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Assessment of Mercury Contamination in the St. Paul River and Tumah Creek in Liberia: Implications of Artisanal and Small-Scale Gold Mining on Water Quality and Public Health

Adolphus M.G.D. Glekia[1*], Soehoe-Panhyonon Benedict Powoe[2], Raphael Ngumbu[3]

[1]Department of Mining Engineering, Faculty of Engineering, University of Liberia, Monrovia, Liberia
[2]Department of Materials Science and Engineering, University of Liberia, Monrovia, Liberia
[3]T.J.R. College of Science, Technology, Environmental Science, and Climate Change and Biodiversity, University of Liberia, Monrovia, Liberia
Email: *adolphusgkia@gmail.com

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Abstract

Despite being a vital source of income for millions of people worldwide, artisanal and small-scale gold mining (ASGM) poses significant health and environmental risks due to the unregulated use of mercury in the gold extraction process. This study, therefore, examines two important water bodies in Liberia, the St. Paul River (Montserrado County) and Tumah Creek (Gbarpolu County), to determine the incidence of mercury pollution in areas where ASGM activity is prevalent. To evaluate mercury concentrations and their possible effects on water quality, a total of 15 water samples were taken from these sites. The total mercury content in the samples was measured using Cold Vapor Atomic Absorption Spectroscopy (CVAAS). High mercury levels were found in several locations, especially close to active mining sites, according to the results. Due to the lack of filtration technologies, the local community, which depends on these water sources for drinking and household use, is seriously at risk for health problems as a result of this contamination. To reduce the dangers of mercury exposure, the findings highlight the urgent need for stronger regulation of ASGM activities and serve as a foundation for upcoming environmental health assessments and policy development in Liberia.

Keywords

Artisanal and Small-Scale Gold Mining (ASGM), Mercury Contamination, Water Quality, Environmental Health, Cold Vapor Atomic Absorption

Spectroscopy (CVAAS)

1. Introduction

There are 14 to 19 million directly employed [1] and 100 million [2] [3] individuals relying on the artisanal and small-scale gold mining (ASGM) sector. Political upheaval, a lack of government oversight, and the remote location of many ASGMs are all factors that make working conditions risky and have a significant impact on the health and environment of miners. Several health problems affect the ASGM community, including chronic noise and dust exposure, unsanitary working environments, and a lack of personal protective equipment [4] [5]. These conditions ultimately affect all mining sector participants, even those not directly involved in the extraction and processing of ore, with around 4.5 million women and 600,000 children worldwide involved mostly in non-mining activities, coming in close contact with hazardous chemicals like cyanide and mercury [6].

The main processing method is to grind the silt or ore containing gold into a powder and then mix it with liquid mercury, creating an amalgam [7] [8] which is then burnt in the air, liberating mercury as an elemental Hg^0 gas into the atmosphere [9]. Around 500 - 1000 g of Hg are condensed and deposited in flora, soils, and water bodies per kilogram of recovered Au, amounting to a total emission of 838 tonnes of mercury in 2015 [10].

Several aquatic organisms, especially those near the top of the food chain, gradually bioaccumulate methylmercury [11]. People who live near rivers and eat many aquatic foods are more likely to become mercury-toxic. Ingested mercury poses a serious health concern [1] [4] [10]. Hg is a potent neurotoxin associated with cardiovascular disease in adults and neurocognitive impairments in fetuses [12]. High amounts of mercury vapor exposure for short to medium lengths of time predominantly affect the kidneys. In contrast, long-term exposure to moderate levels of mercury vapor has a greater negative impact on the brain. Children and fetuses are especially susceptible to the hazardous effects of mercury [13] [14].

Many ASGM sites have been discovered to have mercury contamination of human populations and ecosystem components [5] [15]. Compared to other parts of the world, Liberia experiences a lower use of mercury due to the locally held belief that mercury reduces the quality and value of gold, but also because the chemical is expensive to purchase [16] [17]. Surveys conducted on the St. Paul River and its tributary Tumah Creek, located in a region where ASGM is one of the dominant livelihood activities, show that these rivers are a major source of drinking water and other domestic uses for the local population. The water is consumed directly without purification since no water treatment is available.

However, limited research is available concerning mercury concentration in Liberia's environment. To fill this gap and to examine the potential for human mercury exposure, this paper examines the prevalence of mercury in the St. Paul River (Montserrado County) and Tuma Creek (Gbarpolu County). Detailed analyses to clearly define the degree of mercury concentrations in the two water bodies are conducted in this work. The findings of this study will aid in the accomplishment of any local environmental health reconnaissance and serve as a working reference for identifying any changes brought on by ASGM activities in the mercury content of drinking water. Findings from this study will also be used to shape policies on artisanal mining at the national level.

2. Sampling Methodology

Water Quality Sampling

Sampling was conducted during the rainy season (June-October, 2024), in high-flow hydrologic conditions, which are generally linked to increased surface runoff and improved transport of suspended particles. Elevated turbidity and fluctuating flow patterns during this time were indicative of active hydrological inputs from rainstorm episodes. By encouraging the mobilization and downstream transit of mercury-bound particles and perhaps diluting the amounts of dissolved mercury, these factors can affect the distribution of mercury. As a result, the measured mercury levels reflect a balance between hydrological dilution effects typical of the rainy season and increased pollutant intake from ASGM-affected areas.

Sampling protocols were designed, consistent with the objectives of the study. A total of fifteen (15) water samples were collected from artisanal and small-scale gold mines along the upper St. Paul River (Montserrado County) and Tuma Creek (Gbarpolu County). In order to ensure that areas most likely to be impacted by mercury use were represented, the selection of sites for water sampling was deliberately driven by proximity to current artisanal and small-scale gold mining (ASGM) operations. In order to evaluate the dispersion of contaminants throughout the river system, sampling locations were selected to collect both upstream and downstream gradients in relation to mining inputs. A thorough picture of the distribution of mercury throughout the research region was also provided by the inclusion of confluence zones, which were used to assess the mixing of contaminants from various streams.

In order to clearly differentiate sampling locations according to their connection to artisanal and small-scale gold mining (ASGM) operations, the operational criteria employed in this study were developed. Sites that are hydrologically above active mining areas are referred to as upstream locales, and they are anticipated to be less directly impacted by mining activities. On the other hand, downstream areas are those that are situated directly below or inside mining discharge zones, where the likelihood of pollutant inputs is higher. Near-mine sites are sampling locations that are either inside or close to active mining regions (such as T4 and T4B), which indicate places that have been directly impacted by human activity. Confluence sites also refer to mixing zones (such as S6 and T3) between Tumah Creek and the St. Paul River, where water from various sources mixes and may have an impact on patterns of mercury dispersion.

Tumah Creek's status as a directly impacted tributary that receives runoff and effluents from ASGM operations justifies its inclusion in this study. As a result, it plays a crucial role in the movement of mercury and other pollutants into the broader St. Paul River system, which has an impact on the water quality and ecosystem health downstream.

Water samples were taken at each sampling site at a depth of roughly 20 to 30 cm below the surface, either from the main flow path close to the riverbank or at mid-channel, if available. This strategy was used to minimize any bias and guarantee that the samples were representative of the flowing water. To avoid contamination and guarantee the integrity of the samples, care was taken to prevent surface film collection and disturbance of bottom sediments.

The two water bodies were selected based on their strategic locations and role in basic ecosystem services. The St. Paul River runs from southeastern Guinea and enters Liberia about 50 km north of Gbarnga, the capital City of Bong County. The River, which forms part of the boundary between Guinea and Liberia, empties into the Atlantic Ocean at Cape Mesurado in Monrovia, Liberia's capital City. The St. Paul River holds two of the country's most valuable infrastructure: Mount Coffee Hydropower Dam and the White Plains drinking water Plant. The latter provides drinking water for the vast majority of the population of Monrovia.

A crucial body of water, Tuma Creek in Gbarpolu County, Liberia, is home to a wide variety of species and enhances the ecological well-being of the West African region. It provides a habitat for aquatic species that are vital to the regional food chain and local communities, including fish, amphibians, and invertebrates. Terrestrial animals, including birds, mammals, and reptiles, rely on the riparian zones beside the creek as a home, which helps to ensure their survival [18]. In addition, Tuma Creek serves as a natural water filter, capturing pollutants and sediments before they enter larger bodies of water and maintaining water quality downstream. It contributes to a broader watershed that feeds into the St. Paul River, affecting biodiversity not only in the vicinity [19] [20]. Artisanal and small-scale gold mining operations threaten Tuma Creek because they can result in sedimentation, habitat damage, and mercury contamination [20]. In Liberia, conservation efforts necessitate community involvement, sustainable land-use practices, and regulatory measures.

At each site, 500 ml duplicate samples of water were collected from the sampling point and placed in a clean polyethylene bottle. Sample pH was recorded in situ using a pocket-sized pH meter (HI-98127). Each sampling bottle was filled to the brim to prevent gas trapping. Proper labeling of bottles is done (geographical coordinates, sampling code, sampling data, and time) for easy identification, and placed on an ice chest. Samples were pre-treated with 3 drops of 5% v/v nitric acid, and the batch was subsequently transported to the laboratory for analysis. Each batch of samples submitted to the laboratory was accompanied by a signed chain of custody form to ensure that the quality and integrity of the samples were maintained throughout the analytical process.

Replication Strategy: This study used both field and laboratory replication techniques to guarantee data reproducibility and reliability. To evaluate variability related to sampling techniques and environmental heterogeneity, field duplicates were collected separately at each sampling site. Analytical replicates (n = 3) were also carried out for every sample in the laboratory to assess analytical consistency and instrumental precision. As a result, rather than being field duplicates, the provided values (mean ± standard deviation, n = 3) reflect the outcomes of analytical replicates. Data on water sampling are presented in Table 1.

Table 1. Water sampling data across the study area.

Sample ID	Easting (E)	Northing (N)	Description
S1	0374957	0777118	**Gweai Ta**, St. Paul River, downstream, adjacent to the crossing point.
S2	0375086	0777145	Gweai Ta, St. Paul River, upstream
S3	0375223	0777222	Gweai Ta, St. Paul River, upstream
S4	0375388	0777292	Gweai Ta, St. Paul River, upstream
T1	0376615	0779469	Tumah Creek, upstream, adjacent to Molonkpagai
T2	0376729	0779385	Tumah Creek, downstream, adjacent to Molonkpagai
S5	0377848	0778157	St. Paul River, adjacent to Molonkpagai, upstream
T3	0378211	0778319	Mouth of Tumah Creek with St. Paul River, upstream
S6	0378307	0778285	St. Paul is upstream at the upper section of the mouth of the Tumah Creek.
T4	0377029	0795294	Tumah Creek, Dorkor Town
T4B	0377029	0795294	Mine water is contained in an open pit adjacent to Tumah Creek, where T4 was gathered adjacent to Dorkor
T5	0376892	0795550	Tumah Creek, Dorkor Town
T6	0376836	0795696	Tumah Creek, Dorkor Town
T7	0385012	0811252	Tumah Creek, Forkpa Ta (town), Gbarpolu County
T8	0384936	0811326	Tumah Creek, Forkpa Ta (town), Gbarpolu County

3. Analytical Methodology

3.1. Laboratory Analyses

Total mercury analysis was done at the Environmental Protection Agency Laboratory in Sinkor, Monrovia, Liberia. Method 3112B: Cold Vapor Atomic Absorption Spectrometry (CVAAS) was used to measure total mercury (THg) in water samples in compliance with the Standard Methods for the Examination of Water and Wastewater [21] [22]. This technique is especially well-suited for environmental monitoring investigations because of its well-known sensitivity and dependability in identifying tiny amounts of mercury in aqueous matrices.

3.2. Total Mercury Analyses in Water Samples

Sample Preparation and Digestion—To guarantee total oxidation of all mercury species to Hg^{2+}, water samples (100 mL) were acid digested using concentrated nitric acid (HNO_3) and heated at 95˚C for one hour. Before being subjected to instrumental analysis, the solutions were filtered, cooled, and diluted to the necessary volume after digestion, and were transferred into a 125 mL conical flask. A working solution of 0.1 mg/L was prepared from a commercially prepared solution of 10 mg/L. A calibration standard solution of 2.0, 5.0, and 10.0 μg/L was prepared from the working solution in a 50 mL volume with the addition of 1 mL each of concentrated HNO_3 and 1.0 g each of NaCl. The samples and reference materials were prepared using the same methodology. A 50 mL volume of blank and the calibration standards were transferred into flasks, and 1.0 mL of 5.0% stannous chloride was then added.

Instrumental Analysis—A Hach DR 6000 spectrophotometer with CVAAS capability was used to quantify mercury. In this procedure, stannous chloride ($SnCl_2$) was used to chemically convert mercury ions to elemental mercury (Hg_4), and the resultant vapor was detected using spectrophotometry. To guarantee analytical accuracy and stability, absorbance values were taken at 30 and 60 seconds.

Calibration and Linearity: Standard solutions made from a certified stock solution with concentrations of 2.0, 5.0, and 10.0 μg/L were used for calibration. Excellent linearity over the working concentration range is indicated by the coefficient of determination ($R^2 \geq 0.995$) obtained from the application of a linear regression model.

Method Performance Characteristics: The analytical method showed a Limit of Quantification (LOQ) of 0.15 μg/L and a Method Detection Limit (MDL) of 0.05 μg/L. The dependability of the reported results was confirmed by the fact that every measured concentration in the research was higher than the LOQ.

3.3. Quality Control and Assurance

Quality control samples, including blanks and certified reference material (CRM), were prepared according to the American Public Health Association Standards [23] [24]. NIST 1641d was used as reference material for the water samples. The CRM was digested along with the samples to check the accuracy of the method. A quality control standard was run routinely during the sample analysis to monitor instrument drift and the overall quality of the analysis.

APHA criteria were followed in the implementation of quality assurance procedures. Analysis of reagent blanks revealed that they were consistently below the MDL, indicating no contamination. Analytical accuracy was verified using a certified reference material (NIST 1641d), resulting in a recovery of 98%, which is within the allowed range of 90 - 110%. To guarantee instrument stability, calibration verification standards were examined every 10 samples. While replication precision was assessed using relative standard deviation (RSD), which stayed below 10%, instrument drift was tracked and kept under ±5% of the calibration response. Overall, the research revealed no discernible analytical bias or contamination.

3.4. Statistical Method

The Statistical Package for the Social Sciences (SPSS) version 20 was used to analyze the data. To summarize the data distribution, descriptive statistics, such as mean and standard deviation, were computed for mercury concentrations across all sampling locations. Because of the limited sample size and non-normal distribution of the data, a non-parametric Mann-Whitney U test [25] was used to evaluate regional variations in mercury contamination. Tumah Creek and the St. Paul River, near-mine sites and non-mining or confluence areas, and upstream and downstream sites were all compared [26].

4. Results

This study assessed the levels of total mercury in fifteen (15) water samples collected from artisanal and small-scale gold mines along the upper St. Paul River (Montserrado County) and Tuma Creek (Gbarpolu County). The precision and accuracy of the analytical procedure were evaluated by repeated analyses of samples and certified reference materials (CRM) [27] [28]. The validity of the method has been proved by agreement between the measured and the certified concentrations in the CRM. The result of the analysis of the CRM showed a recovery of 98.0% (**Table 2**). All analyses were within the 95% percent confidence limit.

Table 2. Results of total mercury in CRM for the water samples.

Sample Matrix	SRM	Mercury Certificate Value (μg/L)	Measured Mercury Value (μg/L)	Percent Recovery (%)
Water	NIST 1641d	1500	1470	98.0

Conversion: 1.5 μg/g ≈ 1500 μg/L.

To further determine the degree of accuracy of the overall procedure, three replicates of one randomly selected water sample were spiked with increasing concentrations of elemental mercury. The spiked replicates were taken through the same analytical procedure as all other samples and then analyzed for total mercury. The recoveries are presented in **Table 3**. Generally, recoveries between 85 - 105% for spiked samples demonstrate good accuracy of the methods used [29].

Table 3. Recovery of total mercury from replicates of a water sample.

Sample	Hg added (ng)	Hg found (ng)	Hg recovered	% recovery
Water replicate 1	0	46	-----	-----
	20	67	21	105.0
	40	87	41	102.5
	50	91	45	90.0
Sample	**Hg added (ng)**	**Hg found (ng)**	**Hg recovered**	**% recovery**
Water replicate 2	0	46	-----	------
	20	67	21	105.0
	40	86	40	100.0
	50	95	49	98.0

Continued

Sample	Hg added (ng)	Hg found (ng)	Hg recovered	% recovery
Water replicate 3	0	46	-----	------
	20	66	20	100.0
	40	86	40	100.0
	50	95	49	98.0

4.1. Total Mercury in Water Samples

Watercourses close to artisanal gold mining sites provided all of the water samples used in this investigation. The findings show high mercury concentrations in a number of places, which is indicative of the extensive and uncontrolled use of mercury in ASGM activities. The research area's mean total mercury (tHg) levels varied from less than the detection limit (<0.005 μg g^{-1}, or <5 μg L^{-1}) to 0.668 μg g^{-1} (≈668 μg L^{-1}). The World Health Organization's (WHO) recommended limit of 6 μg L^{-1} for mercury in drinking water is significantly exceeded by these quantities (30). The high mercury levels found are in line with data from other ASGM-affected areas, where artisanal mining has been connected to serious environmental damage and long-term risks to public health. The results of mean tHg levels across the study are presented in Table 4.

Table 4. Concentration (μg/g) of total mercury in water samples across the study area (St. Paul River and Tumah Creek, Liberia).

Sample ID	Location	THg (μg/L) Mean ± SD (N = 3)
S1	Gweai Town, Montserrado County	320 ± 30
S2	Gweai Town, Montserrado County	491 ± 12
S3	Gweai Town, Montserrado County	517 ± 19
S4	Gweai Town, Montserrado County	537 ± 10
S5	Molonkpagai	367 ± 20
S6	Confluence of Tumah Creek & St. Paul River	215 ± 20
T1	Tumah Creek upstream, near Molonkpagai	692 ± 12
T2	Tumah Creek downstream, near Molonkpagai	578 ± 17
T3	Confluence of Tumah Creek & St. Paul River	302 ± 15
T4	Tumah Creek, Dorkor Town	514 ± 3
T4B	Mine Pit near Tumah Creek, Dorkor Town	672 ± 21
T5	Tumah Creek, Dorkor Town	606 ± 11
T6	Tumah Creek, Dorkor Town	621 ± 9
T7	Tumah Creek, Forkpa Town, Gbarpolu County	518 ± 17
T8	Tumah Creek, Forkpa Town, Gbarpolu County	533 ± 25

The highest total mercury (tHg) levels (692 μg L^{-1}) were recorded in sample T-

1 collected near Molonkpagai, upstream of the Tumah Creek in Liberia. Out of a total of fifteen water samples collected across the study, only four samples showed tHg below the 6 μg L^{-1} limits recommended by the World Health Organization [30]. This raises a lot of concern considering that the sampling points in this study are situated upstream of the White Plains drinking water Plant, which provides potable water for the majority of the population of Monrovia and its environs. Other studies carried out corroborate the negative effects of mercury on the environment due to artisanal and small-scale mining operations.

Tumah Creek has much greater mercury content than the St. Paul River ($p < 0.05$), according to the statistical analysis's findings. Similarly, compared to other sampling locations, near-mine sites showed considerably higher mercury levels ($p < 0.05$), especially those situated in active mining zones like T4 and T4B. The St. Paul River, on the other hand, showed no statistically significant difference between upstream and downstream locations ($p > 0.05$), indicating that mercury pollution in this river system is more localized than widespread.

Additionally, estimated effect sizes (r) showed moderate to large differences between comparison groups, supporting the finding that the distribution of mercury in the research area is significantly influenced by artisanal and small-scale gold mining activities.

4.2. Mercury Pollution Due to Artisanal Mining: Ghana, Peru, Indonesia, and Tanzania

Ghana: Ghana suffers from serious issues with mercury pollution, just like many other countries that practice artisanal and small-scale gold mining (ASGM). When gold is extracted from ore using ASGM procedures, mercury is commonly utilized, which poses serious risks to human health and the environment. Mercury concentrations in Ghanaian water bodies near mining sites have been studied; results show values between 420 to 930 μg/L, which is comparable to other ASGM-affected areas like Liberia. For instance, mercury concentrations ranging from 420 to 930 μg/L, suggesting high pollution levels, were observed by Rajaee *et al.* [15] in water samples from the Tarkwa region, a major gold mining area in Ghana.

These analyses are directly comparable to Liberia's range (215 - 692 μg/L), indicating that the levels of contamination in West African ASGM regions are comparable. Both significantly exceed the WHO's 6 μg/L recommendation, indicating that uncontrolled mercury utilization is the main source.

The World Health Organization (WHO) advises a maximum mercury concentration of 6 μg/L in drinking water to prevent harmful health consequences, which makes this contamination alarming [30]. These Ghanaian water bodies frequently have mercury concentrations over this threshold, endangering human health and the environment, particularly in the populations that depend on these sources for agriculture, drinking, and fishing.

Furthermore, sediments and the food chain are also contaminated by mercury from ASGM in Ghana, not just aquatic bodies. Fish and other aquatic organisms bioaccumulate mercury, which increases the health hazards when it enters the local population's diet. These results are consistent with global trends in ASGM locations where mercury usage is common. Long-term exposure to mercury, especially in its methylated form (methylmercury), can cause neurological abnormalities, cognitive impairments in children, and cardiovascular ailments in adults. Mercury is a strong neurotoxin [3].

Ghana's scenario emphasizes the necessity for more stringent laws and environmentally friendly mining methods. Although the government has taken some steps to control ASGM activity, such as implementing mercury-free mining methods like gravity concentration, these actions must be expanded to lessen the severe mercury pollution that is harming the nation's waterways [6].

Peru: Peru, particularly the Amazon basin, faces significant mercury contamination due to artisanal and small-scale gold mining (ASGM). This activity contributes to severe environmental degradation and biodiversity loss, primarily because mercury is often used in gold extraction. Improper handling and disposal of mercury lead to pollution in rivers, especially in areas like Madre de Dios, which suffers from alarmingly high mercury levels with serious ecological consequences [31] [32].

A study in the Peruvian Amazon reveals significant alterations to local ecosystems due to mercury contamination from mining. Fish, birds, and mammals are affected across the food chain, with predators reliant on fish facing heightened risks from methylmercury, which bioaccumulates in aquatic life. Mercury levels in local fish exceed health authority consumption limits, impacting residents who depend on fishing for their livelihoods and wildlife [9] [32].

The impact of mercury exposure on wildlife is severe, leading to behavioral and reproductive issues in birds and mammals, which threatens biodiversity. Fish populations important for indigenous food sources and ecological health have declined due to mercury poisoning [33]. Birds ingesting contaminated fish face mercury toxicity, harming their brain function and reproductive ability. Similarly, mammals, including aquatic species such as river dolphins, are adversely affected by mercury exposure [33] [34].

The socioeconomic challenges faced by indigenous communities in Peru's Amazon intensify the ecological damage caused by mercury poisoning. Many of these communities depend on fish from polluted rivers, leading to elevated mercury levels in their bodies. Health risks are particularly significant for vulnerable populations like children and pregnant women, who are more affected by mercury's neurotoxic impact. Long-term exposure has been linked to neurological and cardiovascular diseases in adults, as well as developmental issues and cognitive impairments in children [35] [36].

In line with the Minamata Convention on Mercury, to which Peru is a member, efforts to mitigate mercury contamination in Peru have involved both national and international collaboration. Nonetheless, because ASGM operations are informal and frequently unlawful, enforcing laws is still difficult. Although innovative techniques for extracting gold, like those devoid of mercury, have been advocated, their extensive use is still restricted. According to Steckling *et al.* [1], in addition to technological fixes, stronger environmental education initiatives and monitoring are needed to lessen the consequences of mercury contamination and safeguard ecosystems and public health in the Peruvian Amazon.

According to studies, fish species have mercury levels exceeding consumption limits, indicating serious mercury contamination in aquatic ecosystems [9] [32]. The implication is obvious: mercury from ASGM penetrates rivers, bioaccumulates, and endangers food security, even though Peru's data frequently concentrate on biota rather than water. Liberia's dependence on fish from Tumah Creek and the St. Paul River points to comparable exposure paths.

Indonesia: Southeast Asia's artisanal and small-scale gold mining (ASGM), particularly in Indonesia, is a leading source of mercury pollution, contributing significantly to global emissions. The unregulated use of mercury in these mining operations poses serious risks to human health and the environment, contaminating soils, waterways, and the atmosphere [37].

Extensive contamination of rivers, lakes, and coastal areas in Indonesia has occurred due to mercury use in artisanal and small-scale mining (ASGM), particularly in Kalimantan and Sulawesi. Studies show that mercury levels in water bodies near ASGM facilities far exceed international health safety standards, posing significant health risks to communities reliant on these water sources for drinking, fishing, and agriculture, while also negatively impacting local ecosystems [1].

Fish in Indonesia's ASGM regions serve as a significant protein source for locals but contain high mercury levels due to contamination, threatening human health and biodiversity [38] [39]. Mercury bioaccumulates in fish, impacting predatory animals and humans who consume them, especially through methylmercury, which can cause serious health issues like neurological damage and developmental interference in children [40]. Besides aquatic systems, mercury pollution affects terrestrial ecosystems, contaminating crops and soils, further entering the food chain. Despite Indonesia's commitment to the Minamata Convention on Mercury, enforcement of mercury restrictions in the ASGM sector is inadequate due to unregulated mining and economic reliance on gold production. However, initiatives to encourage safer mining operations through community engagement programs and to develop mercury-free gold extraction techniques like gravity concentration have been made [41] [42].

The widespread use of mercury in the extraction of gold and the absence of regulations in these locations provide serious environmental and public health issues, which are reflected in the problem of mercury contamination in Indonesia and other ASGM regions.

Mercury levels in water bodies in Kalimantan and Sulawesi are higher than those required by international safety regulations [1]. Fish contamination is pervasive and at levels similar to those found in the aquatic ecosystems of Liberia. The matrix (water and fish) and the common difficulty of unofficial, uncontrolled ASGM operations are what make them comparable.

Tanzania: Tanzania's artisanal and small-scale gold mining (ASGM) industry, like that of many other nations, has serious problems with mercury pollution. Since ASGM uses a lot of mercury to extract gold, it is not only an important source of income for many Tanzanians but also significantly contributes to environmental damage. [7] [43] In Tanzania's informal mining industry, amalgamation of mercury continues to be a common process that poses health and environmental dangers. [43]

To address these issues, the Tanzanian government has launched several initiatives to promote mercury-free gold mining techniques and lower the country's mercury consumption. The United Nations Environment Programme (UNEP) and non-governmental organizations (NGOs) have supported these activities, which have centered on informing miners about the risks associated with mercury and adopting safer, alternative mining methods. In place of the conventional mercury amalgamation method, for example, gravity concentration and cyanidation are being marketed as workable, mercury-free substitutes [6].

The problem of mercury pollution in Tanzania still exists despite these measures, especially in areas where ASGM activities are concentrated, such as the Geita and Mwanza areas. [44] According to studies, there are dangerously high levels of mercury in certain locations, polluting water sources and endangering nearby ecosystems and communities. In contaminated rivers and lakes, fish and other aquatic species frequently absorb mercury, which causes bioaccumulation in the food chain. Locals who depend on these bodies of water for agriculture, fishing, and drinking should be especially concerned about this [4].

Tanzanian government-led initiatives aimed at teaching miners have also aimed to reinforce legislative frameworks and uphold current mining-related rules. Tanzania has ratified the Minamata Convention on Mercury, which attempts to lower mercury emissions worldwide, and the government has pledged to phase out the use of mercury in ASGM. [45] However, comprehensive enforcement is challenging due to the unofficial character of the industry and the reliance on gold mining for the economy. However, the Tanzanian government is still collaborating with foreign partners to create policies that strike a balance between environmental preservation and the mining communities' financial demands [1] [46] [47].

Tanzania's mercury pollution experience serves as a reminder of the difficulties that many ASGM-dependent nations confront. Maintaining livelihoods and advancing safer mining methods need careful balancing, necessitating ongoing support from the public and private sectors. Tanzania is making strides toward implementing mercury-free extraction techniques and raising public knowledge of the hazards associated with mercury; however, more emphasis on regulation and education to completely address the problem is lacking.

Rivers and lakes in the Geita and Mwanza regions have been shown to be contaminated with mercury, with fish exhibiting bioaccumulation [4]. The pattern is similar to Liberia's scenario, even though exact water concentrations differ: mercury usage in ASGM contaminates food chains and water, endangering communities that depend on these resources.

5. Discussion

The results of this investigation shed important light on the levels of mercury pollution in water sources linked to small-scale and artisanal gold mining (ASGM) operations in Liberia, namely in the Tuma Creek and upper St. Paul River districts. The findings show worrying patterns in mercury levels in these bodies of water, suggesting possible risks to human health and the environment. The relevance of these results is further highlighted by comparison with other research conducted in the sub-region and elsewhere.

5.1. Mercury Contamination and ASGM

Trends reported in other ASGM regions worldwide are in line with the increasing mercury levels found in this study. Mercury levels, for example, varied in the research from below detection limits to a maximum of 692 μg/L; 11 out of 15 samples had values over the WHO-recommended drinking water limit of 6 μg/L [30]. The significance of these water sources in providing Monrovia's residents and others in the surrounding areas with drinkable water makes this concerning.

Many regions, most notably Southeast Asia, Latin America, and Sub-Saharan Africa, have extensive records of mercury pollution in ASGM sites. Similar increased mercury levels have been found in water bodies around mining sites in Ghana, another country in West Africa with substantial ASGM activity, according to studies conducted there. For instance, total mercury levels of 420 - 930 μg/L were found in water samples from Ghanaian gold mining locations, according to Rajaee *et al.* [15]. These results imply that Liberia is dealing with similar environmental issues related to ASGM because they are identical to those observed in Tuma Creek and the St. Paul River. Moreover, the presence of mercury in ASGM areas in Peru and Indonesia underscores a global pattern of substantial mercury pollution stemming from uncontrolled gold mining operations [1].

5.2. Implications for Human Health and Biodiversity

Screening-Level Exposure Assessment: A straightforward screening-level exposure estimate was carried out in order to put the public health consequences of mercury contamination in Liberia's water bodies into perspective. Given that the maximum detected concentration in this study was 692 μg/L and an adult consumes two liters of drinking water daily (the WHO default intake scenario), the daily intake would be:

$$692\,\mu g/L \times 2\,L/day = 1384\,\mu g/day$$

This amount is more than two orders of magnitude higher than the WHO recommendation of 6 μg/L. Daily intake would be 430 μg/day even at the lower end of detected amounts (215 μg/L), which is still much higher than health-based standards. It is crucial to stress that this computation is not a clinical exposure outcome, but rather a screening-level evaluation meant to draw attention to possible danger. However, the findings highlight how urgent monitoring and intervention are.

As fish and other aquatic species are important dietary components in many cultures, the bioaccumulation of mercury in aquatic ecosystems is a well-known problem. Consuming organisms higher up the food chain can easily lead to mercury contamination, notably methylmercury, which can have major health effects on humans. The risk of mercury exposure is increased for the local population who depend on Tuma Creek and the St. Paul River for fishing and drinking. Significant neurological damage can result from long-term mercury exposure, even at low concentrations. This is especially true for susceptible populations, including children and expectant mothers [13]. Mercury is a powerful neurotoxin.

The results of this investigation are consistent with the larger body of research on mercury pollution in ASGM areas, which links mercury exposure to several health problems, such as adult cardiovascular diseases, mental impairments in children, and kidney damage from breathing in mercury vapor [4]. This demonstrates the critical need to control mercury contamination to preserve both the ecosystem and public health, especially in areas where ASGM activity is common.

5.3. Consolidated Implications

Liberia's mercury data, expressed in μg/L for water samples, align most directly with findings from Ghana, where comparable studies have documented similarly elevated concentrations in mining-affected rivers. Evidence from Peru, Indonesia, and Tanzania, although often focused on sediments and biota rather than water, reinforces the broader ecological and health risks associated with artisanal and small-scale gold mining (ASGM). In all cases, mercury contamination originates from unregulated amalgamation practices, which remain the dominant method of gold extraction in informal mining sectors. Once released, mercury enters river systems, accumulates in sediments, and bioaccumulates in fish and other aquatic organisms, ultimately biomagnifying through food webs and increasing exposure risks for local populations. International experiences suggest that effective management requires a combination of mercury-free extraction techniques—such as gravity concentration and cyanidation—alongside community education and stronger regulatory enforcement. These strategies provide a practical framework for Liberia to mitigate mercury pollution while balancing environmental protection with the livelihoods of mining communities.

5.4. Conservation and Environmental Concerns

Tuma Creek is an important watercourse in Gbarpolu County, Liberia, that is crucial to the preservation of the region's biodiversity. The study's elevated mercury levels are especially worrying for aquatic life since mercury can build up in flora and sediments, further polluting the food chain [7]. The ecological impact of mercury exposure extends beyond aquatic species; terrestrial animals that depend on riparian ecosystems are also at risk.

According to the results of this study, Liberia's biodiversity may be negatively impacted by mercury pollution in a similar way to other ASGM-affected areas. According to research conducted in the Peruvian Amazon basin, for example, mercury poisoning from mining activities seriously disturbs local ecosystems, leading to fish, bird, and animal population decreases [9]. The biological variety of the area, as well as the livelihoods of the residents who depend on these natural resources, are in danger of being threatened by similar trends that are expected to appear in Liberia's water bodies.

5.5. Policy Implications

To reduce mercury contamination resulting from ASGM activities in Liberia, the study's findings emphasize the necessity of swift regulatory action. Even though Liberia uses mercury at a far lower rate than other nations, the results show that mercury contamination is still a serious problem [16] [17]. This implies the possibility of serious environmental effects even from small-scale mercury usage when paired with inappropriate handling and disposal.

Research already in existence highlights the significance of community-based programs that support safer mining methods in conjunction with regulatory frameworks to regulate mercury use in ASGM [6]. Government-led initiatives have been put in place in nations like Tanzania and Ghana to inform miners about the risks associated with mercury and to encourage mercury-free techniques for extracting gold, like cyanidation and gravity concentration. Such actions could be modified and implemented in Liberia to lessen mercury pollution in waterways while protecting the livelihoods of miners.

Furthermore, the present investigation offers crucial baseline data that can function as a point of reference for subsequent environmental evaluations. It emphasizes the necessity of extensive monitoring programs to monitor variations in mercury concentrations over time, especially in regions like the St. Paul River and Tuma Creek, where human exposure is probably highest because of the proximity to ASGM activities and the reliance on these water bodies for domestic use.

5.6. Comparison with Global Mercury Regulations

Liberia is a party to the Minamata Convention on Mercury, which attempts to lower mercury pollution on a worldwide scale. The implementation of regulations about the use of mercury in ASGM is still difficult, nevertheless. Due to a lack of funding, insufficient government control, and the informal character of the ASGM sector, nations like Ghana, Peru, and Indonesia have all had trouble putting into practice efficient mercury reduction plans. Since Liberia most certainly faces comparable difficulties, the international community must work together and provide technical support to enhance the nation's ability to control the use of mercury and lessen its negative effects on the environment and public health.

The St. Paul River and Tuma Creek have significant quantities of mercury, which emphasizes the urgent need for local and national actions to minimize mercury contamination and safeguard the health of the surrounding populations. Although Liberia's predicament is not exceptional in the worldwide context of ASGM-related mercury pollution, it does require immediate action. Addressing this complex issue that endangers human and environmental health will require cooperation between the government, local communities, and international organizations.

5.7. Limitations of the Study

The upper St. Paul River and Tuma Creek were the only water sources in the study's designated regions of Liberia. The results may not accurately reflect mercury levels in other ASGM-affected parts of the nation, although these areas are important for understanding mercury contamination linked to artisanal and small-scale gold mining (ASGM). Variations in the amount of mercury-contaminated water bodies or other environmental factors across Liberia might not be taken into consideration by the limited scope. The study only used 15 samples, which may have limited how broadly the results can be applied. A more precise and thorough understanding of mercury contamination levels and their variations over time would be possible with a larger, more thorough sampling effort conducted throughout various locations and seasons.

The study gives an overview of mercury pollution at a specific point in time, but it doesn't take seasonal or temporal fluctuations in mercury levels into consideration. Water source mercury concentrations may be greatly impacted by meteorological conditions, flooding, or shifts in ASGM activity. A deeper understanding of how mercury levels fluctuate over time would be provided by longitudinal studies that sample regularly and for lengthy periods.

Although the study tested the overall amounts of mercury in the water, it did not distinguish between elemental, inorganic, and methylmercury mercury. As the most dangerous form of mercury, methylmercury is especially prone to bioaccumulation in aquatic food chains. To further understand the bioavailability and toxicity issues caused by various forms of mercury in these water bodies, speciation analysis should be incorporated into future studies. This study excluded soil, sediment, and biota as potential environmental compartments and instead concentrated only on mercury pollution in water sources. Particularly in regions where ASGM activity is elevated, mercury can build up in sediments and living things. A more comprehensive understanding of the ecological and health concerns related to mercury pollution would come from a more extensive environmental evaluation that takes sediments, fish, and other species into account.

Even while the study emphasizes the possible health hazards associated with mercury exposure, it omitted direct evaluations of the effects of mercury exposure on human health, such as biomonitoring mercury levels in nearby populations. To better determine the degree of human exposure and associated health hazards, future studies in populations dependent on these contaminated water sources may include hair or blood mercury analysis. The socioeconomic factors impacting ASGM activities, such as poverty, lack of access to alternative livelihoods, and lack of knowledge about safer mining techniques, were not covered in the study.

Comprehending these variables is vital to devising efficacious strategies that mitigate mercury consumption while upholding the standard of living of mining communities. By recognizing these limitations, future studies can concentrate on filling in these gaps to offer a more thorough grasp of mercury pollution and its wider effects on the environment and public health in Liberia.

6. Conclusion and Recommendations

6.1. Conclusions

This study offers vital new information about the level of mercury contamination in Tumah Creek and the St. Paul River, two important bodies of water in Liberia. The results show that there are alarmingly high mercury concentrations, especially in Tumah Creek, where artisanal and small-scale gold mining (ASGM) operations have a significant impact. The area near Tumah Creek in Dorkor Town, where open pit mining was conducted, had the greatest levels of mercury, indicating the direct effect of mining activities on the quality of the local water.

The findings imply that even while there may be less mercury use in some areas, as with the St. Paul River, there is still a chance of pollution, especially upstream of important facilities like the Mount Coffee Hydropower Dam and the White Plains drinking water facility. To stop additional environmental degradation and to protect public health, it is crucial to maintain ongoing monitoring and regulatory oversight. The study's overall findings emphasize the serious concern that is presented by mercury pollution in water bodies that provide local people with their main supplies of drinking water and other domestic uses. The results highlight the pressing requirement for practical approaches to reduce mercury pollution and safeguard the ecosystem and the health of communities depending on these water supplies.

6.2. Recommendations

1) **Enhanced Monitoring and Regulation**:

- Establish a routine program for monitoring the quality of the St. Paul River and Tumah Creek's water, with an emphasis on Mercury levels and other possible contaminants. This will assist in monitoring changes in water quality over time and spotting new dangers [48].
- Establish and implement more stringent regulations regarding the use of mercury in ASGM operations to fortify the regulatory framework. To ensure that mining operations adhere to environmental requirements, licensing and oversight of those operations should be included [49].

2) **Public Awareness and Education**:

- Launch educational initiatives aimed at local communities, particularly those in close proximity to ASGM sites, to increase awareness of the risks associated with mercury exposure and the significance of clean water practices [50].
- To minimize the use of mercury and its environmental damage, train miners

in alternate, mercury-free ways of extracting gold, such as cyanidation or gravity concentration [51] [52].

3) Infrastructure and Technological Interventions:

- Especially for villages that depend on untreated water from the St. Paul River and Tumah Creek, invest in the construction and upkeep of water treatment facilities. It's advisable to take into account sophisticated filtration systems that can eliminate heavy metals [53] [54].
- Promote the use of technologies that, during the process of amalgamating gold, collect and recycle mercury to lessen its discharge into the environment.

4) Policy Development and International Collaboration:

- To aggressively combat mercury pollution nationwide, the government should create a thorough National Mercury Action Plan that conforms to international agreements, such as the Minamata Convention on Mercury [55].
- To assist with mercury reduction efforts and to advance sustainable mining practices in Liberia, seek the help of international groups for financial and technical support.

5) Further Research:

- To gain a more thorough grasp of the mercury contamination in Liberia, expand the study to cover more water bodies and areas affected by ASGM.
- To inform public health actions, conduct epidemiological studies to evaluate the health effects of mercury exposure on the local population, paying particular attention to vulnerable groups, including pregnant women and children [56].

Through the implementation of these guidelines, Liberia can effectively limit the detrimental impacts of mercury pollution, preserve its water resources, maintain public health, and encourage more sustainable mining methods.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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