



Water Quality and Sediment Mercury Risk Analysis in an ASGM-Impacted Rawas River

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Abstract

Background: Illegal artisanal and small-scale gold mining (ASGM) can degrade river water quality while transferring mercury (Hg) from the water column to sediments, where contamination may persist beyond the sampling period.

Objective: This study assessed water quality, pollution status, sediment Hg contamination, potential ecological risk, spatial differences, and associations between Hg and water-quality parameters in the Rawas River, Indonesia.

Methods: A quantitative observational survey was conducted during a single sampling campaign at upstream, midstream, and downstream stations, with three spatial replicates per station, yielding nine water samples and nine sediment samples.

Results: Total suspended solids ranged from 159.50 to 260.33 mg/L, while dissolved oxygen ranged from 0.43 to 0.57 mg/L. Pollution Index values of 2.62–3.36 classified all stations as lightly polluted. Mean water Hg concentrations remained below the Class II standard, although one downstream sample reached 0.00240 mg/L. Mean sediment Hg concentrations ranged from 0.12 to 0.20 mg/kg and exceeded the geochemical reference value of 0.08 mg/kg at every station. The CF indicated moderate contamination, Igeo indicated unpolluted to slightly polluted conditions, and the ecological risk was moderate upstream but considerable in the midstream and downstream areas. ANOVA and Pearson correlation analyses showed no statistically significant results ($p > 0.05$).

Conclusion: The paired water–sediment evidence indicates that water-only compliance measurements may understate persistent sediment Hg risk, supporting integrated monitoring in ASGM-affected tropical rivers.

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INTRODUCTION

Globally, artisanal and small-scale gold mining (ASGM) is the largest anthropogenic source of mercury emissions, accounting for approximately 37.7% of total global mercury emissions to the atmosphere (Keane et al., 2023). The United Nations Environment Programme estimates that ASGM releases 800–1,000 tonnes of mercury annually into the environment, posing severe risks to aquatic ecosystems and human health through bioaccumulation in food webs (Esdaile & Chalker, 2018; Kosai et al., 2023). In Southeast Asia, including Indonesia, ASGM operations are widespread across river systems, making mercury contamination a pressing transboundary environmental and public health concern (Veiga et al., 2025).

The Rawas River is a major tributary within the upper Musi River system and supports

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domestic water use, smallholder agriculture, local mobility, and traditional fisheries in North Musi Rawas Regency, South Sumatra. In Pulau Kidak Village, these ecological and social functions coexist with illegal artisanal and small-scale gold mining (ASGM), locally referred to as *penambangan emas tanpa izin*. Excavation, ore washing, bank disturbance, and unmanaged tailings can increase erosion and suspended solids, while mercury-based amalgamation creates an additional pathway for toxic metal release. This combination makes ASGM-affected rivers a complex management problem: physical habitat degradation can occur simultaneously with chemical contamination, and the most visible water-quality disturbance does not necessarily identify the contaminant that poses the greatest long-term ecological hazard (Esdaile & Chalker, 2018; Keane et al., 2023; Veiga et al., 2025).

Mercury is particularly important because its environmental behavior differs from that of many routine water-quality parameters. In the water column, Hg may occur in dissolved form, associate with organic matter, or adsorb to fine suspended particles. Hydrological dilution and rapid particle settling can make concentrations measured during a single visit appear low, even when Hg has entered the river system. Once deposited, sediment can act as both a sink and a secondary source: Hg may remain stored, be remobilized during high-flow events, or become available for microbial transformation into methylmercury under suitable biogeochemical conditions. Methylmercury is more bioavailable and can biomagnify through aquatic food webs, linking sediment contamination to ecological and human health concerns beyond the immediate mining site (Al-Sulaiti et al., 2022; Galceran et al., 2021). Consequently, an assessment based only on surface water may capture momentary exposure but miss accumulated contamination.

Recent Indonesian studies show that this problem is geographically widespread but context-dependent. Water-quality deterioration around illegal mining has been reported in Sumbawa, Gorontalo, and North Sulawesi, frequently with high suspended solids or turbidity and location-specific metal concentrations (Barakati et al., 2023, 2024; Tumbelaka et al., 2023). Studies in the Cikaniki and Way Ratai rivers further demonstrate that Hg can be more evident in sediment than in water, although the magnitude varies markedly with mining intensity, waste handling, geology, and hydrodynamics (Erusani et al., 2025; Istighfara et al., 2025). Within North Musi Rawas Regency, mercury has been detected in environmental and community-exposure studies conducted in the Karang Jaya area, confirming that regional ASGM pressure is not hypothetical (Amallia et al., 2024; Jayanti et al., 2025). These studies establish the broader relevance of Hg contamination, but they do not provide an integrated assessment of water-pollution status and sediment ecological risk for the Rawas River reach through Pulau Kidak.

The research gap is therefore both spatial and analytical. No published assessment identified in the thesis review evaluated the Pulau Kidak reach by pairing water and surface-sediment samples at the same upstream, midstream, and downstream stations and interpreting them through two complementary regulatory and geochemical frameworks. Regulatory water assessment indicates whether measured conditions comply with designated-use standards, whereas sediment indices evaluate enrichment relative to a geochemical reference and incorporate the toxic-response weighting of Hg. When these approaches are applied separately, a river may be described as only lightly polluted in the water column while the sediment simultaneously indicates ecologically meaningful Hg risk. Testing this apparent discrepancy is important for monitoring design because decision-makers commonly rely on water samples that are easier to collect but less able to represent historical accumulation.

The scientific novelty of this study lies not merely in combining multiple indices but in demonstrating how paired water-sediment interpretation at spatially matched stations reveals a cross-media risk mismatch that neither matrix alone would detect. The analysis combines Indonesia's Class II river-water standards and Pollution Index with the Contamination Factor (CF), Geoaccumulation Index (Igeo), Pollution Load Index (PLI), and Potential Ecological Risk Index (PERI) for Hg at spatially matched stations. CF and Igeo distinguish direct enrichment from a more conservative geoaccumulation classification, while PERI shows how a metal with a high toxic-response factor can generate substantial potential risk even when enrichment is not extreme. The design also retains individual replicates, explicitly treats below-detection-limit water-Hg results as left-censored observations, and separates statistical nonsignificance from environmental interpretation. This approach provides a transferable framework for tropical rivers where ASGM releases, high sediment loads, and limited monitoring capacity occur together.

Accordingly, this study aimed to evaluate the physicochemical quality and pollution status of the Rawas River; quantify Hg in surface water and sediment; determine sediment contamination, geoaccumulation, pollution load, and potential ecological risk; and test spatial differences and linear associations between Hg and measured water-quality parameters. The analysis was intended as an early environmental assessment rather than a causal source-apportionment study, but it provides site-specific evidence for prioritizing monitoring and intervention in an ASGM-affected river corridor.

The findings are expected to provide site-specific evidence for local governments and watershed managers in designing integrated water-sediment monitoring programs, support mercury reduction strategies under Indonesia's National Action Plan for ASGM in compliance with the Minamata Convention, and inform environmental policy on the inadequacy of water-only compliance assessments in ASGM-affected river corridors.

METHOD

This study used a quantitative observational design with a single-period, descriptive, comparative, and correlational survey. Sampling was conducted on 31 March 2026 along the Rawas River in Pulau Kidak Village, Ulu Rawas District, North Musi Rawas Regency, South Sumatra. Three stations were purposively selected based on their longitudinal positions along the river, accessibility, field-observed mining pressure, and flow direction. The upstream, midstream, and downstream sampling stations were located at $-2.734923, 102.518917$; $-2.726117, 102.547956$; and $-2.718201, 102.564351$, respectively. The upstream station served as a spatial comparator but was not assumed to represent an undisturbed geochemical control. Three nearby spatial replicates were collected at each station, yielding nine water samples and nine sediment samples.

Although the sample size of nine per matrix is modest, it reflects the constraints of a single-campaign exploratory assessment in a remote ASGM-affected area with limited logistical access. This design is consistent with comparable Indonesian river contamination studies that employed similar or smaller sample sizes for preliminary spatial screening (Barakati et al., 2024; Erusani et al., 2025). Statistical analyses, including ANOVA and Pearson correlation, were applied as exploratory rather than confirmatory tests, and all results were interpreted with explicit recognition of the limited statistical power inherent in the small sample size ($n = 3$ per station).

Surface water was collected by grab sampling at an approximate depth of 20–30 cm. Temperature, pH, and dissolved oxygen (DO) were measured in situ using calibrated instruments. Samples for total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), and Hg were preserved and transported under laboratory chain-of-custody procedures. Surface sediment was collected adjacent to each water-sampling point from the upper 0–10 cm layer using a stainless-steel manual scoop. Physicochemical analyses followed applicable Indonesian National Standards or APHA procedures. COD was determined spectrophotometrically, and total Hg in both matrices was measured using cold-vapor atomic absorption spectrometry (CV-AAS).

Water-quality results were compared with the Indonesian Class II river-water criteria specified under Government Regulation No. 22/2021, and the overall water-quality status was calculated using the Pollution Index (PI) specified in Minister of Environment Decree No. 115/2003 (Imelda et al., 2023; Peraturan Pemerintah Republik Indonesia Nomor 22 Tahun 2021 Tentang Penyelenggaraan Perlindungan Dan Pengelolaan Lingkungan Hidup, 2021). Sediment contamination indices were calculated using an Hg background concentration of 0.08 mg/kg as a global average shale reference. This value was used only as a comparative geochemical benchmark and should not be interpreted as the site-specific natural background concentration of the Rawas River. The same value has been applied as a natural background concentration in a recent Indonesian mercury-contamination assessment (Elvince & Ardhani, 2025). Because no locally derived Hg background data were available for this river reach, index values based on the global reference may overestimate or underestimate actual enrichment relative to the true geological baseline. Establishing a site-specific background concentration from minimally disturbed upstream tributaries is therefore recommended for future research.

The Contamination Factor (CF) was calculated as follows:

$$CF = \frac{C_{sample}}{C_{background}}$$

where C_{sample} is the measured Hg concentration in sediment and $C_{background}$ is the selected geochemical reference. The Geoaccumulation Index (I_{geo}) was calculated as:

$$I_{geo} = \log_2 \left[\frac{C_{sample}}{1.5 \times C_{background}} \right]$$

The Pollution Load Index (PLI) was computed as the geometric mean of the CF values:

$$PLI = (CF_1 \times CF_2 \times \dots \times CF_n)^{\frac{1}{n}}$$

Because only Hg was analyzed, n equaled 1, and the PLI was mathematically identical to the CF. The PLI was therefore retained solely for methodological comparability with multimetal studies and does not provide independent evidence of pollution load in this single-metal context. It was interpreted as a supporting indicator rather than as an additional confirmation of contamination:

$$PLI = CF_{Hg} (n = 1)$$

Potential ecological risk for Hg was calculated using a toxic-response factor of 40:

$$E_r^{Hg} = T_r^{Hg} \times CF_{Hg}, \quad T_r^{Hg} = 40$$

As only one metal was evaluated, the Potential Ecological Risk Index (PERI) was equal to the ecological risk factor for Hg:

$$PERI = \sum_{i=1}^n E_r^i = E_r^{Hg} (n = 1)$$

The equations and interpretive classes for I_{geo} and potential ecological risk were applied following recent open-access studies that used the same sediment-contamination and toxic-response framework, including a toxic-response factor of 40 for Hg (Elvince & Ardhani, 2025; Fadlillah et al., 2023; Zhang et al., 2024).

The detection limit (LOD) for Hg in water was 0.0005 mg/L. Six results below this limit were replaced with one-half of the LOD (0.00025 mg/L) for consistency in tabulation, index calculation, and exploratory statistical analysis; the substituted value was not interpreted as an exact concentration. Because two-thirds of the water-Hg observations were nondetects, all resulting inferential statistics were interpreted cautiously, consistent with current U.S. EPA guidance for environmental datasets containing nondetect observations (Agency, 2022).

Descriptive statistics were calculated by station. The Shapiro–Wilk and Levene tests were used to assess the assumptions of normality and homogeneity of variance, respectively. One-way ANOVA was used to test for differences among stations in water and sediment Hg concentrations, and Pearson correlation analysis was used to examine associations between Hg concentrations and temperature, pH, TSS, DO, BOD, and COD at $\alpha = 0.05$.

The study used environmental samples only and involved no human or animal participants; therefore, human- or animal-research ethical approval was not required. Sampling and data handling were conducted in accordance with applicable institutional and laboratory standards.

RESULTS AND DISCUSSION

Result

Study Context and Water Quality

Figure 1 shows the Rawas River study reach and the relative locations of the upstream, midstream, and downstream stations. The midstream station was nearest to the ASGM activity observed during the field survey, whereas the downstream station was located beyond the activity zone in the direction of river flow. The upstream station represented the upper portion of the study reach but remained exposed to broader watershed pressures, including erosion, land clearing, and other human activities.

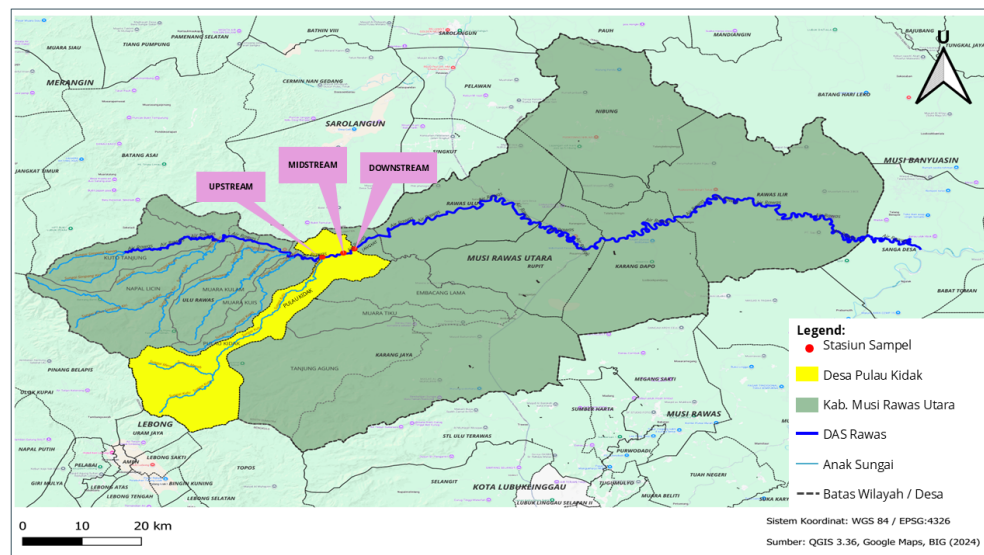


Figure 1. Location of the Rawas River study area in Pulau Kidak Village, North Musi Rawas Regency

Mean temperature was nearly uniform among stations, ranging from 24.47 to 24.57 °C, and mean pH ranged from 7.16 to 7.19 (Table 1). BOD and COD remained below their Class II maximum criteria at every station. In contrast, TSS and DO did not meet the relevant criteria throughout the study reach. Mean TSS was 188.58 mg/L upstream, 260.33 mg/L midstream, and 159.50 mg/L downstream, compared with a maximum criterion of 50 mg/L. Mean DO declined slightly from 0.57 mg/L upstream to 0.43 mg/L downstream and was far below the minimum criterion of 4 mg/L.

Water-column Hg showed a different pattern from TSS. All three upstream results were below the detection limit. At the midstream station, two results were below the detection limit and one was 0.00170 mg/L. At the downstream station, concentrations were 0.00240 mg/L, below the detection limit, and 0.00110 mg/L. After substitution of non-detects, mean water Hg increased from 0.00025 mg/L upstream to 0.00073 mg/L midstream and 0.00125 mg/L downstream. The station means remained below the 0.002 mg/L criterion, but the maximum downstream result exceeded it.

From an ecological perspective, the combination of very low DO and elevated TSS indicates substantial water-quality stress in the study reach. DO values of 0.43–0.57 mg/L were far below the Class II minimum criterion of 4 mg/L, while TSS exceeded the maximum criterion of 50 mg/L at all stations. These findings indicate that the lightly polluted Pollution Index classification should not be interpreted as an absence of environmental pressure, because the classification coexists with clear exceedances of key water-quality parameters.

Importantly, the low water Hg concentrations should not be interpreted as evidence of an absence of mercury pollution. Mercury has a strong affinity for fine particulate matter and organic colloids, meaning that a substantial fraction of the total Hg load may be transported in the particulate phase rather than in dissolved form and subsequently deposited in sediments, where it can accumulate over time. Thus, water-column measurements represent only a transient snapshot, whereas sediment concentrations reflect the cumulative history of mercury inputs to the river system.

Table 1

Mean water-quality and mercury values by station.

Parameter	Upstream	Midstream	Downstream	Class II criterion
Temperature (°C)	24.47	24.47	24.57	Natural deviation ± 3 °C
pH	7.19	7.18	7.16	6–9
DO (mg/L)	0.57	0.47	0.43	≥ 4
BOD (mg/L)	1.97	2.12	2.00	≤ 3
COD (mg/L)	5.48	5.82	5.11	≤ 25

Parameter	Upstream	Midstream	Downstream	Class II criterion
TSS (mg/L)	188.58	260.33	159.50	≤ 50
Water Hg (mg/L)	0.00025	0.00073	0.00125	≤ 0.002

Note. Mean water Hg includes one-half-LOD substitution (0.00025 mg/L) for six non-detect results. Hg sediment is reported separately in Table 3.

Pollution Status

Pollution Index values calculated from station means were 2.85 upstream, 3.36 midstream, and 2.62 downstream (Table 2). All values were within the lightly polluted category ($1 < \text{PI} \leq 5$). TSS produced the maximum transformed ratio at every station and was therefore the dominant index-forming parameter. The midstream station had both the highest TSS and the highest Pollution Index.

Point-level Pollution Index values ranged from 2.09 to 3.57, and all nine sampling points were lightly polluted. Replicate means were 2.77 upstream, 3.35 midstream, and 2.56 downstream. Figure 2 displays the individual values and station mean $\pm$ standard deviation, showing the highest central tendency and the narrowest spread at the midstream station.

Table 2

Pollution Index results and dominant parameter by station

Station	Maximum transformed ratio	Dominant parameter	PI from station means	Point-level PI range	Status
Upstream	3.88	TSS	2.85	2.09-3.39	Lightly polluted
Midstream	4.58	TSS	3.36	3.02-3.57	Lightly polluted
Downstream	3.52	TSS	2.62	2.18-3.15	Lightly polluted

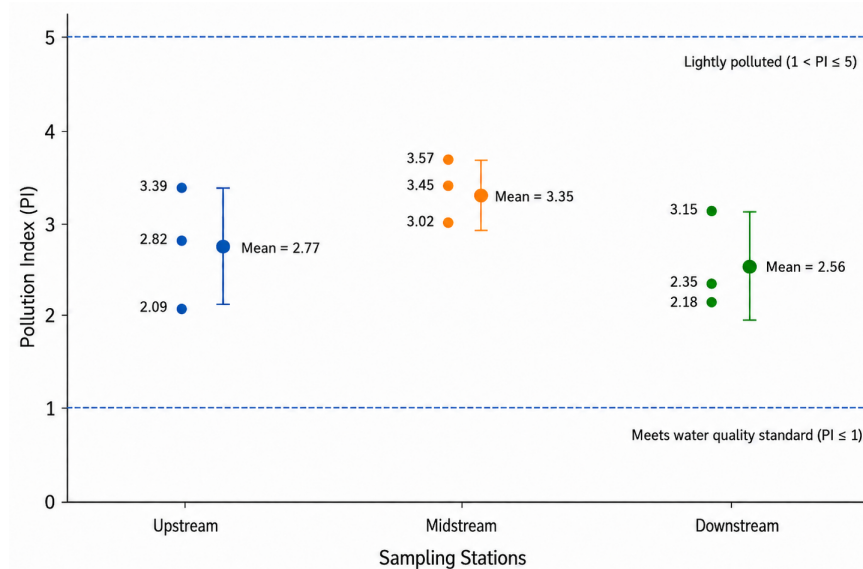


Figure 2. Distribution of point-level Pollution Index values by station. Large markers show means and error bars show standard deviations

Sediment Mercury, Contamination, and Ecological Risk

Sediment Hg ranged from 0.09 to 0.26 mg/kg (Table 3). Mean concentrations were 0.12 mg/kg upstream, 0.20 mg/kg midstream, and 0.19 mg/kg downstream. Every individual sediment result exceeded the 0.08 mg/kg average-shale reference value. The midstream replicates were closely grouped between 0.18 and 0.22 mg/kg, whereas the downstream station had the largest dispersion, with values of 0.09, 0.21, and 0.26 mg/kg (Figure 3).

The spatial variation in sediment Hg concentrations is likely influenced by several controlling factors that were not directly measured in this study but warrant discussion. Sediment

grain size plays a critical role, as finer particles (silt and clay) have larger surface areas and greater adsorption capacity for Hg than coarser fractions (Zhang et al., 2024). Organic matter content similarly affects Hg retention, with higher organic carbon typically enhancing Hg binding in sediments. River hydrodynamic conditions including flow velocity, turbulence, and channel morphology determine the spatial patterns of particle deposition and resuspension, which may explain why the midstream station showed consistently elevated Hg while the downstream station exhibited high variability. Furthermore, the proximity of sampling stations to active ASGM operations, particularly amalgamation sites and tailings-discharge points, likely represents a direct controlling factor for localized Hg enrichment in sediments (Mulyadi et al., 2025).

Mean CF values were 1.54, 2.50, and 2.33 for the upstream, midstream, and downstream stations, respectively, placing all station means in the moderate-contamination category. PLI had the same numerical values because only Hg was analyzed, and all PLI values were greater than one. Mean Igeo values were 0.03 upstream, 0.73 midstream, and 0.50 downstream, corresponding to the unpolluted to slightly polluted category. At the individual-sample level, one downstream result reached the moderately polluted Igeo class.

Potential ecological risk values were 61.67 upstream, 100.00 midstream, and 93.33 downstream. The upstream station was classified as having moderate potential ecological risk, whereas the midstream and downstream stations were classified as having considerable potential ecological risk. The midstream station produced the highest mean Hg, CF, Igeo, PLI, and potential ecological risk values; the downstream station produced slightly lower means but much greater replicate variability.

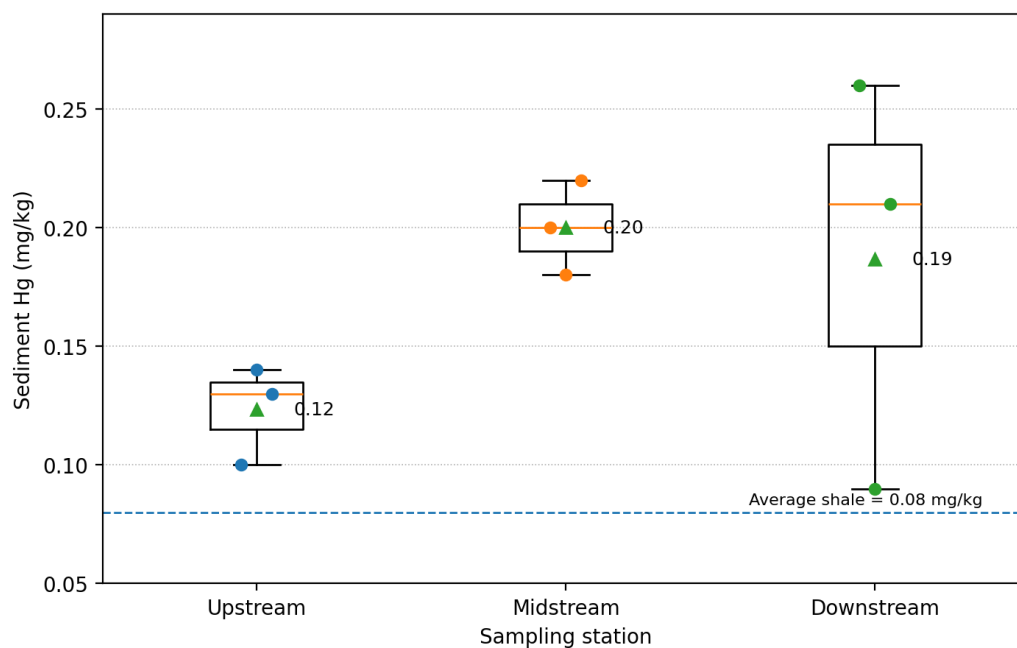


Figure 3. Sediment Hg concentrations by station

Table 3

Mean sediment Hg, geochemical indices, and potential ecological risk by station.

Station	Sediment Hg (mg/kg)	CF	Igeo	PLI	PERI/ E_r^{Hg}	Integrated classification
Upstream	0.12 ± 0.02	1.54	0.03	1.54	61.67	Moderate contamination; unpolluted to slightly polluted; moderate ecological risk
Midstream	0.20 ± 0.02	2.50	0.73	2.50	100.00	Moderate contamination; unpolluted to slightly polluted; considerable ecological risk
Downstream	0.19 ± 0.09	2.33	0.50	2.33	93.33	Moderate contamination;

Station	Sediment Hg (mg/kg)	CF	Igeo	PLI	PERI/ E_r^{Hg}	Integrated classification
						unpolluted to slightly polluted; considerable ecological risk

Note. Values are station means; sediment Hg is mean $\pm$ SD. Background Hg = 0.08 mg/kg. With one analyzed metal, $PLI = CF$ and $PERI = E_r^{\text{Hg}}$.

Statistical Results

Residuals for both the water-Hg and sediment-Hg ANOVA models met the tested parametric assumptions: Shapiro–Wilk p values were 0.312 and 0.381, and Levene's p values were 0.074 and 0.060, respectively. One-way ANOVA did not detect significant differences among stations for water Hg ($F = 1.202$, $p = 0.364$) or sediment Hg ($F = 1.783$, $p = 0.247$); therefore, no Tukey post hoc test was conducted (Table 4).

Pearson correlations between Hg and the six water-quality parameters were also non-significant. The largest absolute coefficients were the negative associations of water Hg with pH ($r = -0.590$, $p = 0.094$) and sediment Hg with pH ($r = -0.503$, $p = 0.168$). Sediment Hg had a weak positive association with TSS ($r = 0.329$, $p = 0.388$), whereas the water-Hg–TSS association was near zero ($r = -0.066$, $p = 0.867$).

Table 4

Summary of ANOVA and Pearson correlation results

Analysis	Matrix/parameter	Statistic	p value	Decision
One-way ANOVA	Water Hg	$F = 1.202$	0.364	Not significant
One-way ANOVA	Sediment Hg	$F = 1.783$	0.247	Not significant
Pearson correlation	Water Hg–pH	$r = -0.590$	0.094	Not significant
Pearson correlation	Sediment Hg–pH	$r = -0.503$	0.168	Not significant
Pearson correlation	Water Hg–DO	$r = -0.105$	0.787	Not significant
Pearson correlation	Sediment Hg–DO	$r = -0.368$	0.330	Not significant
Pearson correlation	Water Hg–TSS	$r = -0.066$	0.867	Not significant
Pearson correlation	Sediment Hg–TSS	$r = 0.329$	0.388	Not significant
Pearson correlation	Water Hg–COD	$r = -0.123$	0.752	Not significant
Pearson correlation	Sediment Hg–COD	$r = -0.108$	0.782	Not significant
Pearson correlation	Water Hg–BOD	$r = -0.046$	0.906	Not significant
Pearson correlation	Sediment Hg–BOD	$r = -0.084$	0.829	Not significant
Pearson correlation	Water Hg–temperature	$r = 0.288$	0.453	Not significant
Pearson correlation	Sediment Hg–temperature	$r = 0.283$	0.461	Not significant

Discussion

Physical Pressure as the Primary Driver of Water-Quality Degradation

The water-quality results identify a physically stressed river reach rather than one dominated by conventional organic loading. TSS exceeded the Class II criterion at all stations and was the largest component of the Pollution Index, whereas BOD and COD complied with their respective criteria. This distinction matters because the lightly polluted classification could otherwise be interpreted as indicating a uniform, low-intensity problem. In fact, the index was driven chiefly by suspended material, with the midstream peak indicating a concentrated sediment-input zone. Excavation, ore washing, bank disturbance, and exposed soil near ASGM operations are plausible contributors, but the high upstream TSS prevents attribution to a single source. Watershed erosion, land clearing, and upstream activities must therefore remain part of the explanatory model. Comparable Indonesian ASGM studies have identified TSS or turbidity as major water-quality pressures, but the Rawas pattern adds an important caution: proximity to mining can intensify suspended solids without making the upper station a valid uncontaminated control (Barakati et al., 2024; Tumbelaka et al., 2023).

The very low DO values indicate an additional ecological constraint. Their coexistence with compliant BOD and COD means that oxygen depletion cannot be attributed solely to degradable organic matter in the sampled water. Limited reaeration in locally slow-flowing

sections, oxygen demand at the water–sediment interface, respiration, oxidation within deposited material, and reduced photosynthetic oxygen production under high turbidity are all plausible mechanisms. Junaidi et al. (2021) and Sahu et al. (2023) showed that river DO recovery reflects the balance between deoxygenation and reaeration, a balance that cannot be resolved from a single daytime measurement. The Rawas data therefore support a process-oriented interpretation rather than a simple pollutant-response relationship. Diel DO measurements, discharge, velocity, sediment oxygen demand, and chlorophyll-a would be required to determine whether the observed deficit is persistent and which mechanism is dominant.

The decrease in TSS from midstream to downstream is consistent with partial settling or dilution, but it should not be treated as evidence that ecological pressure disappeared. Fine particles may remain in transport, larger particles may deposit selectively, and previously deposited material may be resuspended during later flow events. This helps explain why the downstream Pollution Index was lower while downstream water and sediment still contained locally elevated Hg. The water-quality framework is therefore useful for identifying designated-use impairment, but it is not sufficient to describe contaminant storage.

Why Sediment Revealed Mercury Risk More Clearly Than Water

The paired matrices revealed a central asymmetry: mean water Hg was below the regulatory criterion, whereas every sediment sample exceeded the geochemical reference. This is environmentally plausible because water and sediment integrate different time scales. A grab water sample records conditions at a specific moment and is sensitive to dilution, flow, recent discharge, and particle settling. Surface sediment integrates repeated deposition and can retain particle-bound Hg after the water-column signal has weakened. The six non-detect water results further limit the precision of the apparent upstream-to-downstream gradient; replacing them with one-half the LOD allows calculation but does not create measured concentration differences among those samples.

The midstream station provides the clearest evidence of spatially consistent accumulation. Its three sediment values were narrowly distributed and produced the highest station means for all Hg indices. The downstream station, by contrast, contained both the study maximum and a value only slightly above the reference, suggesting patchy deposition. This heterogeneity is consistent with local variations in particle size, organic matter, channel morphology, and flow energy, although these controls were not measured. The pattern is more informative than a simple monotonic expectation that contamination should continually rise downstream. It suggests that transport and storage occur in zones rather than as a uniform longitudinal plume.

In quantitative terms, the Rawas River sediment Hg concentrations (0.12–0.20 mg/kg) are lower than those reported in the Cikaniki River (0.28–1.45 mg/kg; (Erusani et al., 2025) and in amalgamation-tailings sediments in Lebong Regency (1.02–12.37 mg/kg; (Mulyadi et al., 2025), but higher than the global average shale value and comparable to the lower range observed in Way Ratai River sediments (0.05–0.42 mg/kg; (Istighfara et al., 2025). The water Hg levels (up to 0.00240 mg/L) are within the range reported by Amallia et al. (2024) for Karang Jaya water samples (0.001–0.003 mg/L) in the same regency. These comparisons suggest that the Rawas River reach exhibits moderate rather than extreme contamination, yet the ecological risk indices indicate that even this moderate level warrants management attention because of the high toxic-response weighting assigned to mercury.

Comparisons with other Indonesian rivers should be made by mechanism rather than by ranking concentrations alone. Erusani et al. (2025) and Istighfara et al. (2025) reported that sediment can retain a stronger Hg signal than contemporaneous water in ASGM settings, supporting the value of paired matrices. Mulyadi et al., (2025) documented direct disposal of Hg-bearing amalgamation tailings as a sediment source, but the Rawas study did not quantify tailings discharge or establish source fingerprints. Conversely, regional investigations in Karang Jaya demonstrate that Hg exposure occurs within the same regency, yet differences in hydrology, processing intensity, and sampled media preclude direct equivalence (Amallia et al., 2024; Jayanti et al., 2025). The Rawas contribution is therefore not that its concentrations are universally high, but that sediment reveals persistent enrichment even where water results are mostly below a compliance threshold.

This distinction has theoretical importance for environmental assessment. A single-matrix design implicitly assumes that the sampled medium is a sufficient proxy for system condition. The Rawas evidence challenges that assumption for Hg in a sediment-rich tropical river. Regulatory water monitoring and sediment-risk assessment answer different questions: the former tests current designated-use compliance, whereas the latter evaluates stored contamination and potential future exposure. Their joint interpretation reduces the risk of false reassurance.

Interpreting CF, Igeo, PLI, and PERI as Complementary Evidence

The four sediment indices should not be read as interchangeable labels. CF compares measured Hg directly with the selected background and therefore responds linearly to enrichment. Igeo uses the same reference but includes a factor of 1.5 to accommodate natural lithological variability, producing a more conservative classification. The resulting combination moderate CF contamination but unpolluted to slightly polluted mean Igeo is not contradictory. It indicates that enrichment is consistently above the reference, while the magnitude remains modest when the geochemical correction is applied.

PLI requires special caution in a single-metal study. Its conventional value lies in summarizing multiple CF values through a geometric mean. With Hg alone, PLI is mathematically identical to CF and therefore cannot provide independent evidence. Reporting it remains useful for comparability with studies that use the index, but the interpretation must acknowledge this redundancy. Treating single-metal PLI as a separate confirmation would artificially inflate the apparent number of independent findings.

PERI adds genuinely different information because it weights contamination by the toxic-response factor assigned to Hg. The transition from moderate CF to considerable potential ecological risk at the midstream and downstream stations demonstrates that risk is not determined by concentration or enrichment alone. A comparatively moderate excess of a highly toxic metal can yield a substantially higher potential-risk value than the same degree of enrichment for a less toxic element. This is the principal conceptual contribution of the index integration. Similar risk-based studies have emphasized that toxic-response weighting changes the interpretation of ecological concern even when geoaccumulation classes are not severe (Fadlillah et al., 2023; Zhang et al., 2024).

At the same time, PERI remains a screening construct rather than direct evidence of biological damage. It does not measure Hg speciation, pore-water concentration, bioavailability, organism exposure, or toxic effects. The Rawas values therefore justify prioritization, not a claim that benthic impairment has already been demonstrated. This distinction is especially important for Hg because methylation and food-web transfer depend on redox conditions, microbial activity, organic carbon, and habitat characteristics that are not represented in the index.

Statistical Non-Significance and Ecological Meaning

The absence of significant ANOVA results does not negate the descriptive and index-based evidence. ANOVA evaluates whether differences among station means are sufficiently large relative to within-station variability and sample size. With only three replicates per station ($n = 3$), the ability of the analysis to distinguish station differences was limited. The broad downstream sediment range further increased within-group variability, while two-thirds of the water-Hg observations were left-censored and replaced with the same one-half-LOD value. Under these conditions, a non-significant p value should be interpreted as insufficient evidence of a mean difference rather than as evidence of spatial equality.

The correlation results require the same restraint. Moderate negative coefficients with pH and a weak positive sediment-Hg-TSS coefficient are mechanistically plausible, but none was statistically significant. Hg partitioning is controlled by interacting variables including particle size, organic carbon, sulfur chemistry, redox potential, flow, and Hg speciation so a bivariate correlation with a snapshot water-quality parameter may be weak even when the underlying process is real. Moreover, sediment Hg represents accumulation over a longer period than the simultaneously measured water variables. Temporal mismatch alone can attenuate cross-matrix correlations.

This distinction between statistical inference and environmental significance is methodologically important. The statistical tests evaluate patterns within the sampled population,

whereas comparison with standards and reference values evaluates the condition of each observation against an external benchmark. A station can fail a water-quality criterion or show sediment enrichment without being statistically different from another impaired station. The appropriate synthesis is therefore convergence across complementary evidence, not reliance on a single p value.

Practical and International Implications

For local management, the results support a tiered response based on monitoring and management priorities. Priority 1 is to establish routine sediment Hg monitoring at the midstream and downstream stations, where considerable potential ecological risk was identified, because these zones represent the areas of greatest concern for contaminant storage and potential biotic exposure. Priority 2 involves implementing erosion and tailings-control measures to reduce TSS inputs, as TSS was the dominant driver of water-quality impairment across all stations and contributes to particulate Hg transport. Priority 3 is to expand monitoring to include suspended particulate matter, biota sampling, and diel DO measurements to characterize habitat stress and Hg bioavailability more comprehensively. The upstream reach should not be treated as a natural background site but should be included in all monitoring phases. Establishing a local geochemical baseline from minimally disturbed tributaries or catchments is essential for stronger future interpretation of the indices.

Source control should address both sediment production and Hg use. Stabilizing disturbed banks, retaining wash water and tailings, installing settling structures, restoring riparian vegetation, and preventing direct waste discharge can reduce particulate transport. Mercury reduction requires more than enforcement alone. International ASGM experience shows that mercury-free or mercury-reducing technologies are adopted only when they maintain gold recovery, are affordable, and fit miners' technical and livelihood conditions (Keane et al., 2023; Veiga et al., 2025). In Pulau Kidak, environmental control should therefore be linked to formalization options, technical assistance, occupational safety, and viable alternative livelihoods rather than implemented solely through short-term site closure.

The findings also contribute to international discourse under the Minamata Convention because they illustrate a monitoring problem common to ASGM regions in Asia, Africa, and Latin America. Local water samples may appear compliant when discharge is intermittent or Hg has partitioned to solids, while sediments retain a longer-lived signal. A paired-matrix, station-matched design offers a relatively affordable early-warning framework for data-limited tropical watersheds. Its broader value is not tied to a specific Indonesian regulation; the same logic can combine national water-quality criteria with internationally recognized geochemical indices in other jurisdictions.

The study's novelty is thus reaffirmed through its interpretive result. It demonstrates that a river can be classified as lightly polluted primarily because of suspended solids while simultaneously exhibiting moderate sediment Hg contamination and considerable potential ecological risk. This cross-media mismatch is the key evidence supporting a shift in monitoring programs from periodic water-compliance assessment toward integrated watershed surveillance.

From a governance perspective, the results also show why monitoring indicators should be linked to specific decisions. Pollution Index and DO/TSS data are appropriate for evaluating current water-use impairment and for triggering erosion-control measures. Sediment Hg and PERI are more appropriate for identifying zones that require contaminant surveillance, biota testing, or restrictions on sediment-disturbing activities. Conflating these purposes can produce weak policy: a water result below the Hg criterion may be used to defer action even though sediment indicates stored contamination, while an index value may be treated as proof of biological harm despite the absence of exposure measurements. A decision-linked monitoring framework would preserve the evidentiary limits of each indicator and make environmental enforcement more defensible.

Limitations

The study was based on one sampling campaign and three replicates at each of three stations, so seasonal dynamics, flood-driven resuspension, and long-term trends were not captured. The upstream station was a spatial comparator rather than a verified background site,

and the 0.08 mg/kg average-shale value may not represent local geology. Only total Hg was measured; methylmercury, dissolved and particulate fractions, pore water, and biota were excluded. Grain size, total organic carbon, sulfur, redox potential, discharge, and current velocity were not measured, limiting process-level interpretation. Manual scoop sampling targeted surface sediment but may not represent deeper depositional history. The high proportion of water-Hg non-detects and the one-half-LOD substitution reduced statistical resolution. Finally, the study did not quantify mining inputs or conduct isotopic or chemical source apportionment, so associations with observed ASGM activity remain spatially plausible rather than causally established.

These limitations also define the appropriate scope of inference. The findings characterize the sampled Rawas River reach at the end of March 2026 and identify priority hypotheses for subsequent monitoring; they do not estimate annual Hg loads, the proportion attributable to specific mining units, or human health risk. The geochemical indices are best understood as screening tools whose precision depends on the reference value and the representativeness of the sampled sediment. Future confirmation should combine repeated hydrological sampling with locally derived background concentrations and biological measurements.

CONCLUSION

This study demonstrates that the environmental condition of the Rawas River cannot be adequately represented by water-quality assessment alone. The water column was characterized by elevated TSS and severely depleted DO, while Pollution Index values classified all stations as lightly polluted. In contrast, sediment Hg exceeded the 0.08 mg/kg geochemical reference at every station, with CF values indicating moderate contamination and PERI indicating considerable potential ecological risk at the midstream and downstream stations. The principal contribution of the study is therefore the identification of a cross-media mismatch in which relatively low water Hg concentrations coexist with persistent sediment Hg enrichment. The findings should nevertheless be interpreted within the limitations of a single sampling campaign, three replicates per station, and the use of a global average-shale reference rather than a locally derived Hg background.

Future research should incorporate repeated sampling across different hydrological periods, establish a site-specific Hg background, and examine methylmercury, biota, sediment grain size, organic carbon, redox conditions, and other factors relevant to Hg partitioning and exposure. Source-apportionment approaches may also help clarify the contribution of mining activities to observed contamination. For environmental management, the present findings support integrated water-sediment monitoring, particularly at the midstream and downstream stations, together with measures aimed at reducing suspended-solid and Hg inputs in the study reach.

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AUTHOR CONTRIBUTION STATEMENT

Lipul, Hidayat Yorianta Sasaerila, and Dewi Elfidasari contributed to the conceptualization of the study, research methodology, data collection and analysis, interpretation of the findings, and preparation of the manuscript. All authors contributed to the refinement of the manuscript and approved the final version for publication.

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