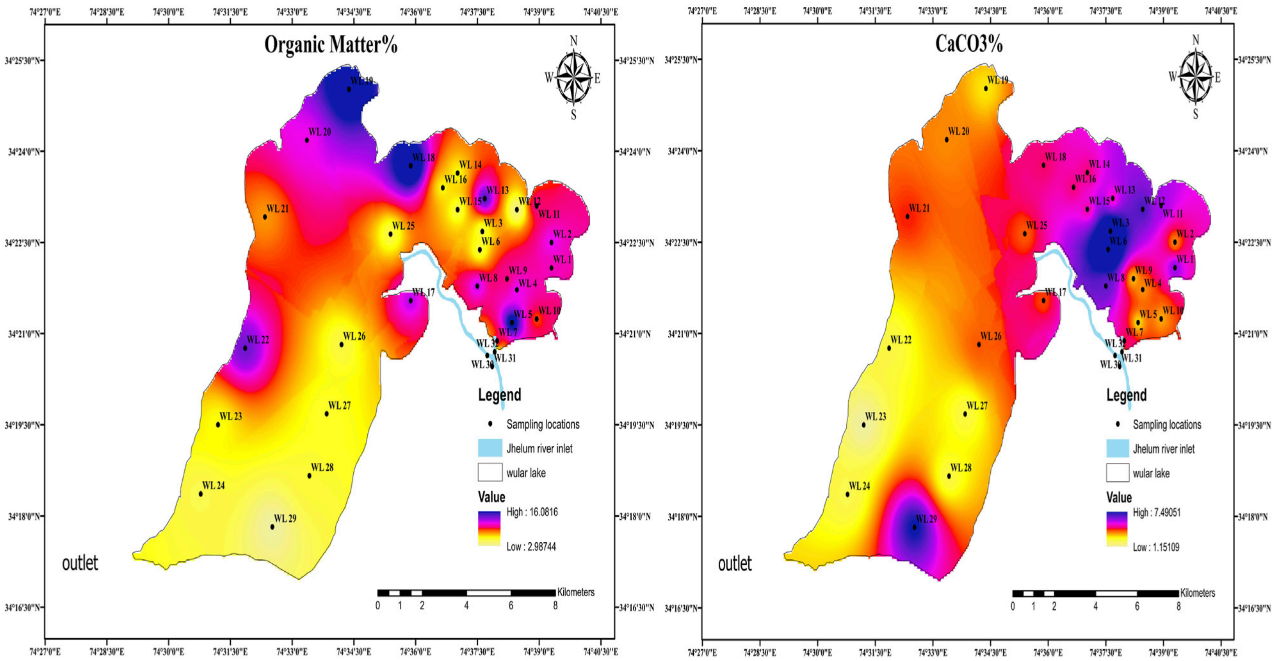

FIGURE 4
Interpolation diagrams depicting the spatial distribution of CaCO3, Organic matter percentages in the surface sediments of Wular Lake.

spatial pattern was observed for OM content. However, several sites displayed notably elevated OM levels, in the northern and eastern sites including WL 18 (14.89%), WL 5 (14%), WL 19 (14.89%), and WL 8 (9.98%) (Figure 4).

3.3 Heavy element distribution and concentrations in Wular lake sediments

The spatial distribution and concentrations of heavy metals within the sediments of Wular Lake were systematically analyzed to assess the levels of enrichment, contamination, and potential ecological risks associated with these elements. A total of 32 distinct sampling locations were examined, with measurements taken for heavy metals including Cobalt (Co), Copper (Cu), Iron (Fe), Manganese (Mn), Nickel (Ni), Lead (Pb), Zinc (Zn), and Chromium (Cr) as shown in Supplementary Table 1. The concentrations were subsequently compared to the natural background levels of these elements by Turekian and Wedepohl (1961) in the Earth's crust to determine deviations indicative of anthropogenic contamination [43]. The spatial distribution of Nickel, Lead, Zinc and Manganese is shown in Figure 5. Manganese concentrations exhibited significant variability, ranging from 1,046 mg/kg at WL1 to 2,041 mg/kg at WL17, with an average concentration of 1,478 mg/kg. When compared to the Earth's crustal value of 850 mg/kg, the manganese levels in Wular Lake are considerably higher, indicating potential contamination from human activities. Manganese is commonly used in industrial

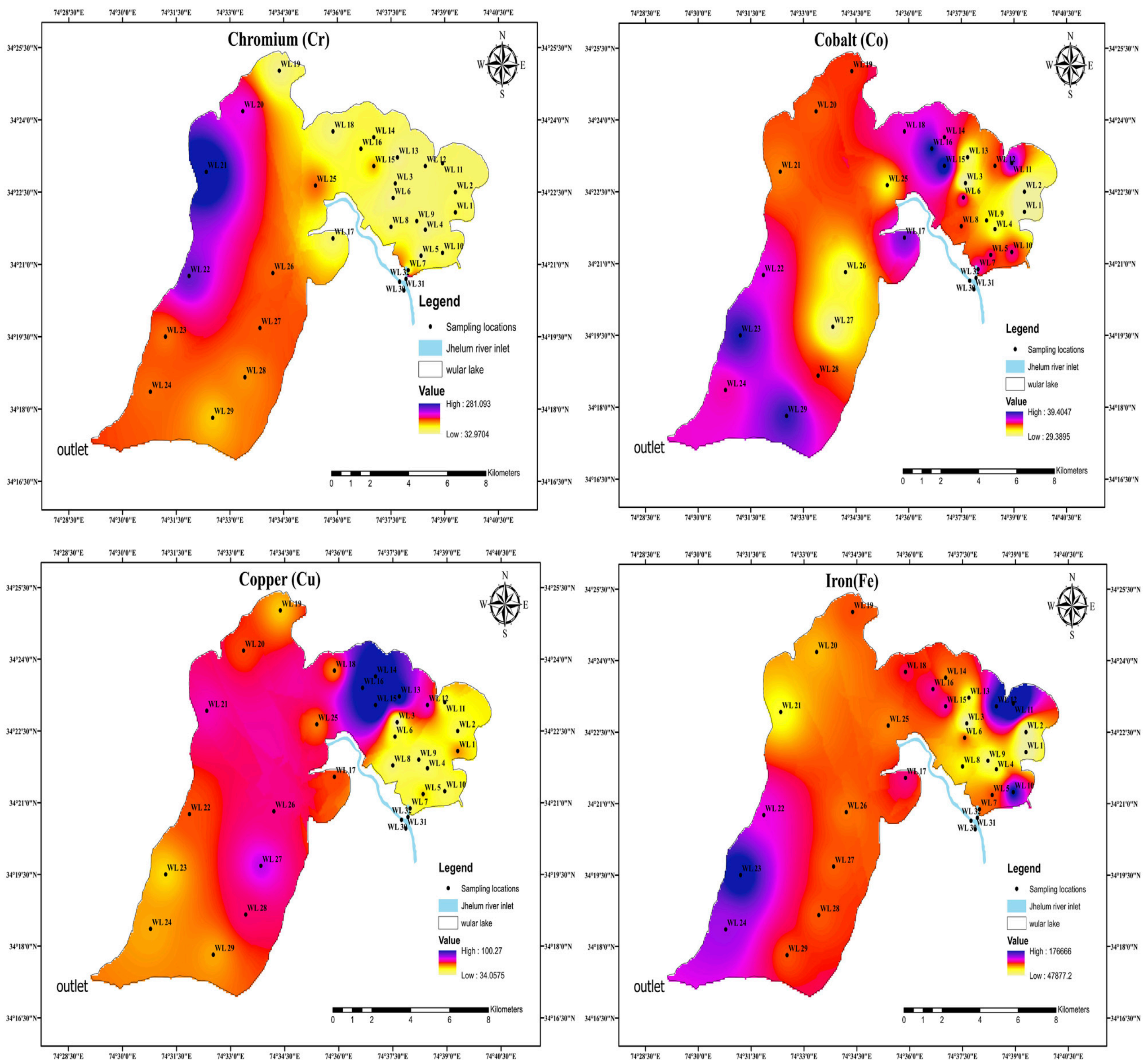

FIGURE 5
Spatial distribution of Chromium, Cobalt, Copper and Iron in the sediment samples collected from the Wular Lake.

processes such as steel production and can be introduced into aquatic environments through runoff or atmospheric deposition. The spatial distribution of manganese shows higher concentrations in the central and western parts of the lake.

Nickel concentrations in the sediments ranged from 62.57 mg/kg at WL3 to 97.72 mg/kg at WL15, with an average concentration of 78.85 mg/kg. Although these values are elevated, they are relatively close to the Earth's crustal value of 68 mg/kg. The slight enrichment of nickel in certain locations may be attributed to anthropogenic sources such as industrial effluents, urban runoff, and vehicular emissions. Nickel is commonly used in various industries, including electroplating and manufacturing. Higher concentrations were observed in the southern and eastern regions of the lake, aligning with areas of potential human influence. Lead concentrations across the sampling locations ranged from 6.33 mg/kg at WL1 to 12.03 mg/kg at WL13, with an average concentration of 9.43 mg/kg. These values are below the Earth's crustal background level of 20 mg/kg, suggesting that lead contamination in the sediments is relatively low compared to other heavy metals. However, localized enrichment at specific sites (e.g., WL13) may indicate potential sources of lead pollution, such as the use of lead-based paints, batteries, and vehicle emissions. Lead distribution is generally more uniform, with no significant hotspots of contamination but showing higher values on the norther region of the lake Zinc concentrations in Wular Lake sediments showed substantial variation, with the highest concentration of 237.74 mg/kg recorded at WL23 and the lowest concentration of 72.13 mg/kg at WL3. The average concentration of zinc across all locations was 113.3 mg/kg. These values are higher than the Earth's crustal average of 95 mg/kg, indicating

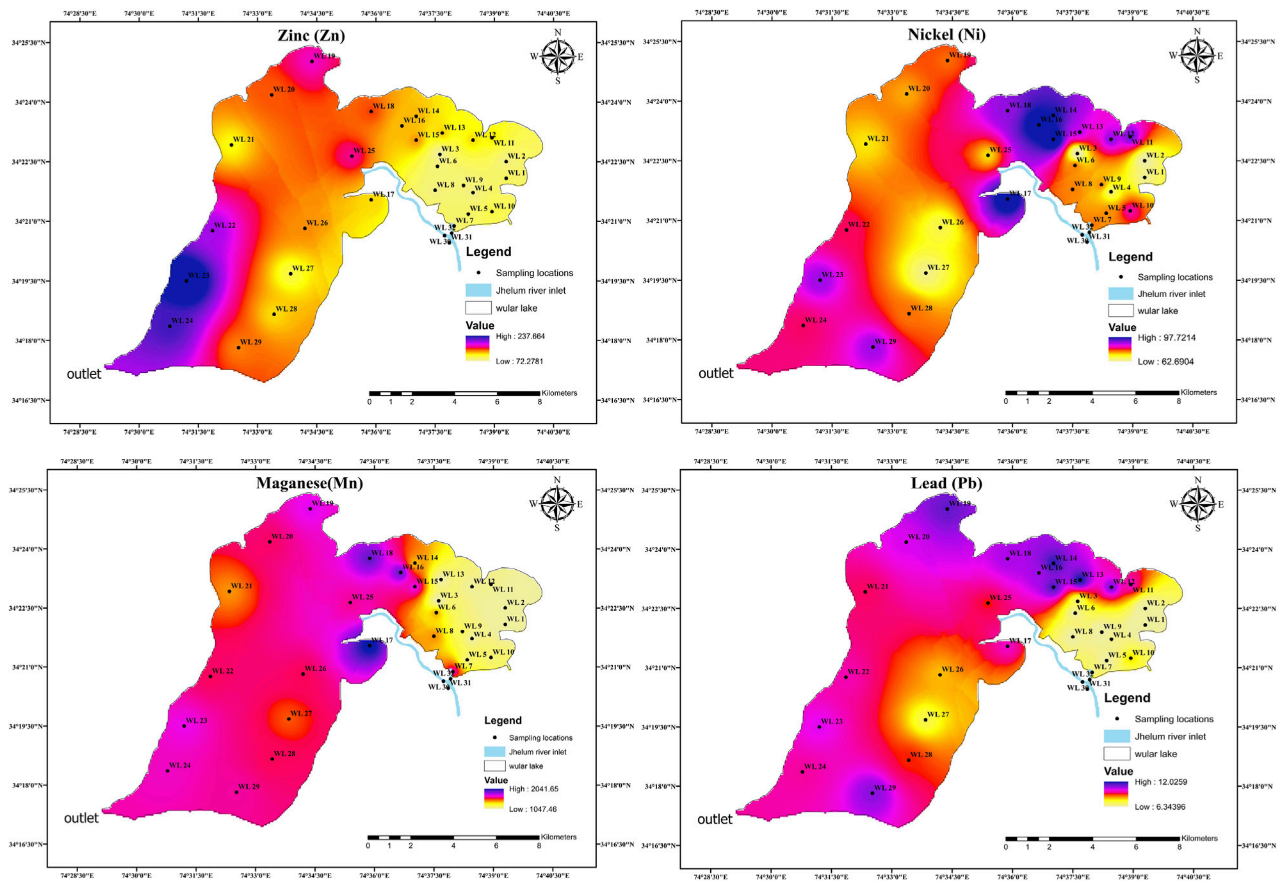

FIGURE 6
Spatial distribution of Nickel, Lead, Zinc and Manganese in the sediment samples collected from the Wular Lake.

anthropogenic enrichment. Zinc is commonly used in fertilizers, pesticides, and various industrial applications, and its presence in elevated concentrations suggests contamination from agricultural runoff. The highest concentrations of zinc were observed in the southern parts of the lake near the outlet, particularly at WL23.

The spatial distribution of Chromium, Cobalt, Copper and Iron in the sediment samples collected from the Wular Lake is shown in Figure 6. The concentrations of cobalt in the Wular Lake sediments ranged from a minimum of 29.35 mg/kg at sampling location WL3 to a maximum of 39.41 mg/kg at WL15, with an average concentration of 34.26 mg/kg across all locations. When compared to the Earth's crustal average of 19 mg/kg, cobalt levels in the sediments of Wular Lake are significantly elevated, suggesting potential inputs from, agricultural, or urban sources. The highest concentrations were observed in the southern and central regions of the lake, where anthropogenic activities are likely to contribute to the elevated cobalt levels. Copper concentrations varied widely across the sampling locations, with the lowest concentration of 33.91 mg/kg recorded at WL3 and the highest concentration of 100.29 mg/kg observed at WL15. The average concentration of copper was 53.2 mg/kg. These values exceed the natural background concentration of copper in the Earth's crust, which is 45 mg/kg. The elevated copper levels indicate possible contamination from agricultural runoff, and other human activities, as copper is commonly used in fertilizers, pesticides, and industrial processes. The spatial distribution of copper shows higher concentrations predominantly in the southern and central regions of the lake. Iron was the most abundant metal in the Wular Lake sediments, with concentrations ranging from 47,758 mg/kg at WL1 to 176,867 mg/kg at WL11. The average concentration of iron across all locations was 83,553 mg/kg. These values are close to the natural background level of 47,200 mg/kg in the Earth's crust, suggesting that iron concentrations in the lake may be primarily of natural origin, such as weathering of rocks and soil erosion. However, the extremely high concentrations observed at certain locations (e.g., WL11) may point to localized contamination from urban discharges, particularly in the southern and northeastern parts of the lake.

Chromium concentrations exhibited a broad range, from 32.6 mg/kg at WL5 to 282.5 mg/kg at WL31, with an average concentration of 96.08 mg/kg. The average chromium concentration in the lake sediments is slightly higher than the Earth's crustal value of 90 mg/kg, with some locations exhibiting significantly elevated levels. Chromium is often associated with industrial processes, including tanning, electroplating, and the production of stainless steel. The high concentrations observed at certain locations suggest potential contamination from industrial sources or urban runoff. Chromium distribution in the lake is more

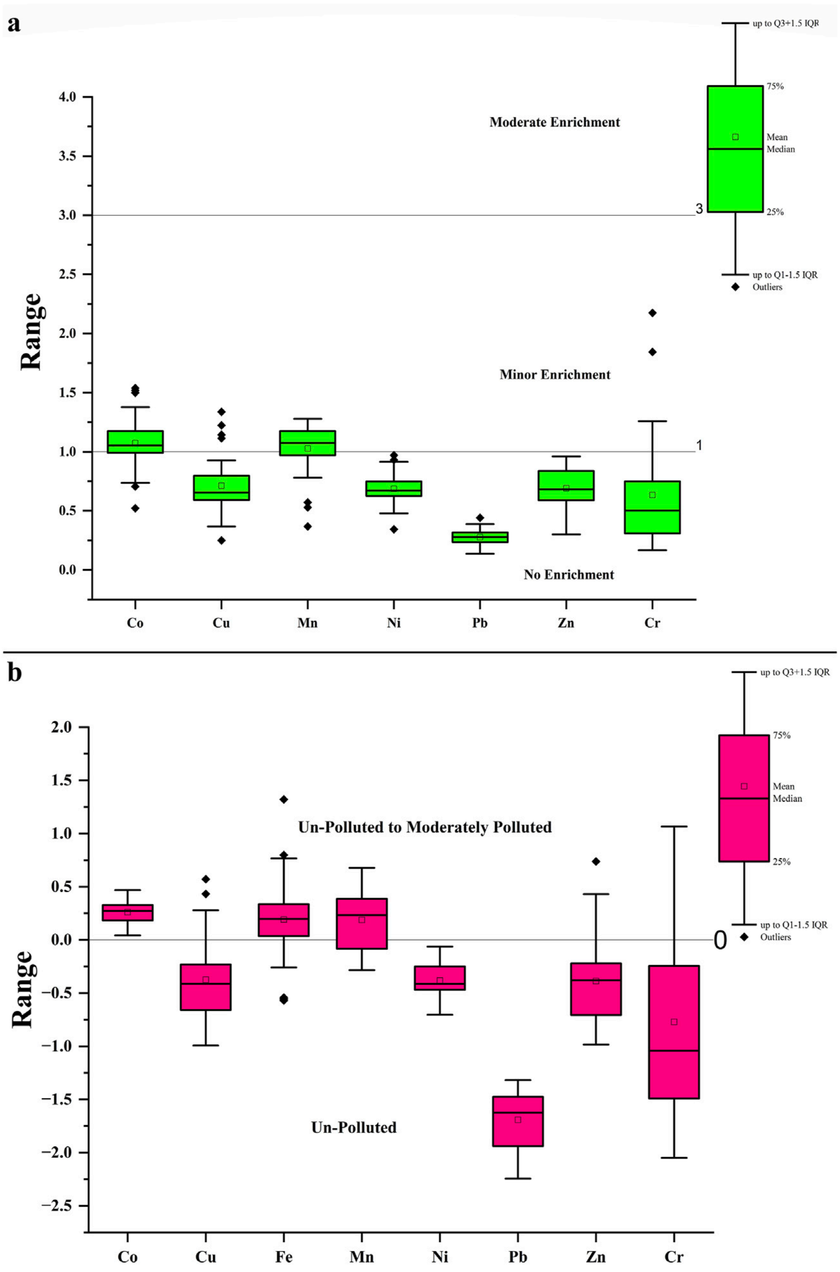

FIGURE 7
Box plot illustrating the enrichment factor **(a)** and the geo-accumulation (Igeo) index **(b)** for the sediments of Wular Lake.

prominent in the central and southern regions. A comparison of the heavy metal concentrations in Wular Lake sediments with Earth's crustal values reveals varying degrees of enrichment for different elements. Cobalt, copper, manganese, nickel, zinc, and chromium all exhibit concentrations above their respective natural background levels, suggesting anthropogenic input. Iron, while present in high concentrations, remains close to its crustal average, indicating that natural processes likely dominate its distribution. Lead concentrations, on the other hand, are lower than the Earth's crustal background, indicating minimal contamination. These findings underscore the influence of human activities on the lake's sediment composition, particularly in relation to agricultural runoff, and urban development.

3.4 Environmental risk assessment

The study used well-known environmental indicators, such as Contamination Factor and Degree of Contamination, Enrichment Factor (EF), geo-accumulation index (Igeo), Pollution Load Index and Potential Ecological Risk Index (PERI).

3.4.1 Contamination factor (Cf) and degrees of contamination

The evaluation of Contamination Factors (Cf) across all sampling locations from WL1 to WL32 as shown in Supplementary Table 2 highlights distinct patterns of heavy metal contamination, indicating varying environmental risks. Cobalt (Co) consistently exhibited moderate contamination, with Cf values ranging from 1.544 to 2.074 across the locations, suggesting a moderate ecological concern. Copper (Cu) displayed low to moderate contamination, with Cf values between 0.753 and 2.228, indicating that some sites experienced elevated contamination but generally remained below considerable risk levels. Iron (Fe) showed considerable variability, with Cf values from 1.011 to 3.747, implying low to considerable contamination, particularly at certain sites such as WL11 and WL32 where contamination levels were significantly higher. Manganese (Mn) demonstrated moderate contamination across most locations, with Cf values ranging from 1.231 to 2.402, while Nickel (Ni) was generally classified under low to moderate contamination. Lead (Pb) remained at consistently low contamination levels across all sites, with Cf values below 1, reflecting minimal environmental concern. Zinc (Zn) and Chromium (Cr) exhibited Cf values that indicated low to moderate contamination, although Cr contamination approached considerable levels at certain locations, such as WL32.

The analysis of the Degree of Contamination (Dc) across locations WL1 to WL32 revealed that most sites exhibited moderate contamination, with Dc values ranging from 7.216 at WL3 to 13.237 at WL32, indicating a more significant contamination risk in certain areas (Supplementary Table 2). Sites such as WL1, WL3, WL7, and WL10 demonstrated the lowest Dc values, indicating relatively lower contamination risks, whereas sites like WL23, WL29, and WL32, exhibited higher Dc values, raising concerns about elevated ecological threats. The average Cf values across the metals, in ascending order, are as follows: Pb (0.477) < Ni (1.209) < Cu (1.271) < Zn (1.344) < Cr (1.630) < Fe (1.758) < Mn (1.807) < Co (1.801). These values highlight that Lead (Pb) poses the least contamination risk, while Iron (Fe), Chromium (Cr), and Manganese (Mn) present higher contamination potential, particularly in locations with higher Dc values like WL32. The results suggest that while overall contamination is moderate, continuous monitoring is essential in areas with elevated contamination to mitigate potential environmental impacts.

3.4.2 Enrichment factor

The analysis of the Enrichment Factor (EF) for heavy metals in Wular Lake reveals a varying degree of contamination across different elements at different locations. The distribution of EF values across the sites is depicted in the boxplots in Figure 7a. Lead (Pb) exhibits the lowest level of enrichment, with an EF of 0.31 at location WL1 and 0.18 at location WL10, indicating that lead concentrations are well within natural background levels across all sampled locations. The mean EF for lead is 0.25, confirming that there is no significant lead contamination in the lake sediments. For Nickel (Ni), the EF values indicate no significant contamination, with an EF of 0.97 at location WL1 and 0.48 at location WL10. The mean EF for nickel across the sampled locations is 0.69, suggesting that nickel is largely present at background levels with little evidence of anthropogenic enrichment. Chromium (Cr) shows more variability, with location WL32 exhibiting an EF of 2.18, indicating minor enrichment, while at location WL11, the EF is as low as 0.17, suggesting no enrichment. The mean EF for chromium is 0.72, suggesting that while most locations show no enrichment, certain areas may experience localized chromium contamination.

In the case of Copper (Cu), the EF values vary significantly across locations, with an EF of 1.11 at location WL1 indicating minor enrichment, while location WL13 has a much lower EF of 0.51, suggesting copper concentrations near natural background levels. The mean EF for copper is 0.77, placing it in the no enrichment category at most locations, with minor enrichment only observed in specific sites. For Zinc (Zn), the EF values remain close to 1 across all locations, with 0.91 at location WL1 and 0.82 at WL2, suggesting little to no enrichment. The mean EF for zinc is 0.83, which further confirms that zinc contamination is minimal, with concentrations largely remaining at background levels across the sampling sites. Manganese (Mn) displays higher enrichment compared to other metals, with an EF of 1.58 at location WL8, indicating minor enrichment, while location WL11 shows a lower EF of 0.37, indicating no enrichment. The mean EF for manganese is 1.04, suggesting minor enrichment across most locations, with a few areas showing elevated levels that could be linked to anthropogenic activities. Finally, Cobalt (Co) shows an EF of 1.54 at location WL1, indicating minor enrichment, while location WL10 exhibits a lower EF of 0.74, suggesting no enrichment. The mean EF for cobalt is 1.03, which suggests that there is minor enrichment of cobalt in some locations, likely due to localized anthropogenic inputs. The Mean Enrichment values in Ascending Order are Lead (Pb): 0.25 <Nickel (Ni): 0.69 <Chromium (Cr): 0.72<Copper (Cu): 0.77<Zinc (Zn): 0.83<Cobalt (Co): 1.03 <Manganese (Mn): 1.04.

3.4.3 Geo-accumulation index (Igeo)

The Geo-accumulation Index (Igeo) assessment for heavy metals in Wular Lake's surface sediments revealed that most metals fall within the unpolluted to moderately polluted range, with mean Igeo values as follows: Cobalt (Co) recorded a mean Igeo of 0.26, indicating slight contamination, while Copper (Cu) had a mean of −0.37, reflecting an uncontaminated status. Similarly, iron (Fe) and Manganese (Mn) exhibited Igeo values of 0.19, suggesting potential minor contamination. Nickel (Ni), with an Igeo of −0.38, and Lead (Pb), the lowest at −1.69, are well within the uncontaminated category, indicating no significant pollution. Zinc (Zn), with an Igeo of −0.39, and Chromium (Cr), with a mean of −0.77, also point to low contamination levels. The boxplot (Figure 7b) visualization further supports these findings, showing that most metals are categorized as unpolluted or slightly contaminated, with some variability for chromium, iron, and manganese, but overall, the lake's sediments are largely uncontaminated, posing minimal ecological risk from heavy metal pollution.

3.4.4 Pollution load index (PLI)

Pollution Load Index (PLI) assessments conducted at 32 sites throughout Wular Lake, which indicate a wide range of pollution levels around the lake (Figure 8; Supplementary Table 2). A moderate amount of pollution inside the lake's ecology is suggested by the average PLI, which stands at 1.17 for all tested areas. The cumulative influence of several pollutants on environmental quality is reflected in this score. There are

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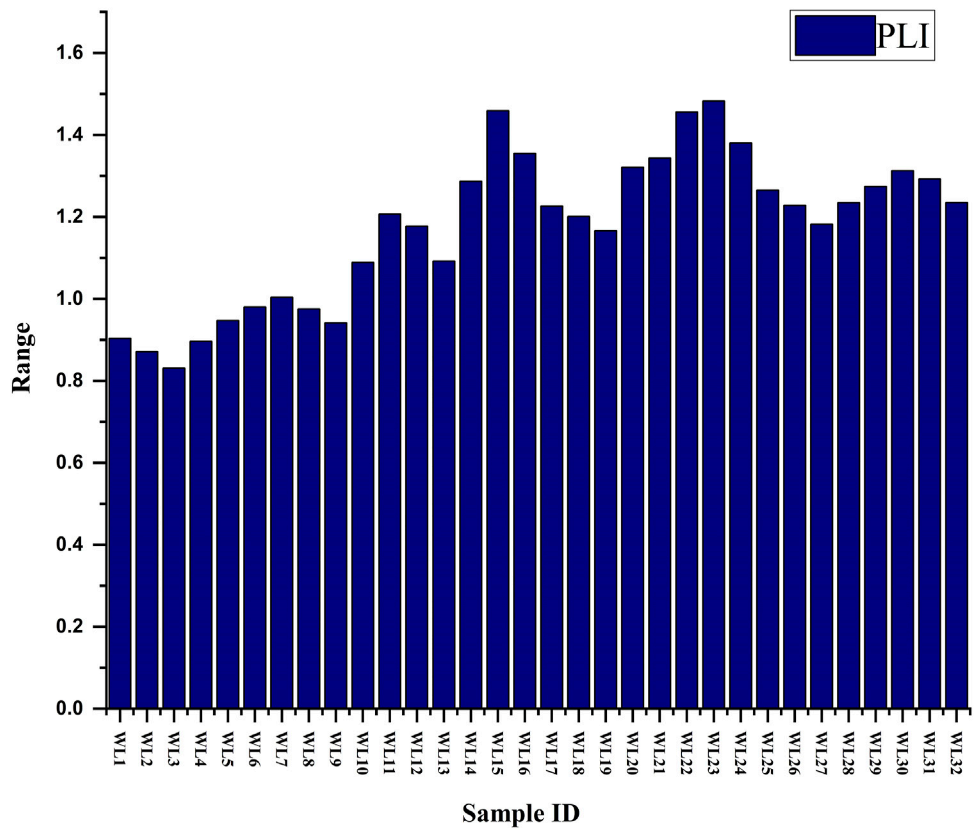

FIGURE 8
Pollution Load Index (PLI) values of surface sediment samples from the Wular Lake.

noticeable pollution patterns that emerge from point-by-point analyses. With heightened contamination factors for nickel (Ni), zinc (Zn), and chromium (Cr), Location WL23 records the highest PLI score of 1.48. This indicates large pollutant concentrations that boost the PLI, signalling a critical environmental problem. As a result of lower copper (Cu) and manganese (Mn) contamination factors, Location WL3 stands out with the lowest PLI of 0.83. This site's PLI is much lower than the lake-wide average, indicating a comparatively unpolluted environmental situation due to the reduced pollution. The necessity for targeted monitoring and cleanup in the most severely polluted areas is highlighted by the fact that PLI levels vary throughout Wular Lake.

3.4.5 Potential ecological risk index (PERI)

The assessment of the Potential Ecological Risk Index (PERI) for heavy metals across 32 sampling locations in Wular Lake (Supplementary Table 3) revealed an average PERI value of 19.20, categorizing the lake under the low-risk level of ecological threat. The individual ecological risk index (Ri) values for heavy metals also suggest varying contributions to the overall ecological risk, with manganese (Mn) having an average Ri of 1.74, chromium (Cr) at 2.14, copper (Cu) at 5.98, lead (Pb) at 2.36, zinc (Zn) at 1.19, and nickel (Ni) presenting the highest average Ri value at 5.80. Despite these differences, all Ri values remain well below 40, indicating that each of these metals presents a low ecological risk according to the established risk classification criteria. The PERI values for the individual sampling locations range between 13.4 and 26.6, with the highest PERI recorded at Location WL15 and the lowest at Location WL3. The consistency of these values, all of which remain below the threshold of 150, confirms that Wular Lake is currently subjected to low potential ecological risk. No sampling locations approach the moderate or higher risk thresholds, underscoring the relatively stable and non-threatening levels of heavy metal contamination in the lake's sediments. The overall findings suggest that while heavy metals such as nickel (Ni) and copper (Cu) exhibit the highest individual ecological risk values, their concentrations do not pose an immediate threat to the aquatic environment. The cumulative PERI for all metals across the lake remains firmly within the low-risk category, indicating that Wular Lake is not facing significant ecological danger from metal pollution at present. However, continued monitoring and preventive measures are essential to maintain these low-risk levels and to avoid potential future escalations in contamination that could lead to more severe ecological risks.

3.5 Multivariate statistical analysis

3.5.1 Pearson's correlation

The Pearson correlation matrix was used to assess the linear relationships between various heavy metals and sediment properties

Pearsons Correlations

	COBALT	COPPER	IRON	MANGANESE	NICKEL	LEAD	ZINC	CHROMIUM	CLAY	SLIT	SAND	CALCIUM	OM
COBALT	1												
COPPER	0.285	1											
IRON	.626**	0.020	1										
MANGANESE	.629**	0.228	0.162	1									
NICKEL	.839**	.578**	.540**	.502**	1								
LEAD	.557**	.627**	.418*	.469**	.724**	1							
ZINC	.439*	0.161	.410*	.516**	0.341	.585**	1						
CHROMIUM	-0.032	0.088	-0.032	0.206	-0.142	0.074	0.207	1					
CLAY	0.281	0.078	0.324	.359*	0.160	.477**	.531**	-0.012	1				
SLIT	-0.169	0.197	-0.075	-0.314	0.024	-0.011	-0.154	-.449**	0.006	1			
SAND	-0.019	-0.206	-0.121	0.056	-0.110	-0.260	-0.173	.376*	-.568**	-.826**	1		
CALCIUM CARBONATE	-0.085	0.162	-0.123	-0.182	0.144	-0.027	-.359*	0.055	-.447*	0.123	0.151	1	
OM	0.037	-0.310	-0.036	0.109	-0.092	-0.096	0.090	-0.301	.357*	-0.036	-0.171	-.615**	1

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

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

FIGURE 9
Pearson Correlation Coefficients between Heavy Metals and Sediment Characteristics.

within the Wular Lake shown in (Figure 9). The following are the key relationships found in the matrix: Cobalt (Co) demonstrated strong positive correlations with Nickel (Ni) ($r = 0.83$), Iron (Fe) ($r = 0.62$), and Manganese (Mn) ($r = 0.62$). The association of Co with other metals such as Lead (Pb) ($r = 0.55$) and Zinc (Zn) ($r = 0.43$) points toward potential urban pollution or vehicular emissions. Nickel (Ni) displayed significant positive correlations with Cobalt (Co) ($r = 0.83$), Lead (Pb) ($r = 0.72$), and Iron (Fe) ($r = 0.54$). Copper (Cu) had a positive correlation with Lead (Pb) ($r = 0.62$) and a moderate correlation with Nickel (Ni) ($r = 0.57$), suggesting overlapping pollution pathways, Iron (Fe) correlated with Nickel (Ni) ($r = 0.54$, $p < 0.01$) and Lead (Pb) ($r = 0.418$, $p < 0.05$). Its correlation with Zinc (Zn) ($r = 0.410$) also points toward common geochemical or industrial sources. Lead (Pb) exhibited strong positive correlations with Nickel (Ni) ($r = 0.724$), Copper (Cu) ($r = 0.62$), and Zinc (Zn) ($r = 0.58$), underscoring their probable anthropogenic origins, particularly linked to urban runoff. Zinc (Zn) correlated positively with Lead (Pb) ($r = 0.58$), Iron (Fe) ($r = 0.41$), and Nickel (Ni) ($r = 0.34$), which suggests that Zn is co-deposited with these metals through similar processes. Clay content was positively correlated with Zinc (Zn) ($r = 0.53$) and Lead (Pb) ($r = 0.47$), indicating that finer particles tend to accumulate higher concentrations of heavy metals. Sand content exhibited a strong negative correlation with Clay ($r = -0.56$) and Silt ($r = -0.82$), which is expected as sand represents the coarser sediment fractions, while clay and silt are finer fractions. These correlations underscore the interplay between sediment properties and heavy metals, suggesting that fine particles (clay and silt) act as important reservoirs for metals, while sand shows weaker relationships.

3.5.2 Factor analysis

Factor analysis was applied to simplify the dataset and reveal underlying factors driving the distribution of heavy metals and sediment properties. This analysis identified four main components that together explain 77.104% of the total variance in the dataset as shown in Supplementary Table 4. The rotation of components allowed for a clearer interpretation of the data (Supplementary Table 5). Component 1 explained 32.2% of the variance and was dominated by heavy metals such as Nickel (Ni) (loading = 0.90), Cobalt (Co) (loading = 0.91), and Iron (Fe) (loading = 0.71). This component likely represents industrial pollution sources and indicates that these elements are being deposited from similar sources, possibly linked to vehicular emissions and industrial activities. Component 2, accounting for 18.5% of the variance, was characterized by Zinc (Zn) (loading = 0.75), Lead (Pb) (loading = 0.61), and Manganese (Mn) (loading = 0.53), which suggests that this factor is associated with urban and wastewater pollution. Component 3 accounted for 16.8% of the variance within the dataset, predominantly associated with sediment texture variables, namely, Sand (loading = 0.91) and Silt (loading = −0.91). The opposing loadings indicate that higher sand content aligns positively with this component, while higher silt content aligns negatively. This component underscores the influence of sediment texture in shaping the distribution of heavy metals within the sediment matrix, suggesting that variations in sand and silt proportions are critical factors in the environmental dynamics of heavy metal accumulation. Component 4, which explained 9.475% of the variance, displayed strong associations with Calcium Carbonate ($CaCO_3$) (loading = 0.73) and Organic

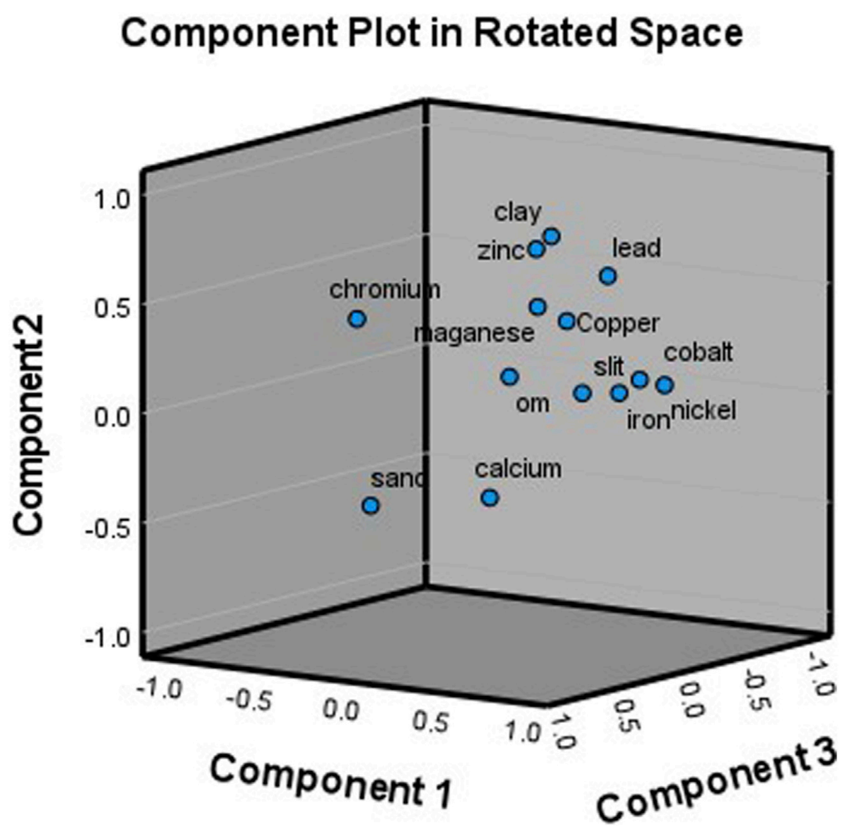

FIGURE 10
3D factor plot illustrating the association between various parameters in Wular Lake.

Matter (OM) (loading = −0.83). The high loading for $CaCO_3$ alongside the inverse association with OM suggests that this component represents biogeochemical cycling processes within the sediment, particularly those involving the interaction between organic and inorganic constituents. This component highlights the role of organic and inorganic material turnover in influencing sediment composition, reflecting processes that may impact nutrient dynamics and chemical stability in the sediment environment.

The rotated component matrix offers a clear understanding of how different heavy metals and sediment properties are grouped together Supplementary Table 5, revealing underlying geochemical and pollution sources that influence sediment composition. The rotated component plot in 3D space (Figure 10) provides a visual representation of these relationships, clearly showing how metals and sediment characteristics cluster according to their loadings on the different components. For example, metals like cobalt, iron, and nickel cluster closely, supporting their co-occurrence, while zinc, clay, and lead form another group, indicating a shared geochemical behavior or source.

3.5.3 Cluster analysis

Cluster analysis was used to classify sampling locations into distinct groups based on their similarity in heavy metal concentrations and sediment characteristics. The dendrogram produced using Ward's linkage method identified three primary clusters among the sampling sites (Figure 11), revealing the spatial distribution and source patterns of pollution across the lake. Cluster 1 which is the largest cluster, consisting of sites 1, 2, 3, 4, 5, 6, 7, 8, 9, 13 14, 15, 16, 17, 18, 19, 20, 21, 22, 24, 25, 26, 27, 28, 29, 30, 31, and 32, is spread across the eastern and southern portions of the lake. These locations are likely influenced by diffuse pollution sources, such as atmospheric deposition or general agricultural runoff, and waste water, leading to moderate contamination levels across multiple elements, including Fe, Ni, and Co. Cluster 2 includes sites, 10, 11, 12, and 23 which are concentrated in the eastern region mostly near the lake boundary regions of the lake. These sites exhibit similar sediment characteristics, possibly due to their proximity to urban or agricultural runoff sources, which introduce heavy metals like Pb, Cu, and Zn into the lake. The dendrogram for heavy metals (Figure 12) also revealed four distinct clusters, reflecting similarities in the behavior of these elements in the lake's sediment. Cluster I include Co, Ni, and Fe, suggesting that these metals share a common natural or anthropogenic source. Cluster II, containing Cu and Pb, likely reflects urban or industrial pollution, while Cluster III, comprising Mn and Zn, points to agricultural or mixed natural-anthropogenic inputs. Cluster IV, represented by Cr, indicates a distinct industrial origin or localized contamination.

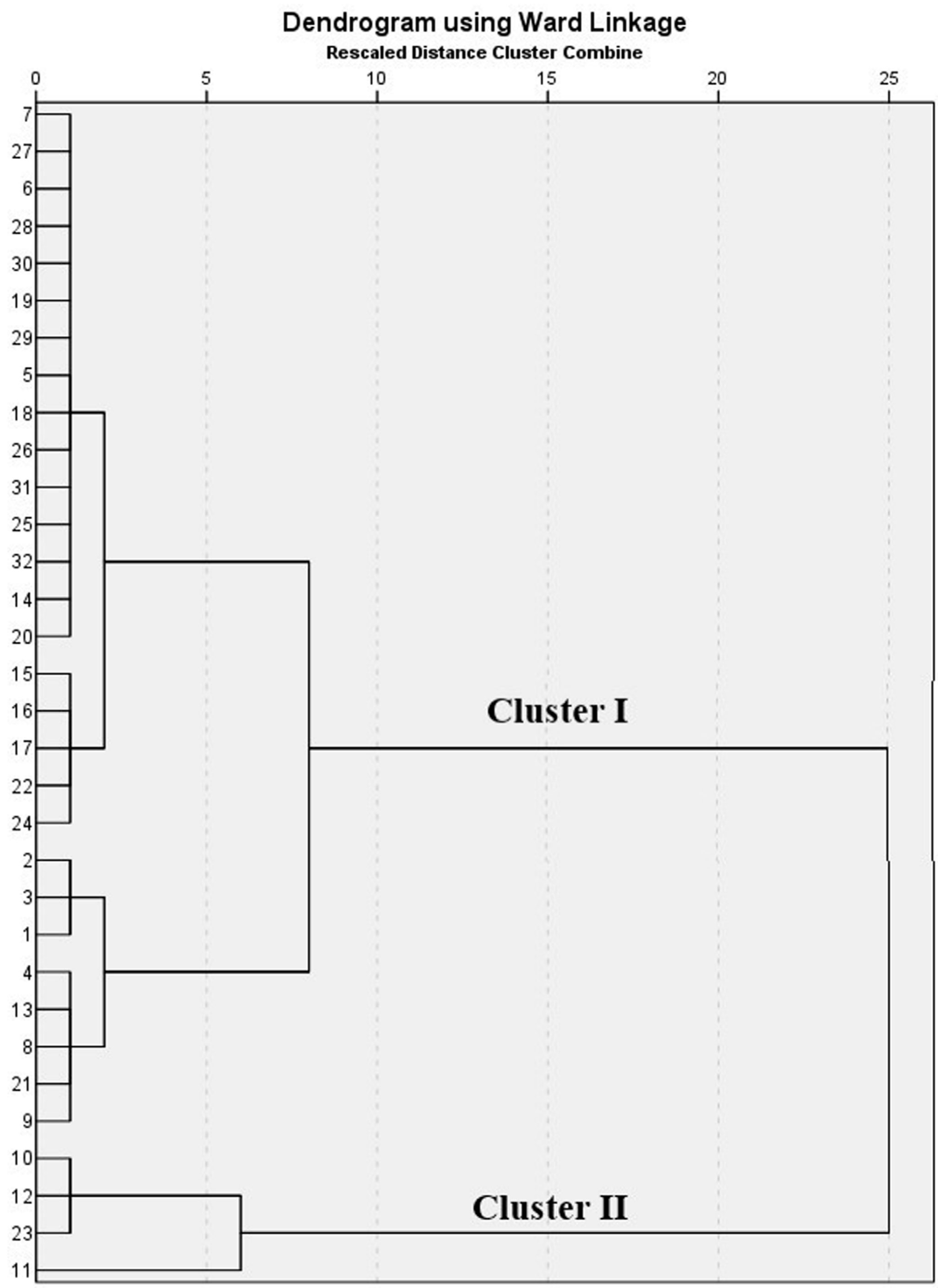

FIGURE 11
Hierarchical cluster dendrogram demonstrating the association between sediment sampling stations in Wular Lake.

4 Discussion

4.1 Sediment texture characteristics

The grain size analysis of Wular Lake sediments revealed significant variability in sediment texture across the 32 sampling locations. Sand content ranged from 0.2% to 92.4%, while silt was the predominant grain size fraction at most sites. Clay content varied substantially, ranging from 0% to 60%, reflecting the influence of the lake's hydrodynamic processes on sediment deposition. The spatial distribution of sediment textures suggests that areas with higher sand content are located in regions of stronger water flow, while finer particles such as silt and clay accumulate in quieter regions of the lake (Fang et al., 2019). These patterns are consistent with sediment deposition trends observed in other large freshwater systems, where

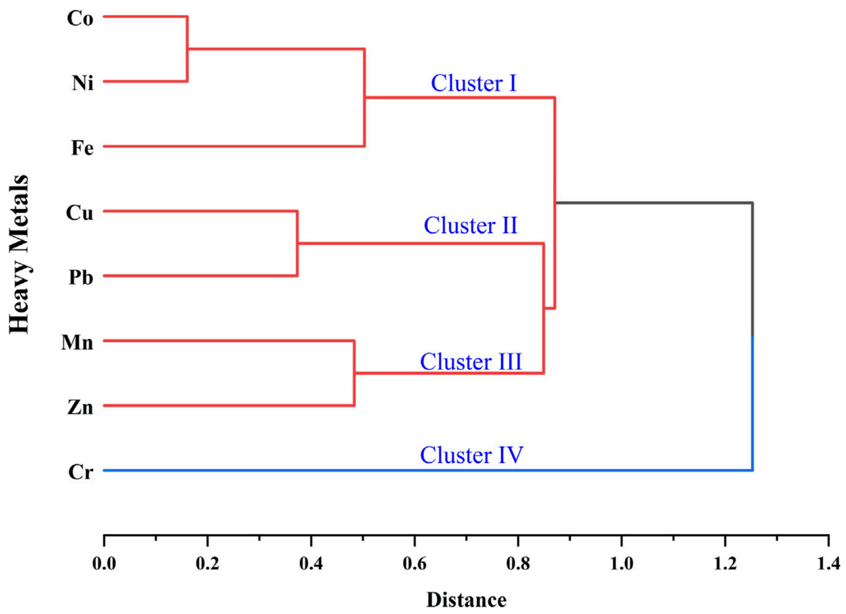

FIGURE 12
Hierarchical cluster dendrogram demonstrating the association between Heavy metals in Wular Lake.

hydrodynamics play a critical role in shaping sediment characteristics (Shah et al., 2021).

4.2 Geochemical properties: Calcium carbonate and organic matter

The geochemical analysis of calcium carbonate ($CaCO_3$) and organic matter (OM) content in Wular Lake sediments revealed significant spatial variability. $CaCO_3$ content ranged from 1.15% to 7.5%, with higher concentrations in the central and western regions of the lake. This suggests active carbonate sedimentation processes influenced by both natural and anthropogenic inputs, including agricultural lime and biological carbonate production (Keil, 2017). Organic matter (OM) content ranged from 1.74% to 16.1%, with several sites displaying elevated OM levels, particularly in areas with abundant vegetation and reduced water flow. High OM content typically indicates regions of organic enrichment, often driven by biological activity and sediment deposition (Swann et al., 2020). These patterns are consistent with observations in other lake systems where OM accumulation is closely tied to hydrodynamic conditions and biological productivity (Xu et al., 2023).

4.3 Heavy metal distribution and concentrations in Wular lake sediments

The analysis of heavy metal concentrations in Wular Lake sediments offers crucial insights into the lake's environmental status, emphasizing the significant anthropogenic pressures affecting the ecosystem. Concentrations of key heavy metals, including cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), zinc (Zn), and chromium (Cr), were compared against crustal baseline levels. The findings reveal considerable anthropogenic enrichment, especially in areas near populated villages and agricultural zones. Anthropogenic inputs such as sewage, slope tilling, eutrophication, and agrochemical runoff have led to a noticeable shift in the lake's geochemistry, particularly in regions surrounding villages such as Saderkoot, Papchan, and Baba Gund. Siltation from the Jhelum River and its tributaries further contributes to the influx of chemicals (Jeelani et al., 2013). Cobalt (Co) concentrations ranged from 29.35 mg/kg to 39.41 mg/kg, with an average of 33.9 mg/kg, exceeding the global crustal average of 19 mg/kg (Turekian and Wedepohl, 1961). This elevation indicates substantial anthropogenic inputs and the highest concentrations were detected in the southern and central regions, likely influenced by nearby urban centers. The association between cobalt enrichment and anthropogenic activities is well-documented, particularly in regions subjected to metal processing and vehicular emissions (Du Preez et al., 2016; Poznanović Spahić et al., 2019). Similar findings have been reported in other freshwater systems, where urbanization has significantly contributed to metal enrichment (Tang et al., 2021; Shah et al., 2021).

Copper (Cu) concentrations exhibited a wide range, with the lowest value of 33.91 mg/kg at WL3 and the highest of 100.2 mg/kg at WL15. The average concentration of 53.2 mg/kg exceeds the natural background of 45 mg/kg (Turekian and Wedepohl, 1961), highlighting substantial contamination from anthropogenic sources such as agricultural runoff, which often contains copper-based pesticides and fertilizers (Gallagher et al., 2001; Tamm et al., 2022). This aligns with findings in other freshwater bodies where copper contamination is linked to intensive farming and waste disposal (Mantovi et al., 2003). Elevated copper levels in sediments can pose risks to aquatic organisms, as copper is known to bioaccumulate and cause toxic effects in benthic communities (Rand and Schuler, 2009; Fu et al., 2016). Iron (Fe), the most abundant metal in Wular Lake sediments, ranged from 47,758 mg/kg to 176,867 mg/kg, with an average of 83,558 mg/kg. These values are consistent with natural background levels, suggesting that iron in the lake sediments is primarily of geogenic origin (Saleem et al., 2022). However, localized hotspots, such as WL11, which recorded extremely high iron levels, may indicate inputs from soil erosion exacerbated by human activities (Vareda et al., 2019). Manganese (Mn) concentrations ranged from 1,046 mg/kg to 2,041 mg/kg, significantly higher than the natural background of 850 mg/kg (Turekian and Wedepohl, 1961). The spatial distribution suggests that industrial runoff, particularly from manufacturing processes, may be contributing to the manganese load in the lake (Wu et al., 2022b). Elevated manganese levels have been observed in other lake systems exposed to industrial pollution, which can lead to ecological disturbances, particularly affecting the lake's redox dynamics (Zhang et al., 2018). Nickel (Ni) concentrations varied from 62.5 mg/kg to 97.7 mg/kg, with an average of 76.4 mg/kg, exceeding the crustal average of 68 mg/kg (Turekian and Wedepohl, 1961). The elevated nickel levels in the central and southern regions point towards industrial activities as significant contributors. Nickel is commonly used in electroplating, alloy production, and battery manufacturing, all of which are known sources of nickel pollution in aquatic systems (Zhang et al., 2023). Similar enrichment has been observed in other lakes near urban and industrial areas, where nickel contamination poses ecological risks, particularly to benthic organisms (Mrozińska and Bąkowska, 2020).

Lead (Pb) concentrations, ranging from 6.33 mg/kg to 12.03 mg/kg, with an average of 9.27 mg/kg, were notably lower than the crustal background of 20 mg/kg (Turekian and Wedepohl, 1961). Although lead levels appear low, localized enrichments at specific sites may still reflect historical use of lead-based products such as paints, gasoline, and batteries (Olson et al., 2022). The relatively low concentrations in most areas suggest that regulations on lead usage have successfully reduced its presence in the environment, a trend observed in many regions worldwide following the phase-out of leaded gasoline (Lacerda et al., 2023). Zinc (Zn) concentrations exhibited significant variability, with values ranging from 72.13 mg/kg to 237.7 mg/kg and an average of 118.5 mg/kg, exceeding the crustal average of 95 mg/kg (Turekian and Wedepohl, 1961). Zinc is commonly used in agriculture, industry, and urban applications, which explains its elevated concentrations in certain areas of the lake. The highest zinc concentrations were observed in the southern parts of the lake, likely reflecting agricultural runoff and urban pollution (Sun et al., 2022). Zinc is essential for biological processes, but at elevated levels, it can be toxic to aquatic organisms, particularly in sediment-rich environments where it accumulates (Baran et al., 2019). Chromium (Cr) concentrations ranged from 32.62 mg/kg to 282.5 mg/kg, with an average of 94.3 mg/kg. The elevated concentrations at certain locations, particularly WL31, suggest contamination from industrial sources, such as tanning and electroplating industries, which are known to release chromium into aquatic systems (Sharma et al., 2021). Chromium is a well-documented pollutant in lake sediments, where it poses ecological risks due to its toxicity, particularly in its hexavalent form (Cr VI), which is more toxic than trivalent chromium (Cr III) (Pathak et al., 2023). The significant variability in chromium concentrations across the lake suggests both natural and anthropogenic sources, a pattern observed in other heavily industrialized regions (Fang et al., 2019). These findings highlight that Wular Lake is subject to varying degrees of metal contamination, with particularly high levels of Co, Cu, Mn, Zn, and Cr, which suggest ongoing pollution from agricultural, industrial, and urban sources. While iron and lead concentrations remain close to natural levels, the spatial variability indicates localized contamination that may be linked to specific anthropogenic activities. These trends are consistent with observations in other freshwater systems that are under the pressure of industrial and agricultural development (Fang et al., 2019; Xia et al., 2020).

4.4 Environmental risk assessment of heavy metals

The environmental risk posed by heavy metal contamination in Wular Lake was assessed using several well-established indices, including the Contamination Factor (CF), Geo-Accumulation Index (Igeo), Enrichment Factor (EF), Pollution Load Index (PLI), and Potential Ecological Risk Index (PERI). These indices provide a comprehensive assessment of the contamination levels and potential ecological risks posed by heavy metals in the lake sediments. The Contamination Factor (CF) analysis revealed moderate contamination levels for Co, Mn, and Zn, while Cu and Cr exhibited moderate to considerable contamination at certain sites. These findings align with recent studies that have highlighted the ongoing threat of industrial and agricultural pollution in freshwater systems (Davies et al., 2024; Soetan et al., 2024). The moderate contamination observed for most metals indicates that anthropogenic activities are exerting significant pressure on the lake ecosystem, particularly in areas influenced by urban runoff and industrial discharge (Nasr et al., 2023; Raudonytė-Svirbutavičienė et al., 2023). The Geo-Accumulation Index (Igeo) categorized most metals as unpolluted to moderately polluted, with minor contamination observed for Mn, Cr, and Zn. Lead and Ni were generally classified as unpolluted, reflecting the success of environmental regulations in reducing lead usage and the relatively low industrial inputs of nickel in this region. The Igeo values for chromium suggest localized pollution in specific areas, likely related to industrial contributions, as seen in similar lake systems affected by urbanization (Hu et al., 2024). Research on urban lake systems shows significant spatial variations in chromium speciation, correlating with anthropogenic activities, indicating localized pollution effects (Gupta et al., 2013). Conversely, while industrial activities are a primary source of chromium pollution, natural geological factors and historical land use may also contribute to localized contamination, complicating the assessment of pollution sources and impacts (Granmo et al., 2020).

The Enrichment Factor (EF) revealed significant enrichment of Co, Mn, and Zn, particularly in areas influenced by agricultural runoff. These metals are known to accumulate in sediments due to their persistent nature and tendency to bind to fine particles (Meena et al., 2018; Haynes and Zhou, 2022; Fadlillah et al., 2024). High concentrations of these metals in sediments correlate with increased toxicity in aquatic environments, posing risks to both aquatic life and human health (Fadlillah et al., 2024). The enrichment of these metals highlights the need for ongoing monitoring and targeted mitigation efforts to reduce the input of contaminants into the lake. The Pollution Load Index (PLI) values ranged from 0.83 to 1.48, indicating moderate pollution across the lake. Elevated PLI values were primarily associated with Ni, Zn, and Cr contamination in the southern and central regions of the lake, where local anthropogenic activities are more pronounced. The PLI findings suggest that while pollution is present, it remains at a moderate level that requires attention but does not yet pose an immediate ecological threat. The Potential Ecological Risk Index (PERI) categorized the lake under low-risk for ecological threats, with all metals contributing to low to moderate ecological risk levels. However, localized hotspots for Ni and Cu present a potential risk to benthic organisms and aquatic life, particularly in regions where metal concentrations exceed safety thresholds (Amini and Qishlaqi, 2020). These findings underscore the importance of continued monitoring to prevent future degradation of the lake's ecological health. In addition, the environmental risk assessment indicates that while Wular Lake is under moderate pressure from heavy metal contamination, the overall ecological risk remains relatively low. However, the presence of contamination hotspots and the ongoing input of metals from local and agricultural sources necessitate targeted remediation efforts to mitigate the potential for long-term ecological damage.

4.5 Multivariate statistical analysis

Multivariate statistical analyses, including Pearson's correlation analysis, factor analysis, and cluster analysis, were conducted to identify the relationships between heavy metals and sediment characteristics and to explore potential sources of contamination. Pearson's correlation analysis revealed strong positive correlations between Co, Ni, and Fe, suggesting that these metals share common sources, likely related to industrial pollution or urban runoff (Zhu et al., 2024). Similarly, Cu, Pb, and Zn showed significant correlations, pointing to urban and vehicular emissions as likely contributors (Monaci et al., 2000). The correlations between sediment texture and metal concentrations underscore the role of fine particles (clay and silt) in retaining heavy metals, which is a well-documented phenomenon in freshwater systems (Isotuk et al., 2023).

Factor analysis identified four main components that together explained 77.1% of the total variance in the dataset. The first component, dominated by Co, Ni, and Fe, likely represents industrial and urban pollution sources, (Wang et al., 2023). The natural geological setting, such as the presence of ophiolitic rocks, can contribute to the natural occurrence of these metals in sediments (Negahban et al., 2021). While the second component, characterized by Zn, Pb, and Mn, reflects inputs from agricultural runoff and urban wastewater. The presence of Zn, Pb, and Mn in environmental samples is often indicative of inputs from agricultural runoff and urban wastewater. These metals are commonly associated with anthropogenic activities, including agriculture and urbanization, which contribute to their elevated levels in soils and water bodies. Agricultural activities contribute to metal contamination through the use of fertilizers and pesticides, which often contain metals like Zn and Pb. These metals can leach into the soil and water systems, leading to increased concentrations in agricultural runoff. For instance, the study by Banerjee and Gupta (2017) highlights the enrichment of Pb and Cd in soils irrigated with industrial wastewater, which can be linked to agricultural practices. The third component highlights the role of sediment texture in influencing metal distribution, particularly the influence of fine-grained particles on the retention of heavy metals (Meena et al., 2018; Fadlillah et al., 2024).

Cluster analysis grouped sampling locations into distinct clusters based on heavy metal concentrations and sediment characteristics. The largest cluster, which included the majority of the sites, reflected moderate contamination levels from diffuse pollution sources such as atmospheric deposition and agricultural runoff (Semenov et al., 2019). The second cluster, concentrated in the northern regions of the lake, exhibited higher contamination levels, likely driven by urban and local population. This clustering pattern is consistent with findings from other lake systems affected by a combination of natural and anthropogenic influences (Ji et al., 2019). These multivariate analyses provide a comprehensive understanding of the complex interactions between heavy metals and sediment properties in Wular Lake. The identification of distinct pollution sources and spatial patterns of contamination emphasizes the need for targeted monitoring and remediation efforts to address the ongoing contamination of the lake.

4.6 Sediment quality benchmark assessment for Wular lake

The average concentrations of heavy metals in Wular Lake sediments with the ERL (Effect Range Low) and ERM (Effect Range Median) thresholds to assess ecological risks as shown in Supplementary Table 6. Nickel exhibits an average concentration of 78.8 mg/kg, well above the ERM threshold of 50 mg/kg, which signals a high likelihood of adverse biological impacts on benthic organisms. This elevated level suggests significant contamination, likely stemming from anthropogenic activities and agricultural runoff in the Wular Lake region. Persistent nickel contamination at these concentrations poses a risk of bioaccumulation, which can impact local fauna over time (Nguyen et al., 2021; Zhang et al., 2023). Chromium levels in Wular Lake are above the ERL (80 mg/kg) and approach the ERM (145 mg/kg), with an average concentration of 96.08 mg/kg. This places chromium within a moderate to high-risk range, particularly in areas with known urban or industrial runoff. Chromium contamination at these levels can disrupt biological functions in sediment-dwelling organisms, and hotspot areas require targeted mitigation efforts to prevent further ecological degradation (Vignati et al., 2019; Sun et al., 2022). Copper concentrations are below the ERL, averaging 53.80 mg/kg. Although within safe levels for most areas, copper contamination remains a concern in certain localized spots where concentrations approach the ERL threshold. Sources may include agricultural runoff and household wastewater, which contribute to copper's presence in sediment. Monitoring is recommended to ensure that copper concentrations do not rise to levels that might pose toxicity risks to aquatic life (Stern, 2010).

Zinc averages 113.35 mg/kg, close to the ERL of 120 mg/kg. Although zinc poses a low to moderate risk overall, some regions near urban runoff points show localized elevated levels, suggesting moderate risk. As zinc can bioaccumulate in aquatic organisms and disrupt enzyme functions, continued monitoring and preventive actions are advisable in areas with higher zinc content (Zhao et al., 2024). Lead levels in Wular Lake are consistently below the ERL, with an average concentration of 9.44 mg/kg. This low concentration suggests that lead contamination is minimal and poses little ecological risk under current conditions. Effective regulatory measures may have contributed to the low levels of lead in the lake sediments, indicating successful reduction of anthropogenic lead sources in the region (Algül and Beyhan, 2020). Overall, the ecological risk assessment for Wular Lake shows that nickel and chromium levels pose significant risks, with nickel concentrations consistently exceeding the ERM threshold and chromium levels surpassing the ERL in multiple locations. Copper and zinc present moderate risks, primarily in urban-adjacent areas, and lead contamination remains minimal. These findings are consistent with studies on lakes impacted by industrial and agricultural runoff, underscoring the importance of regulatory actions to limit metal inputs and protect the lake's biodiversity.

5 Conclusion

This study provides a comprehensive assessment of heavy metal contamination in the surface sediments of Wular Lake, a vital Ramsar site in Kashmir, India. The findings reveal significant spatial variability in sediment texture, with silt dominating most sampling sites, while clay and sand fractions showed localized variations. Heavy metal concentrations, particularly for Co, Cu, Mn, Zn, and Cr, exceeded natural background levels, indicating substantial anthropogenic enrichment. The spatial distribution of heavy metals highlighted hotspots of contamination in areas influenced by agricultural runoff, urban discharges, and industrial activities. Environmental risk assessment indices, including CF, Igeo, EF, PLI, and PERI, indicated moderate contamination levels across the lake, with localized areas of higher ecological risk. Multivariate statistical analyses identified industrial, agricultural, and urban runoff as the primary sources of heavy metal pollution, with sediment texture playing a significant role in metal retention and distribution. The study underscores the importance of continuous monitoring and targeted remediation efforts to mitigate the ecological risks posed by heavy metal contamination in Wular Lake. The findings provide valuable insights for policymakers and environmental managers to develop effective strategies for pollution control and ecosystem conservation. By addressing the sources of contamination and implementing sustainable management practices, the ecological integrity of Wular Lake can be preserved, ensuring its continued role as a critical habitat for biodiversity and a vital resource for local communities. This research contributes to the broader understanding of heavy metal pollution in freshwater ecosystems and highlights the need for integrated approaches to safeguard such environmentally sensitive regions.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

AN: Validation, Writing – review and editing, Conceptualization, Writing – original draft. MR: Writing – original draft, Validation, Writing – review and editing. MZ: Writing – review and editing, Data curation. MA: Writing – review and editing, Data curation.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2025.1630494/full#supplementary-material

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