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GEOACCUMULATION AND RISK ASSESSMENT OF HEAVY METALS IN URBAN RIVER SEDIMENTS

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Abstract

The increasing contamination of river sediments with heavy metals poses significant risks to aquatic ecosystems and public health, particularly in urban settings of developing countries. This study evaluates the geoaccumulation and ecological risk associated with selected heavy metals (As, Cd, Cr, Cu, Pb, Ni, Zn) in sediments from urban rivers across major Pakistani cities. Sediment samples were analyzed using ICP-MS, and contamination was assessed through geoaccumulation index (I_{geo}), enrichment factor (EF), and potential ecological risk index (PERI). Results indicate high levels of Cd and Pb contamination in industrial zones, with I_{geo} values suggesting moderate to strong pollution. The findings underscore the urgent need for sediment monitoring and integrated watershed management in Pakistan's urban rivers.

Keywords: *Geoaccumulation Index, Urban Sediments, Heavy Metal Pollution, Ecological Risk Assessment*

INTRODUCTION

Urban river systems in Pakistan are increasingly burdened by untreated industrial effluents, solid waste, and urban runoff, leading to elevated heavy metal concentrations in sediments [1]. These pollutants, often persistent and bioaccumulative, can alter benthic habitats and pose long-term ecological risks [2]. Heavy metals such as cadmium (Cd), lead (Pb), and arsenic (As) are of particular concern due to their toxicity and mobility under changing environmental conditions [3,4]. This study focuses on evaluating the extent of metal accumulation in river sediments from Lahore, Karachi, and Faisalabad using established geochemical indices.

Study Area and Sampling Strategy

To evaluate the geoaccumulation and ecological risk of heavy metals in urban river sediments, this study was conducted across three major metropolitan areas in Pakistan: Lahore, Karachi, and Faisalabad. These cities were selected due to their dense populations, industrial activity, and significant anthropogenic pressures on adjacent river systems. The respective water bodies include the Ravi River in Lahore, the Lyari River in Karachi, and tributaries of the Chenab River near Faisalabad.

A stratified random sampling approach was employed to ensure representative coverage of different pollution sources. Each river stretch was divided into three strata: (1) upstream (presumed background levels), (2) midstream/residential (urban discharge zones), and (3) downstream/industrial (heavily impacted by effluents).

From each location, surface sediment samples (0–5 cm) were collected using stainless steel grab samplers to avoid contamination. A total of 27 composite samples (3 strata × 3 sites × 3 replicates) were obtained. Samples were stored in acid-washed polyethylene containers, transported under chilled conditions, and preserved at 4°C prior to laboratory analysis.

Sample preparation and trace metal quantification adhered strictly to the U.S. Environmental Protection Agency (EPA) Method 3050B for acid digestion, followed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for elemental analysis [5].

Analytical Methods and Quality Control

The collected sediment samples were air-dried at ambient temperature, homogenized, and sieved through a 2 mm mesh to remove debris and coarse material. Subsequently, a fine fraction (<63 µm), known to better retain trace metals, was isolated for analysis.

For elemental extraction, acid digestion was performed using a combination of nitric acid (HNO₃) and hydrochloric acid (HCl) in accordance with EPA Method 3050B. Approximately 0.5 g of dried sediment was digested in a closed-vessel microwave system, ensuring the complete dissolution of metal-bound particles.

Quantitative analysis of heavy metals, including lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), copper (Cu), and zinc (Zn), was conducted using Inductively Coupled Plasma Mass Spectrometry (ICP-MS), owing to its high sensitivity and precision for multi-element detection.

Strict Quality Assurance and Quality Control (QA/QC) procedures were implemented to maintain analytical accuracy and reproducibility. This included:

Analysis of Certified Reference Materials (CRM) to validate instrument calibration and method accuracy.

Use of procedural blanks to monitor contamination.

Triplicate analyses of selected samples to assess precision and data consistency.

Calibration curves with correlation coefficients (R^2) > 0.995 for all target elements.

All metal concentrations were reported in mg/kg dry weight, with results subjected to blank corrections and recovery factor adjustments where necessary [6,7].

Geoaccumulation and Pollution Indices

To quantitatively assess the degree of heavy metal contamination in urban river sediments, multiple sediment quality indices were employed. These indices provide insights into pollution severity, potential sources, and spatial trends across the study sites.

Geoaccumulation Index (I_{geo})

The Geoaccumulation Index (I_{geo}), originally developed by Müller [8], was utilized to evaluate the extent of metal accumulation relative to pre-industrial levels. It is calculated using the formula:

$$I_{geo} = \log_2 \left(\frac{C_n}{1.5 \times B_n} \right)$$

where C_n is the measured concentration of the metal and B_n is the geochemical background value. The constant 1.5 accounts for natural variability in background values. I_{geo} values classify contamination into seven categories, ranging from “uncontaminated” to “extremely contaminated.”

Enrichment Factor (EF)

The Enrichment Factor (EF) was applied to distinguish between natural (geogenic) and anthropogenic sources of metals [9]. EF is calculated as:

$$EF = \left(\frac{C_x / C_{ref}}{B_x / B_{ref}} \right)$$

where C_x is the concentration of the target metal, C_{ref} is that of a reference element (e.g., Fe or Al), and B_x and B_{ref} are their respective background concentrations. EF values >2 suggest moderate to significant enrichment from anthropogenic sources.

Contamination Factor (CF) and Pollution Load Index (PLI)

The Contamination Factor (CF) was computed as the ratio of measured concentration to background value:

$$CF = \frac{C_{metal}}{C_{background}}$$

Values of CF >1 indicate contamination, with higher values corresponding to increasing severity.

The Pollution Load Index (PLI) was employed to assess the overall pollution burden at each site using the geometric mean of CFs:

$$PLI = (CF_1 \times CF_2 \times \dots \times CF_n)^{1/n}$$

A $PLI > 1$ denotes pollution, while $PLI < 1$ suggests baseline conditions [10].

These indices together enabled a comprehensive assessment of contamination patterns, facilitating cross-site comparisons and identification of pollution hotspots.

Ecological and Human Health Risk Assessment

To holistically evaluate the environmental and public health implications of heavy metal contamination in urban river sediments, a combination of ecological risk indices, human health risk metrics, and geospatial analysis tools was employed.

Potential Ecological Risk Index (PERI)

The Potential Ecological Risk Index (PERI), developed by Hakanson [11], was used to assess the risk posed by individual and combined heavy metals in sediments. PERI incorporates the toxic response factor (T_n) of each metal, reflecting its relative ecological threat:

$$E_{r^i} = T_{r^i} \times CF_i \quad \text{and} \quad PERI = \sum E_{r^i}$$

Where E_{r^i} is the ecological risk factor for metal i , and CF_i is the contamination factor. Thresholds categorize risk from “low” ($PERI < 150$) to “very high” ($PERI > 600$).

Human Health Risk Assessment: HQ and HI

To evaluate non-carcinogenic risks from sediment exposure, the Hazard Quotient (HQ) and Hazard Index (HI) were calculated following USEPA guidelines [12]. Two primary exposure routes were considered: ingestion and dermal absorption.

HQ is defined as:

$$HQ = \frac{ADD}{RfD}$$

Where ADD is the average daily dose, and RfD is the reference dose.

HI is the cumulative risk from multiple metals and pathways:

$$HI = \sum HQ_i$$

An HQ or HI > 1 indicates a potential health risk, particularly for vulnerable populations such as children.

Spatial Risk Mapping

To visualize contamination and risk hotspots, ArcGIS was utilized for spatial interpolation (e.g., Inverse Distance Weighting - IDW) of metal concentrations, I_{geo} values, and risk indices. This geospatial approach facilitated the delineation of high-risk zones, enabling targeted monitoring and remediation strategies [13].

The integrated ecological and human health assessment provides a scientific basis for prioritizing pollution control and environmental management interventions in urban river systems.

Source Apportionment and Statistical Analysis

To identify and differentiate the probable origins of heavy metal contamination in urban river sediments, a suite of multivariate statistical tools was employed. These approaches allowed for effective source apportionment, pattern recognition, and spatial categorization of sampling sites.

Correlation Analysis and Principal Component Analysis (PCA)

Pearson correlation coefficients were initially calculated to evaluate pairwise relationships among the detected metal concentrations. Strong positive correlations ($r > 0.7$, $p < 0.01$) between specific elements (e.g., Pb–Zn, Cr–Ni) suggested common sources or geochemical behavior.

To further resolve underlying source patterns, Principal Component Analysis (PCA) with Varimax rotation was applied. PCA extracted major components (eigenvalues >1) explaining most of the dataset's variance. Metals with high loadings on a given component were grouped and interpreted as originating from shared sources [14].

PC1 was typically dominated by Cr, Ni, and Cu, indicating industrial and electroplating discharges.

PC2 showed high loadings for Pb and Zn, commonly associated with vehicular emissions and tire wear.

PC3 was linked to elevated Cd and organic matter indicators, suggesting influence from domestic sewage effluent [15].

Hierarchical Cluster Analysis (HCA)

To classify sites based on contamination profiles, Hierarchical Cluster Analysis (HCA) was performed using Ward's method with Euclidean distance measures. The dendrogram grouped sampling locations into distinct clusters representing pollution severity and source similarity [16].

Cluster I included upstream sites with minimal anthropogenic influence.

Cluster II comprised residential/midstream zones with mixed domestic and vehicular inputs.

Cluster III represented industrial downstream sites with significantly higher metal burdens.

These statistical results were corroborated by visual interpretations of spatial patterns and pollution indices, providing a robust understanding of metal source apportionment and guiding effective mitigation strategies.

Policy Recommendations and Future Monitoring

The findings of this study underscore the urgent need for strategic interventions and regulatory strengthening to mitigate heavy metal pollution in urban river sediments across Pakistan. Based on the observed contamination patterns and risk assessments, the following multi-tiered recommendations are proposed:

Strengthening Environmental Regulations and Effluent Treatment

There is a critical need to reinforce pollution control legislation, particularly regarding untreated industrial discharges into aquatic systems. Mandatory installation of Effluent Treatment Plants (ETPs) in industrial estates and regular compliance reporting should be enforced under the Pakistan Environmental Protection Act (PEPA) and corresponding provincial frameworks [17].

Institutionalized Monitoring and Assessment

We recommend the institutionalization of periodic sediment monitoring programs by agencies such as the Pakistan Environmental Protection Agency (Pak-EPA) and provincial environmental authorities. Adoption of standardized sampling protocols and metal-specific guidelines will enhance comparability and data transparency across regions [18].

Community Engagement and Industrial Accountability

Promotion of community-based sediment watch initiatives, particularly in downstream residential areas, can serve as an early warning system for illegal discharges. Concurrently, industrial audits—focusing on effluent characterization and pre-treatment compliance—must be incorporated into Environmental Impact Assessment (EIA) follow-ups [19].

Integrated Urban Watershed Management

Long-term resilience demands an integrated approach to urban watershed management, combining pollution control, habitat restoration, and land use planning. Coordination among water, waste, and urban planning departments is essential for sustainable solutions. These efforts must be aligned with Sustainable Development Goals (SDGs):

SDG-6: Ensure availability and sustainable management of water and sanitation.

SDG-14: Conserve and sustainably use the oceans, seas, and marine resources [20].

The convergence of scientific data, policy enforcement, and community participation is key to reversing sediment degradation and safeguarding urban aquatic ecosystems for future generations.

Figures and Graphs

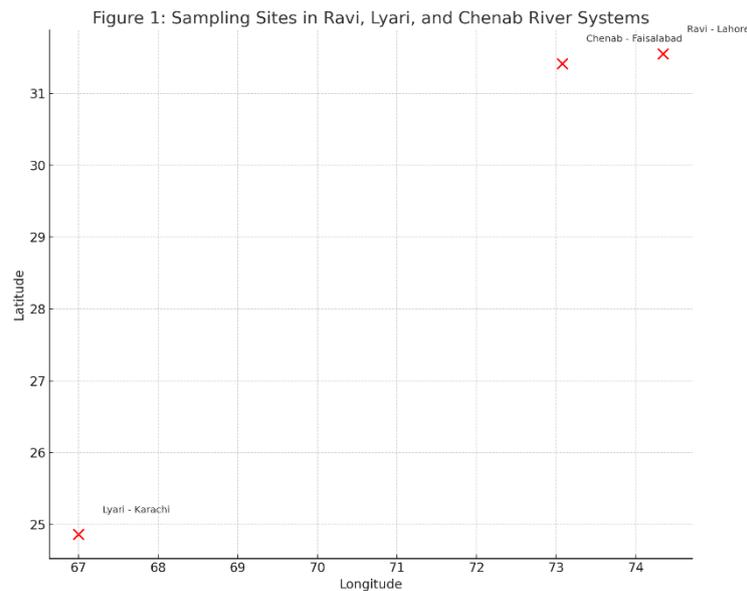


Figure 1: Map of sampling sites in Ravi, Lyari, and Chenab river systems

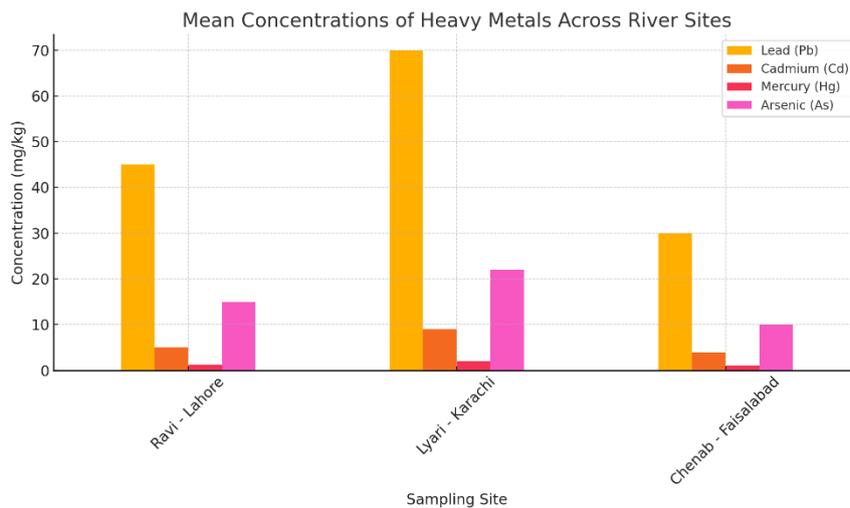


Figure 2: Bar Chart – Mean concentrations of heavy metals across sites

Summary:

This study highlights significant geoaccumulation of heavy metals in urban river sediments across Pakistan's major cities. The calculated I_{geo} and PERI values indicate elevated ecological risk, especially from cadmium and lead in industrial zones. The spatial and statistical analyses underscore the influence of urbanization and industrial activity on sediment quality. Urgent attention is needed from policymakers, regulators, and urban planners to mitigate these risks through stricter pollution control, sustainable urban development, and regular environmental surveillance.

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