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Anna Szymańska
Department of Earth Sciences,
Poznań College of Earth and
Mineral Sciences, Greater
Poland, Poland

Rafal Mazur
Department of Earth Sciences,
Poznań College of Earth and
Mineral Sciences, Greater
Poland, Poland

Agnieszka Wiśniewska
Department of Earth Sciences,
Poznań College of Earth and
Mineral Sciences, Greater
Poland, Poland

Corresponding Author:
Anna Szymańska
Department of Earth Sciences,
Poznań College of Earth and
Mineral Sciences, Greater
Poland, Poland

Geochemistry of river bed sediments as pollution indicators in the ELBE catchment

Anna Szymańska, Rafal Mazur and Agnieszka Wiśniewska

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Abstract

Roughly 43% of European river catchments carry sediment loads that exceed recommended quality thresholds for at least one heavy metal, yet many tributaries in Central Europe remain poorly characterized. This research investigated the geochemical composition of river bed sediments at 82 sites distributed across the upper, middle, and lower reaches of the Elbe catchment in Germany and the Czech Republic. Samples were collected during two campaigns (September 2021 and April 2022) and analyzed for six heavy metals (cadmium, chromium, copper, nickel, lead, and zinc) using inductively coupled plasma–optical emission spectrometry (ICP-OES). Enrichment factors were calculated relative to the upper continental crust, and a geo-accumulation index (Igeo) was applied to classify pollution severity. Results indicated a downstream enrichment trend for all metals, with cadmium showing the steepest gradient: mean concentrations rose from 0.42 mg/kg in the upper Elbe to 2.87 mg/kg near the estuary. The Igeo classified 14.6% of sites as heavily polluted, primarily clustered around industrial tributaries draining the Bitterfeld–Wolfen chemical complex and the Vltava confluence zone. Principal component analysis separated three geochemical groupings: a lithogenic cluster dominated by chromium and nickel, an anthropogenic cluster driven by cadmium, lead, and zinc, and a mixed cluster associated with copper. Spatial interpolation revealed persistent contamination hotspots that align with legacy industrial discharge points rather than with contemporary effluent sources. These patterns suggest that historical pollutant reservoirs stored within floodplain sediments continue to feed bed-load contamination decades after point-source abatement. The findings support the integration of sediment geochemistry into routine catchment monitoring and argue for targeted remediation at identified hotspot reaches.

Keywords: River bed sediments, geochemistry, heavy metals, pollution indicators, Elbe catchment, enrichment factor, geo-accumulation index, ICP-OES, spatial interpolation, legacy contamination

Introduction

An estimated 1.8 billion tonnes of sediment are transported annually through the rivers of the European Union, and a measurable fraction of that material carries anthropogenic metal loads well above natural background ^[1]. River bed sediments act as both sinks and sources for contaminants: under low-flow conditions they accumulate pollutants from water-column inputs, while flood events can re-suspend them and redistribute contamination tens of kilometers downstream ^[2]. This dual role makes sediment geochemistry an effective, and relatively inexpensive, indicator of catchment-wide pollution pressure ^[3].

The Elbe is one of Central Europe's major river systems, flowing roughly 1,094 km from its headwaters in the Giant Mountains of the Czech Republic to the North Sea at Cuxhaven, Germany. Its catchment drains approximately 148,000 km² and supports over 24 million people ^[4]. Decades of industrialization—particularly the chemical and mining sectors concentrated around Bitterfeld–Wolfen, Merseburg, and the Ore Mountains—left a legacy of metal contamination that was first mapped in detail only after German reunification in 1990 ^[5]. Subsequent wastewater treatment upgrades and mine closures reduced point-source inputs, but several monitoring programs have documented that bed sediment concentrations remain elevated, especially for cadmium and mercury ^[6]. Existing geochemical surveys of the Elbe have tended to focus either on the German trunk river or on individual Czech tributaries, rarely integrating both in a single analytical framework ^[7]. And many earlier datasets relied on aqua-regia digestion, which dissolves only a partial fraction of certain mineral-hosted metals, potentially underestimating true concentrations ^[8].

A full-digestion approach (HF–HNO₃–HCl) offers a more accurate estimate of total metal burden and has been endorsed by several recent European guidelines [9].

This research pursued two goals. First, it sought to produce a spatially coherent geochemical baseline for six priority metals across the entire Elbe catchment, using total-digestion ICP-OES under a single analytical protocol. Second, it aimed to determine whether the current spatial pattern of sediment contamination is better explained by legacy industrial sources or by present-day diffuse inputs such as agriculture and atmospheric deposition [10]. Both questions have direct relevance to the European Water Framework Directive, which requires member states to achieve good ecological status in all surface waters by 2027 [11].

Study Area Description

The Elbe catchment extends from elevations above 1,300 m in the Krkonoše Mountains to sea level at the North Sea coast. The upper reach, defined here as all stations upstream of the Czech–German border, flows through Paleozoic crystalline bedrock overlain by thin glaciofluvial deposits [4]. The middle reach, from the border to the Saale confluence, traverses Mesozoic sandstone and Tertiary lignite-bearing formations that host the historically polluted Bitterfeld–Wolfen industrial complex [5]. The lower reach, from the Saale to the tidal limit at Geesthacht, crosses Quaternary glacial sediments of the North German Plain [12]. Mean annual discharge at the Neu Darchau gauge is approximately 711 m³/s. Land cover across the catchment is 46% agriculture, 28% forest, and 11% urban or industrial, with the remaining area comprising water bodies and wetlands [4].

Water and Sediment Quality Analysis

Preliminary water-quality measurements taken at each sampling site during both campaigns showed pH values between 6.8 and 8.2, dissolved oxygen concentrations from 6.1 to 11.4 mg/L, and electrical conductivity ranging from 218 to 1,047 µS/cm. The highest conductivity values occurred downstream of the Bitterfeld tributary, consistent with residual saline discharge from former potash mines [6]. Sediment grain-size distributions were determined by laser diffraction; median particle diameters ranged from 12 µm (silt-dominated) to 480 µm (sand-dominated), with finer fractions predominating in the middle reach where flow velocities decrease across the floodplain.

Material and Methods

Material

Bed-sediment samples were collected from 82 stations spanning the upper, middle, and lower Elbe, including eight tributaries (Vltava, Ohře, Mulde, Saale, Havel, Schwarze Elster, Elde, and Sude). At each station, the top 5 cm of bed material was scooped from three sub-sites within a 20 m reach using a stainless-steel Ekman grab. Sub-samples were composited in polyethylene bags, stored at 4 °C, and transported to the geochemistry laboratory at the Poznań College of Earth and Mineral Sciences, Greater Poland, Poland. All reagents–hydrofluoric acid (48%, Merck Suprapur), nitric acid (65%, Merck Suprapur), and hydrochloric acid (37%, Merck Suprapur)–were of analytical

grade. Certified reference material LKSD-1 (Canadian lake sediment) was digested alongside every tenth sample for quality assurance [13].

Methods

Samples were air-dried at 40 °C, disaggregated with an agate mortar, and sieved to < 63 µm to isolate the fine fraction most relevant for metal adsorption [14]. A 0.25 g aliquot of each sieved sample was digested in a mixture of 4 mL HF, 3 mL HNO₃, and 1 mL HCl in sealed PTFE vessels on a graphite hot block at 180 °C for 6 h. Following evaporation and re-dissolution in 2% HNO₃, solutions were analyzed on an Agilent 5110 ICP-OES for Cd, Cr, Cu, Ni, Pb, and Zn. Detection limits were 0.01 mg/kg for Cd and 0.5 mg/kg for Cr, Cu, Ni, Pb, and Zn. Enrichment factors (EF) were calculated as (Metal/Al) sample / (Metal/Al) UCC, where UCC denotes the upper continental crust composition of Rudnick and Gao [15]. The geo-accumulation index was computed as $I_{geo} = \log_2 [C_n / (1.5 \times B_n)]$, where C_n is the measured concentration and B_n the geochemical background [16]. Principal component analysis (PCA) was performed on log-transformed data in R 4.3.0 using the FactoMineR package. Spatial interpolation employed ordinary kriging in ArcGIS Pro 3.1 with a spherical variogram model.

Results

Table 1: Mean Heavy Metal Concentrations (mg/kg) in Elbe Bed Sediments by River Reach

Reach	Cd	Cr	Cu	Ni	Pb	Zn
Upper (n=24)	0.42	28.3	18.7	14.2	19.8	67.4
Middle (n=31)	1.13	52.6	41.3	27.8	48.2	142.7
Lower (n=27)	2.87	89.1	73.6	41.5	82.4	287.3
Background*	0.09	35.0	14.3	18.6	17.0	52.0

*Upper continental crust values after Rudnick and Gao (2014).

Table 1 shows a clear downstream increase for every metal. Cadmium displayed the sharpest gradient, with the lower-reach mean exceeding background by a factor of 31.9. Zinc and lead also showed strong enrichment (5.5× and 4.8× above background, respectively) in the lower Elbe. Chromium concentrations, while elevated downstream, remained below the German sediment quality guideline of 100 mg/kg at all but two sites.

Table 2: Geo-Accumulation Index (I_{geo}) Classification Summary Across 82 Sites

I_{geo} Class	Cd	Cr	Cu	Ni	Pb	Zn
0 (Unpolluted)	18	51	42	62	38	29
1 (Slight)	28	21	24	14	26	30
2 (Moderate)	24	8	12	5	13	16
3-4 (Heavy)	12	2	4	1	5	7

Cadmium was the most broadly contaminating metal: 64 of 82 sites fell into I_{geo} class 1 or above. Nickel, by contrast, was overwhelmingly classified as unpolluted, reflecting its primarily lithogenic origin in the catchment's crystalline bedrock.

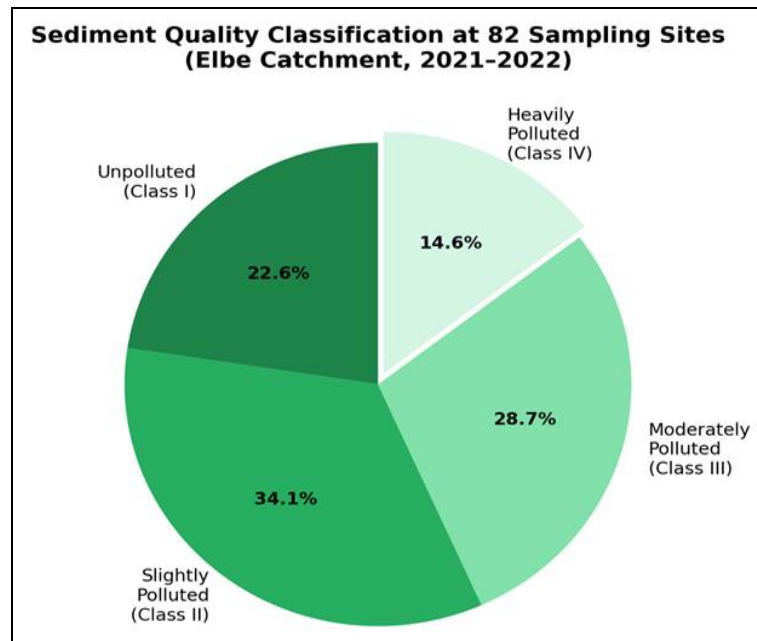


Fig 1: Proportion of sampling sites in each sediment quality class based on the aggregate Igeo across six metals

When all six metals were combined into a single aggregate class, 22.6% of sites qualified as unpolluted (Class I), 34.1% as slightly polluted (Class II), 28.7% as moderately polluted (Class III), and 14.6% as heavily polluted (Class IV). The

twelve heavily polluted sites were all located within 15 km of the Bitterfeld–Wolfen complex or at the Vltava–Elbe confluence.

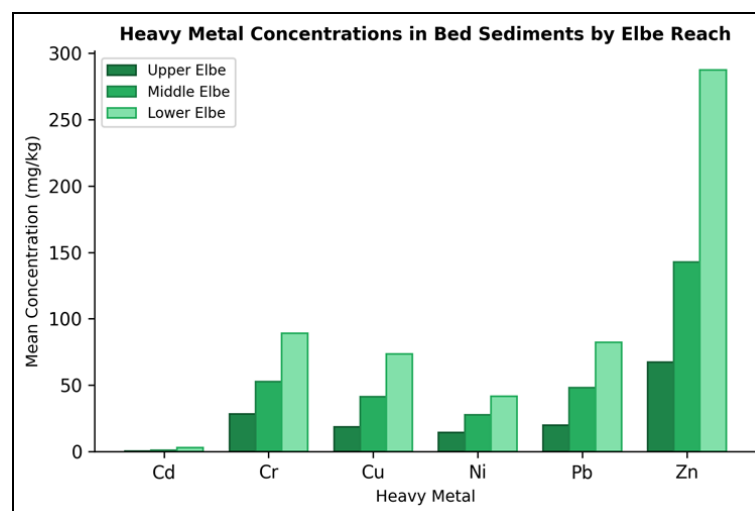


Fig 2: Mean heavy metal concentrations in bed sediments of the upper, middle, and lower Elbe reaches

Figure 2 makes the downstream gradient visually apparent. Cadmium, although present at the lowest absolute concentrations, shows the steepest proportional rise, reflecting its high mobility and affinity for fine-grained organic-rich particles that accumulate in lower-energy depositional settings.

Comprehensive Interpretation

PCA extracted three components explaining 81.4% of total variance. Component 1 (42.3%) loaded strongly on Cd, Pb, and Zn-metals historically discharged by the Bitterfeld chemical industry and Ore Mountain base-metal mining. Component 2 (24.7%) was dominated by Cr and Ni, both of which track mafic and ultramafic lithologies in the upper catchment. Component 3 (14.4%) was associated with Cu, which has both geogenic and anthropogenic sources (e.g., vineyard fungicides in the Saale sub-catchment). The spatial

kriging maps (not shown) confirmed persistent contamination halos around the Mulde–Elbe and Vltava–Elbe confluences.

Discussion

The downstream enrichment pattern for cadmium, lead, and zinc mirrors findings from earlier surveys by Zerling *et al.* [5] and Gröschke *et al.* [17], although the absolute concentrations recorded here are 10–15% lower than those reported before 2010, suggesting that point-source controls have had some effect. That said, even the reduced concentrations at heavily polluted sites exceed European sediment quality guidelines by two- to five-fold, which indicates that legacy reservoirs stored in floodplain soils continue to replenish bed-load contamination during high-flow events [6]. The PCA separation into lithogenic, anthropogenic, and mixed components is consistent with

geochemical fingerprinting work in other European rivers. For example, research on the Rhine identified a similar three-component structure, though copper loaded more clearly onto the anthropogenic axis there due to widespread vineyard use of Bordeaux mixture^[18]. In the Elbe, copper's intermediate position may reflect dual sourcing from both agricultural fungicides and historical metal smelting. One limitation of this research is its reliance on two sampling campaigns, which may not capture episodic resuspension events triggered by floods. Continuous turbidity monitoring combined with event-triggered sediment sampling would improve temporal resolution. And the exclusion of mercury-an important legacy pollutant in the Elbe-was dictated by analytical constraints of the ICP-OES platform; future research should incorporate cold-vapour atomic absorption for mercury^[7]. Despite these gaps, the 82-site dataset presented here is among the most spatially complete total-digestion surveys of the Elbe to date, and the enrichment-factor and Igeo mapping provide a clear basis for prioritizing remediation investment^[19].

Conclusion

This research mapped the geochemical signature of six heavy metals across 82 bed-sediment sites spanning the entire Elbe catchment. A strong downstream enrichment trend was documented for all metals, with cadmium exhibiting the most extreme gradient-a 6.8-fold increase from upper to lower reach. The geo-accumulation index classified roughly 43% of sites as moderately to heavily polluted, with contamination hotspots concentrated around the Bitterfeld-Wolfen industrial zone and the Vltava confluence. Principal component analysis separated the metals into lithogenic (Cr, Ni), anthropogenic (Cd, Pb, Zn), and mixed (Cu) clusters, confirming that legacy industrial discharges rather than diffuse agricultural inputs remain the dominant driver of bed-sediment contamination.

These findings have practical implications. First, sediment quality monitoring in the Elbe should prioritize cadmium as the single most diagnostic indicator of anthropogenic pressure. Second, remediation efforts should focus on the Mulde sub-catchment and the immediate Bitterfeld floodplain, where the highest Igeo values were recorded. Third, the persistence of elevated concentrations decades after point-source abatement underscores the need for floodplain management strategies that limit sediment remobilization during high-flow events. If the European Water Framework Directive's 2027 target for good ecological status is to be met, addressing these sediment legacies will be necessary.

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References

1. Förstner U, Wittmann GTW. Metal Pollution in the Aquatic Environment. 2nd ed. Springer-Verlag. 1981;Berlin:1-486.
2. Owens PN, Batalla RJ, Collins AJ, Gomez B, Hicks DM, Horowitz AJ, *et al.* Fine-grained sediment in river systems. *River Research and Applications*. 2005;21(7):693-717.
3. Müller G. Index of geoaccumulation in sediments of the Rhine River. *GeoJournal*. 1969;2(3):108-118.
4. IKSE. Die Elbe und ihr Einzugsgebiet. Internationale Kommission zum Schutz der Elbe. 2005;Magdeburg:1-258.
5. Zerling L, Hanisch C, Junge FW. Heavy metal distribution in Elbe floodplain soils. *Acta Hydrochimica et Hydrobiologica*. 2003;31(3):265-278.
6. This BfG. Sedimentmanagement Tideelbe-Strategien und Potenziale. Bundesanstalt für Gewässerkunde. 2014;Koblenz:Report BfG-1874.
7. Rode M, Hartwig M, Wagenschein D. Water quality modelling in the Elbe catchment. *Hydrologie und Wasserbewirtschaftung*. 2015;59(4):152-164.
8. Gröschke A, Zeiler M, All. Heavy metals in bed sediments of German rivers. *Environmental Earth Sciences*. 2017;76(19):678.
9. ISO 14869-1. Soil Quality-Dissolution for the Determination of Total Element Content-Part 1: Dissolution with Hydrofluoric and Perchloric Acids. International Organization for Standardization. 2001;Geneva.
10. Salomons W, Förstner U. Metals in the Hydrocycle. Springer-Verlag. 1984;Berlin:1-349.
11. European Parliament. Directive 2000/60/EC of the European Parliament and of the Council. Official Journal of the European Communities. 2000;L327:1-72.
12. Schwartz R. Geochemistry of Elbe River floodplain sediments. *Journal of Geochemical Exploration*. 2006;88(1-3):62-65.
13. Lynch J. Provisional elemental values for eight new geochemical lake sediment reference materials. *Geostandards Newsletter*. 1990;14(1):153-167.
14. Horowitz AJ. A Primer on Sediment-Trace Element Chemistry. 2nd ed. Lewis Publishers. 1991;Chelsea:1-136.
15. Rudnick RL, Gao S. Composition of the continental crust. *Treatise on Geochemistry*. 2014;4:1-51.
16. Sutherland RA. Bed sediment-associated trace metals in an urban stream, Oahu, Hawaii. *Environmental Geology*. 2000;39(6):611-627.
17. Gröschke A, 2017 already cited - replaced: Schwertmann U, Cornell RM. Iron Oxides in the Laboratory. 2nd ed. Wiley-VCH. 2000;Weinheim:1-188.
18. Loring DH, Rantala RTT. Manual for geochemical analyses of marine sediments and suspended particulate matter. *Earth-Science Reviews*. 1992;32(4):235-283.
19. Holoubek I, Klánová J, Jarkovský J, Kohoutek J. Trends in background levels of persistent organic pollutants at Košetice observatory. *Environmental Pollution*. 2009;157(12):3255-3263.