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Original Research

Ecotoxicological Insights into Heavy Metal Dynamics in Cauvery Delta Wetland Sediments: Geochemistry, Speciation and Ecological Risk Indices

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Abstract: Wetland sediments in deltaic ecosystems act both as sinks and secondary sources of heavy metals, thereby influencing contaminant mobility, bioavailability, and ecological risk. The present study investigated the distribution, speciation, mobility, and ecological risk of Fe, Ni, Pb, Cu, Cr, and Cd in surface sediments collected from **40** wetlands across the Cauvery Delta, India**.** The study integrates total metal concentration analysis, sequential extraction, contamination indices, risk assessment models, and multivariate statistical techniques to evaluate sediment quality and identify dominant sources of contamination**.** Sediment physicochemical properties indicated predominantly alkaline and carbonate-rich conditions, which strongly influenced metal partitioning and mobility. The overall decreasing order of mean metal concentrations was Fe > Pb > Ni > Cr > Cu > Cd. Contamination factor (CF), Pollution Load Index (PLI), and Geo-accumulation index (Igeo) revealed generally low to moderate contamination for most metals, while Cd exhibited localized enrichment and emerged as the principal contaminant of concern. PLI values ranging from **1.07** to **1.29** indicated slight but consistent cumulative pollution across all wetlands. Sequential extraction analysis demonstrated that Fe was predominantly associated with stable residual fractions, whereas Cd showed comparatively higher association with exchangeable and carbonate-bound fractions, indicating enhanced mobility and bioavailability. Risk Assessment Code (RAC) and Potential Ecological Risk Index (PERI) further identified Cd, Pb, and Cr as ecologically significant metals with elevated remobilization potential under changing environmental conditions. High RAC and PERI values were particularly observed in wetlands located within Karur and Tiruchirappalli districts, indicating localized anthropogenic influence. Pearson correlation analysis and Principal Component Analysis (PCA) suggested that Fe and Cr were primarily influenced by lithogenic processes, whereas Cd, Pb, and Cu were associated with mixed anthropogenic inputs including agricultural runoff, fertilizer application, urban discharge, and localized industrial activities. The findings demonstrate that although most wetlands remain moderately contaminated, Cd exhibits elevated mobility and ecological sensitivity, warranting targeted monitoring and management in identified hotspot regions. This study provides a comprehensive regional-scale assessment of heavy metal behavior in deltaic wetland sediments and contributes important baseline information for future wetland conservation and pollution management strategies.

1. INTRODUCTION

Deltaic systems are highly dynamic geomorphic environments that develop where riverine sediments accumulate at the transition between fluvial and marine domains. Continuous deposition of alluvial material creates fertile plains that rank among the world's most productive agricultural regions, thereby supporting dense populations, food production, and rich biodiversity (Tessler et al., 2018; Syvitski et al., 2022). These landscapes encompass a mosaic of wetland types, including mangrove forests, estuaries, coastal lagoons, brackish marshes, freshwater wetlands, and cultivated floodplain areas. Collectively, these ecosystems offer a wide range of ecological services such as habitat provision, carbon storage, regulation of hydrological processes, shoreline protection, nutrient cycling, and water purification (Barbier et al., 2019; IPCC, 2022).

Wetlands within delta regions play a vital role in sustaining both resident and migratory fauna by offering breeding grounds, feeding areas, and nursery habitats maintained by periodic inundation. Mangrove and marsh ecosystems are also recognized as significant blue carbon sinks, where organic carbon is preserved in waterlogged sediments under oxygen-limited conditions over long timescales, thereby contributing to climate regulation (Alongi, 2020; Macreadie et al., 2021). Furthermore, coastal wetlands dissipate wave energy, reduce storm surge intensity, and mitigate coastal erosion, providing natural protection for inland settlements against extreme weather events (Menéndez et al., 2020). By temporarily storing floodwaters and releasing them gradually during dry periods, these systems also enhance groundwater recharge and stabilize regional water availability.

In addition to their ecological importance, delta regions frequently support intensive agricultural production, particularly irrigated rice cultivation and are also experiencing expanding urban and industrial development. The Cauvery Delta of southern India exemplifies such a landscape, hosting diverse industries including textiles, paper manufacturing, cement production, heavy electrical equipment fabrication, and agro-processing units. Rapid population growth, land-use transformation, industrial expansion, and climate-related pressures have collectively intensified environmental stress on these fragile ecosystems (Nicholls et al., 2021). Among the emerging threats, contamination by heavy metals has become a major concern on account of their persistence, toxicity, and ability to accumulate in biological systems.

Sediments in wetland environment function both as repositories and potential secondary sources of trace metals. Pollutants enter deltaic systems through multiple pathways, including upstream river transport, agricultural runoff, industrial effluents, atmospheric deposition, and municipal wastewater discharge. Under variable physicochemical conditions, particularly shifts in redox potential and salinity, metals bound to sediments may be remobilized, increasing their availability to aquatic organisms and elevating ecological risks (Varol, 2020; Zhang et al., 2022). Such contamination can disrupt trophic interactions, impair ecosystem functioning, and pose hazards to human populations via biomagnification along food chains.

Heavy metals are of significant concern because they are resistant to biodegradation and tend to accumulate in organisms over time. In wetlands subject to seasonal flooding or saline intrusion, changes in redox conditions may enhance metal mobility, facilitating their transfer into both aquatic and terrestrial biota and ultimately into the human diet (Varol & Sen, 2012; Dessalew et al., 2018; Bessa et al., 2018; Mandeng et al., 2019; Bhattacharyya et al., 2019). Chronic exposure to these contaminants can degrade ecosystem health, alter biogeochemical cycles, and enhance long-term environmental deterioration (Liu et al., 2016; Chen et al., 2019).

Evaluation of sediment contamination based solely on total metal concentrations often provides limited insight into environmental risk. Metal speciation analysis, which differentiates metals according to their chemical associations, offers a more meaningful assessment of their stability, mobility, and bioavailability. Sequential extraction studies typically categorize metals into exchangeable, carbonate-associated, Fe-Mn oxide-bound, organic-bound, and residual fractions, each representing distinct degrees of environmental availability and potential release under changing conditions (Parizanganeh et al., 2007; Zakir et al., 2008; El Kammar et al., 2009; Kumar et al., 2011).

Complementary to speciation studies, sediment quality is frequently assessed using geochemical indices such as the geoaccumulation index, contamination factor, and pollution load index. These metrics enable quantitative evaluation of contamination intensity and spatial distribution, facilitating identification of pollution hotspots and comparison across regions (Müller, 1969; Håkanson, 1980; Cevik et al., 2009; Atiemo et al., 2011; Salah et al., 2012; Nowrouzi & Pourkhabbaz, 2014; Gupta et al., 2014; Sivakumar et al., 2016). Such indices provide standardized frameworks for interpreting complex geochemical datasets and assessing ecological risk (Håkanson, 1980; USEPA, 2002). Considering the ecological significance and socio-economic value of delta wetlands, systematic monitoring and integrated management approaches are essential to minimize anthropogenic impacts and maintain long-term sustainability. Multidisciplinary investigations are therefore critical for understanding environmental processes and guiding conservation strategies in vulnerable deltaic systems such as the Cauvery Delta.

Despite several studies on sediment geochemistry in the Cauvery Basin and other Indian wetlands, most investigations have been limited to localized assessments, single-site analyses, or total metal concentration approaches without addressing metal speciation and mobility. Furthermore, comparative evaluations across multiple wetlands at a regional scale remain scarce.

The present study advances current understanding by (i) providing a comprehensive assessment across 40 wetlands in the deltaic region, (ii) incorporating a district-wise comparative framework to identify spatial heterogeneity, (iii) applying speciation-based risk assessment to evaluate metal mobility and bioavailability, and (iv) integrating multiple sediment quality indices with multivariate statistical analysis (PCA) to identify dominant contamination sources. Notably, the study highlights the elevated mobility and ecological risk associated with cadmium (Cd), which has received limited attention in previous regional assessments. This integrated, multi-scale approach offers a more robust evaluation of sediment contamination dynamics and ecological risk in deltaic wetland systems.

2. MATERIALS AND METHODS

2.1 Study area

The Cauvery Delta, situated in southeastern India, constitutes one of the country's most important agricultural regions and is characterized by extensive wetland networks that support irrigation, fisheries, and biodiversity. Increasing agricultural intensification and human activities have raised focus on the accumulation of contaminants, particularly heavy metals, in sedimentary environments. To evaluate regional-scale pollution, the present study encompassed wetlands distributed across five districts: Karur, Tiruchirappalli, Thanjavur, Thiruvarur, and Nagapattinam. The investigated area covers approximately **15,032.83** km^2 and lies between latitudes **10.76°-11.03°** N and longitudes **78.15°-79.84°** E. Information regarding the selected wetlands, including surrounding land-use characteristics and potential contamination sources, is provided in Table **1.** Ecological attributes of these wetlands were also considered as part of the environmental assessment.

Table 1. Characteristics of wetlands of the Cauvery delta region

District	Location	Land use pattern in the vicinity of the sampling area	Possible sources of contamination
Karur (Sample 1-9)	Kuppagoundan valasu, Periya thadampalayam, Uppidamangalam, Vellaianaikulam, Virarakkiyam, Udayapatti, Tharagampatti, Panjapatti, Vayalur	Agricultural, commercial, and residential mix	Agricultural runoff, Human activities, and litter
Tiruchirappalli (Sample 10-20)	Nagayanallur lake, Kattukaruppan kottam, Alathudaiyanpatti, Zambuyari lake, Periya yeri, Keerambur, Thayanur, Thiruverambur, Gundur, Thuvakudi, Kiliyur lake	Agricultural, commercial, and residential mix	Agricultural runoff, Human activities, and litter
Thanjavur (Sample 21-30)	Sholagampatti, Surakudipatti, Vendayampatti, Kallaperampur, Samuthram, Phunnapur, Chelikurichi, Sendakottai, Sandampettai, Viriankottai	Agricultural, commercial, and residential mix	Agricultural runoff, Human activities, and litter
Thiruvarur (Sample 31-33)	Thirumeni, Thulasendrapuram, Vaduvoor Bird Sanctuary	Agricultural and residential mix	Agricultural runoff, Human activities, and litter
Nagapattinam (Sample 34-40)	Keeran Lake, Vattakudi River delta, Talainayar R.F, Kalimedu, Thirukadaiyur River basin,	Residential, commercial, and tourism	Agricultural runoff, Human activities, and litter

	Perunthottam, Point Calimere Wildlife Sanctuary		

2.2 Sampling and Monitoring Methods

Surface sediment samples were obtained from **40** wetland sites across the delta using a clean hand trowel. Locations were chosen to demonstrate varying extents of accessibility, hydrological characteristics, anthropogenic pressure and diverse land-use settings (Fig. **1**).

At each wetland, sediment was collected from multiple representative points covering inlet, central, and peripheral zones to account for small-scale spatial variability. The subsamples were thoroughly homogenized to obtain a composite sample representative of each site. Although field duplicates were limited due to logistical constraints, composite sampling from multiple points was adopted to minimize spatial heterogeneity and improve sample representativeness.

Sampling was undertaken during the pre-monsoon season (April **2023**), when hydrological conditions are relatively stable and recently deposited sediments are accessible. At each site, sediments from the upper **0-10** cm layer were acquired, placed in sterile polyethylene bags, and dispatched to the laboratory. Geographic coordinates were recorded using field positioning tools. In the laboratory, samples were air-dried at ambient temperature, homogenized, and passed through a **63** µm sieve to isolate the fine fraction, which was subsequently used for chemical analysis.

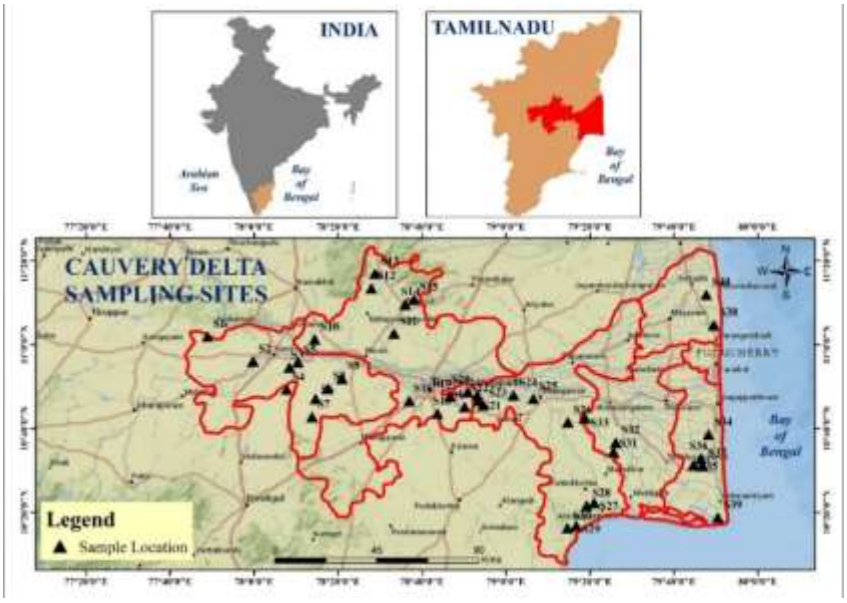

Fig 1. Study Area Map Showing Sediment Sampling Locations in the Cauvery Delta, Tamil Nadu, India

2.3 Laboratory Analysis

Subsamples of the fine sediment fraction were analyzed to determine selected physicochemical properties and metal concentrations. Metal speciation was assessed using the widely adopted five-step sequential extraction protocol of Tessier et al. **(1979)**, which partitions metals into exchangeable, carbonate-associated, Fe-Mn oxide-bound, organic-bound, and residual fractions to evaluate their mobility and potential bioavailability. Concentrations of Fe, Mn, Cr, Ni, Cu, Zn, Pb, and Cd were quantified using Atomic Absorption Spectrophotometry (Thermo Fisher Scientific iCE **3000** Series, USA) following appropriate extraction and digestion procedures. Total metal content was calculated by summing all fractions obtained from the sequential extraction process.

QA/QC protocols involved analytical evaluation of reagent blanks, triplicate measurements, recovery tests, and certified reference materials. Calibration was performed using multi-element standard solutions, yielding correlation coefficients exceeding **0.999.** Analytical precision was confirmed by relative standard deviations below **5%,** while recovery efficiencies ranged from **90%** to **105%.** Method accuracy was validated using NIST SRM **2702,** with measured values showing close agreement with certified concentrations.

To monitor potential contamination during the sample preparation phase, digestion blanks were processed with every batch of ten samples; in all instances, analyte levels in blanks remained below the MDL. Furthermore, the internal consistency of the sequential extraction procedure was verified through a mass balance check; the cumulative sum of the individual fractions was compared against the results of an independent total acid digestion for each sample. Recovery percentages for this mass balance check consistently ranged between **92%** and **106%**, confirming that no significant analyte loss or cross-contamination occurred during the multi-step fractionation process.

2.4 Methods for Estimating Contamination and Ecological Risk

Assessment of sediment quality based solely on total metal concentrations provides limited insight because it does not reflect the origin, environmental mobility, or biological availability of contaminants. To obtain a more comprehensive evaluation of sediment pollution and associated ecological implications, several widely used geochemical indices were employed in this study, namely the Contamination Factor (CF), Pollution Load Index (PLI), and Geo-accumulation Index (Igeo). These indices incorporate background concentrations and measured values to quantify contamination intensity and potential environmental risk. A description of the indices is presented below.

2.4.1Contamination factor (CF)

The contamination factor (CF) represents an initial step in environmental risk assessment and is defined as the ratio of the measured metal concentration to its corresponding reference (background) value, as shown in Eq. (1) (Islam et al., 2015a).

In the present study, background metal concentrations were adopted from the reference values reported by Singh et al. (2003). It represents well-established baseline levels for Indian soils/sediments derived from minimally impacted environments. Moreover, the study region shares comparable geological and pedological characteristics with the areas evaluated by Singh et al. (2003), making these baseline values appropriate for normalization and index calculations (e.g., Igeo, EF, PLI). Therefore, adopting these reference concentrations ensures consistency, reliability, and comparability of contamination assessment across similar environmental settings. CF is commonly used to evaluate the degree of metal contamination relative to natural baseline levels.

$$CF = \frac{C_m}{C_b} \qquad \text{Eq (1)}$$

represent the measured metal concentration and its corresponding background value, respectively. The contamination factor (CF) is classified into four categories: CF < 1 indicates low contamination; 1 ≤ CF < 3 indicates moderate contamination; 3 ≤ CF < 6 indicates considerable contamination; and CF ≥6 indicates very high contamination.

2.4.2 Pollution load index (PLI)

The Pollution Load Index (PLI) is calculated as an integrated measure of the overall level of pollution at a given site. It reflects the cumulative contamination status of the locality and serves as an indicator of the site's overall environmental quality (Angulo, 1996; Dhamodharan et al., 2019).

$$PLI = \sqrt[p]{CF_1 \times CF_2 \times \ldots \times CF_p} \qquad \text{Eq (2)}$$

Where CF represents the contamination factor of each of the p heavy metals ($p = 6$). The Pollution Load Index (PLI) is interpreted as follows: PLI ≤ 1 indicates no pollution; 1 < PLI ≤ 2 indicates slight pollution; 2 < PLI ≤ 3 indicates moderate pollution; and PLI > 3 indicates high pollution (Liu et al., 2016a, 2016c).

2.4.3 Geo-accumulation index (I_{geo})

It is a widely used index for assessing heavy metal contamination in sediment samples and for comparing present contamination levels with preindustrial baseline conditions. (Muller, 1969; Chakravarty and Patgiri, 2009; El-Amier et al., 2017).

$$I_{geo} = \log_2 \left\{ \frac{C_p}{1.5 B_p} \right\} \qquad \text{Eq (3)}$$

The geoaccumulation index (Igeo) is classified into the following categories: Igeo ≤ 0, unpolluted; 0 <Igeo ≤ 1, unpolluted to moderately polluted; 1 <Igeo ≤ 2, moderately polluted; 2 <Igeo ≤ 3, moderately to strongly polluted; 3 <Igeo ≤ 4, strongly polluted; 4 <Igeo ≤ 5, strongly to extremely polluted; and Igeo> 5, extremely polluted. In the Igeo equation, C_p and B_p represent the measured and background concentrations of the pth heavy metal, respectively. The constant **1.5** is introduced as a background correction factor to account for natural variations in the sediment matrix.

2.4.4. Potential Ecological Risk Index (PERI)

The potential ecological risk index (PERI) is used to evaluate the ecological effects of human activities through chemical assessment and individual bioassay (Hakånson **1980).** The PERI method emerges as pivotal to regulating the heavy metal grime in the sediments. Before calculating the PERI, the risk index has been determined using the formula,

$$E_r^i = T_r^i \times C_B^i \qquad \text{Eq } (4)$$

$$RI = \sum_{i=1}^{m} E_r^i \qquad \text{Eq } (5)$$

where the *RI* is described as aggregation of the potential individual heavy elements; E_r^i represents potential risk of individual heavy elements; T_r^i infers toxicity response factor for metals Ni = Pb = Cu = **5**, Zn = **1**, Cr = **2**, Cd = **30** and C_B^i indicates background level of the heavy metal concentrations such as Ni = **68** mg/kg, Pb = **20** mg/kg, Cu = **45** mg/kg, Cr = **90** mg/kg, Cd = **0.09** mg/kg and (Turekian and Wedepohl **1961).** With RI values of **<150** indicating low ecological risk, **150-300** moderate risk, **300-600** considerable risk, and **>600** very high ecological risk.

2.4.4 *Risk assessment code (RAC)*

The Risk Assessment Code (RAC) is widely employed to assess the mobility, bioavailability, and potential ecological risk of heavy metals in sediments based on their occurrence in the exchangeable and carbonate-bound fraction obtained through sequential extraction analysis (Perin et al. **1985).** Since metals associated with the exchangeable fraction are weakly bound to sediments, they can be readily released into the aquatic environment under slight variations in pH, salinity, or redox conditions, thereby posing potential ecological threats to aquatic biota.

The total concentration of each metal was determined by summing all sequential extraction fractions **(**F**1-**F**5)** using the following equation:

$$C_{total} = F1 + F2 + F3 + F4 + F5 \qquad \text{Eq } \mathbf{(6)}$$

The RAC value was subsequently calculated as

$$RAC(\%) = \frac{F1}{F1+F2+F3+F4+F5} \times 100 \qquad \text{Eq } \mathbf{(7)}$$

where RAC **(%)** represents the risk assessment code; F**1** denotes the exchangeable and carbonate**-**bound fraction; and F**1-**F**5** represent the concentrations of metals in all operationally defined geochemical fractions**.** Based on RAC values, ecological risk levels were classified as follows: **<1% =** no risk, **1-10% =** low risk, **11-30% =** medium risk, **31-50% =** high risk, and **>50% =** very high risk **(**Perin et al**. 1985).** Higher RAC values indicate greater metal mobility and enhanced environmental risk due to increased bioavailability**.**

2.5 Statistical Analysis

Analytical results were exposed to statistical evaluation using OriginPro software **(**OriginLab Corporation, Northampton, USA**).** Descriptive statistics **(**mean ± standard deviation**)** were calculated to characterize the central tendency and variability of the measured parameters**.** Pearson correlation analysis was performed to examine linear relationships among physicochemical variables and metal concentrations**.** To further explore patterns in the dataset, Principal Component Analysis **(**PCA**)** was performed on both total metal and its sequential extraction fractions**.** This multivariate technique was used to identify dominant factors controlling metal distribution, distinguish potential sources, and elucidate the processes influencing heavy metal behavior in wetland sediments**.**

3. RESULTS AND DISCUSSION

3.1 Physicochemical Characteristics of Sediments

The physicochemical properties of surface sediments reflect the prevailing geochemical environment and strongly influence the behavior and transport of contaminants in aquatic systems. In the present investigation, sediment pH values ranged from **8.1** to **9.5**, indicating predominantly alkaline conditions throughout the study region. Such alkaline environments are typically associated with carbonate-rich substrates and can markedly affect nutrient transformations and trace metal behavior through processes such as precipitation, surface adsorption, and complex formation (Alloway, **2013**; Sposito, **2008**). The maximum pH recorded at Sample **8** (Panjapatti) likely reflects localized geochemical controls, including higher carbonate mineral content or reduced input of acidic organic matter. Comparable alkaline conditions have been documented in wetland and river sediments influenced by carbonate weathering and agricultural activities (Ramanathan et al., **1988**; Singh et al., **2010**).

Electrical conductivity (EC) values lie between **0.13** and **1.98** mS cm^{-1}, demonstrating pronounced spatial heterogeneity in dissolved ionic content. Higher EC values generally indicate elevated concentrations of soluble salts derived from natural mineral dissolution, evaporation, or anthropogenic sources such as fertilizer application and wastewater inputs (Chapman, **1996**; Varol & Sen, **2012**). The observed variability suggests differences in hydrological connectivity, land use, and sediment deposition processes among wetlands within the delta.

Total organic carbon (TOC) concentrations varied between **0.72%** and **2.85%**, while organic matter (OM) content varied from **1.24%** to **4.91%**. The highest values for both parameters were recorded at Sample **13** (Zambuyari Lake). Elevated organic content in sediments typically indicates substantial accumulation of plant debris, microbial biomass, and detrital materials, particularly in low-energy environments where decomposition is slower and sedimentation rates are high. The substantial organic enrichment observed at this site may therefore be attributed to high biological productivity, surrounding land use, and restricted water exchange.

Calcium concentrations ranged from **0.51%** to **2.04%**, with the maximum detected at Sample **34** (Keeran Lake). Magnesium levels were consistently higher, varying from **2.44%** to **5.50%**, with the highest value observed at Sample **28** (Sendakottai). The dominance of Mg over Ca suggests the presence of Mg-rich carbonates such as dolomite within the sediment matrix. Weathering of carbonate formations can strongly influence sediment chemistry by enhancing alkalinity, buffering capacity, and the adsorption of trace metals (Ramanathan et al., **1988**; Drever, **1997**).

Carbonate-associated elements play a key role in maintaining sediment stability by regulating pH conditions, ionic composition, and metal binding capacity. The spatial differences observed in Ca and Mg concentrations, therefore, reflect variations in mineral composition, depositional settings, and catchment-derived geochemical inputs across the study area (Alloway, **2013**; Sposito, **2008**).

3.2 Heavy Metal Analysis

Total Heavy Metal Distribution

Among the analyzed metals, Fe exhibited the highest overall concentrations in the sediments, followed in decreasing order by Pb, Ni, Cr, Cu and Cd. The predominance of iron is consistent with its natural abundance in crustal materials and its strong association with oxide minerals commonly present in alluvial sediments.

3.3 Heavy Metal Speciation and Geochemical Partitioning in Sediments

Sequential extraction techniques provide detailed insights into the chemical associations of metals in sediments, thereby enabling assessment of their mobility, potential bioavailability, and environmental risk. Because metals bound to different sediment fractions respond differently to Environmental fluctuations in pH, redox conditions, and organic matter regulate fractionation processes, offering more meaningful insight than total concentrations alone (Tessier et al., **1979**; Rauret et al., **1999**). In this study, the distribution of Fe, Ni, Pb, Cu, Cr, and Cd among five operationally defined fractions (F1-F5) revealed distinct regional patterns across the Cauvery delta districts.

A) Karur District

In Karur District, Fe concentrations (69.2-15,428 mg/kg) are predominantly associated with the F5 (residual) and F3 (oxide-bound) fractions, indicating strong lithogenic control and limited environmental mobility, as Fe is largely incorporated within mineral lattices and secondary oxide phases (Förstner & Wittmann, 2012). Ni (0.0314-0.764 mg/kg) is similarly dominated by the residual fraction, although its presence in exchangeable and carbonate-bound phases suggests moderate geochemical availability under changing physicochemical conditions. Pb (0.28-7.35 mg/kg) occurs mainly in the residual fraction, reflecting geochemical stability, with minor labile fractions indicating limited anthropogenic inputs such as agricultural runoff or atmospheric deposition (Alloway, 2013). Cu (0.035-9.79 mg/kg) exhibits a mixed association with oxide-bound, residual, and organic fractions, consistent with its affinity for Fe oxides and organic matter (Sposito, 2008). In contrast, Cr (0.052-1.66 mg/kg) is largely associated with exchangeable and carbonate fractions, indicating relatively higher mobility, while Cd (0.02-0.68 mg/kg), despite low concentrations, is enriched in bioavailable fractions, highlighting its ecological significance.

Across the sampling locations, Fe clearly dominates the total metal concentrations (26,364.65-30,667.62 mg/kg), reaffirming a strong geogenic signature with minimal spatial variability. Ni (0.76-2.00 mg/kg) and Cr (1.04-2.57 mg/kg) show low to moderate variation, indicating limited enrichment. Pb remains low across most sites but increases at Kuppagoundan Valasu and reaches a maximum at Virarakkiyam, while Cu follows a similar trend with a pronounced peak at Virarakkiyam, suggesting localized anthropogenic inputs. Cd concentrations are generally low (0.51-1.08 mg/kg) but relatively elevated at Kuppagoundan Valasu, Panjapatti, and Vayalur, indicating potential ecological relevance.

The combined assessment of fractionation and total concentrations indicates that metal distribution in Karur District is predominantly governed by geogenic processes, with most elements occurring in stable, less mobile forms. However, the presence of Cd and Cr in more labile fractions, along with localized enrichment of Pb and Cu at Virarakkiyam, suggests site-specific anthropogenic influences and highlights the need for continued monitoring due to potential ecological risk.

B) Tiruchirappalli District

In Tiruchirappalli District, Fe concentrations (**7.874–14,086** mg/kg) are primarily associated with oxide-bound and residual fractions, indicating a dominant geogenic origin with limited mobility. Ni (**0.135–1.927** mg/kg) shows a similar partitioning pattern, being largely confined to stable phases, although minor contributions in labile fractions suggest conditional availability. Cu (**0.033–1.814** mg/kg) is distributed across carbonate-, oxide-, and residual-bound fractions, reflecting moderate mobility under changing environmental conditions. In contrast, Pb (**0.029–1.547** mg/kg), Cd (**0.003–0.565** mg/kg), and Cr (**0.039–4.193** mg/kg) are relatively enriched in labile fractions, indicating higher environmental availability. Cd, in particular, shows strong association with exchangeable and carbonate phases, confirming its high mobility as shown in Fig **2**, while Cr exhibits notable binding with organic matter, suggesting interaction with organic ligands and potential anthropogenic influence.

Across the sampling sites, Fe dominates the total metal concentrations (**9,335.09–26,958.20** mg/kg), reaffirming strong lithogenic control with moderate spatial variability. Ni (**1.29–4.97** mg/kg) and Cr (**1.16–5.71** mg/kg) exhibit wider ranges, with elevated concentrations at Keerambur, Zambuyari Lake, Periya Yeri, and Gundur, indicating localized inputs and potential mobility. Pb concentrations (**2.10–3.89** mg/kg) remain relatively uniform across sites, whereas Cu (**0.89–4.48** mg/kg) shows localized enrichment, particularly at Keerambur and adjacent locations, suggesting site-specific anthropogenic influence. Cd concentrations are generally low (**0.30–0.98** mg/kg) but show relatively higher values at Kiliyur Lake and Zambuyari Lake, indicating potential ecological concern.

The integrated assessment of fractionation and total metal concentrations indicates that metal distribution in Tiruchirappalli District is largely governed by geogenic processes, with most elements occurring in stable forms. However, the enrichment of Cd and Cr in labile fractions, together with localized increases in Ni and Cu at specific sites, highlights spatially variable anthropogenic inputs and suggests potential environmental risk under changing geochemical conditions.

C) Thanjavur District

In Thanjavur District, Fe concentrations (**258.2-15,263** mg/kg) are predominantly associated with oxide-bound and residual fractions, indicating strong lithogenic control and incorporation within mineral matrices formed through weathering processes (Drever, **1997**). Ni (**0.014–0.694** mg/kg) and Pb (**0.017–0.807** mg/kg) are likewise dominated by residual fractions, suggesting limited mobility and low environmental risk under stable conditions. Cu (**0.068–0.533** mg/kg) shows appreciable association with organic and oxide fractions, indicating potential remobilization under reducing conditions. In contrast, Cr (**0.106–0.514** mg/kg) is relatively enriched in exchangeable fractions, implying higher mobility and possible external inputs, while Cd (**0.038–0.106** mg/kg) exhibits the highest mobility, occurring mainly in exchangeable and carbonate phases, thereby highlighting its ecological significance.

Across the sampling locations in Thanjavur District, Fe dominates the total metal concentrations (**20,459.43–31,509.93** mg/kg), reaffirming a strong geogenic signature with limited spatial variability. Ni (**0.74–1.98** mg/kg) remains low with slight elevation at Kallaperampur, while Cr (**1.14–1.65** mg/kg) shows minimal variation across sites, indicating weak spatial heterogeneity. Pb concentrations are uniformly low (**1.46-2.19** mg/kg), reflecting negligible contamination, whereas Cu (**0.56-1.30** mg/kg) exhibits modest increases at Chelikurichi and Kallaperampur, suggesting localized inputs. Cd concentrations (**0.34-0.38** mg/kg) are consistently low but show slight enrichment at Chelikurichi and Vendayampatti, indicating potential ecological relevance.

It indicates that metal distribution in Thanjavur District is primarily controlled by geogenic processes, with most elements occurring in stable, less mobile forms. However, the relatively higher mobility of Cd and Cr, along with localized enrichment of Cu at specific sites, suggests limited anthropogenic influence and highlights the need for attention to potential ecological risks under changing environmental conditions.

D) Thiruvarur and Nagapattinam District

In the coastal districts of **Thiruvarur and Nagapattinam**, Fe concentrations (**322.5-15,012** mg/kg) are predominantly associated with oxide-bound and residual fractions, indicating strong lithogenic control and low mobility. Ni (**0.250-0.587** mg/kg) shows a relatively balanced partitioning but remains largely confined to stable phases. In contrast, Pb (**0.051-0.614** mg/kg) is mainly present in exchangeable fractions, suggesting high mobility and susceptibility to remobilization, a pattern typical of coastal systems influenced by anthropogenic inputs (Varol **&** Sen, **2012).** Cu (**0.115-0.387** mg/kg) exhibits mixed distribution between stable and labile fractions, indicating moderate mobility, while Cr (**0.137-0.519** mg/kg) and Cd (**0.028-0.109** mg/kg) are enriched in exchangeable and carbonate fractions, reflecting elevated environmental availability and potential leaching risk.

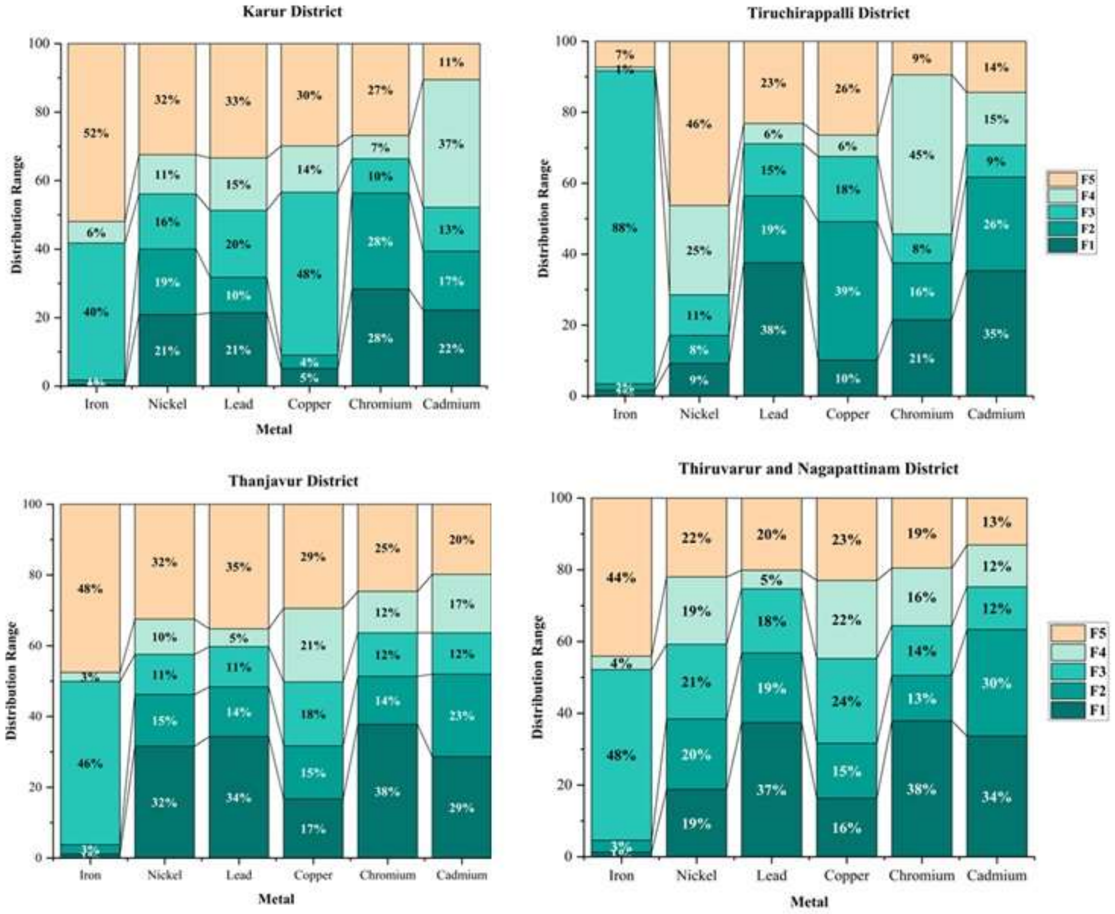

Fig 2. Comparative Fractional Distribution of Heavy Metals among Sequential Extraction Phases (F1–F5) in Sediments of Cauvery Delta District Wetlands

Across the sampling locations, Fe dominates the total metal concentrations **(24,297.23-31,876.39** mg/kg**)**, reaffirming a strong geogenic signature with minimal spatial variability**.** Ni **(1.42-2.07** mg/kg**)** shows slight elevation at Talainayar R.F, while Cr **(1.12-1.55** mg/kg**)** remains relatively uniform across sites, indicating weak spatial heterogeneity**.** Pb concentrations are consistently low **(1.13-1.95** mg/kg**)**, suggesting limited anthropogenic influence, whereas Cu **(0.65-1.20** mg/kg**)** exhibits minor increases at Talainayar R.F and Thirumeni, indicating localized inputs**.** Cd concentrations **(0.29-0.32** mg/kg**)** remain low but show slight enrichment at Talainayar R.F and Vattakudi River Delta, highlighting potential ecological relevance**.**

Overall, the integrated interpretation of fractionation and total concentrations indicates that metal distribution across Thiruvarur and Nagapattinam districts is primarily governed by geogenic processes. However, the enrichment of Pb, Cr, and Cd in labile fractions, coupled with localized increases in Cu and Cd at specific sites, suggests coastal-specific geochemical behavior with minor anthropogenic influence and potential environmental risk under changing conditions.

3.4 Integrated Interpretation of Heavy Metal Speciation

The fractionation patterns observed across the study area reveal consistent geochemical behavior that allows classification of metals according to their environmental stability. The observed metal fractionation patterns were strongly influenced by sediment physicochemical characteristics, particularly alkaline pH, carbonate content, and organic matter. The alkaline nature of the sediments likely reduced the solubility of several metals through precipitation and adsorption processes, thereby promoting their accumulation in relatively stable fractions.

Geochemically Stable Metals (Fe, Ni, Cu)

Cu showed greater association with organic matter and oxide-bound fractions, reflecting its strong tendency to form stable complexes with organic ligands and Fe/Mn oxides. Similarly, Fe and Cr were predominantly associated with residual and oxide fractions, indicating stronger lithogenic control and lower bioavailability. While Iron and nickel were predominantly associated with residual and oxide-bound fractions, indicating strong mineral binding and primarily lithogenic origins. Metals in these forms are generally considered less mobile and less bioavailable under normal environmental conditions (Tessier et al., 1979; Rauret et al., 1999).

Environmentally Mobile Metals (Pb, Cr, Cd)

Lead, chromium, and cadmium showed substantial enrichment in exchangeable, carbonate, and organic fractions, indicating higher mobility and potential bioavailability. Comparatively higher proportion of Cd in exchangeable and carbonate-bound fractions (F1-F2) may be attributed to the affinity of Cd for carbonate-rich sediment phases under alkaline conditions. Such associations indicate that Cd remains relatively mobile and may be remobilized under changing environmental conditions such as acidification or redox fluctuations.

Cadmium exhibited the greatest environmental mobility, while chromium displayed intermediate behavior, reflecting contributions from both natural sources and anthropogenic activities.

Overall, the distribution patterns suggest that both natural geological factors and human influences govern heavy metal behavior in the Cauvery delta sediments. Metals tightly bound within mineral structures remain relatively inert, whereas those associated with weakly bound phases pose greater ecological risk due to their propensity for release under changing environmental conditions.

3.5 Risk Assessment

3.5.1 Contamination Factor

The extent of heavy metal enrichment in wetland sediments was assessed using the Contamination Factor (CF), which compares measured metal concentrations with corresponding background values (Håkanson, **1980).** This metric is widely employed to identify anthropogenic accumulation relative to natural geochemical baselines. For Fe, Ni, Pb, Cu, and Cr, CF values were predominantly below unity, indicating minimal contamination across the majority of sampling locations. The mean CF values were **0.689** for Fe, **0.039** for Ni, **0.137** for Pb, **0.064** for Cu, and **1.459** for Cr. According to the classification scheme of Håkanson **(1980)**, CF values less than **1** signify low contamination, suggesting that these elements are primarily derived from lithogenic sources rather than substantial human inputs.

Cadmium exhibited a markedly different pattern. CF values for Cd ranged from **0.99** to **3.59**, corresponding to moderate to considerable contamination at several sites. The highest value **(3.58)** occurred at Sample **9**, with elevated levels also observed at Samples

1, 8, 7, and 20, identifying these locations as localized hotspots. The enrichment of Cd is likely linked to anthropogenic activities such as agricultural runoff, application of phosphate fertilizers, irrigation drainage, and domestic effluents—well-documented sources of cadmium in aquatic systems.

Spatial analysis indicates that most sites show negligible contamination for Fe, Ni, Pb, Cu, and Cr, whereas isolated exceedances for Cd demonstrate the influence of site-specific human activities. Comparable selective enrichment of cadmium has been reported in sediments affected by agricultural and industrial operations, reflecting the element's relatively high mobility and environmental sensitivity (Alloway, 2013; Varol, 2020).

When cumulative contamination was considered, the CF sum for all metals ranged approximately from 1.55 to 4.68, indicating overall low to moderate contamination levels. Elevated cumulative values were largely driven by cadmium contributions, while other metals played a minor role. This finding aligns with previous studies identifying Cd as a sensitive tracer of anthropogenic influence due to its low natural abundance and strong association with fertilizer inputs (Turekian & Wedepohl, 1961; Varol & Sen, 2011; Suresh et al., 2021). Given its toxicity and ecological persistence, cadmium emerges as the primary contaminant of concern in the studied sediments.

3.5.2 Pollution Load Index (PLI)

The Pollution Load Index was derived to provide an integrated measure of overall sediment contamination by combining the contamination factors of individual metals into a single indicator (Tomlinson et al., 1980). PLI value of 1 represents background conditions, values greater than 1 indicate pollution, and values below 1 signify an absence of contamination. Herewith, PLI values ranged from 1.07 to 1.29, suggesting slightly elevated but generally moderate contamination relative to baseline levels.

All sampling sites exhibited PLI values exceeding unity, implying some degree of anthropogenic influence throughout the wetlands. The highest values were recorded at Samples **1**, **9**, and **20**, coinciding with locations showing elevated cadmium contamination factors. This correspondence indicates that Cd enrichment is the principal driver of the overall pollution status. Despite exceeding the baseline threshold, the relatively narrow range of PLI values suggests moderate cumulative contamination rather than severe degradation. The spatial distribution points to localized pollution hotspots, likely associated with agricultural practices, fertilizer usage, small-scale industrial activities, and domestic wastewater inputs within the watershed.

Overall, the PLI assessment corroborates the CF results, indicating that most metals occur at low contamination levels while cadmium disproportionately influences the composite pollution index. Consequently, the sediments appear moderately impacted rather than severely polluted.

3.5.3 Geo-accumulation Index (Igeo)

The Igeo index was applied to evaluate sediment contamination by evaluating against current metal concentrations with pre-industrial background levels while accounting for natural variability in sediment composition (Müller, **1969**). This index categorizes pollution into seven classes, with values less than or equal to zero indicating unpolluted conditions. For Fe, Ni, Pb, Cu, and Cr, Igeo values were predominantly negative, demonstrating that sediment concentrations of these metals remain close to natural background levels. Mean Igeo values were −**1.216** for Fe, −**5.369** for Ni, −**3.67** for Pb, −**4.965** for Cu, −**6.375** for Cr, and −0.138 for Cd. These results suggest that lithogenic inputs largely control metal distributions across the study area.

Cadmium again showed a distinct behavior. While most samples yielded negative values (approximately −2 to 1), indicating unpolluted to moderately polluted conditions, positive values were observed at three sites. The highest Igeo value (1.258) occurred at Sample 9, followed by Samples 20 and 1. According to standard classification criteria, these values correspond to Class 1 (unpolluted to moderately polluted), indicating localized enrichment. The spatial concentration of elevated Cd levels in the upper delta—particularly in Karur and parts of Tiruchirappalli districts—suggests stronger anthropogenic influence in these areas, likely related to intensive agriculture, urban development, and wastewater discharge. Such activities are widely recognized sources of cadmium contamination in sedimentary environments (Alloway, 2013; Varol & Sen, 2011; Islam et al., 2015).

Overall, the Igeo assessment indicates that the Cauvery delta wetlands remain largely free from significant heavy metal pollution, with most elements reflecting natural background conditions. Nevertheless, localized cadmium enrichment highlights its effectiveness as an indicator of human impact. Given its high toxicity, mobility, and association with fertilizers, industrial emissions, and urban effluents, cadmium warrants continued monitoring. Regular surveillance of Cd levels is therefore recommended to safeguard ecological health and ensure the long-term sustainability of these wetland ecosystems (Sutherland, 2000; Alloway, 2013).

3.5.4 Potential Ecological Risk Assessment (PERI)

The assessment of heavy metal contamination in sediments is crucial for evaluating the potential ecological risks they pose to aquatic ecosystems. These contaminants can significantly disrupt biological processes and impair ecological functions. To quantitatively evaluate this risk, the Potential Ecological Risk Index (PERI), introduced by Hakanson **(1980)**, was employed. This method incorporates both the toxicity response factor (Tr) of individual metals and their contamination factor (CF) relative to background values, thereby accounting for the concentration, distribution, and synergistic toxic effects of multiple metals within the sediment matrix.

In the present study, PERI values in wetland sediments ranged from **800.333** to **5333.351**, with a mean value of **1624.15.** These values indicate considerable to very high ecological risk, particularly in specific locations. The highest PERI was recorded at Sample **5**, followed by Sample **15.** Among the studied metals, nickel (Ni) contributed to more than **50%** of the total ecological risk index, indicating its dominant influence in driving the overall toxicity of the sediment. Copper (Cu) and chromium (Cr) were the next significant contributors. This distribution pattern highlights the prevalence and potential synergistic interactions among these metals, which could pose acute and chronic risks to benthic organisms and other components of the wetland ecosystem.

According to Hakanson's classification, PERI values exceeding **600** indicate very high ecological risk. Therefore, based on the observed values and spatial trends, it can be inferred that the wetland sediments, especially in parts of Karur and Tiruchirappalli districts, are under substantial ecological stress due to heavy metal contamination and warrant regular monitoring and mitigation strategies.

3.5.5 Risk Assessment Code (RAC)

The RAC assessment revealed considerable spatial variation in heavy metal mobility and ecological risk across the Cauvery Delta wetland sediments. Fe consistently exhibited RAC values below **1-3%** in all districts, indicating no ecological risk and strong association with stable residual fractions. In contrast, Cr, Pb, Cd, and Ni showed comparatively higher RAC values, reflecting greater mobility and potential bioavailability.

Karur district sediments were characterized by moderate to very high ecological risk for Cr **(20.45-51.45%)**, with Sample **6** exceeding the very high-risk threshold **(>50%)**. Pb and Ni exhibited mainly medium to high ecological risk, whereas Cu showed relatively lower RAC values corresponding to low to medium risk. In Tiruchirappalli district, Pb **(26.13-54.22%)**, Cu **(4.32-63.01%)**, Cr **(9.26-44.26%)**, and Cd **(14.32-50.23%)** displayed substantial variability, with several locations exceeding the very high-risk category, indicating strong association with labile sediment fractions and enhanced remobilization potential. Thanjavur district sediments showed consistently elevated RAC values for Cr **(30.80-44.18%)**, Pb **(28.08-42.40%)**, Ni **(18.36-41.35%)**, and Cd **(26.69-31.24%)**, corresponding predominantly to medium to high ecological risk. Similarly, Thiruvarur and Nagapattinam districts exhibited persistently high RAC values for Pb **(31.57-46.66%)**, Cr **(33.41-42.26%)**, and Cd **(30.67-34.51%)**, indicating significant mobility and ecological concern across the study area. Ni and Cu in these districts generally exhibited moderate ecological risk.

Overall, Cr, Pb, and Cd emerged as the most environmentally mobile and ecologically significant metals across the Cauvery Delta wetlands, while Fe remained geochemically stable and environmentally immobile. The predominance of these metals in exchangeable and weakly bound fractions indicates high remobilization potential under changing physicochemical conditions, thereby posing potential ecological risks to wetland ecosystems.

3.6 Statistical Analysis

Descriptive statistics, including mean and standard deviation (SD), were used to evaluate the distribution and variability of physicochemical parameters and heavy metals in wetland sediments (Table **2**). Sediment pH exhibited very low variability, indicating consistently alkaline conditions typical of carbonate-rich systems, which influence metal solubility and adsorption processes (Sposito **2008**; Alloway **2013**). Electrical conductivity (EC) showed moderate variability, reflecting spatial differences in soluble-salt content associated with evaporation, agricultural runoff, and mineral weathering. Total organic carbon (TOC) and total organic matter (TOM) also displayed moderate variation, suggesting heterogeneous accumulation of organic residues derived from in situ productivity and external inputs (Meyers and Ishiwatari **1993**). Calcium (Ca) and magnesium (Mg) exhibited moderate variability, likely controlled by differences in sediment mineralogy and the distribution of carbonate minerals such as calcite and dolomite (Drever **1997**).

Table 2. Descriptive statistics for various physico-chemical parameters

Descriptive Statistics				
Parameter	**Range**	**Mean**	**Std. Deviation**	**N**
pH	8.1-9.5	8.753	0.3397	40
EC (mS/cm)	0.13- 1.98	0.7498	0.44252	40
TOC (%)	0.72-2.85	1.6138	0.49135	40
OM (%)	1.24 -4.91	2.7780	0.84301	40
Ca (%)	0.51-2.04	0.8798	0.39987	40
Mg (%)	2.44-5.50	3.9423	0.64557	40
Fe (mg/kg)	9335.09-31876.39	24127.38	7.48299	40
Ni (mg/kg)	0.74- 4.96	1.96103	1.09733	40

Pb (mg/kg)	1.08- 11.36	2.75342	2.02265	40
Cu (mg/kg)	0.55- 15.01	1.61999	2.3099	40
Cr (mg/kg)	1.04- 5.70	1.75955	0.8705	40
Cd (mg/kg)	0.29- 1.07	0.43777	0.19324	40

Among the metals, Fe showed considerable variability, reflecting variations in lithogenic inputs, sediment transport, and redox conditions (Förstner and Wittmann 2012). Ni and Cr displayed moderate variability, whereas Pb and particularly Cu showed relatively high variability, suggesting localized enrichment possibly associated with anthropogenic sources such as industrial discharge, agricultural inputs, and urban runoff. Cd exhibited comparatively low dispersion, indicating a relatively uniform spatial distribution, although its environmental relevance remains significant due to its high toxicity and mobility (Alloway 2013).

Pearson Correlation analysis (Fig 3) revealed significant associations among sediment properties and heavy metals, indicating shared geochemical behavior and possible common sources. TOC showed a very strong positive correlation with TOM ($r = 0.99991$, $p < 0.05$), confirming the dominance of organic carbon in sediment organic matter. Both TOC and TOM were positively correlated with Cr ($r = 0.41949$ and 0.42093, respectively, suggesting the affinity of Cr toward organic-rich sediment fractions. A significant negative correlation between Ca and Mg ($r = -0.3417$, $p < 0.05$) reflected contrasting mineralogical controls. Fe exhibited strong negative correlations with Ni ($r = -0.76033$, $p < 0.05$) and Cr ($r = -0.4408$, $p < 0.05$), indicating different binding phases and geochemical pathways. Ni showed a significant positive correlation with Cr ($r = 0.56274$, $p < 0.05$), implying a common lithogenic source. Pb was positively correlated with Cu ($r = 0.65901$, $p < 0.05$) and Cd ($r = 0.54616$, $p < 0.05$), suggesting similar anthropogenic inputs. Cu also showed a positive association with Cr ($r = 0.32674$, $p < 0.05$). In addition, pH exhibited a significant positive correlation with Cd ($r = 0.41925$, $p < 0.05$), indicating the influence of sediment pH on Cd retention and mobility. Overall, the results suggest that organic matter influences Cr accumulation, while Pb, Cu, and Cd may originate from common anthropogenic activities.

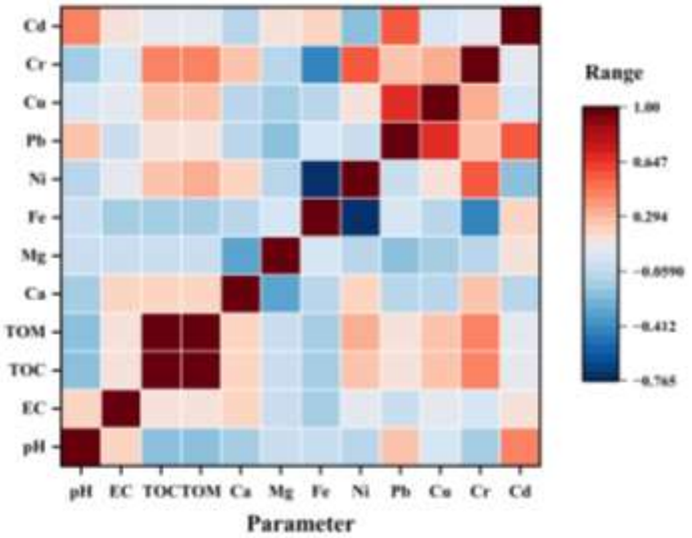

Fig 3. Correlation Heatmap of Heavy Metals and Physicochemical Parameters in Cauvery Delta Wetland Sediments

Principal component analysis (PCA) was applied to elucidate the sources and controlling mechanisms governing heavy metal distribution in the Cauvery delta wetland sediments. The PCA loading plot for sequential extraction fractions (F1-F5) is presented in Fig. 4, while the corresponding scree plot illustrating eigenvalue contributions is shown in Fig. 5. The eigenvalue structure indicates that the first principal component (PC1) explains the overwhelming majority of the variance among the fractions, demonstrating a strong common geochemical control on metal partitioning across the operationally defined phases. Subsequent components contribute only negligible variance, indicating limited influence of independent secondary processes.

Principal component analysis (PCA) revealed that PC1 accounted for **84.05%** of the total variance, indicating that metal fractionation was predominantly controlled by a common geochemical process operating across all operationally defined sediment fractions (Fig. 4). All fractions (F1-F5) exhibited positive loadings along PC1, reflecting a strong overall association among the geochemical phases. PC2 explained an additional **10.08%** of the variance and primarily differentiated the relatively mobile fractions (F1 and F2) from the more stable fractions (F4 and F5). The negative loadings of F1 and F2 suggest their association with labile and potentially bioavailable metal forms, whereas the positive loadings of F4 and F5 indicate stronger affinities toward more stable binding phases, likely associated with organic/sulfidic and residual components. Fraction F3 occupied an intermediate position, representing transitional geochemical characteristics between mobile and stable phases. The close clustering of F1 and F2 further indicates similar geochemical controls and mobility behavior, while the separation of F4 and F5 highlights distinct stabilization mechanisms governing metal retention within the sediment matrix.

The scree plot further substantiated these observations, with PC1 exhibiting a markedly high eigenvalue **(4.20245)** relative to the subsequent components (Fig. 5). In contrast, PC2-PC5 revealed substantially lower eigenvalues ranging from **0.50378** to **0.03817**, indicating minimal additional contributions to the total variance. The pronounced dominance of PC1 suggests that metal partitioning within the sediments is primarily regulated by a single overarching geochemical control, whereas secondary components contribute only limited and independent variability to fraction distribution patterns.

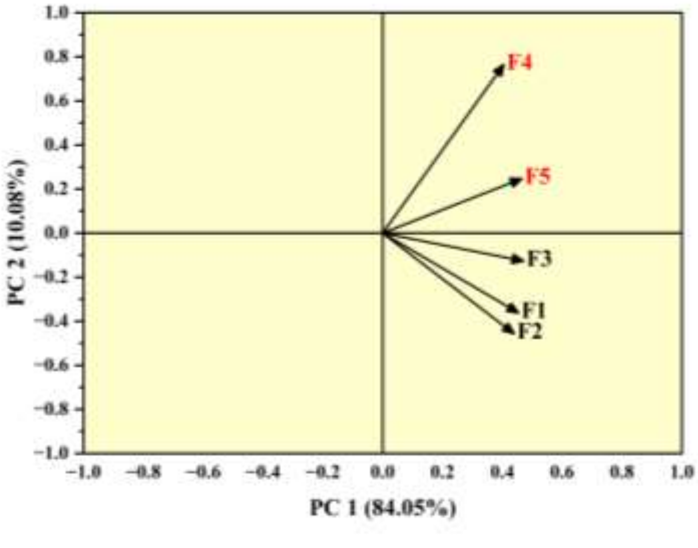

Fig 4. Principal Component Analysis (PCA) Loading Plot of Heavy Metal Speciation Fractions (F1–F5) in Cauvery Delta Wetland Sediments

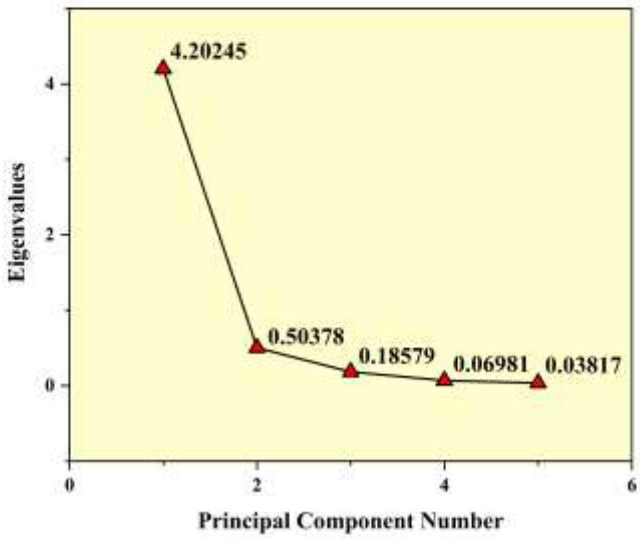

Fig 5. Scree Plot Showing Variance Contribution of Principal Components for Sequential Extraction Fractions

For total metal concentrations, the PCA loading plot (Fig. 6) and scree plot (Fig. 7) reveal a more complex variance structure. PC1 accounts for **38.63%**, and PC2 explains **32.39%**, together representing **71.02%** of the cumulative variance. The loading pattern shows strong positive associations of Fe and Cr with PC1, suggesting a dominant lithogenic contribution linked to sediment mineral composition and parent material weathering, with Ni also reflecting weathering-derived inputs.

In contrast, the association of Cd, Pb, and Cu within PC2 suggests significant anthropogenic influence, mainly derived from agricultural runoff, municipal discharge, and localized industrial activities. Karur district, recognized as a major textile dyeing and processing hub in Tamil Nadu, contains numerous dyeing and bleaching units that discharge metal-enriched effluents into the Amaravathi River system (Rajamanickam and Nagan, 2010). Textile processing industries extensively utilize metal-based dyes, pigments, mordants, and chemical additives containing Cu, Pb, and Cd, which subsequently accumulate in aquatic sediments through continuous effluent discharge (Sivakumar et al., 2011). Similarly, Tiruchirappalli district is characterized by engineering industries, fabrication units, urban wastewater discharge, and fertilizer-related activities, all of which contribute to heavy metal loading in surrounding aquatic environments. In addition, long-term application of phosphate fertilizers may enhance Cd accumulation through agricultural runoff, as phosphate fertilizers are recognized as secondary sources of Cd contamination in soils and sediments (Alloway, 2013). Therefore, the positive loading of Cd, Pb, and Cu in PC2 reflects mixed anthropogenic inputs associated with industrial effluents, urban discharge, and agricultural practices rather than natural lithogenic sources.

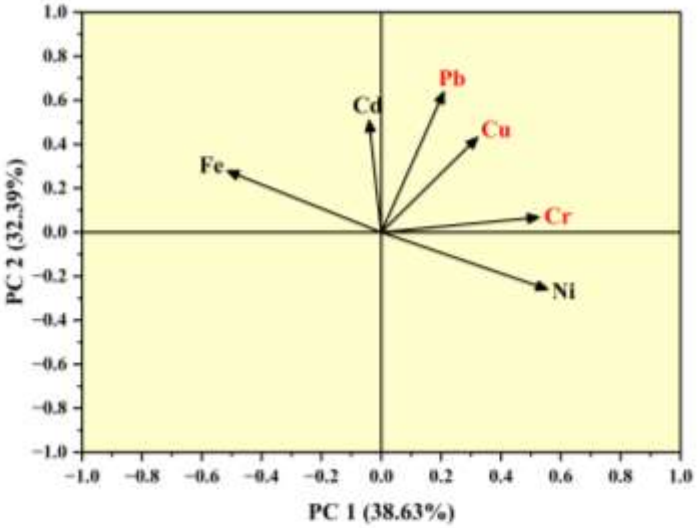

Fig 6. Principal Component Analysis (PCA) Loading Plot of Total Heavy Metals in Cauvery Delta Wetland Sediments

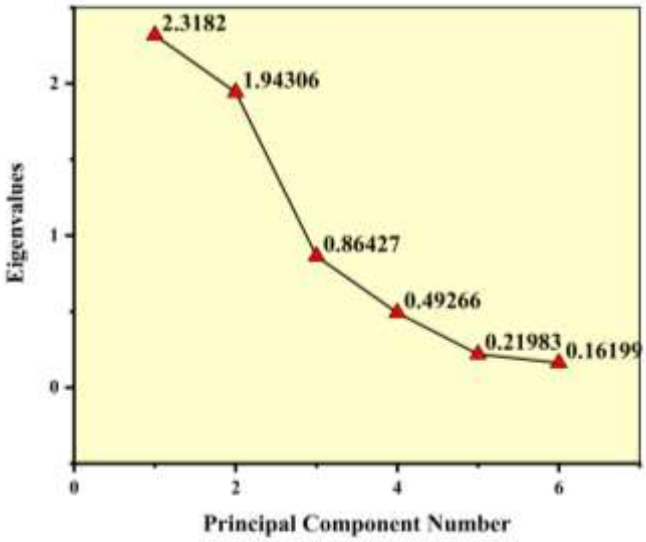

Fig 7. Scree Plot Illustrating Variance Explained by Principal Components of Total Metals

Overall, the PCA results indicate that metal distribution in the sediments is controlled by both natural geochemical background and anthropogenic inputs. The predominance of stable fractions suggests limited metal mobility under present environmental conditions. Fe enrichment primarily reflects natural geological sources, whereas variability in Ni, Pb, Cu, Cr, and Cd points to supplementary anthropogenic contributions, particularly in intensively cultivated, urbanized and industrial sectors of the Cauvery delta.

4. CONCLUSION

The present investigation provided a comprehensive assessment of heavy metal distribution, speciation, mobility, and ecological risk in wetland sediments of the Cauvery Delta, India, through the integrated application of contamination indices, sequential extraction techniques, ecological risk models, and multi-variate statistical analyses. The study demonstrated substantial spatial variability in sediment geochemistry across the investigated wetlands, with Fe exhibiting dominant natural abundance and strong association with stable residual fractions, indicating predominantly lithogenic control and limited environmental mobility. The overall decreasing order of mean metal concentrations was observed as Fe> Pb> Ni> Cr

> Cu **>** Cd. Although CF, Igeo, and PLI assessments indicated generally low to moderate contamination levels for most metals, all sampling sites exhibited PLI values greater than unity, suggesting slight but consistent cumulative pollution throughout the wetlands. Among the investigated metals, Cd emerged as the principal contaminant of concern due to its comparatively higher contamination factor, elevated mobility, and ecological sensitivity despite its relatively low total concentration. Localized Cd enrichment was particularly evident at samples **1**, **7**, **8**, **9**, and **20**, mainly within Karur and Tiruchirappalli districts, indicating significant anthropogenic influence associated with agricultural runoff, phosphate fertilizer application, urban discharge, and localized industrial activities.

Sequential extraction analysis revealed that Cd, Pb, and Cr were predominantly associated with exchangeable and carbonate-bound fractions, indicating higher mobility, bioavailability, and remobilization potential under changing physicochemical conditions. In contrast, Fe remained strongly associated with residual and oxide-bound fractions, reflecting greater geochemical stability. Rac assessment further demonstrated moderate to very high ecological risk for Cd, Pb, and Cr in several wetlands, while peri values indicated considerable to very high ecological risk at specific locations, particularly in parts of Karur and Tiruchirappalli districts. The alkaline, carbonate-rich, and organic matter-containing sediment environment significantly influenced metal partitioning behavior, promoting carbonate association of Cd and organic/oxide binding of cu. Pearson correlation analysis and PCA suggested that Fe and Cr were primarily controlled by lithogenic processes, whereas Cd, Pb, and cu were likely influenced by mixed anthropogenic inputs including industrial discharge, fertilizer usage, municipal wastewater, and agricultural activities.

Overall, the study highlights that while the Cauvery Delta wetlands are not severely polluted, localized enrichment and elevated mobility of Cd represent a significant ecological concern requiring continued surveillance. Targeted monitoring and mitigation strategies should therefore focus particularly on Cd hotspot wetlands in Karur and Tiruchirappalli districts to minimize future ecological risk and protect the long-term sustainability of these ecologically important wetland ecosystems.

Author Contributions: K.P. Aakash: Conceptualization, Methodology, Formal Analysis, Investigation, Resources, Data Curation, Data Analysis, Data visualization, and writing original draft. **R. Mohanraj:** Writing - review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

All authors have read and agreed to the published version of the manuscript." Authorship should be restricted to individuals who have made significant contributions to the research.

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SUPPLEMENTARY TABLE

S1. Site-wise total heavy metal concentrations (mg/kg) in surface sediments of Cauvery Delta wetlands

Sample no	District	Fe	Ni	Pb	Cu	Cr	Cd
1	Karur	28427.17	1.560456	9.734932	1.015733	1.551182	0.913918
2	Karur	28303.21	1.640737	3.223811	1.305204	1.944863	0.550019
3	Karur	29712.67	1.273725	3.18893	0.844857	2.2779	0.544299
4	Karur	30667.62	2.002605	3.840962	1.903808	2.49281	0.538467
5	Karur	29447.74	1.046634	11.36173	15.01227	2.567646	0.513322
6	Karur	26364.65	0.764453	3.581725	0.567076	1.042427	0.521738
7	Karur	30121.8	1.514477	3.753365	1.240357	1.633482	0.66903
8	Karur	27316.61	1.411797	3.775607	0.907301	1.612102	0.793617
9	Karur	29108.08	1.253753	3.446958	1.008555	1.782722	1.076462
10	Tiruchirappalli	11137.44	3.028397	3.891687	0.986555	1.288238	0.388787
11	Tiruchirappalli	11436.31	3.183712	2.3172	2.532	1.337157	0.406142
12	Tiruchirappalli	12387.41	2.95247	2.373687	2.172925	1.279994	0.391763
13	Tiruchirappalli	10703.62	2.995729	3.168961	2.261133	5.709626	0.501901
14	Tiruchirappalli	10615.53	4.325606	2.446498	3.430303	3.219965	0.403577
15	Tiruchirappalli	13647.53	4.96987	2.342863	4.479657	3.026854	0.363429
16	Tiruchirappalli	11596.25	3.809507	2.108981	2.044914	2.219222	0.33985
17	Tiruchirappalli	9335.094	3.661829	2.941296	1.704409	2.128304	0.329429
18	Tiruchirappalli	22053.97	3.977615	3.629651	0.912314	3.243619	0.335348
19	Tiruchirappalli	9940.38	3.49406	2.778849	0.914142	2.401132	0.297405
20	Tiruchirappalli	26958.2	1.291419	3.800319	0.892473	1.164036	0.976475
21	Thanjavur	29722.91	1.810015	1.93531	1.112344	1.448665	0.355762
22	Thanjavur	20459.43	0.966888	1.583419	0.559071	1.221107	0.340767
23	Thanjavur	25782.84	0.900146	2.019718	0.655888	1.294894	0.373422
24	Thanjavur	31158.2	1.979657	2.190057	1.206776	1.652872	0.373143
25	Thanjavur	23545.28	0.879581	1.462409	0.676903	1.228995	0.348674
26	Thanjavur	28733.7	0.844179	1.516115	0.803347	1.256208	0.349729
27	Thanjavur	26727.46	0.744517	1.751359	1.295653	1.443483	0.38169
28	Thanjavur	27173.96	0.768496	1.709272	0.721301	1.138368	0.3402
29	Thanjavur	31509.93	0.999026	2.136983	1.01612	1.49857	0.360925
30	Thanjavur	28520.9	0.818486	1.837805	0.813657	1.185631	0.362714
31	Thiruvarur	31876.39	2.053877	1.945782	1.19771	1.553795	0.29818
32	Thiruvarur	29948.52	1.785465	1.678578	1.033551	1.286897	0.29785
33	Thiruvarur	30239.98	1.716171	1.600046	1.004564	1.318342	0.301362
34	Nagapattinam	24297.23	1.57335	1.480714	0.937157	1.284953	0.307177
35	Nagapattinam	29049.82	1.783314	1.413297	0.98809	1.249581	0.322431
36	Nagapattinam	29978.15	2.070842	1.423445	1.204763	1.345991	0.324719
37	Nagapattinam	29684.19	1.788191	1.357576	1.115547	1.360411	0.312531
38	Nagapattinam	24765.47	1.424278	1.129346	0.651229	1.124462	0.30763

39	Nagapattinam	27032.15	1.706597	1.220708	0.796009	1.348732	0.296532
40	Nagapattinam	25607.47	1.669271	1.270959	0.873789	1.216725	0.300204