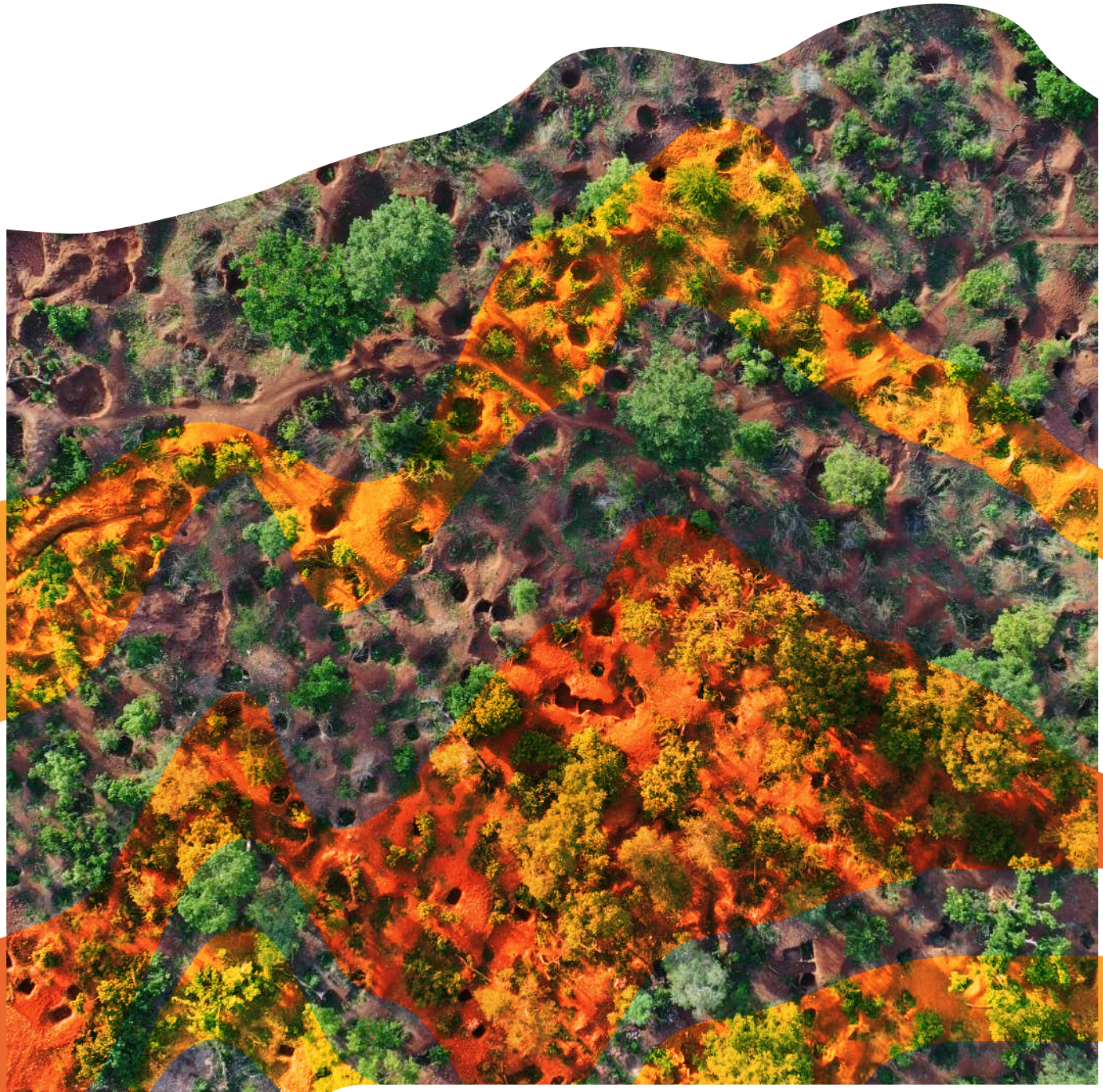
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ECOLOGICAL AND HEALTH RISK ASSESSMENT OF ARTISANAL SMALL-SCALE GOLD MINING SITES AND IDENTIFICATION OF "NO-GO" AREAS

IN WEST GONJA, BOLE, AND SAWLA-TUNA-KALBA DISTRICTS (SAVANNAH REGION)

GOLD FOR GOOD BASELINE STUDY SERIES

TECHNICAL REPORT 3 OF 3

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FOREWORD

Gold has come late to the Savannah Region, and it has come quickly. What was, a decade ago, a landscape defined by farming, shea and livestock is now one in which pits and crushers sit alongside fields, forest reserves and the Black Volta. That speed is the essential fact behind these three studies. It has outrun the region's regulatory institutions, its land administration systems and its security architecture; and it has outrun the evidence base on which any of them might act.

For too long, research and policy attention on Ghanaian artisanal and small-scale mining (ASM) has concentrated on the long-established mining landscapes of the south. This has left a critical gap in evidence for the north, and in particular for the West Gonja, Bole and Sawla-Tuna-Kalba districts, precisely where the intersection of resource extraction, fragile institutions and regional insecurity carries the highest stakes. The three baseline studies introduced by this foreword were commissioned by the Gold for Good (G4G) project to close that gap.

Gold for Good, funded by the European Union under NDICI Crisis Response (FPI/2025/488-718 – PC69961) and implemented by Association Coginta, pursues an integrated and inclusive model of ASM governance that brings together institutional strengthening, environmental protection and rehabilitation, market formalisation and value-chain improvement, conflict-sensitive security governance, and inclusive local development. The project's working premise is that ASM in these districts cannot be governed sector by sector. A patrol post sited without reference to migration corridors will police the wrong road. A rehabilitation programme designed without reference to household income will restore land that people will come back to and remine. They will not leave the land alone. A licensing reform that ignores customary tenure will be complied with only where the state is watching, because the authority that actually allocates land will not have consented to it.

Three studies, one evidence base

The first study, a *Diagnostic Assessment of Governance, Security and Conflict Risks in ASM Zones*, led by Prof. Ebenezer Owusu-Sekyere, maps ASM communities and site typologies, examines the statutory and customary systems that regulate them, and identifies the drivers of conflict and the security threats emerging in the zone. It documents a landscape of largely unlicensed operations, overlapping and contested institutional mandates, and conflict pressures sharpened by the region's proximity to active cross-border insecurity.

The second study, a *Socio-economic Profiling and Mapping of ASM Sites*, led by Prof. Paul Kwame Nkegbe, builds a demographic and livelihood portrait of mining communities and their non-mining neighbours. It traces economic organisation and specialisation along the value chain, analyses land ownership and tenure arrangements at mining sites, and follows the labour mobility and gold-trading networks that connect the corridor to markets and to countries beyond Ghana's borders.

The third study, an *Ecological and Health Risk Assessment of ASM Sites and Identification of "No-Go" Areas*, led by Dr Dzigbodi Adzo Doke, quantifies the environmental and public-health consequences of mining and delineates areas where mining should not occur. Drawing on water, soil and biological sampling, probabilistic health-risk modelling and ecological survey, it finds measurable heavy-metal contamination and serious occupational hazards, while offering an important note of hope: because much mining remains localised surface activity, substantial opportunities for ecological restoration still exist.

The three assessments were conducted independently by separate expert teams, using distinct methods and answerable to distinct disciplinary standards. They were not, however, conceived independently. They share a geography, a set of study communities and a common set of questions, and they were designed as three lenses on one corridor rather than three separate enquiries that happen to fall within the same district boundaries. That shared design is what this foreword records, and it is why the same foreword appears in each of the three volumes.

An integrated reading

Although each study stands on its own, their fuller value lies in being read together, and the most reliable findings in this series are those that emerge in more than one volume, arrived at by different means. Three such convergences deserve particular emphasis.

The first concerns land and protected areas. The socio-economic profiling establishes that mining in this corridor is taking place at sites that are too close and some even inside the Yerada Forest Reserve, and along the fringes of the Bui National Park. Approaching the same landscape through an entirely different method, the ecological and health risk assessment reaches a compatible conclusion — that encroachment on forest reserves, rather than proximity to water, is the dominant driver of composite environmental risk across the mapped sites. Read alongside the governance assessment's account of contested and overlapping institutional mandates, the implication is uncomfortable but clear: the areas under greatest ecological pressure are also those where regulatory authority is least settled.

The second concerns contamination and who bears it. The ecological and health risk assessment finds cadmium above international guideline values in every soil sample analysed and mercury in the great majority, with probabilistic modelling indicating that a substantial share of child exposure scenarios exceeds acceptable non-carcinogenic thresholds — a markedly higher share than for adults. That finding acquires its full weight only when placed beside the socio-economic profiling, which documents the settlement patterns, household composition and

dependence on mining income that determine which children live on that soil and why their families are unlikely to move. Environmental risk in this corridor is not evenly distributed, and it is not freely avoidable.

The third concerns mobility and the border. The governance assessment records that migrant miners from Burkina Faso, Côte d'Ivoire, Mali and Nigeria outnumber local miners at several sites, while the socio-economic profiling maps the labour and gold-trading networks along which those movements run. Together they describe an economy that does not stop at the national boundary — a fact of direct consequence for how border security in this corridor is conceived, and one that a study confined to any single district, or to any single discipline, could not have established.

Governance weaknesses enable the informality that drives environmental harm; environmental degradation and health risk erode the very livelihoods the socio-economic profile documents; and competition over land, water and gold feeds the conflict dynamics that threaten community stability and regional security. A companion synthesis report draws these threads together in detail, but readers of any single volume are encouraged to hold the others in view, for the challenges described here are, in reality, one interconnected challenge.

From evidence to action

These are baseline studies, and their purpose is operational. Their findings feed directly into the project's activity chain:

- **Joint border patrol post siting** draws on the governance assessment's conflict hotspot mapping and the socio-economic profiling's migration and trading-network analysis, so that posts are placed where movement actually occurs rather than where the map suggests it should.
- **Land rehabilitation prioritisation** draws on the ecological and health risk assessment's no-go delineation and site risk classification, together with the socio-economic profiling's findings on land tenure, so that rehabilitation is directed to sites that are both ecologically critical and institutionally feasible to secure.
- **Inter-agency training for security and environmental enforcement agencies** draws on the governance assessment's analysis of institutional mandates, so that training addresses the specific overlaps and gaps identified rather than generic capacity deficits.

The findings presented here were reviewed by regional stakeholders at the Gold for Good Regional Validation Workshop held in Damongo from 14 to 17 July 2026, where district assemblies, traditional authorities, regulatory agencies, security services and mining community representatives examined the evidence and contributed to the selection of priority sites.

Limitations held in common

Three constraints apply across the series and are stated here once, so that each volume need not rephrase them separately. The studies were conducted within a single field season and therefore capture a seasonal snapshot of activity known to fluctuate with the agricultural calendar and with rainfall. Sampling in the mining communities was purposive rather than probabilistic, reflecting the absence of any reliable population register for a largely informal and highly mobile workforce; the findings characterise the sites studied and should be extrapolated with care. And access to some locations was shaped by prevailing security conditions and by the willingness of operators to be observed, which introduces a known direction of bias in the documentation of unlicensed operations and of child labour. None of these constraints is unusual in ASM research, and none unsettles the convergent findings described above — but readers should hold them in view.

Acknowledgements

We record our thanks to the lead and national experts and their teams, whose rigour produced these assessments; to the Savannah Regional Coordinating Council and the Savannah Regional Minister; to the District and Municipal Assemblies of West Gonja, Bole and Sawla-Tuna-Kalba; to the Yagbonwura and the traditional authorities of the Gonja Kingdom; to the Minerals Commission, GoldBod, the Environmental Protection Authority, the National Security Coordinating Secretariat and the security services; and to colleagues at Coginta headquarters in Geneva, in particular Anne Moltes, Victoria Walker and Hervé Gonsolin, for their review throughout.

Our principal debt is to the miners, farmers, traders, chiefs, women's groups and young people across the three districts who gave generously of their time and spoke candidly about work that is often conducted at the edge of legality. This series exists because they were willing to be counted.

Together, these studies provide the first integrated, district-level evidence base on ASM in the Savannah Region. They are intended to serve regulators, traditional authorities, security agencies, mining actors, development partners and the communities themselves as a shared foundation for more inclusive, peaceful and sustainable mining governance. The ambition that gives the project its name, that gold might be turned to good rather than becoming a curse, depends on exactly this: honest evidence, applied with care. It is our hope that the evidence assembled here will be matched by the collective will to act upon it.

Bole, Savannah Region, Ghana — July 31, 2026

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EXECUTIVE SUMMARY

This publication is the third of three complementary diagnostic assessments produced under the Gold for Good project, funded by the European Union and implemented by Coginta. Together, the three studies provide an integrated evidence base on artisanal and small-scale mining (ASM) in Ghana's Savannah Region by examining (i) governance, security and conflict dynamics, (ii) the socio-economic profile of ASM communities, and (iii) environmental and public health risks. This third study measures what the first two could only observe: it quantifies the contamination, ecological damage and disease burden that ASM generates, and converts that evidence into a spatial framework of environmentally sensitive "no-go" areas. A companion synthesis report brings the findings of all three together to inform more inclusive, peaceful and sustainable ASM governance.

Background

Artisanal and small-scale mining (ASM), known widely as galamsey, sits at the intersection of livelihood dependence, socio-political dynamics, ecosystem degradation and human health risk. These risks are well documented in Ghana's southern mining belt, but a less understood dimension is the rapid expansion of ASM into historically non-mining regions. In the Savannah Region, mining is a recent arrival that has pushed into ecologically sensitive river systems, woodlands, protected landscapes and agricultural areas, introducing exposure pathways and ecological vulnerabilities that have never been systematically characterized. This assessment was commissioned to close that gap. It covers the Bole, West Gonja and Sawla-Tuna-Kalba Districts, with water quality assessment extended along the Black Volta from Wechiau to Bamboi to capture conditions along the river gradient. It pursues four objectives: to quantify human health risks; to evaluate ecological risks; to identify and validate "no-go" areas through participatory governance involving traditional leaders; and to produce GIS-based decision-support tools for environmental management.

Methods

The study applied a multidisciplinary design combining field investigation, laboratory analysis, geospatial mapping, ecological survey, participatory stakeholder consultation and quantitative health risk assessment. Sixty (60) water samples, 49 soil samples, three fish samples (*Clarias gariepinus*), five plant samples and indoor dust brushed from a room used for burning gold amalgam were collected and analysed. Arsenic, cadmium, mercury and lead were determined by Atomic Absorption Spectrophotometry. Ecological survey covered woody flora structure and diversity at Dollar Power, Wakawaka and Tinga, together with pitfall trapping of ground arthropods as a proxy for soil-habitat condition. Noise was measured across equipment types in five mining communities. Health risk assessment followed the U.S. Environmental Protection Agency (USEPA) framework, using probabilistic Monte Carlo simulation to propagate uncertainty across ingestion, dermal and inhalation pathways for both children and adults. Contamination patterns and pollution sources were interrogated through Principal Component Analysis, Self-Organizing Maps and Positive Matrix Factorization. These were complemented by household interviews, focus group discussions, key informant interviews and photographic documentation, with "no-go" area delineation applying Ghana's riparian buffer zone policy of 300 m around water bodies and a 500 m buffer around protected fores/game reserve in a GIS environment.

Ecological condition

The ecological findings indicate better-than-expected ecosystem quality: although: ASM has altered vegetation structure, it has not destroyed the woodland ecosystem. Across the three assessed sites, 94 individual tree stands representing 13 species were recorded. Wakawaka held the highest species richness and diversity ($H' = 2.30$), including valuable timber species such as *Pseudocedrela kotschyi* and *Pterocarpus erinaceus*, and the tallest, most even-aged stand, consistent with regenerating fallow farmland. Dollar Power retained the largest average tree diameter and the greatest structural variability, reflecting a mature canopy of *Burkea africana*, *Parkia biglobosa* and *Ficus* spp. and indicating high conservation value. Tinga recorded the lowest diversity ($H' = 2.06$), dominated by *Vitellaria paradoxa* (shea) and *Terminalia* spp., which together accounted for nearly half of all individuals, yet contained the single tallest tree and largest-diameter individual in the dataset. Evenness approached unity at all sites, confirming that no species has been competitively eliminated. Ground-arthropod sampling captured 61 individuals across 10 taxa, with ants comprising 74 per cent of captures – a signature typical of compacted, vegetation-reduced savanna soils – and diversity declining with proximity to active mining. Because operations are localized surface pits rather than large-scale clearance, many mature trees survive. This is the study's most actionable ecological finding: restoration through assisted natural regeneration, enrichment planting, pit backfilling and protection of remaining mother trees is still viable, and the window for it is open now.

Occupational hazards

Occupational conditions expose workers to physical, chemical, biological, ergonomic and psychosocial hazards. Noise is the most systematically documented: primary grinders generated levels exceeding both the 85 dB occupational exposure limit set by the World Health Organization, the Ghana Standards Authority and the Ghana Environmental Protection Authority (EPA), and Ghana's 65-75 dB daytime light-industrial standard. Machines were operated for around eleven hours a day by young men, none observed wearing hearing protection, and processing takes place close to residential quarters, extending exposure to women and young children who are not themselves miners. Hearing loss, tinnitus, fatigue, sleep deprivation

and stress are therefore probable outcomes. Documented hazards also include pit collapse, falling rocks, dust inhalation, ergonomic strain and chemical exposure. Headache was the most commonly reported symptom, followed by chronic cough and breathing difficulty, alongside musculoskeletal pain and fatigue, a profile consistent with sustained dust, noise and physical loading. The clinic at Dollar Power corroborated this, reporting upper respiratory disease predominating in the dry season and malaria in the raining season. Published evidence from comparable settings records recurrent fatal accidents from blasting, falls and pit collapse, and elevated mortality from respiratory, circulatory, metabolic and neoplastic disease in populations living near mining sites.

Environmental contamination

Soil contamination is the dominant environmental concern. Cadmium exceeded international guideline values in 100 per cent of soil samples, with a mean of 33.45 mg/kg against a 0.8 mg/kg threshold and a maximum of 288.12 mg/kg. Mercury exceeded guidelines in approximately 94% of samples (mean 1.38 mg/kg against 0.3 mg/kg). Lead breached its threshold at localised hotspots, reaching 561.19 mg/kg, while arsenic remained generally below soil guideline values. In water, mean concentrations of most metals fell within WHO drinking water guideline standard, but localised exceedances occurred – notably for cadmium, and with maxima for lead and arsenic above WHO limits at specific points. Indoor dust from an amalgam-burning room carried very high loads (lead 395.5 mg/kg; arsenic 83.47 mg/kg; mercury 29.37 mg/kg), establishing inhalation in domestic space as a significant exposure pathway. Fish did not exceed the Codex value for lead, though all four metals were detectable, and plant samples approached Codex limits for arsenic and lead. Multivariate analysis was consistent across methods: PCA, SOM and PMF each resolved two contamination signatures – one dominated by cadmium and lead, the other by arsenic and mercury – indicating multiple but mining-related sources, with strong inter-metal correlations in soil pointing to common accumulation pathways and more complex geochemical behaviour in water.

Human health risk

Probabilistic risk assessment establishes soil, not water, as the principal exposure medium. Approximately 46 per cent of child exposure scenarios and 20 per cent of adult scenarios exceeded acceptable non-carcinogenic risk thresholds for soil, with cadmium contributing over three-quarters of the total hazard index. Water exposure generally presents low non-carcinogenic risk, though localised high-exposure scenarios remain a concern. Children were consistently at higher risk owing to lower body weight and greater exposure per unit body mass, and sensitivity analysis identified dermal contact and incidental ingestion of soil as the pathways driving the result. A hazard prioritisation matrix rated mercury exposure, cadmium exposure and dust inhalation as extreme; pit collapse and noise as high;

and falls, water contamination and malaria as moderate. Women and children are the most vulnerable groups: women through their concentration in ore processing and daily handling of contaminated material, children through soil contact and residential proximity to processing. This converges with the socio-economic assessment's finding that women dominate downstream processing while being wholly absent from the governance structures that could alter those conditions.

No-go zone delineation

Ninety-four mapped ASM sites covering approximately 1,001.79 hectares were classified by proximity to and overlap with protected areas and water bodies. Under the combined forest-and-water composite, 68.64 per cent of the mapped area falls in the critical risk category, meaning most ASM activity is occurring inside or immediately adjacent to environmentally sensitive land. The driver is unambiguous: forest encroachment, not water encroachment. Assessed on water risk alone, only 0.23 per cent of the mapped area is critical, and most sites lie outside the prescribed riparian buffer. Risk is also unevenly distributed. Dollar Power and Tinga together account for 59 sites in the critical composite zone, with every one of their mapped sites so classified. Tinga has the largest average site size and is the only community with sites inside the water-critical zone, suggesting weaker adherence to buffer requirements there. Wakawaka presents a lower profile, with most sites in the far-to-moderate range, though two sites in the moderate water-risk band mean this should not be read as an absence of risk. Dollar Power and Tinga are therefore the priority intervention areas, a conclusion that independently corroborates the socio-economic assessment's identification of the same communities as being under extreme mining pressure.

Conclusion

ASM in the Savannah Region has caused measurable degradation of environmental quality and elevated health risk in affected communities. Contamination – particularly by cadmium and mercury, with localised lead – extends beyond active sites into surrounding soils, water, fish and plants, and the cumulative Hazard Index exceeds acceptable limits at several locations. Yet the picture is not uniformly grave, and the distinction matters for policy. Ecological effects on biodiversity are adverse but not critical, largely because rudimentary tools produce localised surface disturbance rather than wholesale clearance, leaving mature trees standing and restoration feasible. Water quality is broadly within guidelines, with contamination concentrated in soil and in domestic dust. The risks that are severe are severe in specific, addressable ways: cadmium and mercury in soil, dust and noise at processing points, children's exposure through soil contact, and forest encroachment at Dollar Power and Tinga. This specificity is what makes intervention tractable. The delineation of no-go areas provides a science-based framework for land-use planning, and should encompass riparian buffers, food-producing farmland, schools, health facilities and residential settlements, supported by GIS

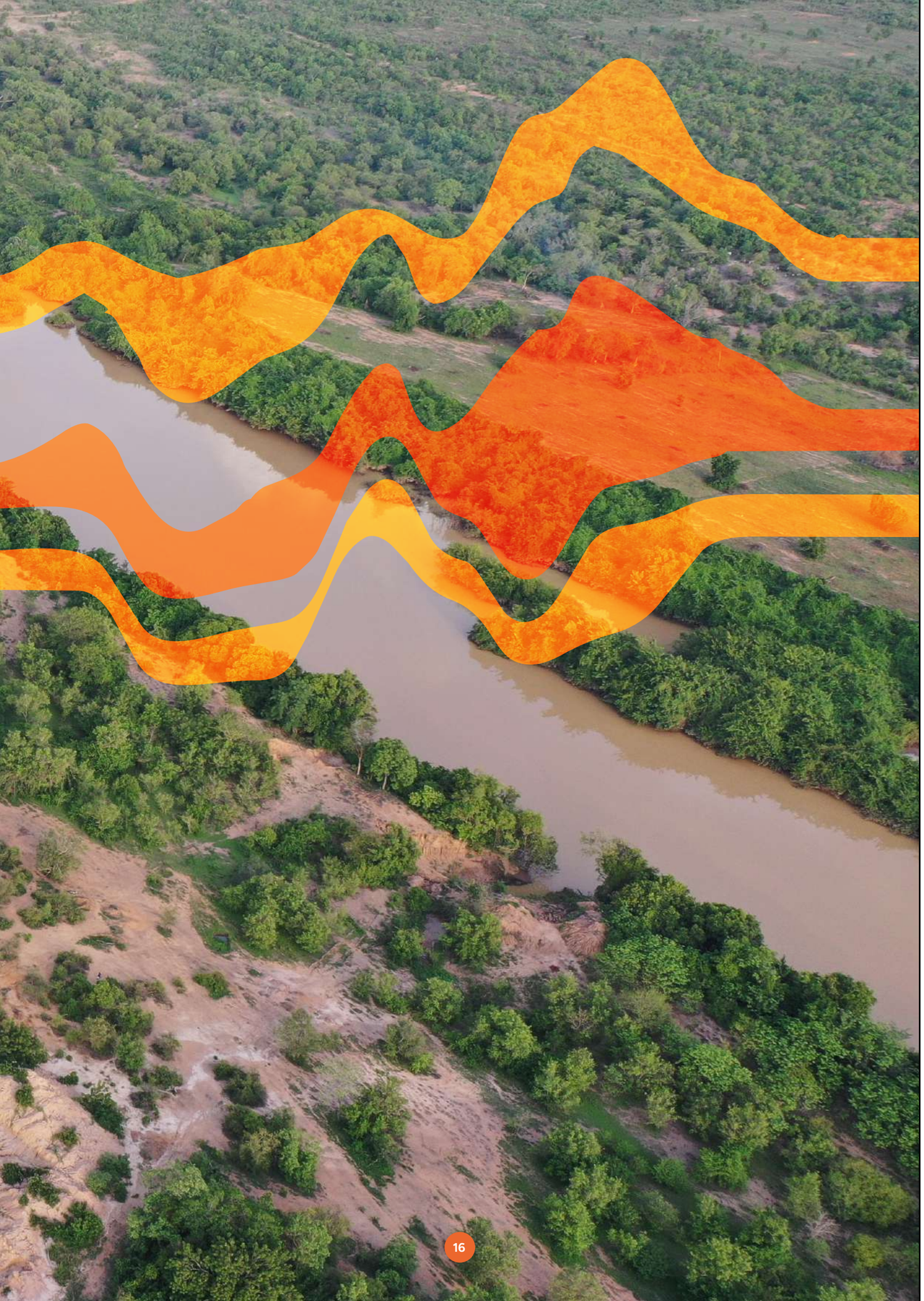
contamination maps, ecological sensitivity assessment and health risk mapping to ensure transparency and enforceability. Implemented alongside continuous monitoring, land rehabilitation, community risk communication and regulatory enforcement, these measures offer a route to reconciling mineral extraction with ecosystem conservation and community health. This assessment supplies the environmental and public health baseline against which reconciliation can be planned, monitored and measured across the three districts.

Recommendations

Recommendations are organised across three domains. For ecological health, the study calls for protection of mature mother trees as seedbanks, embedded in miner education and in NGO and CSO awareness work so that trees are identified and spared during prospecting and extraction; assisted natural regeneration through silvicultural thinning and weeding; enrichment planting with indigenous fruit species to add socio-economic value without compromising structural integrity; mandatory pit backfilling as immediate post-mining practice, which simultaneously reduces erosion, creates a seedbed and removes the falling hazard to children and livestock; and community-managed nurseries propagated from surviving mother trees to preserve local genetic integrity, paired with permanent monitoring plots tracking recruitment, growth and species turnover over five years. For human health, it recommends comprehensive hearing conservation programmes combining noise monitoring, audiometric screening, provision and enforcement of hearing protection, worker education and job rotation, delivered jointly by the EPA, Minerals Commission and district environmental health officers; an integrated health management programme for children combining community education, environmental monitoring and biomonitoring; dust suppression and the promotion of mercury-free extraction technologies as the two highest-severity hazards; physical separation of sensitive populations from mining and processing, including relocation of children's play areas and residential separation from active and abandoned sites; and intensified periodic monitoring of the Volta by the Water Resources Commission, extended to heavy metals, with results made accessible to communities through the District Assemblies. For no-go zones, it recommends concentrating monitoring and enforcement first on Dollar Power and Tinga; immediate investigation of the two critical-zone sites at Tinga – the only ASM activity directly overlapping a water body – and assessment of remediation or closure options; routine GIS-based monitoring of the 500 m forest and 300 m riparian buffers using periodic satellite or drone imagery to detect encroachment before it becomes critical; community-specific reclamation plans weighted toward Dollar Power and Tinga; and engagement with operators on the riparian buffer policy to build awareness and encourage voluntary compliance.

ABBREVIATIONS

APHA	American Public Health Association
As	Arsenic (metal)
ASGM	Artisanal and Small-Scale Gold Mining
ASM	Artisanal and small-scale mining
ATSDR	Agency for Toxic Substances and Disease Registry
CAPI	Computer-assisted Personal Interviews
Cd	Cadmium (metal)
DBH	Diameter at Breast Height
EC	Electrical conductivity
EFSA	European Food Safety Authority
EPA	Environmental Protection Authority
ERA	Ecological Risk Assessment
FGD	Focus Group Discussions
GIS	Geographic Information System
Hg	Mercury
HI	Hazard Index
HQ	Hazard Quotient
HHRA	Human Health Risk Assessment
HRA	Health Risk Assessment
IARC	International Agency for Research on Cancer
IQ	Intelligence Quotient
KII	Key Informant Interviews
Pb	Lead (metal)
PCA	Principal Component Analysis
PLI	Pollution Load Index
PMF	Positive Matrix Factorization
SOM	Self-Organizing Maps
TDS	Total Dissolved Solids
TOR	Termes of References
USEPA	U.S. Environmental Protection Agency
WHO	World Health Organization



1. BACKGROUND

Artisanal and small-scale mining (ASM) known widely as ‘Galamsey’ represents a complex intersection of livelihood dependence, socio-political dynamics, ecosystem degradation and human health risks. While these risks are well documented in the southern mining belt of Ghana an emerging and less understood dimension is the rapid expansion of ASM into historically non-mining regions where gold mining is a newer phenomenon. What warrants research is the escalation of this phenomenon particularly in newer regions which are historically not referred to as ‘Galamsey’ sites. In the Savannah Region- particularly Bole, West Gonja and Sawla-Tuna-Kalba, ASM has encroached into ecologically sensitive areas, notably river systems and protected landscapes.

This geographic shift introduces new and poorly characterized exposure pathways, ecological vulnerabilities and human health challenges, underscoring the need for a systematic ecological and human health risk assessment.

The assignment was under the Gold for Good Project and required a scientifically rigorous but also socially acceptable risk assessment to:

- Quantify human health risks,
- Evaluate ecological risks,
- Identify and validate “no-go” areas through participatory governance involving traditional leaders,
- Produce GIS-based decision-support tools for environmental management.

2. METHODOLOGICAL APPROACH

Based on the scope of the project, the consulting team relied on both primary and secondary data sources. Participatory approach was employed in data sourcing, consultations and Focus Group Discussions (FGD).

This approach utilized the following data collection methods to satisfy the 5 key objectives specified in the Terms of Reference (TOR) .

2.1 Geographic scope and target population

The study covered 3 districts (West Gonja, Bole, and Sawla-Tuna-Kalba) in the Savannah regions of Northern Ghana. However, to trace the quality of water along the Black Volta water quality data was collected from Wechiau (Wa West District) to the Bamboi area (Bole district), to appreciate the factors influencing the water quality of the Volta along the gradient.

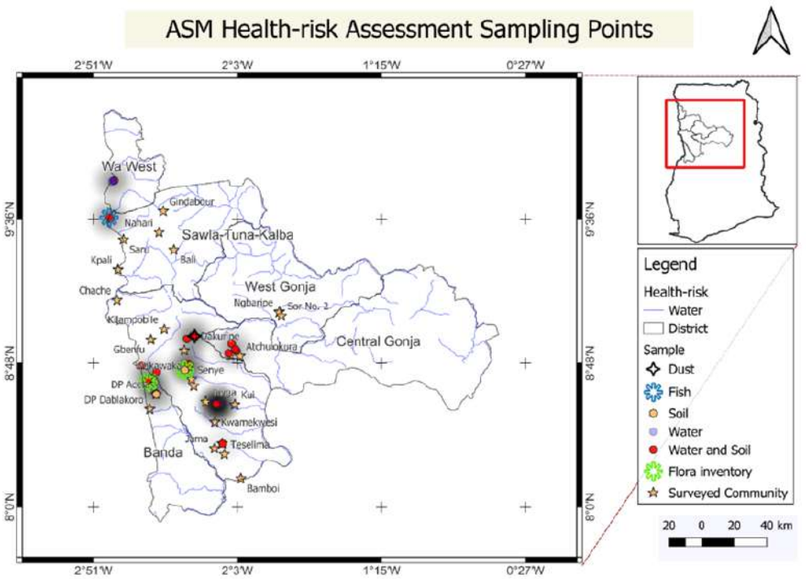


Figure 1: Study area and health risk sampling location

1. Conduct field surveys and environmental sampling (soil, sediment, tailings, surface/ground water, selected biota) at suspected ASM sites, downstream/upstream locations, community water points, and reference/background sites.
2. Measure total mercury (Hg) and, where possible, methylmercury (MeHg), plus other priority metals (As, Pb, Cd, Cr), and basic water quality parameters (pH, EC, turbidity, dissolved oxygen).
3. Produce a GIS-based hotspot map indicating contamination intensity, exposure pathways (water, food, dust), and population exposure (villages, schools, water points).
4. Conduct a human health risk assessment (HRA) for key exposure groups (miners, processors, women involved in amalgamation/processing, children), and an ecological risk assessment (ERA) for aquatic and terrestrial receptors.
5. Provide ranked site prioritization (short, medium, long-term interventions) with recommended mitigation and monitoring actions and capacity building for local institutions.

2.2 Secondary data

Published and unpublished data from the Water Resources Commission-Ghana, information from the Ghana Environmental Protection Authority (EPA), Minerals Commission, Ghana, U.S. Environmental Protection Agency (USEPA), World Health Organization (WHO) and statistics on the population of Ghana were assessed to estimate health risk to the population.

2.3 Field sampling

Sampling design

The main focus was to sample soil and water to assess its quality and draw inferences on its implications for human and ecological health. Although the idea was to stratify the collection of samples, conditions on the ground made it difficult to achieve. For ASM communities, we relied on water supply and soil samples where we were allowed to pick samples. However, efforts were made to ensure that sampling was done randomly in active ASM sites and adjoining land uses in the communities visited.

In all, 60 water samples, 49 soil samples, 3 samples of fish (*Clarias gariepinus)* and 5 samples of plant material (leaves) were collected and transported to the laboratory for various analysis. Also, dust was sampled from a room where gold amalgam was burnt off to separate the ore. The dust particles were brushed off a ceiling fan in the room and on windowsills.

2.4 Health risk assessment

The study used face-to-face interviews, key informant interviews (KII), focus group discussions (FGD), geospatial mapping, soil, water, dust and fish heavy metal loads, observation and photographic documentation. Computer-assisted personal interviews (CAPI) were used to collect data from ASM actors through face-to-face interviews. Details of this method is contained in the report provided by the socio-economic profiling group.

Human health risk assessment was conducted to estimate the non-carcinogenic risks associated with exposure to As, Cd, Hg, and Pb in soil and water. The assessment followed the U.S. EPA human health risk assessment framework, where exposure dose is first estimated for each pathway and then compared with an element-specific reference dose to obtain the hazard quotient (HQ). The total hazard index (HI) was calculated as the sum of element-specific HQ values.

2.4.1 Health risk effects of arsenic, cadmium, lead, and mercury

Arsenic is a naturally occurring toxic metalloid that can contaminate soil, water, and food through both natural processes and human activities such as mining and industrial operations (WHO, 2022). Chronic exposure to arsenic has been associated with skin lesions, hyperkeratosis, and pigmentation disorders (WHO, 2022). Long-term ingestion of arsenic-contaminated drinking water increases the risk of cancers of the skin, bladder, and lungs (IARC, 2012). Arsenic exposure may also contribute to cardiovascular disease, diabetes, and neurological disorders (ATSDR, 2007). Children are particularly vulnerable because arsenic can impair growth, cognitive development, and immune function (WHO, 2022).

Cadmium is a persistent toxic heavy metal that accumulates in the kidneys and liver following long-term exposure (WHO, 2022). Humans are exposed to cadmium through contaminated food, drinking water, cigarette smoke, and industrial emissions (ATSDR, 2012). Chronic cadmium exposure can cause kidney dysfunction and reduce bone mineral density, increasing the risk of fractures (WHO, 2022). Cadmium inhalation has also been linked to respiratory diseases and lung cancer (IARC, 2012). Because cadmium persists in soils and is readily absorbed by crops, contaminated agricultural land represents an important pathway for human exposure (EFSA, 2009).

Lead is a toxic heavy metal with no known safe level of exposure for humans, particularly children (WHO, 2023). Exposure occurs through contaminated soil, water, food, dust, and industrial emissions (WHO, 2023). Lead damages the nervous system and can reduce intelligence quotient (IQ), impair learning, and cause behavioral problems in children (WHO, 2023). In adults, prolonged exposure has been associated with hypertension, kidney damage, anaemia, and reproductive disorders (ATSDR, 2020). Lead has also been classified as probably carcinogenic to humans based on evidence from epidemiological and experimental studies (IARC, 2006).

Mercury is a highly toxic heavy metal that exists in elemental, inorganic, and organic forms, with methylmercury being the most toxic to humans (WHO, 2021). Human exposure commonly occurs through the consumption of contaminated fish and occupational activities involving mercury (WHO, 2021). Mercury primarily damages the nervous system, leading to tremors, memory loss, and impaired coordination (ATSDR, 2022). Prenatal exposure can interfere with fetal brain development and result in cognitive and behavioural disorders in children (WHO, 2021). Long-term mercury exposure may also impair kidney function and weaken the immune system (ATSDR, 2022).



With practiced hands, a woman mixes mercury into the slurry, producing the gold-mercury amalgam that will later be heated to recover the precious metal

2.4.1 Soil Exposure Assessment

For soil, the average daily dose from incidental ingestion was calculated as equation:

$$ADD_{ing,soil} = \frac{C_s \times IR_s \times EF \times ED \times 1.0 \times 10^{-6}}{BW \times AT_{nc}}$$

The average daily dose from dermal contact with soil was calculated as equation:

$$ADD_{derm,soil} = \frac{C_s \times SA \times AF_s \times ABS_d \times EF \times ED \times 1.0 \times 10^{-6}}{BW \times AT_{nc}}$$

The average daily dose from inhalation of resuspended soil particles was calculated as equation:

$$ADD_{inh,soil} = \frac{C_s \times IR_a \times EF \times ED}{PEF \times BW \times AT_{nc}}$$

where $ADD_{ing,soil}$, $ADD_{derm,soil}$, and $ADD_{inh,soil}$ are the average daily doses through incidental soil ingestion, dermal contact, and inhalation, respectively, in mg · kg^{-1} · day^{-1}. C_s is the concentration of the element in soil in mg · kg^{-1}. IR_s is soil ingestion rate in mg · day^{-1}. *EF* is exposure frequency in days · year^{-1}. *ED* is exposure duration in years. 1.0×10^{-6} is the soil unit conversion factor from mg to kg. *BW* is body weight in kg. AT_{nc} is the non-carcinogenic averaging time in days. *SA* is exposed skin surface area in cm^2. AF_s is the soil adherence factor in mg · cm^{-2}. ABS_d is dermal absorption fraction. IR_a is inhalation rate in m^3 · day^{-1}. *PEF* is the particulate emission factor in m^3 · kg^{-1}.

Soil exposure factors used are stated in Table 1 below.

Table 1: Soil exposure factors

Parameter	Adult	Child	Unit
Exposure frequency	350	350	days year^{-1}
Exposure duration	30	6	years
Body weight	70	15	kg
Averaging time			days
Soil ingestion rate	100	200	mg day^{-1}
Exposed skin surface area			cm^2
Soil adherence factor	0.2	0.2	mg cm^{-2}
Dermal absorption fraction	0.03	0.03	unitless
Inhalation rate	20	12	m^3 day^{-1}
Particulate emission factor	1.36×10^9	1.36×10^9	
Soil conversion factor	1.0×10^{-6}	1.0×10^{-6}	

2.4.2 Water exposure assessment

For water, ingestion and dermal contact were considered. Inhalation was not included. The chronic daily intake from water ingestion was calculated as equation:

$$CDI_{ing,water} = \frac{C_w \times IR_w \times EF \times ED}{BW \times AT_{nc}}$$

The dermal absorbed dose from water contact was calculated as equation (24):

$$DAD_{derm,water} = \frac{C_w \times SA \times K_p \times ET \times EF \times ED \times 1.0 \times 10^{-3}}{BW \times AT_{nc}}$$

where CDI_{ing},water is the chronic daily intake through water ingestion in mg · kg^{-1} · day^{-1}. DAD_{derm},water is the dermal absorbed dose from water contact in mg · kg^{-1} · day^{-1}. C_w is the concentration of the element in water in mg · L^{-1}. IR_w is water ingestion rate in L · Day^{-1}. K_p is the dermal permeability coefficient in cm · h^{-1}. *ET* is exposure time in h · day^{-1}. 1.0×10^{-3} is the water unit conversion factor from cm^3 to *L*.

Water exposure factors used are presented in table 2.

Table 2: Water exposure factors

Parameter	Adult	Child	Unit
Exposure frequency	350	350	days $year^{-1}$
Exposure duration	45	9	years
Body weight	70	15	kg
Averaging time	1.6425×10^{4}	3.285×10^{3}	days
Water ingestion rate	2	01	L day^{-1}
Exposed skin surface area	1.800×10^{4}	6.600×10^{3}	cm^{2}
Exposure time	0.58	0.58	h day^{-1}
Water conversion factor	1.0×10^{-3}	1.0×10^{-3}	L cm^{-3}

Reference doses and permeability coefficients

Non-carcinogenic toxicity values were assigned using reference doses for ingestion, dermal contact, and inhalation, depending on the medium and exposure pathway. The U.S. EPA Regional Screening Level tables provide toxicity values and screening equations used in risk-based calculations.

Table 3: Soil Reference Dose

Metal	RfD_{ing}	RfD_{derm}	RfD_{inh}	Unit
As	3.00×10^{-4}	3.50×10^{-3}	1.50×10^{-5}	mg kg^{-1} day^{-1}
Cd	1.00×10^{-3}	2.50×10^{-5}	1.00×10^{-5}	mg kg^{-1} day^{-1}
Hg	3.00×10^{-4}	2.10×10^{-5}	3.00×10^{-4}	mg kg^{-1} day^{-1}
Pb	3.50×10^{-3}	5.25×10^{-4}	3.52×10^{-3}	mg kg^{-1} day^{-1}

Table 4: Water Reference Doses and Dermal permeability Coefficients

Metal	RfD_{ing}	RfD_{derm}	Unit for *RfD*
As	3.00×10^{-4}	1.23×10^{-4}	mg kg^{-1} day^{-1}
Cd	5.00×10^{-4}	1.00×10^{-5}	mg kg^{-1} day^{-1}
Hg	3.00×10^{-4}	2.10×10^{-5}	mg kg^{-1} day^{-1}
Pb	3.50×10^{-3}	5.25×10^{-4}	mg kg^{-1} day^{-1}

2.4.3 Non-carcinogenic risk estimation

The hazard quotient for each exposure pathway was calculated by dividing the estimated exposure dose by the corresponding reference dose.

An *HQ* or *HI* value less than or equal to 1 indicates that non-carcinogenic adverse effects are unlikely under the assumed exposure conditions. Values greater than 1 indicate potential non-carcinogenic health concern and require closer interpretation or risk-management attention, consistent with the U.S. EPA hazard index approach.

2.4.4 Probabilistic Monte Carlo simulation

A probabilistic HHRA was conducted using Oracle Crystal Ball to account for variability and uncertainty in metal concentrations and exposure parameters. Concentrations of As, Cd, Hg, and Pb were treated as element-specific probabilistic assumptions. Lognormal or fitted distributions were assigned to concentration data because environmental metal concentrations are commonly right-skewed. Spearman rank correlation matrices were used to preserve dependence among metal concentrations during simulation.

For soil, the following assumptions were used in the probabilistic model.

Table 5: Assumptions used for Monte Carlo simulation

Parameter	Distribution	Parameters
C_s	Lognormal or fitted	Based on raw soil concentration data
IR_s	Triangular	Adult: 50, 100, 200; Child: 100, 200, 400
BW	Truncated normal	Adult: mean 70, SD 12, min 40; Child: mean 15, SD 3, min 8
EF	Discrete	350
ED	Discrete	Adult 30; Child 6
SA	Normal	Adult SD 2000; Child SD 1200
AF_s	Lognormal	GM 0.2; GSD 1.5
ABS_d	Uniform	0.01 to 0.05
IR_a	Triangular	Adult: 12, 20, 24; Child: 8, 12, 16
PEF	Discrete	1.36×10^{9}

For water, the following assumptions were used.

Parameter	Distribution	Parameters
C_w	Lognormal or fitted	Based on raw water concentration data
IR_w	Triangular	Adult: 1.5, 2.0, 2.5; Child: 0.5, 0.78, 1.0
BW	Truncated normal	Adult: mean 78, SD 12, min 40; Child: mean 15, SD 3, min 8
EF	Discrete	350
ED	Discrete	Adult 45; Child 9
SA	Normal	Adult SD 2000; Child SD 1200
ET	Uniform	0.25 to 1.0
K_p	Discrete	From toxicity table
CF	Discrete	1.0×10^{-3}

The simulation was run for 10,000 trials for each medium and receptor group. Adult and child receptors were evaluated separately. The output distributions were summarized using the mean, median, 5th percentile, 95th percentile, and the percentage of trials exceeding *HI* = 1.

The probability of exceeding the non-carcinogenic threshold was then calculated.

2.5 ECOLOGICAL ASSESSMENT

2.5.1 Flora

Study Area and Plot Establishment

Three communities where ASM activities were known to be prominent were visited for assessment. These mining communities are the Dollar Power , Tinga and Wakawaka (all in the Bole District). In these areas mining occurs in some few kilometres (about half and above kilometre) away human settlements. The mining occurs within natural vegetated woodlands and fallow lands where remnant vegetation is present. Miners adopt open-pit surface mining method with the help of handheld scanners for detecting mineral deposits.

Vegetation assessment was conducted at sites where mining was ongoing or at abandoned sites. A one-hectare sampling plot (**100 m × 100 m)** was established at the site of each of the three ASM communities (Figure 1) for the inventory.



Once the gold is gone, abandoned pits and degraded land remain, increasing erosion, reducing biodiversity, and slowing the natural recovery of forests and agricultural land

Species identification

All trees with Diameter at Breast Height (DBH) of 1.3 meters and above were identified to species level and individuals of each species were counted within each plot. Tree species were identified and recorded on standardized data sheets using either scientific or local names. Photographs were taken of trees that the team could not identify and later matched to regional taxonomic keys and standard West African floral reference databases and books (Arbonnier, 2004).

Measurement of structural parameters

For each identified individual tree, two primary structural parameters were measured:

- **Height (m):** Total height of each tree was estimated using a graduated measuring pole coupled with ocular estimation especially for taller trees.
- **Diameter (cm):** The girth of each stem was measured at 1.3 m above ground (DBH) using a flexible diameter tape. For multi-stemmed individuals branching below 1.3 m, the diameter of the largest main stem was recorded.

Data processing and standardization

Prior to further analysis, the raw dataset underwent pre-analysis cleaning to ensure data completeness and accuracy. The following data preparation was done:

- All species names were harmonized to accepted scientific nomenclature.
- Individuals with missing height values due to field entry errors were excluded from height-based descriptive statistics but retained for species richness and diameter calculations.
- Similarly, individuals with missing diameter values were excluded from diameter-based statistics.
- Unidentified specimens were grouped under "Unknown" category for richness counts but excluded from specific species-level dominance analyses.
- All data entry, cleaning, and statistical computations were performed using Microsoft Excel (Version 365).

Data analysis

To characterize each site for the class distribution of the trees on each plot, descriptive statistics were computed per site. The mean height and diameter of the recorded tree species were computed for each plot. Also, the range (i.e. the minimum and maximum) height and DBH were computed for the recorded tree species on each site. Lastly, the Standard Deviation (SD) was calculated to measure the variability of the measured parameters within each plot.

Floral diversity assessment

To evaluate the ecological richness and distribution of species, Shannon-Wiener Diversity Index (H'), Species Richness (S), were computed for each site. Species Richness (S), is the simplest measure of biodiversity, defined as the total number of different species recorded within a given plot. It provides a baseline count of the floristic inventory of the study site.

Pielou's Evenness Index (J) was applied to assess how individual species are evenly distributed among species in a plant community, with values ranging from 0 (low evenness) to 1 (perfect evenness). It builds on the Shannon Diversity Index (H'), which combines species richness and abundance.

2.5.2 Fauna

Arthropods play a dominant role in natural and human-modified terrestrial ecosystem dynamics. Spatially explicit arthropod population time-series data are crucial for understanding the dynamics and assessment of their ecological impacts. Much as it was desired to gather Arthropod abundance, due to the situation on the ground in ASM communities, it was impractical to assess arthropods that meant repeat visit across sites. The team were only able to take a count in Tinga community where 3 pit fall traps were placed per methods described by Valantin-Morison, 2021; Saji et al., 2021, active for 5 conservative days. Each trap consisted

of a plastic container of 13 cm diameter buried flush with the soil surface. Traps were filled to one-third volume with plain water, and a drop of unscented detergent was added to reduce surface tension. Diversity metrics calculated per trap include total abundance (raw individual counts), Shannon diversity index (H'), Simpson's Diversity Index (1–D form), richness (S). The diversity is a preliminary indicator of habitat disturbance associated with mining activity.

2.5.3 Soil and water quality

The sampling of soil from the study area was conducted using a randomized design based on the intensity of ASM activity, 49 soil samples were collected. High ASGM activity zones for example ore-processing areas, tailings, and excavation pits were of high interest and control zones at least 1 km away from any known ASGM activity. At each site, composite soil samples were collected from the top 0–10 cm layer using a stainless-steel auger. All samples were stored in clean, clear polyethylene bags, labelled, and transported in coolers to the laboratory for heavy metal analysis.

Surface water samples were collected from streams and rivers found in the ASM communities. In all 60 water samples were collected for analysis. Traditional grab sampling techniques were used, as recommended by the American Public Health Association (APHA) guidelines (2017). For sampling on the Black Volta, samples were collected mid-stream at a depth of approximately 30 cm to avoid surface contamination. Water was collected both upstream and downstream of ASGM activity zones to evaluate the extent of pollutant dispersal. Each water sample



was collected in acid-washed polyethylene bottles for metal analysis. On-site parameters such as pH, EC, TDS, and temperature were recorded using a portable Hanna Multiparameter waterproof meter (Model HI98194).

In addition to surface water, groundwater samples were collected from selected boreholes and wells within the study area to assess potential subsurface contamination (see Figure 1). Sampling sites were chosen based on proximity to ASGM activities and community reliance on the sources for drinking and domestic use. Standard grab sampling techniques were used, with water drawn directly into acid-washed polyethylene bottles. Field measurements including pH, electrical conductivity (EC), and total dissolved solids (TDS) were taken in situ using a portable multiparameter probe. All samples were stored in ice chests and transported to the laboratory for heavy metal analysis.

Lab Analysis

All laboratory analyses were conducted at the Ecological Laboratory (EcoLab) of the University of Ghana, Legon. Heavy metal concentrations in soil, water, and sediment samples were determined using a PinAAcle 900H Atomic Absorption Spectrophotometer (AAS), following standardized procedures. Prior to analysis, samples were digested using appropriate acid digestion protocols (USEPA Method 3050B for solids and Method 200.7 for water). Calibration was performed using certified standard solutions, and quality control measures included the use of blanks, duplicates, and reference materials to ensure analytical accuracy and precision.

2.6 Statistical analysis

Before data analysis was undertaken, replicate measurements were combined into a single representative value for each sample using the arithmetic mean. The final datasets contained concentrations of four heavy metals: As, Cd, Hg, and Pb. Water concentrations were expressed in mg/L, while soil concentrations were expressed in mg/kg. Further, the datasets were checked for missing values, non-numeric entries, and formatting errors before analysis.

For multivariate analyses, the data were standardized to remove the influence of differences in concentration scale among elements. Standardization was performed using the z-score transformation equation.

Spearman correlation analysis

Spearman rank correlation analysis was used to assess monotonic relationships among As, Cd, Hg, and Pb in the composite water and soil datasets. This method was selected because environmental concentration data are often non-normally

distributed and may contain skewed values. Spearman correlation is rank-based and is therefore more suitable for such datasets than Pearson correlation when normality cannot be assumed (Spearman, 1904; Schober et al., 2018).

The strength and direction of association were interpreted from the sign and magnitude of r_s. Positive coefficients indicate that paired elements increase together, while negative coefficients indicate inverse behaviour. Statistical significance was assessed at $p < 0.05$ where significance was indicated using an asterisk.

Principal component analysis

Principal component analysis was applied separately to the composite water and soil datasets to reduce dimensionality and identify dominant metal association patterns. PCA transforms correlated variables into a smaller number of orthogonal components that explain the major variance structure in the dataset (Jolliffe, 2002; Schober et al., 2018).

The suitability of the data for PCA was assessed using the Kaiser-Meyer-Olkin measure of sampling adequacy and Bartlett's test of sphericity. Varimax rotation with Kaiser normalization was applied to improve interpretability by maximizing the variance of squared loadings within each component (Kaiser, 1958). Rotated component loadings were used for interpretation. Loadings with absolute values of 0.40 or greater were treated as meaningful. Chord diagrams were produced from the rotated loadings to visualize the strength of relationships between metals and extracted components.

Self-organizing map analysis

Self-organizing map (SOM) analysis was used to classify the composite water and soil samples based on their heavy-metal signatures. SOM is an unsupervised neural network method that projects high-dimensional data onto a two-dimensional grid while preserving the topological relationships among observations (Kohonen, 2001). This makes it suitable for identifying nonlinear patterns and relationships.

The final SOM configuration was selected based on the lowest combined quantization and topographic error.

After SOM training, K-means clustering was applied to the SOM to group neurons into geochemically similar clusters. The optimal number of clusters was selected using the silhouette coefficient and Davies-Bouldin index equation.

Positive Matrix Factorization (PMF)

PMF is a receptor modelling approach that decomposes an observed concentration matrix into factor contribution and factor profile matrices while incorporating uncertainty estimates (Paatero & Tapper, 1994; U.S. Environmental Protection Agency, 2014).



3. RESULTS AND DISCUSSION

3.1 Ecological risk assessment

3.1.1 Flora structural vegetation diversity

A total of 94 individual stems were recorded across all three sites (Table). Tinga recorded the highest number of individuals of 38, while Dollar Power recorded the lowest of 26. Also, a summary of the structural attributes is presented in Table 6.

Dollar Power contained the largest average tree diameter of 20.50 cm and the highest structural variability (SD: 2.64 m for height; 8.38 cm) for DBH. This could be as a result of the presence of a matured canopy emergent trees like *Burkea africana*, *Parkia biglobosa*, *Ficus* spp interspersed, with smaller understory species like the *Combretum* spp., *Grewia* spp and others (Appendix 1A).

Table 6: Woody vegetation structure

Parameter	Dollar Power	Wakawaka	Tinga
Total Individuals (N)	26	30	38
Mean Height (m)	7.37	8.03	5.95
Height Range (m)	2.8 – 13.0	4.0 – 13.0	3.0 – 15.0
Height Std. Dev. (m)	2.64	1.83	2.50
Mean Diameter (cm)	20.50	13.46	9.77
Diameter Range (cm)	5.0 – 35.0	6.0 – 39.0	3.0 – 40.0
Diameter Std. Dev. (cm)	8.38	7.33	7.70

Wakawaka on the hand, recorded the tallest average tree height of 8.03 m with relatively slender trunks. The site also recorded the lowest standard deviation in the tree height of 1.83 that suggests that the trees are more uniform or even-aged stand. This could be due to fact that the site is a fallow farmland that is regenerating though pit mining occurs there.

Tinga had the lowest overall averages for both height (5.95 m) and DBH (9.77 cm). However, it contained the single tallest tree of 15 m high (i.e. *Vitellaria paradoxa*) and the largest diameter of 40 cm, (i.e. *Lannea microcarpa*) individuals in the entire dataset (Appendix 1C).

Species richness and dominance

Species richness and dominance patterns are summarized in Table 7. Wakawaka recorded the highest species richness of 13 species, including valuable timber species such as *Pseudocedrala kotschyi* and *Pterocarpus erinaceus* and edible economic species like the diverse *Lannea* species (Appendix 1B). Dollar Power showed a balanced mixture of legumes (e.g. *Burkea*, *Isoberlina*, *Parkia*) and shrubs. In contrast, Tinga was heavily dominated by *Vitellaria paradoxa* (Shea) and *Terminalia* spp., which together accounted for nearly 47% of all individuals recorded.

Table 7: Species richness and dominance

Site	Richness (S)	Total (N)	Dominant Species (≥ 4 individuals)
Dollar Power	12	26	Monotes kerstingii (7), Burkea africana (4)
Wakawaka	13	30	Pseudocedrala kotschyi (6), Combretum spp. (5), Pterocarpus erinaceus (5)
Tinga	11	38	Vitellaria paradoxa (10), Terminalia spp. (8), Combretum spp. (5)

Shannon-wiener diversity and evenness

Figure 2 presents the Shannon-Wiener Index (H') and Pielou's Evenness (J') for the three sites.

Wakawaka contained the highest diversity index of H' = 2.30. This could be due to its greater species richness and balanced abundance distribution. Tinga, on the other hand, recorded the lowest diversity index of H' = 2.06. This could be attributed to the high dominance of shea and Terminalia in the area (See Table 7).

Interestingly, Pielou's Evenness Index (J) recorded values toward perfect evenness across all sites. This implies that no single species completely dominated the plant community at all sites. However, Tinga site had a slightly lower evenness of 0.86, indicating a skewed distribution of species toward a few dominant ones especially the shea and terminalia species.



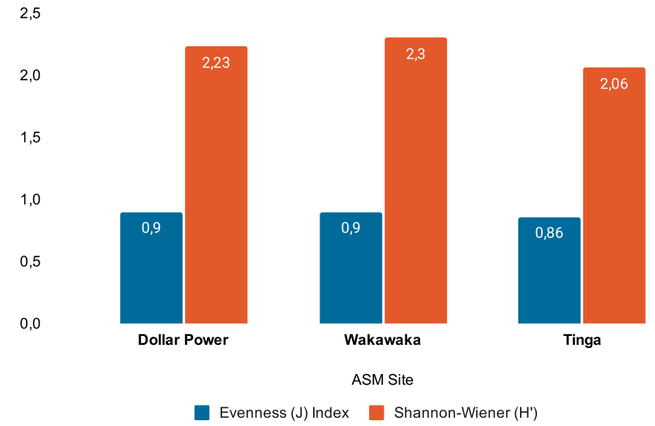


Figure 2: Shannon-Wiener Diversity Index (H') and Pielou's Evenness Index (J) across the three sites

Flora assessment

The mining activities observed across all three sites are characterized by surface pit mining using simple hand tools such as pickaxes, shovels, and hammers etc. This method involves clearing vegetation especially shrubs and herbs for burrowing pits. Though some few mature trees are felled during clearing, the method doesn't involve a complete removal of woody vegetation over a vast area. Thus, the method creates localized disturbances rather than landscape-scale clearing. Therefore, the mined sites retain significant standing vegetation, including mature mother trees that can serve as natural seed banks or propagating materials for future restoration or regeneration. For instance, the mines in Dakurupe have been around for decades and yet the extend of the land damage is minimal because a miner can stay in one pit for 10 - 20 years.

Structurally, Dollar Power is the most complex site with high average DBH and heterogeneous tree heights. This reflects a relatively undisturbed or old-growth woodland patch with high presence of *Parkia biglobosa* and *Isoberlina doka.* The presence of these species in the area offers high conservation potential, as these species are ecologically and socio-economically important.

The site at Wakawaka exhibited the highest floristic diversity despite its being a fallowed farmland that has been subjected to mining. Also, the dominance of high-value timber species such as *Pseudocedrala* and *Pterocarpus* in the site presents great potential for timber production and other environmental benefits if properly managed and mining activities regulated to reduce its impact on the species.

The Tinga site is the least diverse but inhabited with exceptional outliers in terms of tree sizes. The high dominance of shea and *terminalia* may be due to preferential retention because of their economic value (especially the Shea nuts) or specific edaphic conditions. Nevertheless, the presence of large individual trees implies that the site has high restoration potential through assisted natural regeneration or enrichment planting.

A total of 94 woody plant individuals were recorded across the three artisanal mining sites, with Tinga recording the highest number of stems (38) and Dollar Power the lowest (26). The floral inventory confirms that despite ongoing artisanal small-scale mining, the three study sites retain substantial woody vegetation with measurable ecological value. Since the mature trees have survived the mining operations, natural regeneration or assisted natural regeneration (ANR) can be a feasible restoration strategy across all sites. Despite having fewer individuals, Dollar Power exhibited the largest average tree diameter (20.50 cm) and the greatest structural variability, indicating a more complex woodland characterized by mature canopy species such as *Burkea africana*, *Parkia biglobosa*, and *Ficus* spp. Wakawaka recorded the greatest mean tree height (8.03 m) and the most uniform stand structure, suggesting regeneration within a fallowed farmland. Although Tinga had the lowest average tree height and diameter, it contained the largest individual trees recorded, including *Vitellaria paradoxa* and *Lannea microcarpa*, highlighting the presence of important remnant trees. The predominance of small-scale surface pit mining appears to create localized rather than extensive disturbances, allowing many mature trees to remain and providing natural sources of regeneration. Each site exhibited distinct ecological characteristics and conservation values. Dollar Power represents a structurally mature woodland with high conservation significance due to the presence of large-diameter and economically important tree species. Wakawaka, despite experiencing both farming and mining activities, maintained the highest species richness and diversity, indicating strong regenerative capacity and the potential for sustainable woodland recovery under improved management. Although Tinga showed lower species diversity, the presence of large remnant trees and economically valuable species such as *Vitellaria paradoxa* suggests considerable potential for ecological restoration through assisted natural regeneration and enrichment planting.

The study demonstrates that artisanal and small-scale mining has altered vegetation structure and composition but has not resulted in complete loss of woody vegetation across the three study sites. Overall, the findings indicate that the localized nature of surface pit mining in the study area has allowed important vegetation components to persist.



Protecting remaining mature trees, regulating mining activities, and implementing site-specific restoration strategies will be critical for conserving biodiversity, maintaining ecosystem services, and enhancing the long-term ecological resilience of these mined landscapes in northern Ghana. To achieve the restoration, activities such as pit backfilling, levelling, and the protection of existing mother trees would be required to catalyse natural succession. Natural ANR can be supplemented with enrichment planting to rehabilitate these degraded landscapes and safeguard their biodiversity.



Unrehabilitated mining sites pose lasting hazards to nearby communities. Open pits collect stagnant water, increase the risk of accidents, and create breeding grounds for disease vectors such as mosquitoes

3.1.2 Fauna

Across the five-day period, 61 individuals were captured across the three traps, representing 10 distinct taxa across 6 orders. Ants (Dorylus, Camponotus, Pheidole) accounted for 45 of 61 individuals (74%) of total captures, consistent with typical pitfall-trap patterns in disturbed or degraded savanna soils, where ant colonies often persist or even proliferate under moderate soil compaction and reduced vegetation cover.

Table 8: Community composition and abundance

Taxon	Order	Pitfall 1	Pitfall 2	Pitfall 3	Abundance	%
Oedaleus senegalensis	Orthoptera	1	0	0	1	2%
Gryllus bimaculatus	Orthoptera	0	2	1	3	5%
Catharsius sp.	Coleoptera	1	0	2	3	5%
Carabidae sp.	Coleoptera	1	0	2	3	5%
Dorylus sp.	Hymenoptera	5	7	3	15	25%
Camponotus sp.	Hymenoptera	6	8	4	18	30%
Pheidole sp.	Hymenoptera	3	0	9	12	20%
Pentatomidae sp.	Hemiptera	1	2	1	4	7%
Lycosidae sp.	Araneae	0	1	0	1	2%
Scolopendridae sp.	Chilopoda	0	0	1	1	2%
Total Abundance		18	20	23	61	100%

Pitfall 3 recorded the highest abundance (23), richness (8), and both diversity indices (H′ = 0.77, 1–D = 0.78), suggesting this location retained comparatively more heterogeneous ground-arthropod habitat. This reflects the greater distance from active mining disturbance, and denser vegetation cover relative to Pitfalls 1 and 2. Notably, Pitfall 3 was the only trap to capture Scolopendridae sp. (centipede), a taxon often sensitive to soil moisture and litter structure.

Pitfall 2 showed the lowest richness (5) and diversity (H′ = 0.58), driven by strong numerical dominance of *Camponotus sp.* (8 of 20 individuals) and Dorylus sp. (7 of 20), with Pheidole sp. entirely absent. That pattern is consistent with a more disturbed or homogenized microhabitat near this trap. Pitfall 2 did, however, uniquely capture *Lycosidae sp* (wolf spider).

Pitfall 1 sat between the two in diversity terms (H′ = 0.72, richness = 7) and was the only trap to capture *Oedaleus senegalensis*.

Oedaleus senegalensis, *Lycosidae sp*., and *Scolopendridae sp*. were each captured only once across the entire survey, and only at a single trap location. Such singletons

are common in short-duration surveys and suggest that the true taxon richness of the site is likely undersampled. Five trap-days is a relatively brief sampling window for capturing rarer and more mobile taxa.

Table 9: Diversity indices

Metric	Pitfall 1	Pitfall 2	Pitfall 3
Total Abundance	18	20	23
Shannon (H')	0.72	0.58	0.77
Simpson's Diversity Index (1-D)	0.77	0.70	0.78
Richness	7	5	8

The arthropod assemblage recorded at this ASM-adjacent savanna site is numerically dominated by ant taxa, with moderate overall diversity and richness varying spatially across the three trap locations.

3.2 Human Health Risk Assessment (HHRS)

3.2.1 Occupational hazards and safety

ASM is a major livelihood activity in the sampled communities. However, this activity is characterized by many hazardous conditions well researched and reported. In the sampled communities, the hazardous conditions were evident in several instances that led workers to physical, chemical, biological, ergonomic and psychosocial hazards leading to injuries and diseases.



Noise exposure

Noise above 70 dB over time can damage hearing, and sudden exposure above 120 dB can cause immediate harm. Miners and communities built around mining areas are exposed to noise from blasting and drilling, crushing, pumps that supply air to underground workers and that which pumps water out of dug tunnels. Noise levels from these sources were measured in 5 mining communities (Dollar Power, Banda Nkwanta, Tinga, Dakurope and Wakawaka).

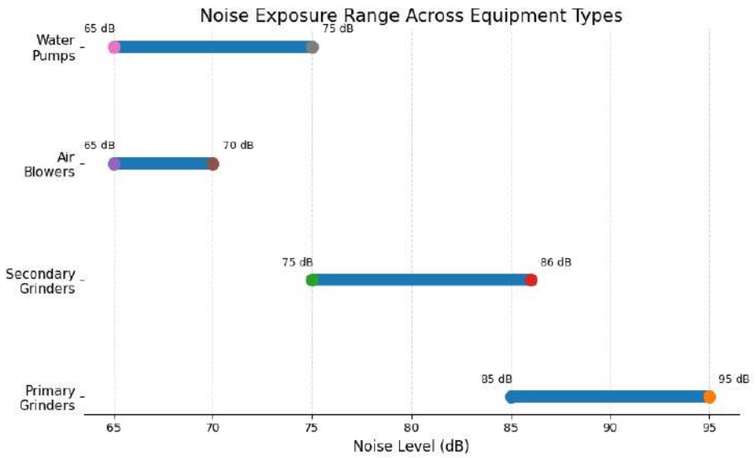


Figure 3: Noise exposure across equipment types

Results of noise from 4 activities are presented in Figure 3. The highest level of noise was from the primary grinders. These machineries were operated by younger men and for an undetermined but usually long hours. None of the operators were seen in any form of hearing protection. From the social surveys, the working hours was estimated at about 11 hours per day. This scenario makes noise exposure a source of concern for possible health outcomes.

Ghana's standard for light industrial work is 65-75dB during the day and 55dB for residential areas in the night, for residential purposes the standard is 48dB. All grinders used exceeded these levels. Hearing loss is therefore probable due to the unregulated exposure duration and lack of PPEs. Compounding the severity of exposure to noise is the fact that processing is done close to residential quarters, thus increasing exposure even to young children.

The noise levels recorded for primary Grinders are particularly concerning because they exceed the 85dB occupational exposure limit recommended by the World Health Organisation and the limit set by the Ghana Standards Authority and Ghana EPA. Ambient noise levels exceeded the recommended occupational exposure indicating potential risks to auditory and non-auditory health effects like noise-induced hearing loss, tinnitus, fatigue, deprived sleep, stress among others. In the

artisanal mining communities visited, these mills were operated without hearing protection for the operators thereby increasing cumulative noise exposure and associated health risks.

The relatively lower noise levels recorded for water pumps and air blowers suggest that these machines pose a comparatively lower risk of hearing damage under normal operating conditions. However, it is important to recognize that workers are often exposed to multiple noise sources simultaneously. The combined exposure from several operating machines, together with extended working hours, may increase overall noise doses beyond acceptable occupational limits even when individual equipment appears to operate below hazardous levels.

The findings also highlight the limited implementation of occupational health and safety measures within artisanal mining sites. The absence or inconsistent use of personal hearing protection, coupled with inadequate maintenance of machinery, may contribute to elevated noise emissions. Older equipment, worn bearings, poor lubrication, and improperly aligned machine parts are known to increase operational noise levels. Consequently, engineering controls such as routine equipment maintenance, installation of vibration-dampening components, and the use of quieter technologies should be promoted where feasible.

From a public health perspective, these results underscore the need for comprehensive hearing conservation programmes in artisanal and small-scale mining communities. Such programmes should include regular noise monitoring, periodic audiometric screening of workers, provision and enforcement of hearing protective devices (such as earmuffs or earplugs), worker education on the risks associated with excessive noise exposure, and administrative controls such as job rotation to reduce the duration of exposure to high-noise activities. It is interesting to note that job rotation was practically non-existent as workers continuously work till the job assigned is done. One of the youths operating the machinery was asked how long he had to do the grinding? He reported that he has to continuously work only take quick breaks to eat or drink and then get back to work.

Overall, the results indicate that grinding operations are the principal contributors to occupational noise exposure within the mining environment. Targeted interventions aimed at reducing noise emissions from primary and secondary grinding equipment will therefore have the greatest impact on protecting workers' hearing, improving occupational health, and promoting safer and more sustainable artisanal and small-scale mining practices.

Improving occupational safety in ASM is warranted due to the wide barrage of symptoms and discomforts experienced by workers. Some engineering controls are warranted examples in wet crushing to reduce the dust. Other administrative controls such as training, limiting exposure time will also help alleviate the risks posed by mining in the communities. It is however recommended that appropriate PPEs such as earplugs/earmuffs, dust masks, safety googles amongst others must be used always. This must be enforced.

Other health risks experienced by the miners

From the FGDs conducted other occupational risks identified included; collapse of mining pits, falling rocks and stones, cuts and injuries, body pains from posture at work as well as the strenuous nature of mining. For the latter, the miners mentioned the heavy lifting of ore under awkward posturing and repetitive movement has led to headaches and joint and muscle pains.

3.2.2 Human health symptoms commonly reported

Respondents of the survey were asked if they had experienced certain symptoms in the last year. The results are presented in Figure 4:

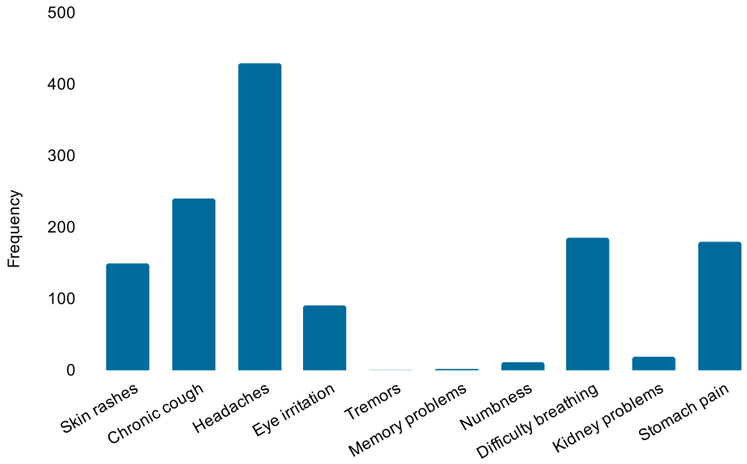


Figure 4: Common Health Symptoms experienced in ASM communities

Headaches were by far the most commonly reported complaint. This is followed by chronic cough and breathing difficulties. These symptoms are consistent with exposure to excessive noise from crushing and grinding equipment, dust inhalation and other environmental stressors that miners are exposed to. The mining areas are dusty (see Picture) where excavation, crushing and grinding take place. Overall, the symptoms show that ASGM communities may be exposed to several hazards simultaneously which affect multiple organs, the prevalence of headaches and respiratory disease suggest that dust, noise and poor air quality are the most immediate health risks.



Stone crushing generates large quantities of dust and exposes workers, often with little protective equipment, to persistent respiratory hazards and unsafe working conditions

A visit to the clinic at the Dollar Power corroborated these findings with a significant percentage of patients reporting in the dry season with Upper respiratory diseases and Malaria in the rainy season. Aggregated data was not available at the time of the visit.

3.2.3 Mortality

Mortality is a major public health concern driven by occupational hazards, environmental contamination, and limited access to healthcare. Studies have identified mine collapses, explosions, drowning and road traffic accidents leading to premature deaths in mining communities in addition to an increase in risky behaviours of miners who are predominantly young. We computed the risk ratio. Evidence from Ghana suggests recurrent fatal accidents from blasting, fatal falls and pit collapse reflecting disease associated with long term exposure to methylmercury, arsenic, silica dust and other contaminants. A review of literature on mining communities reported elevated mortality from respiratory, circulatory, metabolic, and neoplastic diseases among populations living near mining sites. Collectively, published evidence underscores the need for stronger occupational safety regulations, environmental monitoring, formalization of ASM operations, and improved healthcare services to reduce preventable mortality in small-scale mining communities.

Source of potable water

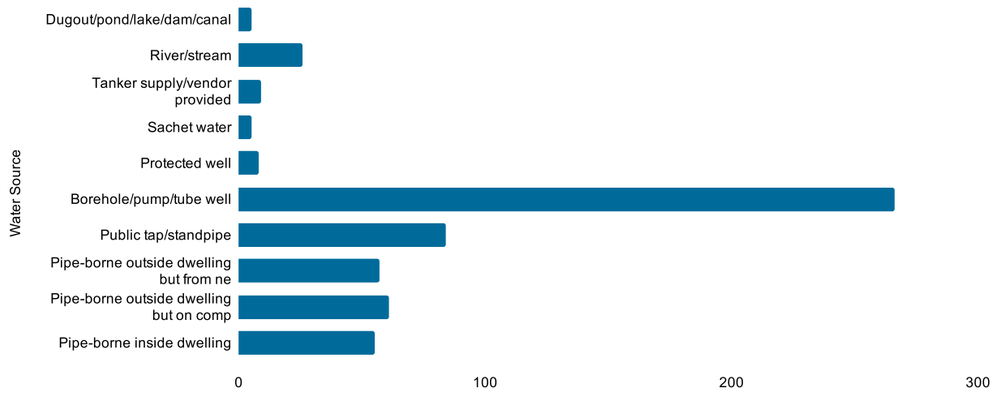


Figure 5: Sources of Water in ASM Communities

The mining communities depends on various sources of water for domestic and other purposes. However, the dominant source of water to the communities is the borehole followed by pipe borne water and then rivers and streams (Figure 5).

3.2.4 Heavy metal loads in environmental media

The heavy metal concentration of water, soils, fish and dust were assessed and is presented in the Table 10 below.

Descriptive statistics

Table 10: Descriptive statistics on heavy metal loads

Matrix	Element	Mean	SD	Min.	Max.	CV_%	Threshold	Source	Threshold_n	Threshold_%
Water	As	0.0008	0.0031	0	0.0186	406.11	0.01	WHO	2	3.77
Water	Cd	0.0024	0.0033	0.001	0.0183	136.81	0.003	WHO	12	22.64
Water	Hg	0.0005	0.0023	0	0.0124	432.11	0.006	WHO	2	3.77
Water	Pb	0.0031	0.008	0.001	0.0567	261.61	0.01	WHO	3	5.66
Soil	As	1.8213	1.0684	0.1367	5.7933	58.66	29	Dutch Ministry	0	0
Soil	Cd	33.4476	53.3206	2.4233	288.12	159.42	0.8	Dutch Ministry	49	100
Soil	Hg	1.3841	0.8443	0.12	4.42	61	0.3	Dutch Ministry	46	93.88
Soil	Pb	77.1371	114.9809	6.34	561.1867	149.06	85	Dutch Ministry	11	22.45
Dust	As	83.4667	N/A	83.4667	83.4667	N/A	N/A	Not assessed	N/A	N/A
Dust	Cd	8.5333	N/A	8.5333	8.5333	N/A	N/A	Not assessed	N/A	N/A
Dust	Hg	29.3667	N/A	29.3667	29.3667	N/A	N/A	Not assessed	N/A	N/A
Dust	Pb	395.5	N/A	395.5	395.5	N/A	N/A	Not assessed	N/A	N/A
Fish	As	0.1257	N/A	0.1257	0.1257	N/A	N/A	Not assessed	N/A	N/A
Fish	Cd	0.0515	N/A	0.0515	0.0515	N/A	N/A	Not assessed	N/A	N/A
Fish	Hg	0.0546	N/A	0.0546	0.0546	N/A	N/A	Not assessed	N/A	N/A
Fish	Pb	0.2111	N/A	0.2111	0.2111	N/A	0.3	FAO/WHO Codex	0	0

Table 10 shows differences in the distribution, variability, and guideline exceedance patterns of As, Cd, Hg, and Pb. In water, mean concentrations were generally low, with As, Hg, and Pb having mean values below their respective WHO guideline values. Arsenic had a mean concentration of 0.0008 mg/L, compared with the WHO threshold of 0.01 mg/L, while Hg had a mean of 0.0005 mg/L against a threshold of 0.006 mg/L. Pb also had a mean concentration of 0.0031 mg/L, which was below the WHO threshold of 0.01 mg/L. However, the maximum values of As, Hg, and Pb exceeded their respective thresholds, indicating that contamination was not widespread across all water samples but was localized in a subset of samples.

Among the water samples, Cd showed the most notable exceedance pattern. Although the mean Cd concentration was 0.0024 mg/L, which was slightly below the WHO threshold of 0.003 mg/L, 12 samples exceeded the guideline value, representing 22.64% of the water dataset. This suggests that Cd contamination was more frequent in water than As, Hg, or Pb. By comparison, As and Hg each exceeded their respective thresholds in only 2 samples, representing 3.77%, while Pb exceeded its threshold in 3 samples, representing 5.66%. These results indicate that Cd is the most important water-quality concern among the measured metals, followed by Pb, while As and Hg appear to occur as more localized exceedances. The high coefficients of variation in water indicate substantial spatial variability in dissolved metal concentrations. Hg had the highest CV at 432.11%, followed by As at 406.11%, Pb at 261.61%, and Cd at 136.81%. Such high variability suggests that metal concentrations in water were not uniformly

distributed across the study area. Instead, the dataset appears to be influenced by localized enrichment, point-source inputs, or site-specific hydrogeochemical conditions. The combination of low mean values and high maximum values further supports this interpretation, showing that most samples were relatively low in metals, but a few samples contained elevated concentrations.

The soil results show a more severe contamination pattern than water, especially for Cd and Hg. Soil As had a mean concentration of 1.8213 mg/kg, which was far below the Dutch Ministry threshold of 29 mg/kg. None of the soil samples exceeded the As threshold, indicating that As did not represent a major soil contamination concern based on the applied guideline. However, As still showed moderate variability, with a CV of 58.66%, suggesting some degree of spatial heterogeneity even though concentrations remained below the threshold. In contrast, Cd showed extensive soil contamination; the mean Cd concentration was 33.4476 mg/kg, which greatly exceeded the Dutch Ministry threshold of 0.8 mg/kg. All 49 soil samples exceeded the Cd threshold, representing 100% exceedance. This indicates that Cd contamination was widespread across the soil matrix rather than being restricted to isolated locations. The maximum Cd concentration of 288.12 mg/kg further confirms the severity of enrichment. The high CV of 159.42% indicates that, although Cd was elevated across all samples, the degree of contamination varied strongly between sampling points.

Hg also showed substantial soil enrichment; the mean Hg concentration was 1.3841 mg/kg, compared with the Dutch Ministry threshold of 0.3 mg/kg. A total of 46 soil samples, representing 93.88% of the dataset, exceeded the threshold. This indicates that Hg contamination was nearly widespread across the soil samples. The maximum Hg concentration of 4.42 mg/kg and CV of 61.00% suggest that Hg was consistently elevated but still showed moderate spatial variability. Pb showed a more moderate pattern, the mean Pb concentration was 77.1371 mg/kg, which was slightly below the Dutch Ministry threshold of 85 mg/kg. However, the maximum concentration reached 561.1867 mg/kg, and 11 samples exceeded the threshold, representing 22.45% of the soil dataset. This indicates that Pb contamination was not as widespread as Cd and Hg, but some locations were strongly enriched. The high CV of 149.06% confirms that Pb was highly variable across the soil samples, suggesting localized enrichment or uneven distribution of Pb-bearing materials.

The dust data show very high concentrations of the measured metals, particularly Pb, As, and Hg. Pb had a concentration of 395.5 mg/kg, As was 83.4667 mg/kg, Hg was 29.3667 mg/kg, and Cd was 8.5333 mg/kg. the elevated concentrations suggest that dust may be an important exposure medium and potential pathway for metal transfer within the environment. The fish results show detectable concentrations of all four metals. Pb had a concentration of 0.2111 mg/kg, which was below the FAO/WHO Codex threshold of 0.3 mg/kg, meaning that no exceedance was recorded for Pb.

Correlation analysis

The Spearman correlation results Figure 6 and 7 show clear differences in the association structure of heavy metals between soil and water. For soil, all metal pairs showed positive and statistically significant correlations. This indicates that As, Cd, Hg, and Pb generally increased together across the soil samples. The strongest relationship was between As and Hg with , followed by Cd and Pb with , As and Pb with , and Hg and Pb with . These strong positive associations suggest that the metals are not randomly distributed in the soil, but are likely influenced by shared accumulation processes, common source inputs, or similar retention mechanisms. The very strong As-Hg correlation is particularly important because it agrees with the PCA, SOM, and PMF results. The results therefore suggest that As-Hg share similar enrichment zones. The strong Cd-Pb correlation suggests that these two metals may share a common accumulation pathway in soil, possibly linked to contaminated particulates, anthropogenic deposition, waste residues, or adsorption onto similar soil phases.



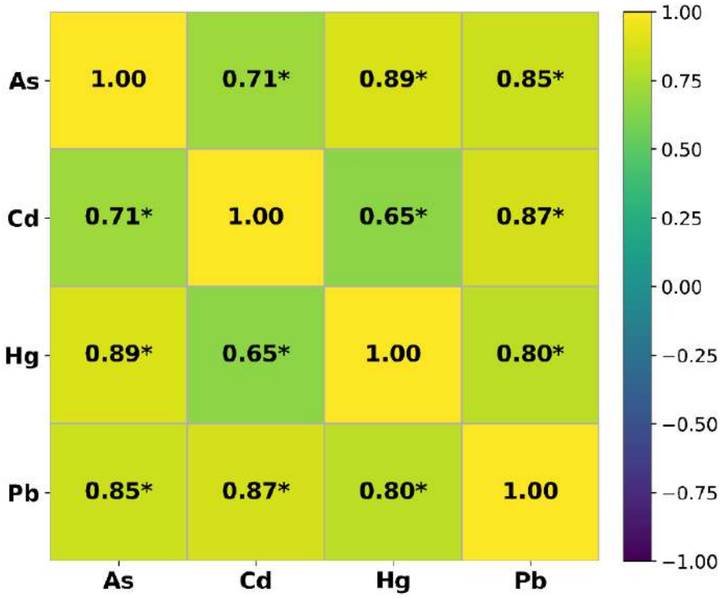


Figure 6: Correlation heatmap for soil



Ore washing releases fine sediments into nearby streams, reducing water quality and affecting aquatic ecosystems that sustain local livelihoods

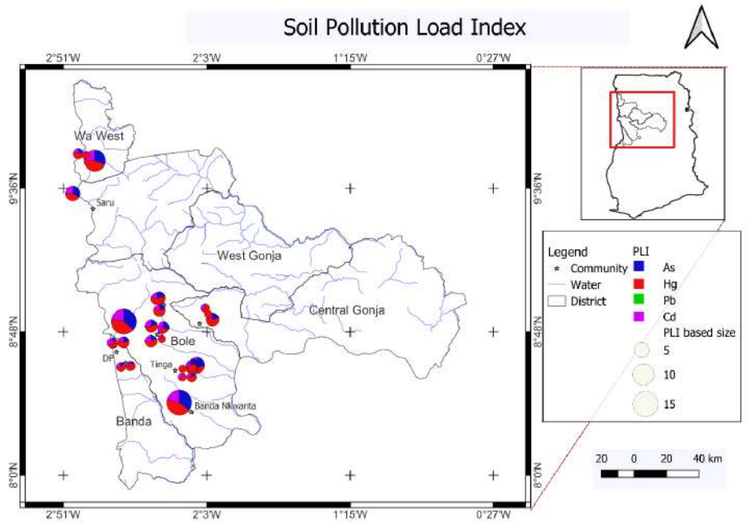


Figure 7: Soil Pollution Index

The soil Pollution Load Index (PLI) map reveals that soil contamination is widespread across the artisanal and small-scale mining (ASM) areas, with pollution concentrated around active mining and ore-processing sites. Larger proportional symbols indicate higher overall pollution loads, while the coloured segments represent the relative contributions of arsenic (As), mercury (Hg), lead (Pb), and cadmium (Cd) at each location.

The highest soil pollution loads are observed around Dollar Power (DP), Banda Nkwanta, Tinga, Wakawaka, and parts of Wa West, where large PLI values indicate severe heavy metal accumulation. Several smaller hotspots are also evident around the Bole mining belt, reflecting localized contamination associated with intensive mining activities. In contrast, relatively few high-PLI sites occur outside the active mining zones, indicating that contamination is largely confined to areas directly influenced by ASM.

The composition of the pollution load varies among locations, but mercury (Hg) and arsenic (As) appear to dominate the pollution profiles at many sites, with cadmium (Cd) and lead (Pb) contributing substantially to several locations. This spatial variability suggests differences in ore characteristics, mining practices, and waste disposal methods across the study area.

Overall, the map demonstrates that soil contamination is more extensive and spatially widespread than water contamination, with numerous localized hotspots exhibiting high pollution loads. These areas represent priority sites for detailed risk assessment, remediation, and the implementation of improved mining and waste management practices to minimize ecological degradation and reduce human exposure to heavy metals.

For water Figure 8, the correlation structure was more selective, only two relationships were statistically significant: As-Hg with and Cd-Pb with . Other correlations were weak and not statistically significant, including As-Cd , Cd-Hg , As-Pb , and Hg-Pb . The significant As-Hg correlation in water is consistent with the same association observed in soil. This repeated relationship suggests that As and Hg may share a common source or mobilization mechanism across both matrices. In water, the relationship may reflect mineral-water interaction, redox-sensitive mobilization, or release from As-Hg-bearing materials. The significant Cd-Pb correlation in water suggests that these two metals share some degree of common behaviour in the dissolved phase. The weak and non-significant correlations between As-Cd, Cd-Hg, As-Pb, and Hg-Pb show that most metal pairs in water were not strongly coupled. In water, metal concentrations are more sensitive to solubility, redox conditions, pH, adsorption-desorption, complexation, dilution, and local source inputs. These processes can separate metals that may accumulate together in soil. Therefore, the weaker correlation structure in water suggests more selective geochemical mobility and greater process-specific control.

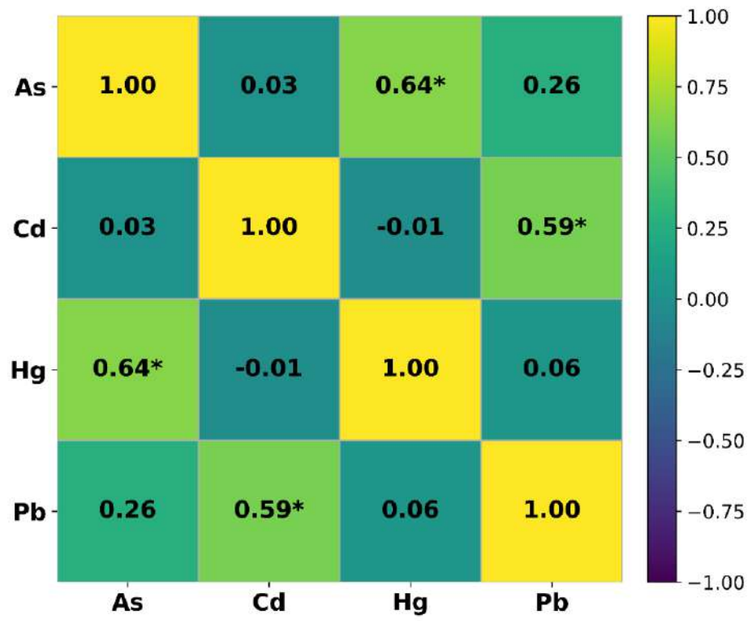


Figure 8: Correlation heatmap for water

Principal Component Analysis (PCA)

Table 11: Summary PCA results for water

Total Variance Explained									
Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.172	54.302	54.302	2.172	54.302	54.302	1.979	49.466	49.466
2	1.042	26.051	80.353	1.042	26.051	80.353	1.235	30.886	80.353
3	0.762	19.051	99.404						
4	0.024	0.596	100						

Extraction Method: Principal Component Analysis.



Table and Figure indicate clear differences in the multivariate structure of heavy metals in water and soil. For the water, the Kaiser-Meyer-Olkin value was 0.544, while Bartlett's test of sphericity was significant with $\chi^2 = 159.015$, df = 6, and $p < 0.001$. This shows that the water dataset had an acceptable level of sampling adequacy for PCA, and that the correlation matrix was suitable for dimensionality reduction. For water, two principal components were extracted, PC1 had an eigenvalue of 2.172 and explained 54.302% of the total variance, while PC2 had an eigenvalue of 1.042 and explained 26.051%. Together, the two components explained 80.353% of the total variance, indicating that most of the heavy-metal variability in water could be represented by two latent geochemical dimensions.

The rotated water component matrix provides a clearer interpretation of the extracted components. PC1 was strongly loaded by As = 0.981 and Hg = 0.983, while Cd and Pb had weaker loadings on this component. This indicates that PC1 represents an As-Hg association, suggesting a shared source, similar mobilization pathway, or related geochemical control. PC2 was mainly loaded by Pb = 0.842 and Cd = 0.700, indicating a second component controlled by Cd and Pb. This suggests that Cd and Pb contributed to a separate metal association in water, distinct from the As-Hg component.

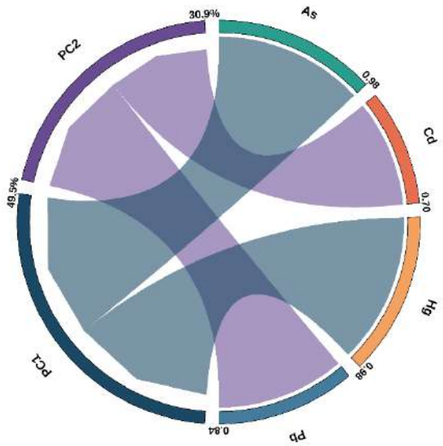


Figure 9: PCA chord diagram for water

For soil matrix Figure 9, the PCA results were stronger and more compact, the KMO value was 0.791, indicating good sampling adequacy, and Bartlett's test of sphericity was significant with $\chi^2 = 258.684$, df = 6, and $p < 0.001$. This shows that the soil dataset was well suited for PCA and that the metals were sufficiently intercorrelated to justify extraction of principal components. Only one component was extracted for soil, this component had an eigenvalue of 3.600 and explained 89.989% of the total variance. The very high variance explained indicates that As, Cd, Hg, and Pb in soil were strongly controlled by a single dominant multivariate pattern. This contrasts with the results for water, where two components were needed to explain the major structure. The soil result suggests stronger co-accumulation or shared retention of metals in the soil environment. The soil component loadings were all strongly positive: As = 0.968, Cd = 0.917, Hg = 0.940, and Pb = 0.968. This indicates that the soil component represents a broad multi-metal enrichment gradient rather than a source dominated by only one or two elements.

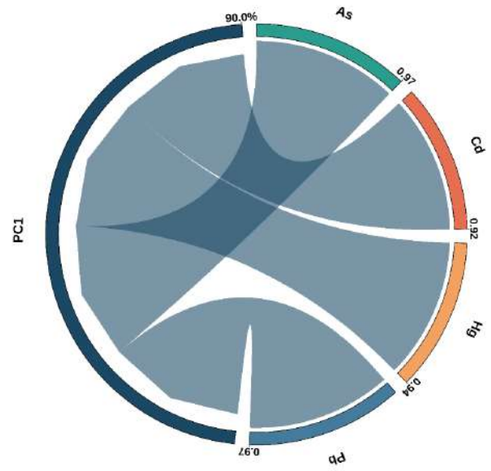


Figure 10: PCA chord diagram for soil

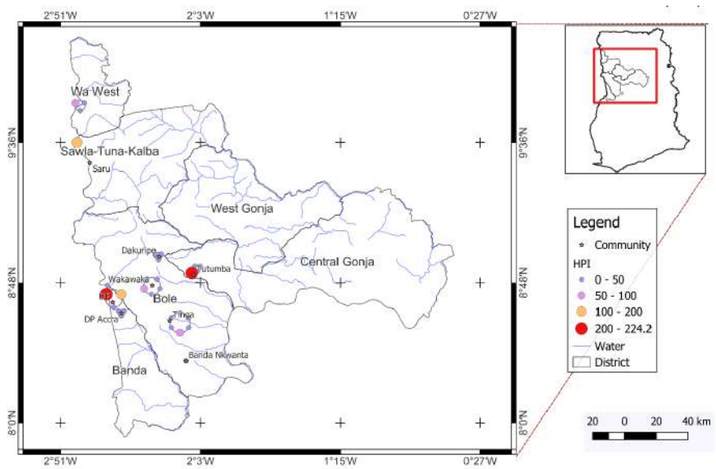


Figure 11: Heavy Metal Water Pollution Index

The Heavy Metal Water Pollution Index (HPI) map indicates that water quality across most of the study area is generally within low to moderate pollution levels, with considerable spatial variability. Most sampling locations fall within the low (0–50) and moderate (50–100) HPI categories, suggesting that heavy metal concentrations at these sites remain relatively low and pose limited immediate concern.

However, several localized hotspots of elevated contamination are evident. The highest pollution levels (HPI = 200–224.2) occur around Tutumba in the West Gonja District and Dollar Power near Bole, indicating severe heavy metal contamination

that likely reflects the influence of active artisanal and small-scale mining (ASM) activities. Additional sites, including Sawla-Tuna-Kalba, ie kulibie, exhibit high HPI values (100–200), while communities such as Wa West, Tinga, Wakawaka, and parts of Bole generally show moderate pollution levels.

These contamination hotspots warrant priority monitoring, source control, and remediation to protect aquatic ecosystems and reduce human exposure through drinking water and other domestic uses.



Once a vital source of drinking water, irrigation, and fisheries, sections of the Black Volta now carry heavy sediment loads that increase treatment costs and threaten water security

Self-Organising Maps (SOM)

For the soil dataset Figure 10, the SOM produced a two-cluster solution. The final model had a quantization error of 0.0242 and a topographic error of 0.0204, indicating good mapping quality. The low quantization error shows that the trained neurons represented the input data well, while the very low topographic error indicates that the SOM preserved the neighbourhood relationships among samples. The cluster validation statistics also supported the two-cluster structure, with K = 2 producing the highest silhouette coefficient of 0.7341 and a low Davies-Bouldin index of 0.5627. This indicates that the two clusters were compact and reasonably well separated. The soil cluster map shows that most samples belonged to the dominant cluster, with Cluster 0 containing 43 samples, representing 87.76% of the dataset, while Cluster 1 contained 6 samples, representing 12.24%. This suggests that most soil samples shared a broadly similar geochemical background, while a smaller subset had a distinct enriched metal signature. The soil component planes show that As, Hg, Cd, and Pb have broadly similar enrichment zones, especially toward the lower-left part of the SOM grid. This indicates that the enriched soil cluster is characterized by simultaneous elevation of multiple metals rather than enrichment by only one element mirroring the results from PCA.

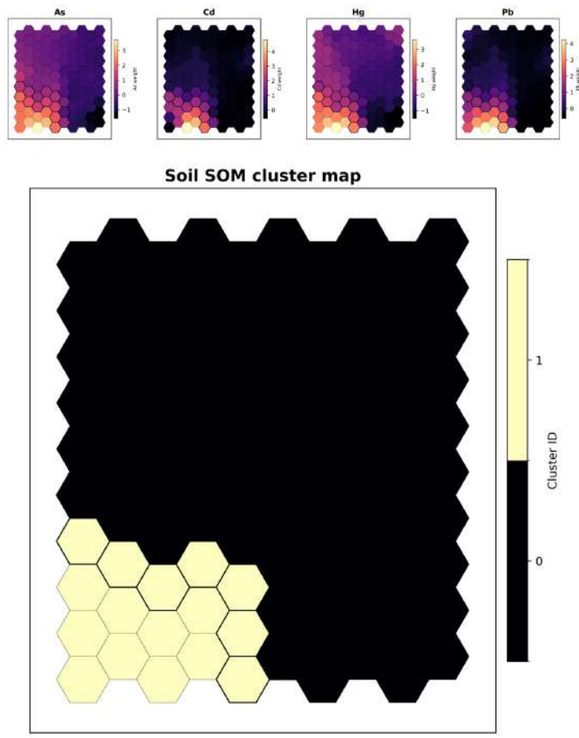


Figure 12: SOM cluster map and component plane for soil

For water (Figure 11), the SOM produced a three-cluster solution. The model had an extremely low quantization error of 3.36×10^{-7} and a topographic error of 0.0000, indicating excellent representation of the water dataset and complete preservation of topological relationships among samples. The selected number of clusters was also statistically supported. The three-cluster solution had the highest silhouette coefficient of 0.7686 and the lowest Davies-Bouldin index of 0.2543, indicating that the water clusters were highly compact and clearly separated. The water cluster distribution shows that the majority of samples belonged to the background cluster, with Cluster 0 containing 47 samples, representing 88.68% of the dataset. Two smaller clusters were also identified: Cluster 1 contained 2 samples, representing 3.77%, while Cluster 2 contained 4 samples, representing 7.55%. This pattern indicates that most water samples had relatively low or similar metal signatures, while a small number of samples showed distinct enrichment patterns. The presence of two minor clusters suggests that the water dataset contains multiple anomalous or specialized geochemical signatures rather than one single contaminated group. The SOM component planes show a Cd-dominated factor, a Pb-dominated factor, and an As-Hg-dominated factor. As and Hg share a similar map structure, while Cd and Pb occur in different enriched regions.

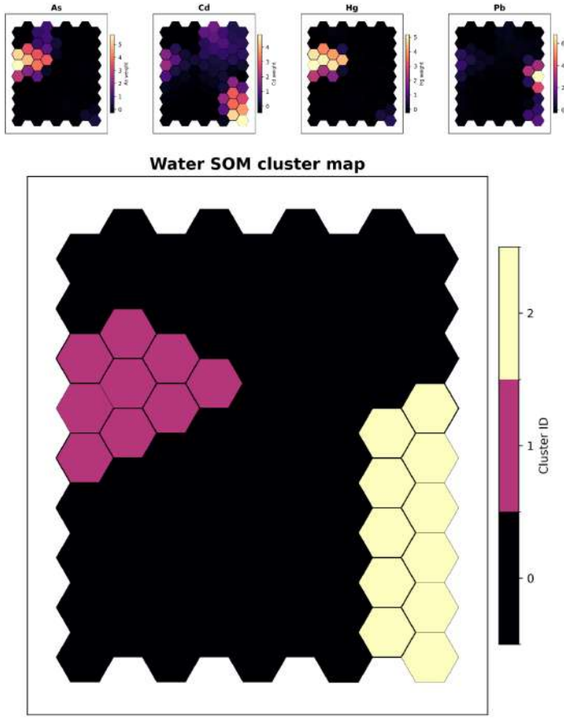


Figure 13: SOM cluster map and component plane for water

Positive Matrix Factorisation (PMF)

Table 12: Summary of PMF results

Matrix	PMF run	Species	Factor 1 conc.	Factor 2 conc.	Factor 3 conc.	Factor 1 %	Factor 2 %	Factor 3 %	Dominant factor
Water	18	As	0	1.66E-05	0.000797	0	2.04	97.96	Factor 3
Water	18	Cd	0.002169	6.21E-05	0.000192	89.5	2.56	7.94	Factor 1
Water	18	Hg	7E-07	6E-07	0.00059	0.11	0.09	99.79	Factor 3
Water	18	Pb	0.000255	0.002507	0.000292	8.36	82.07	9.57	Factor 2
Soil	16	As	1.1617	0.6152	N/A	65.38	34.62	N/A	Factor 1
Soil	16	Cd	5.4903	27.997	N/A	16.4	83.6	N/A	Factor 2
Soil	16	Hg	0.9514	0.4216	N/A	69.29	30.71	N/A	Factor 1
Soil	16	Pb	12.428	54.7	N/A	18.51	81.49	N/A	Factor 2

From Table 12, the water dataset was best represented by a three-factor solution, while the soil dataset was best represented by a two-factor solution. The water model was based on Base Run 18; this run produced a robust Q value of 40.0228 and a true Q value of 67.6546. The Q true to Q expected ratio was 1.6501. The result suggests that the three-factor water model explained the dataset well and that the residual structure was not excessive. The soil model was based on Base Run 16; this run produced a robust Q value of 251.6320 and a true Q value of 356.4340. The Q true to Q expected ratio was 3.9604.

In the water model Figure 7 and 8, Factor 1 was dominated by Cd, explaining 89.50% of the Cd contribution. This indicates a distinct Cd-related source or geochemical process in the water system. The low contribution of As, Hg, and Pb to this factor suggests that Cd was not controlled by the same process as the other metals. This may reflect a Cd-specific input, differential mobility, or release from materials enriched in Cd. Water Factor 2 was dominated by Pb, explaining 82.07% of the Pb contribution. This suggests a separate Pb-related source or mobilization process. Water Factor 3 was dominated by As and Hg, explaining 97.96% of As and 99.79% of Hg. This strong association indicates that As and Hg likely share a common source or similar mobilization pathway in the water system. The association may reflect redox-sensitive release, mineral-water interaction, or contamination linked to mining-related processes.

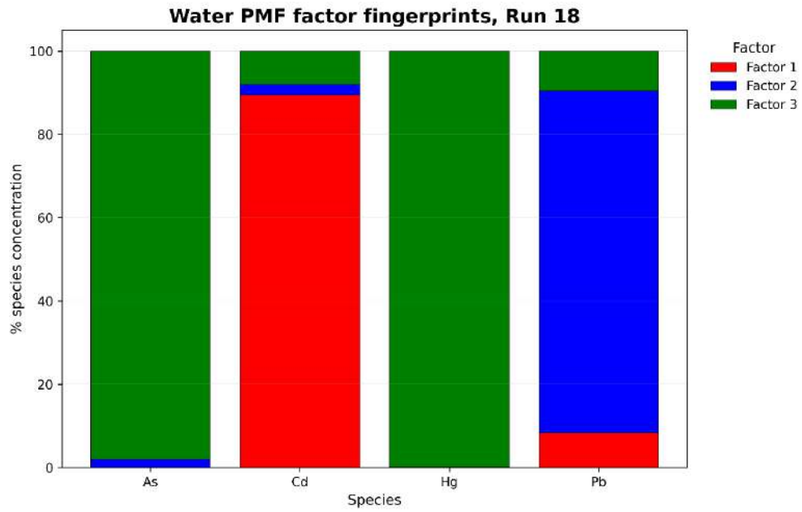


Figure 14: PMF Factor fingerprints for water

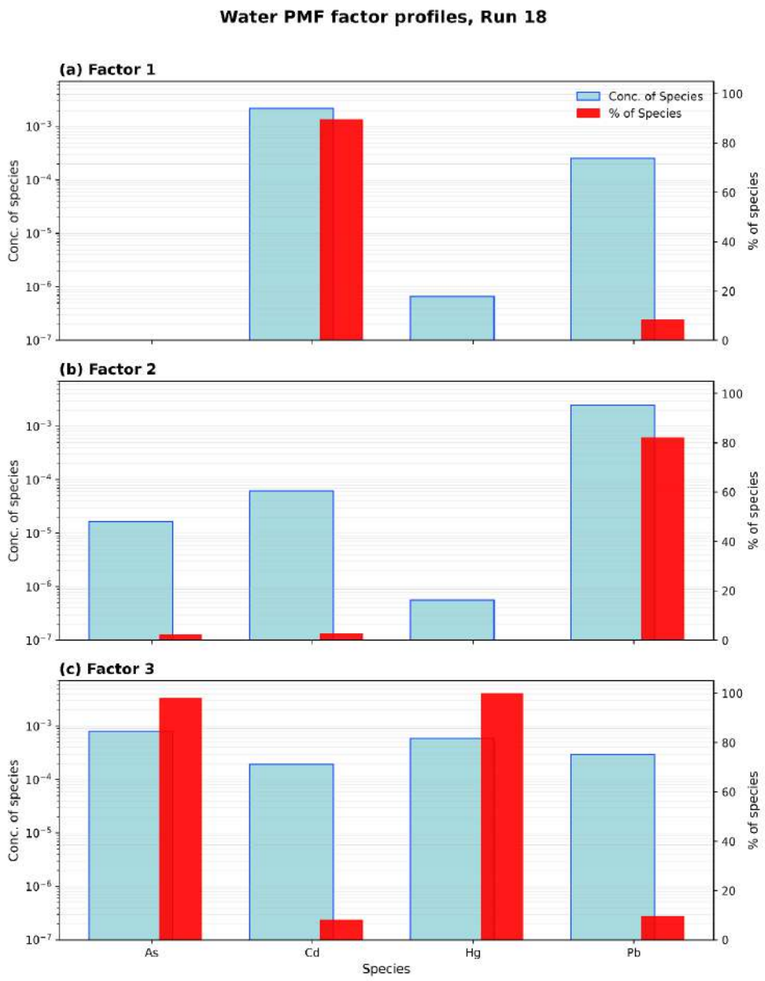
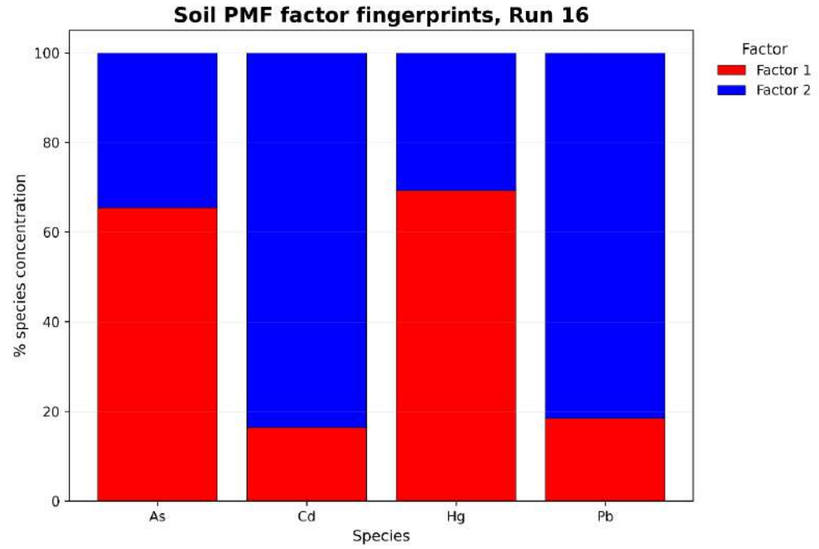


Figure 15: PMF Factor profiles for water

In the soil model Figure 9 and 10, Factor 1 was dominated by As and Hg, explaining 65.38% of As and 69.29% of Hg. This suggests a shared soil source or retention process for these two elements. The As-Hg association may reflect mineralized materials, mining-related deposition, geogenic inputs, or co-retention by fine particles, oxides, and organic matter. Soil Factor 2 was dominated by Cd and Pb, explaining 83.60% of Cd and 81.49% of Pb. This indicates a second major source or accumulation process in the soil. The Cd-Pb association may reflect anthropogenic inputs, contaminated particulates, atmospheric deposition, waste residues, or shared retention in the soil matrix. Unlike in water, where Cd and Pb separated into distinct factors, the soil model grouped them together. This suggests that Cd and Pb may share an accumulation source in soil but become decoupled after mobilization into water.



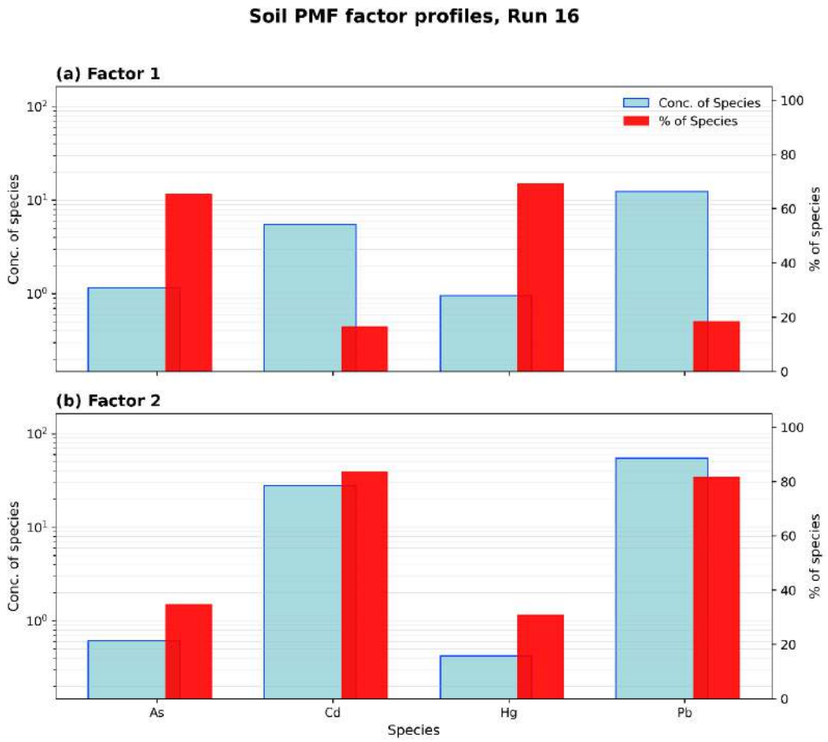


Figure 16: PMF Factor fingerprints for soil

3.2.5 Non-carcinogenic health risk

The probabilistic HHRA results show that soil exposure Figure 11, presents a non-carcinogenic health concern, especially for children. The adult hazard index had a mean of 1.4041, a median of 0.2289, and a 95th percentile of 4.4906. Although the median value was below the acceptable threshold of HI = 1, the mean and upper-tail values exceeded the threshold. This pattern shows that most adult exposure scenarios were within the acceptable range, but a smaller proportion of simulations produced elevated risk. The exceedance result supports this interpretation, with 19.69% of adult simulations exceeding HI = 1.

Children showed higher soil-related risk than adults. The child HI had a mean of 2.8214, a median of 0.9283, and a 95th percentile of 8.9479. The median was close to the non-carcinogenic threshold, while the mean and 95th percentile was above 1. In total, 46.32% of child simulations exceeded HI = 1. This means nearly half of the simulated child exposure scenarios indicated potential non-carcinogenic concern. The higher risk among children reflects their lower body weight and greater exposure dose per unit body mass.

Element-specific HQ contributions indicate that Cd was the dominant risk driver in soil. Cd contributed 81.47% of total adult HQ and 75.46% of total child HQ. Pb was the second most important contributor, accounting for 9.84% in adults and 13.42% in children. Hg contributed 6.73% and 7.15% for adults and children, respectively, while As contributed 1.96% and 3.97%. These results show that the non-carcinogenic risk from soil was controlled mainly by Cd, with Pb and Hg acting as secondary contributors.

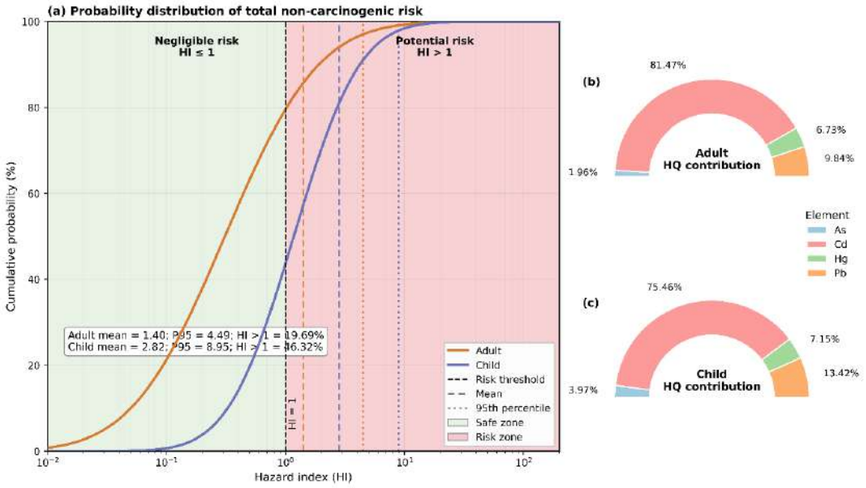


Figure 17: HI results for soil

Discussion of water non-carcinogenic health risk

The probabilistic HHRA results for water Figure 12, indicate generally low non-carcinogenic health risk under the simulated exposure conditions. For adults, the mean HI was 0.2923, the median was 0.0011, and the 95th percentile was 0.1756. For children, the mean HI was 0.5743, the median was 0.0024, and the 95th percentile was 0.4161. These values show that most simulated water exposure scenarios were below the acceptable threshold of HI = 1.

The exceedance probabilities were also low. Only 1.98% of adult simulations and 3.12% of child simulations exceeded HI = 1. This suggests that water exposure was generally within acceptable non-carcinogenic limits for both receptor groups. However, the presence of exceedance values above 1 show that some high-end exposure scenarios may still pose concern, especially where metal concentrations or exposure assumptions are elevated.

The element-specific HQ contribution pattern for water differed from soil. As was the leading contributor to total water risk, accounting for 61.17% of adult HQ and 57.24% of child HQ. Cd was the second major contributor, accounting for 32.74% and 36.62% for adults and children, respectively. Hg and Pb made smaller contributions, with Hg contributing 2.58% for adults and 2.32% for children, while Pb contributed 3.52% and 3.83%.

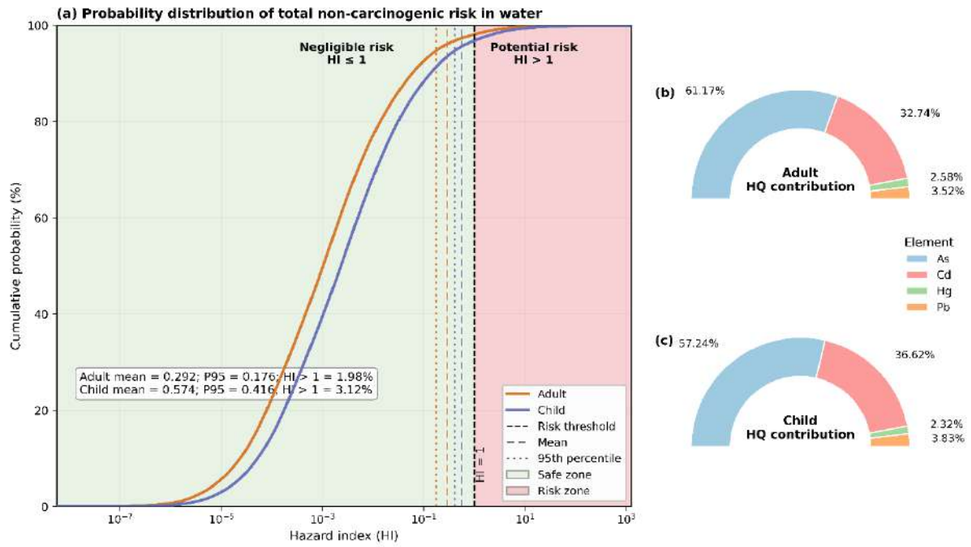


Figure 18: HI results for water

Discussion of soil sensitivity results

The soil tornado plot Figure 13 shows that the adult and child HI outputs were controlled by different exposure assumptions. For adults, the strongest sensitivity driver was the adult soil adherence factor. This indicates that uncertainty in soil adherence strongly influenced the adult non-carcinogenic risk estimate. For children, the child soil adherence factor was also the dominant driver, with a coefficient of 0.804. This shows that dermal soil contact was a major source of variability in the simulated soil risk.

Metal concentrations showed moderate positive sensitivity. For children, As, Pb, Hg, and Cd had coefficients of 0.286, 0.278, 0.278, and 0.255, respectively. For adults, the same metals had lower but still positive coefficients, ranging from 0.166 to 0.181. This means that increasing metal concentrations increased the total HI, as expected. However, concentration variability was less influential than soil adherence in the soil model.

Body weight had a negative effect, especially for children. The child body weight coefficient was -0.271, showing that higher body weight reduced estimated dose and therefore reduced HI. Child ingestion rate also had a positive coefficient of 0.239, confirming that incidental soil ingestion contributed meaningfully to child risk. Inhalation showed very weak sensitivity for both receptor groups, indicating that the inhalation pathway made little contribution to total non-carcinogenic soil risk compared with dermal contact and ingestion.

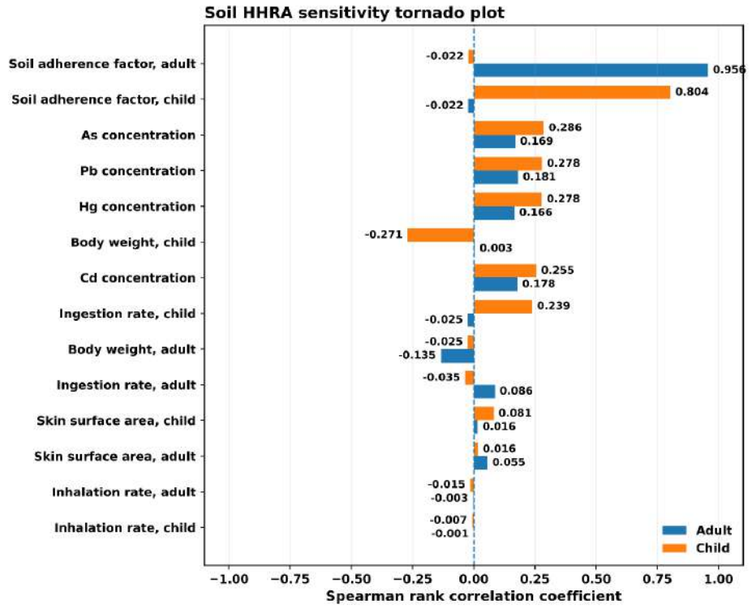


Figure 19: Sensitivity analysis results for soil

Discussion of water sensitivity results

The water tornado plot Figure 14 shows a different pattern. In water, sensitivity was controlled mainly by metal concentrations rather than exposure factors. As had the strongest sensitivity for both adults and children, with coefficients of 0.622 and 0.625, respectively. Cd was the second strongest driver, with coefficients of 0.592 for adults and 0.587 for children. Pb and Hg also showed strong positive sensitivity, with coefficients above 0.51 in both receptor groups.

This pattern indicates that variation in water metal concentrations had the greatest effect on simulated HI. Exposure parameters such as body weight, ingestion rate, and skin surface area had much smaller effects. Child body weight had the strongest exposure-factor effect in water, but its coefficient was only -0.084. Higher body weight lowers the calculated dose, resulting in lower HI. The positive coefficients for ingestion rate show that increased water intake raises risk, but the effect was weak compared with metal concentration.

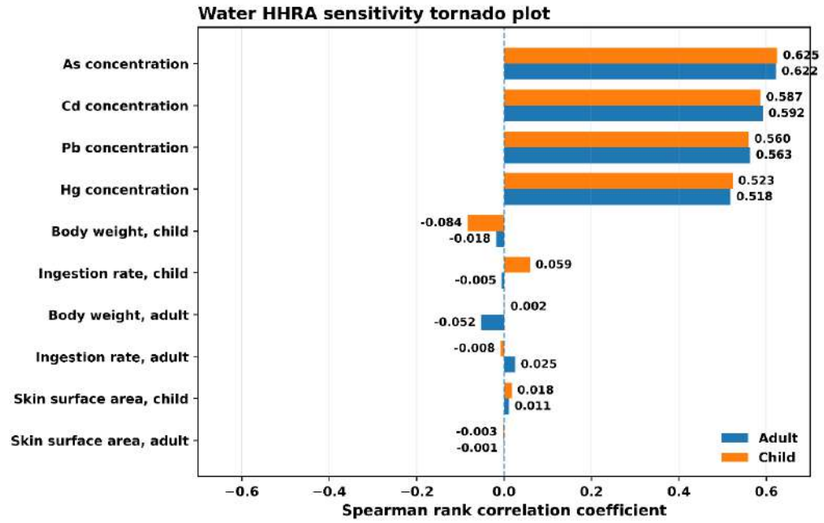


Figure 20: Sensitivity analysis results for water.

3.2.6 Vulnerability assessment

A simple risk matrix was developed to prioritize hazards in terms of the human health risks. This is based on researchers' perception of results gathered through observation, household survey, key informant interviews and the focus group discussions.

Table 13: Simple risk matrix of known hazards

Hazard	Likelihood	Severity	Risk Level
Mercury Exposure	High	High	Extreme
Cadmium Exposure	High	High	Extreme
Pit Collapse	Medium	High	High
Falls and Trips	High	Medium	Moderate
Dust Inhalation	High	High	Extreme
Water Contamination	Medium	Medium	Moderate
Noise Exposure	High	Medium	High
Malaria	Medium	Medium	Moderate

It is therefore recommended that dust, cadmium and mercury exposure be addressed since they pose the highest severity. Thus, dust suppression and promotion of mercury free gold extraction technologies must be explored by and institution interested in improving mining safety. Also, frequent monitoring of water sources, monitoring of environmental media like soils is needed. The most vulnerable groups are the women and children due to their roles and proximity to hazardous exposures to dust and heavy metals in soils.

3.3 No-go zone delineation

Using combined spatial layers of water bodies and protected areas (forest/game reserves), each mapped ASM site was assessed based on the risk it poses to these resources. A 500-metre buffer was applied around protected forest areas and a 300-metre buffer around water bodies according to the riparian buffer zone policy for managing freshwater bodies in Ghana (Ministry of Water Resources, Works and Housing, 2011). The results (*please see annex 2)* point to very important implications of ASM-related environmental risks and how they could be managed in this landscape:

Forest encroachment was noted to be the primary driver of the overall risk. Only 0.23% of the mapped area is classified as critical under only the water-related risk assessment, compared with 68.64% under the combined forest-and-water composite.

ASM sites at Dollar Power and Tinga are the major contributors to the critical-zone risk accounting for 59 sites under the composite framework. All their mapped sites fall in this category. This raises concerns about both environmental risk and also immediate intervention in these two communities.

Tinga has the largest average ASM site size and also the only community with sites in the water-critical zone. This suggest that ASM operations at Tinga may be less regulated than elsewhere with regards to adhering to the buffer zone policies.

Wakawaka presents a comparatively lower, but not negligible, risk profile. Most of its sites fall in the far-to-moderate range for both water and composite risk, suggesting that current impacts are more limited, though this should not be read as an absence of risk, particularly for the two sites in the moderate water-risk zone.

The assessment classified the risk posed by 94 ASM sites mapped, covering approximately 1,001.79 hectares, based on their proximity to or overlap with protected areas and water bodies. The results showed that majority of the mapped area (68.64%) falls within the critical risk category when forest and water exposure are considered together, indicating that most ASM activities in the study area are occurring inside or adjacent to environmentally sensitive areas. The risk is not evenly distributed, as sites at Dollar Power and Tinga pose the greatest risk, with all of their sites falling in the critical zone. Wakawaka, on the other hand, portrays a comparatively lower risk profile.

When water bodies are considered in isolation, the majority of the mapped sites lie outside the prescribed riparian buffer zone, indicating that direct water body encroachment is very minimal with more localised concern, as noted at Tinga. Taken together, these findings indicate that forest or game reserve encroachment is the dominant environmental risk associated with ASM activity in this landscape, and that Dollar Power and Tinga should be treated as priority areas for intervention.

1.4 Gold Cyanidization

Gold cyanidation is a hydro-metallurgical technique allowing for the extraction of gold from low-grade ores. This method is not widely practiced in ASGM in Ghana but associated with neighbouring countries of Burkina Faso and Mali and therefore the method is nicknamed 'Burkina' in Ghana. Although cyanide reacts readily in the environment and may quickly degrade when exposed to sunlight or form complexes of varying stabilities, its toxicity to many living organisms, at even low concentrations, is the primary reason for which it is guided globally by the International Cyanide Management Code (ICMC).

According to the Ghana EPA, the use of cyanide for gold processing by artisanal small-scale gold miners is not illegal. However, any ASGM operator seeking to use this method, must meet stringent requirements prior to obtaining an environmental permit as is the case in the large-scale mining sector where leaching with cyanide is allowed. Presently, this is an illegal activity for ASGM since no ASGM operator has obtained the requisite approvals to do so (GoG, 2020).

Results from the survey conducted in the study area revealed that 5.84% (26 out of 445) of respondents agreed to using cyanide in their mining operations. This use has the potential to affect the miners as well as the surrounding communities. The USEPA IRIS database evaluates the risk from Cyanide exposures mainly through oral and inhalation routes and exposures even at low doses may cause headaches, neurological disturbances and thyroid dysfunction among many other health effects. Its use was however limited in the Savanna Region where the study was conducted.

4. CONCLUSION

The ecological and human health assessment indicates that artisanal and small-scale mining (ASM) activities have caused measurable degradation of environmental quality and increased potential health risks in affected communities. Elevated concentrations of heavy metals, particularly cadmium, arsenic, mercury and lead in soils, sediments, surface water, fish, and plants demonstrate that mining-related contamination extends beyond active mining sites into surrounding ecosystems. Ecological risk assessments consistently show adverse effects though not critical effects on biodiversity, and ecosystem functioning mainly because of the rudimentary tools used by miners. The human health risk assessment reaches similarly high levels, and identifies exposure through multiple pathways – including ingestion of contaminated water and food, incidental soil ingestion, dermal contact, and inhalation of contaminated dust – as posing significant non-carcinogenic and, in some cases, carcinogenic risks, particularly to children, women, and mining households. The cumulative Hazard Index (HI) exceeding acceptable limits in several locations highlights the need for immediate interventions to reduce exposure.

Based on the integrated ecological and human health risk assessment, the delineation of No-Go Areas provides a science-based framework for sustainable land-use planning and environmental protection in ASM landscapes. Areas where contaminant concentrations exceed national and international guideline values, where groundwater recharge zones are threatened, or where critical habitats and community water sources are located should be designated as permanent exclusion zones for mining activities. These no-go areas should also encompass riparian buffer zones, agricultural lands producing food crops, schools, healthcare facilities, and residential settlements where vulnerable populations are concentrated. Delineation should be supported by GIS-based contamination maps, ecological sensitivity assessments, and human health risk maps to ensure transparency and enforceability. Implementing these exclusion zones, alongside continuous environmental monitoring, land rehabilitation, community risk communication, and strict regulatory enforcement, will significantly reduce environmental degradation, protect public health, and promote responsible and sustainable mineral resource governance in the ASM sector in the Savanna region of Ghana



5. RECOMMENDATIONS

5.1 Ecological health

Based on the findings of this assessment, the following recommendations are proposed for ecological restoration and sustainable management of the ASM sites:

- Protect mature mother trees that are seedbanks or propagation materials against felling, pit encroachment or other negative human impact. This can be included in educational sessions with the miners to reiterate the importance of trees. Also, a deliberate attempt should be made by NGOs and CSOs during Awareness creation and training of miners on the identification and protection of "mother trees" during prospecting and extraction phases.
- Deliberate implementation of Assisted Natural Regeneration (ANR) through silvicultural practices (e.g. thinning and weeding) to increase vegetal cover and tree populations.
- Introduce enrichment planting of especially indigenous fruit trees to enhance socio-economic benefits for the local community without compromising structural integrity.
- Mandate pit backfilling as an immediate post-mining standard practice. This will reduce erosion and create a favourable seedbed for natural regeneration while reducing the risk of falls of children and livestock in the area.
- Establish community-managed tree nurseries or engage the Forestry Commission for seedlings from the surviving mother trees at each specific site to maintain local genetic integrity while establishing permanent monitoring plots to quantitatively assess recruitment, growth, and species turnover over a 5-year period.

5.2 Human Health

From a public health perspective, the findings underscore the need for:

- Comprehensive hearing conservation programmes in ASM communities. Such programmes should include regular noise monitoring, periodic audiometric screening of workers, provision and enforcement of hearing protective devices (such as earmuffs or earplugs), worker education on the risks associated with excessive noise exposure, and administrative controls such as job rotation to reduce the duration of exposure to high-noise activities. This like many integrated programmes should be an effort undertaken by stakeholders such as the EPA, Minerals commission and the environmental health officers in the various District Assemblies.

- Children were particularly vulnerable to exposure to heavy metals in soils. As such, it is recommended that an integrated health management programme be set up, targeting community education and health awareness, as well as regular monitoring of environmental media and biomonitoring of the health of the children in order to reduce the risk. This can be implemented through constant education of community members on the vulnerabilities of children especially regarding heavy metal contamination.
- From the Risk Matrix it is imperative that mercury and dust exposure must be addressed. Thus, dust suppression and promotion of mercury free gold extraction technologies must be explored by any institution or the government interested in improving mining safety.
- A buffer should be instituted between the mining activities and the sensitive population to protect children, pregnant women, playgrounds and residential areas. As such, children play area should be established away from the mining activities but closer to homes where they can be monitored. Therefore, by extension, residential areas should be removed from active and past artisanal areas to reduce exposure to toxic metals and dust to reduce long term environmental and public health risks.
- Periodic monitoring of the Volta River by the Water Resources Commission should be intensified and include heavy metal monitoring. Such results should be made accessible to the communities through the District Assemblies.

5.3 No-go zones

Based on the findings, the following are recommended:

- Prioritise monitoring and enforcement in Dollar Power and Tinga, where all mapped ASM sites fall within the critical composite risk zone, before extending the same level of scrutiny to lower-risk areas such as Wakawaka. This is suggested for the multi sector actors in the mining regulatory sphere.
- Investigate the two critical-zone sites at Tinga as an immediate priority, given that this is the only community with ASM activity directly inside or overlapping a water body and assess options for remediation or closure.
- Strengthen routine, GIS-based monitoring of the 500 m forest and 300 m water riparian buffers, using periodic satellite or drone imagery to detect new or expanding ASM activity before it reaches the critical zone.
- Develop community-specific reclamation and remediation plans, with the largest allocation of resources directed to Dollar Power and Tinga given the extent of critical-zone area involved.
- Engage mining communities and operators on the riparian buffer zone policy (Ministry of Water Resources, Works and Housing, 2011) to build awareness of buffer requirements and encourage voluntary compliance.

The growing use of Changfan engines has intensified gold extraction, allowing mining to expand more rapidly while dramatically increasing river pollution and environmental destruction

APPENDICES

Annex 1: List of Floral species and structural characteristics

Appendix 1A: List of species and structural characteristics at Dollar Power

S/N	NAMES	HEIGHTS (M)	DIAMETERS (CM)
1	*Monotes kerstingii*	6	22
2	*Isoberlina doka*	3	9
3	*Burkea africana*	10	25
4	*Pterocapus erinaceus*	2.8	8
5	*Monotes kerstingii*	9	19
6	*Monotes kerstingii*	12	25
7	*Combretum sp*	6	10
8	*Entanda africana*	6	18
9	*Entanda africana*	5	16
10	*Grewia sp.*	5	20
11	*Rubiacea sp*	5	10
12	*Parkia biglobosa*		12
13	*Burkea africana*	10	30
14	*Terminalia subterra*	8	20
15	*Monotes kerstingii*	7	23
16	*Burkea africana*	3	5
17	*Monotes kerstingii*	9	19
18	*Monotes kerstingii*	10	15
19	*Pterocapus erinaceus*	13	32
20	*Burkea africana*	9	29
21	*Ficus sp*	7	35
22	*Ficus sp*	7	32
23	*Ficus sp*	7	30
24	*Vitellaria paradoxa*	7.5	28
25	*Combretum sp*	9	25
26	*Monotes kerstingii*	8	16

Appendix 1B: List of species and structural characteristics at Wakawaka

S/N	NAMES	HEIGHTS (M)	DIAMETERS (CM)
1	*Spseudo cedrilla (Doli)*	8	8
2	*Combretum sp*	6	9
3	*Pseudocedrala kotschyi*	9	19.3
4	*Unidentified*		7
5	*Rubiacea sp*	7	8
6	*Pterocapus erinaceus*	10	15
7	*Pterocapus erinaceus*	10	27
8	*Pterocapus erinaceus*	10	30
9	*Lannea acida*	7.5	11
10	*Lannea bateri*	10	14
11	*Combretum sp*	6	11
12	*Vitellaria paradoxa*	13	39
13	*Sarcocephalus latifolius*	4	9
14	*Burkea africana*	10	
15	*Combretum sp*	7.5	15
16	*Combretum sp*	7	7
17	*Pseudocedrala kotschyi*	9	7
18	*Pseudocedrala kotschyi*	8	12
19	*Pterocapus erinaceus*	7	11

S/N	NAMES	HEIGHTS (M)	DIAMETERS (CM)
20	*Pseudocedrala kotschyi*	7.5	15
21	*Hymnocardia acida*	7.5	13
22	*Terminalia Subterra*	8	11
23	*Lannea microcarpa*	8	6
24	*Burkea africana*	7.5	12
25	*Pseudocedrala kotschyi*	10	17
26	*Combretum sp*	6	11
27	*Pterocapus erinaceus*	7.5	12
28	*Unidentified*	5	9
29	*Burkea africana*	9	12
30	*Terminalia Subterra*	8	13

Appendix 1C: List of species and structural characteristics at Tinga

S/N	NAMES	HEIGHTS (M)	DIAMETERS (CM)
1	*Hymnocardia acida*	6.8	10
2	*Lannea acida*	6	15
3	*Terminalia*	3	3
4	*Terminalia*	4	3
5	*Terminalia*	4	3
6	*Spinosa*	3	3
7	*Daniellia oliveri*	9	19
8	*Vitellaria paradoxa*	8	11
9	*Combretum sp*	5.4	6
10	*Vitellaria paradoxa*	8	7
11	*Vitellaria paradoxa*	3.6	5

S/N	NAMES	HEIGHTS (M)	DIAMETERS (CM)
12	*Vitellaria paradoxa*	9	12
13	*Terminalia*	5.4	10
14	*Vitellaria paradoxa*	7.5	8
15	*Terminalia*	3.6	6
16	*Combretum sp*	5.4	5
17	*Acacia dudgeoni*	3.6	6
18	*Vitellaria paradoxa*	7.2	8
19	*Vitellaria paradoxa*	4	5
20	*Combretum sp*	8	5.4
21	*Vitellaria paradoxa*	4	7
22	*Vitellaria paradoxa*	15	18
23	*Detarium microcarpum*	9	15
24	*Lannea acida*	6.5	12
25	*Daniellia oliveri*	7.2	22
26	*Detarium microcarpum*	5	15
27	*Detarium microcarpum*	3.5	6
28	*Daniellia oliveri*	5.4	6
29	*Terminalia*	3.5	6
30	*Lannea acida*	7.2	30
31	*Vitellaria paradoxa*	8	8
32	*Combretum sp*	3.6	5
33	*Combretum sp*	8	5
34	*Terminalia*	4.5	7
35	*Acacia seyal*	3.9	5
36	*Terminalia*	3.6	6
37	*Lannea microcarpa*	9	40
38	*Detarium microcarpum*	4.5	8

Annex 2: No-go area delineation

In the delineation of No-go zones, Geospatial Risk Assessment of Artisanal and Small-Scale Mining (ASM) sites on water and protected areas (Forest and Game Reserves) was undertaken, particular emphasis should be on

ASM activities are important source of livelihood in Ghana. However, where the activities occur close to or within ecologically sensitive areas, may pose a serious threat to these areas especially forest/game reserves and freshwater resources. This section of the report presents a geospatial risk classification of ASM sites in the Dollar Power, Tinga, and Wakawaka communities, based on their proximity to, or overlap with, protected areas and water bodies. The assessment is intended to support evidence-based decision-making on monitoring, enforcement, and reclamation priorities.

Methods

The analysis combined spatial layers of water bodies and protected areas (forest/game reserves) to assess the risk each mapped ASM site poses to these resources. A 500-metre buffer was applied around protected forest areas and a 300-metre buffer around water bodies according to the riparian buffer zone policy for managing freshwater bodies in Ghana (Ministry of Water Resources, Works and Housing, 2011). Each ASM site was then classified according to its distance from the nearest water body or protected area boundary, using the six-tier risk framework summarised in Table 1.

Table 1: Risk classification framework

Zone Category	Distance Range (Metres)	Interpretation (Ecological Rationale)
Critical Zone	0	ASM sites inside /overlapping the protected area or water body posing very high risk to resource degradation.
Very Close	>0 ≤ 500	Adjacent or bordering to the boundary of the protected area or the water body. Poses high risk of encroachment.
Close	5001 – 2,000	Significant edge effects. High risk of fragmentation and noise disturbance.
Moderate	2,001 – 5,000	Indirect ecological impacts; habitat connectivity disruption and cumulative hydrological changes.
Far	5,001-7,000	Lower immediate risk, but within the 6km maximum edge-effect range for some mammals.
Very far	< 7,000	Negligible direct edge effects.

Results

OVERVIEW OF MAPPED ASM SITES

A total of 94 ASM sites were analysed and assessed for their potential contribution to water pollution or forest degradation, based on their proximity to or overlap with protected areas and water bodies. Dollar Power recorded the highest number of mapped ASM sites (41 sites) and the largest total area (393.33 ha), representing 39.26% of the total mapped area. Although Tinga has comparatively few ASM sites (18), these sites have significantly larger average patch size (approximately 16.4 ha per site) than those in Dollar Power and Wakawaka (approximately 9.0 ha per site each), as shown in Table 2.

Table 2: ASM Sites Mapped by Community

Community	Number of sites	Total Area (ha)	Area Share (%)
Dollar Power	41	393.331	39.26
Tinga	18	294.32	29.38
Wakawaka	35	314.138	31.36
Grand Total	94	1001.789	100.00

COMBINED RISK CLASSIFICATION (FOREST AND WATER COMPOSITE)

Risk classification based on the combination of forest/game reserves and water bodies composite showed that 68.64% of the mapped area (687.65 ha, 59 sites) falls within the critical category (Table 3). This indicates that these ASM sites are located inside or overlapping a protected area or water body and pose a very high risk to both resources. All ASM sites mapped in Dollar Power and Tinga fall within the critical zone under this composite classification (Figure 1).

Table 3: Risk Classification Based on Water and Forest Composite

Category	Number of sites	Total Area (ha)	Area Share (%)
Critical	59	687.65	68.64
Close	7	72.46	7.23
Moderate	28	241.68	24.12
Grand Total	94	1,001.79	100.00

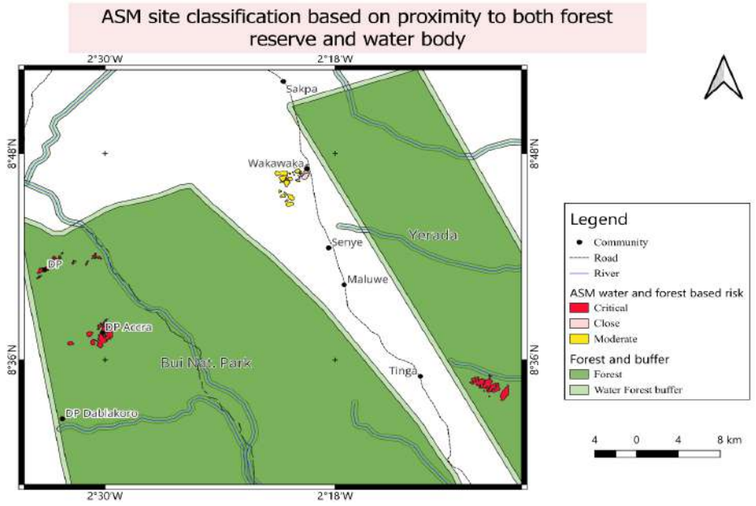


Figure 21: Risk Classification based on water and forest composites

WATER-RELATED RISK CATEGORIZATION

Table 4 and Figure 22 2 present the results of the water-related risk classification of the ASM sites in isolation. Of the 94 sites, only 2 sites fall within the critical zone, while 39 sites fall within the far zone. This indicates that, when assessed against water bodies alone, the majority of ASM activity in the study area lies outside the prescribed riparian buffer zone.

Table 4: Water-Related Risk Categorization of ASM Sites

Category	Number of sites	Total Area (ha)	Area Share (%)
Critical	2	2.33	0.23
Very close	9	187.56	18.72
Close	14	132.56	13.23
Moderate	26	349.42	34.88
Far	39	236.55	23.61
Very far	4	93.37	9.32
Grand Total	94	1001.79	100.00

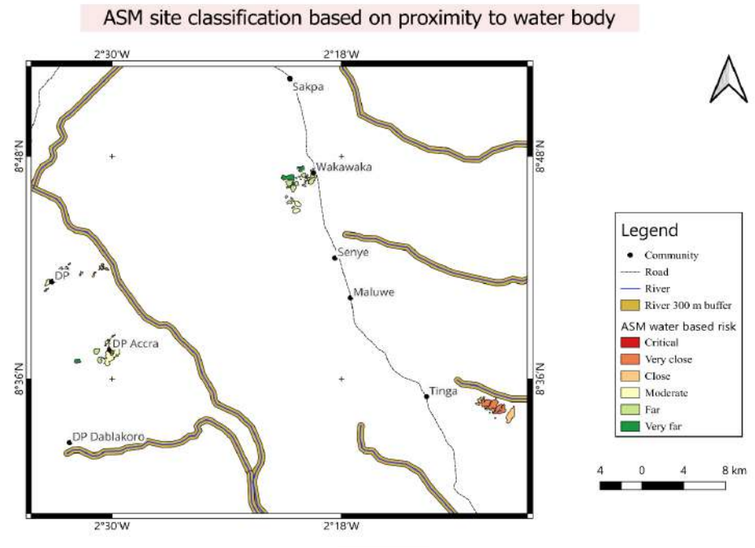


Figure 22: Water-Related Risk Categorization of ASM Sites

COMMUNITY-SPECIFIC WATER-RELATED RISK CLASSIFICATION.

At the community level, Tinga is the only community with sites falling within the critical water-risk zone. Two (2) sites, together accounting for 0.79% of its mapped area (Table 5 and Figure 23 3) are the sites within the buffer zone of the water body. At Wakawaka, all sites are located far from water bodies, with the exception of two sites that fall within the moderate zone (Figure 24 4). At Dollar Power, 24 sites covering 297.59 ha (75.66% of its mapped area) fall within the moderate zone (Table 5 and Figure 25 5).

Table 5: Community Specific Water Risk Category

Community	Risk Category	Number of sites	Total Area (ha)	Area Share (%)
Dollar Power	Very close	2	10.60	2.70
	Close	5	17.53	4.46
	Moderate	24	297.59	75.66
	Far	9	49.17	12.50
	Very far	1	18.44	4.69
		41	**393.33**	**100.00**
Tinga	Critical	2	2.33	0.79
	Very close	7	176.96	60.13
	Close	9	115.03	39.08
		18	**294.32**	**100.00**
Wakawaka	Moderate	2	51.83	16.50
	Far	30	187.38	59.65
	Very far	3	74.93	23.85
		35	**314.14**	**100.00**
Grand Total		94	1001.789	

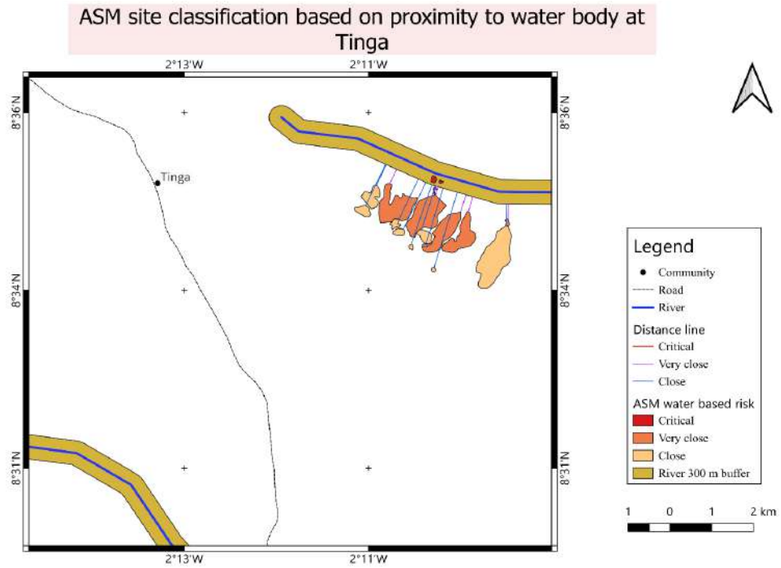


Figure 23: Water-related risk classification at Tinga

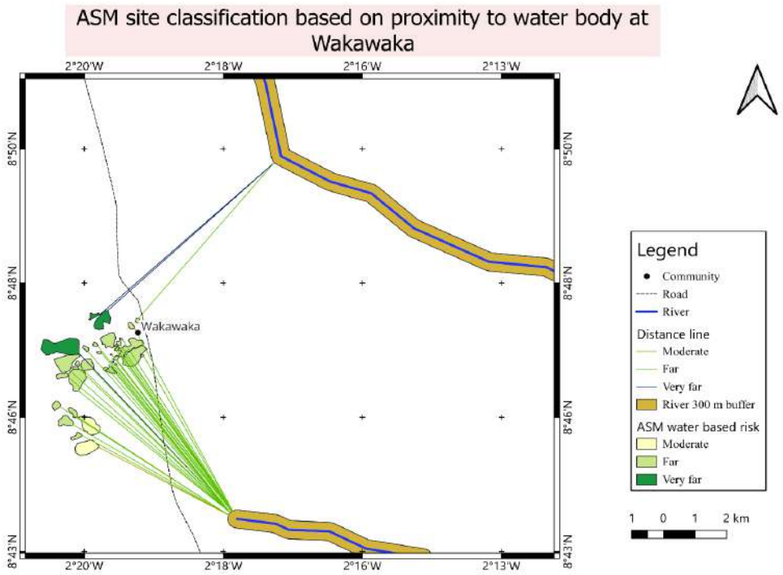


Figure 24: Water-related risk classification at Wakawaka.

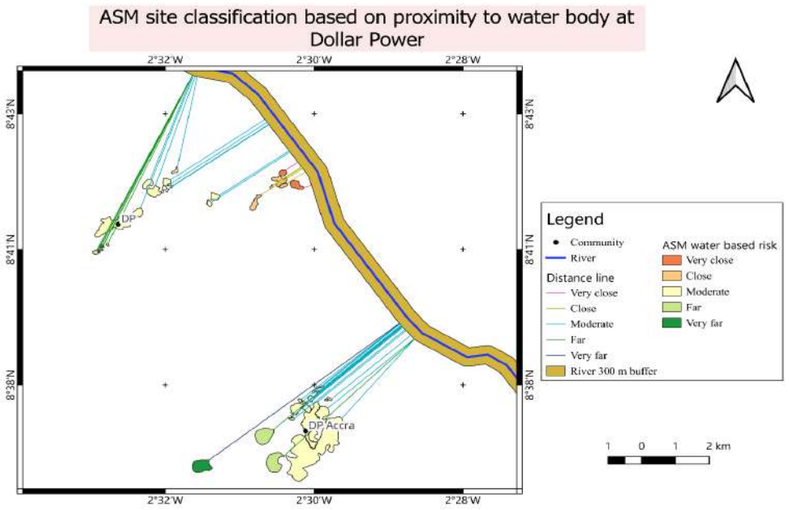


Figure 25: Water-related risk classification at Dollar Power

It is worth noting that unlike the water-related risk classification, which showed considerable variation across communities, the combined water and forest composite classification showed that all three communities fall predominantly within the critical zone, with the exception of Wakawaka, which falls within the close-to-moderate range.

IMPLICATIONS OF THE FINDINGS

The above results point to very important implications of ASM-related environmental risks and how they could be managed in this landscape:

Forest encroachment was noted to be the primary driver of the overall risk. Only 0.23% of the mapped area is classified as critical under only the water-related risk assessment, compared with 68.64% under the combined forest-and-water composite.

ASM sites at Dollar Power and Tinga are the major contributors to the critical-zone risk accounting for 59 sites under the composite framework. All their mapped sites fall in this category. This raises concerns about both environmental risk and immediate intervention in these two communities.

Tinga has the largest average ASM site size and the only community with sites in the water-critical zone. This suggest that ASM operations at Tinga may be less regulated than elsewhere with regards to adhering to the buffer zone policies.

Wakawaka presents a comparatively lower, but not negligible, risk profile. Most of its sites fall in the far-to-moderate range for both water and composite risk, suggesting that current impacts are more limited, though this should not be read as an absence of risk, particularly for the two sites in the moderate water-risk zone.

Conclusion

The assessment classified the risk posed by 94 ASM sites mapped, covering approximately 1,001.79 hectares, based on their proximity to or overlap with protected areas and water bodies. The results showed that majority of the mapped area (68.64%) falls within the critical risk category when forest and water exposure are considered together, indicating that most ASM activities in the study area are occurring inside or adjacent to environmentally sensitive areas. The risk is not evenly distributed, as sites at Dollar Power and Tinga pose the greatest risk, with all their sites falling in the critical zone. Wakawaka, on the other hand, portrays a comparatively lower risk profile.

When water bodies are considered in isolation, most of the mapped sites lie outside the prescribed riparian buffer zone, indicating that direct water body encroachment is very minimal with more localised concern, as noted at Tinga. Taken together, these findings indicate that forest or game reserve encroachment is the dominant environmental risk associated with ASM activity in this landscape, and that Dollar Power and Tinga should be treated as priority areas for intervention.

Recommendations

Based on the findings, the following are recommended:

- Prioritise monitoring and enforcement in Dollar Power and Tinga, where all mapped ASM sites fall within the critical composite risk zone, before extending the same level of scrutiny to lower-risk areas such as Wakawaka.
- Investigate the two critical-zone sites at Tinga as an immediate priority, given that this is the only community with ASM activity directly inside or overlapping a water body and assess options for remediation or closure.
- Strengthen routine, GIS-based monitoring of the 500 m forest and 300 m water riparian buffers, using periodic satellite or drone imagery to detect new or expanding ASM activity before it reaches the critical zone.
- Develop community-specific reclamation and remediation plans, with the largest allocation of resources directed to Dollar Power and Tinga given the extent of critical-zone area involved.
- Engage mining communities and operators on the riparian buffer zone policy (Ministry of Water Resources, Works and Housing, 2011) to build awareness of buffer requirements and encourage voluntary compliance.

Annex 3: Methodology for social survey

Data Collection Approach

The study relied on survey information collected by the Socio and economic Profiling group and their methods are stated below.

For the survey of the primary target population (i.e., ASM actors), a two-stage sampling procedure was adopted to achieve the goal of drawing an acceptable sample from all the target districts. The first stage involved purposive sampling of communities in each district. This sampling approach focused on communities that were more involved in mining. Therefore, 30 communities across the study area were purposively sampled. The number of communities in each district was proportionally apportioned. In the Bole district, 20 communities were selected, and five communities each were selected from the Sawla-Tuna-Kalba and West Gonja districts. The basis for the proportional allocation is premised on the fact that the scale of ASM activities is disproportionate across these districts. The Bole district has a higher concentration of ASM activities than the West Gonja and Sawla-Tuna-Kalba districts.

To provide a basis for comparing some characteristics across mining and non-mining communities, the communities were partitioned into these two classifications. Because Bole has the highest concentration of mining communities, all 20 selected communities were mining communities. One mining community was selected in the Sawla-Tuna-Kalba district, while 2 mining communities were selected in the West Gonja district. Figure 26 2 presents the community distribution across the districts.

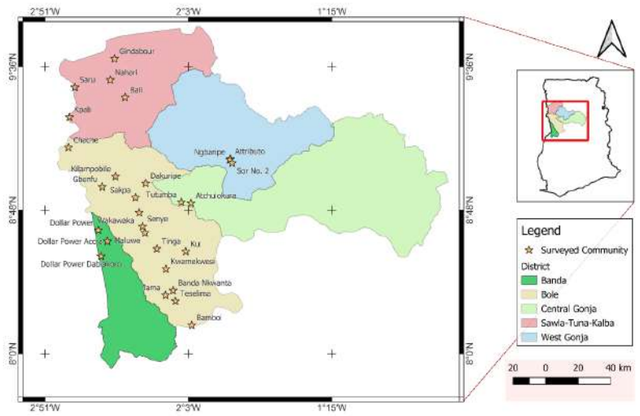


Figure 26: Map of study communities across the districts

It was determined that in each mining community, a sample of 25 respondents would be selected, while 50 respondents would be selected in non-mining communities. The rationale for this disparity was to compensate for the (low) number of non-mining communities in the sample. This implies that given the 23 mining communities and seven non-mining communities, a sample of 925 was to be drawn (23 mining communities * 25 respondents + 7 non-mining communities * 50 respondents). At the district level, 500 respondents in Bole District (20 mining communities × 25 respondents), 225 respondents in Sawla-Tuna-Kalba (1 mining community × 25 respondents + 4 non-mining communities × 50 respondents), and 200 respondents in West Gonja District (2 mining communities × 25 respondents + 3 non-mining communities × 50 respondents) were selected.

The second stage was the selection of respondents from purposively selected communities. We used stratified sampling in this stage, where gender and mining status were the bases of stratification. Gender stratification is important because mining is a male-dominated activity. Randomly drawing a sample may overly represent men compared to women. Therefore, a gender stratum was necessary to ensure a reasonable representation of women. Mining status stratification was based on the objective of analysing the social and economic status of miners after quitting ASM. A stratum was created for current and former miners (i.e., those who were miners but had quitted). We relied on the literature to propose representations of men and women. Baddianaah et al. (2022) found that the proportions of men and women involved in artisanal mining in the Upper West region were 64 and 36 percent, respectively. We modified this proportion to 62 and 38 percent, respectively, to account for the time difference between the time of the study and now. For the mining status stratum, we used proportions of 80 and 20 percent, respectively for current and former miners (i.e., those who have quitted), respectively. Table 2.1 presents a summary of the actual sample and its distribution.

Table 1: Actual sample size and distribution

District	Male			Female			Total
	Miner	Former miner	Non-miner	Miner	Former miner	Non-miner	
Bole	242	80	0	162	20	0	**504**
Sawla-Tuna-Kalba	0	10	137	0	5	92	**244**
West Gonja	25	9	91	16	2	62	**205**
Total	267	99	228	178	27	154	953

In each stratum, respondents were systematically selected, having determined a random start. For former miners, associations and cooperatives provided useful information on people who used to be miners but have since stopped. This approach was used to create a list of former miners for systematic selection. These lists provided data for the application of the stratified sampling approach. However, in Saru, the team struggled to follow the plan of 25 respondents as mining operations stopped due to a crackdown on operations. It was resolved to interview former mineworkers and non-mineworkers. Therefore, Saru was the only community designated as both mining and non-mining. Furthermore, in the field, enumerators interviewed slightly more than the required samples across some communities. In total, 953 respondents were interviewed, as shown in Table 2.1. See Table A.1 in the appendices for the distribution of samples across communities. For the selection of the other respondent types (i.e., key stakeholders), relevant stakeholders were mapped and contacted. Thus, the basis was strictly purposive sampling and institutional protocol (i.e., the person identified by the institution to have the relevant information).

Since the proposal on the selection of the various respondents is basically (quasi-) random, participation was non-discriminatory. To guarantee confidentiality and anonymity, some personal information of respondents that aid in the identification of people would not be shared with any other party. For example, names of respondents, house names and numbers, and addresses (postal or digital) would be dropped from the data files to be submitted. Consent forms were designed for respondents to sign if they agreed to participate in the survey. While the importance of the survey was shared, respondents were duly informed by enumerators that they had the right to decline to participate in the survey, and those who declined were replaced by other respondents. All respondents were assured that they had nothing to lose if they declined to participate.

The study used face-to-face interviews, key informant interviews (KII), focus group discussions (FGD), spatial (GIS) mapping, and observation and photographic documentation. Computer-assisted personal interviews (CAPI) were used to collect data from ASM actors through face-to-face interviews. KIIs were conducted with other respondent types (i.e., stakeholders) itemised earlier to gather data pertaining to institutional mandates, governance challenges, enforcement bottlenecks, socioeconomic dynamics, and informal network structuring of ASM. In all, nine (9) FGDs were conducted, comprising mineworkers, farmers, women, youth, and migrant workers drawn from the selected communities to collect group data pertaining to livelihoods and income diversification, security and conflict risks, gender roles and vulnerabilities, relations between mineworkers and host communities, and access to social services and natural resources.

1 Because of community-level conversions of the sample sizes, there are some slight differences between the targeted distribution proportions and the actual sample.

Participatory spatial mapping and GIS were conducted in each district to spatially map ASM sites, infrastructure, and the environmental features. Its participatory nature ensured that stakeholders (e.g., mineworkers and community leaders) were involved in the process of developing the plan. This exercise produced GIS outputs (e.g., geo-referenced maps) that were integrated with socio-economic data for each district. It specifically covered satellite image classification to delineate larger ASM sites, drone flight missions to acquire high-resolution imagery, and transect walks to geolocate all identified sites. We also undertook observation and photographic documentation using structured observation checklists and cameras to capture physical site layouts, safety conditions, waste management, and environmental impacts.

The following instruments were used:

- Interview Guide
- Questionnaire
- Computer tablets for CAPI and geolocation data
- Digital recorders for FGD
- Field diaries
- FGD Guide
- Cameras
- Drones

The questionnaire was designed to collect a range of data that were sufficient to analyse and deliver the objectives of this study, including demographic and household data, economic roles and income sources, working conditions and occupational risks, access to land, credit, and equipment, gender participation, decision-making, social mobility, and perceptions of governance, security, and the environment. Quantitative and qualitative data were collected using these instruments.

It is important to note that data collection involving human subjects raises ethical issues; thus, ethical considerations must be catered for. We applied for ethical clearance to undertake this assignment from the Institutional Review Board (IRB) of the University for Development Studies (UDS). The process of applying for ethical clearance required, among other things, a consent form. Thus, an appropriate consent form was developed and submitted for clearance. In the process of data collection, this consent form was read out and approved by the sampled respondents through signing or thumbprinting before data were sought from them. Therefore, data were collected only from those who voluntarily consented to participate.

Enumerators were recruited with a minimum qualification of a bachelor's degree and demonstrable experience in data collection, especially related to livelihoods. Enumerators who understood and could operationally translate questions into the local dialect of a particular community where they were assigned were recruited. We prevented heavy workloads per enumerator by presenting reasonable, achievable, and time-bound targets. Enumerators worked in teams to ensure that quality data were collected. In the Bole district, seven people were recruited, comprising six enumerators and one supervisor. Four people each were recruited from the Sawla-Tuna-Kalba and West Gonja districts, with one supervisor and three enumerators each. In total, 15 people were recruited (12 enumerators and 3 supervisors). Supervisors provided all-round monitoring of enumerators to ensure that the quality control measures planned were strictly adhered to and led the process of sampling respondents. They also ensured data transmission. The role of each team's supervisor and the regular monitoring of the investigation team were well-placed to deliver quality assurance and meet other needs. For example, because each supervisor was freelancing, no enumerator had the opportunity to do anything untoward in their engagements with respondents. We used the Kobo toolbox to economise time and boost the quality of the data. The Kobo toolbox enhanced the quality of the data because the data could be reviewed instantly or shortly after the end of the day's collection. The project team could view the data collected for completeness and appropriateness, even when the collection was ongoing.

Data Analysis and Presentation

Data were analysed in strict compliance with the stated objectives. Both qualitative and quantitative data were analysed, aided by use of the computer and data management software.

Qualitative data were analysed using content analysis, which involved the following five steps, as noted by Erlingsson and Brysiewicz (2017): a. data familiarisation, b. data organisation, c. data coding, d. observation of pattern and categorisation of themes, and e. summarising findings. The method of qualitative analysis in practice requires that responses to interviews are clustered into themes and codes assigned. This enabled the research team to systematically reduce the data and categorise them into manageable analytic frames.

Quantitative analysis was performed using Stata version 18. T-tests and Chi-square tests were used to test for differences depending on whether the variables were continuous or categorical.



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ABOUT COGINTA

Coginta is a non-governmental organisation incorporated under Swiss law and recognised as being of public benefit, which works to promote economic and social development by addressing the structural causes of instability, poverty and exclusion. Its work lies at the intersection of local governance and security, conflict prevention, natural resource management and socio-economic development, recognising that these aspects are closely interlinked and essential to social stability and cohesion. Coginta has its headquarters in Geneva and country offices in Burkina Faso, the Central African Republic, Chad, Côte d'Ivoire, the Democratic Republic of Congo, Ghana, Guinea, Mozambique, Niger and Senegal.

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