Risk Analysis of Mercury Content in Seawater, Sediment, and Fish in the Sinabar Mining Coastal Area, Huamual District, West Seram Regency

Bainuddin Sillehu*[1], Anwar Daud[2], Anwar Mallongi[3], Hasnawati Amqam[4], Stang[5], Damayanti Sima Sima Sohilauw[6], Setiawan Kasim[7]

Abstract

Background: There is increasing recognition that cinnabar (HgS) mining, particularly in coastal settings, constitutes a major source of environmental mercury (Hg) pollution. **Objectives:** This research was conducted to examine mercury (Hg) concentrations in seawater, sediment, and fish in the coastal area of the cinnabar mine in Huamual District, West Seram Regency, and the associated health risks to coastal populations. **Methodology:** The present work is an observational, analytical investigation using a spatial approach with Geographic Information Systems (GIS) to map the distribution of mercury concentrations as a function of distance from the mine site. **Results:** The results showed that mercury concentrations in all saltwater samples exceeded the quality limit of 0.001 mg/L, ranging from 0.0023 to 0.0663 mg/L. The mercury concentrations in the sediments were well above the threshold limit of 0.15 µg/L, ranging from 14.3173 to 1951.7 µg/L. Mercury levels in fish ranged from 0.2129 to 1.3227 mg/kg, and 70% of samples were above the allowable limit for seafood intake (0.5 mg/kg). The spatial study shows a diminishing dispersion pattern with increasing distance from the mine, and the highest concentration is observed within a radius of 0 - 3 km. The health risk study (Risk Quotient) of mercury exposure from fish intake showed an RQ > 1, indicating a considerable potential health risk with chronic exposure to methylmercury, specifically harm to the nervous system, kidneys, and cardiovascular function. **Conclusion:** The results highlight the necessity for comprehensive pollution control programs and coastal environmental management strategies to preserve public health and marine ecosystems in the Huamual cinnabar mining area.

[1,2,3,4] Department of Environmental Health, Faculty of Public Health, Hasanuddin University, Makassar, Indonesia
[5] Department of Biostatistics, Faculty of Public Health, Universitas Hasanuddin, Makassar, Indonesia
[6] Maluku Health Polytechnic, Ministry of Health, Ambon, Indonesia
[7] Department of Health, Faculty of Health, Patria Artha University, Gowa, Indonesia
Corresponding Author*: Bainuddin Sillehu, Department of Environmental Health, Faculty of Public Health, Hasanuddin University, Makassar, Indonesia. Email: bainuddin.sillehu@gmail.com

Keywords: Mercury, Seawater, Sediment, Fish, Risk Analysis

Introduction

There is increasing recognition that cinnabar (HgS) mining, particularly in coastal settings, constitutes a major source of environmental mercury (Hg) pollution. Mercury is a highly hazardous heavy metal with persistence, bioaccumulation, and biomagnification potential, which allows it to accumulate in living species and magnify through aquatic food chains, thus posing significant threats to ecosystems and human health [1,2]. Global mercury emissions from artisanal and small-scale cinnabar mining are substantial, with mercury being released into adjacent environments, including seawater, sediments, and aquatic biota [3].

Coastal habitats, transition zones between land and sea, are especially vulnerable to mercury pollution because of the hydrological connection and sediment deposition processes. Mercury entering aquatic systems can be biogeochemically transformed into methylmercury (MeHg), a highly toxic organic compound that is rapidly bioaccumulated in marine organisms, especially fish [4,5]. This mechanism is very important because fish consumption is the main pathway of human exposure to mercury in coastal populations [6]. Chronic exposure to methylmercury has been linked to adverse health effects, including neurotoxicity, cardiovascular disease, and developmental problems in children [7].

Indonesia is the largest archipelagic country in the world, with extensive coastal areas and rich natural resources, including cinnabar deposits. However, unregulated and illegal mining has also contributed to environmental degradation, especially mercury contamination of coastal habitats [8]. Mining operations are often located near coastal areas, increasing pollution risks since mercury may be transported through rivers, surface runoff, and groundwater to marine ecosystems, thus raising Hg concentrations in seawater, sediments, and aquatic species [9].

New research indicates that mercury pollution in coastal areas is still a major issue in Indonesia. In several mining-impacted areas, high concentrations of mercury in seawater and marine organisms have been reported, often exceeding environmental quality criteria and posing ecological and public health risks [10,11]. The accumulation of mercury in sediments is of particular concern, as sediments are a reservoir and a secondary source of pollution through remobilization processes, affecting long-term exposure risks in marine ecosystems [12].

Predatory fish species are known to bioaccumulate high concentrations of methylmercury through trophic magnification. This tendency increases the risk for people who depend heavily on seafood consumption, e.g., coastal communities in Indonesia [13]. Therefore, measuring mercury levels in environmental compartments (seawater, sediments, and fish) is important for understanding the distribution, exposure pathways, and potential health effects of mercury contamination.

The Sub-district of Huamual, West Seram Regency, Maluku Province, is one of the areas that is potentially affected by mercury contamination due to cinnabar mining. Since 2015, this region has been mined unlawfully, with insufficient environmental management and regulatory oversight. The closeness of mining to coastal zones increases the chances of mercury being released into marine ecosystems, posing a threat to environmental sustainability and public health.

However, data on mercury contamination in saltwater, sediments, and fish in the Huamual coastal area are still limited. This information is needed to assess environmental hazards, inform public health programs, and inform evidence-based policy decisions. Mercury contamination leads to socio-economic problems, as well as ecological impacts, including decreased fishery production and increased health burden for coastal communities.
The present study was conducted to evaluate the mercury concentrations in seawater, sediments, and fish of the whole coastal area of the Huamual Sub-district. The results are expected to provide a scientific basis for understanding the extent of mercury pollution and to assist in developing effective mitigation measures and policies for environmental management in mercury-polluted coastal areas.

Methods and materials

Study design and setting

This study employed a cross-sectional analytical design to determine mercury (Hg) concentrations in seawater, sediments, and fish, using spatial modelling in a Geographic Information System (GIS) framework. This research was carried out in the coastal area of Huamual Sub-district, West Seram Regency, Maluku Province, Indonesia, where artisanal cinnabar (HgS) mining activities have been taking place since 2015. The study area is a land-sea interface affected by the mining runoff and small river discharges, and is a good candidate to evaluate mercury transport and accumulation in coastal ecosystems.

Sampling strategy and collection

Sampling was performed in the dry season to reduce the temporal variability associated with rainfall and runoff. Spatial sampling was conducted according to distance from the main mining sites, in near-field (<1 km), midfield (1–3 km), and far-field (>3 km) zones. Sampling sites were georeferenced with a handheld Global Positioning System (GPS) with an accuracy of ±3 meters.

Seawater, sediment, and fish samples were collected simultaneously at each station. Surface seawater (0–50 cm depth) was collected in pre-acid-washed polyethylene bottles and immediately acidified to pH <2 with ultrapure nitric acid to prevent metal adsorption. Sediment samples were taken from the upper 0–5 cm layer with a stainless-steel grab sampler, homogenized, and stored in acid-cleaned containers. Fish samples of commonly consumed species were collected from the local catches within the sampling area. Muscle tissues were dissected, homogenized, and stored at −20 °C until analysis. All samples were measured in triplicate for analytical reliability.

Determination of mercury and preparation of samples

Total mercury (THg) concentrations were measured by thermal decomposition–amalgamation atomic absorption spectrophotometry (TDA-AAS) according to protocols analogous to USEPA Method 7473. Seawater samples were measured directly after preservation, whereas sediment samples were oven dried at <40°C, sieved to <63 µm, and homogenized before measurement. Fish tissue samples were homogenized and analyzed on a wet weight basis. Calibration was performed using multi-point standard solutions, and instrument performance was verified from time to time to maintain analytical precision, and the relative standard deviation was maintained below 10%.

Quality control and quality assurance

Quality assurance and quality control procedures were strictly applied during the whole sampling and analysis process. These included the use of procedural blanks, field blanks and certified reference materials for each matrix. A minimum of 10% of the samples were analyzed in duplicate, and spike recovery tests were conducted to verify the analytical accuracy, with acceptable recovery rates between 80% and 120%. Detection and quantification limits were determined for each sample type and included in the data validation procedures.

Spatial assessment

GIS-based interpolation techniques were used to analyze the spatial distribution of mercury concentrations. Ordinary kriging was used to model the spatial variability based on semivariogram analysis and cross-validation performance. Spatial outputs consisted of continuous distribution maps of mercury concentrations in seawater, sediments, and fish, and gradient analyses with respect to distance from mining activities. Spatial analyses were carried out in a WGS 84 coordinate system to maintain consistency in geospatial representation.

Statistical Analyses

Statistical analysis was performed using R or SPSS. The data normality was tested with the Shapiro–Wilk test. Spatial zone differences in mercury concentrations were evaluated by one-way analysis of variance (ANOVA) for normally distributed data or the Kruskal-Wallis test for non-parametric data. Post hoc analyses were performed by either Tukey's HSD or Dunn's test as appropriate. Pearson or Spearman correlation coefficients were computed to find out the correlations between mercury concentrations in seawater, sediments, and fish. Significance level was accepted at $p < 0.05$ in the entire analysis.

Health risk assessment

The Target Hazard Quotient (THQ) approach was used to assess potential health risk from mercury exposure through fish consumption. Exposure parameters were obtained from standard reference values, such as exposure frequency, duration, ingestion rate, body weight, and reference dose. THQ values > 1 were interpreted as a potential non-carcinogenic health risk. Furthermore, Estimated Daily Intake (EDI) values were calculated to put the exposure levels in context of established safety thresholds.

Ethical considerations

The present study did not include human subjects. Samples of fish were obtained from local fishermen, with no attempt to target protected species. All field procedures were carried out in a manner to minimize environmental disturbance.

Results

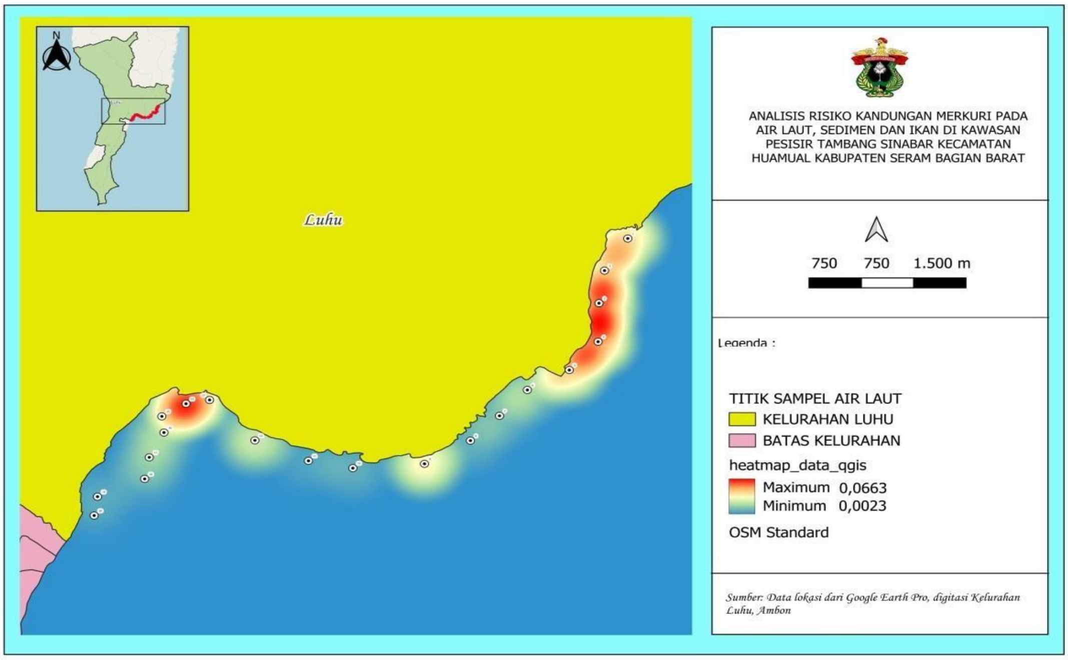
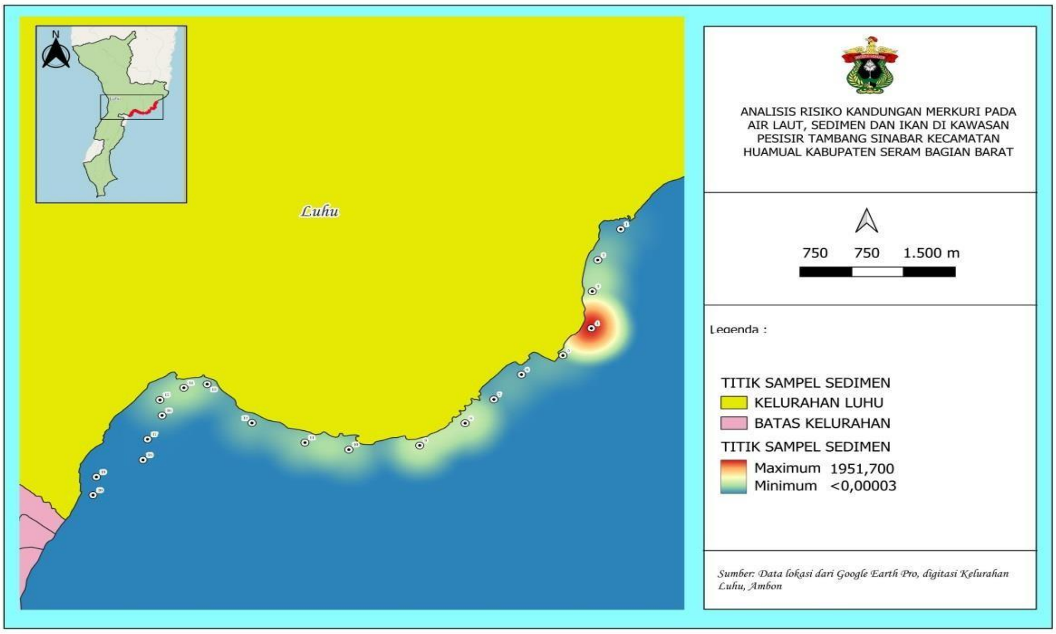


Figure 1. Map of Mercury Distribution in Seawater

Based on Figure 1, the results show that the mercury content in all seawater samples in the coastal area of the cinnabar mine in Huamual District exceeds the standard seawater quality threshold for marine biota, which is set at 0.001 mg/L. The mercury concentration values obtained ranged from 0.0023 mg/L to 0.0663 mg/L. Ecologically, high mercury content in water can disrupt the balance of coastal ecosystems, especially through bioaccumulation in plankton and pelagic fish. Environmental factors such as ocean currents, tides, and coastal geographical characteristics also influence the distribution of mercury in seawater. High mercury content in seawater indicates that heavy metal contamination is not only local in nature but can spread more widely through open water systems.

Figure 2. Map of Mercury Distribution in Sediments

Based on Figure 2, mercury in sediments was found to be very high, with values ranging from 14.3173 µg/L to 1951.7 µg/L, far exceeding the environmental quality standard for sediments of 0.15 µg/L. This indicates that



mercury particles released from cinnabar mining activities not only float in the water column but also accumulate at the bottom of the water.

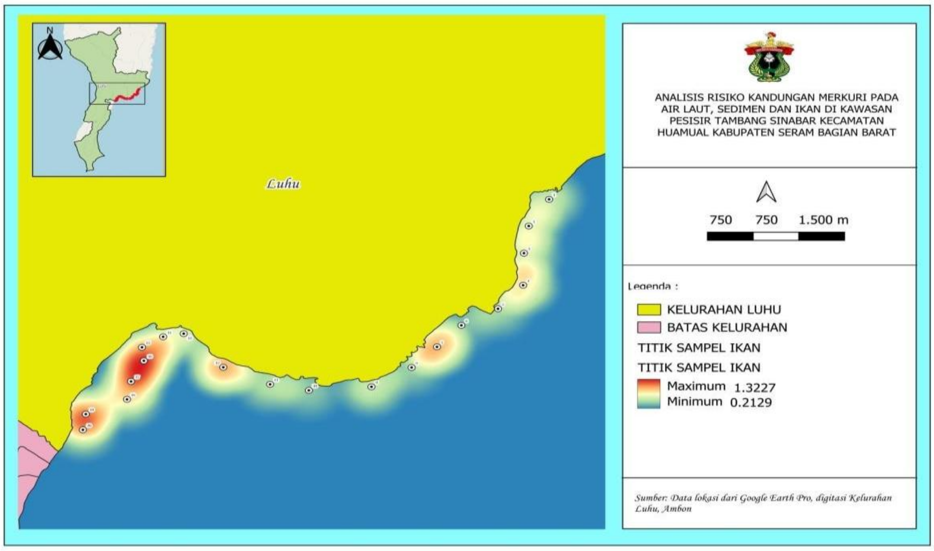


Figure 3. Map of Mercury Distribution in Fish

As a Figure 3, fish, as marine biota, play an important role in indicating the level of mercury bioaccumulation. The mercury content in the fish studied varied from 0.2129 µg/L to 1.3227 µg/L, with 70% of the samples exceeding the mercury quality standard for seafood consumption of 0.5 µg/L.

Table 1. Spatial distribution patterns of mercury in coastal environmental components (seawater, sediment, and fish) related to distance from the cinnabar mine location

Environmental Component	**Source of Contamination**	**Spatial Distribution Pattern**	**Potential Exposure**	**Ecological & Health Impacts**	**Risk Categories Based on Distance**
Seawater	Cinnabar mine wastewater, tailings seepage, surface runoff	High concentrations in areas near the mine mouth (0–2 km), decreasing exponentially with distance, diluted by currents and tides	Plankton, pelagic fish, humans (direct contact & fish Consumption)	Acute poisoning of plankton, disruption of pelagic ecosystems, bioaccumulation in small fish, neurotoxic risk to humans	High (0–2 km), Moderate (2–5 km), Low (>5 km)
Environmental Components	Source of Contamination	Spatial Distribution Pattern	Potential Exposure	Ecological & Health Impacts	Risk Categories Based on Distance
Sediment	Heavy metal particles from mining land erosion, suspended sediments that are deposited	Very high concentrations in the area around the mine mouth (0–1 km), decreasing gradually with distance towards the sea	Benthic organisms, shellfish, and potential remobilization to the water column	Chronic accumulation in sediments, disturbance of benthic organisms, secondary source of long- term pollution	Very High (0–1 km), High (1–3 km), Moderate (3–5 km), Low (>5 km)

Fish	Bioaccumulation of mercury (especially methylmercury) through the food chain	High mercury levels in fish near the mine (0–3 km), decreasing with distance. Predatory fish have higher accumulation levels	Humans (fish consumption), marine apex predators	Bioaccumulation, biomagnification, nervous system disruption, potential cancer, kidney, and liver damage	High (0–3 km), Moderate (3–7 km), Low (>7 km)

In Table 1, several spatial patterns of the distribution of mercury in seawater, sediments, and fish in relation to the distance from the cinnabar mining site are shown. The main source of mercury in seawater is from mine wastewater, tailings seepage, and surface runoff. High concentrations 0-2 km from the source are observed, and a considerable reduction with increasing distance from the source owing to hydrodynamic dilution processes. This gradient has obvious ramifications for the pelagic exposure routes because the first receptor for transmission of mercury through the aquatic food chain is plankton and tiny fish. Ecological effects include the disturbance of plankton populations and bioaccumulation at early stages that could pass up the food chain.

Sediments, on the other hand, exhibit a more stable and permanent accumulation pattern, with very high concentrations near the mine outflow (0-1 km) and diminishing offshore. This reflects the role of sediments as a long-term reservoir of mercury with the possibility for remobilization to the water column under changing environmental conditions. Mercury concentrations in the 0–3 km range are over 0.3 mg/kg, especially for predatory species, due to biomagnification. Fish contamination reflects the ambient exposure and trophic dynamics. The near-field zones are therefore the locations with the highest ecological and human health hazards, reflecting the combined effect of physical transport and biological mechanisms on limiting mercury distribution.

Table 2. Estimated mercury risk in coastal environmental components (seawater, sediment, and fish) related to distance from the cinnabar mine location

Distance from Mine (km)	**Seawater**	**Sediment**	**Fish**
0–1 km	High	Very High	High
1–3 km	Moderate	High	High
3–5 km	Moderate	Moderate	Moderate
5–7 km	Low	Low	Moderate
>7 km	Low	Low	Low

Table 2 shows a clear spatial gradient of the mercury-related risk across environmental compartments, with a progressive reduction of the risk levels with increasing distance from the mining site. Sediments are categorized as “very high risk” and seawater and fish as “high risk” for intensive contamination in the immediate vicinity of mining operations within the 0–1 km range. At 1-3 km, sediment risk remains high while seawater risk declines to moderate risk levels, indicating dilution effects. Fish risk remains high, indicating ongoing bioaccumulation despite reduced environmental concentrations.

After 3 km, the risk levels for all the components change to moderate and then to low. Seawater and sediments decrease at a faster rate than fish. Importantly, fish still show moderate risk levels up to 7 km, suggesting mercury persistence in the food chain and lagged biological response to environmental improvement. All components at distances >7 km show low risk levels, indicating little direct influence from mining sources.

Table 3. Risk analysis of the spatial distribution pattern of mercury in coastal environmental components (seawater, sediment, and fish) in relation to distance from the cinnabar mining site

Sample point	**Distance to Mine (Meters)**	**Hg Concentration in Water (mg/L)**	**Sediment Hg Concentration (mg/kg)**	**Fish Hg Concentration (mg/kg)**	**Risk Level**		
					Water	**Sediment**	**Fish**
001	1138.94	0.0488	104.5966	0.5999	Moderate	High	High
002	1032.64	0.0438	322.5544	0.7171	Height	High	High
003	924.96	0.0629	462.5666	0.6380	High	Very High	High
004	907.25	0.0596	1951.700	0.9438	High	Very High	High
005	1269.94	0.0513	224.8825	0.4317	Moderate	High	High
006	1820.14	0.0210	187.2281	0.2708	Moderate	High	High

007	2236.26	0.0124	163.2357	1.2153	Moderate	High	High
008	2,680.59	0.0099	652.9859	0.3926	Moderate	High	High
009	2834.66	0.0427	663.7358	0.6285	Moderate	High	High
010	3119.93	0.0093	411.0996	0.3483	Moderate	Moderate	Moderate
011	3793.79	0.0065	403.7419	0.5110	Moderate	Moderate	Moderate
012	3807.53	0.0305	293.4128	1.3026	Moderate	Moderate	Moderate
013	4036.31	0.0134	281.1684	0.5958	Moderate	Moderate	Moderate
014	4336.48	0.0663	217.1325	0.3220	Moderate	Moderate	Moderate
015	4358.16	0.0082	281.1684	0.2129	Moderate	Moderate	Moderate
016	4593.09	0.0115	11.6499	1.3227	Moderate	Moderate	Moderate
017	4,624.41	0.0138	3.8195	0.8088	Moderate	Moderate	Moderate
018	5112.24	0.0062	1.9475	0.6274	Low	Low	Low
019	5475.33	0.0068	1.2724	1.1636	Low	Low	Low
020	5,771.23	0.0023	>0.00003	0.6186	Low	Low	Low

The comprehensive empirical data of mercury contents at sampling sites are shown in Table 3. The results demonstrate a high geographical heterogeneity with distance from the mining site. Highest concentrations are systematically located in near-field regions (approx. <1.5 km), especially in sediments, where values are substantially increased, supporting their major role as a sink for mercury accumulation. The high concentrations of Seawater in these places indicate direct inputs from mining activities, and Fish samples frequently surpass established safety criteria, thus indicative of severe bioaccumulation and health hazards for surrounding residents.

The mercury concentration in saltwater and sediments generally decreases with distance from the mining site, but the levels in the sediments are very high compared to the water, indicating persistent pollution. Fish mercury contents, however, are declining more gradually, with some intermediate distance sampling stations still showing high values indicative of ongoing trophic transfer and biomagnification. Far-field locations (>5 km) often have lower concentrations in all matrices, which is consistent with lower risk ratings.

Table 4. Characteristics of Respondents' Body Weight and Consumption Activity Patterns in the Coastal Community of the Cinnabar Mine

Variable	**Min**	**Max**	**Mean**
Age (years)	27	59	43.5
Body Weight (kg)	45	83	57
Food Portion (kg/day)	0.125	0.25	0.125
Consumption Frequency per Week	1	7	4

Table 4 shows that the respondents' ages ranged from 27 to 59 years, with an average of 43.5 years. The respondents' weight ranged from 45 kg to 83 kg, with an average of 57 kg. The respondents' dietary pattern (fish consumption) in grams per day ranged from 0.125 kg/day to 0.25 kg/day, with an average of 0.125 kg/day. The frequency of fish consumption per week ranged from 1 to 7 times per week, with an average of 4 times per week.

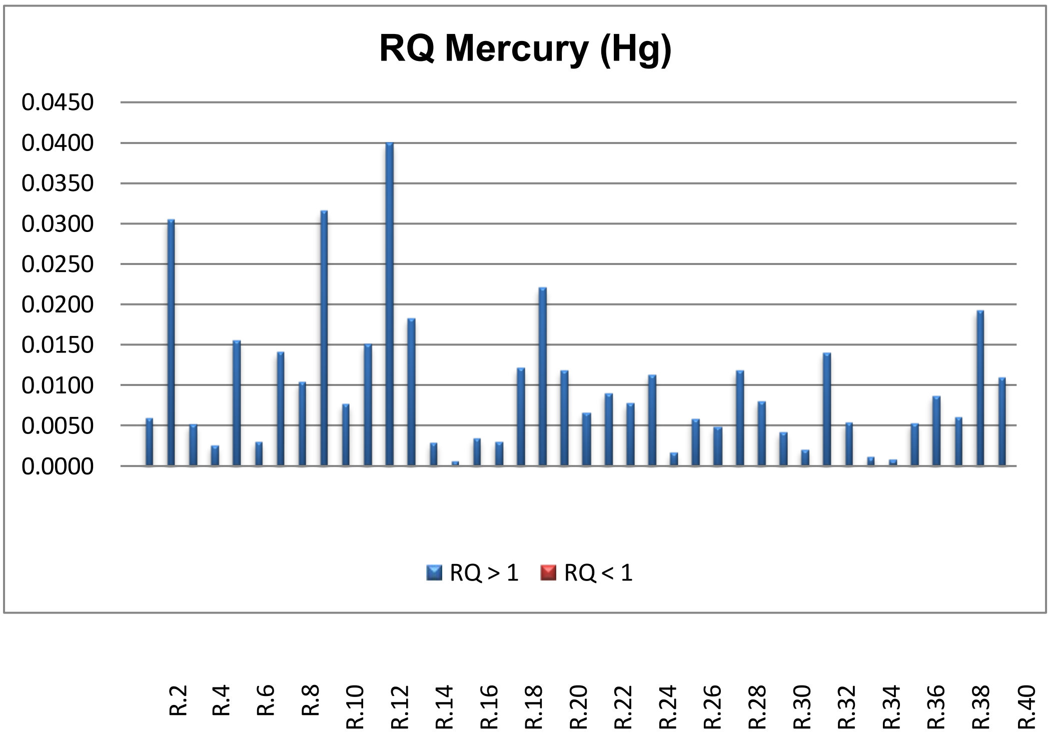


Figure 4. Risk Characteristics of Mercury

The Risk Quotient (RQ) for mercury exposure through fish consumption shows an RQ value > 1, meaning that the daily exposure of the community to mercury exceeds the safe threshold of 0.0001 mg/kg/day and poses a significant risk to health. Potential health impacts from chronic mercury exposure include central nervous system disorders, kidney damage, and developmental disorders in children. This reinforces the urgency of intervention and risk management, such as prohibiting fish consumption from red zones and educating the public.

Discussion

This study shows a significant spatial gradient of mercury contamination in seawater, sediments, and fish, which is substantially connected to the vicinity of cinnabar mining activities. High quantities of mercury found in near-field zones confirmed that artisanal mining continues to be an important localized source of contamination to coastal ecosystems. Similar spatial patterns of mercury inputs with distance, due to dilution, dispersion, and sedimentation processes, have been described in other mining-impacted coastal settings [14]. However, the fact that very high concentrations can be maintained over short distances indicates that hydrodynamics alone cannot prevent contamination in places with permanent pollution sources.

Sediments were the most affected environmental compartment, especially at sites near the mine discharges. This observation is consistent with recent research indicating that sediments are long-term sinks of heavy metals and acquire pollutants by adsorption and particle settling [15]. The relatively high sediment mercury concentrations detected here are indicative of the possibility for chronic exposure to ecology, especially benthic biota. In addition, sediments can be viewed as secondary sources of pollution as a consequence of the remobilization processes generated by physical disturbance or change of redox conditions, extending the environmental contamination even after the decrease of primary inputs [16].

Mercury concentrations in saltwater were more varied, reflecting the dynamic nature of aquatic systems. The considerably lower and more variable quantities of mercury in water than in sediments are explained by processes including tidal mixing, current circulation, and dilution. However, the values measured in near-field saltwater are of ecological importance, as low concentrations of dissolved mercury can be rapidly digested by plankton and microorganisms [17]. This initial intake is crucial as it is the entry site for mercury into the marine food web and will influence the higher trophic levels.

High mercury levels were observed in fish samples, especially in sites adjacent to the mining site (<3 km). This indicates that bioaccumulation and biomagnification are still occurring. High quantities of mercury were found in fish at intermediate distances, which may indicate that biological systems retain the toxins longer than abiotic compartments. This lag effect has been extensively documented, as reductions in environmental mercury do not immediately result in decreased concentrations in biota due to trophic transfer dynamics and metabolic retention [18]. This is especially worrisome for predator fish, which tend to accumulate more mercury because of where they sit in the food web.

From a public health perspective, the mercury levels measured in fish indicate a potential risk to coastal populations that consume large amounts of fish. Chronic dietary exposure to methylmercury has been related to neurodevelopmental impairment, cardiovascular consequences, and other systemic health problems [19]. Fish samples that surpass specified safety criteria indicate the need for risk communication and food warnings in impacted populations. Moreover, modest fish mercury concentrations reflect a far larger spatial extent of danger of exposure than the nearby mining sites.

The spatial risk patterns identified in this study further underscore the need for distance-based environmental assessment. Risks from seawater and silt decrease fairly rapidly with distance, while risks to fish are more extensive spatially. This disparity shows the intricacy of mercury cycling in coastal environments where biological processes can prolong the impacts of contamination beyond the source. These results are consistent with recent studies demonstrating that interactions within food webs may magnify and extend pollutant exposure along spatial gradients [20].

The findings have substantial socio-economic ramifications and also ecological and health implications. Contamination challenges can also threaten the quality and marketability of fish for coastal populations who depend on fisheries, and hence their livelihoods. In addition, environmental deterioration in the long term may affect ecosystem services, including the provision of food security and biodiversity. These difficulties require integrated management approaches that take into account the environmental and socio-economic characteristics of mercury pollution [21].

In summary, our study highlights the importance of focused intervention techniques for mining-affected coastal areas. The focus should be on source management of mercury emissions, rehabilitation of polluted sediments, and the establishment of regular environmental monitoring. Simultaneously, public health activities such as fish consumption advisories and community outreach are crucial for mitigating the possibility of exposure. Further study should examine advanced modelling methodologies, such as spatial risk modelling and trophic transfer simulation, to improve the prediction of long-term repercussions and to promote evidence-based policy-making.

Conclusion

The mercury concentrations in seawater in the coastal area of the cinnabar mine in Huamual District were all above the seawater quality standard threshold for marine biota of 0.001 mg/L. The mercury concentration in sediments also showed values much higher than the sediment environmental quality standard of 0.15 mg/L. And mercury content in fish revealed that 70% of samples were above the safe limit for seafood consumption of 0.5 mg/kg, with values ranging from 0.2129–1.3227 mg/kg.

Spatial analysis indicates that the distribution pattern of mercury content in seawater, sediment, and fish is a decreasing trend with the distance from the mine. The highest concentration of mercury was found in the radius of 0–3 km of the cinnabar mine, which tends to decrease after a distance of 5 km from the source of pollution. The result of the calculation of Risk Quotient (RQ) for exposure to mercury through fish consumption showed that the RQ value > 1. This implies that the daily exposure to mercury for coastal communities is above the safe level, which poses significant health risks, especially neurological, cardiovascular, and other organ disorders caused by the accumulation of methylmercury.

Acknowledgments

The researchers would like to express their deepest gratitude to the Huamual Subdistrict Government of West Seram Regency, located on the coast of West Seram Regency, and to the West Seram Regency Government, Maluku Province, Indonesia.

Conflict of Interest

The authors affirm that there are no conflicts of interest regarding the publication of this case report.

Funding

This case report did not receive any external financial support.

Authors' Contribution

The contributions of the authors are as follows: B.S., A.D., A.M., H.A., and S. were responsible for conceptualizing the study. A.D., A.M., H.A., and S. gathered the data. The study design was developed by B.S., A.D., A.M., H.A., and S. D.S.S.S., and S.K. was responsible for writing and submission. Finally, D.S.S.S. and S.K. reviewed, edited, and approved the final version of the manuscript.

References

1. United Nations Environment Programme. Global mercury assessment 2023. Geneva: United Nations Environment Programme; 2023.
2. World Health Organization. Mercury and health. Geneva: World Health Organization; 2021.
3. Esdaile LJ, Chalker JM. The mercury problem in artisanal and small-scale gold mining. Chem Eur J.

2018;**24**(27):6905–6916. doi:10.1002/chem.201704840
4. Sunderland EM, Li M, Bullard K. Decadal changes in the edible supply of seafood and methylmercury exposure in the United States. Environ Health Perspect. 2018;**126**(1):017006. doi:10.1289/EHP2644
5. Obrist D, Kirk JL, Zhang L, Sunderland EM, Jiskra M, Selin NE. A review of global environmental mercury processes in response to human and natural perturbations. Environ Sci Technol. 2022;**56**(9):5735–5749. doi:10.1021/acs.est.1c06590
6. Karimi R, Fitzgerald TP, Fisher NS. A quantitative synthesis of mercury in commercial seafood and implications for exposure. Environ Health Perspect. 2020;**128**(9):097001. doi:10.1289/EHP4565
7. Bjørklund G, Dadar M, Mutter J, Aaseth J. Mercury exposure and its effects on health. J Trace Elem Med Biol. 2020;**62**:126620. doi:10.1016/j.jtemb.2020.126620
8. Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia. Status lingkungan hidup Indonesia 2022. Jakarta: KLHK; 2022.
9. Liu J, Liu Y, Liu Y, Zhang A, Li R, Wang Y, et al. Transport and transformation of mercury in aquatic systems. Sci Total Environ. 2021;**755**:142543. doi:10.1016/j.scitotenv.2020.142543
10. Thalib I, Kurniawan A, Rahman A, Putra R, Hasanuddin B, Malik F, et al. Mercury and arsenic levels in seawater and fish in Kao Bay, Indonesia. Environ Sci Pollut Res. 2023;**30**:11245–11256. doi:10.1007/s11356-022-23456-1
11. Silalahi J, Simanjuntak M, Siregar A, Ginting R, Sihotang H, Napitupulu R, et al. Mercury contamination in marine fish and shrimp in Indonesia. Mar Pollut Bull. 2021;**170**:112662. doi:10.1016/j.marpolbul.2021.112662
12. Wang Y, Shi Y, Wang D, Zhang C, Li Y, Wang C, et al. Mercury cycling in marine sediments: Sources, transformations, and risks. Sci Total Environ. 2022;**806**:150540. doi:10.1016/j.scitotenv.2021.150540
13. Zhang Y, Liu X, Wang M, Li Y, Chen L, Wang J, et al. Biomagnification of methylmercury in marine food webs. Environ Pollut. 2021;**268**:115845. doi:10.1016/j.envpol.2020.115845
14. Liu Y, Chen L, Feng C, Zhang S. Spatial distribution and source identification of heavy metals in coastal sediments influenced by human activities. Sci Total Environ. 2021;779:146430. doi:10.1016/j.scitotenv.2021.146430
15. Zhao S, Feng C, Quan W, Chen X, Niu J, Shen Z. Role of sediments in heavy metal accumulation and ecological risk in coastal systems. Mar Pollut Bull. 2020;**160**:111689. doi:10.1016/j.marpolbul.2020.111689
16. He Z, Shentu J, Yang X, Baligar VC, Zhang T, Stoffella PJ. Heavy metal contamination of soils: sources, indicators, and assessment. J Environ Indic. 2020;**9**:100094. doi:10.1016/j.indic.2020.100094
17. Wang Z, Chen J, Li H. Mercury uptake and transformation in aquatic microorganisms: implications for food webs. Environ Res. 2022;**204**:112345. doi:10.1016/j.envres.2021.112345
18. Huang J, Liu Y, Wang X. Bioaccumulation and trophic transfer of mercury in marine ecosystems: a review. Ecotoxicol Environ Saf. 2021;**208**:111654. doi:10.1016/j.ecoenv.2020.111654
19. Genchi G, Sinicropi MS, Carocci A, Lauria G, Catalano A. Mercury exposure and heart diseases: a systematic review. Int J Environ Res Public Health. 2020;**17**(22):8310. doi:10.3390/ijerph17228310
20. Lavoie RA, Jardine TD, Chumchal MM, Kidd KA, Campbell LM. Biomagnification of mercury in aquatic food webs: a global meta-analysis. Environ Sci Technol. 2021;**55**(2):873–882. doi:10.1021/acs.est.0c06494
21. Trasande L, Liu Y. Reducing the global burden of mercury exposure: policy and economic implications. Lancet Planet Health. 2021;**5**(12):e859–e866. doi:10.1016/S2542-5196(21)00252-1