



The Impact of Mining Activities on River Water Pollution: A Case Study in the Mahakam Watershed

Neviaisyah Zevani Putri

Universitas Jambi, Indonesia

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Abstract

This study investigates the impact of mining activities on river water pollution in the Mahakam Watershed, East Kalimantan, Indonesia. Using a quantitative case study approach, water samples were collected from five strategically selected sites representing upstream, midstream, and downstream areas, with varying degrees of proximity to coal mining operations. The physicochemical analysis revealed elevated concentrations of total suspended solids (TSS), biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), and heavy metals such as iron (Fe), manganese (Mn), and lead (Pb), especially in midstream and downstream sites. These findings suggest that mining runoff and acid mine drainage (AMD) have significantly altered water chemistry. Biological assessments further confirmed ecological stress, as evidenced by the dominance of pollution-tolerant species and a decline in biodiversity. GIS-based spatial analysis identified pollution hotspots near steep, deforested mining zones. Community interviews revealed adverse socio-economic impacts, including reduced fish populations and waterborne health issues. The results highlight the urgent need for integrated watershed management, environmental regulation enforcement, and community-based ecological monitoring to protect the Mahakam River ecosystem and its dependent communities.

Keywords: Mahakam River, mining pollution, heavy metals, water quality, acid mine drainage

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□ Corresponding author :

Email Address : neviaisyahzevaniputri@gmail.com

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Introduction

The mining industry has played a vital role in Indonesia's economic development, particularly in resource-rich provinces such as East Kalimantan. The region's substantial reserves of coal and minerals have attracted both domestic and international investors, resulting in the rapid expansion of mining activities over the past two decades. Revenues from coal exports contribute significantly to the national Gross Domestic Product (GDP), create employment opportunities, and fund regional infrastructure. However, the very practices that drive economic growth often simultaneously contribute to environmental degradation, especially when mining operations are carried out without adequate environmental safeguards. In the context of the Mahakam watershed, mining concessions frequently overlap with ecologically sensitive zones, leading to deforestation, soil erosion, and, most critically, the pollution of river systems. This juxtaposition of economic gain and ecological loss creates a paradox that demands urgent scholarly and policy attention.



The Mahakam River is not only the longest and most important river in East Kalimantan but also a multifunctional ecosystem that sustains a variety of life forms and economic activities. It serves as the primary source of freshwater for more than one million people and supports transportation, fisheries, agriculture, and tourism. The river's ecological significance is equally immense, encompassing wetlands, peatlands, and mangrove zones that provide critical habitats for both endemic and migratory species. However, the river's proximity to extensive mining areas renders it highly vulnerable to anthropogenic pressures. Sedimentation from overburden removal, acid mine drainage (AMD), and tailings discharges increasingly compromise water quality. Moreover, the cumulative impact of numerous mining operations many of which lack proper environmental impact assessments further amplifies the risk of ecological collapse in downstream communities and wetlands, especially during the rainy season when runoff intensifies.

Pollution in river systems resulting from mining operations is typically multifaceted and occurs through direct and indirect pathways. The most common pollutants include suspended solids, heavy metals, hydrocarbons, and acidic compounds, all of which can drastically alter the physical, chemical, and biological characteristics of freshwater ecosystems. Acid mine drainage, formed when sulfide minerals are exposed to oxygen and water, leads to the release of sulfuric acid into nearby streams, which in turn dissolves heavy metals such as Fe, Mn, Hg, Pb, Cd, and As. These pollutants not only degrade water quality but also persist in sediments and aquatic organisms for years, causing chronic toxicity. Furthermore, surface runoff during rainfall events transports exposed overburden materials and chemical residues into water bodies, creating flash pollution incidents that exceed natural assimilation capacities. The lack of proper sediment ponds, treatment facilities, and vegetative buffer zones exacerbates these issues, reflecting poor environmental planning and oversight in many mining operations.

Although several studies have addressed the environmental impacts of mining in Indonesia, much of the existing literature tends to generalize findings without accounting for site-specific variability, hydrological connectivity, or sociocultural dimensions. For instance, empirical studies have shown that heavy metal concentrations in rivers adjacent to mining zones often exceed the national water quality standards, but these studies frequently lack long-term monitoring data or fail to capture temporal dynamics such as seasonal fluctuations. In the case of the Mahakam River, comprehensive datasets on pollution trends, biodiversity shifts, and community vulnerability remain scarce. Most environmental impact assessments (EIAs) are carried out by the mining companies themselves and often lack third-party verification or community participation. This research, therefore, seeks to fill a critical knowledge gap by integrating scientific water quality analysis with a spatially explicit understanding of pollution sources and ecological risk within the Mahakam watershed.

The degradation of water quality in the Mahakam River has far-reaching implications for the health, well-being, and livelihoods of surrounding communities, many of whom belong to indigenous Dayak and Kutai populations. These communities have historically depended on the river for subsistence fishing, water collection, and agricultural irrigation. However, in recent years, residents have reported declining fish stocks, skin rashes, gastrointestinal illnesses, and crop failures symptoms often associated with environmental contamination. Additionally, local water utilities are forced to invest more in water treatment due to the deteriorating quality of raw water sources, leading to increased service costs that are passed on to consumers. Social conflicts have also escalated, with several instances of protests and legal action taken by affected communities against mining corporations. Yet, without scientific data to substantiate claims and demonstrate causality, community grievances are often ignored or dismissed. This underscores the need for transparent, data-driven environmental monitoring to support social accountability and equitable development.

Beyond human concerns, the Mahakam River is home to a rich array of aquatic and semi-aquatic species that are increasingly under threat due to pollution. Among the most iconic species is the Mahakam freshwater dolphin (*Orcaella brevirostris*), which is classified as critically endangered by the IUCN. This species is highly sensitive to chemical pollutants, changes in water flow, and noise pollution from increased barge traffic linked to mining. In addition to the dolphin, numerous species of fish, amphibians, mollusks, and macroinvertebrates face declining population trends. These organisms not only hold ecological value but also play crucial roles in maintaining the river's trophic structure and nutrient cycling. Habitat fragmentation, the introduction of invasive species, and reduced dissolved oxygen levels further compound biodiversity loss. Over time, such ecological disturbances may become irreversible, especially if keystone species are lost, leading to the collapse of the aquatic food web and the transformation of the river into a biologically impoverished system.

Indonesia's environmental policy framework is relatively comprehensive, encompassing laws and regulations on water quality, environmental impact assessment, pollution control, and reclamation. However, the implementation and enforcement of these policies remain inconsistent, particularly in remote and economically strategic regions like East Kalimantan. Weak institutional capacity, corruption, and lack of community engagement often result in environmental regulations being ignored or bypassed. Effective governance in the mining sector requires not only stronger legal frameworks but also the active involvement of civil society, academia, and local governments. Moreover, environmental monitoring should be independent, continuous, and equipped with modern tools such as satellite imagery, bioindicators, and geospatial information systems. By linking empirical data with governance mechanisms, it is possible to create adaptive management strategies that balance environmental protection with socio-economic development in the Mahakam watershed.

This study is designed to provide a scientifically robust and context-sensitive assessment of how mining operations impact river water quality and aquatic ecosystems within the Mahakam River Basin. Specifically, it aims to: (1) measure key physicochemical and biological parameters of water quality at various distances from mining sites; (2) identify pollution hotspots and potential sources using spatial analysis; and (3) evaluate ecological risks and socioeconomic consequences for local communities. By combining field-based measurements with policy analysis and community perspectives, this research seeks to generate actionable insights for multiple stakeholders, including policymakers, environmental NGOs, industry regulators, and academic institutions. The ultimate goal is to contribute to the long-term sustainability of the Mahakam River as both a vital natural resource and a symbol of environmental heritage for East Kalimantan.

Metodologi

This study adopts a quantitative, field-based case study methodology, aiming to systematically examine the extent of water pollution in the Mahakam River as a result of nearby mining activities. The quantitative approach is appropriate because it allows for the collection of measurable and verifiable data that can be statistically analyzed to determine correlations, trends, and differences among various sampling sites. The case study design enables contextualization of findings within the specific geographic, environmental, and socioeconomic characteristics of the Mahakam watershed, allowing the research to capture the complexity of pollution sources and impacts. The combination of environmental science, hydrology, and geospatial analysis used in this methodology is particularly suited to assess the ecological effects of industrial activities on tropical river systems.

Sampling was conducted at five carefully selected points along the Mahakam River that reflect different land-use pressures and environmental conditions. These include:

- Site A (upstream control area with minimal anthropogenic influence),
- Site B and C (midstream zones near active coal mining concessions),
- Site D (a tributary with visible runoff from mining roads), and

- Site E (downstream accumulation zone near dense population and barge activity). Each site was selected based on proximity to mining operations, hydrological connectivity, catchment topography, and accessibility. Sampling was conducted during two different seasons the wet season (January–March) and the dry season (July–September) to account for seasonal variations in pollutant concentration, sediment load, and runoff patterns. Water samples were collected in triplicates at each site using sterilized Niskin bottles, then stored in cold boxes and transported to the laboratory within 24 hours for analysis. In-situ measurements (e.g., pH, temperature, dissolved oxygen) were also performed using calibrated handheld meters at the point of collection to preserve the integrity of data.

The physicochemical parameters selected for analysis include temperature, pH, electrical conductivity (EC), total suspended solids (TSS), turbidity, biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), dissolved oxygen (DO), and concentrations of key heavy metals such as Iron (Fe), Manganese (Mn), Lead (Pb), Cadmium (Cd), Mercury (Hg), and Arsenic (As). These parameters were chosen based on their relevance to mining-related pollution and their known toxicity to aquatic organisms and humans.

- Heavy metals were measured using Atomic Absorption Spectrophotometry (AAS) and Cold Vapor AAS for mercury.
- BOD and COD levels were determined following the APHA 5210B and 5220D methods, respectively.
- TSS and turbidity were assessed via gravimetric and nephelometric methods. Laboratory procedures were conducted at a certified environmental testing facility, and all analyses adhered strictly to the protocols outlined in the APHA Standard Methods (23rd Edition). To ensure accuracy, instrument calibration, duplicate analysis, and reagent blank controls were regularly implemented.

In addition to physicochemical analyses, biological assessments were performed to evaluate the ecological health of the river using bioindicator organisms. Biological data were collected through plankton sampling (phytoplankton and zooplankton), macroinvertebrate surveys, and benthic fauna collection.

- Plankton were sampled using vertical net tows (mesh size 20 µm), and species were identified under a compound microscope using identification keys.
- Macroinvertebrates were collected using a Surber sampler and Ekman dredge from the riverbed, sorted, and classified down to the family level.

These biological indicators are sensitive to pollution stress and serve as early warning signs of ecosystem degradation.

The Shannon-Wiener Diversity Index (H'), Evenness Index (E), and Family Biotic Index (FBI) were calculated to quantify community structure and pollution tolerance levels. A significant reduction in diversity and dominance by a few pollution-tolerant taxa (e.g., Chironomidae) would suggest ecological imbalance induced by mining waste.

Data from field measurements and laboratory results were tabulated and subjected to descriptive statistical analysis, including means, medians, standard deviations, and coefficient of variation. These were used to understand general water quality trends and compare them to permissible limits set by Government Regulation No. 22 of 2021 on Water Quality Standards. Inferential statistics were then applied using Analysis of Variance (ANOVA) to determine whether statistically significant differences in pollutant levels exist among the sampling sites. Furthermore, Pearson correlation coefficients were computed to assess relationships between heavy metal concentrations and other variables such as TSS, EC, and distance from mining sites. Multivariate statistical techniques, such as Principal Component Analysis (PCA) and Cluster Analysis, were also applied to identify pollutant groupings, source patterns, and site similarities. This approach allows a deeper understanding of pollution dynamics across the watershed and helps isolate mining-specific impacts from other anthropogenic influences.

To visually analyze spatial trends in water pollution and their relationship to land use patterns, Geographic Information Systems (GIS) were employed using ArcGIS Pro 3.1. Land use and land cover data were obtained from Sentinel-2 and Landsat 8 imagery, which were classified into categories such as mining area, forest, water bodies, agricultural fields, and settlements. These maps were overlaid with sampling locations and the spatial extent of mining concessions using official mining permit data from the Ministry of Energy and Mineral Resources. Buffer zones of 1 km, 3 km, and 5 km around each

mining site were created to assess spatial gradients of contamination. Digital Elevation Models (DEM) were used to identify flow accumulation patterns and potential pollution transport routes. This spatial component enables the identification of pollution hotspots, the estimation of affected population centers, and the planning of future mitigation zones based on topographic and hydrologic connectivity.

Given the environmental and social sensitivity of the research area, ethical considerations were taken seriously throughout the study. Prior to conducting fieldwork, research permits were obtained from the local environmental agency (DLH) and village authorities. Community leaders and residents were informed about the purpose and scope of the study through public meetings and focus group discussions.

Informed consent was obtained from all interview participants, who provided qualitative insights into water use patterns, observed ecological changes, and the health impacts of pollution. These community-based observations were triangulated with scientific data to enhance validity and contextual understanding. Special attention was given to ensuring that the research process did not disrupt local livelihoods or provoke conflict with industry stakeholders. To ensure the accuracy, reliability, and reproducibility of the findings, the study adhered to strict Quality Assurance/Quality Control (QA/QC) protocols. Instruments were calibrated daily, and each sample was analyzed in triplicate. Field blanks and spiked recovery tests were used to check for contamination and analytical precision.

Despite these measures, certain limitations are acknowledged. For instance, weather-related access issues during the rainy season limited data collection in some tributary areas. Furthermore, the study focused on surface water and did not include groundwater assessments, which may also be affected by mining leachate. Nevertheless, by combining quantitative analysis, biological indicators, and spatial mapping, the methodology provides a robust framework for understanding the relationship between mining activities and riverine pollution.

Result and Discussion

The study revealed a distinct spatial gradient in the physicochemical quality of water along the Mahakam River. The upstream site (Site A), which is relatively undisturbed by industrial activity, consistently exhibited water quality parameters within the acceptable limits set by the Indonesian Government Regulation No. 22 of 2021. Parameters such as pH (7.2), DO (6.8 mg/L), and TSS (26.3 mg/L) indicated a relatively healthy aquatic environment. In contrast, Sites B, C, and E located near active coal mining and transportation corridors displayed alarming deviations. TSS levels increased dramatically, with Site C recording an average of 123.4 mg/L, more than four times the permissible threshold. pH levels dropped to as low as 5.6 in downstream areas, indicating acidic conditions likely caused by acid mine drainage (AMD). BOD₅ and COD values at Site D were recorded at 7.9 mg/L and 48.6 mg/L, respectively signifying organic overloads and low oxygen availability. These values suggest an elevated organic and chemical burden resulting from mining runoff, unregulated wastewater discharge, and erosion from exposed overburden surfaces.

Heavy metal analysis further supported the hypothesis of severe anthropogenic contamination in mining-impacted areas. Iron (Fe) concentrations ranged from 0.9 mg/L at Site A to 2.6 mg/L at Site C, while Manganese (Mn) ranged from 0.2 mg/L to 1.8 mg/L. These values far exceeded the recommended limits for Class II water usage (1.0 mg/L for Fe and 0.3 mg/L for Mn). Lead (Pb) concentrations at Site D reached a critical level of 0.29 mg/L almost six times higher than the maximum allowable limit of 0.05 mg/L. Mercury (Hg), although present in lower concentrations (0.003–0.006 mg/L), poses significant long-term bioaccumulative risks, especially to aquatic life and humans consuming fish from the river. A strong positive correlation ($r = 0.81$) was found between the distance from mining areas and the concentration of heavy metals, indicating direct pollution input from mining waste, overburden exposure, and leaching from coal stockpiles. The Pollution Load Index (PLI) classified Sites C and D as "heavily polluted," while Site A remained "unpolluted."

Biological monitoring revealed a clear decline in biodiversity and ecological health at sites closer to mining operations. At Site A, the Shannon-Wiener Diversity Index (H') for macroinvertebrates was 2.78, indicating a diverse and stable aquatic community. However, at Site C, H' dropped to 1.23, and at Site D, further declined to 0.89, reflecting biological stress and dominance by pollution-tolerant species such as Chironomidae (bloodworms), Tubificidae, and Lymnaeidae. Similarly, plankton populations exhibited notable shifts; phytoplankton density dropped from 6,200 cells/L at Site A to just

1,150 cells/L at Site D. The dominance index increased significantly at mining-influenced sites, indicating ecological imbalance. These results demonstrate that chronic exposure to mining effluents disrupts the food chain, reduces reproductive success in sensitive taxa, and leads to the collapse of ecological niches.

GIS analysis further illustrated the spatial correlation between mining operations and degraded water quality. Using spatial overlays of sampling points and land use data from Sentinel-2 imagery, pollution hotspots were identified within 3 to 5 km buffers surrounding open-pit mines. Digital elevation models (DEMs) confirmed that polluted tributaries originated from areas with steep slopes and high erosion risk. Areas in Kutai Kartanegara and Tenggarong Seberang showed a concentration of heavy metal deposition in low-lying floodplains. The Water Quality Index (WQI) classified Site A as “Good,” Site B as “Moderate,” and Sites C and D as “Poor” and “Very Poor,” respectively. These spatial findings provide a valuable tool for identifying critical zones for remediation and for establishing monitoring networks. They also illustrate the role of landscape features such as slope, runoff direction, and vegetation loss in mediating pollutant transport.

Community-based observations and qualitative interviews reinforced the scientific findings. Inhabitants of riverine villages near Sites C and D reported a sharp decline in fish availability, especially native species like *ikan baung* and *ikan lais*, over the past five years. Many families reported increased skin rashes, gastrointestinal issues, and dependency on bottled water for drinking and cooking due to fears of contamination. Furthermore, visual indicators such as water discoloration (yellow-brown hue), oil sheens, and sulfuric odors were commonly reported during rainy seasons. Respondents also linked these changes to heightened flooding frequency, suggesting that sedimentation and riverbank instability caused by mining have altered the river’s hydrology. These community insights add social depth to the environmental data, emphasizing the multidimensional impact of mining activities not only on ecosystems but also on human health, livelihood security, and cultural practices tied to the river.

The degradation of water quality in the Mahakam River, particularly in areas adjacent to mining operations, underscores the profound influence of anthropogenic activities on freshwater ecosystems. The sharp increase in Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), and Biochemical Oxygen Demand (BOD₅) at midstream and downstream sites reflects intensified sedimentation, organic enrichment, and potential input from untreated waste discharges. These findings are consistent with earlier research conducted in the Barito and Bengkulu River basins, which also recorded elevated pollutant levels downstream from coal mining activities (e.g., Putra et al., 2020; Saragih et al., 2022). In this study, the significant decline in pH in several sites (as low as 5.6) further suggests the onset of acid mine drainage (AMD) a process where sulfur-bearing rocks react with oxygen and water to produce acidic runoff. AMD not only lowers the buffering capacity of water bodies but also increases the solubility and mobility of toxic metals, exacerbating contamination risks. Collectively, these changes point to a shifting river chemistry profile that disrupts the natural equilibrium and reduces the river's capacity to self-purify.

The presence of hazardous heavy metals such as iron, manganese, lead, and mercury in concentrations exceeding both national and international water quality standards is a major environmental red flag. These metals are not only toxic to aquatic organisms but also pose long-term health risks to human populations through bioaccumulation and biomagnification, particularly when local communities rely on fish as a staple protein source. For instance, lead contamination at levels approaching 0.3 mg/L as found in Site D is known to cause neurological and developmental impairments, especially in children. Chronic exposure to iron and manganese, while essential in trace amounts, can impair organ function and trigger oxidative stress when present in high concentrations. The relationship between mining proximity and metal accumulation revealed in this study aligns with findings in Kalimantan and Papua, where open-pit and artisanal mining have been implicated in widespread contamination (Suwondo et al., 2021). Moreover, the sedimentation of heavy metals in riverbeds may lead to delayed and persistent toxic effects, even if mining activities cease, as metals can be remobilized during floods or seasonal hydrologic changes.

The biological findings of this study particularly the sharp reduction in plankton density and macroinvertebrate diversity signal the collapse of ecological complexity in polluted zones. The dominance of pollution-tolerant species, such as *Chironomidae* and *Tubificidae*, indicates a significant shift in community structure from diverse, functionally-rich assemblages to simplified, resistant populations. This reflects what ecologists refer to as “biotic homogenization,” where stressed ecosystems lose specialist species and become dominated by a few generalist taxa. Such homogenization

is not merely a loss of species, but a weakening of ecological function, including nutrient cycling, detritus breakdown, and primary productivity. These findings are corroborated by previous ecological assessments in mining-affected rivers in Latin America and Southeast Asia (e.g., Mol et al., 2017; Kurniawan et al., 2018). The reduced presence of phytoplankton also disrupts the trophic pyramid, which can lead to lower fish recruitment and productivity thereby threatening food security, local economies, and traditional livelihoods dependent on the river's natural resources.

Spatial analysis using GIS adds another critical layer of understanding, illustrating how landscape configuration and watershed characteristics mediate pollution exposure and impact. Mining operations located on steep terrains with minimal vegetative buffers were found to contribute significantly to sediment and metal flow into the river. The use of buffer analysis and digital elevation models (DEM) confirmed that unprotected slopes and altered drainage paths act as direct pollution conduits, funneling contaminants into major tributaries and floodplains. The spatial clustering of “heavily polluted” classifications within 3–5 km of mining sites suggests a predictable and mappable pollution footprint, which can serve as a reference for regulatory zoning and environmental monitoring. These patterns align with the Pressure-State-Response (PSR) model in environmental management, which emphasizes the importance of understanding pressure sources (e.g., land use, slope, rainfall) in mitigating environmental degradation. Studies in the Mekong Basin and Amazonian sub-watersheds support similar conclusions, where spatial planning and slope rehabilitation have been employed to successfully reduce mining runoff and river degradation.

Beyond the biophysical evidence, the lived experiences of riverine communities underscore the socio-environmental dimension of water pollution. Residents near Sites C and D, who rely on the Mahakam River for fishing, bathing, and household needs, reported observable changes in water color, odor, and fish availability over the past five to ten years. Such community accounts are consistent with empirical data and serve as crucial validation mechanisms for environmental research. The reported increase in health complaints such as skin irritation, diarrhea, and respiratory issues aligns with literature on exposure to contaminated water in mining areas (WHO, 2022; Saputra et al., 2020). This underscores the concept of environmental injustice, where marginalized populations disproportionately suffer the consequences of industrial pollution while often lacking access to mitigation tools, health services, or policy influence. The findings advocate for a community-based environmental governance model that integrates local knowledge, public health interventions, and participatory monitoring to promote resilience and justice in affected watersheds.

Conclusion

This study concludes that mining activities along the Mahakam River have caused significant degradation of water quality, ecological health, and community well-being. Physicochemical parameters such as total suspended solids (TSS), biochemical oxygen demand (BOD), and heavy metal concentrations including iron (Fe), manganese (Mn), and lead (Pb) exceeded national and international safety standards in sites located downstream of mining operations. The acidic conditions found in several locations further indicate the presence of acid mine drainage (AMD), which exacerbates the mobilization of toxic pollutants. Biological assessments revealed a marked decline in biodiversity, with sensitive aquatic species replaced by pollution-tolerant organisms, signaling a breakdown of ecological balance. Spatial analysis using GIS confirmed that pollution intensity is closely associated with proximity to mining concessions, steep terrain, and deforested areas, highlighting the role of landscape vulnerability in pollutant transport. Additionally, qualitative data from local communities revealed that river-dependent households are facing growing health risks and economic losses due to reduced water quality and fish availability. Overall, this research underscores the urgent need for integrated watershed management, stricter mining regulations, ecological rehabilitation, and community-centered monitoring programs to safeguard the Mahakam River and its surrounding ecosystems.

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