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Natural and anthropogenic controls on sediment geochemistry in tropical floodplain lakes of Central Kalimantan, Indonesia

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Natural and anthropogenic controls on sediment geochemistry in tropical floodplain lakes of Central Kalimantan, Indonesia

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Abstract

Three oxbow and one backwater lakes located within tropical floodplains of the Kayahan-Rungan river system, Central Kalimantan, Indonesia, were studied geochemically to assess the extent and distinguish provenience of heavy metal pollution (i.e., distribution of elements and identification of key geochemical processes controlling their association) in their sediments. For this purpose, 5 sediment cores were taken and studied using the Inductively Coupled Plasma Mass Spectrometry method, followed by statistical data treatment. Physicochemical parameters of water (temperature, pH, oxidation–reduction potential, electrical conductivity, dissolved oxygen, total dissolved solids, salinity, transparency) were measured in situ using portable tools and Secchi discs. Most elements occur at normal levels, comparable to average worldwide lacustrine sediment values. Bismuth (0.1-0.3 ppm, geometric mean of 0.21 ppm), Hg (0.02-0.24; 0.09 ppm), Se, Co (0.2-14; 1.8), Sc (0.5-12; 3.3), and Th (0.2-6.2; 1.7), and to a lesser extent V, Fe, La, As, Pb, Cu, Cd, and Sb are (locally) found elevated. Some of those elements are also typical constituents of Mid-Bornean hydrothermal ore mineralization systems, while others (Sc, Th, V, La, Fe) are naturally enriched in lateritic soils. A single Hg anomaly concerns a site located at a mouth of a channel connecting one of the lakes with the Rungan river, thus proving movement of known riverine anomalies caused by the local artisanal gold mining. However, Hg is immobilized via co-deposition with selenium, in the form of HgSe (tiemannite). Natural (detrital/weathering) and anthropogenic (i.a., mining) processes comprise the mixed geochemical background of the sediments.

Keywords: oxbow lake, lake-river connection, anthropogenic impact, sediment geochemistry

1. Introduction

Floodplain lakes constitute dynamic components of riverine systems and play a key role in regional biogeochemical cycling. Among them, oxbow lakes form as a result of river meander cutoff, creating semi-isolated water bodies that remain periodically connected to the main channel (Allen 1965). Due to this episodic hydrological connectivity, oxbow lakes act as efficient traps for suspended sediments, organic matter, and associated chemical elements transported from upstream catchments. As a result, their sediments provide valuable archives of environmental processes operating within river basins over time.

Lake sediments integrate both natural and anthropogenic signals, making them widely used for reconstructing environmental change and assessing contamination. Fine-grained sediments act as sinks for trace elements transported in association with suspended particles, where they may accumulate and persist over long periods (Mills et al. 2017; He et al. 2022). Under changing environmental conditions, such as variations in redox potential, pH, or hydrological regime, these elements may be remobilized into the water column, turning sediments into secondary sources of pollution (He et al. 2022). Consequently, the geochemical composition of lake sediments reflects not only source inputs but also post-depositional processes controlling element behavior in aquatic systems.

Mining activities represent one of the most significant anthropogenic factors influencing sediment geochemistry in freshwater environments. Artisanal and small-scale gold mining (ASGM), in particular, is known to introduce large quantities of mercury and other trace metals into aquatic systems (Setijadji et al. 2010; Dana et al. 2024). The use of mercury during gold amalgamation leads to its release into river systems, where it can be transported downstream and accumulated in floodplain lakes. In aquatic environments, mercury may be transformed into methylmercury, a highly toxic compound that bioaccumulates in food webs and poses significant ecological and human health risks (Poste et al. 2019; Tsui et al. 2020). This issue is further complicated by the limited effectiveness of mitigation strategies applied in ASGM-affected regions (Veiga et al. 2025).

Central Kalimantan (Indonesian Borneo) is part of the Central Kalimantan Gold Belt, a region characterized by long-term and widespread gold mining activity (Setijadji et al. 2010). Despite regulatory restrictions, ASGM remains common and continues to introduce mercury and other potentially toxic elements, including arsenic, lead, and zinc, into freshwater systems (Stapper 2011; Dana et al. 2024). At the same time, natural geochemical backgrounds in the region are strongly influenced by tropical weathering processes, particularly lateritization, which leads to the formation of iron- and aluminum-rich soils capable of binding and transporting trace elements (Roquin et al. 1990; Sahoo et al. 2016). The coexistence of strong natural geochemical signals and potential mining-derived contamination makes it challenging to distinguish between geogenic and anthropogenic sources in sediment records.

Despite the ecological importance of tropical floodplain lakes, geochemical studies of their sediments remain limited, particularly in Southeast Asia. In Central Kalimantan, freshwater systems are still poorly investigated, and the extent to which mining activities influence sediment composition is not well constrained. Addressing this knowledge gap is essential for understanding element cycling, assessing environmental risks, and supporting sustainable management of mining-affected river systems.

The present study investigates the geochemistry of sediments from four lakes belonging to the Kahayan–Rungan river system in Central Kalimantan. The objectives of this study are to (1) characterize the distribution of major and trace elements in lake sediments, (2) identify the key geochemical processes controlling element associations, and (3) evaluate the relative contributions of natural weathering-derived inputs and mining-related contamination. By integrating bulk geochemical data with multivariate statistical analyses, this study contributes to a better understanding of element behavior in tropical floodplain lake systems affected by artisanal gold mining.

2. Materials and methods

2.1 Study area

The study area is situated in Central Kalimantan (Indonesian Borneo), within the Kahayan–Rungan river system in the vicinity of the city of Palangkaraya (Fig. 1). The region hosts numerous floodplain water bodies associated with meandering river channels, including oxbow lakes that remain periodically connected to the main river during seasonal flood events. Such lakes represent important depositional environments where suspended material transported by rivers accumulates and is preserved in bottom sediments, providing records of both natural geological processes and anthropogenic inputs within the catchment (Ardianor et al. 2010).

Four lakes were investigated in this study: Batu, Hanjalutung, Lutan, and Sabuah (Fig. 1). Three of them (Lutan, Sabuah, and Hanjalutung) are typical oxbow lakes formed by abandoned river meanders, whereas Batu represents a backwater floodplain lake not directly associated with a recent meander cutoff. These lakes are relatively shallow and experience pronounced seasonal fluctuations in water level related to monsoonal rainfall and river discharge. Their periodic hydrological connectivity with the Kahayan River allows suspended sediments and dissolved components transported from upstream areas to enter the lakes, making them effective sediment traps that record environmental changes within the river basin (Ardianor et al. 2010; Junk et al. 1989). The selected lakes differ in their degree of hydrological connectivity with the main river channel and in their proximity to areas affected by anthropogenic activities, particularly artisanal gold mining and deforestation within the catchment area (Ardianor et al. 2010; Elvince et al. 2008). This variability provides a useful framework for evaluating both natural sedimentary processes and potential mining-related geochemical signals preserved in lake sediments. In particular, the Lutan lake has a channel connection with the Kahayan river with water flowing into the NE part from the Palagkaraya-Buntok (Pahandut Seberang, Kec. Pahandut) buildings, alongside the Tumbang Rungan street. In addition, the W part of the lake is located so close to the river that water exchange is evident even during the dry season. Two arms of the Sabuah lake - the SE and NE ones - are also very close to the Kayahan river, although the southern one is ephemerically overgrown with vegetation. The Hanjalutung lake is connected with the Rungan river via an inflow channel that is active during dry seasons. Wet seasons elevate the extent of the lake so that its waters spread up to 0.5 km inland. The Batu lake is not directly connected with the Kayahan river, but has a channel connection with the nearby Tehang oxbow lake. What is more, two streams running from a watershed of surrounding peatlands deliver, monthly, humus-rich waters to the lake (Ardianor 2010).

Geologically, the region belongs to the Central Kalimantan Gold Belt, which hosts numerous gold deposits and has been affected by long-term mining activity (e.g., Simmons and Browne 1990; Al Hakim et al. 2023). The surrounding catchments comprise volcanic, volcaniclastic, and intrusive rocks associated with hydrothermal polymetallic mineralization. Ore assemblages reported from the region include chalcopyrite, $CuFeS_2$, bornite, Cu_5FeS_4, galena, PbS, sphalerite, ZnS, arsenopyrite, FeAsS, stibnite, Sb_2S_3, pyrite, FeS_2, and locally molybdenite, MoS_2, reflecting mineralization enriched in Cu, Pb, Zn, As, Sb, Fe, and Mo (Setijadji et al. 2010; Anjarwati et al. 2018; Dana et al. 2024). Epithermal, porphyry, and volcanic-hosted massive sulfide (VHMS) deposits have been recognized within the Central Kalimantan metallogenic province, indicating a diversity of potential geogenic sources for trace elements transported through river catchments. In addition, intense tropical weathering promotes the formation of lateritic materials rich in Fe and Al and may contribute other elements associated with secondary oxide and clay minerals. Consequently, sediments transported through the Kahayan–Rungan river system may record both natural geological inputs and mining-related contributions.

In addition to natural geological sources, freshwater systems in Central Kalimantan are affected by anthropogenic inputs related to ASGM. Mining activities may introduce mercury and other potentially toxic elements into river systems, where they can be transported downstream and accumulate in floodplain lakes and wetlands (Stapper 2011; Dana et al. 2024).

Sampling sites were selected according to several criteria, including (1) their spatial location within the lake basin and (2) water-column depth. Particular attention was given to spatial variability within individual lake. In Hanjalutung Lake, one site was located close to the channel inflow, whereas the second site was situated farther from the inflow, allowing for the assessment of potential differences in sediment supply and geochemical composition across the lake.

2.2 Water analysis

Basic physicochemical parameters of lake water were measured in situ during sampling campaigns at the investigated lakes. Measurements were performed at each sampling site, using portable tools, to characterize environmental conditions during sediment coring.

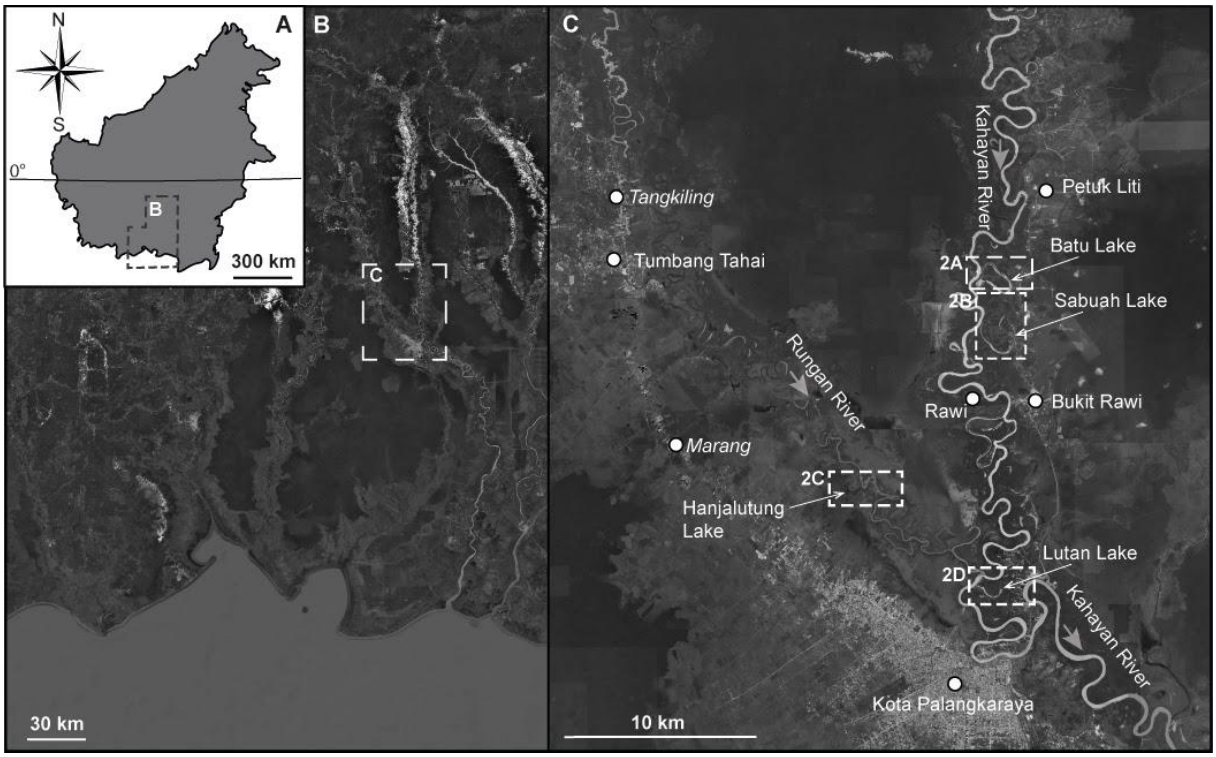
Water depth at each sampling location was measured using a portable depth sounder. Physicochemical parameters of lake water were measured in situ during field sampling using a water quality checker (Horiba U-10; Horiba Ltd., Kyoto, Japan). The measured parameters included temperature, pH, oxidation–reduction potential (ORP), electrical conductivity (EC), dissolved oxygen (DO), total dissolved solids (TDS), and salinity. Measurements were conducted directly in the water column, typically at the water surface. Water transparency

was measured using a Secchi disk, with transparency values recorded as Secchi depth (cm). These parameters were recorded to characterize the environmental conditions of the investigated lakes and to provide background information for the interpretation of sediment geochemistry.

2.3 Sediment coring and geochemical analysis

Lake sediment cores from four lakes were investigated in this pilot study, including three oxbow lakes (Hanjalutung, Lutan, and Sabuah) and one non-oxbow floodplain lake (Batu). In total, five short sediment cores were collected using a Livingstone corer. Two of these cores were obtained from Hanjalutung Lake in order to capture spatial variability within the lake basin (Fig. 2).

After splitting the cores longitudinally, the upper sections of the profiles (top to middle), representing the part most sensitive to recent anthropogenic influence, were selected for geochemical analyses and transported to Poland. Prior to transport, the cores were not sectioned into individual samples. Upon arrival, the selected core sections were subsampled at 2-cm intervals whenever possible. However, moisture loss during storage and transport resulted in sediment shrinkage and the formation of drying cracks, discontinuities, and voids within some profiles. Consequently, certain intervals could not be sampled at the intended resolution.



These gaps were recorded in the depth profiles and excluded from further analyses. Where insufficient material was available from individual intervals, adjacent sections were combined and treated as a single sample to obtain sufficient material for geochemical analyses. The subsamples were subsequently dried and homogenized using an agate mortar. In total, 44 sediment samples were obtained: 10 samples from Batu Lake (BAT2; 0–30 cm), 7 samples from Hanjalutung Lake (HAN1 1; 0–38 cm), 10 samples from Hanjalutung Lake (HAN4; 0–46 cm), 8 samples from Lutan Lake (LUT3; 0–46 cm), and 9 samples from Sabuah Lake (SB2; 0–46 cm).

Bulk geochemistry (main and selected trace elements) of powdered samples was analyzed using the Inductively Coupled Plasma E Spectroscopy (ICPES) method in ACME Labs (Bureau Veritas), Canada. Due to the content of refractory minerals like spinels and mullite a multi-acid digestion package was selected, as suggested by the paper of Arefieva et al. (2019). In this package, 0.25 g sample split is dissolved in a heated mixture of HNO_3, $HClO_4$, and HF, with residue being dissolved in HCl.

2.4 Numerical analysis

The statistical treatment of the geochemical dataset was designed to account for the compositional nature of the data. Prior to statistical analysis, the data were transformed using the centered log-ratio (clr) transformation in order to minimize the effects of data closure and to allow for appropriate interpretation of element relationships.

Following transformation, non-parametric Kendall's tau (τ) correlation coefficients were calculated to assess relationships between individual elements. This method was selected due to its robustness to non-normal data distributions and its suitability for geochemical datasets.

Principal Component Analysis (PCA) was subsequently applied to the clr-transformed data to identify the main factors controlling variability within the dataset and to recognize potential geochemical associations among elements.

All statistical analyses were performed using the R and PAST software package (Hammer et al. 2021; R Core Team. 2023). Prior to transformation, raw data were examined using the Shapiro–Wilk test to evaluate normality and using mean-and-whisker plots to assess data dispersion and identify potential outliers.

3. Results

3.1 Basic water analysis results

Across all investigated sites, the measured physicochemical parameters showed relatively limited variability typical of shallow tropical floodplain lakes. The reported values represent mean measurements obtained at each sampling site. Water depth at the coring sites ranged from 0.6 to 3.7 m, while water transparency (Secchi depth) varied between 12 and 23 cm. Maximum lake depth was between 8 and 15.9 m. Water temperature ranged from 29.3 to 33.4 °C, whereas pH values varied between 5.67 and 6.63, indicating slightly acidic to near-neutral conditions. ORP ranged from 152.4 to 292 mV, suggesting generally oxidizing conditions within the water column. Electrical conductivity values ranged from 0.014 to 0.031 mS cm^{-1}, and DO concentrations varied between 8.99 and 21.86 mg L^{-1}. TDS ranged from 0.009 to 0.024 g L^{-1}, whereas salinity values were very low, between 0 and 0.04 ppt, confirming the freshwater character of the investigated lakes. The results of the physicochemical analysis of lake water are summarized in Table 1.

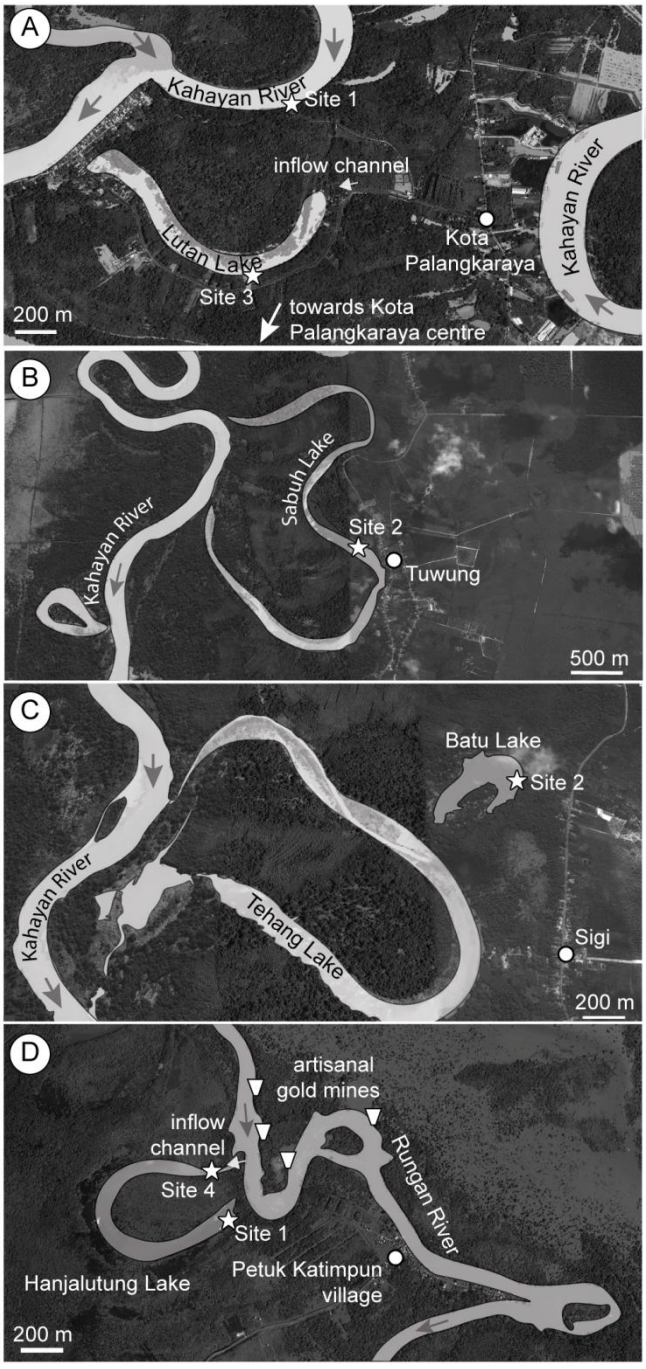
3.2 Elemental composition of sediments

Absolute concentrations of all analyzed elements are presented in Online Resource 1, whereas average contents, expressed as geometric means (GMs), are summarized in Table 2. Their vertical distribution in sediment core profiles is illustrated in Online Resources 2-6, whereas selected geochemical indicators are presented in downcore profiles shown in Figures 3–6.

Of the 36 elements analyzed, only boron and tungsten were below detection limits. Gold, molybdenum and bismuth were recorded in >30 samples, while thallium and arsenic in >20 ones. Most of the elements show relatively normal to low (as for lacustrine sediments) levels, with an exception of bismuth, selenium, scandium, thorium, cobalt, and single records of iron and lanthanum. Silver is recorded at the Hanjalutung's site 4 (HAN4) and two samples derived from Lutan's profile of the site 3 (LUT3). Cadmium and antimony are positively determined exclusively in some Lutan and Sabuah samples. Sulfur is only seen in a few samples (5 records in HAN4 (0-12 cm), and Sabuah's site top layers (SAB2; 0-6 cm). Arsenic, bismuth, and thallium are below detection limits in Hanjalutung's site 1 samples (HAN1).

Silver, cadmium, and antimony occur at low concentrations (0.1–0.2 ppm), whereas sulfur ranges from 0.05 to 0.10 ppm and arsenic from 0.5 to 4.0 ppm (GM = 1.7). Among the remaining trace elements, concentrations vary as follows: Ba 4–117 ppm (GM = 28), Bi 0.1–0.3 ppm (0.21), Hg 0.02–0.24 ppm (0.09), Ga 1–11 ppm (6.4), Sr 1–17 ppm (4.3), Th 0.2–6.2 ppm (1.7), Tl 0.1–0.3 ppm (0.19), and U 0.2–1.1 ppm (0.56).

Major elements display broader variability, including Ca 100–3500 ppm (GM = 812), Mg 100–3000 ppm (689), P 30–560 ppm (146), K 100–900 ppm (324), Na 20–190 ppm (48), and Ti 20–140 ppm (43). Comparable ranges are observed for several trace elements, such as V 5–99 ppm (34), Zn 4–89 ppm (21), Cu 1.6–37 ppm (10), Co 0.2–14 ppm (1.8), Sc 0.5–12 ppm (3.3), Ni 1.1–18 ppm (5.2), and Pb 0.2–6.2 ppm (1.7).



Most of the maximum element levels concern the Lutan lake, especially the 6 cm (Co, Mn, K), 22 cm (Al, Cr, Fe, La, Mg, Sc, and Th), 30 cm (Ba, Tl), 40 cm (Ni, Zn), and 46 cm zones (Ag, As). However, contents of most elements (with only slight variations for Ca, Mn, P, and Ti) are largely invariable through the Lutan's core. This includes Pb, with its highest contents observed through the whole profile. So is, more or less, true for K. The highest Ti levels are detected in Lutan's site toplayer. The Sabuah's site toplayer shows the highest anomalies of Cd, Cu, Mo, Pb, Sb, S, P, and - exe quo with Lutan - Bi and La. At once, the highest gold level is observed for

Sabuah's 42 cm layer. The maximum levels of mercury and selenium are found in the middle (12 or 12-18 cm) portion of the Hanjalutung's site 4 core; and that of uranium - at the 30 cm depth of the same core. The Batu core shows the record anomalies only for two elements - vanadium, in the toplayer, and gallium (30 cm depth).

In the Batu case, the topmost layer is distinguished by a clear enrichment in Fe, Cr, Cu, K, Mg, Ni, Th, Ti, and Zn. The whole profile shows elevated Bi and Tl concentrations, local enrichment in Al and Ga, and enrichment in Sr in the bottom layers. The top layer of Sabuah also shows elevated Al, Ba, Ca, Cr, Fe, Hg, Mn, Na, Ni, U, V, and Zn. The sub-top layer is enriched in Sb, in turn. Local enrichment in the Sabuah core concerns Au and Tl. The Hanjalutung's site 4 core characterizes in the presence of elevated mercury, silver and bismuth, while some levels are also somewhat enriched in gold. Locally elevated Al, Ga, La, Tl, and lowermost-layer enrichment in Ti are also noticed. The site 1 only shows some Hg anomalies, although lower than those at the site 4. The Lutan core is also somewhat enriched in Au, Mn, Mo, and U; and, locally, in Cd, Cu, Fe, Sb, Sr, and V.

The downcore geochemical profiles revealed distinct differences among the studied lakes (Online Resources 2-6 and Figures 3–6). Lake Lutan (LUT3) was generally characterized by the highest concentrations of major and trace elements, particularly Ti, Fe, Sc, Zn, Pb, and Cu, as well as elevated Fe/Al ratios throughout the profile. In contrast, HAN1 typically showed the lowest concentrations of several elements, including Cr, V, Zn, Pb, Hg, and Cu.

Most elements displayed relatively stable downcore trends within individual cores, with only moderate fluctuations at specific depths. Aluminum, Mg, and K varied only slightly throughout the sediment profiles, whereas Cr, V, Zn, Pb, Hg, and Cu showed greater variability between lakes.

Elemental ratios (Th/Sc, La/Sc, Cr/Th, Fe/Al, and K/Al) also differed among the lakes. Fe/Al ratios were consistently highest in LUT3, while K/Al values remained comparatively stable across most profiles. Cr/Th and La/Sc exhibited greater variability, particularly in HAN4 and SAB2. The highest K/Al values were generally observed in the less element-enriched profiles, whereas elevated La/Th values occurred mainly in LUT3, suggesting variability in weathering intensity and sediment source characteristics among the studied lakes.

Among the analyzed trace metals, Pb and Cu reached their highest concentrations in LUT3, whereas Hg showed locally elevated values in HAN4. Overall, the geochemical records indicate substantial spatial variability in sediment composition and elemental distribution among the studied lakes.

The measured element concentrations were compared with literature-based reference values for average lake sediments, which were used to calculate enrichment factors (EFs; Fig. 7). The literature dataset used for these calculations is provided in Online Resource 7. Only enrichment factors exceeding 2 in at least two samples for a given element are shown in Figure 6. Selenium in the Sabuah (SAB2) core represents an exception and was included despite not meeting the selection criterion, as the EF value in the surface sample reached 4.

The EF analysis revealed clear differences in trace element accumulation among the studied lakes and within sediment profiles. Most of the analyzed elements showed EF values corresponding to deficiency to minimal enrichment ($EF < 2$) across the studied sediment profiles.

In Lake Batu (BAT2), Bi showed moderate enrichment ($EF \approx 5$) throughout the sediment profile, whereas V exhibited generally low EF values (~1–2), with only slight increases in the surface layer and around 26 cm depth.

The sediment profile of Lake Hanjalutung (HAN4) displayed a more variable EF distribution. Bi remained consistently moderately enriched (EF ~5), while Se reached locally elevated values, particularly at approximately 12 cm depth (EF ~6), suggesting episodic increases in selenium input. Mercury (Hg) showed low enrichment levels (EF ~1–2) across the profile.

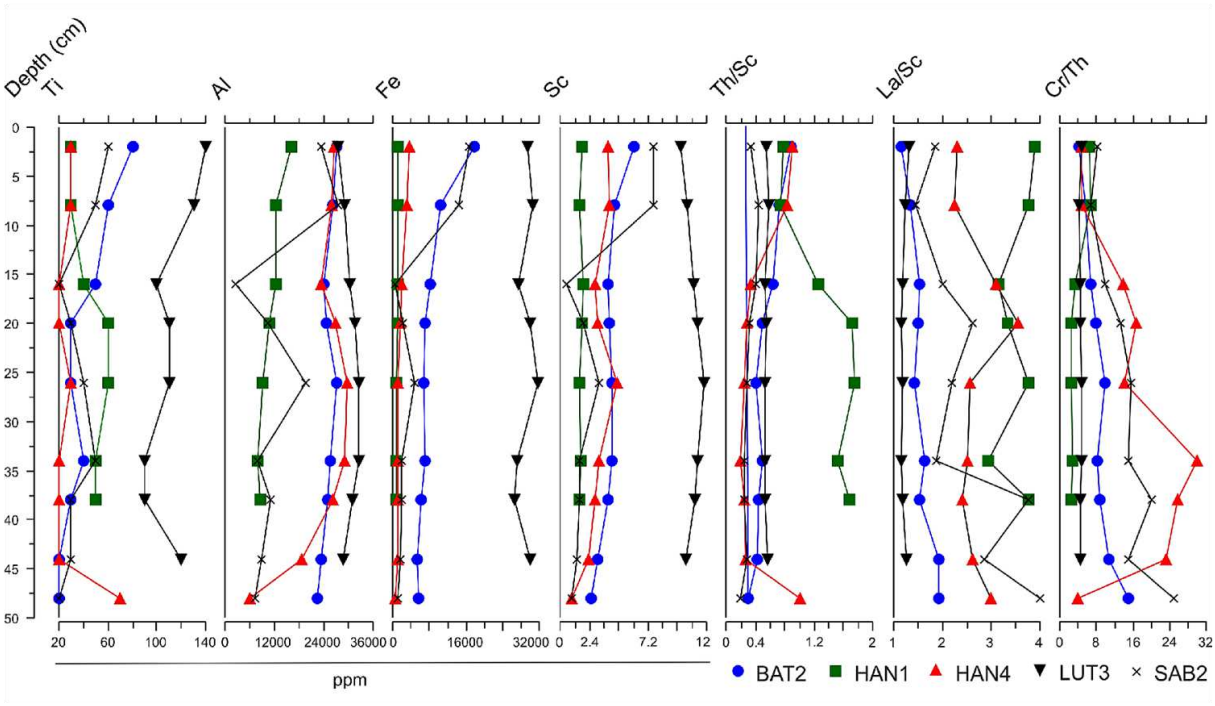
The highest EF values were observed in Lake Lutan (LUT3), where Bi reached values of approximately 8 throughout the entire profile, indicating significant enrichment. The remaining elements (Co, Th, V, and Sc) were characterized by low to minimal enrichment (EF ~1–2), with occasional decreases in Co approaching background levels.

In Lake Sabuah (SAB2), pronounced Bi enrichment was recorded in the upper part of the profile (EF up to ~8), decreasing with depth to moderate values (EF ~3–5). Selenium showed moderate enrichment only in the surface layer (EF ~4), whereas V and Sc remained at low EF values.

3.3 Statistical analysis results

The Shapiro–Wilk test (W) was used to evaluate the normality of element distributions. Based on the obtained *p(normal)* values (≤ 0.4), several elements, including Cr, Pb, U, V, P, and La, show high W values (≥ 0.9). This indicates close-to-normal distributions. Most of the remaining elements exhibit the W values above 0.8, whereas slightly lower values (W ≥ 0.7) are observed for Sr, Bi, Ba; Fe and Na. The lowest W (≥ 0.6) occurs for Co, Tl; and Mn.

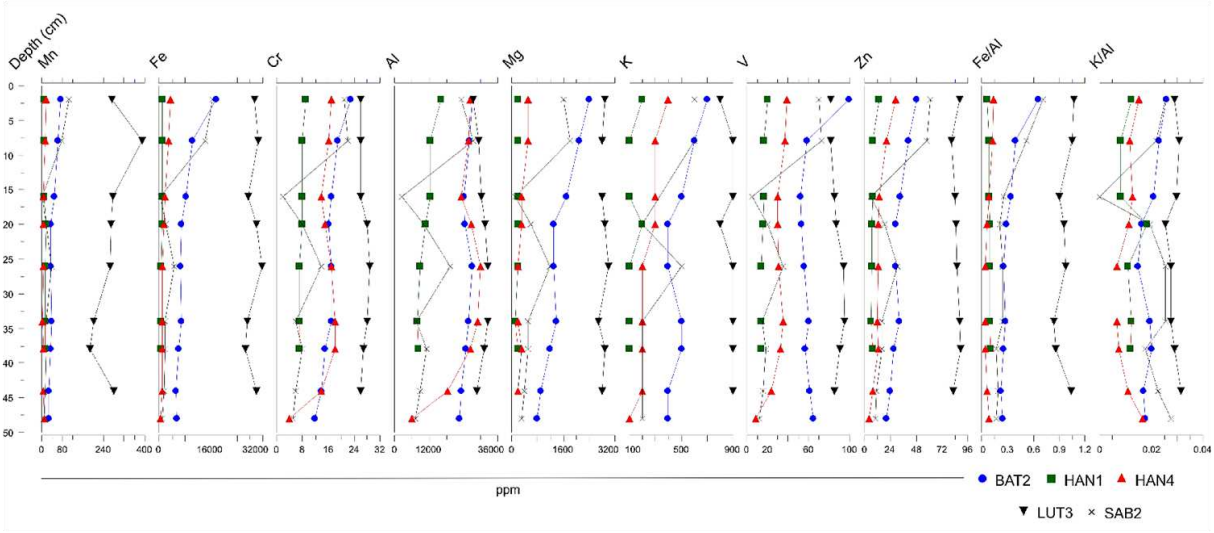
The mean-and-whisker plots (Online Resources 8 and 9) indicate that Fe and Al display the largest variability within the dataset, while Ca and Mg show only minor variation. The remaining elements exhibit relatively limited variability across the studied sediment samples.

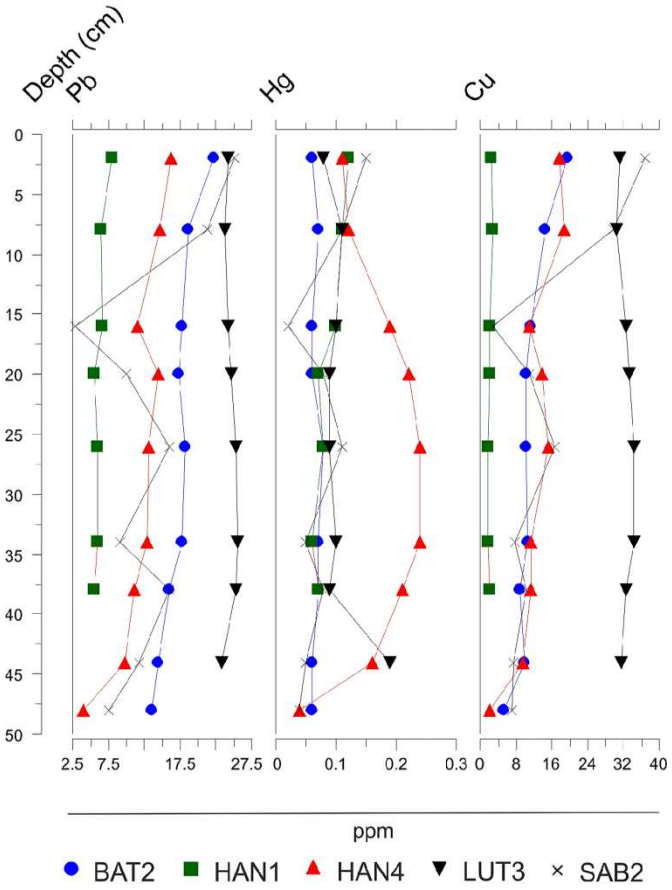


No clear negative correlations were identified via the Kendall correlation analysis (Table 3). Several strongly correlated element pairs (τ ≥ 0.89) were observed, including Zn-Co, Zn-Fe, Zn-Mg; Co-Fe, Co-K; Fe-Mg, Fe-K; and Cr-Sc. Slightly weaker correlations (τ ≥ 0.80) include element systems such as Pb-Zn-Ni-Co-Fe-K-V-Mg-Ba-K-Sc as well as Cr-Al, Sc-Al, and V-Cr. Moderate correlations (τ ≥ 0.70) involve several multi-element associations, including Cu-Pb-Zn-Co-Ca-La-Cr-Ba-Sc-Al, Pb-Bi-Cr, Zn-Mn-Bi-V-Cr-Cs, Mn-Fe-As-K-V-Cr-Sc, U-Cr-Al, V-Mg-Al, Cr-Ba-K, and Ga-Al. Some elements show more limited relationships: Mo weakly correlates with P, La, Cu, and Sr; Au with Bi; Tl with Ga; and P with La and Hg. Gallium also shows minor associations with Hg and Tl.

Principal component analysis (PCA) performed on the reduced dataset revealed distinct grouping of sediment samples and geochemical variables (Fig. 7). The first principal component (PC1) explained 71% of the total variance, indicating that the majority of geochemical variability among the studied sediments is controlled by a single dominant gradient. Samples from LUT3 are clearly separated along the positive side of PC1, whereas HAN1 and part of HAN4 samples plot predominantly on the negative side of this axis. In contrast, HAN4

samples are characterized by elevated PC2 scores, indicating differences in geochemical composition relative to the remaining sites.



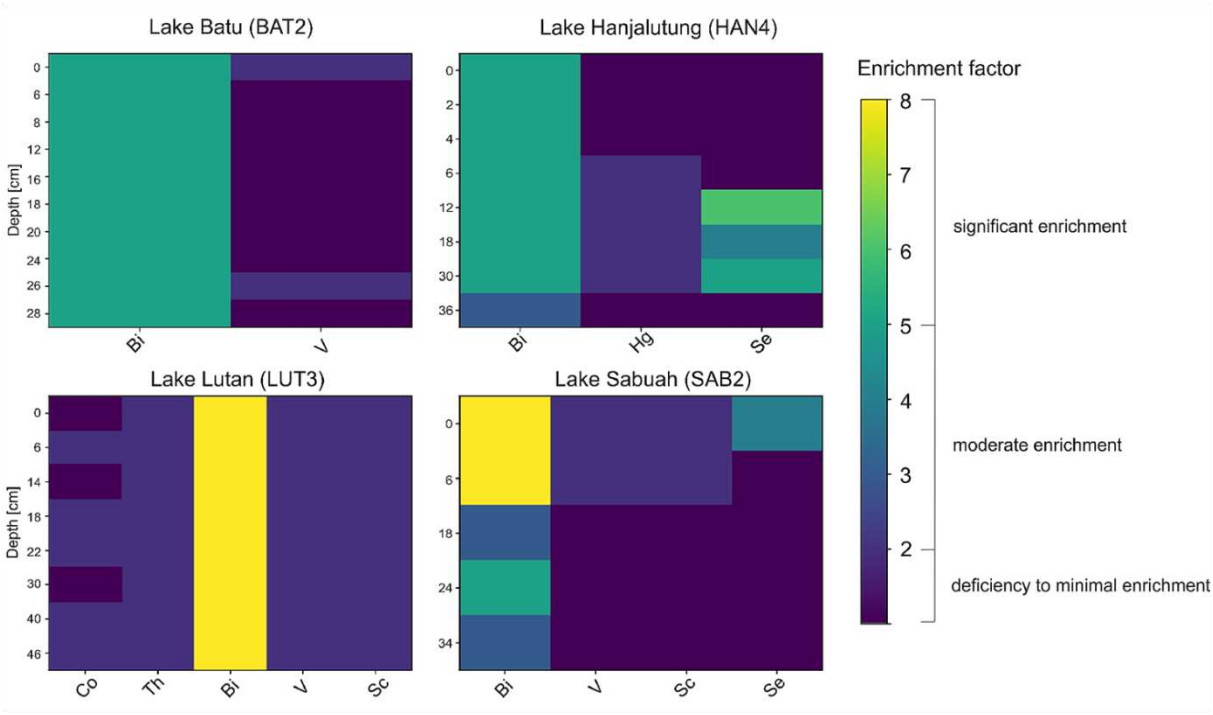


Among the analyzed variables, P, Cu, Ca, Al, and Pb show positive loadings on both PC1 and PC2, whereas Fe, Mn, Th, and Ti are associated with positive PC1 and negative PC2 values. Arsenic plots close to the origin, indicating a relatively minor contribution to the variance explained by the first two principal components, while Tl displays weak negative loadings on both axes.

The ordination suggests several geochemically coherent element associations. Phosphorus is closely associated with Cu and Ca, whereas Fe, Mn, Th, and Ti form a second group related to the negative PC2 direction. Lead, Al, and Zn occupy intermediate positions between these groups. The distribution of samples and element loadings indicates that the main geochemical gradients represented by PC1 and PC2 reflect differences between weathering-derived mineral phases and elements potentially associated with ore-related and anthropogenic inputs.

Discussion

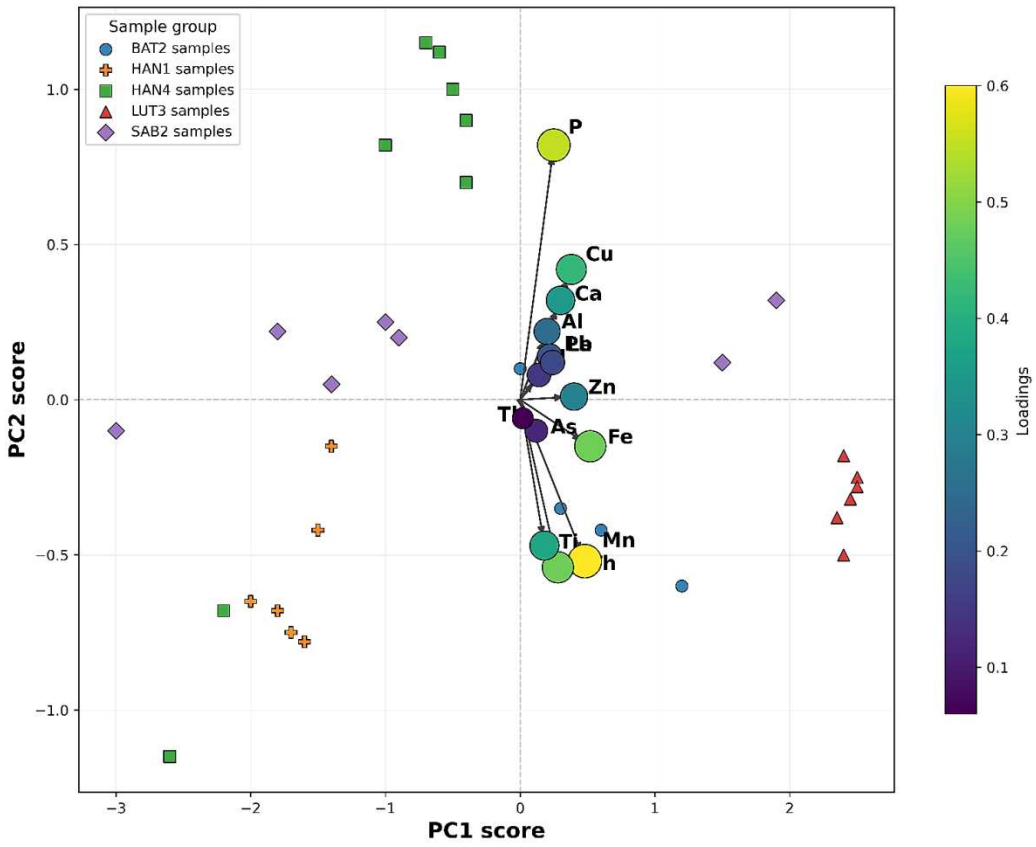
The investigated lakes form part of a floodplain lake–river system that functions as an efficient trap for suspended material transported by the Kahayan–Rungan river network. Due to their shallow character and periodic hydrological connectivity with the main river channel, these lakes receive mineral particles, organic matter, and dissolved components derived from upstream catchments. As a consequence, lake sediments represent integrated archives of both natural geological processes occurring within the drainage basin and anthropogenic inputs related to human activity in the region. Such depositional environments are known to effectively accumulate fine-grained sediments and associated trace elements transported during seasonal flood events (Allen 1965; Junk et al. 1989). The obtained results indicate that, despite a generally uniform geochemical background, element distributions are strongly site-specific and exhibit pronounced depth-dependent variability across the studied lakes.



There are two major sources of most elements studied: the gold/polymetallic mining and local, barren-rock lithology as well as rock weathering. The latter is collectively known as lateritization, responsible for the formation of specific soil layers known as saprolites, duricrusts, oxisols, and mottled horizons.

It should be noted that numerous correlations observed by us can be simply explained by the rules of diadochy, i.e., similar ionic radii of the elements studied. This phenomenon is responsible for preferential sorption of selected elements by the particular mineral structures. As such, the Zn-Fe, Zn-Mg, Fe-Mg, Fe-K, Ti-K, and V-Cr-Ba-K-Mg-Al systems comprise elements that are known constituents of the mica-group minerals, especially represented by their clayey fraction that is well-known for sorption capabilities. The Zn-Fe, Zn-Mg and Fe-Mg pairs may also point to the presence of the chlorite-group species in the sediments studied. Typical, geochemically well-known diadochy systems that also concern our materials include the Cr-Al and Ga-Al pairs. Meanwhile, association of Hg with Ga, Tl with Ga, Au with Bi, and Cu with Pb, Zn, and Ba – typically derived

from hydrothermal ore deposits – stand for a potential confirmation of the delivery of the post-mining material from the orefield areas.



3.3 Natural geochemical background

The bulk geochemical composition of the studied sediments indicates that most elements occur within concentration ranges typical of lacustrine deposits and primarily reflect the influence of natural lithological sources and tropical weathering processes operating within the catchment. The dominance of major elements such as Al, Fe, Mn, Ti, and Ca, together with trace elements including Cr, Ni, Sc, and V, suggests that sediment composition is largely controlled by detrital inputs derived from weathered bedrock and transported into the lakes by fluvial processes.

In tropical environments, intense chemical weathering plays a major role in shaping sediment geochemistry. Under the warm and humid climatic conditions characteristic of Central Kalimantan, lateritization promotes the formation of thick weathering profiles enriched in Fe- and Al-bearing secondary minerals, particularly hematite, goethite, and gibbsite (Roquin et al. 1990; Sahoo et al. 2016). These phases act as important sorbents and geochemical hosts for numerous trace elements, including Ni, Ga, Sc, Cr, and V, thereby exerting a strong influence on the composition of sediments transported through river systems (Freitas et al. 2024). The observed associations among Fe, Mn, Cr, Sc, Ni, and V are consistent with contributions from lateritic weathering products and mafic to intermediate lithologies occurring within the Central Kalimantan Gold Belt (Setijadji et al. 2010; Sai Babu et al. 2025). In addition, rare-earth-bearing minerals such as monazite may contribute to the occurrence of lanthanum in the studied sediments.

Additional insight into sediment sources and weathering processes is provided by the elemental ratios K/Al, Fe/Al, La/Sc, Cr/Th, and Th/Sc. Potassium is relatively mobile during intense tropical weathering, whereas aluminum tends to be retained in secondary clay minerals and weathering products; consequently, variations in the K/Al ratio may reflect differences in weathering intensity and the relative contribution of detrital versus

highly weathered material (Nesbitt and Young 1982). The Fe/Al ratio may further indicate variations in the relative abundance of iron-rich weathering products formed during lateritization (Sahoo et al., 2016; Freitas et al., 2024). In contrast, ratios involving relatively immobile trace elements, such as La/Sc, Cr/Th, and Th/Sc, are commonly used to assess sediment provenance and lithological variability because they reflect differences in source-rock composition and sediment supply (Taylor and McLennan 1985; Cullers 2000). Together, these indices suggest that both weathering intensity and variability in sediment sources influenced the geochemical composition of the studied floodplain lake sediments.

Scandium and chromium are typically associated with mafic rocks like basalts and such an association also explains strong Zn-Co, Co-Fe, Ni-Co, and V-Co correlations (Sai Babu et al., 2025). In tropical weathering rock profiles common element-controlling minerals are the iron minerals hematite, Fe_2O_3, and goethite, FeO(OH), and to some extent also gibbsite, $Al(OH)_3$ (Fe, As, Pb, Zn, V, Cr, Sc), while monazite-group species, e.g., monazite-(Ce), $(Ce,La,Nd,Th,Ca)PO_4$, controls, i.a., La (Freitas et al., 2024). Lateritic ferricretes of south Mali concentrate, i.a., Al, Fe, V, and Cr, while slope-residing gritty layers rich in kaolinite may pose a sink for Ni Ba, and K (Roquin et al. 1990). Some laterites are collectively mined for Co, Ni, Zn and Mn, and may also be associated with Cr derived from chromite overburden, as shown by Mishra et al. (2016). Similarly, association of Zn, Mn, Co, and Fe is reported for cobaltiferous limonitic laterites of Uganda (Smith et al. 2016). Sahoo et al. (2016) pointed to Al (oxy)hydroxides to largely control behavior of most elements in upland lacustrine sediments of Amazon, while also pointing to iron oxyhydroxides as a sink for Mn, As, and to some extent also Co. Similar species in the area under our scope could explain correlations of U-La-Sc-Cr-Al, Ni-Al, and Mn-Fe-As. Industrial activity including phosphate mining, domestic waste inflow, traffic, and atmospheric particulate matter deposition may largely alter both inputs and relations of some elements in sediments, as exemplified by behavior of Cd, As, U, and Th in the Togo lake watershed (Avumadi et al. 2019).

The physicochemical characteristics of lake water further support the interpretation of a predominantly detrital and weathering-controlled geochemical background. The investigated lakes are shallow freshwater systems characterized by low electrical conductivity and total dissolved solids, indicating weakly mineralized waters typical of tropical floodplain environments. Slightly acidic pH values (5.7–6.6), together with positive ORP values and relatively high dissolved oxygen concentrations, suggest generally oxidizing conditions within the water column. Under such conditions, iron and manganese oxyhydroxides remain stable and may act as efficient scavengers for numerous trace elements, thereby influencing the geochemical composition of lake sediments (Förstner and Wittmann 1981). The generally low sulfur concentrations observed in the sediments likely reflect oxidizing conditions that limit sulfate reduction and the formation of sulfide minerals. Consequently, sulfur is expected to occur predominantly as dissolved sulfate rather than being incorporated into sedimentary sulfides.

3.4 Anthropogenic mining signal

Despite the generally natural geochemical background observed in the studied sediments, several elements display localized enrichment patterns that suggest additional anthropogenic influences. In particular, elevated concentrations and localized enrichments of Hg, Pb, Cu, As, Sb, and Cd, together with moderate to high enrichment factors observed for Bi and locally Se, indicate that mining-related and ore-related inputs may contribute to the geochemical composition of some sediment layers.

Mercury anomalies are most clearly expressed in the Hanjalutung Site 4 core (HAN4), where elevated Hg enrichment factors coincide with the presence of other trace elements potentially associated with ore-related mineralization. No distinct Hg anomaly was observed in the HAN1 core, likely because this site is not directly connected to the Rungan River. Similar enrichments are also present in the upper layers of the Sabuah core. Such patterns are consistent with the influence of artisanal and small-scale gold mining (ASGM), which is widespread within the Kahayan–Rungan river basin and commonly involves the use of mercury during gold amalgamation. During this process, mercury may be released into the surrounding environment and subsequently transported through river systems in both dissolved and particulate forms (Stapper 2011; Poste et al. 2019). In the environment, Hg is commonly methylated into the extremely toxic and bioavailable methylmercury form. It is thus important to note that, although the Hg anomaly at the Hanjalutung Site 4 coexists with Se anomaly. Selenium is well-known for immobilizing mercury, as mercury(II) selenide, HgSe (i.e., the mineral tiemannite, Mindat 2026c), is extremely low-soluble, thus preventing environmental spread of Hg. Tiemannite

microparticles are essential in Hg (in particular, its methylated form) detoxification, e.g., in marine mammals (von Hellfeld et al. 2024).

The observed enrichment of Cu, Pb, Zn, As, and locally Sb is consistent with the geological characteristics of the Central Kalimantan Gold Belt. Ore assemblages reported from the region contain chalcopyrite, bornite, galena, sphalerite, arsenopyrite, and stibnite, whereas epithermal, porphyry, and VHMS-type mineralization have been documented upstream of the studied lakes (Setijadji et al. 2010; Anjarwati et al. 2018; Dana et al. 2024). Consequently, part of the geochemical signal recorded in the sediments may reflect erosion and transport of ore-related material derived from mineralized areas, potentially enhanced by mining activities and land disturbance within the catchment.

Floodplain lakes connected to river channels represent particularly effective sinks for mining-derived contaminants. Suspended sediments and fine-grained particles enriched in trace elements may be transported downstream during seasonal flood events and subsequently deposited in adjacent oxbow lakes and floodplain basins. Such processes have been widely documented in tropical river systems affected by gold mining, where lake sediments act as long-term repositories of mining-related metals (Tsui et al. 2019; Dana et al. 2024). The enrichment patterns observed in the studied cores therefore likely reflect the combined effects of upstream inputs, riverine transport, and sediment trapping within the lake–floodplain system.

The measured physicochemical parameters of lake water, including positive ORP values and relatively high dissolved oxygen concentrations, indicate oxidizing conditions that may reduce the remobilization of certain trace elements from sediments. However, periodic flooding and sediment resuspension in these shallow lakes may still facilitate the redistribution of mining-derived contaminants within the floodplain system.

In addition to mining-related inputs, some trace elements may also originate from natural geological sources. Lateritic deposits occurring in Kalimantan have been reported as potential sources of scandium and other trace elements associated with tropical weathering profiles (Arief et al. 2022). Furthermore, local occurrences of mafic and ultramafic lithologies may contribute Ni and related elements to the sediment load (Nurhawaisyah et al. 2020; Tamehe et al. 2024). Therefore, the geochemical composition of the studied sediments likely reflects a combination of natural geological inputs and anthropogenic influences associated with mining activities.

Peatlands are widespread within the Central Kalimantan floodplain and may additionally influence the distribution and retention of trace elements in lake sediments. Organic matter is known to effectively bind metals such as Hg, Pb, Cu, and Zn, thereby affecting their mobility and long-term accumulation in aquatic environments (Yang et al. 2001; Gallego et al. 2013). Consequently, part of the variability observed in the studied sediment profiles may reflect not only differences in external element inputs but also interactions between trace elements and organic-rich deposits occurring within the floodplain.

Elevated Bi concentrations observed in some sediment intervals may also be influenced by the presence of organic matter. Bismuth is capable of forming relatively stable complexes with organic compounds (Berggren Kleja et al. 2022).

3.5 Element associations and geochemical controls

The element associations discussed below are based on the combined interpretation of Kendall's rank correlations and PCA results. The statistical analyses performed on the logratio-transformed dataset reveal several distinct groups of elements that reflect different geochemical controls operating within the studied lake sediments. These associations likely correspond to specific mineralogical carriers and source processes influencing the sediment composition.

The first group includes elements such as Fe, Mn, Cr, Sc, and V, which display strong mutual correlations. Several of these relationships are expressed by particularly strong correlations within the dataset, including Zn–Co, Zn–Fe, Co–Fe, and Cr–Sc pairs. This association is consistent with a lateritic weathering signature characteristic of tropical environments. In lateritic soils and weathering profiles, iron oxyhydroxides such as hematite and goethite commonly act as major hosts for numerous trace elements. Elements such as Cr, Sc, and V are often associated with mafic lithologies and can be incorporated into Fe-bearing phases during weathering

processes. Consequently, the Fe–Mn–Cr–Sc–V association likely reflects detrital inputs derived from weathered lateritic materials transported from the surrounding catchment into the lake basins.

A second group of elements, including Zn, Fe, Mg, and K, appears to be linked to the presence of clay minerals and fine-grained detritic material within the sediments. Such associations are typical for aluminosilicate minerals belonging to the mica (Mindat 2026a) and chlorite groups (Mindat 2026b) which are common constituents of weathered volcanic and sedimentary rocks. Clay minerals are known for their high sorption capacity and therefore may act as important carriers for various trace elements in lacustrine environments (e.g., Wang et al. 2024). The observed correlations among these elements suggest that a significant portion of the sediment geochemistry is controlled by the mineralogical composition of the clay fraction.

Some of the observed correlations may also be explained by crystal-chemical substitution (diadochy), whereby ions of similar size and charge are incorporated into the same mineral structures. This mechanism may contribute to associations such as Cr–Al and Ga–Al, as well as to broader element groupings involving Fe, Mg, K, V, and Zn. Such relationships are commonly observed in clay minerals, micas, chlorites, and iron oxyhydroxides, which constitute important carriers of trace elements in weathered tropical sediments.

The third group comprises elements such as Hg, Ga, Tl, Au, Pb, and Zn, which may reflect inputs related to hydrothermal mineralization and mining activity within the region. Associations among these elements are commonly observed in polymetallic ore deposits and may indicate the transport of ore-derived material into the studied lakes. In particular, associations involving Cu–Pb–Zn systems may suggest contributions from artisanal and small-scale gold mining activities occurring in the Kahayan–Rungan river basin. These patterns are consistent with the geological setting of the Central Kalimantan Gold Belt, where epithermal, porphyry, and volcanogenic massive sulfide (VHMS) mineralization has been documented upstream of the studied lakes (Setijadji et al. 2010; Anjarwati et al. 2018; Dana et al. 2024).

Associations involving Cu, Pb, Zn, As, Cd, and Sb are particularly noteworthy because these elements commonly occur together in hydrothermal ore systems of the Central Kalimantan metallogenic province. Their occurrence in the studied sediments may therefore reflect contributions from mineralized source rocks containing sulfide minerals such as chalcopyrite, galena, sphalerite, arsenopyrite, and stibnite. The transport of fine-grained ore-related particles through the river network provides a plausible mechanism linking upstream mineralization with sediment composition in downstream floodplain lakes. Nevertheless, the influence of natural geogenic sources and weathering-derived sediment inputs cannot be excluded, particularly in a region characterized by widespread mineralization and intense tropical weathering.

Taken together, the identified element associations indicate that the geochemical composition of the sediments reflects a combination of natural weathering-derived inputs, mineralogical controls related to clay fractions, and localized anthropogenic signals associated with mining activities.

Conclusions

By studying 5 sediment cores derived from 3 oxbow and a single backwater lake of Central Kalimantan's tropical floodplains located within the Kahayan-Rungan river system we can conclude that:

- the sediments of the lakes under scope usually show normal, i.e., similar to worldwide average levels of most elements analyzed;
- exceptions belong to Bi, Se, Hg, Co (mostly related to mining operations), and Th, Sc, and V (rather associated with local lateritic soils);
- some of those elements as well as Fe, La, As, Cu, Pb, Zn, Cd, Sb show somewhat elevated concentrations only locally;
- a single Hg anomaly is found at the Hanjalutung's Site 4 – located at the mouth of the channel connecting the lake with the Rungan river where both artisanal gold mining and resulting mercury anomalies are known;

- although the riverine Hg anomalies may thus move into the lake, Hg is immobilized by co-deposition with Se, thus forming HgSe (tiemannite);
- record concentrations of most elements measured are found in Lutan's lake sediments, most likely reflecting its proximity to the Kota Palangkaraya city
- the lakes' geochemical background is a combination of both natural (detrital/weathering) and anthropogenic (mining and other activities) processes.

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Tables

Table 1. Mean physicochemical parameters of lake water measured *in situ* at the sampling sites within the Kahayan–Rungan river system, Central Kalimantan (Indonesia). Abbreviations: Temp.—water temperature; ORP—oxidation–reduction potential; EC—electrical conductivity; DO—dissolved oxygen; TDS—total dissolved solids. Sampling sites: BAT2—Batu Lake (site 2); HAN1—Hanjalutung Lake (site 1); HAN4—Hanjalutung Lake (site 4); LUT3—Lutan Lake (site 3); SAB2—Sabuah Lake (site 2).

Parameter	Study site				
	BAT2	HAN1	HAN4	LUT3	SAB2
Depth (m)	3.7	0.6	0.7	1	0.6
Depth max (m)	12	8		15.9	11
Transparency (cm)	12	15	12	23	12
Temp.	29.3	31.49	30.695	33.442	31.14
pH	6.23	5.67	5.69	6.63	5.79
ORPmV	247	292	271.75	152.4	215
EC (mS/cm)	0.03	0.014	0.0145	0.0308	0.023
DO (mg/L)	21.86	10.99	8.99	12.49	14.41
TDS (g/L)	0.02	0.009	0.0095	0.0194	0.024
Salinity (ppt)	0.01	0	0.005	0.012	0.04

Table 2 Average (geometric mean, GM) levels of the elements measured. All elements but Au – in ppm (Au: ppb).

	GM_{wh}[1]	n[2]	GM_B	GM_H	GM_{H1}	GM_{H4}	GM_L	GM_S
Al	17720	44	25140	14690	10700	18340	30380	10620
As	1.7	22	1.2	0.55		0.55	3.5	1.7
Au	1.9	38	1.4	1.4	1.1	1.6	3.5	2.6
Ba	28	44	34	16	11	22	113	19
Bi	0.21	31	0.20	0.18		0.18	0.30	0.18
Ca	812	44	693	550	295	851	2430	761
Co	1.8	44	2.4	0.69	0.58	0.78	13	1.3
Cr	13	44	16	10	7.7	12	27	8.1
Cu	10	44	10	5.0	2.2	9.0	32	11
Ga	6.4	44	9.4	5.5	4.3	6.4	9.5	3.9
Hg	0.09	44	0.07	0.11	0.08	0.12	0.10	0.07
Fe	3820	44	7650	1150	966	1300	29100	2810
K	324	43	482	168	122	211	874	295
La	6.8	44	6.2	6.4	6.0	6.7	13	4.9
Mg	689	42	1330	234	181	293	2850	569
Mn	29	44	41	10	13	8.6	263	22

	Mo	0.19	37	0.17	0.19	0.10	0.29	0.26	0.17
662	Na	48	43	51	34	24	44	74	59
	Ni	5.2	44	7.5	2.7	1.8	3.6	16	4.2
663	P	146	44	97	111	38	234	306	198
	Pb	13	44	17	8.3	6.3	10	24	11
664	Sc	3.3	44	3.9	2.1	1.7	2.5	11	2.0
	Sr	4.3	43	3.9	3.2	2.2	4.1	16	2.5
665	Th	1.7	44	1.8	1.5	2.2	1.1	5.9	0.61
	Ti	43	44	34	36	44	31	110	34
666	Tl	0.19	23	0.20	0.10		0.10	0.22	0.16
	U	0.56	43	0.67	0.56	0.48	0.63	0.82	0.32
667	V	34	44	61	20	16	24	87	21
	Zn	21	44	30	10	8.0	11	85	19

668

669 [1] wh – whole data; B – Batu lake (BAT2); H – Hanjalutung lake; H1 – site 1 (HAN1),
670 Hanjalutung lake; H4 – site 4 (HAN4), Hanjalutung lake; L – Lutan lake (LUT3); S– Sabuah
671 lake (SAB2); [2] n – number of records

672 **Table 3** Statistically significant Kendall's tau correlation coefficients among the analyzed elements

Mo	1.00																				
Cu	0.62	1.00																			
Pb	0.41	0.73	1.00																		
Zn	0.38	0.71	0.85	1.00																	
Ni	0.41	0.72	0.85	0.85	1.00																
Co	0.35	0.70	0.88	0.91	0.88	1.00															
Mn		0.46	0.65	0.73	0.65	0.73	1.00														
Fe	0.31	0.66	0.84	0.89	0.82	0.94	0.77	1.00													
As		0.35	0.55	0.54	0.53	0.62	0.73	0.71	1.00												
U	0.57	0.54	0.49	0.48	0.53	0.51		0.48	0.48	1.00											
Au	0.33	0.50	0.45	0.47	0.43	0.47	0.45	0.44	0.34		1.00										
Th		0.40	0.46	0.49	0.50	0.51	0.57	0.48	0.38	0.42	0.37	1.00									
Sr	0.60	0.65	0.61	0.57	0.56	0.59	0.40	0.58	0.58	0.64	0.32	0.42	1.00								
Bi	0.47	0.68	0.71	0.71	0.73	0.71	0.67	0.69	0.72	0.43	0.53	0.71	0.75	1.00							
V	0.33	0.64	0.81	0.76	0.79	0.80	0.58	0.78	0.67	0.54	0.31	0.48	0.68	0.70	1.00						
Ca	0.59	0.72	0.61	0.61	0.58	0.58	0.42	0.57	0.52	0.46	0.46	0.30	0.73	0.64	0.60	1.00					
P	0.69	0.62	0.41	0.36	0.37	0.35		0.33		0.45	0.34	0.05	0.48		0.34	0.62	1.00				
La	0.67	0.70	0.62	0.57	0.61	0.58	0.40	0.54	0.51	0.64	0.37	0.51	0.77	0.75	0.60	0.65	0.51	1.00			
Cr	0.57	0.75	0.76	0.73	0.79	0.76	0.53	0.71	0.49	0.75	0.41	0.56	0.70	0.75	0.80	0.61	0.43	0.75	1.00		
Mg		0.62	0.81	0.89	0.81	0.89	0.82	0.92	0.58	0.41	0.48	0.50	0.47	0.66	0.72	0.52		0.45	0.67	1.00	
Ba	0.49	0.73	0.84	0.81	0.81	0.84	0.66	0.81	0.50	0.54	0.47	0.55	0.70	0.75	0.81	0.67	0.41	0.66	0.78	0.76	
Ti				0.35	0.33	0.35	0.55	0.35	0.61		0.47	0.63		0.64						0.51	
Al	0.55	0.68	0.69	0.63	0.72	0.67	0.44	0.63	0.44	0.73		0.48	0.69	0.64	0.73	0.59	0.45	0.74	0.86	0.56	
Na	0.51	0.65	0.63	0.62	0.68	0.60	0.45	0.57	0.41	0.39	0.44		0.50	0.60	0.55	0.59	0.46	0.48	0.53	0.57	
K	0.38	0.69	0.85	0.87	0.84	0.90	0.74	0.89	0.70	0.49	0.47	0.49	0.63	0.76	0.82	0.61	0.31	0.58	0.74	0.86	

Correlation coefficient
>0.9
0.8-0.89
0.7-0.79
0.6-0.69
0.5-0.59
<0.5

Hg	0.50	0.35								0.45			0.40			0.35	0.53	0.57	0.37	-0.02
Sc	0.50	0.73	0.80	0.77	0.83	0.81	0.59	0.75	0.51	0.66	0.40	0.59	0.70	0.76	0.82	0.61	0.40	0.71	0.90	0.71
Tl			0.52	0.46	0.54	0.46	0.40	0.47	0.41	0.35				0.45	0.58				0.42	0.48
Ga	0.41	0.46	0.53	0.48	0.51	0.50		0.48		0.63			0.64		0.64	0.49	0.43	0.55	0.64	0.39
	Mo	**Cu**	**Pb**	**Zn**	**Ni**	**Co**	**Mn**	**Fe**	**As**	**U**	**Au**	**Th**	**Sr**	**Bi**	**V**	**Ca**	**P**	**La**	**Cr**	**Mg**

Figure captions

Fig. 1 Location of the studied area and sampling sites in Central Kalimantan, Indonesia: (A) regional setting, (B) overview of the investigated peatland area, and (C) detailed location of the studied lakes and sediment cores

Fig. 2 Detailed location of the sampling sites

Fig. 3 Downcore distribution of Ti, Al, Fe, and Sc concentrations, together with selected geochemical ratios (Th/Sc, La/Sc, and Cr/Th), in sediment cores from Lakes Batu (BAT2), Hanjalutung (HAN1 and HAN4), Lutan (LUT3), and Sabuah (SAB2)

Fig. 4 Downcore distribution of Mn, Fe, Cr, Al, Mg, K, V, and Zn concentrations, together with Fe/Al and K/Al ratios, in sediment cores from Lakes Batu (BAT2), Hanjalutung (HAN1 and HAN4), Lutan (LUT3), and Sabuah (SAB2)

Fig. 5 Downcore distribution of Pb, Hg, and Cu concentrations in sediment cores from Lakes Batu (BAT2), Hanjalutung (HAN1 and HAN4), Lutan (LUT3), and Sabuah (SAB2)

Fig. 6 Vertical distribution of enrichment factor (EF) values for selected trace elements in sediment cores from Lakes Batu (BAT2), Hanjalutung (HAN4), Lutan (LUT3), and Sabuah (SAB2). Color scale indicates the degree of enrichment, ranging from deficiency/minimal enrichment to significant enrichment

Fig. 7 Principal component analysis (PCA) biplot showing relationships between selected geochemical variables and sediment samples from the studied lakes. Arrows represent element loadings on the first two principal components (PC1 and PC2), whereas symbols indicate sediment samples from individual study sites

Online Resources captions

Online Resource 1 Location of the studied area and sampling sites in Central Kalimantan, Indonesia: (A) regional setting, (B) overview of the investigated peatland area, and (C) detailed location of the studied lakes and sediment cores

Online Resource 2 Location of the studied area and sampling sites in Central Kalimantan, Indonesia: (A) regional setting, (B) overview of the investigated peatland area, and (C) detailed location of the studied lakes and sediment cores

Online Resource 3 Location of the studied area and sampling sites in Central Kalimantan, Indonesia: (A) regional setting, (B) overview of the investigated peatland area, and (C) detailed location of the studied lakes and sediment cores

Online Resource 4 Location of the studied area and sampling sites in Central Kalimantan, Indonesia: (A) regional setting, (B) overview of the investigated peatland area, and (C) detailed location of the studied lakes and sediment cores

Online Resource 5 Location of the studied area and sampling sites in Central Kalimantan, Indonesia: (A) regional setting, (B) overview of the investigated peatland area, and (C) detailed location of the studied lakes and sediment cores

Online Resource 6 Location of the studied area and sampling sites in Central Kalimantan, Indonesia: (A) regional setting, (B) overview of the investigated peatland area, and (C) detailed location of the studied lakes and sediment cores

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