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E_mail : jm_platax@unsrat.ac.id

Integrated Assessment of As, Cd, Cr, Cu, Pb, Zn, and Hg Pollution and Potential Ecological Risk in Coastal Sediments of Bunaken Island, Indonesia, Using Igeo, CF, PLI, and PERI

(Penilaian Terintegrasi Pencemaran As, Cd, Cr, Cu, Pb, Zn, dan Hg serta Potensi Risiko Ekologis pada Sedimen Pesisir Pulau Bunaken, Indonesia, Menggunakan Indeks Igeo, CF, PLI, dan PERI)

James J. H. Paulus[1]*, Hariyani Sambali[2], Nickson Kawung[1], Desy M. H. Mantiri[1], Ari B. Rondonuwu[3], Eva L. Baideng[4]

Study Program Marine Science Faculty of Fisheries and Marine Science, Sam Ratulangi University.
[2] Study Program Aquaculture, Faculty of Fisheries and Marine Science, Sam Ratulangi University
[3]Study Programme Water Management, Faculty of Fisheries and Marine Science, Sam Ratulangi University
4 Study Program Biology, Faculty of Mathematics and Basics Science Sam Ratulangi University
**Corresponding author:* Jamespaulus@unsrat.ac.id

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Abstract. Sediments along coastlines frequently retain metals introduced from adjacent land and human activities, and these metals can become environmentally relevant again whilst local conditions vary. In this take a look at, we evaluated heavy metal contamination and ecological hazard in coastal sediments from Bunaken Island, North Sulawesi, Indonesia. We examined As, Cd, Cr, Cu, Pb, Zn, and Hg and assessed pollution risk using the Igeo, CF, and PLI indices, even as ecological chance was evaluated the use of the PERI. Sediments were accrued from three nearshore stations on Bunaken—P01 (1°36′02″N, 124°46′25″E), Pi (1°37′07″N, 124°45′41″E), and Pif (1°36′58″N, 124°44′32″E)—and in comparison, with a historical past site (1°35′42″N, 124°46′52″E). Measured concentrations (mg kg^{-1}, dry weight) varied across stations: As <1–3 (Pif: <1), Cd 0.23–0.39, Cr 4.40–7.80, Cu 5–10, Pb 6.7–11.2, and Zn 7–12. Mercury becomes underneath the detection restriction at all stations (<0.05). The indices recognized Cd and Pb as the number one contributor to contamination, with CF values of 2.3–3.9 for Cd and a pair of 48–4.15 for Pb, while Cr, Cu, and Zn commonly indicated low to slight contamination depending on station. standard pollution pressure (PLI) surpassed 1 at all stations, with the highest cost at Pi (≈2.91), observed with the aid of Pif (≈2.34) and P01 (≈1.56). PERI values advised low to moderate ecological threat and showed the same spatial sample, peaking at Pi (≈186) compared with Pif (≈135) and P01 (≈103); Cd accounted for the most important proportion of ecological danger throughout stations. Those findings provide a baseline for identifying priority regions for tracking and management in Bunaken's coastal area, even though Hg-related danger remains uncertain because Hg turned into beneath the detection limit in the sediments.

Keywords: sediment; metal; Status

INTRODUCTION

Coastal sediments are widely recognized as the predominant sinks for heavy metals because abundant detritus, organic matter, and reactive mineral phases effectively bind dissolved and particle-bound contaminants introduced by rivers, runoff, atmospheric deposition, shipping, and coastal development (Al-Mutairi & Yap, 2021; Sidoruk, 2023). This "garage" characteristic is environmentally essential; but, it additionally creates a latent chance: as soon as metals collect in floor sediments, modifications in nearby physicochemical situations—along with redox potential, pH, salinity, and resuspension—can promote remobilization, increasing steel bioavailability to benthic organisms and facilitating switch via food webs (Sidoruk, 2023; Truchet et al., 2021). Because many metals are persistent, potentially toxic, and capable of bioaccumulation, even moderate sediment enrichment can translate into ecological stress in which exposure is persistent and where touchy habitats (e.g., coral reef–related coasts) overlap with anthropogenic pressure (Al-Mutairi & Yap, 2021; Özbay et al., 2025).

In tropical island settings, sediment–environment interactions are particularly relevant. Shallow, reef-fringed coasts experience energetic hydrodynamics, tourism, and episodic storm-driven resuspension that might redistribute infected particles throughout nearshore habitats. Inside the length in among, speedy land-use change and coastal development can improve steel inputs, especially for factors related to urbanization, ports, and small-scale employers (Veluchamy et al., 2025; Mishra et al., 2026). Indonesia lies within the Coral Triangle and encompasses massive quantities of Wallacea, a globally vital area for marine biodiversity and endemism (Struebig et al., 2022). Maintaining the ecological integrity of reef-related waters, therefore, requires no longer best addressing direct physical consequences however moreover, monitoring sediment-related contamination that can undermine the surroundings' functioning through long-term, diffuse exposure pathways.

Bunaken Island (North Sulawesi, Indonesia) is a part of a nationally targeted marine covered region and is across the world diagnosed for coral reef tourism. Although safety measures can reduce some direct extraction pressures, marine covered regions are not automatically insulated from land-based inputs and coastal contamination. In exercise, nearshore sediments can nevertheless replicate surrounding human pastime, in particular wherein coastal settlement, tourism intensity, delivery lanes, and watershed runoff deliver contaminants which can be ultimately trapped in depositional environments (Al-Mutairi & Yap, 2021; Yap & Al-Mutairi, 2022). From a monitoring attitude, sediment analyses offer an integrated record of environmental exposure due to the fact that metals can persist locally for long after quick-lived water-column pulses have dissipated (Sidoruk, 2023; Sojka et al., 2022). But, Bunaken-particular baseline statistics on sediment-associated hint metals and their blended ecological implications stay constrained compared with more intensively studied city bays within the vicinity, consisting of Jakarta Bay (Ikhsani et al., 2025). To address this hole, we evaluated sediment-related infection with the aid of As, Cd, Cr, Cu, Pb, Zn, and Hg and assessed pollution popularity the usage of the geoaccumulation index (Igeo), contamination factor (CF), and pollutants load index (PLI), at the same time as capability ecological hazard was evaluated the usage of the ability ecological threat index (PERI). To translate uncooked concentration statistics into environmental perception, many recent studies integrate metal measurements with geochemical and ecological indices. The geoaccumulation index (Igeo) is broadly used to evaluate the extent to which a steel is enriched relative to a historical past reference; it additionally includes a correction element to account for natural variability, allowing a standardized class of contamination throughout websites (Sidoruk, 2023; Ikhsani et al., 2025). more directly, the contamination aspect (CF) expresses every measured concentration as a ratio to its historical past degree, which enables obvious comparisons among metals and stations and highlights the factors that deviate most strongly from baseline conditions (Mishra et al., 2026; Veluchamy et al., 2025). To evaluate normal strain from more than one metals, the pollutants load index (PLI) integrates CF values right into a single metric, which is especially beneficial for rapid hotspot screening and for ranking stations or sub-areas (Sidoruk, 2023; Özbay et al., 2025). Complementing those enrichment-centered tools, the capability ecological chance index (PERI; regularly said as RI on the web page level) applies toxic-reaction elements to estimate ecological hazard, thereby highlighting metals that may pose the finest chance even when their absolute concentrations are not the very best (Sojka et al., 2022; Truchet et al., 2021).

Multi-index approaches have emerged as especially common in recent years because they provide distinct but complementary views: geochemical indices normally describe enrichment and pollutants reputation, whereas PERI emphasizes the ability of biological effects through toxicity weighting (Al-Mutairi & Yap, 2021; Gkaragkouni et al., 2025). In many coastal and estuarine environments, combining those indices facilitates distinguishing (i) extensively elevated infection hundreds from (ii) threat profiles pushed through one or pretty toxic factors. Index-based totally checks often become aware of cadmium and lead as the most important members to ecological danger, even as zinc and copper regularly indicate sturdy anthropogenic impact associated with urban inputs, port sports, and material corrosion (Mishra et al., 2026; Veluchamy et al., 2025). In mangrove-adjacent and combined coastal sediments, incorporated danger assessments are increasingly used to aid conservation planning and prioritize monitoring (Guo et al., 2025; Meng et al., 2021). Comparable frameworks are also applied to sediment cores to reconstruct pollution histories and interpret vertical trends in industrialized marine basins (Filippi et al., 2023; Gkaragkouni et al., 2024).

No matter those advances, several realistic issues motivate website-specific baseline studies in pretty understudied areas, including island structures. First, metallic distributions are regularly surprisingly heterogeneous, and hotspots can arise over short distances relying on microhabitat, sediment grain size, natural count content, and proximity to nearby assets (Özbay et al., 2025; Mishra et al., 2026). 2d, background choice strongly influences Igeo, CF, PLI, and PERI outputs; the use of the appropriate reference website or background fee is vital to keep away from overstating enrichment in naturally metal-wealthy lithogenic settings or understating it when background stages are low (Sidoruk, 2023; Yap & Al-Mutairi, 2022). third, factors including mercury may be analytically hard at low concentrations but remain ecologically critical because of toxicity and the potential for methylation under appropriate environmental situations, underscoring the need for clear reporting of detection limits and uncertainty whilst non-detects arise (Al-Mutairi & Yap, 2021; Sojka et al., 2022). therefore, this observe provides an integrated assessment of As, Cd, Cr, Cu, Pb, Zn, and Hg in coastal sediments of Bunaken Island with the aid of making use of Igeo, CF, PLI, and PERI to (1) evaluate steel enrichment relative to a historical past reference, (2) quantify website online-degree pollutants intensity and perceive spatial hotspots, and (3) estimate capability ecological threat and determine which metals most strongly drive risk patterns. via producing baseline, multi-index proof from a reef-related covered island setting, the effects are supposed to help chance-focused tracking, help prioritize management attention to the maximum influential metals and stations, and provide a defensible reference factor for future time-series comparisons in Bunaken’s coastal zone (Ikhsani et al., 2025; Gkaragkouni et al., 2025).

MATERIALS AND METHODS

Study Area

Sampling was conducted in the coastal waters of Bunaken Island, within Bunaken National Park, North Sulawesi, Indonesia. Sampling was carried out at three observation stations: P01 (1°36′02″N, 124°46′25″E), P1 (1°37′07″N, 124°45′41″E), and P2 (1°36′58″N, 124°44′32″E). A background sampling site was established in the outer waters of Bunaken Island, as shown in Figure 1 (Background site: 1°37′43″N, 124°46′25″E). At each station, three replicate samples were collected and then composited into a single representative sample. The samples were immediately placed in zip-lock plastic bags and transported to the Water Laboratory Nusantara in Manado, an Indonesian nationally accredited laboratory, for further analysis.

Pengukuran Logam Berat

Digests are analyzed by means of ICP-OES following multi-element strategies, constant dengan prosedur: WI-(identification)-[EHS]-la-070 (ICP-OES). ICP-OES outputs concentrations within the digest answer (e.g., mg L^{-1}), which are converted to sediment concentrations (mg kg^{-1} dry weight) the use of the final digest volume, dilution element(s), and dry sample mass.

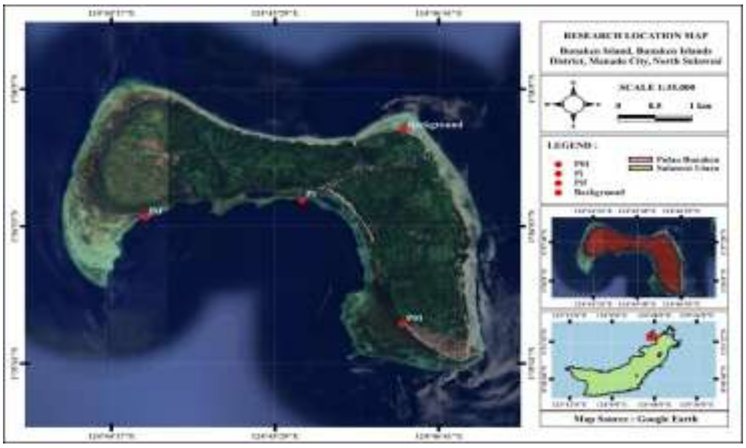


Figure 1. Research Location (The Bunaken Island)

Contamination Factor (CF)

To quantify sediment metal enrichment relative to local baseline conditions, the contamination factor (CF) was calculated for each metal i as the ratio of the measured concentration in the sample (C_i) to the corresponding background (reference) concentration ($C_{\beta}g_{,i}$) (Calmuc et al., 2021; El Ouaty et al., 2024; Laaraj et al., 2025)

$$\mathbf{CF_i = C_i / C_{\beta}g_{,i}}$$

Where C_i is the concentration of metal i in the sediment sample (mg kg^{-1}, dry weight) and $C_{\beta}g_{,i}$ is the background concentration of the same metal at the designated reference site (El Ouaty et al., 2024; Laaraj et al., 2025). CF values were interpreted using commonly used thresholds: CF < 1 (low contamination), 1 ≤ CF < 3 (moderate contamination), 3 ≤ CF < 6 (considerable contamination), and CF ≥ 6 (very high contamination) (El Ouaty et al., 2024). The geo-accumulation index (I_geo) was used to evaluate metal enrichment in sediments by comparing measured concentrations with a background (reference) level (Müller, 1969; Calmuc et al., 2021; El Ouaty et al., 2024).). For concentrations reported as below the analytical detection limit, non-detects were treated consistently during index calculation (e.g., using **½×DL** or **DL** as a conservative substitute), and cases where both sample and background values were non-detect were not over-interpreted (Laaraj et al., 2025).

Geo-accumulation Index (Igeo)

The geo-accumulation index (I_geo) was used to evaluate metal enrichment in sediments by comparing measured concentrations with a background (reference) level (Müller, 1969; Calmuc et al., 2021; El Ouaty et al., 2024). Igeo was calculated as:

$$\boldsymbol{Igeo = log_{\,2}\left(\frac{C_n}{1.5 \times B_n}\right)}$$

Where C_n is the measured concentration of metal n in the sediment (mg kg^{-1}, dry weight), and B_n is the background concentration of the same metal. The constant 1.5 is included to account for natural (lithogenic) variability in background values (Müller, 1969). I_geo values were interpreted using Müller's classification scheme, ranging from unpolluted to extremely polluted, which remains widely applied in sediment quality assessments and reviews (Müller, 1969; Birch, 2023).

Pollution load index (PLI)

The Pollution Load Index (PLI) was used to summarize the overall (multi-metal) pollution pressure in sediments at each station. Following Tomlinson et al. (1980), PLI is calculated as the geometric mean of the contamination factors (CFs) for *n* metals:

$$PLI = (CF_1 \times CF_2 \times \cdots \times CF_n)^{1/n}$$

where CF_i is the contamination factor for metal i, and n is the number of metals included in the assessment (Tomlinson et al., 1980). PLI is commonly interpreted as follows: PLI < 1 (no overall pollution; baseline conditions), PLI ≈ 1 (background-level pollution), and PLI > 1 (overall deterioration of sediment quality due to metal pollution) (Uddin et al., 2021; Liu et al., 2025).

Potential Ecological Risk Index (PERI / RI)

The Potential Ecological Risk Index (PERI; also denoted RI) was applied to estimate the toxicity-weighted ecological risk posed by sediment-bound metals. The method was originally proposed by Håkanson (1980) and remains widely used in sediment risk screening. For each metal *i*, the single-metal ecological risk factor was calculated as:

$$E_{r,i} = T_{r,i} \times CF_i$$

where $CF_i$is the contamination factor and $T_{r,i}$is the **toxic-response factor**. The overall risk at a station was then computed as the sum of all metals:

$$PERI\ RI = \sum E_{r,i}$$

(Håkanson, 1980; Saleem et al., 2024).

on this observe, the commonly used T_rvalues were adopted: As = 10, Cd = 30, Cr = 2, Cu = five, Pb = five, Zn = 1, Hg = 40 (Håkanson, 1980; Saleem et al., 2024). hazard lessons had been interpreted the use of broadly carried out thresholds: for E_(r,i), <40 (low), 40–80 (moderate), 80–160 (significant), 160–320 (high), and ≥320 (very excessive); and for RI, <a hundred and fifty (low), 150–300 (moderate), 300–600 (vast/big), and ≥600 (very high)

RESULTS AND DISCUSSION

Heavy-metal concentrations in sediments

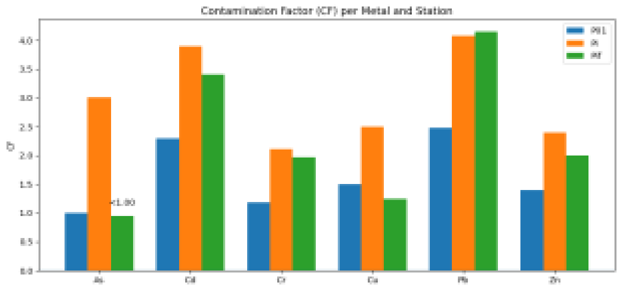
Measured concentrations (mg kg^{-1}, dry weight) varied among stations (Table 1). Station Pi showed the highest concentrations of As (3.00), Cd (0.39), Cr (7.80), Cu (10.00), and Zn (12.00). For Pb, the highest concentration occurred at Pif (11.20), slightly higher than at Pi (11.00). Hg changed under the detection restriction at all points, which include the history web site (<0.05); consequently, Hg-based indices couldn't be calculated reliably from this dataset.

Table 1. Metal concentrations (mg kg^{-1}, dry weight)

Metal	Background	P01	Pi	Pif
As	1	1	3	<1
Cd	0.10	0.23	0.39	0.34
Cr	3.7	4.40	7.8	7.3
Cu	4	6	10	5
Pb	2.7	6.7	11.0	11.2
Zn	5	7	12	10
Hg	<0.05	<0.05	<0.05	<0.05

Contamination factor (CF)

CF (C/B) indicated the most powerful enrichment for Cd and Pb, mainly at Pi and Pif (Figures 1). Cr, Cu, and Zn typically confirmed lower-to-moderate enrichment. At Pif, as < 1 implies CF < 1.



Figures 1. CF values

Cd: CF 2.30–3.90 (highest at Pi), Pb: CF 2.48–4.15 (maximum at Pif). Cr, Cu, Zn: normally CF ~1–3, with Pi continually better.

Geo-accumulation index (Igeo)

Igeo become calculated as Igeo = $\log_2 (C / (1.5 \times B))$. Values generally ranged from unpolluted to moderately polluted, with clearer elevation for Cd and Pb at Pi and Pif (Figures 2). For As at Pif, the reported value <1 indicates as is below history, so Igeo could be bad (unpolluted).

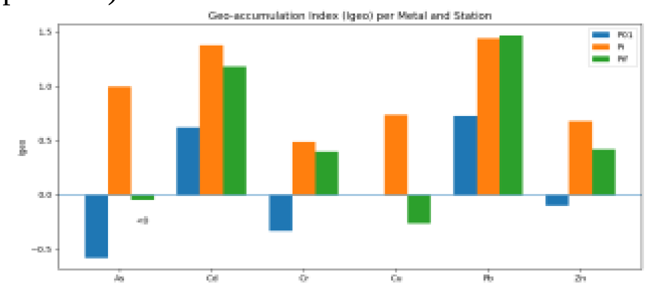
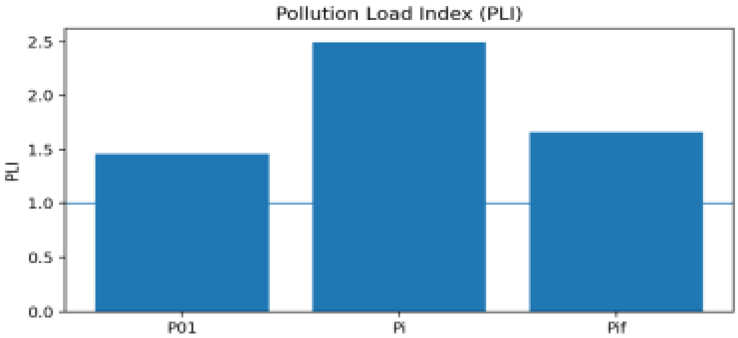


Table 2. Igeo values

Pollution load index (PLI)

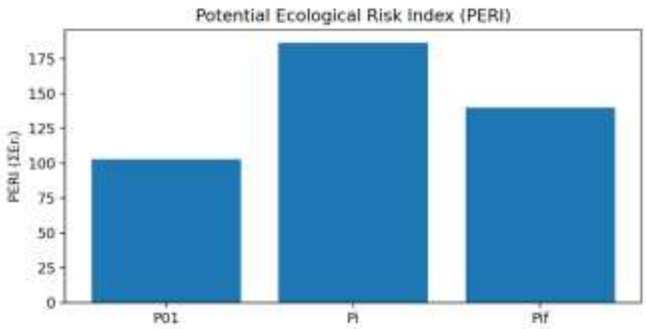
PLI (geometric mean of CF throughout metals) become > 1 in any respect stations, indicating general multi-metal pollutants pressure: P01: PLI ≈ 1.56 Pi: PLI ≈ 2.91 (highest) For Pif, PLI depends barely on how the non-quantified As (<1) is treated:
Excluding As (using Cd, Cr, Cu, Pb, Zn): PLI ≈ 2.34; Assuming As equals background (CF = 1): PLI ≈ 2.03; Assuming As is half background (CF = 0.5): PLI ≈ 1.81
Regardless of the assumption, Pif remains > 1, and Pi is continuously the primary hotspot.



Figures 3. Pollution Load Index (PLI)

Potential ecological risk (PERI / RI)

Potential ecological risk became calculated using $E_{ri} = T_r \times CF$, then summed throughout metals as PERI (RI) = ΣE_{ri}. using typically carried out toxic-action factors (e.g., As=10, Cd=30, Cr=2, Cu=five, Pb=5, Zn=1), the effects were: P01: PERI ≈ 102.69; Pi: PERI ≈ 186.49. For Pif, PERI varies barely with As (<1): without As: PERI ≈ 134.ninety four; If As CF = 0. five: PERI ≈ 139.94; If as CF = 1: PERI ≈ 144.94. Throughout all stations, Cd contributed the biggest proportion of PERI (about 63–76%), indicating Cd as the dominant ecological risk driving force in this dataset.



Figures4. Potential Ecological Risk Index

DISCUSSION

Spatial pattern: Pi as the primary hotspot

The attention records and index outputs align in figuring out Pi as the most impacted station. Pi now not only recorded the highest concentrations for most metals, but also exhibited the highest PLI (~2.91) and PERI (~186.49). This sample indicates spatially choppy inputs and/or sedimentary controls such as finer material or better organic content. that promote metal retention at Pi relative to different locations. It requires an important interest in coastal environmental control, no longer most effective on Bunaken Island itself, but additionally in the surrounding environment as an interconnected and closely connected environment.

Cd and Pb control the contamination signal and risk ranking

Both CF and Igeo continually spotlight Cd and Pb because the most enriched metals relative to the historical past. Cd reached CF 3.90 at Pi and 3.40 at Pif, at the same time as Pb reached CF ~4.07–4.15 at Pi–Pif. In Igeo, Cd and Pb at Pi–Pif fall in the range 1–2, usually interpreted as mild contamination. Ecological threat patterns, however, are even more strongly shaped by means of Cd due to its highly toxic reaction weighting. Consequently, Cd dominates PERI throughout stations, which means that control prioritization primarily based on risk is likely to focus attention first on Cd, then Pb, even if different metals display measurable enrichment.4.3 Cu and Zn: moderate enrichment consistent with nearshore activity pressure. Cu and Zn display moderate enrichment, in particular at Pi (CF Cu = 2.50; CF Zn = 2.40). In many coastal settings, elevated Cu and Zn are frequently related to nearshore human interest (e.g., boating, coastal infrastructure, corrosion-related inputs, and related preservation materials). At the same time, this observation does not immediately apportion assets; the Cu–Zn sample supports the sensible advice to increase sampling round hobby facilities to test whether these metals co-range with proximity to boating or coastline use intensity

As and Cr: localized elevation but smaller ecological contribution

As at Pi (3 mg kg^{-1}) suggests a clear localized increase (CF=3; Igeo≈1.00), whereas As at Pif (<1) indicates no enrichment. Cr shows moderate elevation (CF ~1.19–2.11; Igeo basically <0.5). Inside the chance framework used here, each As and Cr makes contributions much less to the general PERI than Cd because their CF values are decreased and (for Cr) toxicity weighting is relatively small.

Hg non-detects: interpretation and limitations

Hg being always under detection indicates no measurable Hg enrichment beneath the analytical sensitivity implemented. However, "non-discover" does not imply "absent"—it method concentrations are below the reporting limit. Consequently, Hg-associated ecological danger can't be optimistically quantified from this dataset, and any Hg contribution to chance may be underestimated if authentic concentrations are low but non-zero.

Implications and recommended next steps

Taken together, the included Igeo–CF–PLI–PERI assessment distinguishes standard pollutant stress (PLI) from threat-weighted impacts (PERI). The effects identify Pi as the priority station and Cd as the key risk-driving metal, with Pb as the secondary driver of infection intensity. For stronger inference, observe-up paintings ought to encompass: (i) more sampling stations (particularly close to suspected activity zones), (ii) sediment residences (grain length, TOC) to explain retention mechanisms, and (iii) seasonal replication to test stability of the hotspot pattern.

CONCLUSION

An incorporated assessment of the usage of Igeo, CF, PLI, and PERI showed that heavy-steel contamination in Bunaken Island sediments varies among factors, with Pi continually identified as a main hotspot. Cd and Pb have been the most enriched metals relative to the historic beyond (the highest CF values and Igeo in the mild contamination variety at Pi–Pif). PLI values >1 at all stations suggest a popular multi-metal pollution strain, at the same time as PERI indicates low to slight ecological threat, peaking at Pi, and ruled by way of using Cd. Mercury was under detection at all sites, so the Hg-related threat could not be robustly evaluated. On the whole, the one index offers a baseline for centered tracking and control, prioritizing Pi and hazard-riding metals (Cd, then Pb).

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