MULTIVARIATE ANALYSIS OF ABY LAGOON SEDIMENTS: IDENTIFICATION OF METAL CONTAMINATION SOURCES.

ABSTRACT

This study aimed to identify probable sources of trace metal pollution in sediments of the Aby Lagoon (Etuessika sector – Assinie Canal) through multivariate statistical analyses. Conducted as a field-based geochemical observational study, sediment samples were collected during the campaign of 7-8 October 2025 and analyzed for trace metals (As, Cd, Cr, Cu, Fe, Hg, Ni, Pb, Zn, Al). Principal Component Analysis (PCA) and Pearson correlations were applied to determine associations between elements and to distinguish lithogenic, anthropogenic, and historical sources of contamination. Results showed that three principal components explained the total variance: PC1 (61%) reflected lithogenic/diagenetic control dominated by Al, Cr, Cu, and As in opposition to Fe; PC2 (26.22%) revealed a recent anthropogenic signature characterized by Hg-Zn, typical of artisanal gold mining; and PC3 (12.78%) highlighted historical contamination, opposing Ni of lithogenic origin and Pb as a persistent pollutant linked to industrial discharges and former use of leaded fuels.

Keywords: Aby Lagoon**;** Sediment; Trace metals;Principal Component Analysis; Ecological risk**;** Côte d'Ivoire.

1. INTRODUCTION

West African lagoon and lake ecosystems are fragile environments subject to increasing anthropogenic pressures. In Côte d'Ivoire, several studies have shown that surface sediments in these lagoons and lakes are accumulating concerning levels of trace metal elements (TMEs), primarily originating from mining, agricultural, and urban activities. Once trapped in the sediments, these contaminants pose a long-term threat to benthic organisms and the local populations that rely on these aquatic resources.

Thus, Irie Bi et al. (2019) highlighted significant lead and zinc contamination in the Ébrié Lagoon, linked to urban and industrial discharges. Similarly, N'dri et al. (2024) demonstrated that Lake Bra Kanon in Daloa exhibited high pollution levels for cadmium and copper, confirming the vulnerability of lacustrine systems to anthropogenic inputs. More recently, M'Bra et al. (2026) revealed concerning concentrations of Cd, Cr, Ni, and As in the sediments of the Grand Lahou Lagoon, exceeding ecotoxicological thresholds and calling for enhanced monitoring. These regional studies illustrate the severity of metal contamination and underscore the need for analytical approaches to understand its origins.

In this context, geochemical analysis of sediments is an essential step in characterizing the contamination status. However, conventional indices such as the enrichment factor (EF), the geo-accumulation index (Igeo), or the effects range quotient (ERQ) do not always make it possible to distinguish between multiple sources. While they quantify the degree of pollution, they are limited when it comes to differentiating natural lithogenic inputs from recent or historical anthropogenic influences.

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For this reason, the integration of multivariate statistical methods specifically Principal Component Analysis (PCA) and Pearson correlations is essential. These tools make it possible to highlight associations between metals, reveal the dominant axes reflecting lithogenic, diagenetic, or anthropogenic processes, and identify sources of contamination.

The aim of this study is therefore to use PCA and statistical correlations to identify sources of metal contamination in the sediments of the Aby Lagoon (Etuessika–Assinie Canal sector). By cross-referencing analytical data with multivariate methods, it becomes possible to gain a better understanding of multi-metal pollution dynamics (Kra et al. 2026) and to provide scientific insights useful for the sustainable management of this lagoon ecosystem.

2. MATERIAL AND METHODS

2.1 Data used

ICP-MS geochemical analysis of sediment cores ETUc01 through ETUc04, conducted according to Kra et al. (2026), reveals the presence of trace metal elements: arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), nickel (Ni), lead (Pb), zinc (Zn), and aluminum (Al). The high concentrations of these elements in the sediments indicate an ecological risk for the Aby Lagoon in the Etuessika-Assinie Canal sector.

2.2 Statistical methods

2.1.1 Data standardization

To place all variables on a common scale and avoid biases associated with the orders of magnitude of concentrations, raw data were transformed using the Z-score method (Adriano, 2001). In environmental geochemistry, data standardization via centering and scaling is a mandatory prerequisite for multivariate statistical analysis, as it eliminates scale effects balso enables the processing of compositional data and resolves mathematical biases associated with the closure effect.

2.2.2 Pearson correlations

The Pearson correlation matrix was used to assess linear relationships between trace metals (TMs), with r representing the Pearson correlation coefficient. Thus:

- $r > 0.7$: strong correlation (same source or similar behavior);
- $0.3 < r < 0.7$: moderate correlation;
- $r < 0.3$: weak correlation.

This approach makes it possible to identify natural associations and suggest common sources.

2.2.3 Principal Component Analysis (PCA)

PCA was applied to reduce data dimensionality and highlight the main axes explaining variance. Eigenvalues were extracted from the covariance matrix and ranked in descending order. Thus, the principal components (PCs) retained were those with $\lambda \geq 1$ (Kaiser's

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criterion). Moreover, the station scores represent their coordinates in the factorial space, whereas the loadings indicate the contribution of each variable to a component. Each factor axis reflects a specific combination of sources and geochemical processes, allowing for the distinction between lithogenic, anthropogenic, and diagenetic contributions. In this study, three principal components were retained:

- PC1 (61%): lithogenic/diagenetic axis (Al, Cr, Cu, As vs. Fe);
- PC2 (26.22%): mining axis (Hg, Zn);
- PC3 (12.78%): historical anthropogenic axis (Pb, Ni).

2.2.4 Component selection criteria

The selection of principal components is based on several complementary statistical criteria, allowing only the most significant axes to be retained. The Kaiser criterion ($\lambda \geq 1$) ensures that each component retains a variance greater than that of an initial variable; the scree test identifies the inflection point of the eigenvalue curve; finally, cumulative variance ensures that the retained components explain a sufficient proportion of the total variance ($\geq$ 70-80%), thereby guaranteeing the robustness of the interpretation.

2.2.5 Graphical representations

The PCA graphical outputs (correlation circle, biplot, variable contributions) allowed visualization of relationships among variables and sampling stations, and identification of those contributing most to each axis.For their implementation, SPHINX (statistical calculations and correlation matrices) and RStudio (PCA and graphical representations) were used.

2.3. Interpretation criteria

Eigenvalues indicate the relative importance of each principal component; according to the Kaiser criterion, only those with $\lambda \geq 1$ are retained as significant. Explained variance represents the proportion of total variance accounted for by each factorial axis, making it possible to assess the amount of information retained by the selected components. Furthermore, correlation circles allow for the assessment of the quality of variable representation; the closer a variable is to the circle, the better its projection onto the factorial axes. Loadings reflect the contribution of variables to the formation of each component; values exceeding 0.5 are generally considered significant and indicate the most influential variables.

3. RESULTS

3.1. Pearson correlation matrices

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The PCA was conducted on four stations (ETUc 01 to ETUc 04) and ten geochemical variables (As, Cd, Cr, Cu, Fe, Hg, Ni, Pb, Zn, Al). The data were standardized beforehand (Z-score) to eliminate differences in orders of magnitude between elements. The Pearson correlation matrix (Table 1) reveals linear associations between variables and allows for the anticipation of groupings that will emerge in the factor space.

Table 1. Pearson correlation matrix

	As	Cd	Cr	Cu	Fe	Hg	Ni	Pb	Zn	Al
As	1	0.608	0.937	0.824	-0.72	-0.351	0.805	0.572	-0.18	0.988
Cd	0.608	1	0.847	0.949	-0.83	0.445	0.139	0.577	0.506	0.721
Cr	0.937	0.847	1	0.97	-0.856	-0.047	0.593	0.651	0.091	0.979
Cu	0.824	0.949	0.97	1	-0.894	0.16	0.397	0.669	0.262	0.901
Fe	-0.72	-0.83	-0.856	-0.894	1	0.053	-0.168	-0.929	0.042	-0.8
Hg	-0.351	0.445	-0.047	0.16	0.053	1	-0.478	-0.293	0.969	-0.234
Ni	0.805	0.139	0.593	0.397	-0.168	-0.478	1	0.029	-0.247	0.717
Pb	0.572	0.577	0.651	0.669	-0.929	-0.293	0.029	1	-0.344	0.632
Zn	-0.18	0.506	0.091	0.262	0.042	0.969	-0.247	-0.344	1	-0.078
Al	0.988	0.721	0.979	0.901	-0.8	-0.234	0.717	0.632	-0.078	1

3.1.1 Strong positive associations (r ≥ 0.70)

Several significant correlations stand out. Notable are the As-Al (r = 0.988) and As-Cr (r = 0.937) associations. Here, arsenic is strongly linked to aluminum and chromium two elements representative of the lithogenic clay fraction. This association suggests control by detrital mineralogy, although an anthropogenic component linked to artisanal and small-scale gold mining (ASGM) cannot be ruled out.

A second association involves chromium: Cr-Al (r = 0.979) showing high values that confirm its lithogenic origin and Cr-Cu (r = 0.970), reflecting the coexistence of natural inputs and diffuse contamination.

Cadmium (Cd–Cu, r = 0.949; Cd–Cr, r = 0.847) shows a strong association with lithogenic elements, likely linked to diagenetic redistribution within the fine clay fraction.

Finally, the Hg-Zn association (r = 0.969), which exhibits an exceptional correlation, points to a common source typical of artisanal gold mining effluents, where mercury and zinc are co-mobilized during the oxidation of metal sulfides.

3.1.2Strong negative associations

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Iron shows marked negative correlations with Cu (r = –0.894), Cr (r = –0.856), Cd (r = –0.830), Al (r = –0.800), and As (r = –0.720). These inverse relationships reflect the contrast between Fe-rich sites (ETUc 02, ETUc 03) and those dominated by lithogenic elements (ETUc 01, ETUc 04). Lead also exhibits a very strong negative correlation with Fe (r = –0.929), consistent with the anomaly observed at ETUc 01, which is characterized by low Fe content but a high Pb load.

3.2. Contributions of variables to principal components

The contributions of trace metal elements (TME) to the principal components help identify the variables that most strongly influence the structure of the factorial axes (Table 2). First, PC1 (61% of the total variance) is mainly driven by Cr (16.18%), Al (15.57%), Cu (15.13%), As (14.21%), and Fe (13.54%). Thus, this axis reflects a strong lithogenic influence dominated by aluminosilicate minerals and metallic oxides, while also incorporating a diagenetic component linked to iron. Next, PC2 (26.22% of the total variance) is dominated by Hg (37.26%) and Zn (34.41%). Consequently, it indicates a recent anthropogenic source, generally associated with mining and artisanal gold extraction, where mercury and zinc are co-mobilized. Finally, PC3 (12.78% of the total variance) is characterized by Ni (37%) and Pb (32.89%). Therefore, this axis corresponds to historical anthropogenic contamination, resulting both from industrial discharges and the former use of leaded fuels.

Table 2. Contributions (%) of ETM variables to the principal components

Variables	CP1	CP2	CP3
As	**14.21**	2.7	4.88
Cd	11.25	**11.82**	0.28
Cr	**16.18**	0.14	1.21
Cu	**15.13**	2.93	0.01
Fe	**13.54**	0.34	12.9
Hg	0.24	**37.26**	0.68
Ni	4.82	8.89	37
Pb	9.16	0.8	**32.89**
Zn	0	**34.41**	7.65
Al	**15.57**	0.7	2.5

3.3. Eigenvalues and explained variance

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Figures 2 and 3 show the variance explained by each principal component and the cumulative explained variance. The PCA extracted three non-zero principal components, which together account for 100% of the total variance. These are:

- PC1: 61.00% of the variance ($\lambda = 6.10$);
- PC2: 26.22% of the variance ($\lambda = 2.62$);
- PC3: 12.78% of the variance ($\lambda = 1.28$).

According to the Kaiser criterion (eigenvalue ≥ 1), only PC1 and PC2 are considered statistically significant. However, PC3 was retained for its interpretative value, as it highlights historical anthropogenic contamination.

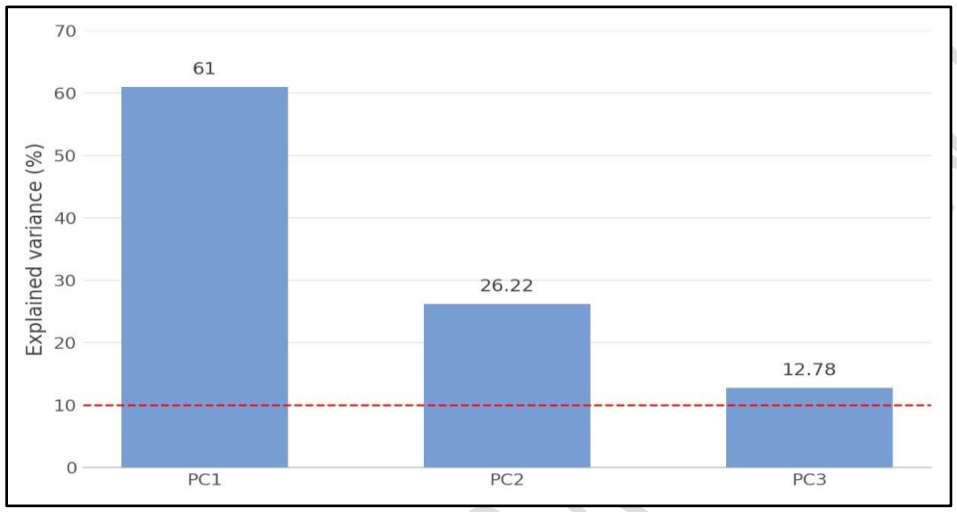


Figure1. Explained variance

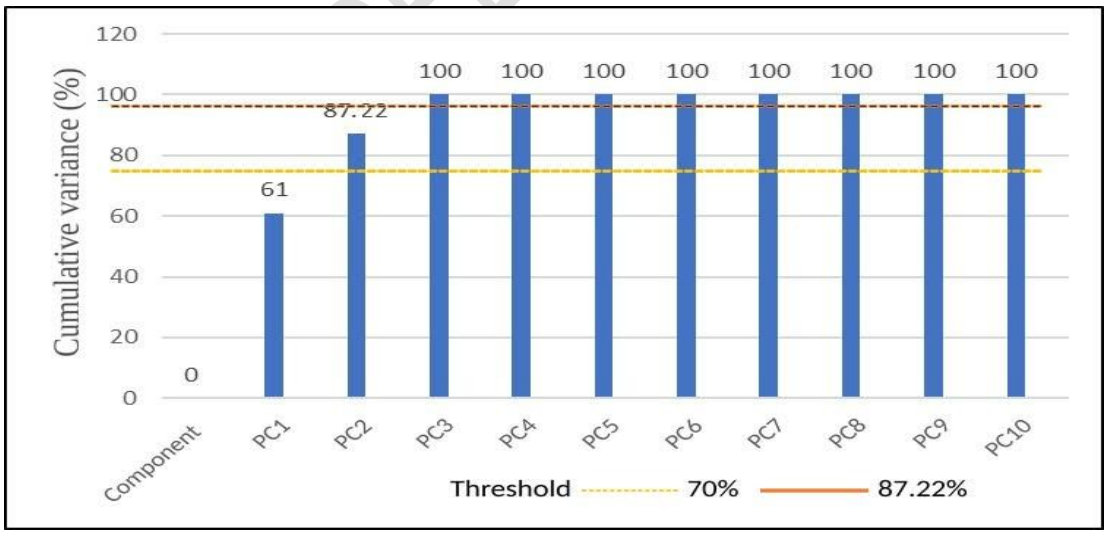


Figure 2. Cumulative variance

3.4. Correlation circles and loadings

Correlation circles and loading coefficients make it possible to visualize the contribution of variables to the factorial axes and to interpret the dominant geochemical processes.

3.4.1. Principal Component 1 (PC1 lithogenic / diagenetic axis)

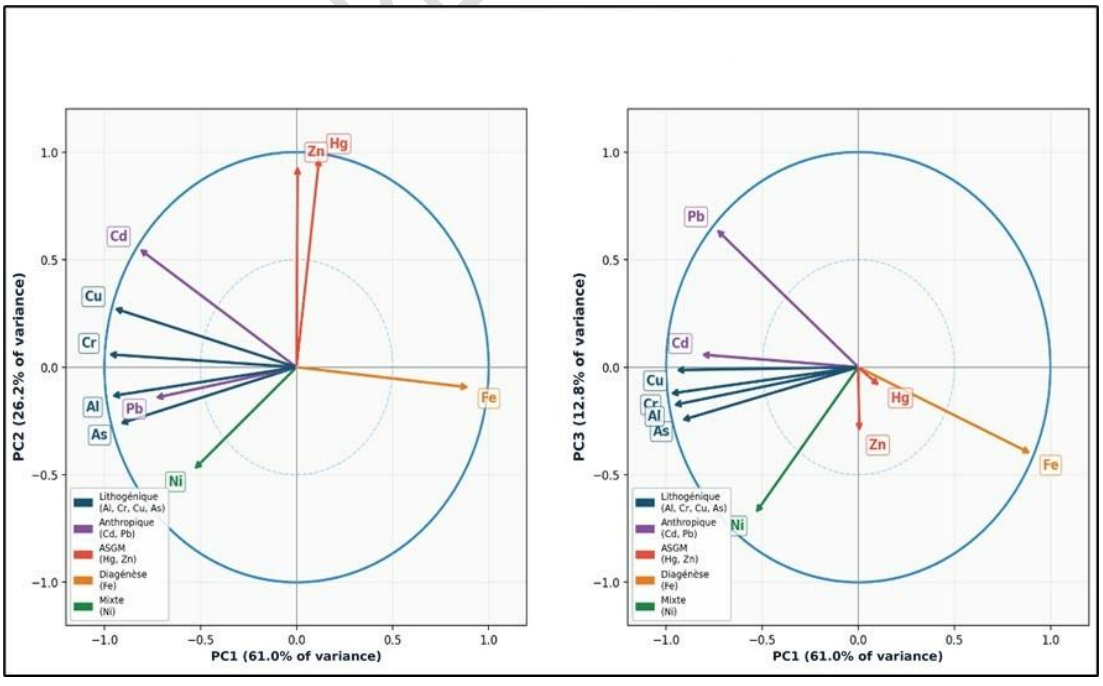
The negative pole consists of the lithogenic elements Cr (-0.990), Al (-0.975), Cu (-0.961), As (-0.931), Cd (-0.829), Pb (-0.747), and Ni (-0.542). These variables exhibit strongly negative loadings and covary positively with one another, reflecting a strong influence of the clay fraction in the aluminum-rich cores (ETUc 01 and ETUc 04). The positive pole is dominated by iron (Fe = 0.909) and stands in opposition to the lithogenic elements. This behavior reflects a pronounced diagenetic process in cores ETUc 02 and ETUc 03, which are characterized by high Fe concentrations (839-1115 mg/kg).

3.4.2. Principal Component 2 (PC2 recent mining/anthropogenic axis)

The positive pole is strongly characterized by the Hg (0.998) and Zn (0.950) pairing. This highly significant association constitutes a geochemical signature typical of artisanal and small-scale gold mining (ASGM) discharges, a phenomenon widely documented in both African and international literature. The negative pole is marked by Ni (-0.483) and As (-0.266). Nickel partially opposes the Hg-Zn association, suggesting that its lithogenic sources (ultrabasic rocks) are independent of anthropogenic inputs linked to ASGM.

3.4.3. Main component 3 (CP3 historical anthropogenic axis)

An opposition is noted between Ni (-0.688) and Pb (0.648). This dichotomy reflects distinct contamination histories: nickel of lithogenic origin and lead of anthropogenic origin. The axis highlights historical contamination, particularly at ETUc 01 (10-20 cm horizon), where a Pb anomaly is observed (1187 mg/kg).



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Figure 3. Correlation circles of variables on PC1/PC2 and PC1/PC3

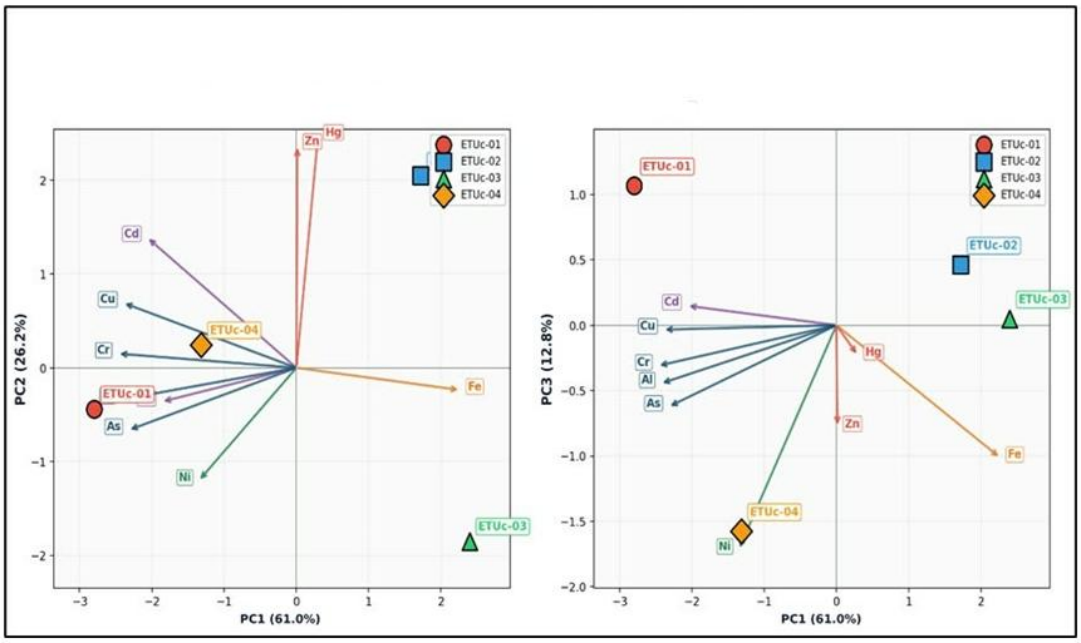


Figure 4. Biplot showing the simultaneous projection of variables and sampling stations

3. DISCUSSION OF RESULTS

Multivariate analyses using PCA identified three main axes reflecting the sources and processes controlling the distribution of trace metal elements (TMEs) in the sediments of the study basin: a lithogenic/diagenetic axis (PC1), a recent mining/anthropogenic axis (PC2), and a historical anthropogenic axis (PC3). These results are consistent with previous observations made in Côte d'Ivoire, notably the work of Coulibaly et al. (2009) and Irié Bi Trazie et al. (2019) on Ivorian lagoon systems. By applying multivariate statistical analyses (PCA), these authors also confirmed the coexistence of natural factors controlling geochemical background levels and anthropogenic pressures (both historical and recent) that shape sediment distribution.

3.1 Lithogenic and diagenetic control (PC1)

The first principal component, explaining 61% of the total variance, contrasts lithogenic elements (Cr, Al, Cu, As, Cd, Pb, Ni) with iron. This contrast reflects the major role of the clay fraction at sites ETUc 01 and ETUc 04, in contrast to the Fe-rich cores ETUc 02 and ETUc 03. These results align with those of M'Bra et al. (2024) regarding the Grand Lahou Lagoon, which demonstrated that detrital mineralogy and terrigenous inputs largely control the distribution of trace metals (TMs), while also revealing significant Pb, Cd, and Zn contamination. Similarly, Douohon et al. (2025), working on the Ebrié Lagoon, highlighted

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the combined influence of lithogenic inputs and urban/industrial discharges, noting high spatial variability in TMs. Furthermore, Wognin et al. (2023) emphasized the direct impact of artisanal gold mining on Hg and Zn levels in the Aby Lagoon, a finding that perfectly matches the signature observed on PC2 in the present study. Finally, Aka et al. (2022) demonstrated in their work on the Ivorian offshore margins that detrital mineralogy (clays and metal oxides) plays a decisive role in the geochemical structuring of sediments, confirming the lithogenic influence observed on PC1. These comparisons demonstrate that the results obtained fit into a broader national scientific context while providing specific insights into the spatial and statistical structuring of TMs in the Aby Lagoon.

3.2 Recent mining and anthropogenic signature (CP2)

The second axis of the Principal Component Analysis (PCA), explaining 26.22% of the total variance, is dominated by the exclusive association between mercury (Hg) and zinc (Zn). This exceptional correlation constitutes an anthropogenic geochemical signature typical of discharges from artisanal and small-scale gold mining (ASGM). This result corroborates local observations in Ivorian gold districts, where mercury introduced artificially for amalgamation and zinc are co-mobilized during the oxidation of deep-seated metal sulfides (pyrite, sphalerite) exposed to atmospheric agents through excavation (Kouadio, 2023). Furthermore, the frequent use of zinc shavings for gold cementation during processing explains this co-enrichment (Torkaman, Veiga et al., 2023).These findings align perfectly with statistical geochemical processing methods that effectively isolate recent anthropogenic signatures from the natural geochemical background. These physicochemical disturbances confirm that artisanal mining activities leave a lasting and vertically mobile environmental footprint within sedimentary and subsurface matrices.

3.3 Historical anthropogenic contamination (PC3)

The third axis (12.78% of the variance) contrasts Ni and Pb, two elements with distinct contamination histories. The Pb anomaly observed at ETUc 01 (1187 mg/kg) reflects long-standing, persistent contamination, primarily linked to industrial discharges and the historical use of lead in fuels. This finding aligns with observations made in the sediments of Ivorian coastal basins and lagoons, where Pb is identified as a pollutant with a strong anthropogenic footprint (Yao et al., 2009; Wognin et al., 2017). Ni, in contrast, retains a strictly lithogenic signature. This behavior is entirely consistent with previous geological studies highlighting the direct link between Ni concentrations and the ultrabasic rock complexes present in the region's bedrock (Camil, 1984).

3.4 Environmental implications, comparative analysis, and health perspectives

The structure of the factorial axes derived from Principal Component Analysis (PCA) unequivocally demonstrates that the studied watershed is subject to dual geochemical constraints. The distribution of variables within the factorial space aligns perfectly with major trends documented in Ivorian scientific literature:

- Lithogenic and diagenetic origin: The dominant role of clays and iron (Fe) on the first factorial axis is corroborated by the seminal work of Yao et al. (2009) and Ahoussi et al.

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(2012) regarding the characterization of water and sediments in Ivorian tropical ferrallitic environments;

- Recent anthropogenic footprint (ASGM): The specific and significant association between mercury (Hg) and arsenic (As) confirms local assessments regarding the impacts of artisanal and small-scale gold mining. This contamination, particularly evident in the sediment matrix, is corroborated by high pollution indices, aligning perfectly with recent findings by Kouamé et al. (2020) on the degradation of hydrosystems under intense mining pressure in Côte d'Ivoire.

- Historical anthropogenic legacy: The persistence of lead (Pb) on the secondary axes is likely attributable to the long-term accumulation of this metal in older deposits.

In summary, the variance explained by these various factors highlights a natural geochemical control dictated by detrital mineralogy, overlaid by multi-temporal anthropogenic contamination both recent (linked to ASGM) and historical (linked to Pb). This convergence of exogenous and endogenous pressures exacerbates the overall ecological risk and critically threatens the health security of riverside communities, which rely heavily on the basin's

fisheries and water resources. Given the persistence of lead and the immediate toxicity of mercury entering the aquatic environment, it is imperative to establish regular ecotoxicological monitoring of the food chain (fish, sediments, and drinking water). Furthermore, the immediate implementation of targeted awareness campaigns and environmental management plans is crucial to limiting human exposure and restoring the quality of this ecosystem.

4. CONCLUSION

Multivariate statistical analysis of sediments from the Aby Lagoon (Etuessika sector/Assinie Canal) has highlighted the coexistence of lithogenic, diagenetic, and anthropogenic factors influencing the distribution of trace metal elements (TMEs). Three main axes structure the data:

- PC1 reflects lithogenic and diagenetic controls, dominated by Al-Cr-Cu-As associations contrasting with Fe, confirming the importance of detrital mineralogy and iron mobilization processes under reducing conditions.

- PC2 reveals a recent anthropogenic signature, marked by the Hg-Zn association typical of artisanal and small-scale gold mining (ASGM) discharges and demonstrates the direct impact of mining activities on sediment quality.

- PC3 highlights historical anthropogenic contamination, illustrated by a Pb anomaly stemming from industrial practices and the past use of lead in fuels, whereas Ni retains a lithogenic origin.

These results confirm previous observations made in Côte d'Ivoire while providing further insight into the spatial and statistical structuring of TMEs. They underscore the dual influence exerted on the basin: natural control via detrital mineralogy and both recent and historical anthropogenic contamination.

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From an environmental perspective, this combination increases ecological risk, particularly for riparian communities dependent on aquatic resources. From a scientific standpoint, the study demonstrates the value of multivariate approaches (PCA, correlations, geochemical indices) in distinguishing between natural and anthropogenic sources and in guiding sustainable management strategies for Ivorian sedimentary ecosystems.

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COMPETING INTERESTS

The authors declare no conflicts of interest regarding the publication of this paper.

AUTHORS CONTRIBUTIONS

All authors contributed to the conceptualization of the manuscript. They have read and approved the published version of the manuscript.

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