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Impact of Urban and Agricultural Discharges on Trace Metal Accumulation in Semi-Arid River Sediments: A Case Study of Wadi Djedra (Northeast Algeria)

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Abstract: This study aimed to assess the contamination of sediments in Wadi Djedra and its tributaries by seven trace elements. The average concentrations of Mn, Pb, Zn, Cu, Ni, Cd, and Cr in the sediments ranged from 31.4 to 59.2, 1.2 to 18.4, 15.1 to 54.7, 11.2 to 19.7, 1.1 to 14.7, 0.1 to 0.3, and 0.1 to 4.3 mg/kg, respectively. Sediment contamination was evaluated using the enrichment factor (EF), geoaccumulation index (I_{geo}), and potential ecological risk index (Eri). The I_{geo} values for Cd indicated moderate contamination at sites S2, S4, S5, and S7, while for other sites and elements, the values were negative, indicating no contamination. The results revealed very high enrichment of Cd and Cu in the analyzed sediments, attributed to human activities. In contrast, chromium and manganese concentrations were comparable to those observed in the Earth's crust. Suggesting even a depletion of metals in the sediments (EF < 2). The Eri index measurements showed that the sediments in the Djedra basin exhibited moderate to high pollution levels for Cd at most study sites. Lithogenic sources, urban discharges, and agricultural activities were the main factors affecting the concentrations of Cd, Cu, Zn, and Pb in the studied sediments. Although the current contamination is not alarming in the short term, it should be considered in future monitoring and management efforts.

Keywords: Djedra watershed, pollution, trace metals, sediments, ecological risks

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1. Introduction

Trace metals, known for their toxicity, persistence in the environment, and ability to accumulate in living organisms, represent a major environmental pollution issue [*Kumar et al.*, 2022; *Li et al.*, 2012; *Zeng et al.*, 2020]. Their presence in river sediments is particularly concerning, as sediments often act as reservoirs for heavy metals, potentially releasing these pollutants into the water through natural or anthropogenic disturbances and remobilization [*Duan et al.*, 2020; *Gbadamosi et al.*, 2018]. These substances are considered highly hazardous to human health and ecosystems due to their chronic toxicity, bioaccumulation and environmental persistence. Inhalation, ingestion, or contact with them can lead to adverse effects such as neurological disorders, cancers, or reproductive impairments [*Khemis et al.*, 2017]. Their widespread use in mining, metallurgical, chemical, and agricultural industries, as well as in domestic and technological activities, facilitates their extensive dispersion in the environment [*Bisone*, 2012; *Chang et al.*, 2013; *Pradhan and Kumar*, 2014].

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Soils and sediments, as natural reservoirs, play a crucial role in the dispersion of trace metals. In particular, river sediments, which accumulate these elements over time, serve as valuable archives for assessing historical and current pollution. For example, in the Saf-Saf wadi in eastern Algeria – an urban watercourse – the study showed that heavy metal contamination in sediments reflects both industrial and domestic discharges [*Rouidi et al.*, 2022]. Elsewhere in Africa, particularly in the Nile Valley, research has documented increased cadmium, copper, and zinc contamination in sediments, linked to both geogenic and anthropogenic sources [*El-Anwar et al.*, 2021]. These studies also indicate that the remobilization of metals present in sediments can lead to continuous aquatic pollution, affecting water quality and the health of local populations. In Europe, in the Artois-Picardie basin in France, studies have shown that heavy metal contamination in sediments reflects the impact of both urban activities and agricultural runoff [*Zhou*, 2009]. Similarly, a study conducted on the Volga River in Russia identified a clear trend of heavy metal accumulation in sediments, associated with increasing urbanization [*Tikhomirov et al.*, 2022].

Globally, research on the San Pedro River, located in a semi-arid region of Mexico, has revealed significant accumulation of Cd, Pb, and Cu in sediments due to anthropogenic activities related to mining, untreated wastewater discharge, and livestock farming [*Gómez-Álvarez et al.*, 2011]. Similarly, studies on the Ganges in India have highlighted severe contamination from untreated urban and industrial effluents [*Siddiqui and Pandey*, 2019]. These examples underscore the universality of metallic pollution in river systems, emphasizing the need for accurate sediment contamination assessment to enable effective environmental management. The remobilization of metals in sediments can lead to persistent aquatic pollution, compromising water quality and public health.

This context highlights the importance of studying metal contamination in river sediments, particularly in regions experiencing rapid urbanization and intensive agriculture, often without adequate environmental oversight. Sediment analysis helps establish pollution indicators, identify potential contamination sources, and propose management strategies.

This study provides the first assessment of heavy metal pollution in sediments from the Djedra River basin, a strategic tributary of Wadi Medjerda (Algeria–Tunisia), which faces increasing population density and intense agricultural/industrial activity. The objectives are to quantify seven trace metals, identify their potential sources, and evaluate their enrichment levels using Upper Continental Crust reference values [*Wedepohl*, 1995]. Through this work, we aim to advance understanding of pollution dynamics in semi-arid fluvial systems and provide a scientific basis for sustainable water and sediment management policies.

The findings will deliver crucial baseline data for environmental management in this understudied region while contributing to the growing body of knowledge on trace metal pollution in semi-arid watersheds. By comparing our results with prior studies from diverse geographical contexts. including the Seybouse and Saf-Saf wadis (Eastern Algeria) [*Rouidi et al.*, 2022; *Talbi and Kachi*, 2019], Tafna Wadi (Western Algeria) [*Mechouet et al.*, 2024], and Tunisia's Medjerda and Meliane wadis [*Helali et al.*, 2016; *Yahyaoui et al.*, 2021], we identify transboundary pollution patterns and propose strategic guidelines for integrated regional water resource management.

2. Materials and Methods

2.1. Study Area

The Djedra watershed is in the extreme north-east of Algeria, between latitudes 7°51' and 8°3'E and longitudes 36°18' and 36°23'N (Figure 1). It covers an area of 127 km^2. Average annual rainfall is 736 mm. It has a Mediterranean climate, with hot, dry summers and cold, rainy, snowy winters at higher altitudes. Temperatures range from 9.9 °C (January) to 32.4 °C (July). Hydrographically, this watershed is characterized by a very important network that will supply water to the Djedra River dam, where construction works are nearing completion.

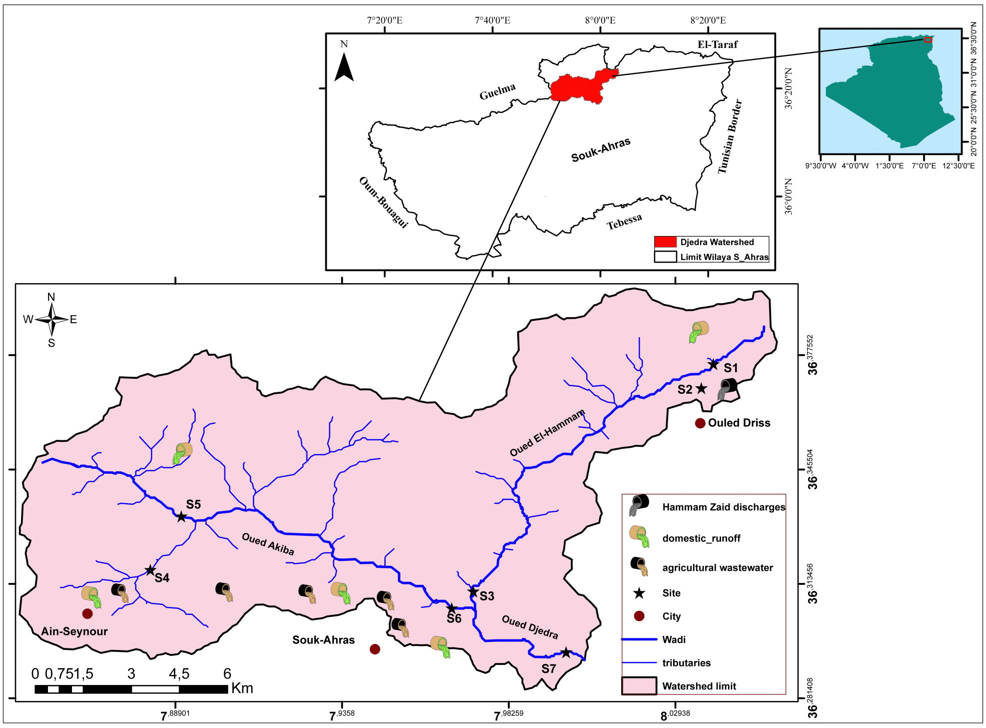

Figure 1. Study area. sampling stations and discharge points.

2.2. Sampling and Analysis:

Seven sampling stations were selected along the Djedra Wadi and its tributaries based on field reconnaissance and investigations to identify discharge points and potential pollution sources. Sampling was conducted during four campaigns, from November 2020 to December 2021, covering low-flow and high-flow periods. Water samples were taken from the same place where sediment samples were taken, to compare water pollution by metallic trace elements with that of sediment. Polyethylene bottles of 1.5 L, pre-cleaned for ease and practicality, were used for water sampling. Prior to filling, the bottles were rinsed three times with the sampled water to prevent contamination. Samples were collected manually by immersing the bottle 30–50 cm below the surface to avoid air incorporation. For sediment sampling, a manual auger was used within the watercourse at a depth of 5 cm, especially in areas with low flow. The auger was rotated until reaching the maximum depth, then withdrawn to collect the sample by inversion. Collected sediments were dried at 105 °C for 24 hours, then ground in an agate mortar and sieved at 2 mm and 63 µm [*Serpaud et al.*, 2005]. The mineralization by acid digestion with aqua regia was performed on 1 g of this powder with 12 ml of 37 % HCl and 4 ml of 60% HNO_3. This step was carried out at 95 °C for 75 minutes on a heating block. After cooling, the digestate was filtered into a volumetric flask through a Whatman No. 42 filter, and the mineralized solution was then adjusted to 50 ml. An appropriate dilution was performed before analysis by atomic absorption spectroscopy [*Hébrard et al.*, 2005; *Reish and Oshida*, 1987]. After preparing the soil samples, we used a type of atomic absorption spectrometer (novAA 350. Germany) to measure the concentration of heavy metals in each sample. The pH, carbonate content, and granulometry of the sediments were determined following the protocols described by [*Pansu and Gautheyrou*, 2006].

2.3. Sediment Pollution Indices

The contamination of sediments by Cd, Zn, Cu, Cr, Ni, Mn, and Pb was assessed using the Geoaccumulation Index (I_{geo}), Enrichment Factor (EF), and Ecological Risk Index (Eri). Reference values from the Upper Continental Crust were used for all calculations [*Wedepohl*, 1995].

Enrichment Factor (EF)

The EF method normalizes the measured concentration of heavy metals against a reference metal (Fe or Al). The reference material used in this study follows the globally recognized background concentrations for unpolluted areas, as defined by [*Deely and Fergusson*, 1994]. The EF is calculated using the following equation:

$$\mathrm{EF}_i = \frac{(C_i/C_{\mathrm{Fe}})_{\mathrm{sediment}}}{(C_i/C_{\mathrm{Fe}})_{\mathrm{background}}}, \tag{1}$$

where EF_i is the Enrichment factor for a given metal. C_i, the Concentration of the metal in sediment samples.

Contamination levels are classified into five categories based on EF values [*Sutherland*, 2000]: Minimal enrichment ($\mathrm{EF} < 2$). Moderate enrichment ($2 \le \mathrm{EF} < 5$). Significant enrichment ($5 \le \mathrm{EF} < 20$). Very high enrichment ($20 \le \mathrm{EF} < 40$). Extremely high enrichment ($\mathrm{EF} \ge 40$).

Geoaccumulation Index (I_{geo})

Proposed by [*Muller*, 1969], this index is widely used to assess pollution in freshwater sediments and is calculated as:

$$I_{\mathrm{geo}} = \log_2(C_i/1.5B_n), \tag{2}$$

where: C_i, Metal concentration in the sample. B_n Background concentration of the metal. The 1.5 correction factor minimizes variations due to lithological differences in sediments [*Stoffers et al.*, 1986].

Pollution levels are classified as:

- $I_{\mathrm{geo}} \le 0$ Unpolluted;
- $0 < I_{\mathrm{geo}} \le 1$ Unpolluted to moderately polluted;
- $1 < I_{\mathrm{geo}} \le 2$ Moderately polluted;
- $2 < I_{\mathrm{geo}} \le 3$ Moderately to strongly polluted;
- $3 < I_{\mathrm{geo}} \le 4$ Strongly polluted;
- $4 < I_{\mathrm{geo}} \le 5$ Strongly to extremely polluted;
- $I_{\mathrm{geo}} > 5$ Extremely contaminated.

Ecological Risk Assessment (Eri)

Developed by [*Hakanson*, 1980]. this index evaluates the potential ecological risk posed by toxic metals in soils and sediments. It is calculated as:

$$E_r^i = T_r^i \times \mathrm{CF}_i \tag{3}$$

where: E_r^i – Ecological risk index for metal i. T_r^i – Toxicity response factor (Cd = 30; Cu, Pb, Ni = 5; Cr = 2; Zn, Mn = 1). CF_i – Contamination factor.

Risk levels are categorized as:

- Low risk ($0 \le E_r^i < 20$);
- Moderate risk ($20 \le E_r^i < 40$);
- Considerable risk ($40 \le E_r^i < 80$);
- Very high risk (critical) ($E_r^i \ge 80$).

2.4. Statistical Analyses

To explore complex relationships between variables, we applied between-classes analysis (BCA) combined with principal component analysis (PCA). Between-classes analysis [*Culhane et al.*, 2002; *Dolédec and Chessel*, 1987] helps distinguish groups of sites or periods based on multiple variables. In this study, an inter-wadi analysis was performed using the BCA function, with mean values per wadi stored in "`betWadi$tab`" (Table 1).

Table 1. `betWadi$tab` data frame

	Mn	Pb	Cu	Zn	Ni	Cr	Cd
Hammam	−0.273	−1.102	−0.654	−0.560	−0.856	−0.756	−0.642
Akiba	−0.193	0.772	0.528	0.587	0.426	0.365	0.326
Djedra	1.397	0.990	0.378	−0.082	1.288	1.174	0.948

3. Results and Discussion

The pH values of sediments in the Djedra Wadi basin ranged from 6.96 to 7.94, with a mean of 7.54. Higher pH values downstream (sites S3 and S6) indicate a slightly alkaline environment, likely due to the dissolution of gypsum and carbonate formations. This observation aligns with findings by [*Salhi et al.*, 2014] in Mediterranean basins, where limestone lithology similarly influences pH.

Sediment analysis revealed high carbonate content (13.3–31.2%; mean = 21.7%). consistent with the regional lithology dominated by Tertiary limestone and carbonate-rich sandy-clay formations [*Chabbi*, 2017]. A predominance of fine particles (< 50 µm) was observed at certain sites (S1, S2, S4, S6; 53.32–65.7%), which enhances heavy metal retention, as described in previous studies [*Stone and Droppo*, 1996] (Table 2). In contrast organic matter content remained low (0.6–3.5%). This reflects the arid to semi-arid conditions typical of the region.

Table 2. Physicochemical properties of sediments

	pH	$CaCO_3$ (%)	Granulometry	
			< 50 µm (%)	50–200 µm (%)
Min	6.96	13.34	23	33
Max	7.94	31.20	67	77
Mean ± S. Error	7.5 ± 0.13	21.7 ± 2.37	50.1 ± 6.74	51.3 ± 6.39

Analysis of trace metal elements revealed significant spatial variability. with peak concentrations observed at sites S4, S5, S6, and S7 (Figs. 2 and 3). The metals followed a consistent descending order of abundance: Mn > Zn > Cu > Pb > Ni > Cd > Cr, aligning with trends reported in other arid and semi-arid basins [*Benkaddour et al.*, 2019; *Yahyaoui et al.*, 2021]. Cd concentrations (0.08–0.43 mg/kg) remained below critical contamination thresholds. However, 64.3% of values exceeded 0.15 mg/kg, indicating moderate to highest enrichment. Zn and Cu reached maximum concentrations of 58.9 mg/kg and 17.3 mg/kg, respectively, still below sediment quality guidelines for aquatic life protection (Cu: 35.7 mg/kg; Zn:123 mg/kg) as per Canadian Sediment Quality Guidelines [*Canadian Council of Ministers of the Environment*, 1999]. Cr levels ranged from 0.05 to 6.15 mg/kg, with 75% of samples exceeding 0.17 mg/kg (Table 3; Figures 2 and 3).

The contamination indices corroborate these findings. The mean enrichment factor (EF) for metals ranged from 0.07 (Cr) to 71.86 (Cd). The significant accumulation of Cd and Cu (mean EF: 39.93 and 23.56. respectively) indicates pronounced anthropogenic contamination. In contrast, Cr and Mn exhibited low EFs, suggesting minimal contamination or geogenic origin (Fig. 4).

The geoaccumulation index (I_{geo}) values ranged from −9.04 to 1.00. The highest values were observed for Cd and Cu, followed by Zn and Pb, indicating low to moderate contamination according to standard thresholds.

Ecological risk indices (Eri) varied from 0.01 for Cr to 90 for Cd, with peak values recorded at sites S2, S4, S5, and S7 (Figure 4). The metals followed this descending order of ecological risk: $Er_{Cd} > Er_{Cu} > Er_{Pb} > Er_{Ni} > Er_{Zn} > Er_{Cr} > Er_{Mn}$. Highlighting substantial ecological concerns associated with cadmium and copper. Other metals such as Cr and Mn posed negligible risk, consistent with international guidelines [*EPA*, 2007].

Table 3. Statistical data of Trace Metals levels in sediments (mg/kg)

	Min	Max	Mean ± S. Error	Background [*Wedepohl*, 1995]
Mn	31.4	62.3	43.0 ± 4.46	527
Pb	0.8	20.2	10.8 ± 2.72	17
Cu	9.5	22.8	16.2 ± 1.03	14.3
Zn	13.6	58.9	33.8 ± 6.10	52
Cr	0.05	6.15	1.7 ± 0.68	35
Cd	0.08	0.43	0.2 ± 0.04	0.1
Ni	0.89	15.2	6.7 ± 1.92	18.6
n		28		

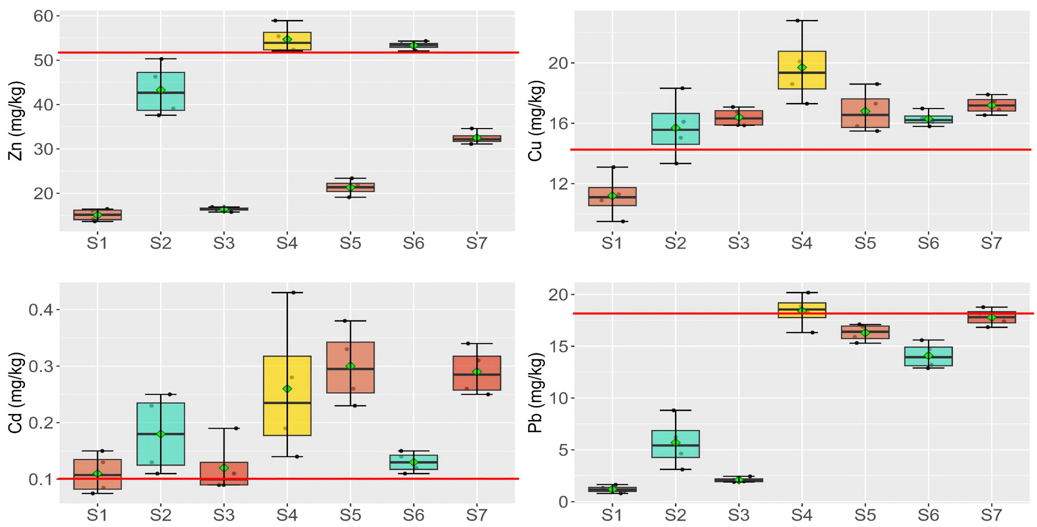

Figure 2. Spatiotemporal distribution of Pb, Cu, Zn et Cd. (The red line represents the reference value proposed by [*Wedepohl*, 1995] for trace elements in the upper continental crust).

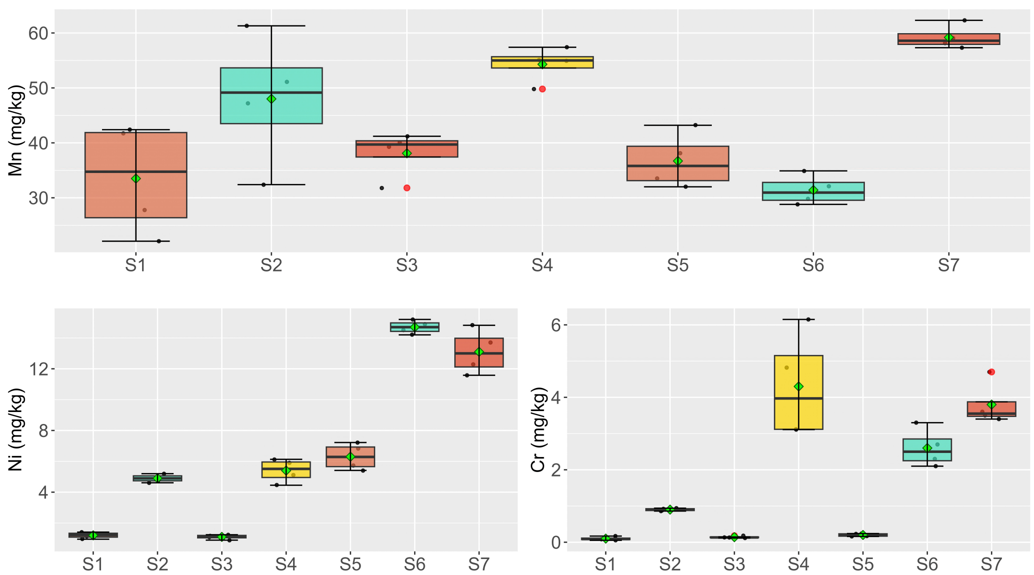

Figure 3. Spatiotemporal distribution of Mn, Cu et Ni.

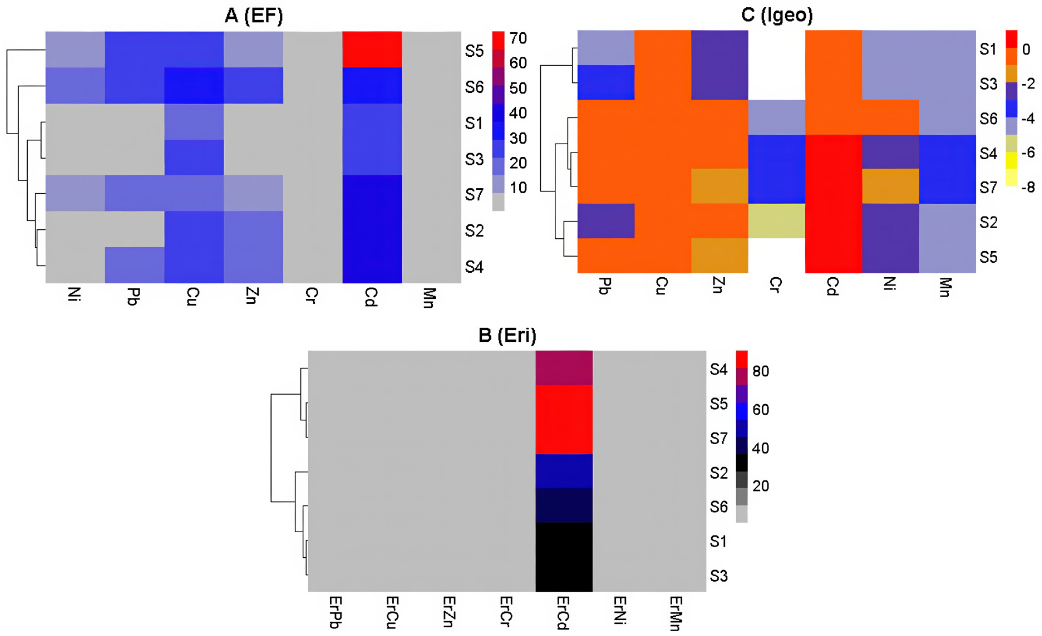

Figure 4. Heatmap of environmental indices.

The findings of this study on sediment characterization in Djedra Wadi align with those reported by [*Ben Ayed et al.*, 2022; *Benkaddour et al.*, 2019; *Rouidi et al.*, 2022], who documented significant heavy metal presence. primarily from anthropogenic sources, in similar fluvial systems across the eastern Mediterranean. Elevated levels of Cd, Zn, Cu. and Pb, particularly near urban and agricultural zones, underscore the dominant role of anthropogenic discharges. These observations are consistent with [*Salhi et al.*, 2014] in the Boumerzoug Basin (Constantine, Algeria), where metal concentrations correlated with agricultural and industrial activity intensity. A comparison with [*El Mrissani et al.*, 2021] in Morocco's Sebou Wadi reveals notable Pb, Cd, Cu, and Zn contamination, linked to industrial, agricultural, and urban effluents. However, concentrations in our study were generally lower than in these regions, where industrial intensity drives higher pollution levels. This disparity likely stems from differences in discharge density, effluent management, and local geomorphology, which affects contaminant transport and dilution. Further comparison with [*Siddiqui and Pandey*, 2019] in India, a region experiencing rapid urbanization and industrialization, highlights significant regional variability. For instance, Ni, Cu, Cr, and Pb concentrations there exceeded contamination thresholds, peaking at 37.8 mg/kg (Ni), 2.73 mg/kg (Cd), and 68.9 mg/kg (Cu), markedly higher than our mean values (6.7 mg/kg Ni, 0.20 mg/kg Cd, 16.2 mg/kg Cu). Mn distribution ($<$ 54.9 mg/kg) further confirms spatial variability and anthropogenic contributions. These results collectively support our conclusion of predominantly human-derived contamination.

In contrast to heavily industrialized sites examined by [*Rouidi et al.*, 2022; *Talbi and Kachi*, 2019] or urban coastal areas analyzed by [*Helali et al.*, 2016]. Djedra Wadi exhibits comparatively lower metal concentrations, aligning more closely with values reported by [*Mechouet et al.*, 2024]. In their study of Tafna Wadi sediments in western Algeria. This disparity likely reflects both limited local industrial impact and natural attenuation mechanisms (e.g. dispersion and dilution) that reduce metal levels.

Contamination indices (EF, I_{geo}, Eri) reveal moderate to high pollution levels, particularly for Cd and Cu. Enrichment factors (EF > 20) for Cd, Cu, Zn, and Pb at sites along Akiba Wadi (a right-bank tributary of Djedra Wadi) and downstream site S7 indicate predominantly anthropogenic origins, likely tied to phosphate fertilizers, agricultural runoff, and urban discharges. These findings align with [*Benabdelkader et al.*, 2018] in intensive farming areas and significantly exceed natural geochemical baselines [*Wedepohl*, 1995]. This anomaly confirms the dominant role of human activities (agricultural practices, livestock, domestic waste) as documented in similar regions [*Benkaddour et al.*, 2019;

Fawzy et al., 2017; *Mechouet et al.*, 2024]. Spatial metal distribution patterns, showing accumulation near urban and agricultural discharge zones, clearly identify these sources as primary contributors to sediment pollution. Ecological risk assessment (Eri) highlights Cd and Cu as highest-risk metals, particularly in Akiba Wadi and downstream Djedra sites (S4, S5, S7), consistent with studies prioritizing these contaminants [*Ben Ayed et al.*, 2022; *El Mrissani et al.*, 2021; *Rouidi et al.*, 2022]. Conversely, Pb and Zn levels remain relatively low, suggesting less intense contamination compared to areas heavily impacted by industrial/domestic effluents.

The current situation demonstrates the immediate impact of human activities. particularly urban and agricultural discharges. on metal pollution in the sediments of the Djedra basin. All our results, as well as those of the cited studies, confirm that this pollution – strongly linked to human activity – remains a major environmental concern requiring rigorous management and increased monitoring to mitigate its harmful effects.

3.1. Statistical Analysis

Inter-Classes Analyses

To validate the findings of this study and examine relationships between sediment metal contamination and pollution sources, a between-classes analysis was performed. This revealed significant correlations between sediment contamination and sites experiencing heightened anthropogenic pressures (Figure 5).

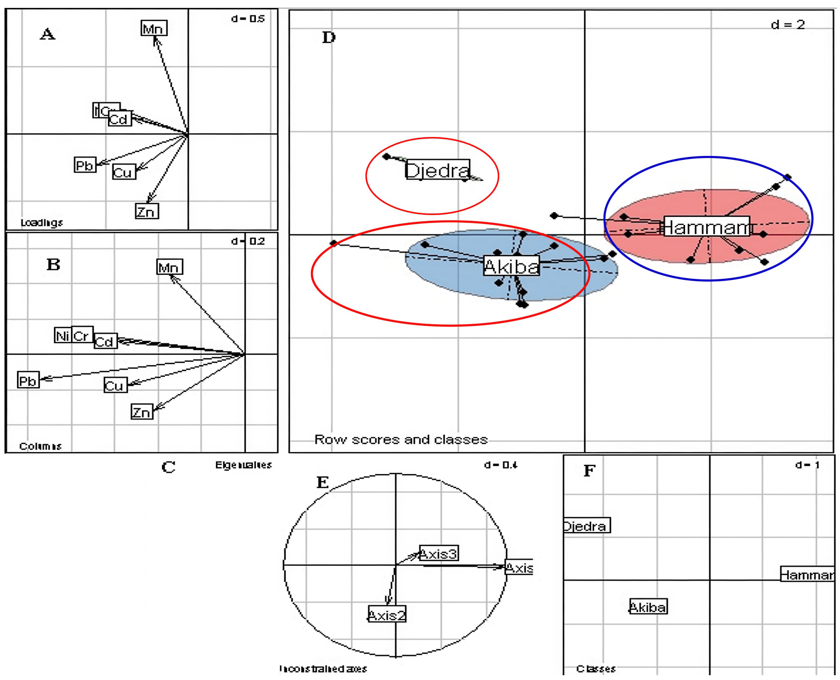

Figure 5. A: Loadings. ($c1 data frame). B: Columns. ($co data frame). C: Eigenvalues. D: Row scores and classes. ($ls data frame). E: Unconstrained axes. F: Classes. ($li data frame).

Graphs (A) and (B) display trace metal projections, with their similarity confirming analytical consistency. Graph (C) presents the eigenvalue histogram, while (E) shows the projection of the first three principal components from the initial PCA. Graph (F) plots between-class scores ($li) for the three studied wadis. Crucially, graph (D) – the core output – clusters samples from each wadi around centroid stars and ellipses labeled with wadi names.

These results demonstrate that sediments from Akiba and Djedra wadis exhibit the highest contamination levels, whereas El-Hammam Wadi shows the lowest concentrations. They highlight the most intense anthropogenic pressure in Wadi Akiba. driven by urban discharges from Souk-Ahras and Aïn-Seynour cities, combined with agricultural/livestock effluents. Downstream Site 7 (Wadi Djedra) also reflects significant pollutant inputs, integrating cumulative watershed contributions.

Relationship Between Water Pollution and That of Sediments by Heavy Metals

To evaluate metal pollution linkages between sediments and water, a principal component analysis (PCA) coupled with between-class analysis was conducted, generating two illustrative figures (Figures 6 and 7).

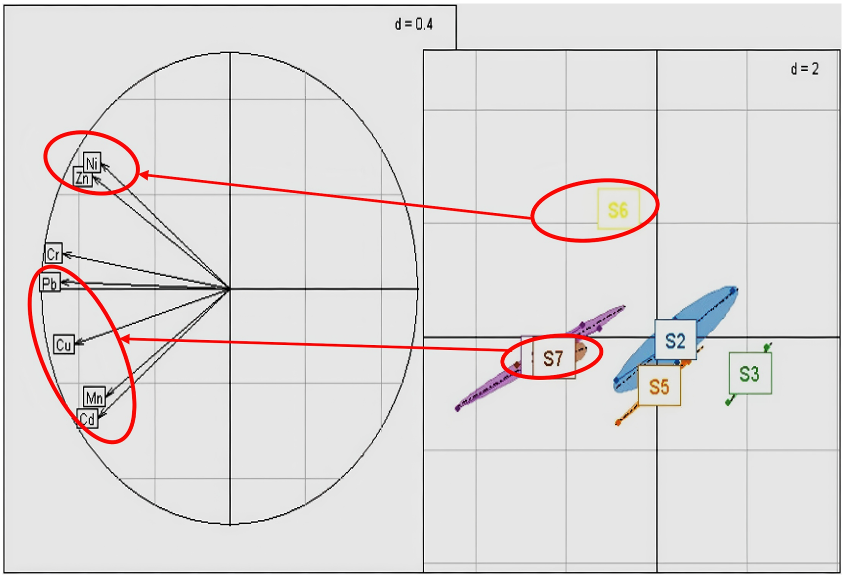

Figure 6. Left: Correlation matrix PCA of the TEM in sediments. Right: PCA sites factor map, with the four samples grouped for each site.

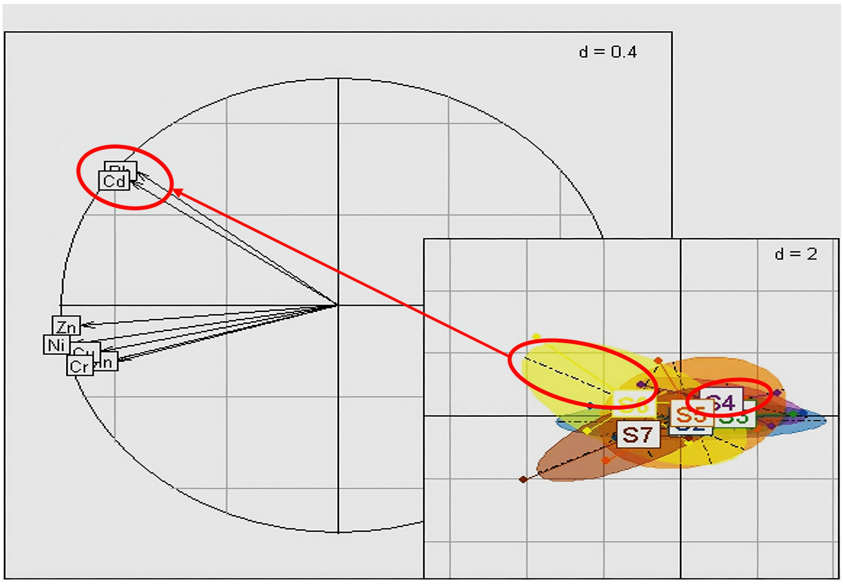

Figure 7. Left: Correlation matrix PCA of the TEM in water. Right: PCA sites factor map, with the four samples grouped for each site.

The correlation circle of the two figures indicates that the first axis represents a pollution gradient by trace elements, with increased pollution on the left. Analysis of the factorial maps reveals that water samples from site 6 exhibit high concentrations of Cd and Pb, while the sediments from this site show elevated levels of Zn and Ni. Furthermore, sediments from site 4 display significant concentrations of Cd, Pb, and Cu. although the water samples from this site are less contaminated. These observations suggest that the pollution profiles in water and sediments differ, indicating a lack of a direct relationship between metal contamination of the water and that of the sediments.

4. Conclusion

This study quantified concentrations of seven trace metal elements in surface sediments collected from seven locations along the Djedra River and its tributaries. Mean sediment concentrations (mg/kg) were: Mn (43.0), Pb (10.8), Cu (16.2), Zn (33.8), Cr (1.7), Cd (0.2), and Ni (6.7). When compared to Upper Continental Crust reference values, significant enrichment was observed for cadmium (85.7% of samples), copper (82.1%), zinc (28.6%), and lead (25%). with peak concentrations at sites S4, S6, and S7, areas receiving domestic wastewater and agricultural/livestock effluents.

The Ecological Risk Index (Eri) identified cadmium and copper as highest-risk elements, particularly in Akiba Wadi and downstream Djedra sites (S4-S5-S7). These findings corroborate previous research demonstrating urbanization as a major source of sedimentary metal pollution. While statistical analyses revealed no clear water-sediment contamination linkage, they established direct correlations between anthropogenic activities and elevated trace metal levels.

Collectively, these results demonstrate that human activities significantly influence sediment contamination in these fluvial systems. The persistence of concerning metal pollution levels, exacerbated by agricultural and urban discharges, underscores the urgent need for rigorous management strategies. We recommend implementing multidisciplinary approaches that combine, pollution indices, chemical and biological analyses and speciation studies to develop effective prevention and control measures for aquatic metal pollution.

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