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Identification of Mercury Content in Groundwater at Post-Processing Land for Gold Mining Materials

Mokhram Ari Arbi Ililirugun [1*], Arif Setiajaya [1]

[1] Environmental Enginerring, Malahayati University, 35158, Bandar Lampung, Indonesia.

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ABSTRACT

Small-scale gold mining activities in Dava Village predominantly rely on mercury (Hg) during the amalgamation process, posing a significant risk of groundwater contamination in surrounding residential areas. This study aims to analyze mercury concentrations in well water using nine sampling points representing locations near tailings disposal sites, amalgam burning areas, and residential zones. Mercury concentrations were measured using Atomic Absorption Spectrophotometry (AAS). The results of the study showed that all samples exceeded the water quality standards in accordance with the Minister of Health Regulation No. 2 of 2023 for mercury (<0.001 ppm), with the highest concentrations detected at sampling points S6, S9, and S2, which are located closest to mining activities. The spatial distribution demonstrates a strong correlation between artisanal gold mining practices and elevated Hg contamination in shallow aquifers. Mercury mobility and accumulation are influenced by environmental factors such as open tailings infiltration, surface runoff, atmospheric deposition from amalgam burning, and pH variations. Prolonged exposure to mercury-contaminated water poses serious health risks, including neurological disorders, kidney damage, and developmental impairments. These findings confirm that traditional gold processing without proper waste management presents substantial threats to environmental quality and public health. Therefore, mitigation measures such as reducing mercury use, improving tailings management, and implementing regular groundwater quality monitoring are urgently required to minimize future exposure.

1. Introduction

Small-scale gold processing activities in many regions of Indonesia still widely use mercury in the amalgamation process to extract gold from ore. Small-scale gold mining or artisanal gold mining is distributed across 850 locations in Indonesia (Ratnasari, 2014; Kristianingsih, 2018). Gold separation in mining operation is done using mercury (Setiabudi, 2005; Ratnasari, 2014; Kristianingsih, 2018). Processing of gold mining materials is carried out separately from the location where the materials to be processed are taken. Mining material processing land referred to in this study includes the tailings disposal area, wastewater settling ponds, amalgam burning locations, and seepage areas remaining after the extraction process. The presence of tailings and purification ponds without

* Corresponding author.
E-mail address: *mokhramariarbi@malahayati.ac.id*
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adequate management increases the likelihood of mercury infiltrating into the saturated zone (aquifer), putting wells used by residents downstream or around the disposal area at risk of contamination. Such conditions require a special study linking the source (post-processing) with the concentration of Hg in groundwater.

Mercury is highly toxic and can undergo microbial-mediated biogeochemical transformations to form methylmercury, which subsequently bioaccumulates along the food chain. The toxicity and metabolism of mercury are influenced by several factors, including its chemical form, duration of exposure, and interactions with other elements present in food. Metallic mercury predominantly accumulates in the kidneys, brain, liver, and fetus, causing severe damage to the central nervous system (Director of Food Safety Assessment and National Agency of Drug and Food Control, 2009). Exposure to mercury, whether acute or chronic, is associated with a range of serious health effects, including neurological disorders, cardiovascular disease, central nervous system impairment, kidney damage, and autism (Irsan et al., 2025). These risks underscore the urgent need for research to assess potential health impacts in communities that depend on well water.

Indonesian water quality regulations stipulate a maximum allowable mercury concentration of 0.001 ppm in drinking and clean water. This threshold serves as the national benchmark for evaluating mercury contamination and is applied in this study to determine the level of pollution in post-processing land in Dava Village.

This research fills the data gap regarding groundwater quality in the post-processing area of gold mining materials on Buru Island, specifically in Dava Village, which is known as a site for traditional gold mining material processing activities. The research aims to identify the level of Hg in groundwater, assess the role of post-processing land conditions of gold mining materials (tailings/amalgam waste) on Hg distribution, and suggest evidence-based management steps for local policymakers. The objectives of this study are: To identify the concentration of mercury (Hg) in groundwater in post-gold mining land in Dava Village; To examine the relationship between tailings disposal locations/processing areas and the distribution of Hg in the local aquifer; and To provide mitigation and waste management recommendations to reduce community exposure risks.

2. Methodology

2.1 Data and Location

The research was conducted in Dava Village, Waelata District, Buru Regency, Maluku, which is the center of gold processing activity for Mount Botak. The location was chosen purposively based on the high intensity of processing activities and the potential for mercury contamination of groundwater. The research uses a descriptive quantitative approach to obtain an overview of groundwater quality conditions thru the analysis of mercury (Hg) and pH parameters.

Groundwater samples were taken at nine points distributed across three treatment lines (Lines A, C, and D), selected based on the distribution of gold processing units and their proximity to residential areas. Samples were taken from dug wells or other groundwater sources that represent the pollution conditions around the site.

2.2 Data Collection Techniques

Sampling followed standard procedures for heavy metal analysis in groundwater. Water samples were collected in pre-cleaned glass or polypropylene bottles and preserved with nitric acid (HNO_3) to achieve pH < 2. All samples were properly labeled, stored at 4–8 °C, and transported to an accredited laboratory for analysis. Mercury concentrations were determined using Atomic Absorption Spectrophotometry (AAS), while pH was measured in situ using a calibrated portable pH meter. The use of AAS for mercury determination is widely recognized for its accuracy and sensitivity at trace

concentration levels and has been extensively applied in environmental mercury studies (Welz & Sperling, 1999; Skoog et al., 2014).

Measured mercury concentrations were compared with national water quality standards stipulated in the Government Regulation of the Republic of Indonesia Number 22 of 2021, Appendix VII (Hg < 0.001 mg/L), as well as the Regulation of the Minister of Health of the Republic of Indonesia Number 2 of 2023 concerning Environmental Health. Data were analyzed descriptively to evaluate spatial variations in mercury concentrations, contamination levels at each sampling point, and potential risks to human health and the environment in Dava Village. Similar descriptive and comparative analytical approaches have been employed in previous studies assessing mercury contamination in groundwater influenced by artisanal and small-scale gold mining activities, demonstrating the suitability of this method for identifying contamination patterns and exposure risks (Castilhos et al., 2006; Bose-O'Reilly et al., 2010; UNEP, 2018)..

3. Results

3.1 Post-Processing Land Conditions

Field observations identified several major sources of mercury pollution that facilitate its transport into the surrounding environment. The presence of open tailings disposal areas reflects inadequate waste management practices, allowing gold-processing residues to be easily dispersed by wind and mobilized through surface runoff during periods of high rainfall. In addition, seepage observed from the purification pond indicates structural deficiencies, such as damaged retaining walls or an unsealed base, which permit mercury-containing effluents to infiltrate directly into the subsurface without undergoing proper treatment or natural attenuation. These conditions collectively enhance the migration of mercury from surface sources into the soil and groundwater system, thereby increasing the risk of environmental contamination and exposure to nearby communities.

Furthermore, amalgam burning activities located in close proximity to residential areas indicate a substantial potential for direct mercury exposure among local communities. The amalgam burning process releases elemental mercury vapor (Hg^o) into the atmosphere, which can subsequently undergo dry and wet deposition onto surrounding soils, rooftops, surface waters, and infiltration zones near residential areas (Telmer & Veiga, 2009; Pirrone et al., 2013). The interaction of open tailings disposal, seepage from processing ponds, and atmospheric deposition from amalgam burning creates a complex mercury migration pathway, particularly during the rainy season when increased infiltration and surface runoff enhance contaminant transport toward the saturated zone. Under these conditions, mercury may migrate downward through soil pores, accumulate in shallow aquifers, and ultimately contaminate groundwater used for domestic purposes. These findings confirm that uncontrolled artisanal gold processing activities significantly contribute to elevated mercury contamination risks across multiple environmental media, including soil, surface water, air, and groundwater (UNEP, 2019; Hilson & van der Vorst, 2002).

3.2 *pH Value at Sampling Point*

Table 1 below shows the pH values measured in situ at nine sampling points.

Table 1. pH Values of Well Water in Dava Village

No.	Sampling Point	pH	Requirement	Notes
1	S1	8.0	6.5 – 8.5	Neutral
2	S2	6.0	6.5 – 8.5	Acid
3	S3	7.0	6.5 – 8.5	Neutral
4	S4	6.8	6.5 – 8.5	Neutral
5	S5	7.3	6.5 – 8.5	Neutral

No.	Sampling Point	pH	Requirement	Notes
6	S6	5.9	6.5 – 8.5	Acid
7	S7	6.5	6.5 – 8.5	Neutral
8	S8	7.1	6.5 – 8.5	Neutral
9	S9	6.3	6.5 – 8.5	Acid

3.3 *pH Value at Sampling Point*

Table 1 below shows the pH values measured in situ at nine sampling points.

Table 2. Mercury (Hg) Concentration in Well Water

No.	Sampling Point	Hg (ppm)	Quality Standard (ppm)	Notes
1	S1	0.0608	0.001	Exceeding
2	S2	0.0625	0.001	Exceeding
3	S3	0.0238	0.001	Exceeding
4	S4	0.0452	0.001	Exceeding
5	S5	0.0385	0.001	Exceeding
6	S6	0.0713	0.001	Exceeding
7	S7	0.0571	0.001	Exceeding
8	S8	0.0419	0.001	Exceeding
9	S9	0.0660	0.001	Exceeding

3.4. Relationship Between Post-Processing Land and Hg Concentration

The results of mercury (Hg) concentration measurements at nine sampling points show that several points near open tailings disposal areas and amalgam burning locations—specifically points S6, S9, and S2—have very high concentration values that far exceed national quality standards. This pattern shows a strong spatial relationship between artisanal gold mining activity and increased Hg content in groundwater. This finding is consistent with the report by Bose-O'Reilly et al. (2010), which states that wells near traditional gold processing sites almost always show Hg levels far above the WHO's safe threshold. This phenomenon indicates that locations with high processing activity intensity tend to be centers for mercury accumulation and release into the surrounding environment.

The open-pit tailings disposal area represents one of the primary pathways for mercury release into the environment. Tailings exposed to rainfall are highly susceptible to leaching processes, allowing dissolved or particle-bound mercury (Hg) to migrate into the subsoil zone (Hilson & van der Vorst, 2002). This infiltration mechanism facilitates the transport of heavy metals into shallow aquifers, resulting in groundwater contamination. In addition, surface runoff during the rainy season contributes to the downslope movement of tailings particles toward lower topographic areas, including seepage zones surrounding residential wells. The mobilization and dispersion of contaminated materials are significantly enhanced under high rainfall conditions, thereby expanding the spatial extent of mercury contamination originating from artisanal gold mining activities (Akagi et al., 2000).

Additionally, the burning of amalgam in open areas near residential settlements results in the emission of elemental mercury (Hg^0) into the atmosphere. The United Nations Environment Programme (UNEP, 2019) identifies amalgam burning as the single largest source of mercury emissions from artisanal and small-scale gold mining (ASGM) in developing countries. During this process, volatilized Hg^0 is released into the air and subsequently redeposited onto soil and surface waters through dry and wet deposition. Atmospheric mercury may then undergo oxidation to divalent mercury (Hg^{2+}), which exhibits higher reactivity and affinity for soil particles and dissolved phases, facilitating its migration into groundwater systems (Pirrone et al., 2013). This deposition–

remobilization mechanism leads to mercury enrichment in topsoil surrounding residential areas and increases the risk of contamination of shallow aquifers and domestic well water.

The mobility of mercury in the subsurface environment is strongly controlled by soil physicochemical properties, particularly pH, texture, organic matter content, and cation exchange capacity. Lower pH conditions reduce the adsorption capacity of soil minerals and organic matter, thereby increasing the solubility and mobility of Hg^{2+} toward the saturated zone (Alloway, 2013). This mechanism is consistent with field observations in Dava Village, where sampling points with relatively acidic pH values exhibited higher mercury concentrations. The interaction of acidic conditions with tailings infiltration, contaminant transport via surface runoff, and atmospheric deposition from amalgam burning creates an integrated migration pathway that facilitates the accumulation of mercury in shallow aquifers. Consequently, elevated Hg concentrations measured near gold-processing areas reflect not only proximity to contamination sources but also hydrogeochemical conditions that enhance mercury transport and persistence in groundwater systems.

3.5. The Role of pH on Hg Mobility in Local Aquifers

pH is a key geochemical parameter controlling the speciation, solubility, and mobility of mercury (Hg^{2+}) in soil–water systems. Sampling points with more acidic conditions, particularly S6 (pH 5.9), exhibited higher mercury concentrations than sites with near-neutral pH. Acidic conditions reduce the adsorption capacity of soil minerals by increasing surface protonation, thereby promoting the desorption and dissolution of Hg-bound complexes. This process enhances the vertical transport of dissolved mercury through soil pores toward the shallow aquifer, increasing the likelihood of groundwater contamination. These observations are consistent with established hydrogeochemical behavior of mercury under low-pH conditions, where increased solubility directly facilitates subsurface migration (Zhang et al., 2020).

Nevertheless, mercury mobility within the hydrogeochemical system is governed by an interplay of multiple physicochemical factors beyond pH alone. Dissolved organic matter (DOM), soil cation exchange capacity, mineralogical composition, and local redox conditions collectively regulate the speciation, transport, and retention of Hg in subsurface environments. DOM is particularly influential, as it forms stable and highly mobile Hg–DOM complexes that enhance mercury transport through pore water flow and vertical percolation, thereby increasing the likelihood of groundwater contamination (Wang et al., 2021). In addition, fluctuating redox conditions control the transformation of Hg between less mobile ionic forms (Hg^{2+}) and more volatile elemental mercury (Hg^{0}), affecting both subsurface migration and atmospheric exchange. These coupled processes facilitate the remobilization and redistribution of mercury under changing environmental conditions, indicating that elevated Hg concentrations observed in shallow aquifers result from the combined effects of organic complexation, redox-driven transformations, and hydrogeochemical dynamics rather than from pH variation alone (Li et al., 2022).

Biogeochemical transformations in saturated and semi-saturated environments further exacerbate mercury (Hg) toxicity through the formation of methylmercury (MeHg). This methylation process predominantly occurs under anaerobic conditions and is mediated by specific microbial groups, particularly sulfate-reducing bacteria (SRB) and methanogenic microorganisms. Low redox potential creates favorable conditions for microbial metabolism, while the availability of sulfate serves as an essential electron acceptor that stimulates SRB activity. Concurrently, the presence of organic matter provides both energy sources for microbial growth and binding sites that facilitate Hg bioavailability. These interacting conditions enhance the conversion of inorganic Hg into MeHg, a form characterized by high toxicity and strong bioaccumulation potential within aquatic and terrestrial food webs (Graham et al., 2019; Yu et al., 2023). Consequently, environments with reduced

redox conditions, elevated organic inputs, and sufficient sulfate concentrations function as hotspots for Hg methylation, thereby substantially increasing ecological and human health risks in contaminated areas.

3.6 Health and Ecological Implications

Mercury (Hg) contamination in small-scale gold mining environments poses substantial health risks to local communities, particularly to populations with elevated exposure levels such as artisanal miners. Mercury is a well-recognized neurotoxic, nephrotoxic, and hepatotoxic element, capable of inducing both acute and chronic adverse health effects. Exposure pathways include inhalation of mercury vapor released during amalgam burning, dermal contact with contaminated materials, and ingestion of polluted water. Prolonged or repeated exposure through these routes may lead to systemic toxicological impacts affecting multiple organ systems. Epidemiological evidence indicates that gold miners exposed to mercury are at increased risk of hepatic dysfunction, hematological alterations such as leukocyte reduction, neuromuscular impairment, sensory disturbances, and tremors resembling Parkinsonian symptoms (Mulasari, 2021).

In addition to acute effects, mercury exposure is also associated with more complex long-term health risks. Inorganic mercury released into the environment can undergo biogeochemical transformation into methylmercury (MeHg) through microbial activity in aquatic and sedimentary environments. Methylmercury is considered particularly hazardous because it is readily absorbed by the human body and exhibits strong bioaccumulative and biomagnification properties within food webs. Epidemiological and toxicological studies have documented associations between chronic methylmercury exposure and adverse health outcomes, including central nervous system impairment, neurodevelopmental deficits in children, and renal dysfunction (Fitzgerald et al., 2007). Similar observations were reported by Harada (1995), who documented severe neurological disorders in coastal populations chronically exposed to methylmercury, even in the absence of acute exposure levels. These findings underscore the long-term health risks posed by persistent mercury contamination in communities reliant on contaminated environmental media.

Health risks are particularly elevated in communities that rely on groundwater as their primary source of domestic water. When well water is contaminated with mercury, exposure can occur through multiple daily pathways, including drinking, food preparation, and the irrigation of household food crops. Chronic intake of contaminated groundwater increases internal mercury burdens, which may subsequently be reflected in human biomonitoring indicators. Empirical evidence supports this pathway, as Bose-O'Reilly et al. (2010) reported significantly higher mercury levels in biological samples from populations residing near artisanal and small-scale gold processing sites compared with the general population. These findings indicate that mercury exposure is not confined to miners but extends to family members and surrounding communities through environmental media, particularly groundwater. Consequently, effective risk mitigation strategies must explicitly address local exposure pathways, including the consumption of contaminated well water, household water use, and the intake of food and aquatic resources originating from mercury-affected environments.

3.7 Research Limitations

The limitations of this study include the restricted temporal scope of monitoring, as groundwater sampling was conducted only once, the absence of mercury speciation analysis (with measurements limited to total Hg), and the lack of detailed hydraulic and hydrogeological data for the local aquifer system. Consequently, the results represent a snapshot of contamination conditions and may not fully capture temporal variability or transport dynamics. Further research is therefore

recommended to incorporate mercury speciation analysis (e.g., methylmercury), seasonal or long-term monitoring, and more comprehensive hydrochemical and groundwater flow modeling to better understand mercury transport processes and associated environmental and health risks.

The implementation of mercury-free gold processing through centralized processing units is essential to reduce miners' dependence on mercury and to control pollutant release at the source. This approach should be supported by the construction of simple wastewater treatment facilities capable of managing tailings and liquid waste through sedimentation, stabilization, and safe handling of mercury-bearing residues. Such measures are consistent with international recommendations emphasizing source control and improved waste management as key strategies for reducing mercury emissions from artisanal and small-scale gold mining (UNEP, 2019; Telmer & Veiga, 2009).

In addition, the establishment of buffer zones between gold processing areas and residential settlements, including the relocation of community wells away from tailings disposal sites, is critical to minimizing human exposure. These technical interventions should be complemented by environmental health education programs that raise community awareness of mercury risks, promote safer processing practices, and encourage the use of alternative water sources. Periodic monitoring of groundwater and biota, including mercury speciation such as methylmercury, is necessary to evaluate mitigation effectiveness and long-term environmental risk. Collectively, these actions directly align with the objectives of the Minamata Convention, which promotes the reduction of mercury use, emissions, and human exposure through technological improvement, environmental monitoring, and community-based risk management in small-scale gold mining contexts (UNEP, 2019; Bose-O'Reilly et al., 2010).

4. Conclusions

The findings of this study demonstrate that gold processing activities in Dava Village are strongly associated with elevated mercury (Hg) concentrations in groundwater, indicating substantial environmental contamination. The spatial distribution of Hg suggests that post-processing land conditions—particularly unmanaged tailings disposal, seepage from processing ponds, and atmospheric deposition from amalgam burning—function as key sources contributing to mercury input into shallow aquifers. Variations in pH further influence Hg mobility, with more acidic conditions enhancing its solubility and transport within the subsurface system. Overall, these results highlight that traditional gold processing practices lacking effective waste management present significant risks to both environmental quality and public health. Consequently, integrated mitigation measures, including mercury reduction strategies, improved tailings management, establishment of buffer zones, and routine groundwater monitoring, are essential to minimize long-term exposure risks and support sustainable environmental management.

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