

Potentially Toxic Elements in Drainage Sediments of the Zang-Tabi Area, Northwest Cameroon and their Implications for Pollution, Ecotoxicological and Human Health Risk

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Abstract

The enrichment of potentially hazardous metals (PHMs) in drainage sediments is an environmental concern in rapidly evolving rural landscapes, yet integrated assessments combining pollution, sediment-quality, ecotoxicological and human-health screening remain limited in northwestern Cameroon. Fifteen stream sediment samples from an agricultural basin underlain by Pan-African granitoids were analysed for nine PHMs (As, Cd, Cr, Cu, Hg, Ni, Pb, Th and Zn) following aqua regia digestion and ICP-based analysis, and evaluated using pollution indices, sediment quality guidelines (SQGs), screening-level human-health modelling, multivariate statistics and spatial mapping. Average Cr (626.80 mg/kg) and Th (61.71 mg/kg) exceed the upper continental crust (UCC) reference by factors of 6.8 and 5.9, respectively, indicating strong enrichment relative to UCC, whereas As, Cd, Hg, Ni, Cu, Pb and Zn are below their UCC reference values. Chromium exceeds all six SQG benchmarks (TEL, PEL, TEC, PEC, ERL and ERM) at every station, indicating a high screening-level potential for adverse biological effects. The contamination degree (9.67–26.61) falls in the moderate to considerable classes, the modified contamination degree (1.07–2.96) ranges from no to moderate contamination, and all pollution load index values remain below 1. Potential ecological risk is uniformly low (PERI = 22.75–69.76), whereas the toxic risk index (TRI = 10.29–28.09) ranges from moderate to very high and toxic units (TU = 5.60–14.91) indicate moderate to high screening-level toxicological concern; Cr contributes approximately 89% of the mean TRI and TU. Screening-level human-health modelling indicates that modeled exposure is dominated by ingestion in children and by dermal and ingestion pathways in adults. Cr produces the largest HQ, HI and TCR values, but the carcinogenic screening estimate assumes that total measured Cr behaves as Cr(VI), so the actual Cr(VI)-specific risk remains uncertain. Overall, multivariate and provenance-related relationships are consistent with predominantly lithogenic control, with possible localized anthropogenic contributions requiring source-specific confirmation. Targeted Cr speciation, bioavailability testing, water-quality monitoring and source-specific sampling are recommended.

Highlights

Fifteen drainage sediment samples were screened for nine hazardous metals.

Cr (up to 1215 mg/kg) and Th are strongly enriched relative to UCC.

Cr exceeds all six sediment quality guidelines at every station.

Sediment toxic-risk indices are significant to very high and dominated by Cr.

Modeled exposure is dominated by ingestion in children and by dermal/ingestion pathways in adults; Cr speciation is warranted.

1 Introduction

The United Nations Sustainable Development Goals number 3 (“good health and well-being”) and number 6 (“clean water and sanitation”) explicitly target the reduction of health challenges and of the global death toll attributable to pollution and the contamination of ecosystems [1–3]. A strong health system is central to socio-economic development, poverty reduction and increased life expectancy, and thus supports the achievement of other United Nations Sustainable Development Goals [4–7]. The utilization of sediment and soil geochemistry is critical to inferring the origins, enrichment and contamination of hazardous metals in surficial environments [8–10]. Hazardous metal pollution is a major environmental concern in localities affected by mining, agricultural and industrial activities, particularly in developing nations where environmental monitoring frameworks remain rudimentary [1, 11, 12].

Water is a vital transport medium for metals, and drainage sediments can act as repositories for lithogenic and anthropogenic inputs from the upstream catchment [5, 7, 13]. Fine-grained sediments are useful for screening metal enrichment because they can adsorb and retain contaminants and integrate recent upstream inputs [1, 3]. Metal mobility and bioavailability in fluvial systems are influenced by physicochemical conditions including pH, salinity, organic matter and redox status [4, 5, 10]. Elevated sediment metal concentrations may increase ecological exposure through sediment–water exchange and trophic transfer, but the magnitude of biological effects depends on metal speciation, phase association and bioavailability [5, 11, 13]. Chronic exposure to some potentially toxic elements has been associated with neurological, renal, cardiovascular and carcinogenic effects, depending on element, dose, chemical form and exposure pathway [1, 3, 14].

Hazardous metals in sediments may originate from natural sources, including weathering of rocks and minerals, erosion and atmospheric deposition [5, 11, 12]. However, pollution of aquatic ecosystems worldwide can be substantially influenced by anthropogenic inputs, including mining activities, domestic discharges, agricultural practices and rapid population growth [3, 6, 13]. Integrated pollution indices, ecotoxicological and human health risk assessments, sediment quality guideline (SQG) comparisons, multivariate statistics and spatial mapping are now standard, complementary tools for quantifying contamination, constraining sources and prioritizing mitigation [1, 4, 15, 16]. Their combined application in data-poor regions of Central Africa provides baseline geochemical information for governmental, non-governmental, academic and industrial agencies engaged in pollution remediation, control and management [2, 5, 7].

The Zang-Tabi area lies in the Mbengwi Subdivision of the Momo Division, North West Region of Cameroon, within the Pan-African belt of central Africa [17, 18]. Previous research in and around the study region has concentrated on the petrogenesis and mineral chemistry of the Mbengwi Pan-African high-K granitoids and Cenozoic mafic volcanics [19, 20], regional tectonic frameworks of the central African fold belt [17, 18], stream sediment geochemical exploration in the Mbengwi area [21], provenance and paleoweathering of sediments of the neighbouring Bamenda Highlands and Cameroon Volcanic Line [22–25], gold exploration in the adjacent gold districts [26–28], and contamination and risk assessments of hazardous metals in various Cameroon stream sediment environments [2, 5, 12, 29]. The Zang-Tabi locality itself is characterized by small-scale farming with agrochemicals, artisanal exploitation of

construction materials, growing rural settlement and unregulated waste disposal, activities that collectively pose a potential threat to drainage sediments, surface water, groundwater and related biodiversity [30].

To our knowledge, a published integrated assessment combining PHM enrichment, SQG screening, ecotoxicological indices, screening-level human-health modelling, multivariate analysis and spatial interpretation has not yet been reported for the Zang-Tabi drainage basin. Stream sediment geochemistry provides a relatively low-cost means of characterizing recent upstream metal inputs when interpreted alongside appropriate crustal references, SQGs and site-specific geological information. This study therefore aims to evaluate the concentrations of nine PHMs (As, Cd, Cr, Cu, Hg, Ni, Pb, Th and Zn) in drainage sediments from the Zang-Tabi area, quantify their enrichment and screening-level ecological and human-health implications, evaluate spatial patterns and probable sources, and establish a baseline for future environmental monitoring.

Recent studies from Cameroon further demonstrate the value of drainage and alluvial sediments for integrated environmental, provenance and mineral-exploration investigations. Fomekong et al. (2026) documented geochemical signatures and mineralization indicators in alluvial sediments from the Bipindi–Kouambo prospect, including an Au–Ag–W–Pb association relevant to follow-up exploration [39]. Yiika et al. (2026) showed that alluvial sediments from the Mugheb watershed can preserve rare-earth-element signatures consistent with predominantly felsic sources with subordinate mafic contributions and may warrant consideration as an unconventional REE resource [40]. Heavy-mineral petrography from Akum also demonstrated that angular to sub-angular zircon, epidote, tourmaline, kyanite, zoisite, apatite, biotite and opaque minerals can constrain provenance, weathering and mineral potential [41]. Complementary studies of hazardous metals in Akum, Manjo and Mesue–Tonkwen have likewise shown the utility of indexical, multivariate and spatial approaches for distinguishing geochemical enrichment, probable sources and environmental implications [2, 8, 29]. Together, these regional studies provide a useful framework for interpreting the Zang-Tabi dataset, while the present work specifically emphasizes potentially hazardous metal enrichment and associated ecological and human-health screening in a rural drainage basin.

2 Geographical and geological setting

2.1 Geographical setting

The Zang-Tabi study area is situated in the Mbengwi Subdivision, Momo Division, North West Region of Cameroon, approximately 20 km northwest of Bamenda, the regional capital (Fig. 1). The sampled drainage network extends between latitudes 5°52'46"N and 6°00'00"N and longitudes 9°53'43"E and 9°58'30"E, covering a surface area of approximately 100 km² within the wider Tudig–Zang-Tabi corridor [30]. Synonymous with other parts of the Western High Plateau of Cameroon, the studied area has a humid tropical climate of the mountain type, marked by two contrasting seasons — a wet season from mid-March to mid-October and a dry season for the remainder of the year — with mean annual rainfall of 1800–2500 mm and mean temperatures of 19–22°C imposed by the elevated (900–2000 m) topography [30].

The drainage network is dendritic and is dominated by the Momo River and its tributaries, including the Njah, Bosa, Mufai, Munama, Muwebi and Tudig streams, which drain northeast to southwest towards the Momo River and ultimately the Niger River basin [30]. The natural vegetation of the submontane Guinea-Congolian rainforest has been largely converted to a mosaic of secondary regrowth, grassland and farmland. The major socio-economic activities in the Zang-Tabi area are subsistence and market gardening with agrochemical inputs, small-scale quarrying of granitic rocks and alluvial exploitation of construction materials, hunting and exploitation of forest products [30]. Most of the population practises subsistence farming using agrochemicals to improve crop yields, and surface and underground waters are commonly used for irrigation and domestic purposes. These activities constitute potential point and diffuse sources of PHMs to the drainage system.

2.2 Geological setting

The Zang-Tabi area lies within the northwestern domain of the Pan-African fold belt of central Africa (the Central African Fold Belt), which resulted from the collision of the Sao Francisco–Congo Craton with the West African Craton and associated terranes during the Neoproterozoic (ca. 620–520 Ma) [17, 18]. In northwestern Cameroon, this belt is represented by wide Neoproterozoic granitoid batholiths emplaced into Migmatitic and Metasedimentary Series, locally capped by Tertiary volcanics of the Cameroon Volcanic Line (CVL) [18, 22, 23]. The CVL is a 1600-km-long Y-shaped alignment of volcanic and plutonic complexes stretching from the Gulf of Guinea into the Saharan domain, of which the continental sector hosts the Bamenda, Bambouto and Oku mountains bordering the study area to the south and east [22, 23].

The Zang-Tabi area itself is underlain predominantly by Pan-African leucogranites and porphyritic monzogranites belonging to the Mbengwi granitic complex, intruded by rhyolitic and microgranitic dykes and overlain along the eastern margin by basaltic lava flows and subordinate rhyolites of the continental CVL (Fig. 2) [19, 20, 30]. The Mbengwi granitoids are high-K calc-alkaline to shoshonitic ferroan rocks generated by partial melting of a heterogeneous lower crust, with subordinate mantle contributions; they host Th-bearing accessory phases (allanite, monazite, zircon and apatite) that concentrate Th and light rare earth elements, together with disseminated Fe–Ti oxides; the interlayered mafic enclaves and Tertiary basalts are the plausible lithologic sources of Cr in the basin [19, 20]. The overlying basalts are transitional to alkaline olivine basalts with elevated Cr, Ni and V contents reflecting their mantle derivation [19, 22]. Regional NW–SE- to NE–SW-trending fracture corridors linked to the Central Cameroon Shear Zone control the drainage geometry and the emplacement of quartz veins and pegmatites observed at Njah-Etu and Upper Zang [17, 30]. Quadrangular relief, intense tropical weathering and a thick ferrallitic to andosolic weathering mantle complete the geological framework of the drainage basin from which the studied sediments were derived [30].

3 Materials and methods

3.1 Sample collection and preparation

Fifteen bulk drainage (stream) sediment samples were systematically collected during the dry season along active stream beds, which favour the settling of hazardous metals by gravity, in the Zang-Tabi area (Fig. 1c). Sampling sites were predetermined by superimposing the area's drainage network on its digital elevation model prior to the field campaign, with locations selected to provide spatial coverage of the principal drainage trails distributed across the Njah, Bosa, Mufai, Munama, Muwebi, Tudig, Zip, Baat, Kemo Bossa and Momo drainage trails [30]. At all sampling points, GPS coordinates were recorded in the WGS 84 datum (UTM zone 32N; Table 2). Samples were collected from active channel sediments by grab sampling, targeting fine-grained depositional zones where suspended and bed-load materials accumulate; at each site a pit was dug into the channel bed and the fine-grained sediment above the clayey layer was recovered as a single composite increment. About 5 kg of sediments were collected at each sampling point using a stainless spade. Gravels, roots and organic debris were instantly discarded, and the sandy, silty to clayey residues were stored in coded transparent plastic sample bags. The samples were air-dried under ambient temperature, disaggregated, thoroughly homogenised and split; one split was packaged in labelled polythene bags and expedited for geochemical analysis, while the companion split was reserved for heavy mineral separation reported elsewhere [30].

3.2 Geochemical analyses

The bulk stream sediments were analysed for As, Cd, Cr, Cu, Hg, Ni, Pb, Th, Zn, La, Sc and a further 41 elements at Australian Laboratory Services (ALS) Limited, Johannesburg, South Africa, using the ME-MS41L Super Trace package based on aqua regia digestion and ICP-based determination. Powdered sediment (< 75 µm) was digested according to the laboratory's ME-MS41L analytical protocol using a 3:1 HCl:HNO₃ (aqua regia) mixture. The resulting solution was diluted with deionised water and analysed under the laboratory's validated instrumental conditions. Analytical quality was monitored with certified reference materials (OREAS 501, 503 and 504), analytical blanks and duplicate samples inserted at regular intervals in the analytical batch, which returned recoveries within acceptable limits (90–110%) and relative differences generally below 15% [30]. Detection limits for the studied PHMs were 0.2 mg/kg (Cr), 0.05 mg/kg (Ni, Cu, Pb, Th, La, Sc), 0.5 mg/kg (As), 0.01 mg/kg (Zn), 0.001 mg/kg (Cd) and 0.002 mg/kg (Hg); non-detects were substituted with half the detection limit, which affected five of the fifteen Cd determinations (reported as 0.0005 mg/kg), while all Hg and other PHM concentrations exceeded their respective detection limits. Because As is a metalloid, the term “potentially hazardous metals” is used here in the broad sense of potentially hazardous elements. The raw geochemical dataset was assembled for pollution, ecotoxicological and screening-level human-health assessments. Spatial distributions were visualised in a GIS environment using the validated sampling base map and concentration classes. Pearson correlation, principal component analysis (PCA), hierarchical cluster analysis (HCA) and empirical provenance/source-discrimination plots were used to examine element associations and likely source domains. PCC, PCA and HCA were computed using standardized concentrations; PCA used Varimax rotation after Kaiser normalisation. Source-discrimination plots were generated from raw concentration ratios. Because the sample size was small (n = 15), multivariate results were interpreted as exploratory rather than definitive source apportionment.

3.3 Pollution and ecotoxicological indices

Ten pollution and ecotoxicological indices — contamination factor (CF), contamination degree (Cdeg), modified contamination degree (mCdeg), pollution load index (PLI), enrichment factor (EF), geo-accumulation index (Igeo), ecological risk factor (ERF), potential ecological risk index (PERI), toxic risk index (TRI) and toxic units (TU) — were used to characterize enrichment and screening-level ecological/toxicological concern for the nine PHMs (As, Cd, Cr, Cu, Hg, Ni, Pb, Th and Zn) in the Zang-Tabi stream sediments. The interpretation classes are compiled in Table 1.

3.3.1 Contamination factor (CF)

The contamination factor (CF) is used to assess the severity of potentially hazardous metal contamination in sediments. The CF for each metal at all stations was calculated using the Hakanson (1980) formula (1):

$$CF_i = C_i / C_{i0} \quad (1)$$

where CF_i denotes the contamination factor of element i , C_i the concentration of element i in the sediment sample and C_{i0} its concentration in the reference material. The Upper Continental Crust (UCC) composition of Rudnick and Gao (2014) was adopted as a common crustal reference for comparative normalization; it is a global compositional reference rather than an uncontaminated local background, and CF values are therefore interpreted as enrichment relative to average crustal proportions [31]. The resulting CF values were interpreted as reported in Table 1.

3.3.2 Contamination degree (Cdeg)

The Cdeg is the sum of the contamination factors for the investigated metals in a sample. The Cdeg is used to evaluate the extent of metal contamination in sediments and is obtained using the formula of Hakanson (1980):

$$Cdeg = \sum_{i=1}^n CF_i \quad (2)$$

where CF represents the contamination factor and n denotes the number of metals considered (nine in this study: As, Cd, Cr, Cu, Hg, Ni, Pb, Th and Zn). The class values used for interpretation of the resultant Cdeg are reported in Table 1.

3.3.3 Modified contamination degree (mCdeg)

The modified contamination degree (mCdeg) provides an assessment of the overall potential for hazardous metal contamination in the sediment samples. The mCdeg is calculated using the formula of Hakanson (1980):

$$mCdeg = (1/n) \sum_{i=1}^n CF_i \quad (3)$$

where CF is the contamination factor while n represents the number of metals investigated (nine in this study). The class values used for interpreting the obtained mCdeg values are presented in Table 1.

3.3.4 Pollution load index (PLI)

The PLI evaluates the overall potentially hazardous metal pollution effect in sediments at various stations in the study area. The PLI is the nth root of the multiplied-together contamination factor values and is calculated using the formula of Tomlinson et al. (1980) [32] as follows:

$$PLI = (\prod_{i=1}^n CF_i)^{1/n} \quad (4)$$

where CF is the contamination factor while n represents the number of metals investigated (nine in this study). The class values used for interpreting the obtained PLI values are presented in Table 1.

3.3.5 Enrichment factor (EF)

The enrichment factor (EF) was used to quantify the degree to which a metal deviates from the UCC metal-to- Al_2O_3 ratio. EF was calculated using the corresponding metal and Al_2O_3 contents of the sample and UCC reference, with UCC Al_2O_3 = 15.41 wt.% [31]. EF indicates relative enrichment but does not, by itself, establish anthropogenic origin. The EF values were interpreted using the classification of Yongming et al. (2006) [33], summarized in Table 1.

$$EF_i = [(C_i/Al_2O_3)_{sample} / (C_i/Al_2O_3)_{UCC}] \quad (5)$$

where C_i -sample and C_i -background are the metal contents in the sediment sample and reference material, respectively, while Al_2O_3 -sample and Al_2O_3 -background are the corresponding Al_2O_3 contents. The upper continental crust (UCC) metal and Al_2O_3 contents from Rudnick and Gao (2014) were used as baselines in this research [31]. The EF values were interpreted following the guidelines in Table 1.

3.3.6 Geo-accumulation index (Igeo)

The Igeo constrains the level of potentially hazardous metals accumulation in samples. To evaluate the Igeo of metals in the studied sediments, the mathematical expression of Müller (1981) was exploited:

$$Igeo_i = \log_2[C_i / (1.5B_i)] \quad (6)$$

where C_i stands for the metal content in the studied sample, B_i is the metal content in the UCC reference material and 1.5 represents the background matrix correction factor due to lithogenic interference. The calculated Igeo values quantify geo-accumulation relative to the selected UCC baseline and were interpreted according to the specifications in Table 1 [31, 34].

3.3.7 Ecological risk assessment (ERA)

Ecological risk assessment (ERA) involves the combined ecological risk factor (ERF) and potential ecological risk index (PERI), which express the potential ecological risk of individual and multiple metals, respectively. The ERF is a single ecological risk assessment index given by the formula of Hakanson (1980):

$$ERF_i = T_r \times CF_i \quad (7)$$

where T_r represents the metal toxic response factor (T_r values for As = 10, Cd = 30, Cr = 2, Cu = 5, Hg = 40, Ni = 5, Pb = 5 and Zn = 1 after Hakanson (1980) and subsequent applications). Th is not included in the original Hakanson (1980) framework; following the cited recent application [1], a default T_r of 1 was adopted for Th. This extension introduces additional uncertainty into the Th contribution to PERI. The significance of the determined ERF values and the PERI classification are presented in Table 1.

$$PERI = \sum_{i=1}^n ERF_i \quad (8)$$

where ERF stands for the ecological risk factor while n signifies the number of metals investigated. The guidelines in Table 1 were used to interpret the computed PERI values.

3.3.8 Toxic risk evaluation

Toxic risk index (TRI) and toxic units (TU) analyses were employed to assess the cumulative potential toxic risks of potentially hazardous metals in the sediments to the environment and organisms at each station. TRI was calculated using the equation of Zhang et al. (2016):

$$TRI_i = \sqrt{[(C_i/TEL_i)^2 + (C_i/PEL_i)^2]} / \sqrt{2}; TRI = \sum_{i=1}^n TRI_i \quad (9)$$

where TRI_i is the metal toxic risk index, C_i denotes concentration, TEL_i represents the threshold effect level and PEL_i stands for the probable effect level of individual metals in the sample. The index was proposed by Pejman et al. (2015) and applied with the class limits of Zhang et al. (2016); TRI is the sum of all metals TRI_i in the sample [4, 35]. The TRI limits are defined in Table 1. The TU of potentially hazardous metals in the sediment samples were computed using the following formula:

$$TU_i = C_i / PEL_i; TU = \sum_{i=1}^n TU_i \quad (10)$$

where TU_i implies metal toxic unit, obtained by $TU_i = C_i/PEL_i$, C_i represents content and PEL_i denotes the probable effect level of single metals in each sediment sample. TU corresponds to the summation of all metals TU_i in the sample. The TU analysis class ranges are documented in Table 1. Because Th

has no published TEL or PEL values, the TRI and TU computations were restricted to the eight SQG-bearing metals (As, Cd, Cr, Cu, Hg, Ni, Pb and Zn).

3.3.9 Human-health risk screening

Human-health screening was conducted to estimate potential exposure under an assumed sediment-contact scenario using the USEPA framework [14]. The assessment considered three routes: dermal contact, incidental ingestion and inhalation. The chronic daily intake (CDI) equations were applied separately to children and adults. Exposure parameters are provided in Supplementary Table S1, and the toxicity values (RfD and cancer slope factor, where available) are provided in Supplementary Table S2. Because cancer slope factors are available only for a subset of elements, carcinogenic-risk calculations were limited to As, Cd, Cr, Ni and Pb, whereas the non-carcinogenic THI calculation was based on the eight PHMs with the required reference-dose values. For screening purposes, stream sediment was treated as a soil-like particulate medium for incidental ingestion and dermal exposure; this is an assumed exposure scenario rather than a measured human-contact rate. For Cr, the carcinogenic calculation applies the Cr(VI) potency factor to total measured Cr because Cr speciation was not available; this therefore represents an upper-bound screening assumption rather than a measured Cr(VI)-specific risk.

$$CDI_{\text{dermal}} = (C \times SA \times SAAF \times ABS \times CF_{\text{conv}} \times EF \times ED) / (BW \times AT) \quad (11)$$

$$CDI_{\text{ing}} = (C \times IR_{\text{ing}} \times CF_{\text{conv}} \times EF \times ED) / (BW \times AT) \quad (12)$$

$$CDI_{\text{inh}} = (C \times PM_{10} \times DAIR \times PLAF \times FSPO \times CF_{\text{conv}} \times EF \times ED) / (BW \times AT) \quad (13)$$

The exposure parameters for children and adults were taken from the source documents identified in Supplementary Table S1. RfD and cancer slope factor values used in the calculations are listed in Supplementary Table S2. The hazard quotient (HQ) was calculated as CDI/RfD , and $HQ > 1$ was used as a screening flag for potential non-carcinogenic concern. Cancer risk (CR) was calculated as $CDI \times SF$, and total carcinogenic risk (TCR) was obtained by summing the pathway-specific CR values. For consistency with the adopted screening framework, CR/TCR values below 1×10^{-6} , between 1×10^{-6} and 1×10^{-4} , and above 1×10^{-4} were interpreted as negligible, acceptable, and potentially unacceptable screening concern, respectively. The equations and parameter definitions are retained in Eqs. 11–18.

The carcinogenic effect was expressed using the carcinogenic risk index (CR) and total carcinogenic risk index (TCR). The CR_{dermal} , CR_{ing} and CR_{inh} denote cancer risk through the dermal contact, oral ingestion and respiratory inhalation pathways, respectively. $TCR < 1.0E-06$ indicates no carcinogenic risk to humans, TCR between $1.0E-06$ and $1.0E-04$ indicates carcinogenic risk within an acceptable range, and $TCR > 1.0E-04$ implies unacceptable carcinogenic risk to human health [3, 14]. The CR and TCR in this study were computed using the following formulae:

$$CR_{\text{pathway}} = CDI_{\text{pathway}} \times SF \quad (14)$$

$$TCR = CR_{\text{derm}} + CR_{\text{ing}} + CR_{\text{inh}} \quad (15)$$

The non-carcinogenic effect was assessed through the hazard quotient (HQ), hazard index (HI) and total hazard index (THI) analyses. The following formulae were applied for non-cancer risk assessment in this study:

$$HQ_{\text{pathway}} = CDI_{\text{pathway}} / RfD \quad (16)$$

$$HI = HQ_{\text{derm}} + HQ_{\text{ing}} + HQ_{\text{inh}} \quad (17)$$

$$THI = \sum HI \quad (18)$$

The HQ is the ratio of pathway-specific CDI to the corresponding reference dose (RfD). $HQ < 1$ indicates that the estimated exposure is below the adopted reference dose, whereas $HQ > 1$ flags potential non-carcinogenic concern under the assumed scenario. The HI is the sum of HQ values across exposure pathways for a given element, and THI is the sum of HI values across the included non-carcinogenic elements. These indices are screening metrics and should not be interpreted as direct measures of disease or observed toxicity.

Table 1
Multiple pollution indices and interpretation of value ranges.

Pollution index	Classes & interpretation	Reference
Contamination factor (CF)	< 1 = Low contamination; 1–3 = Moderate; 3–6 = Considerable; > 6 = High contamination	Hakanson (1980)
Contamination degree (Cdeg)	< 8 = Low; 8–16 = Moderate; 16–32 = Considerable; ≥ 32 = Very high	Hakanson (1980)
Modified contamination degree (mCdeg)	< 1.5 = No contamination; 1.5–2 = Low; 2–4 = Moderate; 4–8 = Considerable; 8–16 = High; 16–32 = Very high; > 32 = Ultra high	Hakanson (1980)
Pollution load index (PLI)	< 1 = No pollution; 1 = Baseline; > 1 = Pollution	Tomlinson et al. (1980)
Enrichment factor (EF)	< 1 = No enrichment; 1–2 = Minimal; 2–5 = Moderate; 5–20 = Considerable; 20–40 = Very high; > 40 = Extremely high	Yongming et al. (2006)
Geo-accumulation index (Igeo)	≤ 0 = No pollution; 0–1 = Low to moderate; 1–2 = Moderate; 2–3 = Moderate to strong; 3–4 = Strong; 4–5 = Strong to extremely strong; > 5 = Extremely strong	Müller (1981)
Ecological risk factor (ERF)	< 40 = Low ecological risk; 40–80 = Moderate; 80–160 = Considerable; 160–320 = High; > 320 = Very high ecological risk	Hakanson (1980)
Potential ecological risk (PERI)	< 150 = Low; 150–300 = Moderate; 300–600 = Considerable; > 600 = Very high ecological risk	Hakanson (1980)
Toxic risk index (TRI)	< 5 = No toxic risk; 5–10 = Low; 10–15 = Moderate; 15–20 = Significant; > 20 = Very high toxic risk	Zhang et al. (2016)
Toxic units (TU)	< 4 = Low toxic risk; 4–6 = Moderate; > 6 = High toxic risk	Zhang et al. (2016)

4 Results and discussion

4.1 Hazardous metals abundance in sediments and pollution

The concentration of metals in sediments is used to evaluate the sediments' pollution status. The concentrations of potentially hazardous metals in the Zang-Tabi sediment samples are presented in Table 2 and Fig. 3. The metals exhibit fluctuating concentrations (in mg/kg) in the analyzed samples: As (0.15–0.46), Cd (0.0005–0.128), Cr (427–1215), Cu (2.36–52.6), Hg (0.004–0.011), Ni (7.63–37.4), Pb (4.56–58.8), Th (15.5–189), Zn (13.6–113.5), La (2.98–74.2) and Sc (1.28–5.81). The average concentrations of these elements are in the decreasing order of Cr (626.80) > Th (61.71) > Zn (43.65) > La (16.99) > Ni (16.03) > Pb (14.87) > Cu (13.63) > Sc (2.63) > As (0.26) > Cd (0.015) > Hg (0.007). Chromium, Th, Zn, Ni, Pb and Cu display coefficients of variation (CV) of 35%, 73%, 65%, 48%, 99% and 109%, respectively, whereas Cd (CV = 219%) and La (CV = 136%) are strongly heterogeneous, indicating marked spatial variability for these elements across the basin. Positively skewed distributions (skewness = 0.74–3.22) characterize all the metals, a typical feature of geochemical datasets in which a few stations capture localized enrichment [30]. The metal content variation in the samples could be ascribed to differential cation exchange capacity, grain size variation, adsorption capacity, organic matter content, pH, redox condition, weathering intensity, climate and tectonic setting constraints [4, 5, 10].

Comparing sediment concentrations with crustal references and regional or published sediment datasets provides context for evaluating enrichment [2, 5, 7]. The average concentrations of PHMs in the Zang-Tabi sediments were compared with the upper continental crust (UCC; Rudnick and Gao 2014) [31], Mewongo sediments of southern Cameroon (Fomekong et al. 2023) [5] and Beiluo sediments of China (Li et al. 2024) [13] (Table 2; Fig. 3). The average concentrations of Cr and Th in the sediments are elevated above their corresponding UCC values (Cr 626.80 vs 92.00 mg/kg; Th 61.71 vs 10.50 mg/kg), corresponding to concentration ratios of 6.8 and 5.9, respectively. These values demonstrate strong enrichment relative to UCC but do not, by themselves, establish anthropogenic contamination. Conversely, the average As, Cd, Hg, Ni, Cu, Pb, Zn, La and Sc contents of the studied sediments are lower than their UCC reference values (Table 2; Fig. 3). Concentrations below a crustal reference do not by themselves establish provenance, but they are consistent with substantial contribution from the felsic, silica-rich Pan-African granitoids that dominate the basin [20, 31].

The average concentrations of Cr and Ni in this study are above the mean values reported in Mewongo stream sediments (Cr 626.80 vs 519.7 mg/kg; Ni 16.03 vs 4.18 mg/kg; Table 2; Fig. 3; [5]), whereas average As, Pb, Th, Zn, La and Sc are below the Mewongo values. Relative to Beiluo River sediments of China [13], the studied sediments are markedly enriched in Cr (626.80 vs 61 mg/kg), whereas Cu (13.63 vs 20 mg/kg), Ni (16.03 vs 27 mg/kg), As (0.26 vs 10 mg/kg), Cd (0.015 vs 0.08 mg/kg), Pb (14.87 vs 20 mg/kg) and Zn (43.65 vs 66 mg/kg) are lower. This comparative pattern is consistent with lithologic control, including contribution from Cr-bearing mafic and Fe–Ti-oxide phases and Th-bearing accessory minerals within the granitoid–mafic source assemblage [20, 21].

Table 2
Concentration (mg/kg) of potentially hazardous metals in stream sediments from the Zang-Tabi area compared with other studies around the v

Sample	As	Cd	Cr	Cu	Hg	Ni	Pb	Th	Zn	La	Sc	Al ₂ O ₃	La/Sc×100	Th/Sc	Ti
SB01	0.46	0.003	588	5.07	0.009	13.25	8.84	35.5	33.5	5.69	2.83	0.37	2.01	12.54	6.
SN02	0.22	0.128	517	9.69	0.006	23.70	7.51	38.3	32.9	3.65	2.33	0.19	1.57	16.44	7.
SZM01	0.31	0.0005	1010	2.43	0.004	7.63	5.23	38.4	16.2	8.79	1.47	0.56	5.98	26.12	3.
STD01	0.35	0.002	703	3.91	0.007	10.20	4.56	23.7	23.0	4.56	2.64	0.46	1.73	8.97	3.
SBA01	0.18	0.003	754	3.50	0.006	10.20	7.46	52.7	23.4	10.5	1.92	0.44	5.47	27.45	6.
SAN01	0.26	0.0005	427	5.41	0.007	18.70	14.45	66.9	36.4	7.18	2.63	0.31	2.73	25.44	15
SKB01	0.24	0.020	501	36.00	0.008	37.40	8.81	34.2	113.5	5.72	3.16	0.45	1.81	10.82	6.
SZP01	0.21	0.0005	453	8.05	0.006	14.65	22.40	86.2	39.5	8.93	2.54	0.48	3.52	33.94	15
SOM01	0.26	0.009	614	3.23	0.007	12.20	10.55	189	43.4	67.1	3.02	0.55	22.22	62.58	30
SG01	0.29	0.044	507	14.90	0.008	15.70	37.00	113.5	100.5	34.6	2.74	0.52	12.63	41.42	22
SN03	0.15	0.0005	459	2.36	0.005	19.05	7.58	31.7	39.8	6.15	5.81	0.62	1.06	5.46	6.
SAT01	0.34	0.004	1215	52.60	0.004	15.30	58.80	15.5	13.6	2.98	1.28	0.38	2.33	12.11	1.
SK01	0.18	0.008	472	24.00	0.011	8.96	10.00	36.4	58.1	5.32	1.68	0.48	3.17	21.67	7.
SN01	0.17	0.0005	550	6.30	0.005	10.70	12.05	65.4	37.1	9.51	2.16	0.47	4.40	30.28	11
SO01	0.33	0.004	632	27.00	0.006	22.80	7.85	98.2	43.9	74.2	3.17	0.70	23.41	30.98	15
Min.	0.15	0.0005	427	2.36	0.004	7.63	4.56	15.5	13.6	2.98	1.28	0.19	1.06	5.46	1.
Max.	0.46	0.128	1215	52.60	0.011	37.40	58.80	189	113.5	74.2	5.81	0.70	23.41	62.58	30
Av.	0.26	0.015	627	13.63	0.007	16.03	14.87	61.7	43.7	17.0	2.63	0.46	6.51	23.50	10
UCC (Rudnick & Gao 2014)	4.8	0.09	92	28	0.05	47	17	10.5	67	31	14	15.41	/	/	/
Mewongo (Fomekong et al. 2023)	0.47	0.05	519.7	5.21	0.02	4.18	204.55	2959.44	19.08	4016.5	29.84	/	/	/	/
Beiluo (Li et al. 2024)	10	0.08	61	20	0.01	27	20	/	66	/	/	/	/	/	/
TEL (MacDonald 2000)	5.9	0.6	37.3	35.7	0.17	18	35	/	123	/	/	/	/	/	/
PEL (MacDonald 2000)	17	3.5	90	197	0.49	36	91.3	/	315	/	/	/	/	/	/
TEC (MacDonald 2000)	9.79	0.99	43.4	31.6	0.18	22.7	35.8	/	121	/	/	/	/	/	/
PEC (MacDonald 2000)	33	4.98	111	149	1.06	48.6	128	/	459	/	/	/	/	/	/
ERL (MacDonald 2000)	8.2	1.2	81	34	0.15	20.9	46.7	/	150	/	/	/	/	/	/
ERM (MacDonald 2000)	70	9.6	370	270	0.71	51.6	218	/	410	/	/	/	/	/	/

Concentrations in mg/kg except Al₂O₃ in wt %. "/" = no guideline or datum available. UCC = upper continental crust [31]; Mewongo sediments, southern Cameroon (Fomekong et al. 2023) [5]; Beiluo sediments, China [13]. SQGs after MacDonald et al. (2000) [16].

4.2 Metals and sediment quality guidelines (SQGs)

Environmental sediment quality guidelines (SQGs) are used to screen sediments for potential adverse biological effects and to identify sites requiring further investigation [2, 3, 6, 16]. Concentrations above individual SQGs are associated with increasing screening-level concern, whereas concentrations below them generally indicate lower concern [7, 9, 16]. Six SQG systems – threshold effect level (TEL), probable effect level (PEL), threshold effect concentration (TEC),

probable effect concentration (PEC), effect range-low (ERL) and effect range-median (ERM) – were used in this study. Chromium is the most notable element in the SQG screening: its concentrations exceed all six benchmarks at all fifteen stations, including the ERM threshold of 370 mg/kg, indicating persistent screening-level concern throughout the drainage network. Copper exceeds the TEL, TEC and ERL at SKB01 and SAT01 but remains below the PEL, PEC and ERM, indicating lower screening concern relative to those higher-effect thresholds. Nickel remains below the TEL on average (16.03 vs 18 mg/kg), but exceeds the TEL at five stations, the TEC and ERL at three stations, and the PEL at SKB01 (37.4 mg/kg), indicating localized screening concern. In contrast, As, Cd, Hg and Zn remain below all six SQG benchmarks, indicating comparatively low screening concern for these elements. Together, the SQG results identify Cr as the principal element requiring follow-up, with localized Ni and Cu anomalies also warranting attention.

4.3 Pollution indices, sediment contamination and toxicological screening

The Cdeg values vary from 9.67 (SN03) to 26.61 (SOM01), with an average of 15.40 (Table S3; Fig. 4b). Using the conventional Hakanson (1980) classes in Table 1, eleven samples (SB01, SN02, SZM01, STD01, SBA01, SAN01, SKB01, SZP01, SN03, SK01 and SN01; $8 \leq \text{Cdeg} < 16$) fall in the moderate class, whereas four samples (SOM01, SG01, SAT01 and SO01; $16 \leq \text{Cdeg} < 32$) fall in the considerable class. No sample reaches the very-high Cdeg class (≥ 32). The mCdeg ranges from 1.07 (SN03) to 2.96 (SOM01), with an average of 1.71 (Table S3; Fig. 4c). Following the mCdeg interpretation scheme, seven samples show no contamination (mCdeg < 1.5), four show low contamination (1.5–2), and four show moderate contamination (2–4). The average mCdeg of 1.71 therefore corresponds to the low-contamination class. The PLI values range from 0.22 (SZM01) to 0.82 (SG01), with an average of 0.43 (Table S3; Fig. 4d). All PLI values are < 1, indicating no overall pollution according to the Tomlinson et al. (1980) classification. The combination of substantial Cdeg and sub-unit PLI reflects strong compositional imbalance: Cr and, to a lesser extent, Th account for most of the additive CF burden, whereas several other metals have CF < 1.

EF values (Table S4; Fig. 5a) vary strongly among elements. The average EF values range from 1.99 (As) to 244.28 (Cr): As shows minimal enrichment; Hg moderate enrichment; Cd, Ni and Cu considerable enrichment; Pb and Zn very high enrichment; and Th and Cr extremely high enrichment according to the adopted EF classes. Because EF is normalized to the UCC metal/ Al_2O_3 ratio, these values indicate strong relative enrichment but do not independently prove anthropogenic input. In particular, the very high Cr and Th EF values may be amplified by the low Al_2O_3 contents of some sediments and by the use of a global rather than local reference. Igeo values (Table S5; Fig. 5b) range, on average, from – 5.34 (Cd) to 2.12 (Cr). Relative to the UCC baseline, mean Igeo values are ≤ 0 for As, Cd, Cu, Hg, Ni, Pb and Zn, while Th (mean Igeo = 1.67) falls in the moderate class and Cr (mean Igeo = 2.12) falls in the moderate-to-strong class. These indices should therefore be interpreted as UCC-normalized enrichment metrics rather than stand-alone proof of anthropogenic contamination.

The average ERF values range from 0.55 (As) to 13.63 (Cr). ERF is low for all element–station combinations except Cd at SN02 (42.67), which falls in the moderate class. The PERI values range from 22.75 (SN03) to 69.76 (SN02), with a mean of 39.55; all fifteen stations are below the PERI threshold of 150, indicating low overall potential ecological risk under the Hakanson framework. This index result should not be interpreted as direct evidence of absence of biological effects.

The TRI values range from 10.29 (SAN01) to 28.09 (SAT01), with a mean of 14.51 (Table S7; Fig. 5e). Ten samples fall in the moderate class (10–15), three in the significant class (15–20), and two in the very-high class (> 20). TU values range from 5.60 (SAN01) to 14.91 (SAT01), with a mean of 7.81 (Table S8; Fig. 5f); four stations fall in the moderate class (4–6) and eleven in the high class (> 6). Cr contributes approximately 88.6% of mean TRI and 89% of mean TU, making it the dominant driver of the SQG-based toxicological screening signal. The contrast between low PERI and higher TRI/TU reflects different index structures: PERI applies metal-specific toxic-response weighting, whereas TRI/TU directly compare concentrations with SQG thresholds. The resulting TRI/TU values indicate screening-level toxicological concern, not demonstrated biological toxicity.

4.4 Human-health screening

4.4.1 Health relevance and exposure scenario

Hazardous metals are metals and metalloids with relatively high densities, bio-accumulative potential along the food chain and high toxicity to living organisms [1, 3, 4, 10]. They accumulate in sediments, water, air and plants, and enter the human system through the gastrointestinal tract, skin and inhalation pathways [3, 6, 36]. This group of metals, including As, Cd, Cr, Cu, Hg, Ni, Pb, Th and Zn amongst others, is associated with adverse health conditions in humans if present above permissive levels, including neurological, cardiovascular, renal and carcinogenic outcomes documented in toxicological literature [1, 3, 14]. The present study models potential exposure to these elements; it does not, and cannot, demonstrate the occurrence of disease, and all risk estimates below are screening-level outputs of an exposure model built on assumed parameters.

4.4.2 Carcinogenic-risk screening

The carcinogenic risk associated with exposure to potentially hazardous metals through distinct pathways provides indications of potential cancer-related health risks that could be prevented [3, 7, 13, 14]. Children and adults are exposed to hazardous metals at different rates due to behavioral patterns, activity level and interaction with the immediate environment [2, 3]. The chronic daily intake (CDI) dose of potentially hazardous metals is used in human health assessment investigations to evaluate the risk degree due to exposure through the dermal contact, oral ingestion and respiratory inhalation pathways. CDI values above the reference dose (RfD) are known to indicate detrimental effect [3, 36]. Tables 3 and 4 present the computed CDI and CR/TCR values, respectively; per-station CDI results for all fifteen samples are compiled in the Supplementary Material (Tables S1 and S2 list the exposure parameters and the RfD/SF values).

Average modeled CDI values were highest through ingestion for children and through dermal contact for adults for Cr, while inhalation was the smallest pathway. Cr and Th produced higher CDI values than most other metals, reflecting their higher sediment concentrations. CDI values were then combined with

pathway- and age-specific RfDs and cancer slope factors to derive screening-level HQ, HI and CR/TCR values. The resulting outputs are scenario-dependent and should not be interpreted as measurements of human disease or actual incidence.

Table 3
Average modeled chronic daily intake (CDI, mg/kg/day) by exposure pathway for the potentially hazardous elements in Zang-Tabi stream sediments.

Metals	Av. C (mg/kg)	CDI _{dermal} (child)	CDI _{ingestion} (child)	CDI _{inhalation} (child)	CDI _{dermal} (adult)	CDI _{ingestion} (adult)	CDI _{inhalation} (adult)
As	0.26	1.39E-08	2.89E-07	8.72E-10	1.41E-07	1.55E-07	2.45E-09
Cd	0.015	2.66E-11	1.66E-08	5.02E-11	2.71E-10	8.90E-09	1.41E-10
Cr	626.80	4.62E-05	6.87E-04	2.08E-06	4.71E-04	3.68E-04	5.83E-06
Cu	13.63	2.39E-08	1.49E-05	4.51E-08	2.44E-07	8.00E-06	1.27E-07
Hg	0.007	1.16E-11	7.23E-09	2.19E-11	1.18E-10	3.87E-09	6.14E-11
Ni	16.03	2.81E-08	1.76E-05	5.31E-08	2.87E-07	9.41E-06	1.49E-07
Pb	14.87	2.61E-08	1.63E-05	4.92E-08	2.66E-07	8.73E-06	1.38E-07
Th	61.71	1.08E-07	6.76E-05	2.04E-07	1.10E-06	3.62E-05	5.74E-07
Zn	43.65	7.65E-08	4.78E-05	1.45E-07	7.80E-07	2.56E-05	4.06E-07

Carcinogenic CDI computed with AT = 25550 days; non-carcinogenic CDI with AT = ED × 365 days. Child/adult exposure parameters are provided in Supplementary Table S1.

Table 4
Average modeled pathway-specific carcinogenic risks and metal-specific total carcinogenic risk (TCR) for children and adults.

Metals	CR _{dermal} (child)	CR _{ingestion} (child)	CR _{inhalation} (child)	TCR (child)	CR _{dermal} (adult)	CR _{ingestion} (adult)	CR _{inhalation} (adult)	TCR (adult)
As	5.07E-08	4.33E-07	1.32E-08	4.97E-07	5.17E-07	2.32E-07	3.70E-08	7.86E-07
Cd	5.32E-10	1.01E-07	3.16E-10	1.02E-07	5.42E-09	5.43E-08	8.89E-10	6.06E-08
Cr	9.23E-04	3.43E-04	8.72E-05	1.35E-03	9.41E-03	1.84E-04	2.45E-04	9.84E-03
Ni	5.90E-08	2.99E-05	4.46E-08	3.00E-05	6.02E-07	1.60E-05	1.25E-07	1.67E-05
Pb	2.22E-10	1.39E-07	–	1.39E-07	2.26E-09	7.42E-08	–	7.65E-08

CR = CDI × SF (Table S2). TCR = sum of CR over the three pathways. “–” = no inhalation slope factor available for Pb. Carcinogenic risk classes (USEPA 2025): < 1.0E-06 no risk; 1.0E-06–1.0E-04 acceptable; > 1.0E-04 unacceptable.

Cr produced the largest pathway-specific and metal-specific carcinogenic screening estimates. The total-Cr-as-Cr(VI) assumption substantially increases the modeled Cr cancer signal; because Cr speciation was not measured, the resulting values should be interpreted as conservative upper-bound screening estimates rather than as evidence of actual cancer risk. The other carcinogenic metals (As, Cd, Ni and Pb) remained at negligible-to-acceptable screening levels under the adopted assumptions.

Non-carcinogenic screening results showed that Cr was the only element with pathway-specific HQ values above 1. Children had average Cr HQ values of 8.98 (dermal), 2.67 (ingestion) and 0.85 (inhalation), whereas adults showed 18.29, 0.286 and 0.476, respectively. All other metals had pathway-specific HQ values below 1. Cr produced HI values of 12.5 for children and 19.1 for adults, and station-level THI values ranged from 8.59–24.48 for children and 13.03–36.99 for adults. These values indicate potential non-carcinogenic concern under the assumed exposure scenario, with Cr accounting for approximately 99% of THI. Adult THI exceeds child THI in this model because of the adopted dermal exposure parameters; this mathematical result should not be interpreted as evidence that adults are intrinsically more susceptible. Children may still warrant particular attention because of age-related behavior and body-weight-normalized ingestion exposure.

Metals	HQ _{child} (child)	HQ _{inf} (child)	HQ _{ad} (child)	HI (child)	HQ _{child} (adult)	HQ _{inf} (adult)	HQ _{ad} (adult)	HI (adult)
As	1.31E-03	1.12E-02	3.38E-05	1.26E-02	2.68E-03	1.20E-03	1.90E-05	3.90E-03
Cd	3.10E-05	1.94E-04	5.86E-07	2.26E-04	6.33E-05	2.08E-05	3.29E-07	8.44E-05
Cr	8.98E+00	2.67E+00	8.47E-01	1.25E+01	1.83E+01	2.86E-01	4.76E-01	1.91E+01
Cu	2.32E-05	4.36E-03	3.71E-05	4.42E-03	4.74E-05	4.67E-04	2.08E-05	5.35E-04
Hg	6.43E-06	2.81E-04	2.96E-06	2.91E-04	1.31E-05	3.01E-05	1.67E-06	4.49E-05
Ni	6.07E-05	1.02E-02	3.01E-05	1.03E-02	1.24E-04	1.10E-03	1.69E-05	1.24E-03
Pb	5.80E-04	5.43E-02	1.63E-04	5.51E-02	1.18E-03	5.82E-03	9.17E-05	7.09E-03
Zn	1.49E-05	1.86E-03	5.62E-06	1.88E-03	3.03E-05	1.99E-04	3.16E-06	2.33E-04
THI				1.26E+01				1.91E+01

4.5 Metals source identification

Potentially hazardous metals in fluvial sediments could be derived from natural and/or anthropogenic sources [2, 4, 7, 10, 11, 13, 28]. Inter-metal relationships (linear correlation, Pearson's Correlation Coefficient–PCC, Principal Components Analysis–PCA & Hierarchical Cluster Analysis–HCA) and empirical source discrimination plots are suitable proxies for constraining the origin of potentially hazardous metals in fluvial ecosystems [5, 8, 12]. Bivariate scatter plots (Fig. 6) indicate that the concentration of As in the studied sediments does not co-vary significantly with any of the other potentially hazardous metals ($|r| \leq 0.40$ for all pairs; only As–Cr reaches $r = +0.40$), suggesting that As is hosted by an independent mineral phase or source relative to the remaining PHM suite.

The combination of PCC, PCA and HCA provides a complementary means of cross-checking metal associations in sediments [8, 12]. PCC was conducted (Fig. 7a) to constrain the potential origins of metals in the stream sediments. The results highlight moderately strong positive correlations for Cu–Pb ($r = 0.63$), Ni–Zn ($r = 0.60$) and Hg–Zn ($r = 0.53$), potentially indicating shared lithologic or anthropogenic sources for the concerned metals. Moderately strong negative relationships between Cr and Hg ($r = -0.55$) and Cr and Zn ($r = -0.52$), together with the positive Cr–Pb ($r = 0.45$) and As–Cr ($r = 0.40$) associations, indicate that the Cr-dominated assemblage behaves independently of the Hg–Zn and Cu–Pb groups. PCA was further implemented (Table 6) as an exploratory descriptor of covariance among the metals. Varimax rotation after Kaiser normalisation yielded four components jointly accounting for 77.64% of the total variance; because the Kaiser–Meyer–Olkin measure was low (0.26) and the sample size was small ($n = 15$), the PCA results are treated as exploratory descriptors of covariance rather than robust evidence of source apportionment.

Potentially hazardous metals	Factor 1	Factor 2	Factor 3	Factor 4
As	0.32	0.20	0.63	0.34
Cd	-0.02	0.03	-0.66	0.18
Cr	0.51	-0.61	0.41	0.26
Cu	0.89	0.12	-0.14	0.21
Hg	-0.14	0.90	0.13	0.01
Ni	0.31	0.38	-0.70	0.20
Pb	0.85	-0.21	0.07	-0.18
Th	-0.05	0.15	0.05	-0.89
Zn	0.24	0.75	-0.43	-0.23
Percentage of variance	23.01	22.30	19.11	13.22
Cumulative percentage of variance	23.01	45.30	64.42	77.64

Factor 1, loaded with Cu (0.89) and Pb (0.85) with a moderate Cr loading (0.51), accounts for 23.01% of the total variance (Table 6). The composition of sediments commonly reflects the natural geochemical composition of the basin and its upstream catchment [8, 13, 27]; statistically, this association is tentatively consistent with weathering and transport of geochemical signatures from the granitoid basement and its sulphide-bearing quartz veins [20, 30], possibly accentuated by agrochemical inputs, although mineralogical confirmation is lacking. Factor 2 (Hg = 0.90, Zn = 0.75; 22.30% of variance) is a statistical association that could reflect either lithologic or anthropogenic Hg–Zn contributions, consistent with the weak negative loading of Cr in this factor. Factor 3 (Ni = -0.70, Cd = -0.66, As = 0.63; 19.11% of variance) groups Ni and Cd with a moderate As loading; this is interpreted as a statistical association rather than proof of a particular mineralogical substitution mechanism. The single-element Factor 4 (Th = -0.89; 13.22% of variance) depicts an independent Th-bearing control, compatible with the Th-rich accessory phases (monazite–allanite–zircon) petrographically documented in the Mbengwi leucogranites [20]. Additionally, HCA was used in this study (Fig. 7b) to supplement the PCC (Fig. 7a) and PCA (Table 6) findings. PCC, PCA and HCA show broad agreement for the Cu–Pb and Hg–Zn associations, whereas relationships involving Cr, As, Cd and Ni vary among the multivariate methods. Within the exploratory limits of the approach, the results are compatible with a predominantly lithogenic metal supply accompanied by possible localized anthropogenic contributions.

4.6 Spatial distribution of potentially hazardous metals

The spatial distribution of potentially hazardous metals provides a basis for identifying concentration patterns and potential hotspot zones relevant to environmental monitoring and follow-up [2, 3, 5–7]. The spatial distribution of the potentially hazardous metals in the Zang-Tabi area, plotted on the hydrographic base map of the drainage network, is presented in Fig. 9. Samples from all stations demonstrated elevated Cr concentrations (Fig. 9c), with the highest values in the northeast (SAT01, 1215 mg/kg) and centre-south (SZM01, 1010 mg/kg), a pattern consistent with widespread input of Cr-bearing detrital material from mafic and/or Fe–Ti-oxide-bearing source lithologies.

Thorium (Fig. 9h) displays a distinctive southward-increasing gradient, with maxima at SOM01 (189 mg/kg), SO01 (98.2 mg/kg) and SZP01 (86.2 mg/kg) along the lower Momo–Oshum drainage and minimum values at SAT01 (15.5 mg/kg) in the northeast, which may reflect progressive hydraulic concentration of resistant Th-bearing minerals down-drainage. Lead and Cu maxima coincide at SAT01 (58.8 and 52.6 mg/kg) and, for Cu, at SKB01 (36.0 mg/kg) near the Gwofon–Kai road corridor, consistent with possible localized contributions from road runoff, market gardening and other local activities (Figs. 9d & g). Zinc and Ni peak together at SKB01 (113.5 and 37.4 mg/kg) and SG01 (100.5 mg/kg) (Figs. 9f & i), mirroring the Hg–Zn–Ni association of Factor 2 and the Ni–Zn PCC pair. Arsenic, Cd and Hg remain uniformly low across the basin (Figs. 9a, b & e), with Cd modestly elevated only at SN02 (0.128 mg/kg) and SG01 (0.044 mg/kg) on the Njah–Gwokong drainages.

Spatial distribution reveals that the Zang-Tabi area exhibits a two-component spatial pattern: a basin-wide lithologic Cr–Th background superimposed on localized Cu–Pb–Zn–Ni anomalies adjacent to human activity corridors, consistent with multiple sources. Stations with comparatively low metal concentrations are consistent with dilution by metal-poor detritus, although low concentration alone does not establish source or absence of risk [2, 3, 5]. The moderate to elevated concentration of metals reported at various sampling stations in this study indicates possible anthropogenic influences such as domestic and mini-industrial activities, urban run-off, poor garbage and sewage disposal, agricultural practices, and small-scale mining of construction materials [1, 7, 11]. The accumulation of potentially hazardous metals in the Zang-Tabi sediments at elevated concentrations may contribute to exposure through pathways that require direct field verification; transfer to surface water or shallow groundwater should therefore be assessed through dedicated water-quality sampling.

4.7 Study's limitation

The study is subject to several limitations. Sampling was conducted in a single season and grain-size distributions were not measured. The analytical method uses partial aqua regia digestion, so concentrations represent an environmentally reactive fraction rather than a total elemental inventory. Cr speciation, sediment bioavailability and bioaccumulation in aquatic organisms were not determined. The small sample size ($n = 15$) and low PCA suitability ($KMO = 0.26$) limit statistical source inference. UCC is a global compositional reference rather than a locally established pre-anthropogenic sediment background, so UCC-normalized enrichment should not be equated directly with anthropogenic contamination. Finally, human-health estimates depend on assumed exposure scenarios and toxicity parameters and therefore represent screening results rather than measured exposure or disease risk. Future work should combine seasonal sediment and water sampling with grain-size analysis, sequential extraction, Cr speciation, bioavailability testing and targeted sampling of suspected source materials.

5 Conclusions

The current study integrates sediment geochemistry, pollution indices, SQG screening, ecotoxicological indices, screening-level human-health modelling, multivariate statistics and GIS mapping to characterize PHM enrichment in the Zang-Tabi drainage basin. Cr (427–1215 mg/kg; mean 626.80 mg/kg) and Th (15.5–189 mg/kg; mean 61.71 mg/kg) are strongly enriched relative to UCC, while the remaining target metals are below their UCC reference values on average. Cr exceeds all six SQG benchmarks at every station, and Ni shows localized exceedances. The Cdeg values (9.67–26.61) fall in the moderate to considerable classes, the mCdeg values (1.07–2.96) range from no to moderate contamination, and PLI values (0.22–0.82) remain below 1.

Cr and Th show the strongest UCC-normalized enrichment signals (mean CF = 6.81 and 5.88; mean Igeo = 2.12 and 1.67; mean EF $\approx$ 244 and 197, respectively), while PERI remains low (22.75–69.76). TRI values range from 10.29 to 28.09, and TU from 5.60 to 14.91, with Cr contributing approximately 89% of each mean toxic-screening metric. Human-health outputs identify Cr as the principal modeled concern, but the cancer estimate is conditional on treating total Cr as Cr(VI); actual Cr(VI)-specific risk cannot be established without speciation. The combined evidence supports predominantly lithogenic Cr–Th enrichment with possible localized human-related Cu–Pb–Zn–Ni inputs that require source-specific confirmation.

Screening-level human-health modelling indicates that ingestion is the dominant modeled pathway for children, whereas dermal exposure is prominent for adults. As, Cd, Hg, Ni, Pb, Cu and Zn do not show pathway-specific HQ values above 1 under the adopted assumptions, while Cr produces the principal non-carcinogenic screening concern. Station-level overall TCR values are elevated under the adopted total-Cr-as-Cr(VI) assumption; because Cr speciation was not measured, these cancer estimates should be treated as conservative screening bounds rather than evidence of actual cancer risk. Targeted Cr speciation, bioavailability testing and water-quality monitoring are therefore priorities before site-specific risk-management decisions.

Multivariate analyses are best regarded as exploratory because $n = 15$ and $KMO = 0.26$. The data support a predominantly felsic provenance with an additional Cr-bearing mafic/Fe–Ti-oxide contribution. Localized Cu–Pb–Zn–Ni anomalies are consistent with possible agriculture, road runoff and other human activities, but they are not uniquely attributable to those sources from the present dataset. Priority follow-up should include Cr(III)/Cr(VI) speciation, bioavailability testing, water-quality monitoring and targeted sampling of suspected source materials. The study provides a useful baseline framework for future environmental monitoring of the Zang-Tabi drainage basin.

Declarations

CRedit authorship contribution statement

T.J. Ndong: Conceptualization, methodology, investigation, fieldwork, formal analysis, writing - original draft. A.N. Aloysius and O.A. Njoh: Conceptualization, supervision, validation, writing - review & editing. L.P. Yiika and B.K. Fomekong: Validation, data curation, writing - review & editing. G.D. Kouankap Nono: Validation, literature review, writing - review & editing.

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Data availability

The complete geochemical dataset, all computed index tables (Tables S1–S8) and the sediment quality guideline comparison figures (Figs. S1–S6) are provided in the Supplementary Material accompanying this article. Additional raw laboratory reports are available from the corresponding author upon reasonable request.

Declarations

Ethics, Consent to Participate, and Consent to Publish declarations: Not applicable. This study does not involve human participants, human data, or human tissue. It is based solely on the geochemical analysis of environmental sediment samples collected from the Zang-Tabi drainage basin.

Clinical Trial Declaration: Not applicable. This study does not meet the criteria for a clinical trial.

Competing Interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

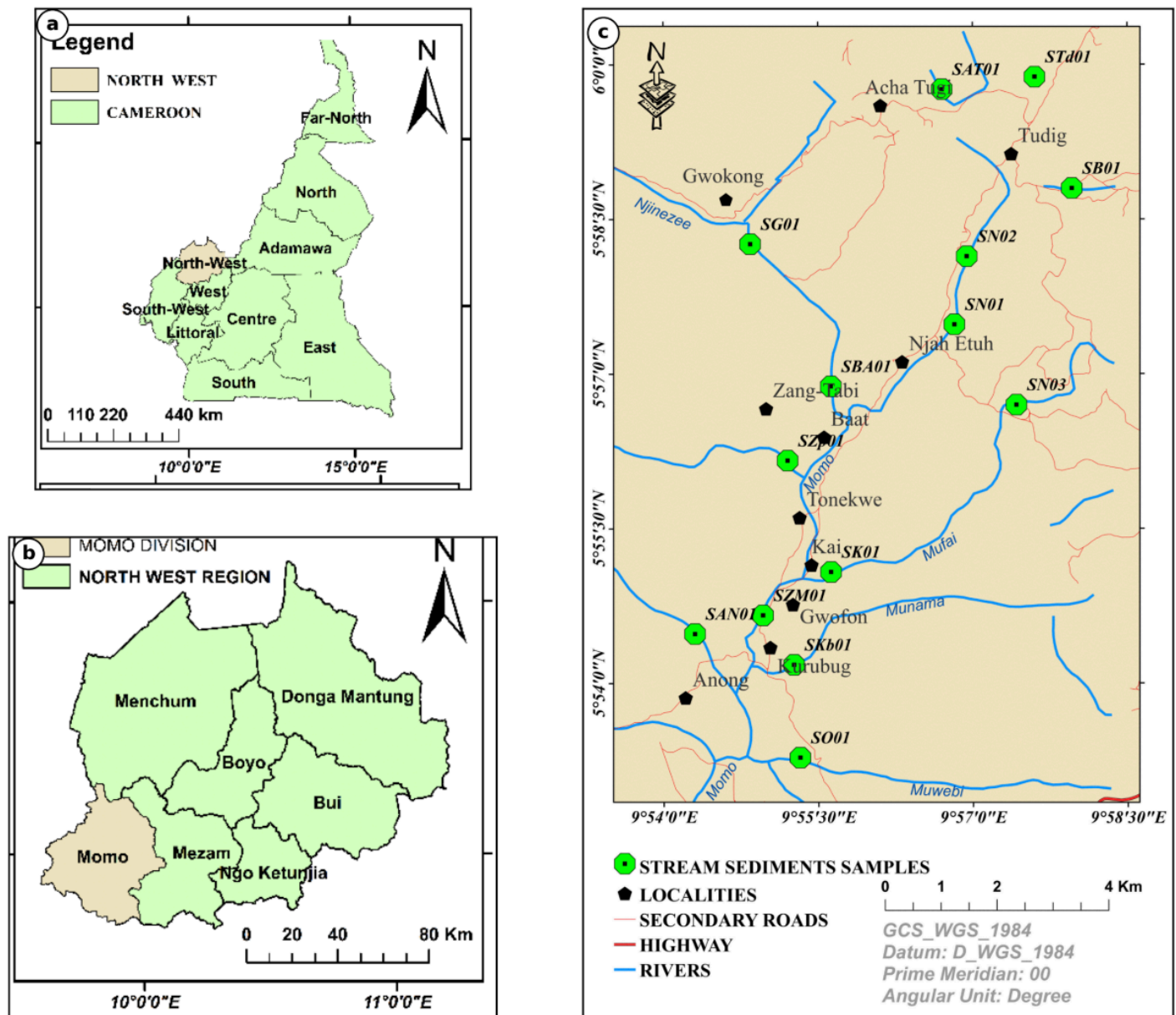


Figure 1

Location map of the Zang-Tabi study area. (a) Administrative map of Cameroon showing the North West Region; (b) administrative map of the North West Region showing the Momo Division; (c) location map of the Zang-Tabi area indicating the stream sediment collection sites, sample codes, drainage network

and access routes (after [30]).

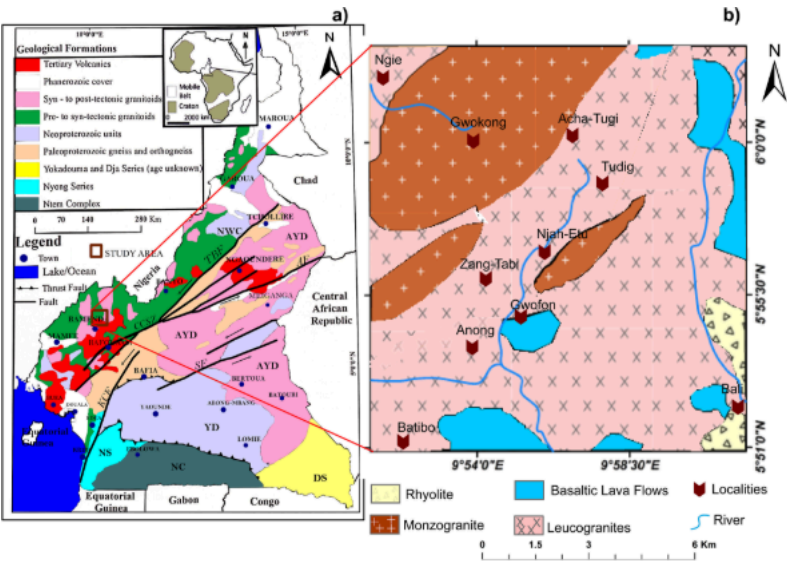


Figure 2 (a) Regional geological map of Cameroon and adjoining areas showing the principal geological formations of the Central African Fold Belt, the Cenozoic volcanics of the Cameroon Volcanic Line and the location of the study area (red rectangle); (b) geological map of the Zang-Tabi study area showing the Pan-African monzogranites and leucogranites, Tertiary rhyolites and basaltic lava flows, and the main rivers (after [20,30]).

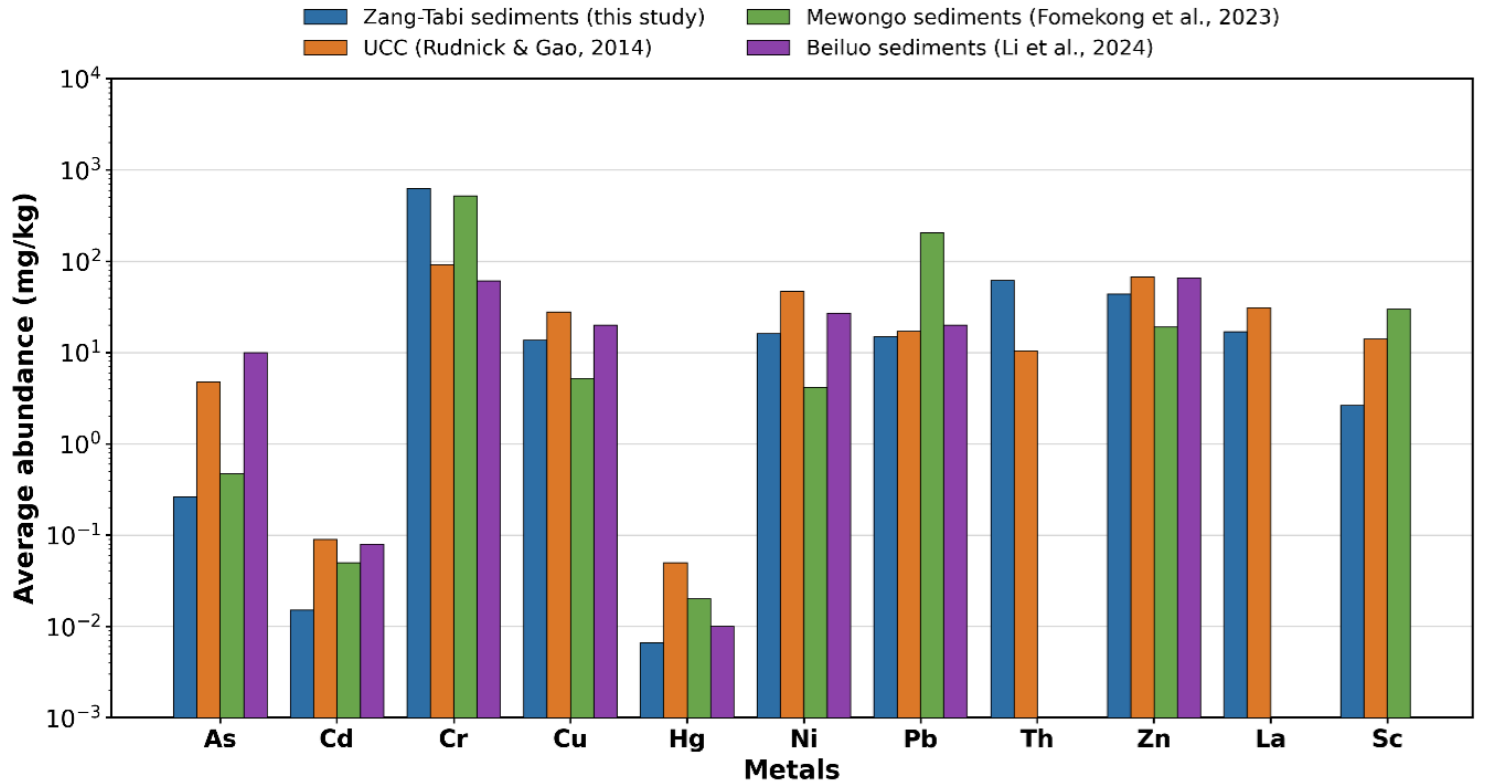


Figure 3 Column chart of average concentrations (mg/kg) in the Zang-Tabi stream sediments compared with upper continental crust (UCC; Rudnick & Gao 2014 [31]), Mewongo sediments (Fomekong et al. 2023 [5]) and Beiluo sediments (Li et al. 2024 [13]).

Contamination discrimination plots

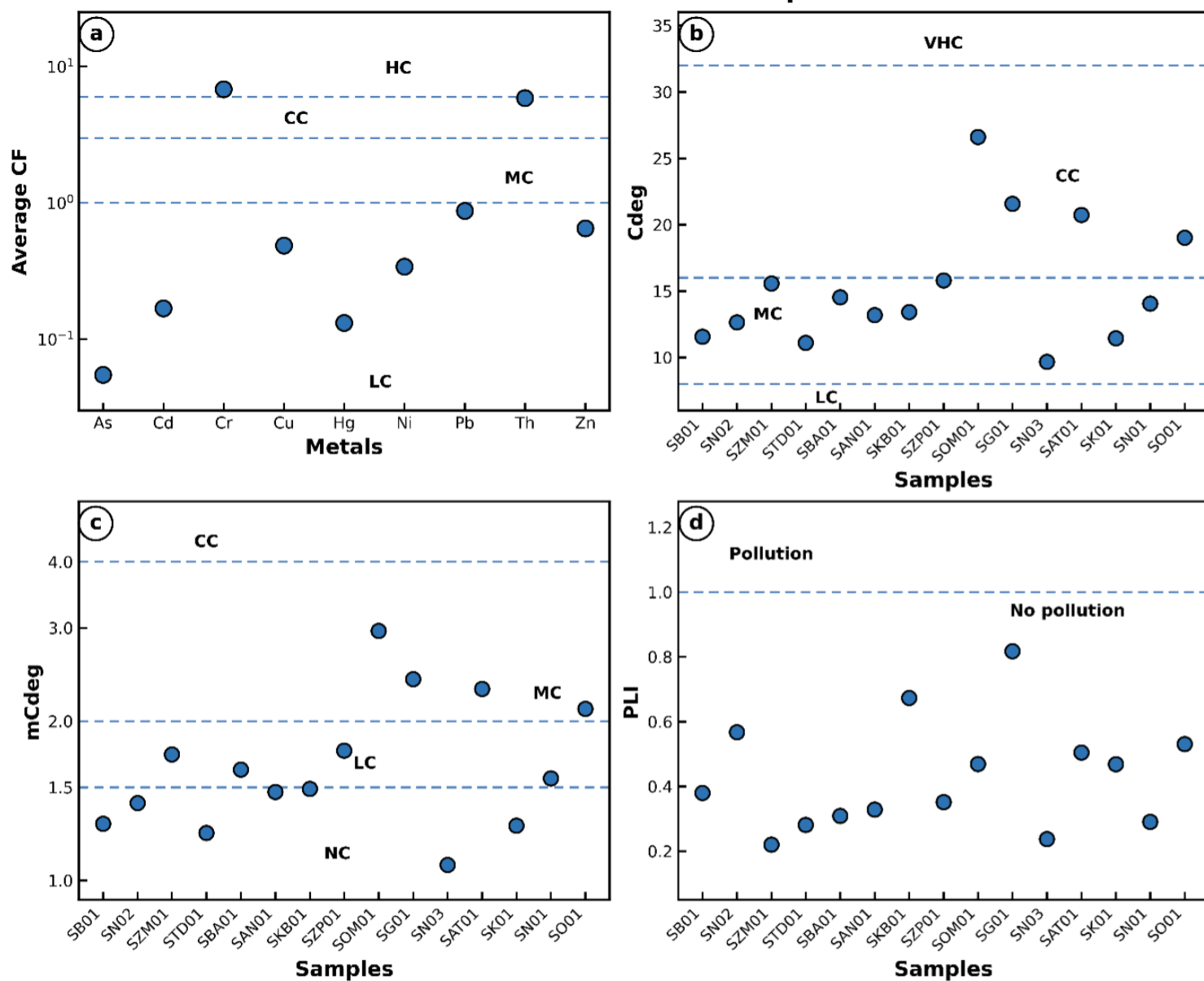


Figure 4

Contamination discrimination plots. (a) CF vs. Metals, (b) Cdeg vs. Samples, (c) mCdeg vs. Samples and (d) PLI vs. Samples. Note: LC = Low Contamination, MC = Moderate Contamination, CC = Considerable Contamination, HC = High Contamination, NC = No Contamination, VHC = Very High Contamination and UHC = Ultra High Contamination

Pollution and ecotoxicological discrimination plots

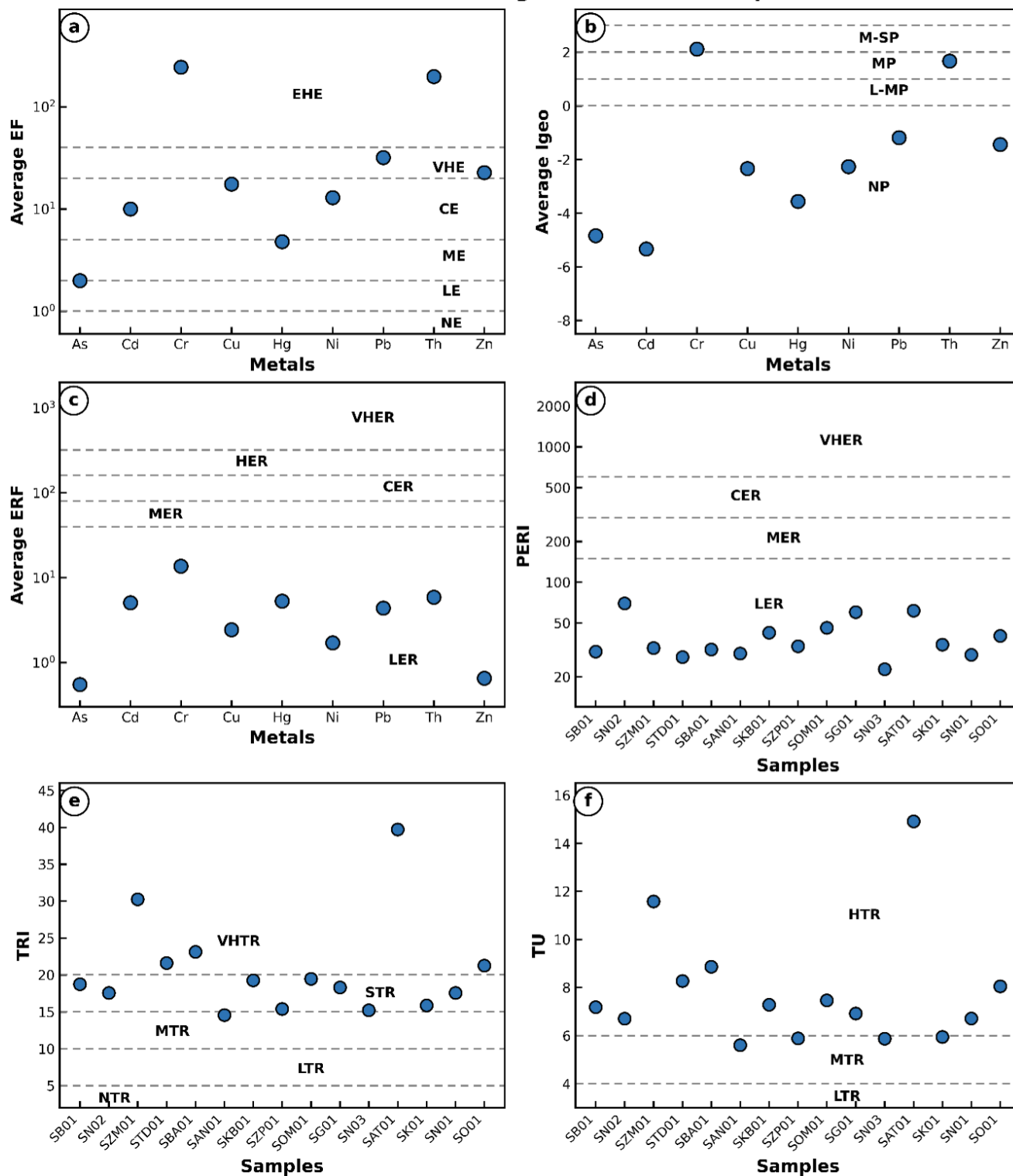


Figure 5

Pollution discrimination diagrams for stream sediments from the Zang-Tabi area. (a) EF vs. metals, (b) Igeo vs. metals, (c) ERF vs. metals, (d) PERI vs. samples, (e) TRI vs. samples and (f) TU vs. samples. Note: NE = No Enrichment, LE = Low Enrichment, ME = Moderate Enrichment, CE = Considerable Enrichment, VHE = Very High Enrichment, EHE = Extremely High Enrichment, NP = No Pollution, L-MP = Low to Moderate Pollution, MP = Moderate Pollution, M-SP = Moderate to Strong Pollution, LER = Low Ecological Risk, MER = Moderate Ecological Risk, CER = Considerable Ecological Risk, HER = High Ecological Risk, VHER = Very High Ecological Risk, NTR = No Toxic Risk, LTR = Low Toxic Risk, MTR = Moderate Toxic Risk, STR = Significant Toxic Risk and VHTR = Very High Toxic Risk.

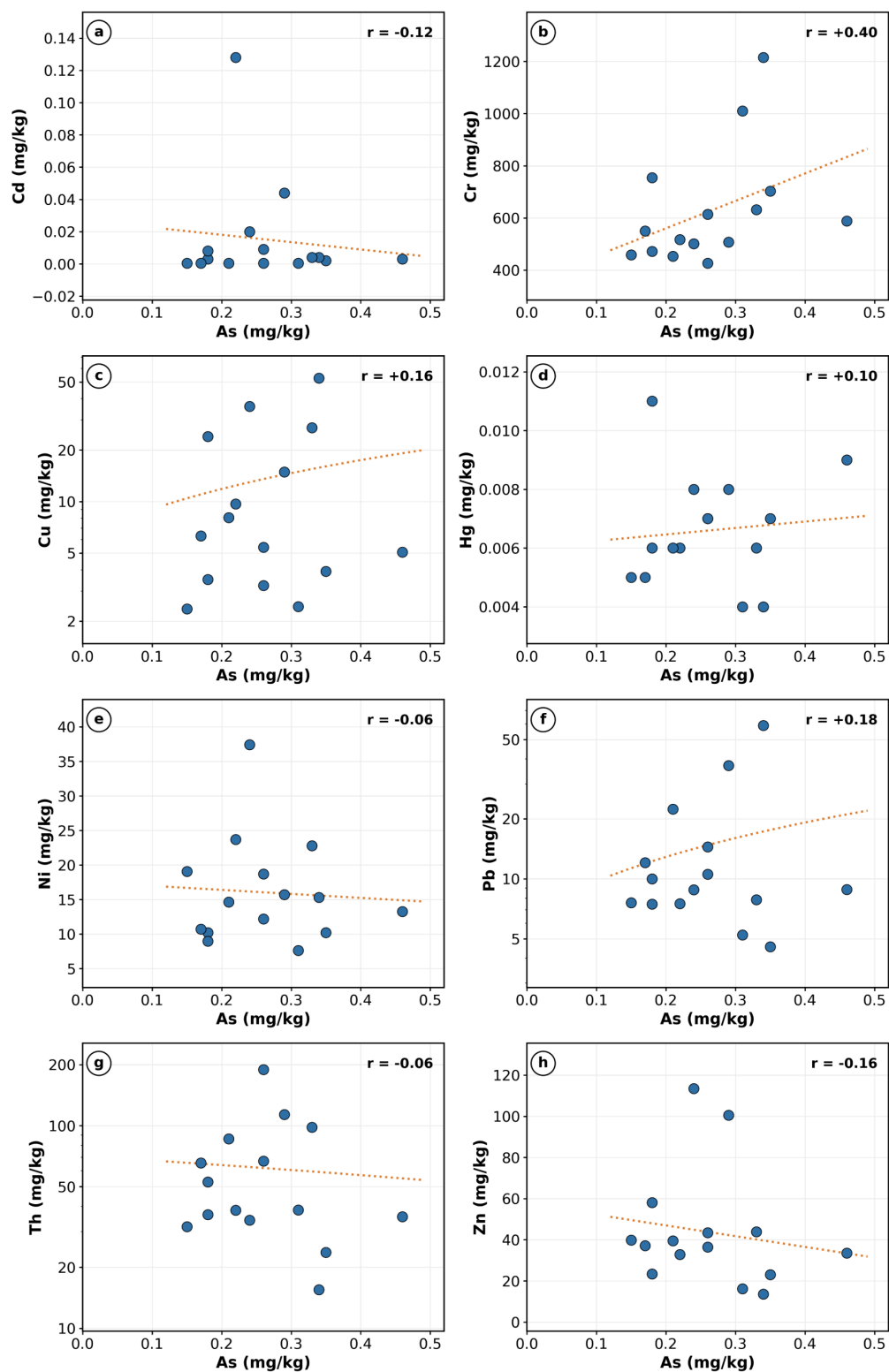


Figure 6
Bivariate scatter plots showing the relationships between As and the other potentially hazardous metals (concentrations in mg/kg) in the Zang-Tabi stream sediments. (a) Cd, (b) Cr, (c) Cu, (d) Hg, (e) Ni, (f) Pb, (g) Th and (h) Zn.

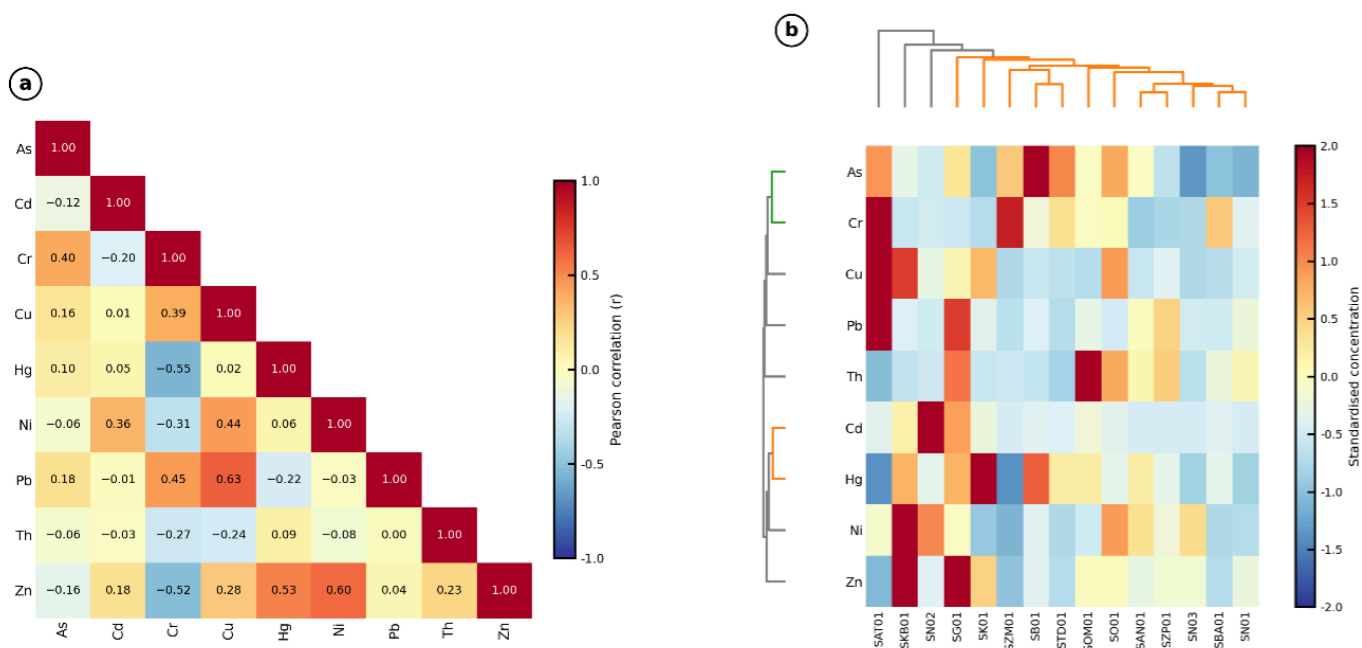


Figure 7

PCC and HCA of potentially hazardous metals in the Zang-Tabi stream sediments. (a) Pearson correlation matrix; (b) hierarchical cluster analysis dendrograms with heatmap of standardized concentrations (average linkage, Euclidean distance).

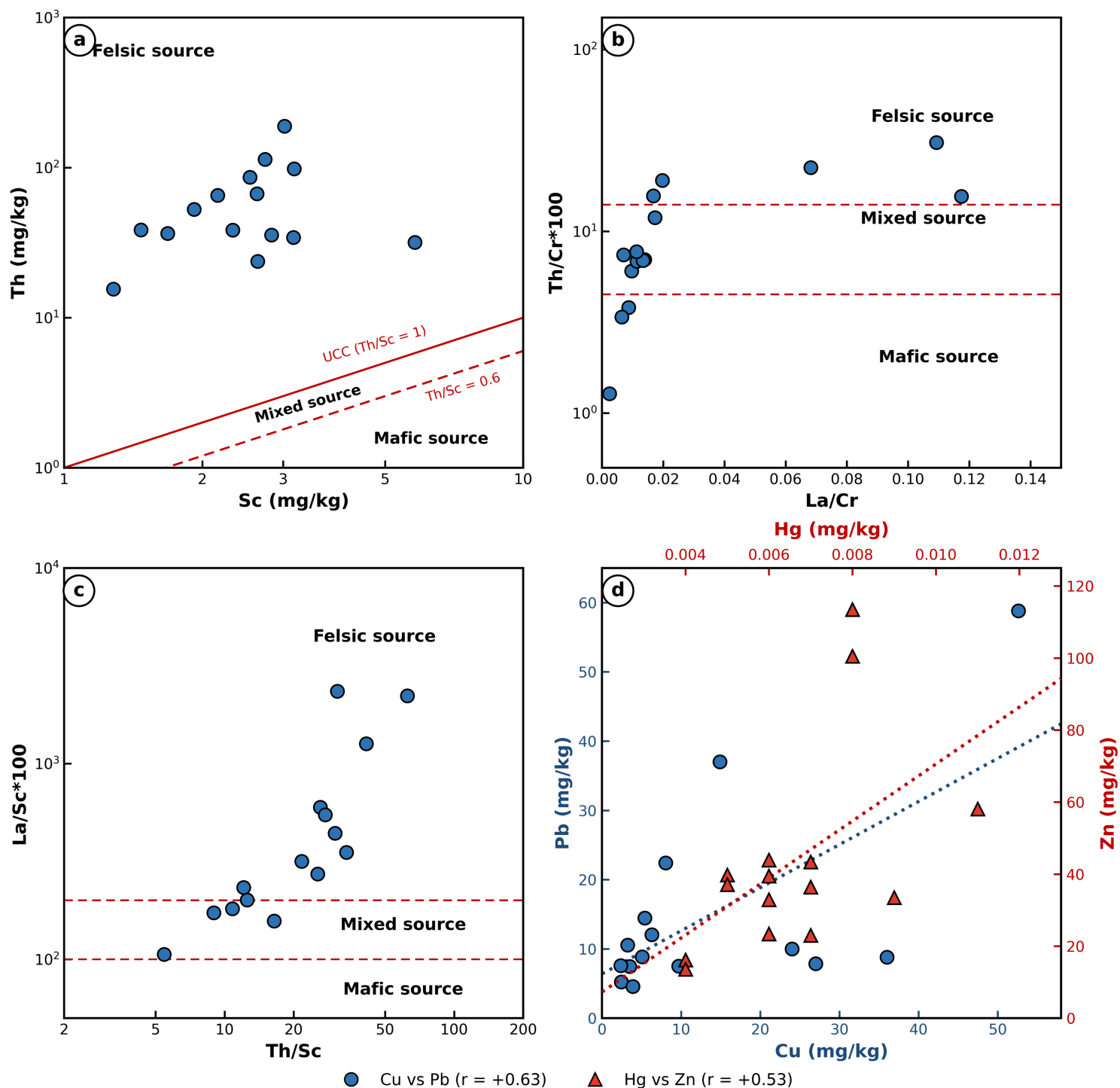


Figure 8

Source characterization plots for potentially hazardous metals in the Zang-Tabi stream sediments. (a) Sc (mg/kg) vs. Th (mg/kg) [37]; (b) La/Cr vs. Th/Cr × 100 [38]; (c) Th/Sc vs. La/Sc × 100 [38]; and (d) Cu-Pb and Hg-Zn covariation biplot, illustrating the two strongest PCC/PCA-defined metal associations (Section 4.5: Factor 1 Cu-Pb, $r = +0.63$; Factor 2 Hg-Zn, $r = +0.53$). An age-calibrated Ni-Cr provenance diagram (Taylor & McLennan 1985) was evaluated but is not reported here: the Zang-Tabi Ni-Cr data plot well outside the calibrated field of that diagram, which was developed from ancient shale compilations and is not applicable to this young, CVL-basalt-influenced catchment.

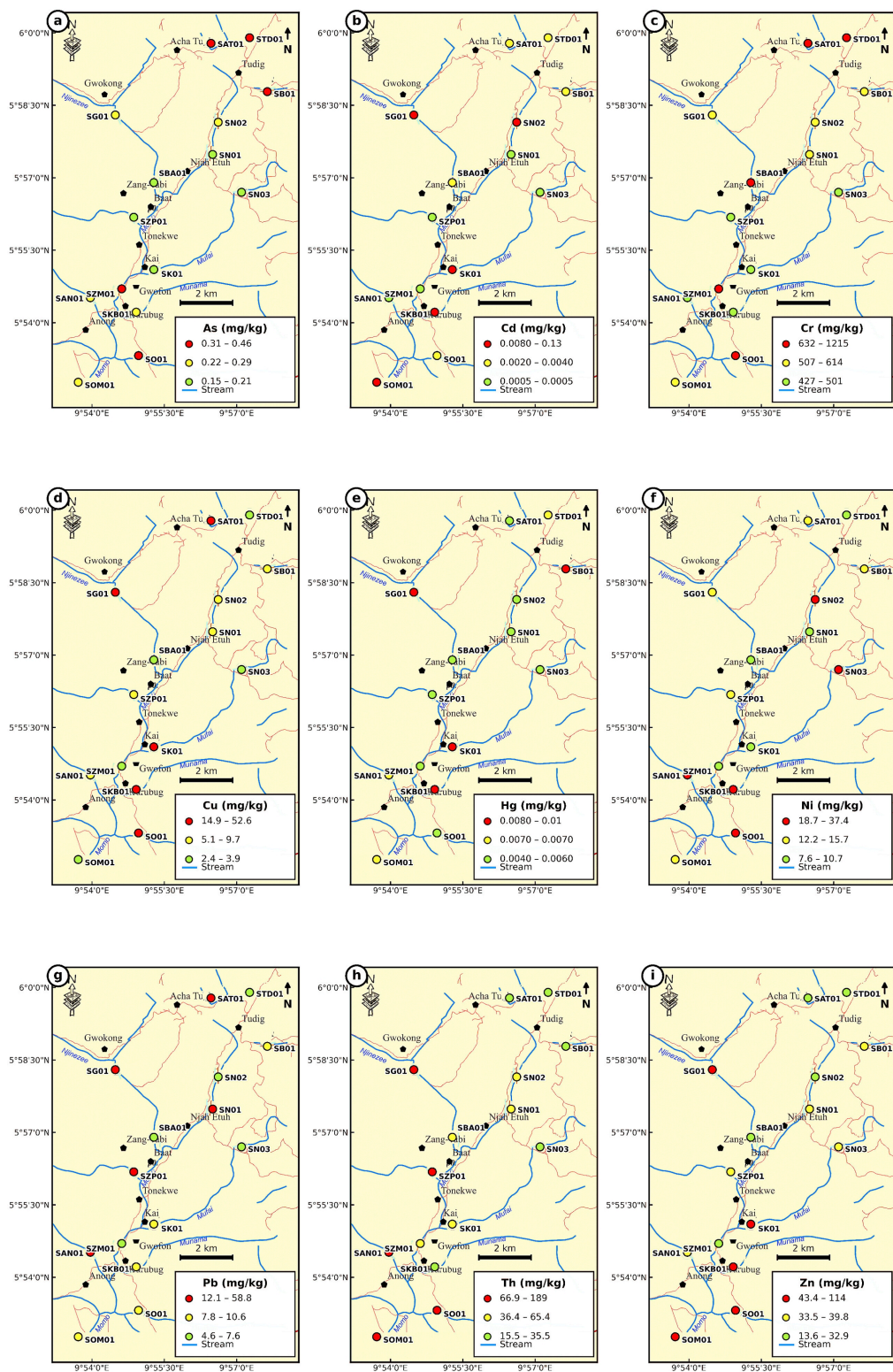


Figure 9

Spatial mapping of potentially hazardous metals in the Zang-Tabi stream sediments on the hydrographic base map of the drainage network. (a) As, (b) Cd, (c) Cr, (d) Cu, (e) Hg, (f) Ni, (g) Pb, (h) Th and (i) Zn.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryMaterialsDGZangTabiNdang.docx](#)