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Geochemical assessment of metal and REE concentrations in a region with exploration of petroleum resources, Democratic Republic of the Congo

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Abstract

The Lemba petroleum sub-basin in the western Democratic Republic of the Congo was investigated to assess the composition of soils and riverbed sediments, the concentrations of contaminants and the environmental pollution hazards derived from the ongoing oil exploration and other anthropogenic activities. Soils and riverbed sediments were sampled and analyzed for physicochemical properties (moisture, organic matter, particle size), trace metals, metalloids, rare earth elements (by ICP-MS), and mercury (by AMA 254). Results revealed that soils and sediments exhibit strong spatial variability in texture, organic matter and metal content. High concentrations of chromium (Cr), iron (Fe), manganese (Mn), nickel (Ni), copper (Cu), zinc (Zn), and lead (Pb) were detected, particularly in soils affected to agriculture and urban soils situated near oil exploration activities. Parameters used to assess environmental contamination indicated strong enhancement of naturally occurring metal

concentrations. Ecological risk indices for metal ecotoxicity indicated low risk at Mvuangu but severe to extreme risk at Kanzi, Fundu-Nzobe, and Ngundji areas, primarily driven by arsenic (As) and chromium in soils. REE patterns showed lithogenic control with dominant light rare-earth elements (REEs), negative cerium (Ce) anomalies, weak europium (Eu) anomalies, and variable thulium (Tm) anomalies. These findings highlighted that there is already a significant contamination of soils in several areas mostly caused by spills from oil exploration but also by poor management of domestic and urban waste. Anticipating future industrial-scale exploitation of oil and other mineral resources of this region, the current assessment is an early warning emphasizing the need for implementing suitable monitoring and waste management plans prior and during mineral resources exploitation.

Keywords: *Environmental monitoring, heavy metals, rare-earth elements, soil, sediment*

1. Introduction

Metals, metalloids, rare-earth elements (REEs) and primordial radionuclides occur in the Earth's crust, but their concentrations vary according to geological settings and geochemical background. Their distribution in surface soils and riverbed sediments is controlled by natural processes such as mineral weathering, erosion, and sediment transport (Yiika et al., 2022; Sique et al., 2025), as well as by anthropogenic activities such as mining, industrial activities, fertilizer application, and urban waste disposal (Carvalho et al., 2017 a, b; Sabiha-Javied, 2009; Tiabou et al., 2025a; Suh et al., 2025).

Beyond the eventual environmental contamination by petroleum hydrocarbons, petroleum exploration and exploitation activities also constitute an additional, and often underestimated, source of contamination by trace metals, metalloids and REEs. Oil drilling operations, well logging, and the management of drilling fluids, cuttings, and process water can mobilize subsurface materials enriched in metals such as Ba, Sr, Ni, V, and Cr. These materials may subsequently accumulate in surface soils and river sediments, modifying the natural geochemical background (Jia et al., 2023; Elrayah, 2024). The environmental contamination by metals, metalloids and rare-earth elements has received increasing attention due to their high toxicity, persistence, and bioaccumulation potential (e.g., Enowakwen et al., 2023; Afahnwie et al., 2025a, 2025b; Tiabou et al., 2025b).

Organic-rich shales, phosphatic layers, and carbonate rocks commonly associated with petroleum basins, may act as geochemical traps favoring the accumulation of metals, REEs, and also naturally-occurring radioactive elements (Deko et al., 2026). The influence of petroleum exploitation activities may thus represent a complex source of environmental contamination, whose intensity depends on the geological variability and extent of anthropogenic disturbance (Ryszko et al., 2023).

In the Democratic Republic of the Congo (DR Congo), particularly within the Lemba petroleum sub-basin in the Kongo Central Province, petroleum exploration activities have been conducted for several years already, with unchecked environmental impacts. Soon, this activity may move on to the oil production phase. The occurrence of phosphate deposits in the same region is another geological resource likely to be developed in the near future. However, data on the geochemical characteristics of soils and riverbed sediments are scarce for this region.

This study aimed to provide an initial assessment of concentrations of metals, metalloids and rare-earth elements in environmental matrices in the Lemba petroleum sub-basin. Furthermore, with the future development of oil and phosphate resources this study aimed also at identifying the needs for environmental and human protection measures (**Congo Mines, 2016**).

2. Material and methods

2.1. Description of the study areas

In view of the presence of significant oil and phosphate resources in the Lemba petroleum sub-basin and ongoing anthropogenic activities, notably oil exploration, several areas were selected for investigation of the current environmental pollution. These areas included Fundu-Nzobe, Ngundji, Mvuangu, and Kanzi, all located in the Lemba sub-basin, western part of the ~~DR emocratic Republic of the~~ Congo.

The Lemba petroleum sub-basin is densely populated and several villages exist in the region. Beyond oil exploration, the human activities include agriculture and machine repair workshops, among other (**Table 1**). The rainfall in this region spreads along the year and averages 95-195 mm/year. The region is crossed by several rivers and streams in which the

residues from human activities may end up and accumulate due to improper waste disposal and surface runoff following rainfalls (**Fig. 1**).

Oil exploration activities are on-going in this region, particularly at the Kanzi area. Soon, with the projected oil exploitation and phosphate development at industrial scale, the amounts of industrial wastes are likely to grow and, with their spread in the environment, their impact on agriculture fields and water courses may increase.

2.2. Sampling procedure

The collection of environmental samples was conducted in January 2023 in the Lemba sub-basin, Kongo Central Province with prior authorization from the relevant local authorities (**Figure 1**). Soil samples were collected across the region in four selected areas with agriculture, human settlements, phosphate deposits, and oil exploration activities. The surface sediments were collected from riverbeds, under 70–100 cm water depths. Each soil and surface sediment sample represents a composite of at least three subsamples collected at each sampling station, with the total mass of composite sample ranging between 200 and 250 g. A total of ten samples were collected at the Mvuangu area, comprising five soil samples (MvSol1 to MvSol5) and five sediment samples from the Kwilu River (MvSed1 to MvSed5). At the Kanzi area, were collected three soil samples (KaSol1 to KaSol3) and two sediment samples from the riverbed of Mfuma River (KaSed1to KaSed2). At the Fundu-Nzobe area, five soil samples and five surface sediment samples from water courses were collected and labeled FNSol1 to FNSol5, and FNSed1 to FNSed5, respectively. At Ngundji area, four soil samples (NGSol1–NGSol4) and two sediment samples from water courses (NGSed1–NGSed2) were collected.

All samples were collected using plastic shovels to avoid metal contamination, placed in polyethylene bags, and stored in portable iceboxes at approximately 4°C (**Mabidi et al., 2024**). Detailed description of the sampling locations and their geographical coordinates are

provided in **Table 1**. The samples were then transported to the analytical platform of the University of Geneva (Switzerland) for analysis.

2.3. Determination of sample physicochemical characteristics

Soil and sediment samples were characterized through the determination of key physicochemical properties, including moisture content, organic matter content, and granulometric composition. The moisture content was determined by drying the samples in an oven at 105 °C until constant weight and calculating the corresponding weight loss (ISO, 1993). The organic matter fraction was estimated by loss-on-ignition, following combustion of the oven-dried sample aliquots at 550 °C for one hour in a muffle furnace (Salvis AG, Lucerne, Switzerland) (Dean, 1974). Grain-size distribution analyses were performed on approximately 1 g of fresh sample material. Prior to this analysis, samples were dispersed in deionized water and subjected to ultrasonic agitation for 5 minutes for particle ~~disaggregation~~disaggregation. Particle size measurements were then carried out using a Coulter LS-100 laser diffraction granulometer (Beckman Coulter, Fullerton, CA, USA), according to previously described procedures (ISO, 2020).

2.4. Determination of heavy metal and rare-earth element concentrations

The sediment and soil samples were lyophilized, homogenized, sieved, and sample aliquots mineralized in acids according to the protocols previously described in Mabidi *et al.*, (2024). In short, approximately 1 g of an accurately weighed sediment or soil aliquot was mixed with 10 mL of 2 M HNO₃ in Teflon pressure vessels and heated at 105 °C during 16 h for metals extraction. The solution was then centrifuged at 4000 rpm during 15 min at 20 °C. The supernatant was recovered and diluted 200 times with 1% HNO₃ solution (Suprapur®, Merck KGaA, Darmstadt, Germany). An aliquot of 10 mL of the diluted solution of metals extract was used for the determination of trace metal elements with an Inductively Coupled Plasma-Mass Spectrometer (ICP-MS, Agilent 7700 × series, Santa Clara, CA, USA). As analytical

quality control, the lake sediment certified reference material (CRM) LKSD-4 and the stream sediment certified reference material STSD-2, both from the National Research Council, Canada, were used to check the sample digestion procedure, the yield of recovery of the elements, the instrument responsiveness, and the reliability of the results.

All trace element determinations were conducted in triplicate and results averaged. Standard deviations of the three replicate measurements were below 2.5% relative standard error and the chemical blanks were less than 1.5% of the sample signal. The bias of metal determinations (coefficient of variation) was lower than 5% of the CRM metal concentrations. The results were expressed in mg kg^{-1} sediment dry weight.

A mercury specific Atomic Absorption Spectrometer named “Advanced Mercury Analyser” (AMA 254, Altec s.r.l., Czech Rep.) was used for the total Hg analysis in sediment and soil samples according to the method described by **Hatch and Ott (1968)**. The method consists on the sample combustion and mercury amalgamation on a gold trap, followed by the measurement of gaseous mercury by AMA.

The marine sediment certified reference material MESS-4 from National Research Council, Canada, was used to check the performance of the entire analytical procedure for Hg and to determine the accuracy of measurements. The value obtained by repeated total Hg analyses of the CRM MESS-4 was $0.081 \pm 0.009 \mu\text{g g}^{-1}$ which was comparable to the CRM certified value of $0.09 \pm 0.04 \mu\text{g g}^{-1}$. The relative uncertainty of these measurements was approximately 4%. The detection limit (value of the blank + 3 SD) was $0.003 \mu\text{g g}^{-1}$ and the reproducibility was better than 5%. The analytical results for Hg concentrations were expressed in mg kg^{-1} dry weight (ppm).

2.5. Assessment of soil and sediment pollution

The degree of contamination of soils and sediments by the investigated trace elements was assessed using two widely applied geochemical indicators: the Enrichment Factor (EF) and the Geo-accumulation Index (Igeo). These indices were calculated following methodological approaches previously reported in the literature (**Nsiala *et al.*, 2025**).

The Enrichment Factor (EF) was determined using the following expression:

$$EF = ([Metal]_{sample}/[Sc]_{Sample}) / ([Metal]_{Background}/[Sc]_{Background})$$

where [Metal] represents the concentration of a given trace metal in both the analyzed samples and the reference background, while [Sc] corresponds to the scandium concentration in the samples and in the background material. Scandium (Sc) was selected as the normalizing element due to its relative immobility and its predominantly lithogenic origin. Average Upper Continental Crust (UCC) concentration values were adopted as background concentrations for the metals, in accordance with **McLennan (2001)**.

The Geo-accumulation Index (Igeo) was calculated using the following formula:

$$Igeo = \text{Log}_2[Ci]/1.5[Bi]$$

where [Ci] is the measured concentration of element “i” in the sediment sample, [Bi] is the corresponding geochemical background concentration, and the constant factor 1.5 accounts for natural variations in the lithogenic background as well as minor anthropogenic influences (**Akonga *et al.*, 2026**).

2.6. Ecological risk assessment parameters

In order to evaluate the level of heavy metal contamination in sediment samples, the contamination factor (CF) was determined following the approach proposed by **Rubio *et al.* (2000)**, **Förstner *et al.* (1989)** and **Nsiala *et al.* (2025)**. The CF is defined as the ratio between

the measured concentration of a given metal in the sediment and its corresponding geochemical background value:

$$CF = [C_n]/[B_n]$$

where C_n denotes the concentration of a heavy metal in the sediment sample and B_n represents its natural background concentration.

To assess the overall degree of polymetallic contamination in each sediment sample, the contamination degree (CD) was calculated according to **Håkanson (1980)**. This index corresponds to the sum of the individual contamination factors for all considered metals and it is expressed as:

$$CD = \sum CF_i$$

where CF_i refers to the contamination factor of the heavy metal i . In this study, the metals included in the CD calculation were Hg, Cd, As, Co, Cu, Pb, Cr, and Zn.

The potential ecological risk associated with individual heavy metals was evaluated using the ecological risk factor (E_{ri}), which integrates both the contamination level and the relative toxicity of each element. This parameter provides an estimate of the potential adverse effects of heavy metals on ecosystems and human health (**Suresh *et al.*, 2012**). The ecological risk factor was calculated as:

$$E_{ri} = Tr_i \times CF_i$$

where Tr_i is the toxic response factor (or biological toxicity coefficient) of the metal i , and CF_i is its contamination factor. The toxic response factor values adopted in this study were 40 for Hg, 30 for Cd, 10 for As, 5 for Co, Cu, and Pb, 2 for Cr, and 1 for Zn (**Islam *et al.*, 2014**).

The overall potential ecological risk index (RI) for each sediment sample was obtained by summing the individual ecological risk factors of all analyzed metals. This composite index reflects the combined influence of metal concentrations, toxicity, and the sensitivity of

biological communities to heavy metal contamination (Singh *et al.*, 2002). The RI is expressed as:

$$RI = \sum Er_i$$

where Er_i represents the ecological risk factor of each heavy metal i .

Finally, the ecotoxicological risk posed by metal contamination in the sediments was further evaluated by comparing the measured metal concentrations in sediments with internationally recognized Sediment Quality Guidelines (SQGs) and Probable Effect Levels (PEL) established for the protection of aquatic organisms, as recommended by the Canadian Council of Ministers of the Environment (CCME, 1999).

2.7. Determination of Ce, Eu and Tm anomalies

The cerium (Ce), europium (Eu), and thulium (Tm) anomalies in soil and sediment samples were determined using the conventional method based on rare-earth element (REE) concentrations normalized to the North American Shale Composite (NASC). This approach allows the identification of departures from the expected REE distribution, which is assumed to follow a smooth, log-linear trend between adjacent elements (Nsiala *et al.*, 2025).

The Ce, Eu, and Tm anomalies were computed using the standard equations:

$$\frac{Ce}{Ce^*} = \frac{Ce_N}{\sqrt{La_N \times Pr_N}}; \frac{Eu}{Eu^*} = \frac{Eu_N}{\sqrt{Sm_N \times Gd_N}}; \frac{Tm}{Tm^*} = \frac{Tm_N}{\sqrt{Er_N \times Yb_N}} \quad (7)$$

where X_N denotes the NASC-normalized concentration of element X , and $\frac{Ce}{Ce^*}$, $\frac{Eu}{Eu^*}$ and $\frac{Tm}{Tm^*}$ are normalized ratios that quantify the Ce, Eu and Tm anomalies.

The resulting anomaly ratios were interpreted as follows: a value equal to 1 indicates the absence of an anomaly, whereas values lower than 1 reflect a negative anomaly and values

greater than 1 indicate a positive anomaly. This interpretative framework applies equally to Ce, Eu, and Tm.

These calculations provide a quantitative means of assessing relative enrichments or depletions of specific REEs with respect to the expected geochemical background. Such deviations may reflect the influence of mineralogical composition, redox conditions, or other geochemical processes operating within the sedimentary environment.

2.8. Data analysis

Heavy metal concentrations were determined in triplicate for each sample, and the results were averaged to ensure accuracy and reproducibility. Statistical analysis, including Spearman correlation, was conducted using the XLSTAT version 2021.1 (Addinsoft, New York, USA; <https://www.xlstat.com>, accessed on June 2025).

3. Results and discussion

3.1. Physico-chemical characteristics of samples

Table 2 summarizes the physicochemical properties of soils and surface sediments collected from the Mvuangu, Kanzi, Fundu-Nzobe, and Ngundji areas within the Lemba sub-basin in DR Congo. The analyzed parameters include water content (WC), organic matter (OM), particle-size distribution (clay, silt, sand), and mean grain size, which together reflect depositional conditions, pedogenic processes, and the environmental behavior of soil/sediment materials.

Water content values showed pronounced spatial variability, ranging from 8.4% (NGSol3) to 34.54% (NGSed1). River sediment samples generally displayed higher water content than soils, particularly at Ngundji (NGSed1: 34.54%) and Mvuangu (MvSed3: 33.62%), indicating low-energy depositional environments and high moisture retention during the January

sampling period. In contrast, soils from the same sites exhibited lower WC values, commonly below 20%, reflecting better drainage conditions (**Cutroneo *et al.*, 2025**).

Organic matter contents varied between 1.07% (KaSol3) and 7.99% (MvSol1). Soils typically showed higher OM levels than sediments, with notable values observed at MvSol1 (7.99%), KaSol1 (6.69%), and NGSed2 (5.51%). These relatively elevated OM contents likely result from dense vegetation cover and organic inputs and are likely to enhance the capacity of these matrices to retain trace elements (**Kobierski and Banach-Szott, 2022**).

Grain-size analysis revealed a strong dominance of the sand fraction in most samples. Several soils contained more than 80% sand, including MvSol1 (81.12%), MvSol2 (87.36%), MvSol4 (89.18%), and KaSed2 (87.32%). Correspondingly, mean grain sizes frequently exceeded 100 μm , reaching 176.7 μm (MvSol4) and 164.3 μm (NGSol4), indicative of medium- to coarse-grained materials derived from erosion of rock formations (**El Bamiki *et al.*, 2021**).

Textural contrasts were evident among specific sites. Ngundji sediment NGSed1 was characterized by a high silt content (63.97%) and a low sand proportion (32.29%), with a fine mean grain size of 24.53 μm , suggesting deposition under low hydrodynamic energy. Similarly, KaSed1 showed a mixed texture with 49.59% silt, 47.48% sand and a mean grain size of 33.55 μm , reflecting transitional depositional conditions.

Overall, the physicochemical variability observed among sites reflected the combined influence of geological setting, hydrological regime, and surface processes associated with erosion and material transport. The prevalence of sandy textures suggested high permeability and limited contaminant retention, whereas fine-grained, OM-rich sediments and soils—particularly at Ngundji and parts of Mvuangu—represented preferential sinks for metals and metalloids, providing a critical framework for interpreting subsequent geochemical and radiological assessments.

3.2. Metal, metalloid and rare-earth element concentrations in soils and sediments

The distribution of trace metals in soils and sediments (**Table 3**) reflects the combined influence of local environmental conditions, hydrodynamics, lithology, and human activities such as agriculture, and domestic washing, fishing, and water collection in the water courses (**Jean-Lavenir *et al.*, 2023**; **Tiabou *et al.*, 2024a**; **Table 1**). In the watercourses, these human activities enhance sediment reworking and favor the accumulation of fine particles which act as effective sinks for dissolved and particulate-bound metals in low-energy fluvial environments (**Tiabou *et al.*, 2025ae**).

At the Mvuangu area, the agricultural soils (MvSol1 to MvSol5) showed elevated Cr, Pb, and Zn contents, suggesting a combined influence of industrial and agricultural materials, especially including oil exploration residues present in the area. Across this area, the Kwilu River sediments (MvSed1 to MvSed5) displayed a gradual enrichment in Fe, Mn, Cr, Zn, As, Cd, and Pb, with peak concentrations in MvSed5 (e.g., Fe = 13,075 mg kg⁻¹; Mn = 590 mg kg⁻¹; Zn = 51.04 mg kg⁻¹; Cd = 0.83 mg kg⁻¹). This trend is consistent with the intensity of human activities along this river.

In the Kanzi area, even stronger enrichments were observed in village soils (Kasol3), affected by housing and oil exploration activities, particularly for Cr, Zn, As, and Cd. Across this area, the riverbed sediments of Mfuma River, collected near washing and fishing zones (KaSed1 to KaSed2) exhibited high Zn, Cd, Cr, and Ni concentrations, with several values exceeding CCME PEL guidelines. The proximity ~~of contaminated~~of contaminated surface soils to water wells used by inhabitants suggested potential pathways for metals transfer toward groundwater systems with the risk of compromising sources of water for human consumption (**Hamed *et al.*, 2024**).

At the Fundu-Nzobe area, the samples of agricultural soils collected near oil exploration points (FNsol3 to FNsol5) displayed very high Fe, Ni, Zn, As, and Cd concentrations, indicating superimposed geogenic and anthropogenic controls. In this area, the Lukula River sediments

showed also marked enrichment in Mn, Zn, Cd, and Pb, especially in FNsed3 and FNsed5, indicating contamination by releases from anthropogenic sources in this area which is heavily impacted by domestic activities and repair workshops (Yiika *et al.*, 2024; Suh *et al.*, 2025). Similarly, at Ngundji, agriculture soils and urban soils (paths used by foot traffic) exhibited extremely high Fe, Mn, Cu, and Zn concentrations indicating to have been affected by nearby oil exploration wastes. Sediments from local water courses used by the population as sources for domestic water-use showed elevated Cr, Zn, and Cd concentrations indicating contamination and accumulation of metals in the aquatic system (Jean-Lavenir *et al.*, 2023; Afahnwie *et al.*, 2025b). This accumulation of contaminants was favored by sediment fine-grained textures, high moisture, and repeated anthropogenic discharges and sediment disturbance.

Spearman correlation analysis for the contaminant concentrations (**Table 4**) revealed strong positive relationships among Fe, Mn, Cr, Ni, Zn, As, and Cd ($\rho = 0.53\text{--}0.90$; $p < 0.05$), that is indicative of co-accumulation processes driven by waste discharges into the environment and human activities, including oil exploration. In contrast, the water content and organic matter displayed moderate correlations with metal concentrations, while Sc and Ti correlated strongly with most elements, confirming their useful role as proxies for assessing metal inputs from lithogenic sources (Suh *et al.*, 2025).

Rare-earth element (REE) concentrations (**Table 5**) showed pronounced spatial variability, with total REEs (ΣREE) ranging from 15.8–24.9 mg kg⁻¹ in Mvuangu sediments to 325.2 mg kg⁻¹ in Ngundji soils. Soils generally contained higher ΣREE than sediments, reflecting stronger retention and post-depositional accumulation. Light REEs dominated over heavy REEs, with $\Sigma\text{LREE}/\Sigma\text{HREE}$ ratios commonly exceeding 8 and reaching extreme values in Ngundji soils, consistent with crustal material signatures. Ce, La, Nd, and Pr were the most abundant REEs, whereas Eu, Tm, and Lu occurred at trace levels.

Strong positive correlations among individual REEs ($R^2 \approx 0.94\text{--}0.99$) indicated coherent behavior and dominant lithogenic control, while weak to moderate negative correlations with organic matter suggest a limited role of OM in REE mobility. Among the studied sites, Fundu-Nzobe and Ngundji soils were the most REE-enriched, whereas Mvuangu sediments displayed the lowest concentrations, in general consistent with dominant fine texture and organic matter content of riverbed sediments.

The anomaly ratios reported in **Table 6** were derived from NASC-normalized REE patterns (**Figure 2**) and provided quantitative support for the observed spectral trends. All samples exhibited negative Ce anomalies ($\text{Ce/Ce}^* = 0.6\text{--}0.9$), consistent with oxic conditions prevailing in fluvial and near-river environments, where intense water–sediment interactions promoted Ce oxidation and removal (**Zhang and Shields, 2022**). Eu anomalies were generally weak ($\text{Eu/Eu}^* \approx 0.7\text{--}1.2$), reflecting dominant lithogenic control, with minor variations attributable to mineralogical composition and sedimentary processes (**Lee *et al.*, 2023**). In contrast, Tm/Tm^* ratios showed high variability, with positive anomalies in soils and sediments near phosphate deposits and cultivated areas, indicating relative enrichment of heavy REEs in these areas, whereas low or null values were observed in some riverine samples which reflect dilution and sediment remobilization.

Overall, metals, metalloids and REE distributions were primarily governed by the lithology and redox conditions, while local human activities modulated metal accumulation and REE fractionation, particularly in disturbed soils and riverbed sediments. These findings highlighted the environmental sensitivity of agricultural soils and freshwater systems to pollution (**Yiika *et al.*, 2024**; **Sigue *et al.*, 2025**; **Tiabou *et al.*, 2025b**). Agriculture soils are the support of food production and rivers are vital water sources for domestic use and fisheries. These signs of metal contamination in soils and riverbed sediments clearly indicate a need for

suitable monitoring plans in areas targeted for mineral resources exploitation (Tiabou *et al.*, 2025ae).

3. 3. Evaluation of soil and sediment pollution and ecological risk

The Geo-accumulation Index (Igeo) and Enrichment Factor (EF) values (Table 7) revealed marked spatial variability in metal contamination across the investigated soils and sediments. Overall, Cr, Mn, Fe, Ni, Cu, Zn, and Pb exhibited very high positive Igeo values at most sites, frequently exceeding $I_{geo} > 5$, which corresponds to Class 6 (extremely polluted) conditions. This trend was particularly evident in samples from Kanzi (Kasol3: Igeo up to 12.3 for Cr and 29.6 for Fe) and Mvuangu (Mvsed5 and Mvsol5), suggesting strong anthropogenic inputs superimposed on a naturally metal-rich lithological background (Afahnwie *et al.*, 2025ae; Tiabou *et al.*, 2024b; Jean-Lavenir *et al.*, 2024). In contrast, As, Cd, and Hg generally showed negative Igeo values ($I_{geo} \leq 0$), thus indicating practically unpolluted to unpolluted conditions for these elements at most locations.

Riverbed sediments generally displayed slightly lower Igeo values than soils, although several sediment samples (e.g., Kased1, FNsed3, NGsed2) still fell within the heavily to extremely polluted classes for Cr, Fe, Zn, and Pb. The consistently high Igeo values for Fe and Mn across all investigated areas reflected their abundance in local parent materials, while elevated Cr, Ni, Cu, Zn, and Pb pointed to additional anthropogenic sources such as oil exploration, mining, urban runoff, and agricultural activities (Jean-Lavenir *et al.*, 2023; Yika *et al.*, 2023; Djibril *et al.*, 2026). The EF results (Table 4) supported this interpretation, indicating significant enrichment for these metals, especially in Kanzi, Fundu, and Ngundji areas.

The contamination factor (CF) values presented in Table 8 indicated that most metals fell within low contamination levels ($CF < 1$) in Mvuangu soils and sediments, except for As, Cu, Zn, and Pb, which locally reached moderate to considerable contamination ($1 < CF < 6$). Higher CF values were observed in Fundu and Ngundji, particularly for As (CF up to 66.2 in

FNsol3 and 51.8 in NGsed2) and Cr (CF up to 5.8 in NGsed2), indicating very high contamination at these sites (Afahnwie *et al.*, 2025b; Yüka *et al.*, 2024). The degree of contamination (CD) parameter values remained generally in the range from low to moderate in Mvuangu, but increased to high or very high contamination categories in Kanzi, Fundu, and Ngundji, reflecting cumulative multi-metal pollution.

The ecological risk factor (Eri) values showed that most individual metals pose low ecological risk ($Eri < 40$) in Mvuangu samples. However, As and Cr emerged as dominant contributors to ecological risk in Fundu and Ngundji, where Eri values reach extremely high levels (e.g., As: $Eri = 1986.7$ in FNsol3 and 1555.1 in NGsed2). In Kanzi soils, Co and Cr also showed very high Eri values (Co up to 814.3 and Cr up to 92.9), indicating considerable to very high ecological risk associated with these elements (Tiabou *et al.*, 2025a).

The integrated potential ecological risk index (RI) further highlighted these spatial contrasts. Mvuangu samples mainly fell within the low ecological risk category ($RI < 150$), whereas Kanzi soils showed very high ecological risk ($RI = 771.5\text{--}959$). Fundu and Ngundji exhibited the highest RI values, reaching extreme levels (RI up to 2051.3 in FNsol3 and 1622.2 in NGsed2), which corresponded to a very worrying level of ecological risk. These elevated RI values were overwhelmingly controlled by As and, to a lesser extent, by Cr, Co, and Pb.

In summary, the combined interpretation of Igeo, CF, CD, Eri, and RI indices indicated that while some areas (notably Mvuangu) remained at environmental relatively low-risk, other areas (namely Kanzi, Fundu, and Ngundji) were affected by severe to extreme metal contamination and thus current metal levels pose ecological hazards. The results pointed to a strong influence of anthropogenic activities, superimposed on a metal-rich geological background (Tiabou *et al.*, 2025be), and underlined the need for targeted environmental management and remediation strategies, especially with respect to arsenic- and chromium-driven ecological risks (Tiabou *et al.*, 2024be; Dorleon *et al.*, 2025).

4. Conclusions

This survey represents a preliminary geochemical assessment of agricultural soils, urban soils and riverbed sediments from four areas in the Lemba petroleum sub-basin, Kongo Central Province of the Democratic Republic of the Congo. In this sub-basin, intensive oil exploration activities have been ongoing for several years and, meanwhile, other mineral resources such as phosphates were identified and may be developed in the near future.

The analysis of physicochemical properties of soil and sediment samples along with the determination of concentrations of a wide range of metals, metalloids and rare-earth elements (REEs) were carried out. The results obtained allowed the calculation of pollution indices, which provided a robust evaluation of current environmental quality and concomitant pollution hazards in the region.

Physicochemical characteristics revealed a strong spatial variability of sediments and soils which is controlled by depositional environments and land use. The grain sizes of most samples were dominated by sandy textures (>80% sand in several soils), implying high permeability, whereas fine-grained, organic-rich sediments—particularly at Ngundji—showed higher water content (up to 34.5%) and enhanced contaminant retention capacity. These features strongly control metal accumulation and mobility in the environment.

Trace metal concentrations in soils and sediments seem to have been governed, so far, by both geogenic sources and anthropogenic activities. Elevated levels of Fe (up to 13,075 mg kg⁻¹), Mn (590 mg kg⁻¹), Zn (51.0 mg kg⁻¹), Cr, Ni, and Pb were observed in surface soils and riverbed sediments. These results demonstrated that while Mvuangu showed relatively low environmental risk, Kanzi, Fundu-Nzobe, and Ngundji are affected already by severe metal contaminations derived from human activities. Pollution indices indicated severe to extreme contamination at Kanzi, Fundu-Nzobe, and Ngundji, with Igeo values frequently exceeding 5 for Cr, Fe, Zn, and Pb. The ecological risk assessment highlighted arsenic and chromium as

the dominant risk drivers, with Eri values for As reaching 1987 and integrated RI values up to 2051, corresponding to a serious level of ecological risk.

REE distributions displayed coherent crustal signatures, with strong LREE enrichment ($\sum\text{LREE}/\sum\text{HREE} > 8$) and systematic negative Ce anomalies ($\text{Ce}/\text{Ce}^* = 0.6\text{--}0.9$), indicative of oxic fluvial conditions. Total REE concentrations ranged from $<25 \text{ mg kg}^{-1}$ in Mvuangu sediments to 325 mg kg^{-1} in Ngundji soils, reflecting contrasting retention capacities of these soils.

These results unveiled, for the first time, the current status of the environment in this region and showed that there are already signs of environmental contamination associated to oil exploration activities combined with improper urban waste management. Hopefully, results of this preliminary investigation will contribute to build up the perception of a need for implementing environmental protection measures (regulatory measures) and may serve also as a baseline in anticipation of oil production and other minerals exploitation.

Upcoming oil production and possible exploitation of phosphate deposits may further expand environmental contamination and bring about enhanced pollution hazards. Overall, this study underscored the necessity of systematic environmental monitoring prior to, and during oil and minerals exploitation in the region.

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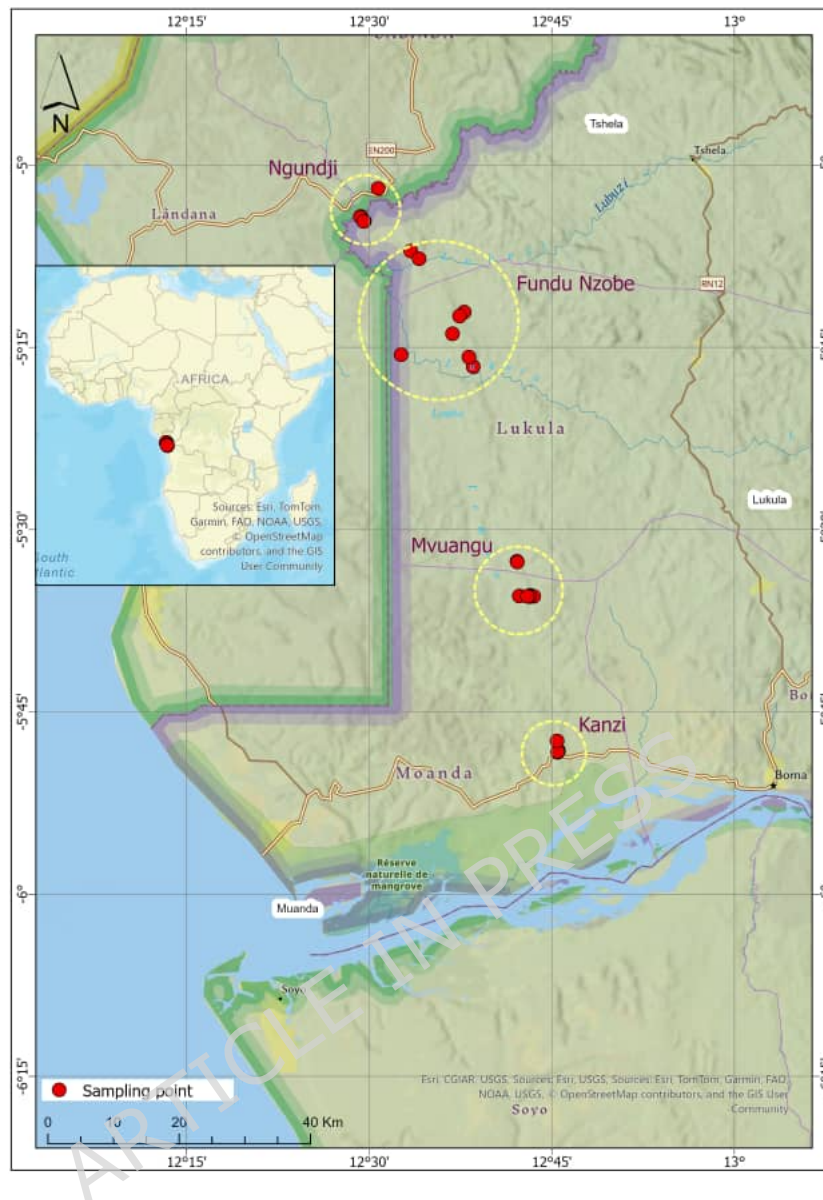


Figure 1: Study areas (Fundu-Nzobe and Ngundji, Mvuangu and Kanzi) and sampling points (red circles). The map was produced using QGIS version 3.40.7 with the Esri National Geographic Style Base basemap, using the following resources: <https://cdn.arcgis.com/sharing/rest/content/items/efa46686e17d44d48dde43b31c62c83e/resources/styles/root.json> and <https://tiles.arcgis.com/tiles/P3ePLMYs2RVChkJx/arcgis/rest/services/NatGeoStyleBase/MapServer>:

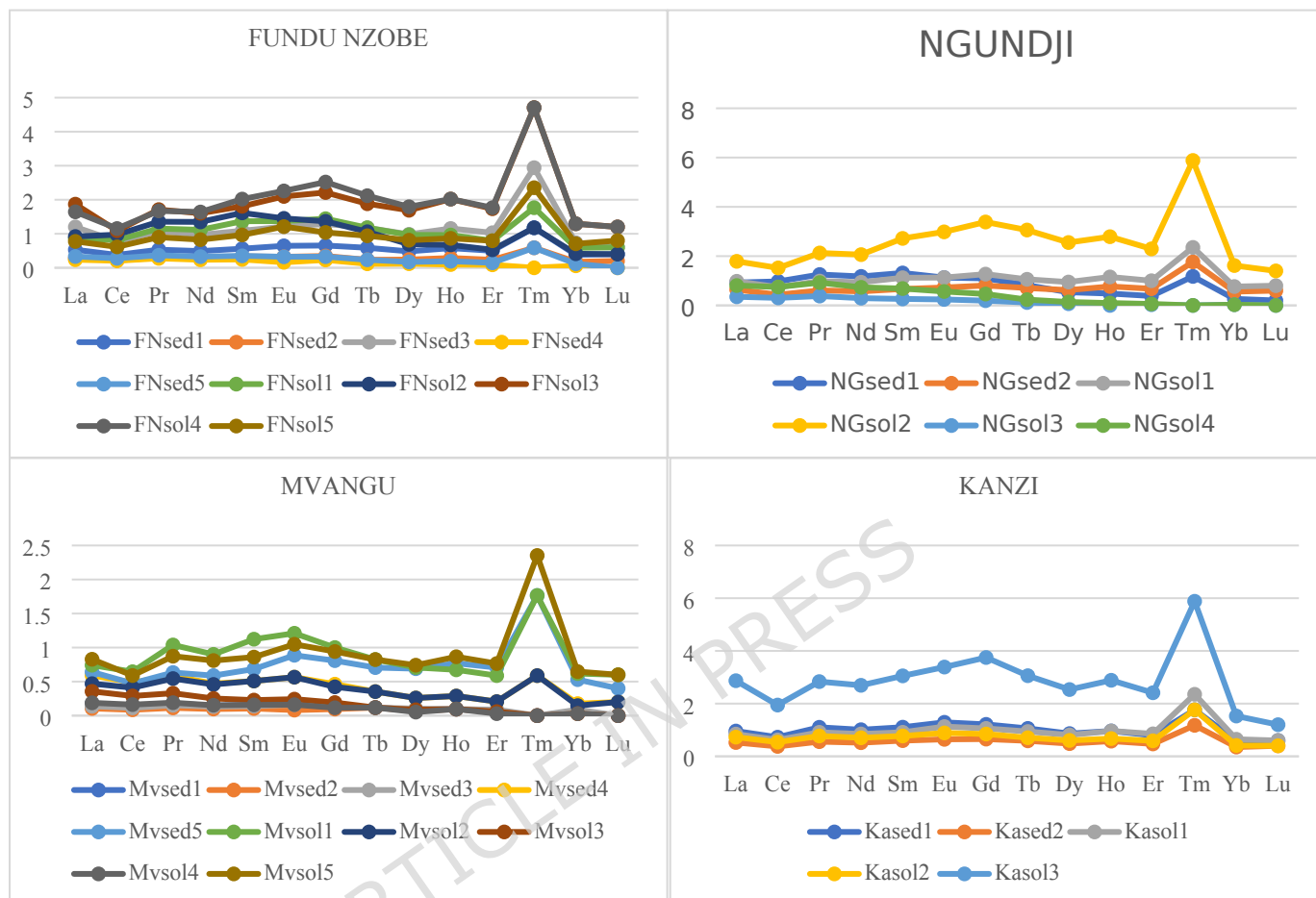


Figure 2: NASC-normalized rare earth element patterns for the four investigated areas.

YY scale values are the ratios of elemental concentrations in samples and the concentrations of the same elements in NASC.

Table 1: Sampling areas, GPS coordinates of sampling sites, and description of human activities carried out nearby.

Area	Sample name	Geographical Coordinates	Human activity/ Use of resources	Observation
MVUANGU (Kwilu River)	MvSed1	5° 35' 26,4" 12° 43' 16,7"	Washing, fishing	Sediment from riverbed
	MvSed2	5° 35' 27,3" 12° 43' 17,2"	Washing, fishing	Sediment from riverbed
	MvSed3	5° 35' 24,7" 12° 43' 14,3"	Washing, fishing	Sediment from riverbed
	MvSed4	5° 35' 26,4" 12° 43' 14,5"	Washing, fishing	Sediment from riverbed
	MvSed5	5° 32' 36,2" 12° 42' 09,0"	Washing, fishing	Sediment from riverbed
	MvSol1	5° 35' 30,0" 12° 43' 30,1"	Agriculture: cassava , groundnut, maize	Soil from a field marked by a sign of oil exploration.
	MvSol2	5° 35' 27,3" 12° 42' 20,7"	Agriculture: cassava groundnut, maize	Soil taken from a field with a sign of oil exploration.
	MvSol3	5° 35' 30,6" 12° 43' 09,9"	Agriculture: cassava, groundnut, maize	Soil taken from a field marked with a sign of oil exploration.
	MvSol4	5° 35' 30,0" 12° 43' 00,0"	Agriculture: cassava,, groundnut, maize	Soil taken from a field by a sign of oil exploration.
	MvSol5	5° 32' 39,9" 12° 42' 10,2"	Agriculture: cassava, , groundnut, maize	Soil taken from an agriculture exploration.
	KaSed1	5° 48' 11,1" 12° 45' 32,7"	Washing, fishing, drinking water	Sediment from riverbed
	KaSed2	5° 48' 14,9" 12° 45' 32,1"	Washing, fishing, drinking water	Sediment from riverbed
	KaSol1	5° 48' 19,4" 12° 45' 29,6"	Home building	Soil sampled t in a field close to the river.

KANZI (Mfuma River)	KaSol2	5° 48' 16,4"	Agriculture: banana	Soil sampled in a field around a
		12° 45' 29,0"	seedlings, pineapple	point of oil exploration activity.
	KaSol3	5° 47' 24,1"	Home building	Soil sampled in the middle of a
		12° 45' 25,2"		village around a point of oil exploration activity.
FUNDU NZOBE (unnamed water course)	FNSed1	5° 06' 57,8"	Laundry, washing,	Sediment from riverbed
		12° 30' 13,1"	fishing, drinking water	
	FNSed2	5° 06' 57,6"	Laundry, washing,	Sediment from riverbed
		12° 30' 15,7"	fishing, drinking water	
	FNSed3	5° 07' 57,6"	Leaching, washing,	Sediment from riverbed
		12° 30' 51,3"	Fishing	
	FNSed4	5° 07' 30,6"	Leaching, washing,	Sediment from riverbed
		12° 30' 46,9"	fishing	
	FNSed5	5° 07' 32,6"	Leaching, washing,	Sediment from riverbed
		12° 30' 44,6"	fishinc	
	FNSol1	5° 07' 00,4"	Agriculture: cassava	Soil collected from an agriculture
		12° 30' 20,5"	groundnut, maize	field near the river.
	FNSol2	5° 07' 04,2"	Agriculture: cassava,	Soil collected from an agriculture
		12° 30' 24,7"	groundnut, maize	field near the river.
	FNSol3	5° 07' 52,8"	Agriculture: cassava,	Soil collected in a field around a
		12° 30' 49,1"	,groundnut, maize	point of oil exploration activity.
NGUNDJI	NGSed1	5° 04' 14,1"	Laundry, washing,	Sediment collected along the river,
		12° 29' 17,8"	fishing, drinking water	between 70 to 100cm.
	NGSed2	5° 04' 14,9"	Laundry, washing,	Sediment collected along the river,
		12° 29' 16,2"	fishing, drinking water	at 70 to 100cm water depth.
	NGSol1	5° 04' 15,2"	Agriculture: cassava,	Soil collected in a field near the
		12° 29' 16,4"	groundnut, maize	river.

(unnamed water
course)

NGSol2	5° 04' 16,6"	Agriculture: cassava, groundnut, maize	Soil collected in a field around a point of oil exploration activity.
	12° 29' 17,3"		
NGSol3	5° 04' 37,2"	Path, walking ground	Soil collected around a point of oil exploration activity.
	12° 29' 36,8"		
NGSol4	5° 04' 38,2"	Path, walking ground	Soil collected around a point of oil exploration activity.
	12° 29' 33,7"		

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Table 2: Physicochemical parameters of sediment and soil samples (% weight) and mean grain size (μm). WC, Water content; OM, Organic matter.

Sampling area	Sample name	WC	OM	Clay	Silt	Sand	Mean grain size
MVUANGU (Kwilu River)	MvSed1	18.37	3.58	0.718	16.8	82.48	121.9
	MvSed2	19.04	2.84	Nd	Nd	Nd	Nd
	MvSed3	33.62	4.01	Nd	Nd	Nd	Nd
	MvSed4	20.42	2.6	Nd	Nd	Nd	Nd
	MvSed5	20.34	4.13	Nd	Nd	Nd	Nd
	MvSol1	9.41	7.99	1.01	17.87	81.12	121.8
	MvSol2	13.09	3.16	2.14	10.5	87.36	86.58
	MvSol3	9.94	5.34	4.34	34.29	61.37	55.37
	MvSol4	8.6	2.81	1.29	9.53	89.18	176.7
	MvSol5	16.5	3.86	2.75	27.94	69.31	68.94
KANZI (Mfuma River)	KaSed1	33.22	2.2	2.93	49.59	47.48	33.55
	KaSed2	21.12	2.24	1.5	11.18	87.32	79.6
	KaSol1	14.4	6.69	0.629	26.56	72.81	71.41
	KaSol2	24.65	2.82	0.654	27.42	71.93	69.79
	KaSol3	18.77	1.07	1.61	39.62	58.77	58.67
FUNDU NZOBE (unnamed water course)	FNSed1	19.95	4.19	1.28	12.93	85.79	132.3
	FNSed2	15.71	5.18	Nd	Nd	Nd	Nd
	FNSed3	21.32	2.57	Nd	Nd	Nd	Nd
	FNSed4	10.17	2.1	Nd	Nd	Nd	Nd
	FNSed5	13.14	2.96	Nd	Nd	Nd	Nd
	FNSol1	13.7	2.11	1.42	19.61	78.97	129.9
	FNSol2	13.5	2.27	4.63	26.56	68.81	75.97
	FNSol3	15.23	4.21	8.54	37.32	54.14	41.1
	FNSol4	13.76	1.12	4.28	28.64	67.08	68.01
	FNSol5	17.32	2.41	2.31	30.86	66.83	58.95
NGUNDJI	NGSed1	34.54	4.43	3.74	63.97	32.29	24.53
	NGSed2	21.12	5.51	Nd	Nd	Nd	Nd

(unnamed water course)	NGSol1	12.4	1.97	3.78	35.29	60.93	51.92
	NGSol2	18.14	1.62	2.87	26.66	70.47	76.16
	NGSol3	8.4	5.86	3.83	13.15	83.02	116
	NGSol4	10.87	3.66	1.61	9.58	88.81	164.3

Nd: not determined

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Table 3 : Trace metal concentrations (mg kg⁻¹ dry weight) in sediment and soil samples.

Area	Sample	Sc	Ti	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Cd	Pb	Hg
MVUANGU	Mvsed1	0.45	21.1	8.99	10.41	867.5	0.35	2.37	1.23	6.33	0.15	0.07	3.97	0.04
	Mvsed2	0.36	19.78	5.99	4.17	862.39	0.43	1.36	0.7	3.98	0.12	0.05	2.36	0.02
	Mvsed3	0.58	24.21	8.7	23.39	3045.66	2.14	10.79	2.1	8.03	0.28	0.08	3.11	0.02
	Mvsed4	3.81	54.04	41.44	92.98	20271.75	1.94	6.31	15.11	19.35	0.9	0.07	15.38	0.07
	Mvsed5	2.78	187.3	76.04	590.33	13075.17	5.26	14.22	4.74	51.04	1.7	0.83	14.6	0.15
	Mvsol1	2.9	71.12	28.09	40.55	15369.42	1.09	5.94	18.29	16.11	1.01	0.02	22.76	0.06
	Mvsol2	1.67	38.38	18.39	25.86	7377.41	0.83	3.35	11.7	11.31	0.38	0.03	8.51	0.06
	Mvsol3	2.22	81.1	30.54	25.95	17023.94	0.79	3.95	6.86	8.93	0.84	0.02	9.92	0.03
	Mvsol4	1.44	46.62	18.41	25.69	10525.03	0.42	2.41	6.86	6.8	0.53	0.02	5.73	0.04
	Mvsol5	1.97	112.55	43.04	201.54	11094.24	3.31	10.06	10.39	43.73	1.6	0.22	16.53	0.04
KANZI	Kased1	2.75	126.33	78.04	439.7	14760.55	4.89	13.91	10.59	133.44	1.91	2.66	15.74	0.07
	Kased2	1.36	78.44	48.29	136.52	7220.43	2.18	7	3.39	37.28	0.91	0.44	8.03	0.04
	Kasol1	1.93	91.7	83.24	331.31	11037.03	6.47	19.38	5.91	68.8	1.88	2.18	11.82	0.11
	Kasol2	1.7	90.01	67.84	285.45	10361.43	4.17	10.29	4.8	57.13	1.65	1.14	11.35	0.04
	Kasol3	3.57	257.43	212.63	191.25	27088.73	4.87	27.29	15.83	110.08	6.44	2.61	19.68	0.13
FUNDU	FNsed1	1.02	57.47	37.56	54.59	15006.58	4.61	14.01	1.20	24.79	1.92	0.88	5.99	0.02
	FNsed2	0.67	38.08	18.05	19.48	6827.44	3.05	5.95	0.61	17.53	1.10	0.41	3.66	0.01
	FNsed3	3.38	208.73	87.43	491.39	19158.03	8.49	19.14	12.34	84.03	1.90	4.04	12.27	0.07
	FNsed4	0.46	31.66	7.43	12.78	2245.45	0.48	1.52	-	4.24	0.24	0.04	1.77	0.01
	FNsed5	0.65	54.11	10.80	25.75	3776.11	1.16	3.38	0.23	7.87	0.43	0.06	23.07	0.02
NZOBE	FNsol1	2.95	88.44	41.83	104.54	24065.98	3.22	8.34	8.96	34.12	2.95	0.17	12.15	0.02
	FNsol2	3.38	78.36	48.55	57.38	27092.72	1.33	5.77	7.52	20.91	3.05	0.08	14.86	0.03
	FNsol3	2.99	196.77	96.48	472.83	15488.56	7.52	47.19	7.76	115.90	5.20	6.49	12.74	0.02
	FNsol4	3.71	188.30	67.19	236.16	25434.19	5.66	17.33	20.78	99.46	4.90	6.05	17.62	0.07
	FNsol5	3.82	123.02	42.01	115.10	27806.67	4.03	16.20	5.18	27.02	2.98	0.12	13.70	0.03
NGUNDJI	NGsed1	3.67	94.51	97.76	14.81	13188.10	1.40	13.00	11.83	21.99	2.46	0.42	16.28	0.08
	NGsed2	1.22	72.82	202.55	156.27	7174.48	5.07	15.07	6.09	112.62	1.94	5.08	6.05	0.05
	NGsol1	2.86	117.56	168.35	1007.93	38133.37	14.93	22.16	30.21	157.54	2.56	3.94	10.44	0.12
	NGsol2	5.24	200.20	73.65	710.18	35193.20	15.13	23.33	38.09	128.24	3.74	0.99	21.93	0.08
	NGsol3	1.57	77.56	46.81	18.16	26020.04	0.40	3.79	3.54	11.50	1.98	0.02	10.58	0.03
	NGsol4	2.29	138.31	65.31	19.58	34992.70	0.58	5.40	8.75	17.25	3.58	0.03	20.51	0.10
SQGs				37.3					35.7	123	5.9	0.6	35	0.17
PELs				90					197	315	17	3.5	91.3	0.486

Values in bold indicate trace metal concentrations exceeding the sediment quality guidelines for the protection of aquatic life (CCME, 1999).

SQG - Sediment quality guidelines; PEL - probable effect levels (sediment dry weight).

Table 4: Spearman correlation matrix for selected parameters analyzed in soil/sediment samples.

	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Cd	Pb	Hg	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
WC	0.298	0.245	-0.243	0.404	0.404	-0.032	0.354	0.004	0.551	-0.043	0.167	0.134	0.076	0.096	0.121	0.098	0.161	0.173	0.178	0.223	0.262	0.276	0.288	0.242	0.240	
OM	-0.115	-0.303	-0.312	-0.237	-0.166	-0.317	-0.273	-0.240	-0.256	-0.156	-0.152	-0.348	-0.336	-0.333	-0.352	-0.353	-0.369	-0.392	-0.409	-0.387	-0.405	-0.383	-0.353	-0.336	-0.303	
Sc	0.600	0.564	0.820	0.500	0.600	0.804	0.583	0.722	0.342	0.707	0.534	0.823	0.864	0.844	0.823	0.815	0.820	0.787	0.780	0.725	0.663	0.655	0.634	0.649	0.626	
Ti	0.821	0.759	0.696	0.708	0.772	0.613	0.800	0.800	0.616	0.652	0.597	0.892	0.841	0.837	0.835	0.802	0.792	0.811	0.806	0.798	0.786	0.781	0.748	0.725	0.708	
Cr		0.721	0.534	0.720	0.796	0.566	0.875	0.761	0.746	0.443	0.674	0.826	0.764	0.770	0.771	0.735	0.708	0.756	0.722	0.706	0.715	0.719	0.696	0.659	0.657	
Mn			0.462	0.901	0.816	0.530	0.901	0.529	0.753	0.402	0.516	0.738	0.622	0.649	0.673	0.661	0.721	0.738	0.788	0.832	0.853	0.860	0.844	0.829	0.817	
Fe				0.372	0.486	0.684	0.501	0.802	0.185	0.581	0.433	0.716	0.752	0.713	0.688	0.677	0.648	0.643	0.625	0.551	0.495	0.478	0.447	0.463	0.448	
Co					0.935	0.429	0.917	0.586	0.903	0.298	0.409	0.732	0.618	0.633	0.676	0.665	0.720	0.767	0.808	0.861	0.896	0.908	0.900	0.877	0.878	
Ni						0.489	0.896	0.710	0.860	0.359	0.467	0.787	0.696	0.703	0.735	0.722	0.762	0.796	0.820	0.850	0.870	0.887	0.886	0.868	0.875	
Cu							0.565	0.539	0.299	0.614	0.680	0.764	0.784	0.759	0.729	0.720	0.688	0.689	0.685	0.654	0.593	0.579	0.566	0.586	0.570	
Zn								0.723	0.882	0.403	0.531	0.841	0.741	0.765	0.790	0.773	0.802	0.836	0.851	0.872	0.897	0.898	0.881	0.853	0.850	
As									0.557	0.549	0.369	0.848	0.866	0.854	0.853	0.839	0.807	0.824	0.779	0.720	0.700	0.685	0.659	0.646	0.642	
Cd										0.160	0.335	0.675	0.556	0.578	0.625	0.608	0.643	0.709	0.723	0.765	0.820	0.830	0.825	0.781	0.782	
Pb											0.513	0.672	0.725	0.729	0.706	0.700	0.654	0.610	0.589	0.562	0.494	0.484	0.463	0.475	0.458	
Hg												0.560	0.547	0.526	0.504	0.475	0.418	0.445	0.438	0.451	0.434	0.446	0.417	0.398	0.398	
La													0.975	0.975	0.977	0.960	0.938	0.965	0.946	0.914	0.883	0.874	0.851	0.840	0.822	
Ce														0.992	0.981	0.971	0.931	0.948	0.911	0.860	0.813	0.797	0.771	0.767	0.747	
Pr															0.994	0.986	0.958	0.963	0.931	0.883	0.837	0.822	0.798	0.795	0.776	
Nd																	0.994	0.973	0.981	0.953	0.909	0.870	0.858	0.836	0.833	0.816
Sm																		0.978	0.981	0.957	0.915	0.876	0.863	0.845	0.850	0.834
Eu																			0.983	0.979	0.946	0.913	0.904	0.890	0.894	0.880
Gd																				0.989	0.960	0.935	0.925	0.907	0.903	0.886
Tb																					0.986	0.967	0.959	0.945	0.943	0.927
Dy																						0.991	0.986	0.978	0.974	0.962
Ho																							0.997	0.988	0.978	0.968

Er	0.994	0.984	0.977
Tm		0.994	0.988
Yb			0.996
Lu			

Statistically significant coefficients ($p < 0.05$) are in bold

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Table 5: Rare-earth element concentrations (mg kg⁻¹ dry weight) in sediment and soil samples.

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	ΣLREE	ΣHREE	ΣLREE/ΣHREE	ΣREE
FNsed1	17	27.6	4.2	16.2	3.2	0.8	3.4	0.5	2.8	0.6	1.7	0.2	1.3	0.2	72.3	7.2	10	79.6
FNsed2	8.9	16	2.4	9.4	1.9	0.4	1.8	0.2	1.4	0.3	0.8	0.1	0.6	0.1	40.8	3.6	11.3	44.4
FNsed3	38.4	56.5	8.5	32	6.2	1.5	6.7	1	5.7	1.2	3.5	0.5	2.5	0.3	149.7	14.7	10.2	164.4
FNsed4	7.6	15.1	2.2	7.8	1.4	0.2	1.2	0.1	0.7	0.1	0.3	0	0.2	0	35.6	1.5	23.2	37.1
FNsed5	10.6	20.3	2.9	10.8	2	0.4	1.7	0.2	1	0.2	0.5	0.1	0.4	0	48.8	2.4	20.1	51.3
FNsol1	27.6	59.5	9.1	36.8	7.8	1.7	7.5	1	5.6	1	2.7	0.3	2	0.3	150	12.9	11.7	162.9
FNsol2	29.4	71.1	10.7	44.5	9.2	1.8	7.1	0.9	4	0.7	1.8	0.2	1.4	0.2	173.8	9.2	19	183
FNsol3	59.8	79.4	13.5	52.9	10.3	2.6	11.5	1.6	9.8	2.1	5.9	0.8	4.4	0.6	230	25.1	9.2	255.2
FNsol4	52.6	84.2	13.2	54.1	11.5	2.8	13.1	1.8	10.4	2.1	6	0.8	4.4	0.6	231.4	26	8.9	257.4
FNsol5	24.8	44.9	7.1	27.3	5.5	1.5	5.4	0.8	4.7	0.9	2.7	0.4	2.4	0.4	116.4	12.2	9.5	128.6
NGsed1	29.7	71.1	9.9	38.8	7.5	1.4	5.7	0.7	3.1	0.5	1.3	0.2	0.9	0.1	164.2	6.9	23.9	171.1
NGsed2	20.4	31.7	4.8	18.8	3.8	0.9	4.2	0.6	3.6	0.8	2.3	0.3	1.9	0.3	84.6	9.7	8.7	94.4
NGsol1	31.3	54	7.8	31	6.4	1.4	6.6	0.9	5.5	1.2	3.4	0.4	2.6	0.4	138.5	14.4	9.6	152.9
NGsol2	57.2	111	16.8	68	15.5	3.7	17.6	2.6	14.8	2.9	7.8	1	5.5	0.7	289.9	35.3	8.2	325.2
NGsol3	11.2	22.3	3	9.7	1.5	0.3	1	0.1	0.4	0	0.1	0	0.1	0	49	0.7	69	49.7
NGsol4	25.8	54.5	7.3	24.2	3.9	0.7	2.4	0.2	0.8	0.1	0.2	0	0.1	0	118.7	1.6	75.7	120.2
Mvsed1	5.6	9.9	1.4	4.9	0.9	0.2	0.8	0.1	0.5	0.1	0.2	0	0.2	0	23.8	1.1	22.3	24.9
Mvsed2	3.4	6.3	0.9	3.2	0.6	0.1	0.5	0.1	0.4	0.1	0.2	0	0.1	0	14.9	0.9	16.7	15.8
Mvsed3	4.4	8.3	1.2	4.4	0.8	0.2	0.8	0.1	0.6	0.1	0.3	0	0.3	0	20.1	1.4	14.5	21.5

Mvsed4	18.9	35.6	4.6	15.5	2.9	0.7	2.4	0.3	1.5	0.3	0.7	0.1	0.6	0.1	80.6	3.6	22.5	84.1
Mvsed5	20.5	34.6	5	19.4	3.9	1.1	4.2	0.6	4	0.8	2.4	0.3	1.8	0.2	88.7	10.2	8.7	98.9
Mvsol1	23.7	47.1	8.2	29.7	6.4	1.5	5.2	0.7	4.1	0.7	2	0.3	2.1	0.3	121.8	10.2	11.9	132
Mvsol2	15	30	4.3	15.1	2.9	0.7	2.2	0.3	1.5	0.3	0.7	0.1	0.5	0.1	70.1	3.4	20.4	73.5
Mvsol3	11.4	21.1	2.6	8.3	1.3	0.3	1	0.1	0.5	0.1	0.2	0	0.1	0	46.2	1.1	43.7	47.2
Mvsol4	6	11.8	1.5	5	0.9	0.2	0.6	0.1	0.3	0.1	0.1	0	0.1	0	25.9	0.7	38.5	26.6
Mvsol5	26.5	43	6.9	26.7	4.9	1.3	4.9	0.7	4.3	0.9	2.6	0.4	2.2	0.3	114.2	11.2	10.1	125.4
Kased1	30.7	53	8.7	33.3	6.3	1.6	6.3	0.9	5	1	2.7	0.3	2	0.3	139.9	12.2	11.5	152.1
Kased2	16.8	27.5	4.4	17.1	3.4	0.8	3.4	0.5	2.8	0.6	1.6	0.2	1.2	0.2	73.5	6.9	10.6	80.4
Kasol1	27	45.4	7.2	28	5.2	1.4	5.5	0.8	4.7	1	2.9	0.4	2.2	0.3	119.6	12.3	9.7	131.9
Kasol2	23.3	39.3	6.1	23.2	4.4	1.1	4.4	0.6	3.5	0.7	2	0.3	1.4	0.2	101.8	8.8	11.6	110.6
Kasol3	91.8	142	22.4	88.9	17.4	4.2	19.5	2.6	14.7	3	8.2	1	5.2	0.6	386.1	35.3	10.9	421.5
PAAS	38	80	8.9	32	5.6	1.1	4.7	0.8	4.4	1	2.9	0.4	2.8	0.4	170.3	12.7	13.4	183

Table 6 : Calculated anomaly values of Ce, Eu and Tm ratios in the sediment and soil samples.

Sample	Ce/Ce*	Eu/Eu*	Tm/Tm*
FNsed1	0.7	1.1	2.7
FNsed2	0.8	0.9	2.9
FNsed3	0.7	1.0	3.4
FNsed4	0.8	0.7	0.0
FNsed5	0.8	1.0	4.5
FNsol1	0.8	1.0	2.6
FNsol2	0.9	1.0	2.5
FNsol3	0.6	1.0	3.1
FNsol4	0.7	1.0	3.1
FNsol5	0.7	1.2	3.1
NGsed1	0.9	0.9	3.7
NGsed2	0.7	1.0	2.9
NGsol1	0.8	0.9	2.7
NGsol2	0.8	1.0	3.1
NGsol3	0.8	1.1	0.0

NGsol4	0.9	1.0	0.0
Mvsed1	0.8	1.0	0.0
Mvsed2	0.8	0.8	0.0
Mvsed3	0.8	1.1	0.0
Mvsed4	0.8	1.2	3.1
Mvsed5	0.7	1.2	2.9
Mvsol1	0.7	1.1	2.9
Mvsol2	0.8	1.2	3.4
Mvsol3	0.8	1.2	0.0
Mvsol4	0.9	1.2	0.0
Mvsol5	0.7	1.2	3.3
Kased1	0.7	1.1	2.6
Kased2	0.7	1.0	2.9
Kasol1	0.7	1.1	3.2
Kasol2	0.7	1.1	3.6
Kasol3	0.7	1.0	3.1

Table 7 : Calculated values of the Geoaccumulation Index (Igeo) and Enrichment Factor (EF) for heavy metals in sediment and soil samples.

Igeo												
Areas	Sample	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Cd	Pb	Hg
MVUANGU	Mvsed1	7.7	12.0	24.6	1.2	5.0	4.4	8.2	-2.7	-7.8	5.7	-9.4
	Mvsed2	7.1	10.7	24.6	1.5	4.2	3.5	7.6	-3.1	-8.3	5.0	-10.4
	Mvsed3	7.7	13.2	26.4	3.8	7.2	5.1	8.6	-1.8	-7.6	5.4	-10.4
	Mvsed4	9.9	15.2	29.2	3.7	6.4	8.0	9.8	-0.2	-7.8	7.7	-8.6
	Mvsed5	10.8	17.8	28.5	5.1	7.6	6.3	11.2	0.8	-4.2	7.6	-7.5
	Mvsol1	9.4	14.0	28.8	2.9	6.3	8.3	9.6	0.0	-9.6	8.2	-8.8
	Mvsol2	8.7	13.3	27.7	2.5	5.5	7.6	9.1	-1.4	-9.0	6.8	-8.8
	Mvsol3	9.5	13.3	28.9	2.4	5.7	6.8	8.7	-0.3	-9.6	7.0	-9.8
	Mvsol4	8.7	13.3	28.2	1.5	5.0	6.8	8.3	-0.9	-9.6	6.3	-9.4
	Mvsol5	10.0	16.3	28.3	4.5	7.1	7.4	11.0	0.7	-6.1	7.8	-9.4
KANZI	Kased1	10.8	17.4	28.7	5.0	7.5	7.5	12.6	0.9	-2.5	7.7	-8.6
	Kased2	10.1	15.7	27.7	3.9	6.5	5.8	10.8	-0.1	-5.1	6.6	-9.4
	Kasol1	10.9	17.0	28.3	5.4	8.0	6.6	11.7	0.9	-8.8	7.3	-7.9
	Kasol2	10.6	16.8	28.2	4.8	7.1	6.3	11.4	0.7	-3.7	7.2	-9.4
	Kasol3	12.3	16.2	29.6	5.0	8.5	8.0	12.3	2.7	-2.6	8.0	-7.7
FUNDU	FNsed1	9.8	14.4	28.7	4.9	7.5	4.3	10.2	0.9	-4.1	6.3	-10.4
	FNsed2	8.7	12.9	27.6	4.3	6.3	3.3	9.7	0.1	-5.2	5.6	-11.4
	FNsed3	11.0	17.6	29.1	5.8	8.0	7.7	12.0	0.9	-1.9	7.4	-8.6
	FNsed4	7.4	12.3	26.0	1.7	4.3	-	7.6	-2.1	-8.6	4.6	-11.4

Interpretation values of Igeo

Igeo ≤ 0 Class 0 : practically unpolluted

0 < Igeo < 1 Class 1 : unpolluted to moderately polluted

1 < Igeo < 2 Class 2 : moderately polluted

2 < Igeo < 3 Class 3 : moderately to heavily polluted

3 Igeo < 4 Class 4: heavily polluted

4 < Igeo < 5 Class 5 : heavily to extremely polluted

5 < Igeo < 6 : extremely polluted

NZOBE	FNsed5	8.0	13.3	26.8	3.0	5.5	1.9	8.5	-1.2	-8.0	8.3	-10.4
	FNsol1	9.9	15.4	29.4	4.4	6.8	7.2	10.7	1.6	-6.5	7.3	-10.4
	FNsol2	10.1	14.5	29.6	3.1	6.3	7.0	10.0	1.6	-7.6	7.6	-9.8
	FNsol3	11.1	17.5	28.8	5.6	9.3	7.0	12.4	2.4	-1.2	7.4	-10.4
	FNsol4	10.6	16.5	29.5	5.2	7.9	8.4	12.2	2.3	-1.3	7.9	-8.6
	FNsol5	9.9	15.5	29.6	4.7	7.8	6.4	10.3	1.6	-7.0	7.5	-9.8
NGUNDJI	NGsed1	11.2	12.5	28.6	3.2	7.4	7.6	10.0	1.3	-5.2	7.8	-8.4
	NGsed2	12.2	15.9	27.7	5.1	7.7	6.7	12.4	1.0	-1.6	6.3	-9.1
	NGsol1	11.9	18.6	30.1	6.6	8.2	9.0	12.9	1.4	-2.0	7.1	-7.8
	NGsol2	10.7	18.1	30.0	6.7	8.3	9.3	12.6	1.9	-4.0	8.2	-8.4
	NGsol3	10.1	12.8	29.5	1.4	5.7	5.9	9.1	1.0	-9.6	7.1	-9.8
	NGsol4	10.6	12.9	30.0	2.0	6.2	7.2	9.7	1.8	-9.0	8.1	-8.1
EF												
Areas	Sample	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Cd	Pb	Hg
MVUANGU	Mvsed1	6.3	0.4	0.5	0.9	2.9	1.2	2.2	2.6	19.4	4.9	17.8
	Mvsed2	5.2	0.2	0.6	1.3	2.1	0.9	1.7	2.6	17.4	3.6	11.1
	Mvsed3	4.7	0.7	1.3	4.1	10.3	1.6	2.1	3.7	17.2	3.0	6.9
	Mvsed4	3.4	0.4	1.3	0.6	0.9	1.7	0.8	1.8	2.3	2.2	3.7
	Mvsed5	8.6	3.9	1.2	2.1	2.8	0.8	2.8	4.7	3.3	2.9	10.8
	Mvsol1	3.0	0.3	1.3	0.4	1.1	2.8	0.9	2.7	0.9	4.3	4.1
	Mvsol2	3.5	0.3	1.1	0.6	1.1	3.1	1.0	1.8	2.2	2.8	7.2
	Mvsol3	4.3	0.2	1.9	0.4	1.0	1.4	0.6	2.9	1.1	2.5	2.7
	Mvsol4	4.0	0.3	1.8	0.3	0.9	2.1	0.7	2.8	1.7	2.2	5.6
	Mvsol5	6.9	1.9	1.4	1.9	2.8	2.3	3.4	6.2	14.0	4.6	4.1
	Kased1	8.9	2.9	1.3	2.0	2.8	1.7	7.5	5.3	120.9	3.2	5.1

Interpretation values of EF

EF < 1: no enrichment

EF < 3: minor enrichment

EF 3-5: moderate enrichment

EF 5-10: moderately severe enrichment

EF 10-25: severe enrichment

EF 25-50: very severe enrichment

EF > 50: extremely severe enrichment

KANZI	Kased2	11.2	1.8	1.3	1.8	2.8	1.1	4.2	5.1	40.4	3.3	5.9
	Kasol1	13.6	3.1	1.4	3.7	5.5	1.3	5.5	7.5	141.2	3.4	11.4
	Kasol2	12.5	3.1	1.5	2.7	3.3	1.2	5.2	7.5	83.8	3.7	4.7
	Kasol3	18.7	1.0	1.9	1.5	4.2	2.0	4.8	13.9	91.4	3.0	7.3
FUNDU NZOBE	FNsed1	11.6	1.0	3.6	5.0	7.6	0.5	3.8	14.5	107.8	3.2	3.9
	FNsed2	8.5	0.5	2.5	5.1	4.9	0.4	4.1	12.6	76.5	3.0	3.0
	FNsed3	8.1	2.7	1.4	2.8	3.1	1.6	3.9	4.3	149.4	2.0	4.1
	FNsed4	5.1	0.5	1.2	1.2	1.8	-	1.4	4.0	10.9	2.1	4.3
	FNsed5	5.2	0.7	1.4	2.0	2.9	0.2	1.9	5.1	11.5	19.6	6.2
	FNsol1	4.5	0.6	2.0	1.2	1.6	1.3	1.8	7.7	7.2	2.3	1.4
	FNsol2	4.5	0.3	2.0	0.4	0.9	1.0	1.0	6.9	3.0	2.4	1.8
	FNsol3	10.1	2.9	1.3	2.8	8.7	1.1	6.0	13.4	271.3	2.4	1.3
	FNsol4	5.7	1.2	1.7	1.7	2.6	2.5	4.2	10.2	203.8	2.6	3.8
	FNsol5	3.5	0.6	1.8	1.2	2.3	0.6	1.1	6.0	3.9	2.0	1.6
NGUNDJI	NGsed1	8.4	0.1	0.9	0.4	2.0	1.4	0.9	5.2	14.3	2.5	4.4
	NGsed2	52.2	2.3	1.4	4.6	6.8	2.2	14.3	12.2	520.5	2.7	8.2
	NGsol1	18.5	6.5	3.3	5.8	4.3	4.7	8.5	6.9	172.2	2.0	8.4
	NGsol2	4.4	2.5	1.6	3.2	2.5	3.2	3.8	5.5	23.6	2.3	3.1
	NGsol3	9.4	0.2	4.1	0.3	1.3	1.0	1.1	9.7	1.6	3.7	3.8
	NGsol4	9.0	0.2	3.7	0.3	1.3	1.7	1.2	12.0	1.6	4.9	8.7

Table 8: Calculated values of the ecological risk parameters CF, CD, Eri and RI in sediment and soil samples.

Areas	CF	Cr	Co	Cu	Zn	As	Cd	Pb	Hg	DC	
MVUANGU	Mvsed1	0	0	0.3	0	0.2	0	0.1	0	0.1	CF Classification
	Mvsed2	0	0	0.2	0	0.2	0	0.1	0	0.1	CF < 1: low contamination
	Mvsed3	0.1	0	0.2	0	0.9	0.2	0.5	0.1	0.1	1 < CF < 3: moderate contamination
	Mvsed4	0.3	0	1.2	0.2	5.8	0.2	0.3	0.6	0.3	3 < CF < 6: considerable contamination
	Mvsed5	0.3	0.1	2.2	1	3.7	0.5	0.7	0.2	0.7	6 < CF: very high contamination
	Mvsol1	0.3	0	0.8	0.1	4.4	0.1	0.3	0.7	0.2	
	Mvsol2	0.2	0	0.5	0	2.1	0.1	0.2	0.5	0.2	CD Classification
	Mvsol3	0.2	0	0.9	0	4.9	0.1	0.2	0.3	0.1	CD < 8: low contamination
	Mvsol4	0.1	0	0.5	0	3	0	0.1	0.3	0.1	8 ≤ CD < 16: moderate contamination
	Mvsol5	0.2	0	1.2	0.3	3.2	0.3	0.5	0.4	0.6	16 ≤ CD < 32: high contamination
KANZI	Kased1	0.3	0	2.2	0.7	4.2	0.5	0.7	0.4	1.9	32 ≤ CD: very high contamination
	Kased2	0.1	0	1.4	0.2	2.1	0.2	0.4	0.1	0.5	
	Kasol1	0.2	0	2.4	0.6	3.2	0.6	1	0.2	1	
	Kasol2	0.2	0	1.9	0.5	3	0.4	0.5	0.2	0.8	
	Kasol3	0.3	0.1	6.1	0.3	7.7	0.5	1.4	0.5	1.6	
FUNDU NZOBE	FNsed1	1.1	0.5	0.0	0.3	1.3	9.0	0.3	0.4	12.9	
	FNsed2	0.5	0.3	0.0	0.2	0.7	4.2	0.2	0.2	6.4	
	FNsed3	2.5	0.8	0.5	1.2	1.3	41.2	0.6	1.3	49.4	
	FNsed4	0.2	0.0		0.1	0.2	0.4	0.1	0.2	1.2	
	FNsed5	0.3	0.1	0.0	0.1	0.3	0.6	1.2	0.4	3.0	
	FNsol1	1.2	0.3	0.4	0.5	2.0	1.7	0.6	0.4	7.0	
	FNsol2	1.4	0.1	0.3	0.3	2.0	0.8	0.7	0.5	6.2	

	FNsol3	2.8	0.8	0.3	1.6	3.5	66.2	0.6	0.4	76.1	
	FNsol4	1.9	0.6	0.8	1.4	3.3	61.7	0.9	1.3	71.9	
	FNsol5	1.2	0.4	0.2	0.4	2.0	1.2	0.7	0.5	6.6	
NGUNDJI	NGsed1	2.8	0.1	0.5	0.3	1.6	4.3	0.8	1.4	11.9	
	NGsed2	5.8	0.5	0.2	1.6	1.3	51.8	0.3	0.9	62.4	
	NGsol1	4.8	1.5	1.2	2.2	1.7	40.2	0.5	2.1	54.3	
	NGsol2	2.1	1.5	1.5	1.8	2.5	10.1	1.1	1.4	22.1	
	NGsol3	1.3	0.0	0.1	0.2	1.3	0.2	0.5	0.5	4.3	
	NGsol4	1.9	0.1	0.4	0.2	2.4	0.3	1.0	1.8	8.0	
Sites	Eri	Cr	Co	Cu	Zn	As	Cd	Pb	Hg	RI	
MVUANGU	Mvsed1	28.6	21.4	1	0.2	0.2	1	0.5	0.1	53	
	Mvsed2	14.3	15.3	0.8	0.2	0.1	0.6	0.3	0.1	31.7	Eri classification
	Mvsed3	14.3	24.5	1.9	1.1	0.4	0.8	0.5	0.1	43.5	Eri < 40: low ecological risk
	Mvsed4	50	21.4	6	1	3	3.8	2.4	0.3	87.9	40 < Eri < 80: moderate ecological risk
	Mvsed5	107.1	254.1	11.3	2.6	0.9	3.7	4.3	0.7	354.3	80 < Eri < 160: considerable ecological risk
	Mvsol1	42.9	6.1	6.7	0.5	3.7	5.7	1.6	0.2	67.4	160 < Eri < 320: high ecological risk
	Mvsol2	42.9	9.2	2.5	0.4	2.3	2.1	1.1	0.2	60.7	Eri > 320: very high ecological risk
	Mvsol3	21.4	6.1	5.6	0.4	1.4	2.5	1.7	0.1	39.3	
	Mvsol4	28.6	6.1	3.5	0.2	1.4	1.4	1.1	0.1	42.4	RI classification
	Mvsol5	28.6	67.3	10.7	1.7	2.1	4.1	2.5	0.6	117.5	RI < 150: low ecological risks/low level of ecological pollution

KANZI	Kased1	50	814.3	12.7	2.4	2.1	3.9	4.5	1.9	891.9	150 ≤ RI < 300: moderate ecological risk/moderate level of ecological pollution
	Kased2	28.6	134.7	6.1	1.1	0.7	2	2.8	0.5	176.4	300 ≤ RI < 600: considerable ecological risk/ severe level of ecological pollution
	Kasol1	78.6	667.3	12.5	3.2	1.2	3	4.8	1	771.5	RI > 600: Very high ecological risk/serious level of ecological pollution
	Kasol2	28.6	349	11	2.1	1	2.8	3.9	0.8	399.1	
	Kasol3	92.9	799	42.9	2.4	3.2	4.9	12.2	1.6	959	
FUNDU NZOBE	FNsed1	2.1	2.3	0.2	0.3	12.8	269.4	1.5	14.3	303.0	
	FNsed2	1.0	1.5	0.1	0.2	7.3	125.5	0.9	7.1	143.8	
	FNsed3	5.0	4.2	2.5	1.2	12.7	1236.7	3.1	50.0	1315.4	
	FNsed4	0.4	0.2	0.0	0.1	1.6	12.2	0.4	7.1	22.2	
	FNsed5	0.6	0.6	0.0	0.1	2.9	18.4	5.8	14.3	42.6	
	FNsol1	2.4	1.6	1.8	0.5	19.7	52.0	3.0	14.3	95.3	
	FNsol2	2.8	0.7	1.5	0.3	20.3	24.5	3.7	21.4	75.2	
	FNsol3	5.5	3.8	1.6	1.6	34.7	1986.7	3.2	14.3	2051.3	
	FNsol4	3.8	2.8	4.2	1.4	32.7	1852.0	4.4	50.0	1951.3	
	FNsol5	2.4	2.0	1.0	0.4	19.9	36.7	3.4	21.4	87.5	
NGUNDJI	NGsed1	5.6	0.7	2.4	0.3	16.4	128.6	4.1	57.1	215.1	
	NGsed2	11.6	2.5	1.2	1.6	12.9	1555.1	1.5	55.7	1622.2	
	NGsol1	9.6	7.5	6.0	2.2	17.1	1206.1	2.6	85.7	1336.9	
	NGsol2	4.2	7.6	7.6	1.8	24.9	303.1	5.5	57.1	411.8	
	NGsol3	2.7	0.2	0.7	0.2	13.2	6.1	2.6	21.4	47.1	
	NGsol4	3.7	0.3	1.8	0.2	23.9	9.2	5.1	71.4	115.6	