Journal of Applied Engineering and Technological Science
Vol 7(2) 2026: 1423-1437

LINKING MERCURY CONTAMINATION TO TRANSPORT DYNAMICS IN AN INDONESIAN RIVER: A DATA-DRIVEN ENGINEERING FRAMEWORK FOR ASGM-IMPACTED WATERSHEDS

Rindi Genesa Hatika[1], Indang Dewata[2*], Ria Karno[3], Ika Daruwati[4], Fadhila Hidayah[5]
Doctoral Program of Environmental Science, Postgraduate Program, Universitas Negeri Padang, 25131, Indonesia[1,2]
Department of Physics Education, Universitas Pasir Pengaraian, 28452, Indonesia[1,4,5]
Department of Biology Education, Universitas Pasir Pengaraian, 28452, Indonesia[3]
indangdewata@fmipa.unp.ac.id[2*]

Received: 22 September 2025, Revised: 15 May 2026, Accepted: 22 May 2026
Corresponding Author

ABSTRACT
While Artisanal and Small-Scale Gold Mining (ASGM) severely contaminates watersheds with mercury (Hg), existing studies primarily diagnose pollution levels without identifying the underlying transport mechanisms or actionable engineering solutions. Addressing this gap, this study analyzes Hg concentrations, identifies physical transport vectors, and proposes a data-driven mitigation framework for the Kuantan River, Indonesia. A targeted spatial sampling (n=10) was conducted during the dry season (June 2025), with water samples analyzed using Cold Vapour Atomic Absorption Spectrometry (CVAAS). Results revealed gross contamination, with 100% of samples exceeding the World Health Organization (WHO) limit of 0.001 mg/L (ranging from 0.0027 to 0.0081 mg/L). The Heavy Metal Toxicity Load (HMTL) indicated critical toxicological risks (3.94–11.81). Crucially, Principal Component Analysis (PCA) identified Total Dissolved Solids (TDS) as the dominant spatial transport vector, demonstrating that Hg is predominantly particulate-bound rather than dissolved. To mitigate this, a hierarchical engineering framework is proposed, featuring source control (mercury-capturing retorts), pathway interruption (sedimentation basins to trap TDS), and receptor protection (point-of-use filtration). Although limited by a small sample size, this study extends foundational environmental engineering knowledge by linking statistical transport diagnostics to structural interventions, offering a replicable policy and watershed management blueprint for ASGM-impacted regions globally.

Keywords: *Mercury Transport, ASGM Contamination, River Water Quality, Watershed Engineering, Environmental Risk Mitigation*

1. Introduction

Artisanal and small-scale gold mining (ASGM) represents a complex socio-economic paradox, offering a crucial, and often sole, source of income for millions in developing nations while simultaneously inflicting severe, and frequently irreversible, environmental degradation and public health risks (Dossou Etui et al., 2024; Pang et al., 2022; Sall et al., 2020). Driven by poverty and the lack of alternative livelihoods, communities turn to ASGM for economic survival, yet the sector's profound reliance on rudimentary and largely unregulated techniques perpetuates a cycle of harm. The use of elemental mercury for gold amalgamation is particularly pernicious, establishing ASGM as the single largest anthropogenic source of global mercury emissions, discharging an estimated 800 to 1,200 tonnes annually into the atmosphere and hydrosphere (Aldous et al., 2024; Outridge et al., 2018; UN Environment Programme, 2019).

The subsequent release of this highly toxic substance into local soils and water bodies permeates entire ecosystems. The sheer volume of mercury released results in pervasive contamination, where concentrations in water and sediment frequently surpass established international safety thresholds by orders of magnitude. These thresholds are not arbitrary; they are critical health-based limits. As a key benchmark, the World Health Organization (WHO) has established a guideline value of 0.001 mg/L (or 1 µg/L) for inorganic mercury in drinking water (WHO, 2011). This value is derived from extensive toxicological data and represents the concentration that is not expected to cause any significant risk to human health over a lifetime of consumption. Exceeding this limit indicates that the water is no longer safe for direct human use and, more broadly, signals a severely degraded aquatic environment where the potential for bioaccumulation into the food web is significantly heightened.

However, in watersheds impacted by ASGM, it is common to find concentrations many times this limit. This contamination does not simply wash away; mercury has a high affinity for sediment particles, causing it to settle into riverbeds and floodplains. This process creates persistent toxic reservoirs where the contaminant can remain trapped, only to be remobilized during high-flow events like floods, re-contaminating the ecosystem long after mining has stopped (Aldous et al., 2024). This long-term sequestration effectively renders local water sources hazardous for decades, acting as a continuous source for methylation and entry into the food web, a phenomenon well-documented in regions like the Amazon basin (Donkor et al., 2024).

Once in the environment, particularly in the anoxic conditions of river sediments, inorganic mercury undergoes a critical microbial transformation into methylmercury, its most toxic organic form (Ma et al., 2019; Regnell & Watras, 2018). This process turns a potent toxin into an even more dangerous, lipid-soluble compound that is readily absorbed by living organisms (Kumar et al., 2023; Sall et al., 2020). Methylmercury then bioaccumulates in the food chain, building up in individual organisms over time and biomagnifying to exponentially higher concentrations at each successive trophic level. This poses a direct and insidious threat to human populations, especially those reliant on local fish for protein (Wu et al., 2024). The consequences are particularly devastating and life-altering for the highly sensitive developing nervous systems of fetuses and children, as methylmercury can cross the placental and blood-brain barriers. Exposure in utero or in early childhood often manifests as severe cognitive impairment, measurable reductions in IQ, developmental delays, and lasting motor deficits such as a lack of coordination (Spiller et al., 2023).

The gravity of this pervasive issue, underscored by its transboundary atmospheric transport and severe public health implications, has elevated the problem to a major international concern. This recognition culminated in a landmark global policy response: the Minamata Convention on Mercury. Adopted in 2013 and entering into force in 2017, this is the first globally legally binding treaty specifically designed to protect human health and the environment from the adverse effects of mercury (Selin et al., 2018). The Convention's provisions are comprehensive, mandating that signatory nations control mercury throughout its entire life cycle. Crucially for contexts like the one in this study, the treaty contains specific articles dedicated to reducing, and where feasible eliminating, mercury use in the ASGM sector, placing a global spotlight on the very issue at the heart of this research.

Recent literature over the last five to ten years has extensively documented the severe ecological impacts of ASGM globally (Dossou Etui et al., 2024) and locally in Indonesian watersheds like the Kahayan and Kapuas rivers (Agustiani et al., 2025; Basri et al., 2020). However, a critical synthesis of these studies reveals a persistent limitation: they predominantly offer descriptive, cross-sectional diagnoses of contamination levels. While the occurrence of Hg is well-documented, a significant research gap persists regarding the mechanistic understanding of how mercury is transported within specific fluvial environments, particularly the interplay between physical landscape disturbance and chemical transport vectors (Cinnirella et al., 2013; Yan et al., 2025). Identifying whether mercury moves primarily in a dissolved state or bound to suspended solids is a prerequisite for effective remediation, yet the literature lacks integrated frameworks that translate these mechanistic findings into actionable engineering solutions.

The novelty of this study lies in its explicit integration of multivariate transport dynamics analysis (using PCA to interpret source-pathway relationships) with the development of a hierarchical engineering framework tailored to the specific hydrological realities of an ASGM-impacted watershed. This approach advances environmental engineering knowledge by shifting the focus from mere pollution reporting to functional structural remediation and sustainable mining governance.

Therefore, to bridge the identified research gaps, the primary objectives of this study are to: (1) quantify spatial Hg concentrations and benchmark them against WHO standards to assess immediate public health risks via the HMTL index; (2) statistically identify the physicochemical drivers (specifically evaluating Total Dissolved Solids/TDS) of Hg transport using Principal Component Analysis (PCA); and (3) formulate a hierarchical engineering mitigation framework based on these empirical transport findings to provide practical relevance for watershed management and pollution control policy.

2. Literature Review

2.1. Environmental Impacts and Global Context of ASGM

ASGM is characterized by its reliance on manual labor and is often situated within the informal economy, a status driven by factors such as lack of access to capital, insecure land tenure, and complex legal frameworks that marginalize small-scale operators (Karikari et al., 2021). This informality leads to a near-total absence of environmental oversight. The sector's environmental footprint is substantial and multifaceted. Physically, it manifests as widespread deforestation to clear land for mining pits, leading to loss of biodiversity and soil stability. The hydraulic sluicing and excavation techniques employed cause severe soil erosion and fundamentally alter river hydrology, increasing channel sedimentation, widening riverbanks, and heightening the risk of downstream flooding during periods of heavy rainfall (Rinaldi et al., 2005).

The primary chemical threat, however, stems from the indiscriminate use of mercury (Hg), a highly toxic heavy metal. The mercury pollution crisis fueled by ASGM is a pervasive global issue, with analogous situations documented across Africa, South America, and Asia (Pang et al., 2022). For instance, studies in the Pra River Basin, Ghana, have demonstrated strong positive correlations between total mercury concentrations and turbidity, confirming that sediment transport is the dominant pathway in that system (Donkor et al., 2006). In the Amazon basin, decades of extensive research in Brazil's Tapajós River and Peru's Madre de Dios River have documented severe contamination of entire river ecosystems. These studies have found dangerously high mercury levels in local and indigenous populations, where fish is a dietary staple, leading to widespread public health crises (Diringer et al., 2015; Martinez et al., 2018).

2.2. Mercury Transport Dynamics and Physico-chemical Controls

The behavior, transport, and ultimate bioavailability of mercury in aquatic systems are intricately governed by ambient physicochemical conditions. pH is a well-established master variable that controls mercury's chemical form (speciation) and its tendency to adsorb to particulate matter. Acidic conditions, for instance, can increase the mobility and toxicity of mercury by keeping it in a dissolved, more bioavailable state, whereas neutral to alkaline conditions may facilitate its precipitation or binding to sediments (Beckers & Rinklebe, 2017).

However, in river systems heavily impacted by the significant physical disturbance characteristic of ASGM, TDS and turbidity become critically important controlling factors (Dethier et al., 2019; Karikari et al., 2021). Geochemically, mercury has a strong affinity for sorbing onto the surfaces of fine-grained particulate matter, such as clay minerals, iron oxides, and organic carbon (Navarro, 2008). The aggressive excavation and sluicing common in ASGM churn up riverbeds and banks, releasing vast quantities of these suspended sediments into the water column. Consequently, the dramatically increased sediment loads and turbidity provide an abundance of surfaces for mercury to attach to, effectively making these suspended particles the primary carriers for the pollutant. This particle-bound transport facilitates the movement of mercury over long distances downstream, far from the original mining sites (Lin et al., 2011). While this process might temporarily reduce the concentration of dissolved, immediately bioavailable mercury, it creates legacy contamination issues. These mercury-laden particles eventually settle in slower-moving depositional zones like floodplains, reservoirs, or deltas, creating toxic hotspots where the mercury can be remobilized or methylated (Gerson et al., 2020).

2.3. Contamination Indices and Multivariate Statistical Modeling

Evaluating the severity of metal contamination requires robust indices to translate raw concentration data into toxicological risk. The Heavy Metal Toxicity Load (HMTL) is particularly advantageous as it integrates the intrinsic hazard score of specific metals (accounting for mercury's severe neurotoxicity), offering a direct indication of human health risk (Badeenezhad et al., 2023; Caeiro et al., 2005). Concurrently, identifying pollution sources in complex watersheds relies increasingly on multivariate statistical techniques. Principal Component Analysis (PCA) is an established method to reduce data dimensionality, isolate underlying anthropogenic mining discharge from natural weathering, and group sampling locations based on spatial pollution gradients (Arıman et al., 2024; Han et al., 2017; Tripathee et al., 2019).

2.4. Engineering Mitigation Frameworks

Traditional responses to ASGM pollution have heavily focused on policy bans, which often fail due to socio-economic realities (Verbrugge & Thiers, 2016). Recent literature emphasizes the hierarchy of controls for occupational and environmental safety (Ajslev et al., 2022). Source control interventions, such as the introduction of mercury-capturing retorts, target the amalgamation process directly to prevent atmospheric release (Liu et al., 2024). Pathway interruption involves structural civil engineering (such as sedimentation basins) to physically decouple Hg-laden particulates from the water column before downstream transport (Förstner, 2004). Finally, phytoremediation via constructed wetlands offers a long-term, nature-based receptor protection strategy, utilizing hyperaccumulating plants to sequester trapped (Bolisetty et al., 2019; Di Stasio et al., 2025).

2.5. Research Gap and Conceptual Framework

While global studies from the Amazon and Ghana extensively document ASGM impacts, a critical synthesis reveals a lack of studies applying localized, data-driven mechanistic modeling to design specific structural interventions. The conceptual framework of this study posits that physical ASGM disturbances generate a high-TDS environment, shifting Hg from a localized dissolved hazard to a basin-wide particulate-bound threat. By statistically validating this dynamic in the Kuantan River using PCA, this study bridges the gap between environmental chemistry diagnosis and applied engineering remediation.

3. Research Methods

3.1. Study Area and Sampling Design

This research was conducted along the Kuantan River in Kuantan Singingi Regency, Riau Province, Indonesia, a region with extensive and well-documented ASGM activities. A targeted, purposive sampling strategy was employed to collect ten water samples (A1–A10) during the dry season (June 2025) to prevent extreme rainfall dilution effects. While acknowledging the limitations of a small sample size (n=10), this preliminary spatial assessment is statistically adequate for initial hazard identification and multivariate gradient analysis (Arıman et al., 2024).

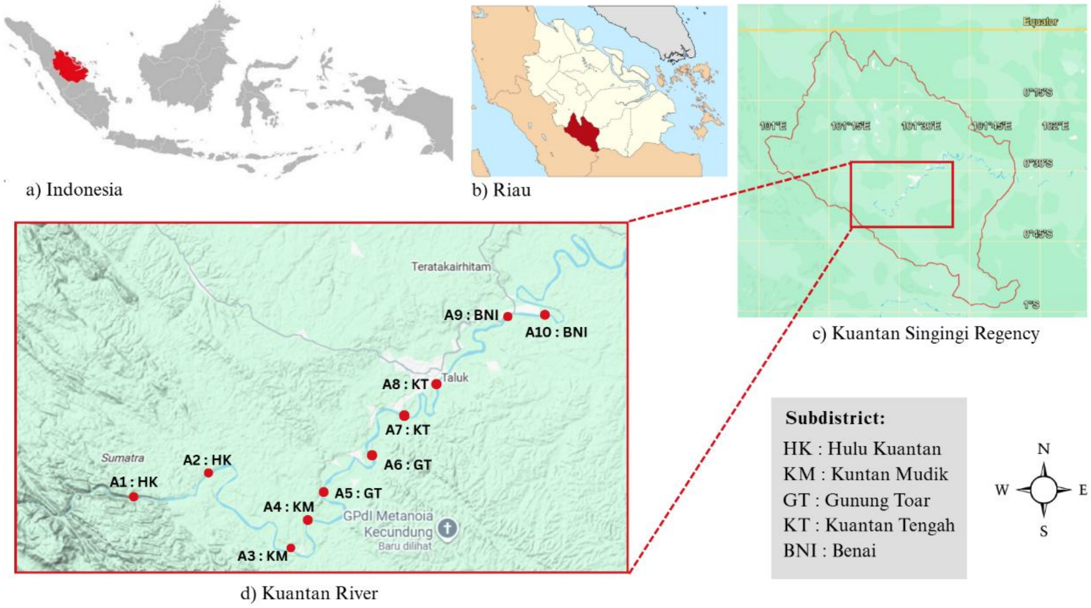

Fig. 1. Distribution of sampling points. (a), (b), (c): the location of the study area; (d): the distribution of sampling points.

The study area encompasses a significant stretch of the Kuantan River, which flows through multiple subdistricts known for intensive ASGM operations, as depicted in Figure 1. The selection of sampling points was deliberate to ensure a comprehensive spatial assessment of contamination. Site A1, located in the Hulu Kuantan subdistrict, was designated as the upstream control point to establish baseline water quality before the river is significantly impacted by mining activities. Sites A2 through A7 are situated in the Kuantan Mudik, Gunung Toar, and Kuantan Tengah subdistricts, areas characterized by a high density of active and abandoned mining sites. These points were specifically chosen to be in close proximity to visible discharge points, tailings piles, and processing areas to capture the maximum potential impact of ASGM effluent. The final sites, A8 through A10 in the Benai subdistrict, were positioned further downstream to evaluate the extent of contaminant transport and dispersion within the river system. To ensure representative flow capture, all water samples were collected at a depth of 30 cm below the surface in the mid-channel.

3.2. Field Procedures and Laboratory Analysis

All collected samples were transported under controlled conditions and analyzed at the West Sumatra Provincial Health Laboratory, an accredited institution with established expertise in environmental contaminant analysis. The measurement of physico-chemical parameters was conducted in strict accordance with the globally recognized Standard Methods for the Examination of Water and Wastewater (Bridgewater, 2017). In situ measurements for parameters such as pH and temperature were measured using calibrated multiparameter water quality sondes (YSI ProDSS) to understand the baseline aquatic conditions, while TDS was selected as a critical indicator of sediment load, a potential primary carrier for mercury.

To preserve the total mercury content and prevent volatilization during transport, samples were collected in acid-washed 500 mL high-density polyethylene (HDPE) bottles, immediately acidified in the field to $\mathrm{pH} < 2$ using 1% nitric acid (HNO_3), and stored in coolers at 4°C.

For the direct quantification of mercury, total mercury (Hg) concentration was determined using Cold Vapour Atomic Absorption Spectrometry (CVAAS) (Dordaa et al., 2025; Zhang & Adeloju, 2008). This highly sensitive technique was chosen for its ability to achieve the very low detection limits required for environmental water monitoring, with a Limit of Detection (LOD) established at 0.0001 mg/L for this study. The method involves the chemical reduction of all mercury species in the sample to elemental mercury (Hg^0), which is then volatilized and measured by its atomic absorption, ensuring a comprehensive measurement of the total mercury present.

To guarantee the validity and reliability of the results, rigorous quality assurance and control (QA/QC) protocols were implemented. The accuracy of the method was verified using a certified reference material (NIST 1641d), yielding a high recovery of 97 ± 4%. The precision of the analysis was confirmed by running duplicate/triplicate samples, which showed a relative standard deviation (RSD) consistently below 5%. Furthermore, procedural blanks were analyzed with each batch of samples to ensure the absence of contamination from laboratory reagents or equipment, thereby confirming the integrity of the data.

3.3. Data Analysis and Risk Assessment

All statistical analyses were performed using the open-source software R (Version 4.3.2), chosen for its robust capabilities in handling complex environmental datasets (J. M. Chambers, 2008). The analytical process was structured in three stages. First, descriptive statistics (mean, median, standard deviation) were calculated to summarize the central tendency and dispersion of each parameter, providing a foundational overview of the river's water quality.

Second, to translate the measured concentrations into a direct measure of potential harm, a quantitative health risk assessment was conducted using the Heavy Metal Toxicity Load (HMTL) index, a validated methodology (Badeenezhad et al., 2023; Caeiro et al., 2005). This index contextualizes risk by weighing contaminant concentration by its intrinsic hazard. The HMTL was calculated as:

$$HTML = \sum_{i=1}^{n} C_i \; x \; HIS_i$$

where C_i is the concentration of the specific heavy metal (in mg/L) and HIS_i is the High Hazard Score. Based on the Agency for Toxic Substances and Disease Registry (ATSDR) toxicity profiles, mercury is assigned a severe *HIS* weight of 1458, reflecting its severe neurotoxicity and bioaccumulation potential (Przybyla et al., 2021).

Third, to identify the mechanisms of contaminant transport, a combination of bivariate and multivariate analyses was employed. A Pearson correlation matrix was generated to quantify the strength and direction of linear relationships between pairs of variables, specifically testing the hypothesis of a link between Hg and TDS. To gain a more holistic understanding of the system, a Principal Component Analysis (PCA) was then performed. Prior to PCA, data were log-normalized to satisfy normality assumptions, and the Kaiser-Meyer-Olkin (KMO) measure alongside Bartlett’s test of sphericity were used to confirm the data's suitability for dimension reduction (Arıman et al., 2024; Tripathee et al., 2019). PCA is a powerful dimensionality-reduction technique that identifies the underlying factors explaining the variance in the data. Its primary output, a biplot, visualizes the relationships between all variables and simultaneously shows how the different sampling sites cluster, making it an effective tool for identifying pollution gradients and spatial patterns of contamination.

4. Results and Discussions

4.1. Physico-chemical Characteristics and Severe Mercury Contamination

The pH (mean 7.04 ± 0.08) and temperature (mean 22.02 ± 0.58 °C) were stable across all sites (Table 1), indicating that the system is not primarily affected by factors such as acid mine drainage. The most significant finding from the baseline analysis was the stark bifurcation of TDS values, which serves as a powerful proxy for direct mining impact. As detailed in Table 1, samples A1-A3, located upstream, exhibited low TDS levels (mean 7.12 mg/L), characteristic of less disturbed, clearer water. In sharp contrast, the remaining seven samples, located within and downstream of the main ASGM areas, showed markedly higher and more variable TDS concentrations (mean 64.94 mg/L). This ten-fold increase strongly suggests that the physical disturbance from ASGM activities, including excavation, sluicing, and tailing discharge, is the primary driver of sediment suspension in the river.

Table 1 - Descriptive Statistics of Water Quality Parameters.

Parameters	Mean	Median	St. Dev.	Minimum	Maximum
TDS (mg/L)	47.60	64.30	27.96	7.05	66.60
Hg (mg/L)	0.0055	0.0057	0.0019	0.0027	0.0081
pH	7.05	7.07	0.09	6.89	7.15
Temperature (°C)	22.02	22.10	0.58	20.90	22.80

The descriptive statistics in Table 1 highlight a system under significant physical stress. The stability of pH near neutral suggests that the geochemical conditions are not the primary driver of mercury's fate, a contrast to systems affected by acid mine drainage where low pH enhances mercury solubility (Aldous et al., 2024; Martinez et al., 2018). Instead, the dramatic elevation in TDS in the mining-impacted zones points to a physical control mechanism. This massive increase in suspended particulate matter, a direct result of landscape alteration and riverbank erosion from hydraulic mining, aligns with findings from other ASGM-affected regions where increased turbidity is a hallmark of mining activity (Dethier et al., 2019). These suspended solids provide a vehicle for contaminant transport, fundamentally altering the river's ecological state from a stable, low-sediment system to one that is physically choked and chemically contaminated.

The core finding of this study is the pervasive and severe mercury contamination throughout the sampled reach of the river. As graphically illustrated in Figure 2, the mercury concentration in all ten samples (100%) substantially exceeded the WHO's permissible limit for safe drinking water of 0.001 mg/L (WHO, 2011). This is not a marginal exceedance but a gross contamination event. The average concentration across all sites was 0.0055 mg/L, which is 5.5 times higher than the international guideline. The contamination reached its peak at site A5, located adjacent to a major mining cluster, with a concentration of 0.0081 mg/L, representing a staggering 810% exceedance of the safety limit. Even the lowest recorded value (0.0027 mg/L at site A6) was nearly three times the limit. This finding unequivocally confirms that the Kuantan River is a significant pollution hotspot, rendering its water unsafe for direct human consumption and posing a grave, long-term threat to the entire aquatic ecosystem and the local communities who rely on it for fish, a primary pathway for exposure to highly toxic methylmercury.

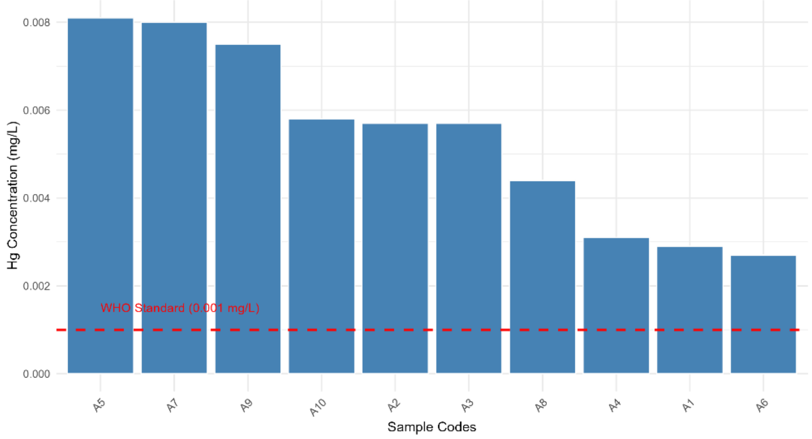

Fig. 2. Comparison of Mercury (Hg) Concentration with the WHO Standard (0.001 mg/L)

The severity of the contamination shown in Figure 2 places the Kuantan River among other significantly polluted river systems globally affected by ASGM. For instance, concentrations observed in parts of the Amazon basin and rivers in Ghana have shown similar, and sometimes higher, levels of mercury, directly linking ASGM activities to public health crises (Diringer et al., 2015; Donkor et al., 2024; Karikari et al., 2021). The uniform exceedance across all ten sampling points suggests a widespread, rather than localized, problem. This has profound implications for the local population, as the primary route of human exposure to mercury in such systems is not through drinking the water, but through consumption of fish in which methylmercury has bioaccumulated to dangerous levels (Bose-O'Reilly et al., 2010; Egendorf et al., 2020; Spiller et al., 2023). Therefore, these water concentrations act as a precursor to a more significant, invisible threat accumulating in the local food web.

4.2. Health Risk and Multivariate Analysis of Contaminant Transport

The high measured concentrations translate directly to a significant public health risk, as quantified by the HMTL index (Table 2). The index values were consistently high, ranging from a concerning 3.94 to an alarming 11.81 at the most contaminated site (A5). These values quantitatively confirm that the river water poses a substantial toxicological threat, not only through direct ingestion but, more critically, through the food chain.

Table 2 - Measured Mercury Concentration and Calculated Heavy Metal Toxicity Load (HMTL).

Sample Code	Hg *(mg/L)*	TDS *(mg/L)*	HMTL
A1	0.0029	7.17	4.23
A2	0.0057	7.14	8.31
A3	0.0057	7.05	8.31
A4	0.0031	66.30	4.52
A5	0.0081	64.20	11.81
A6	0.0027	62.40	3.94
A7	0.0080	66.60	11.66
A8	0.0044	64.40	6.42
A9	0.0075	64.70	10.93
A10	0.0058	66.00	8.46

The HMTL provides a standardized metric for assessing the potential toxicological burden on an ecosystem and the human populations that depend on it. By incorporating the high intrinsic hazard score of mercury, the index translates raw concentration data into a more direct indicator of risk (Caeiro et al., 2005). The consistently high values across all sites, particularly in the ASGM-impacted zone (A4-A10), move the assessment from a general concern to a specific, measurable health threat. These findings strongly suggest that bioaccumulation of mercury in local fish species is highly probable, creating a significant dietary exposure risk for the local population. This pathway is well-documented as the primary cause of mercury poisoning in ASGM communities worldwide, leading to severe neurological and developmental health issues (Kumar et al., 2023).

To elucidate the underlying mechanisms driving this contamination, multivariate statistical analyses were performed. The Pearson correlation matrix (Figure 3) reveals the linear relationships between the measured parameters. The matrix shows a weak positive correlation between Hg and TDS and a moderate negative correlation between Hg and pH. While the Hg-TDS correlation is not strong, it suggests a tendency for mercury to be associated with the higher sediment loads found in the impacted areas.

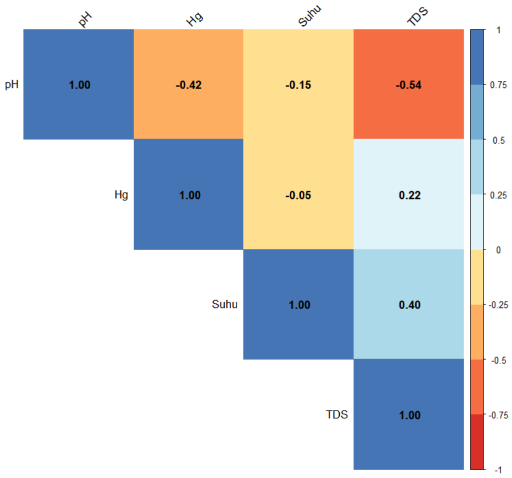

Fig. 3. Pearson Correlation Matrix of Physico-chemical Parameters. Warm colors (orange/red) indicate negative correlations, while cool colors (blue) indicate positive correlations.

The correlation matrix provides a first look at the inter-parameter relationships. The weak positive correlation between Hg and TDS $(r = 0.22)$ suggests that while there is an association, the relationship is complex and may be non-linear or influenced by other factors. However, the moderate negative correlation between TDS and pH indicates that the increase in suspended solids is associated with a slight decrease in pH, a phenomenon that warrants further investigation. Importantly, the lack of a strong, direct correlation between any single parameter and Hg underscores the need for a more sophisticated multivariate approach to understand the system's dynamics.

The relationship between pH and mercury, as visualized in Figure 4, further supports the finding that pH is not the primary controlling factor in this system. The scatter plot shows no clear trend, with high mercury concentrations found across the narrow pH range. This lack of a strong relationship reinforces the hypothesis that physical processes, rather than chemical speciation controlled by pH, are dominant in mercury's transport.

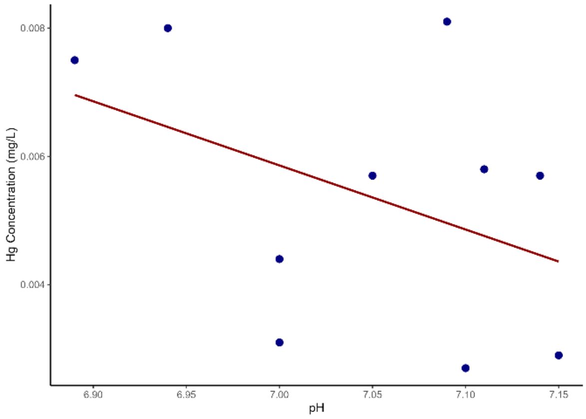

Fig. 4. Scatter plot of pH versus Mercury (Hg) concentration, showing a weak negative relationship.

This finding is critical for understanding the river's specific geochemistry. In many contaminated systems, pH is a master variable controlling the solubility and bioavailability of heavy metals (Beckers & Rinklebe, 2017; Zhang & Adeloju, 2008). However, the data in Figure 4 demonstrate that in the Kuantan River, mercury concentrations are high regardless of minor fluctuations in pH. This suggests that the system is overwhelmed by the high sediment load, and the dominant form of mercury is likely particle-bound rather than dissolved. This effectively decouples mercury's behavior from aqueous chemical controls, meaning that mitigation strategies focused on altering water chemistry (liming) would likely be ineffective. Instead, interventions must target the physical transport vector or the suspended solids.

To gain a more holistic view, a Principal Component Analysis (PCA) was performed, with the results visualized in the biplot in Figure 5. The first two principal components explained a combined 79.4% of the total variance in the dataset. The PCA biplot provides two critical insights. First, it visually confirms the positive association between Hg and TDS, as indicated by the acute angle between their vectors. This relationship, though weak in the bivariate correlation, becomes clearer in the multivariate context, providing the “smoking gun” that links the physical disturbance from ASGM (which increases TDS) to the chemical contamination (Hg). The geochemical basis for this is mercury's high affinity for binding with particulate matter, which is resuspended by mining.

Second, and most strikingly, the PCA clearly segregates the samples into two distinct clusters based on their water quality profiles. Samples A1, A2, and A3 form a tight group on the left side of the plot, characterized by low TDS and lower Hg, representing the upstream or control group. In contrast, samples A4 through A10 form a more dispersed cluster on the right, defined by high TDS and high Hg, representing the impacted group. This clear spatial fingerprint is crucial for targeting mitigation efforts, definitively identifying sites A5, A7, and A9 as the primary pollution hotspots within the studied river section.

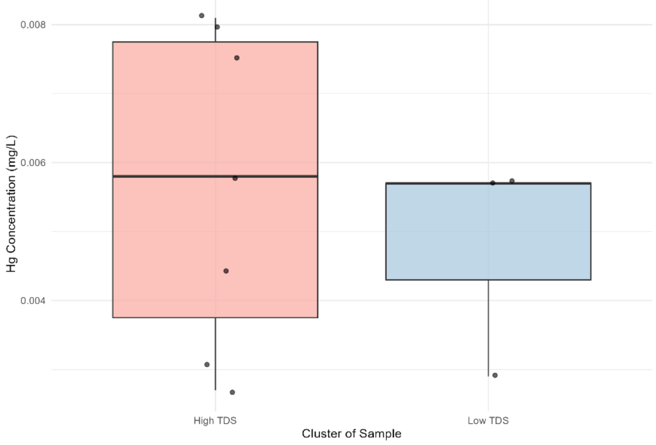

Fig. 5. PCA Biplot of Water Quality Parameters illustrating the spatial clustering of impacted versus unimpacted zones.

The PCA results firmly challenge the traditional assumption that pH is the universal master variable for heavy metal transport in all aquatic systems. The results extend the findings showing that in ASGM-impacted watersheds, the volume of physical disturbance overrides aqueous chemical controls (Karikari et al., 2021). TDS emerges as the dominant transport vector because hydraulic sluicing introduces large amounts of clay minerals and iron oxides, providing abundant sites for the sorption of inorganic mercury.

Furthermore, while this study was conducted during the dry season, these transport dynamics are highly susceptible to seasonal hydrological variations. During the wet season, high-velocity flood events are likely to remobilize these settled, mercury-laden sediments (TDS) from the riverbed and floodplains, causing episodic spikes in particulate-bound mercury transport and expanding the contamination footprint further downstream (Dethier et al., 2019). The positioning of sites A5, A7, and A9 as the most extreme points in the “impacted” cluster validates the sampling strategy and provides specific, actionable information for regulatory agencies. These locations represent the epicenters of contamination where mitigation and enforcement efforts should be concentrated to achieve the greatest impact on improving the river's overall health.

4.3. Proposed Engineering and Risk Management Framework

Based on the conclusive evidence of severe contamination and the identification of sediment-driven transport as the primary contamination mechanism, we propose a comprehensive, multi-layered mitigation strategy. This framework is grounded in the established engineering hierarchy of controls (Ajslev et al., 2022), which prioritizes interventions from most to least effective: eliminating the hazard at the source, controlling its pathway, and finally, protecting the receptor. This tiered approach provides a logical and scientifically defensible roadmap for addressing the complex challenge in the Kuantan River watershed, as visualized in Figure 6.

Tier 1: Source Control and Hazard Elimination.

Representing the most effective and proactive layer of intervention, this tier focuses on preventing mercury from entering the environment in the first place. The primary strategy involves a government-supported transition towards mercury-free gold extraction technologies. Methods such as gravity concentration (using equipment like sluice boxes and shaking tables) or direct smelting have proven effective and, in some cases, can even increase gold recovery rates, providing a powerful economic incentive for adoption (Esdaile & Chalker, 2018). For operations where an immediate transition is not feasible, a mandatory secondary strategy is the implementation of low-cost, high-efficiency mercury capture systems. Simple, locally manufacturable retorts can be used during the amalgam burning process to capture, condense, and recycle up to 95% of the mercury vapor that would otherwise be released directly into the atmosphere and surrounding landscape (Bolisetty et al., 2019; Liu et al., 2024). This dual approach addresses both the supply and release of mercury, tackling the problem at its root.

Tier 2: Pathway Interruption and Environmental Remediation.

This second tier is designed to manage the legacy contamination already present in the river and to intercept any mercury that bypasses source controls. Given this study's key finding that mercury is transported via suspended solids (TDS), interventions in this tier must focus on sediment management. This can be achieved through a combination of civil and environmental engineering solutions. The construction of engineered tailing ponds and strategically placed sedimentation basins can effectively slow water flow, allowing mercury-laden particles to settle out of the water column where they can be contained and managed (Förstner, 2004). Complementing these structural solutions, nature-based approaches like the development of constructed wetlands offer a sustainable method for phytoremediation. Specific hyperaccumulating plant species can be cultivated to absorb and sequester mercury from the water and sediment into their biomass, which can then be harvested and safely disposed of (Di Stasio et al., 2025). The direct scientific rationale for this entire tier is provided by the strong Hg-TDS correlation identified in our analysis, making these sediment-targeting interventions a data-driven and logical step.

Tier 3: Receptor Protection and Public Health Management.

As the final and most immediate line of defense, this tier focuses on protecting the exposed human population while the longer-term solutions in Tiers 1 and 2 are implemented. This requires a multi-pronged public health strategy. First is the establishment of a real-time water quality monitoring network, potentially using turbidity sensors as a low-cost proxy for contamination events, to provide early warnings to downstream communities. Second is the deployment of accessible, community-scale water treatment solutions. Point-of-use systems, such as household filters containing activated carbon, are highly effective at adsorbing dissolved mercury and can provide an immediate source of safe drinking water. Third, and perhaps most critically, is the initiation of a sustained public health communication campaign. This involves issuing clear, culturally appropriate advisories against consuming fish (especially predatory species) from contaminated zones, with a particular focus on protecting vulnerable groups, such as pregnant women, nursing mothers, and young children (Spiller et al., 2023). This campaign must be coupled with education on the long-term neurological risks of mercury exposure to ensure community buy-in and behavioral change.

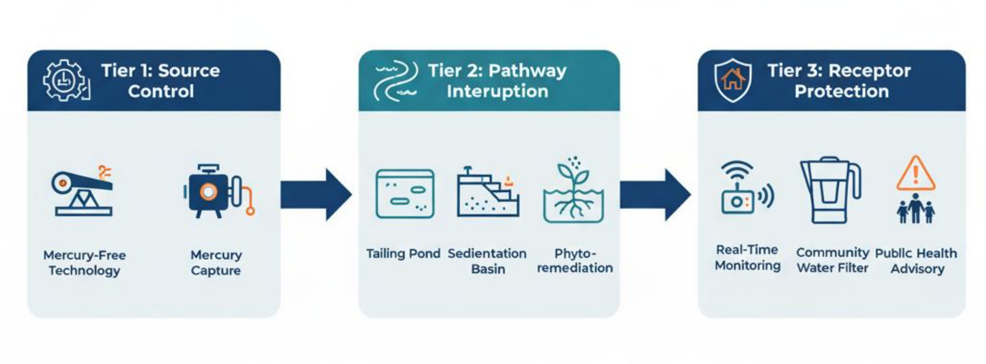

Fig. 6. Conceptual Framework for the Proposed Multi-layered Risk Management and Engineering Mitigation Strategy.

The successful implementation of this integrated framework depends on overcoming significant socio-economic and governance challenges. The high upfront capital costs for mercury-free technologies can be prohibitive for miners operating on subsistence margins, necessitating financial incentives, subsidies, or micro-loan programs. Furthermore, the largely informal nature of the ASGM sector requires strong political will to enact and enforce environmental regulations, formalize mining operations to bring them under legal oversight, and combat corruption that may undermine compliance. Future research should, therefore, focus on conducting detailed techno-economic analyses and feasibility studies for these proposed interventions within the local context, as well as developing robust community engagement and co-management strategies to ensure that the solutions are not only scientifically sound but also socially acceptable and sustainable in the long term.

5. Conclusion

This study provides conclusive answers to three fundamental research questions regarding mercury pollution in the Kuantan River. It first confirms a severe contamination crisis, with mercury levels reaching up to 8.1 times the WHO safety limit, posing a significant threat to ecosystem integrity and public health. Second, moving beyond mere description to a mechanistic diagnosis, this work definitively identifies suspended solids (TDS) as the primary contaminant transport vector, thus statistically linking ASGM's physical disturbance to the mobilization of chemical pollution. Finally, in direct response to this finding, the study presents a tangible, science-backed blueprint for action: a hierarchical engineering framework that logically prioritizes source control, sediment-targeting pathway interruption, and receptor protection. This adaptable model offers a universal principle to diagnose the transport mechanism, then engineer the solution, which can be applied to mitigate similar environmental disasters globally.

From a practical and policy perspective, this mechanistic insight directly informs the proposed hierarchical engineering framework. To achieve sustainable watershed management, local governments and environmental agencies are recommended to enact policies that mandate source control (low-cost retorts), enforce pathway interruptions (sedimentation basins and constructed wetlands to trap the TDS vector), and implement immediate receptor protection (point-of-use filtration and health advisories). This adaptable model offers a universal principle to diagnose the transport mechanism, then engineer the solution, which can be applied to mitigate similar environmental disasters globally.

While the study's conclusions are robust for establishing the pollution gradient and transport mechanism, generalizations regarding the entire basin's temporal dynamics must be approached cautiously due to the preliminary sample size (n=10) and single-season sampling. The urgent next step is to translate this framework from concept to reality, necessitating future work incorporating: (1) multi-seasonal temporal monitoring; (2) sediment and biota analysis to empirically quantify methylmercury bioaccumulation; (3) hydrodynamic modeling of mercury transport; and (4) longitudinal health risk assessments to validate its in situ effectiveness.

Acknowledgement

The authors would like to express their sincere gratitude to the Ministry of Higher Education, Science, and Technology (Kemdiktisaintek) through the Directorate of Research and Community Service, Directorate General of Research and Development for providing the fundamental research grant in 2025. We also extend our appreciation to LPPM Universitas Pasir Pengaraian for their valuable support. Furthermore, the authors acknowledge the facilities, scientific, and technical support from the Testing Laboratory of Nuclear Fuel Technology, National Research and Innovation Agency through ELayanan Sains-BRIN.

References

Agustiani, T., Sulistia, S., Sudaryanto, A., Kurniawan, B., Poku, P. A., Elwaleed, A., Kobayashi, J., Ishibashi, Y., Anan, Y., & Agusa, T. (2025). Mercury contamination and human health risk by Artisanal Small-scale Gold Mining (ASGM) activity in Gunung Pongkor, West Java, Indonesia. *Earth*, *6*(3), 67. https://doi.org/10.3390/earth6030067

Ajslev, J. Z. N., Møller, J. L., Andersen, M. F., Pirzadeh, P., & Lingard, H. (2022). The hierarchy of controls as an approach to visualize the impact of occupational safety and health coordination. *International Journal of Environmental Research and Public Health*, *19*(5), 2731. https://doi.org/10.3390/ijerph19052731

Aldous, A. R., Tear, T., & Fernandez, L. E. (2024). The global challenge of reducing mercury contamination from artisanal and small-scale gold mining (ASGM): evaluating solutions using generic theories of change. *Ecotoxicology*, *33*(4–5), 506–517. https://doi.org/10.1007/s10646-024-02741-3

Arıman, S., Soydan-Oksal, N. G., Beden, N., & Ahmadzai, H. (2024). Assessment of groundwater quality through hydrochemistry using Principal Components Analysis (PCA) and Water Quality Index (WQI) in Kızılırmak Delta, Turkey. *Water*, *16*(11), 1570. https://doi.org/10.3390/w16111570

Badeenezhad, A., Soleimani, H., Shahsavani, S., Parseh, I., Mohammadpour, A., Azadbakht, O., Javanmardi, P., Faraji, H., & Babakrpur Nalosi, K. (2023). Comprehensive health risk analysis of heavy metal pollution using water quality indices and Monte Carlo simulation in R software. *Scientific Reports*, *13*(1). https://doi.org/10.1038/s41598-023-43161-3

Basri, Sakakibara, M., & Sera, K. (2020). Mercury in soil and forage plants from artisanal and small-scale gold mining in the Bombana Area, Indonesia. *Toxics*, *8*(1), 15. https://doi.org/10.3390/toxics8010015

Beckers, F., & Rinklebe, J. (2017). Cycling of mercury in the environment: Sources, fate, and human health implications: A review. *Critical Reviews in Environmental Science and Technology*, *47*(9), 693–794. https://doi.org/10.1080/10643389.2017.1326277

Bolisetty, S., Peydayesh, M., & Mezzenga, R. (2019). Sustainable technologies for water purification from heavy metals: review and analysis. *Chemical Society Reviews*, *48*(2), 463–487. https://doi.org/10.1039/c8cs00493e

Bose-O'Reilly, S., McCarty, K. M., Steckling, N., & Lettmeier, B. (2010). Mercury exposure and children's health. *Current Problems in Pediatric and Adolescent Health Care*, *40*(8), 186–215. https://doi.org/10.1016/j.cppeds.2010.07.002

Bridgewater, L. L. (2017). *Standard methods for the examination of water and wastewater* (23rd ed.). American Public Health Association.

Caeiro, S., Costa, M. H., Ramos, T. B., Fernandes, F., Silveira, N., Coimbra, A., Medeiros, G., & Painho, M. (2005). Assessing heavy metal contamination in Sado Estuary sediment: An index analysis approach. *Ecological Indicators*, *5*(2), 151–169. https://doi.org/10.1016/j.ecolind.2005.02.001

Chambers, J. M. (2008). *Basic Data and Computations BT - Software for Data Analysis: Programming with R* (J. Chambers (ed.)). Springer New York. https://doi.org/10.1007/978-0-387-75936-4_6

Cinnirella, S., Pirrone, N., Horvat, M., & Kocman, D. (2013). Daysimetric mapping of mercury emissions from contaminated sites. *E3S Web of Conferences*, *1*, 7007. https://doi.org/10.1051/e3sconf/20130107007

Dethier, E. N., Sartain, S. L., & Lutz, D. A. (2019). Heightened levels and seasonal inversion of riverine suspended sediment in a tropical biodiversity hot spot due to artisanal gold mining. *Proceedings of the National Academy of Sciences*, *116*(48), 23936–23941. https://doi.org/10.1073/pnas.1907842116

Di Stasio, L., Gentile, A., Tangredi, D. N., Piccolo, P., Oliva, G., Vigliotta, G., Cicatelli, A., Guarino, F., Guidi Nissim, W., Labra, M., & Castiglione, S. (2025). Urban phytoremediation: A nature-based solution for environmental reclamation and sustainability. *Plants*, *14*(13), 2057. https://doi.org/10.3390/plants14132057

Diringer, S. E., Feingold, B. J., Ortiz, E. J., Gallis, J. A., Araújo-Flores, J. M., Berky, A., Pan, W. K. Y., & Hsu-Kim, H. (2015). River transport of mercury from artisanal and small-scale gold mining and risks for dietary mercury exposure in Madre de Dios, Peru. *Environmental Science: Processes & Impacts*, *17*(2), 478–487. https://doi.org/10.1039/c4em00567h

Donkor, A. K., Bonzongo, J. C., Nartey, V. K., & Adotey, D. K. (2006). Mercury in different environmental compartments of the Pra River Basin, Ghana. *Science of The Total Environment*, *368*(1), 164–176. https://doi.org/10.1016/j.scitotenv.2005.09.046

Donkor, A. K., Ghoveisi, H., & Bonzongo, J.-C. J. (2024). Use of metallic mercury in artisanal gold mining by amalgamation: A review of temporal and spatial trends and environmental pollution. *Minerals*, *14*(6), 555. https://doi.org/10.3390/min14060555

Dordaa, S. D. D. P., Gordon, C., Nukpezah, D., Anang, A. K., & Kwawu, M. S. A. (2025). Assessing risks of methylmercury contamination in the Ankobra estuary, Western Region, Ghana. *International Journal of Environmental Studies*, 1–16. https://doi.org/10.1080/00207233.2025.2586283

Dossou Etui, I. M., Stylo, M., Davis, K., Evers, D. C., Slaveykova, V. I., Wood, C., & Burton, M. E. H. (2024). Artisanal and small-scale gold mining and biodiversity: a global literature review. *Ecotoxicology*, *33*(4–5), 484–504. https://doi.org/10.1007/s10646-024-02748-w

Egendorf, S. P., Gailey, A. D., Schachter, A. E., & Mielke, H. W. (2020). Soil toxicants that potentially affect children’s health. *Current Problems in Pediatric and Adolescent Health Care*, *50*(1), 100741. https://doi.org/https://doi.org/10.1016/j.cppeds.2019.100741

Esdaile, L. J., & Chalker, J. M. (2018). The mercury problem in artisanal and small-Scale gold mining. *Chemistry – A European Journal*, *24*(27), 6905–6916. https://doi.org/10.1002/chem.201704840

Förstner, U. (2004). Sediment dynamics and pollutant mobility in rivers: An interdisciplinary approach. *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use*, *9*(1), 25–40. https://doi.org/10.1111/j.1440-1770.2004.00231.x

Gerson, J. R., Topp, S. N., Vega, C. M., Gardner, J. R., Yang, X., Fernandez, L. E., Bernhardt, E. S., & Pavelsky, T. M. (2020). Artificial lake expansion amplifies mercury pollution from gold mining. *Science Advances*, *6*(48). https://doi.org/10.1126/sciadv.abd4953

Han, D., Cheng, J., Hu, X., Jiang, Z., Mo, L., Xu, H., Ma, Y., Chen, X., & Wang, H. (2017). Spatial distribution, risk assessment and source identification of heavy metals in sediments of the Yangtze River Estuary, China. *Marine Pollution Bulletin*, *115*(1), 141–148. https://doi.org/https://doi.org/10.1016/j.marpolbul.2016.11.062

Karikari, A. Y., Duah, A. A., Akurugu, B. A., & Darko, H. F. (2021). Assessing the impacts of artisanal mining on the quality ofvf South-western Rivers System in Ghana. *Environmental Monitoring and Assessment*, *193*(11). https://doi.org/10.1007/s10661-021-09515-y

Kumar, V., Umesh, M., Shanmugam, M. K., Chakraborty, P., Duhan, L., Gummadi, S. N., Pasrija, R., Jayaraj, I., & Dasarahally Huligowda, L. K. (2023). A retrospection on mercury contamination, bioaccumulation, and toxicity in diverse environments: Current insights and future prospects. *Sustainability*, *15*(18), 13292. https://doi.org/10.3390/su151813292

Lin, Y., Larssen, T., Vogt, R. D., Feng, X., & Zhang, H. (2011). Transport and fate of mercury under different hydrologie regimes in polluted stream in mining area. *Journal of Environmental Sciences*, *23*(5), 757–764. https://doi.org/10.1016/s1001-0742(10)60473-1

Liu, Q., Gao, J., Li, G., Zheng, Y., Li, R., & Yue, T. (2024). Bibliometric analysis on mercury emissions from coal-fired power plants: a systematic review and future prospect. *Environmental Science and Pollution Research*, *31*(13), 19148–19165. https://doi.org/10.1007/s11356-024-32369-z

Ma, M., Du, H., & Wang, D. (2019). Mercury methylation by anaerobic microorganisms: A review. *Critical Reviews in Environmental Science and Technology*, *49*(20), 1893–1936. https://doi.org/10.1080/10643389.2019.1594517

Martinez, G., McCord, S. A., Driscoll, C. T., Todorova, S., Wu, S., Araújo, J. F., Vega, C. M., & Fernandez, L. E. (2018). Mercury contamination in riverine sediments and fish associated with artisanal and small-scale gold mining in Madre de Dios, Peru. *International Journal of Environmental Research and Public Health*, *15*(8), 1584. https://doi.org/10.3390/ijerph15081584

Navarro, A. (2008). Review of characteristics of mercury speciation and mobility from areas of mercury mining in semi-arid environments. *Reviews in Environmental Science and Bio/Technology*, *7*(4), 287–306. https://doi.org/10.1007/s11157-008-9139-6

Outridge, P. M., Mason, R. P., Wang, F., Guerrero, S., & Heimbürger-Boavida, L. E. (2018). Updated global and oceanic mercury budgets for the United Nations Global Mercury Assessment 2018. *Environmental Science & Technology*. https://doi.org/10.1021/acs.est.8b01246

Pang, Q., Gu, J., Wang, H., & Zhang, Y. (2022). Global health impact of atmospheric mercury emissions from artisanal and small-scale gold mining. *IScience*, *25*(9). https://doi.org/10.1016/j.isci.2022.104881

Przybyla, J., McClure, P. R., Zaccaria, K. J., & Pohl, H. R. (2021). Chemical interactions and mixtures in public health risk assessment: An analysis of ATSDR's interaction profile database. *Regulatory Toxicology and Pharmacology*, *125*, 104981. https://doi.org/https://doi.org/10.1016/j.yrtph.2021.104981

Regnell, O., & Watras, C. J. (2018). Microbial mercury methylation in aquatic environments: A critical review of published field and laboratory studies. *Environmental Science & Technology*, *53*(1), 4–19. https://doi.org/10.1021/acs.est.8b02709

Rinaldi, M., Wyżga, B., & Surian, N. (2005). Sediment mining in alluvial channels: Physical effects and management perspectives. *River Research and Applications*, *21*(7), 805–828. https://doi.org/10.1002/rra.884

Sall, M. L., Diaw, A. K. D., Gningue-Sall, D., Efremova Aaron, S., & Aaron, J.-J. (2020). Toxic heavy metals: impact on the environment and human health, and treatment with conducting organic polymers, a review. *Environmental Science and Pollution Research*, *27*(24), 29927–29942. https://doi.org/10.1007/s11356-020-09354-3

Selin, H., Keane, S. E., Wang, S., Selin, N. E., Davis, K., & Bally, D. (2018). Linking science and policy to support the implementation of the Minamata Convention on Mercury. *Ambio*, *47*(2), 198–215. https://doi.org/10.1007/s13280-017-1003-x

Spiller, P., van Wijngaarden, E., Adams, H. R., Strain, J. J., McSorley, E. M., Mulhern, M. S., Conway, M. C., Yeates, A. J., Carrington, C., Bolger, P. M., Morgan, K. M., Taylor, C. M., Ralston, N. V. C., Crawford, M. A., Hibbeln, J. R., Brenna, J. T., & Myers, G. J. (2023). Net effects explains the benefits to children from maternal fish consumption despite methylmercury in fish. *NeuroToxicology*, *99*, 195–205. https://doi.org/https://doi.org/10.1016/j.neuro.2023.10.010

Tripathee, L., Guo, J., Kang, S., Paudyal, R., Huang, J., Sharma, C. M., Zhang, Q., Chen, P., Ghimire, P. S., & Sigdel, M. (2019). Spatial and temporal distribution of total mercury in atmospheric wet precipitation at four sites from the Nepal-Himalayas. *Science of The Total Environment*, *655*, 1207–1217. https://doi.org/10.1016/j.scitotenv.2018.11.338

UN Environment Programme. (2019). *Global Mercury Assessment 2018*. UN Environment Programme Economy Division Chemicals and Health Branch International Environment House. https://wedocs.unep.org/handle/20.500.11822/27579

Verbrugge, B., & Thiers, R. (2016). Artisanal and small-scale mining. In *Breaking New Ground* (pp. 313–334). Routledge. https://doi.org/10.4324/9781315541501-17

WHO. (2011). Guidelines for drinking-water quality. In *WHO Press* (Vol. 1, Issue 5, pp. 1–515). WHO Press. https://doi.org/10.1248/jhs1956.35.307

Wu, Y.-S., Osman, A. I., Hosny, M., Elgarahy, A. M., Eltaweil, A. S., Rooney, D. W., Chen, Z., Rahim, N. S., Sekar, M., Gopinath, S. C. B., Mat Rani, N. N. I., Batumalaie, K., & Yap, P.-S. (2024). The toxicity of mercury and its chemical compounds: Molecular mechanisms and environmental and human health implications: A comprehensive review. *ACS Omega*, *9*(5), 5100–5126. https://doi.org/10.1021/acsomega.3c07047

Yan, J., Li, R., Wang, C., Yang, S., Shao, M., Zhang, L., Li, P., & Feng, X. (2025). Transport and transformation of colloidal and particulate mercury in contaminated watershed. *Water Research*, *278*, 123428. https://doi.org/https://doi.org/10.1016/j.watres.2025.123428

Zhang, Y., & Adeloju, S. B. (2008). A novel sequential injection—Cold vapour atomic absorption spectrometric system for rapid and reliable determination of mercury. *Talanta*, *74*(4), 951–957. https://doi.org/https://doi.org/10.1016/j.talanta.2007.07.043