Hydrogeological Controls on Artisanal and Small-Scale Mining (Asm) Impacts on Water Resources in Nigeria

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***Abstract*—In Nigeria, Artisanal and Small-scale Mining (ASM) provides a livelihood for many people. However, the lack of proper control over mining activities has caused serious problems for groundwater and surface water. This review looks at how different geological factors affect the impact of ASM on water resources in various regions of Nigeria. It combines knowledge from sedimentology, structural geology, geochemistry, and hydrogeology to understand how aquifer vulnerability, differences in rock types, and fault-controlled flow paths contribute to the movement and spread of pollutants from ASM sites. The study also analyzes data from areas like the Anambra Basin, Benue Trough, and Basement Area to highlight regional differences in water sensitivity. Finally, the review suggests ways to improve groundwater monitoring and hydrologic zoning in areas affected by ASM.**

***Index Terms*—Artisanal and Small-scale Mining (ASM), groundwater, hydrogeology, Nigeria, aquifer vulnerability, contamination, structural controls.**

1. INTRODUCTION

Nigeria's solid minerals industry has revitalized, with Artisanal and Small-scale Mining (ASM) which account for over 85% of mining activities in the country (Bawa and Malami, 2021). Despite the fact that ASM is important for poverty alleviation, its environmental impact, especially on water resources are alarming. Contaminants such as mercury, lead, and arsenic from gold, zinc, and tantalite mining activities have been noted in aquifers and rivers serving as potable water sources (Olalekan et al., 2022).

Conversely, the hydrological impact of ASM is not uniform; it is strongly regulated by local geological conditions. Hydrogeological controls including lithology, depth and type of aquifers, faulting, permeability, and recharge rates govern the migration and dilution of contaminants. Hence, this review aims to collect existing studies and geological records to analyze how Nigeria's hydrogeological settings respond to ASM-induced pollution.

1.1 Background

According to World Bank, (2020), Artisanal and Small-scale Mining (ASM) plays major role in the livelihoods of millions in sub-Saharan Africa, including Nigeria. It is estimated that over 500,000 to 700,000 Nigerians directly engage in ASM, with an additional 2 to 3 million people dependent on its economic benefits. The informal nature of ASM activities, reveals they are poorly regulated, technologically simple, and environmentally harmful. The industry is mainly associated with several disruption to the hydrological cycle, thereby leading to pollution of surface and groundwater systems, siltation of rivers, and depletion of aquifers (Hilson, 2017; Olalekan et al., 2022).

In Nigeria, ASM activities are concentrated in mineral-rich regions across various geological zones, especially within the Basement Complex, Anambra Basin, Benue Trough, and Jos Plateau, where gold, tin, lead-zinc, and tantalite mining are endemic. These territories have clear lithologies and hydrogeological properties, which in turn modulate how pollutants move through or accumulate in the subsurface. Thus, understanding the hydrogeological controls in these regions is important for evaluating the extent and risk of water contamination due to ASM.

1.2 The Relationship Between Hydrogeology and ASM-Driven Water Pollution

Hydrogeology entails the distribution, movement, and quality of water in the subsurface geological environment. When ASM occurs in hydrogeologically prone areas such as fractured crystalline rocks or shallow unconfined aquifers, the potential for water contamination is amplified significantly (Offodile, 2002; Bala et al., 2019).

For example, in Zamfara State, lead contamination of well water has been attributed to the oxidation and mobilization of galena (PbS) through fracture-controlled aquifers (Human Rights Watch, 2011).

However, pollutants introduced during ASM including mercury, cyanide, lead, arsenic, and suspended sediments often interact with aquifer matrices, depending on the geochemistry and lithology of the subsurface. These interactions determine whether contaminants are reduced, transformed, or mobilized further. Furthermore, groundwater systems within sandstone aquifers, may provide limited filtration, whereas fractured basement aquifers tend to allow rapid pollutant migration with little natural attenuation (Edet and Okereke, 2001; Ako et al., 2012).

1.3 Nigeria's Geological and Hydrogeological Settings

Nigeria's geological complexity means that ASM activities and their effects on water resources vary according to region. However, the main hydrogeological environments include:

i. The Basement Complex: These are territories in Oyo, Ekiti, and Kaduna, characterized by fractured aquifers in weathered crystalline rocks. These zones are typically shallow and susceptible to contamination.

ii. Sedimentary Basins: These are areas in Anambra, Sokoto, Chad, and Niger Delta Basins. They contain layered aquifers with low to high yields and differing depression depending on lithological composition.

iii. Volcanic and Younger Granite Regions: These inlcude regions like Jos Plateau, known for tin and columbite mining with perched groundwaters and radioactive mineral contamination risks (Akanle et al., 2020).

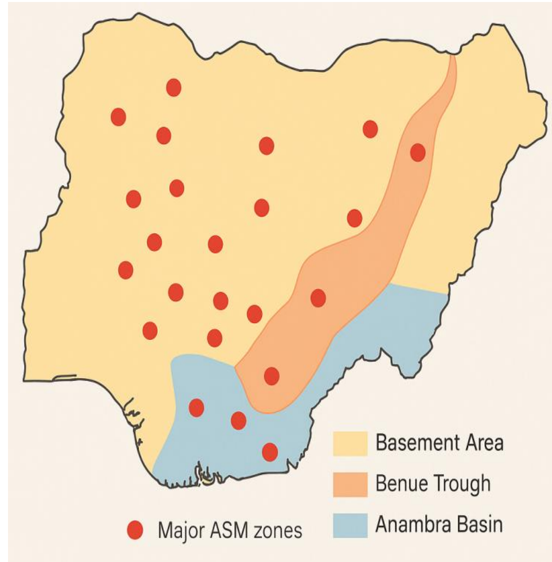

Figure 1: Distribution of major ASM zones across Nigeria's hydrogeological zones.

Source: Modified by author based on data from NGSA, FMMSD, Offodile (2002), and Adelana and MacDonald (2008)

1.4 Rationale

In Nigeria, despite the rising concerns of the environmental impacts of ASM in relation to soil and air contamination, a systematic review with a view on hydrogeological controls on water resource degradation is still lacking. Most environmental studies overlook subsurface processes and groundwater-specific susceptibility assessments. Hence, this review aims to fill this gap by:

i. Identifying the hydrogeological mechanisms that influence the transport and fate of pollutants from ASM sites.

ii. Highlighting regional disparities in aquifer vulnerability to mining contamination.

iii. Providing a scientific foundation for groundwater monitoring and protection strategies tailored to ASM-prone regions.

2. HYDROGEOLOGICAL FRAMEWORK OF NIGERIA

Nigeria's geology comprises of three major provinces including:

i. Basement Complex: These are regions in the southwestern, and northcentral areas, dominated by precambrian rocks with fractured aquifers (ground waters).

ii. Sedimentary Basins: These are regions around Anambra Basin, Niger Delta, and Sokoto Basin respectively. They are characterized by layered aquifers (ground waters) with higher yields.

iii. Younger Granites and Volcanics: These are regions around central Plateau. This area is a hosting pegmatite and tin mining zones.

Table 1. Summary of Hydrogeological Provinces and Vulnerability to ASM

Region	Dominant Lithology	Aquifer Type	Vulnerability to ASM Pollution
Zamfara, Kebbi	Schist, Quartzite	Fractured Basement	High (low buffering capacity)
Niger State	Pegmatites, Granite	Fractured/Weathered	Moderate
Anambra Basin	Sandstone, Shale	Intergranular	Moderate to High
Cross River	Shale, Limestone	Intergranular/Karst	High (leaky aquifers)

Source: Adapted from Offodile (2002); Bala et al. (2019)

2.1 The Basement Complex Aquifers

2.1.1 Geological Setting

The Basement Complex covers about 60% of Nigeria's landmass and consists majorly of Precambrian metamorphic and igneous rocks, including granite, gneiss, schist, and migmatites (Rahaman, 1988). These rocks are impermeable in nature; thereby making groundwater limited to weathered zones and secondary porosity within fractures and joints.

2.1.2 Hydrogeological Characteristics

Generally, the basement groundwaters (aquifers) are discontinuous, heterogeneous, and occur at shallow depths between (5–25 m). Aquifer yields are often less than (<1.5 L/s), and water quality is very sensitive to near-surface contamination due to limited filtration (Edet and Okereke, 2001). However, the vulnerability is high in ASM zones such as Zamfara, Osun, and Niger States, where gold and tantalum mining are predominant.

Furthermore, fracture and joint patterns influence water flow and pollutant transport. As a result of these, zones of intense ASM often coincide with fault intersections, leading to increased risk of contaminant migration into domestic wells.

2.2 Sedimentary Basin Aquifers

2.2.1 Overview of Major Basins

Moreso, Bala et al., (2019) reveals that sedimentary basin covers about 35% of Nigeria and comprises of unconsolidated to semi-consolidated clastic and carbonate sediments. The major basins include: Anambra Basin, Sokoto Basin, Chad Basin, Benue Trough, and Niger Delta Basin. Each of these basins has a layered groundwater (aquifer system), with primary porosity and relatively higher storage and transmissivity compared to the Basement Complex.

2.2.2 Anambra Basin Case Example

The Anambra Basin is an important hydrogeological unit in southeastern Nigeria. It is made up of alternating layers of sandstone, shale, and coal seams. Aquifers here are confined to semi-confined and unconfined sandstone units including the Ajali and Nsukka formations. These groundwaters have moderate yields randing between (1.0–3.5 L/s), and depths ranging from 20 to 100 m (Nwankwoala and Ngah, 2010).

However, ASM activities in coal-rich areas (Enugu and lead-zinc mining in Abakaliki) have threaten groundwater (acquifers) quality through surface runoff and infiltration of acidic mine drainage, heightened by the region's high rainfall and moderate permeability.

2.2.3 Niger Delta Basin

The Niger Delta Basin includes a multi-aquifer system composed of the Benin Formation (coarse sands), Agbada Formation (silty sands and shales), and Akata Formation (clayey units). However, the Benin Formation is the most productive aquifer in Nigeria, with yields of about (>5 L/s) and deep static water levels (Offodile, 2002).

The dominance of oil extraction, isolated sand mining and illegal dredging activities Although ASM is very common in these areas, thus; leading to turbidity and saline invasion in shallow aquifers.

2.3 The Younger Granite Province (Volcanic and Intrusive Regions)

2.3.1 Geological Setting

The Jos Plateau and adjoining areas in North Central Nigeria habours a lot of Jurassic-age younger granites intruding older basement rocks. Since the early 20th century, these areas are known for its rich deposits of tin, columbite, and tantalite, which are mined intensively.

2.3.2 Hydrogeological Setting

More importantly, groundwaters in the Jos Plateau are located within weathered granitic profiles and colluvial sediments. These aquifers are shallow, low-yielding about (<1.0 L/s), and highly susceptible to surface contamination (Akanle et al., 2020). The heavy metal load from tailings dumps and leachates presents a serious threat to springs and hand-dug wells. Furthermore, radionuclide contamination is also a concern in areas with high concentrations of uranium and thorium concentrations (Jibiri and Farai, 2002).

2.4 Structural Controls and Faulting

Nigeria's hydrogeological units are influenced by tectonic structures in the Basement Complex and Benue Trough. Also, fracture zones serve as both conduits and barriers to groundwater flow, depending on its orientation, aperture, and connectivity. These regions are targets for ASM due to associated mineralization, leading to a high level of contaminant migration through preferential pathways (Olorunfemi and Fasuyi, 1993).

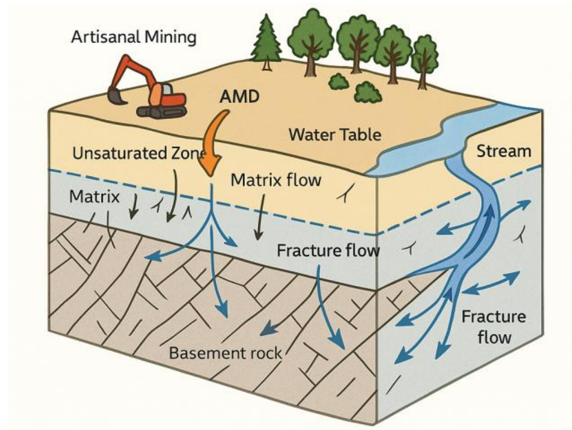

Figure 2. Conceptual Model of Groundwater Flow in Fractured Basement Terrains

Source: Adapted from Wright (1992) and MacDonald et al. (2002) with modifications by the author.

2.5 Summary of Aquifer Vulnerability to ASM Pollution

Table 1. Comparative Aquifer Characteristics and ASM Vulnerability

Hydrogeological Unit	Dominant Lithology	Aquifer Type	Typical Yield (L/s)	Pollution Vulnerability	Common ASM Activities
Basement Complex	Granite, Schist, Gneiss	Fractured/Weathered	0.5–1.5	High	Gold, Tantalite, Lead
Anambra Basin	Sandstone, Shale	Intergranular	1.0–3.5	Moderate to High	Coal, Lead-Zinc
Chad/Sokoto Basins	Sand, Clay, Limestone	Unconfined/Confined	1.0–2.5	Moderate	Salt, Gypsum
Niger Delta Basin	Sand, Gravel	Multi-layered	>5.0	Low to Moderate	Sand Mining (Localized)
Jos Plateau (Granites)	Weathered Granite	Perched/Colluvial	<1.0	High	Tin, Columbite, Tantalite

3. ASM-RELATED WATER CONTAMINATION: GEOCHEMICAL EVIDENCE

The introduction of heavy metals, suspended solids, and toxic processing chemicals into hydrological systems through Artisanal and Small-scale Mining (ASM) activities, has put a lot of pressure on local water resources. These effects are often mediated by the underlying hydrogeological setting such as the Basement Complex, the Sedimentary Basins, and the Volcanic and Intrusive Provinces (Offodile, 2002; Bala et al., 2019).

3.1 Common Pollutants Associated with ASM

Depending on the mineral type, extraction methods, and waste disposal practices, ASM operations generate substantial amount of contaminants. (Table 2) summarizes major contaminants from selected Nigerian ASM zones and their associated health risks. Some of the most common pollutants include:

i. Heavy metals including Lead (Pb), Arsenic (As), Mercury (Hg), Cadmium (Cd), Chromium (Cr), and Zinc (Zn)

ii. Metalloids and radionuclides such as Uranium (U), Thorium (Th)

iii. Process chemicals like Mercury (used in gold amalgamation), Cyanide (for gold leaching)
iv. Suspended sediments such as Clay, silt, and fines from mine tailings
v. Acid mine drainage (AMD) including Sulfide mineral oxidation producing sulfuric acid and leaching metals

Table 2. Major Geochemical Contaminants from ASM and Health Effects

Contaminant	Source Mineral or Process	Health Effect	Typical ASM Regions
Lead (Pb)	Galena (PbS), Pb-rich tailings	Neurological damage, kidney dysfunction	Zamfara, Ebonyi, Niger
Arsenic (As)	Arsenopyrite (FeAsS)	Skin lesions, cancer, cardiovascular issues	Nasarawa, Kaduna
Mercury (Hg)	Gold amalgamation	Neurotoxicity, reproductive effects	Osun, Kebbi, Niger
Cyanide (CN)	Gold leaching (rare in Nigeria)	Respiratory failure, acute poisoning	Rare but potentially used
Uranium (U)	Associated with tin mining	Carcinogenic, nephrotoxic	Jos Plateau

Sources: Bawuro et al., 2018; Akanle et al., 2020; Oladeji et al., 2021)

3.2 Gold Mining and Mercury Contamination

According to UNEP, (2013) report, in Ilesha (Osun State) and Bagwai (Kano State), artisanal gold miners make use of mercury in crude composition processes to extract gold. This mercury is often released directly into water bodies or soils, where it undergoes methylation, forming methylmercury (a highly toxic, bioavailable compound).

Case Study of Ilesha Gold Belt, Osun State

The total amount of mercury concentrations in aquifers near ASM sites in Ilesha exceeded WHO permissible limits (0.001 mg/L) by over 10-fold, especially in shallow wells within 500 m of active mining zones. It was also observed that fractured basement groundwaters encouraged the rapid migration of mercury (Oladeji et al. 2021).

3.3 Lead Poisoning in Zamfara State

The most notorious incidence of ASM-related water contamination in Nigeria occurred in Zamfara State, where lead-rich gold ore was processed within residential areas. This led to a widespread lead poisoning among children. According to the Human Rights Watch (2011) report and follow-up studies, groundwater and well water samples in villages such as Bagega and Yargalma recorded lead levels above 1.2 mg/L, far exceeding the WHO guideline of 0.01 mg/L for drinking water.

Also, geochemical analysis by Bawuro et al. (2018) confirmed high concentrations of lead and associated metals such as cadmium (Cd) and arsenic (Ar) both in soil and water samples. The migration of these metals was attributed to oxidizing conditions and acidic pH as a result of mine waste interactions with rainwater.

3.4 Tin and Radionuclide Contamination in Jos Plateau

ASM in the Jos Plateau is largely focused on tin and columbite extraction from alluvial and pegmatitic accumulations. Meanwhile, tailings are often dumped into surface waters or in pits, where they leach metals and naturally occurring radioactive materials (NORMs) into shallow groundwater's and springs.

3.4.1 Geochemical Profile of Contaminated Waters

Accordingly, water samples collected downstream of tailings dumps in the Jos area showed uranium concentrations up to 0.02 mg/L (WHO limit: 0.015 mg/L) and thorium levels above background (Akanle et al. 2020). Additionally, heavy metals including Zn, Cu, and Fe were high. Radioactivity levels were found to surpass safe exposure thresholds, thus; raising long-term health challenge for local communities.

3.5 Acid Mine Drainage and Metal Mobilization

Nganje et al., (2014) document that; in the lead-zinc mining zones of Ebonyi State, around Enyigba and Abakaliki, mine spoils rich in sulfide minerals including galena, sphalerite, and pyrite oxidize in the presence of water and air to produce acid mine drainage (AMD). This therefore, lowers the pH of receiving waters and mobilizes metals such as Fe, Pb, and Cd into solution.

Furthermore, field measurements indicate pH values as low as 4.2 in impacted streams, with Fe and Pb concentrations was above environmental guidelines. The geochemical mark includes high sulfate (SO_4^{2-}), Fe^{2+}, and Mn^{2+}, all indicative of pyrite oxidation and AMD formation.

3.6 Summary of ASM-Induced Geochemical Contamination

Table 3. Summary of Geochemical Evidence of ASM Contamination in Nigerian Regions

Location	Main Mineral Mined	Contaminants Detected	Water Body Affected	Reference
Ilesha, Osun	Gold	Mercury (Hg), Suspended solids	Hand-dug wells, Streams	Oladeji et al., 2021
Zamfara State	Gold	Lead (Pb), Arsenic (As), Cd	Wells, Boreholes	Bawuro et al., 2018; HRW 2011
Jos Plateau	Tin, Columbite	Uranium (U), Thorium (Th), Zn	Springs, Perched aquifers	Akanle et al., 2020
Ebonyi State	Lead-Zinc	Fe, Pb, Cd, SO_4^{2-} (AMD)	Streams, Shallow aquifers	Nganje et al., 2014

4. STRUCTURAL CONTROLS AND FAULT-MEDIATED FLOW

The migration, attenuation, and accumulation of pollutants in aquifers are influenced by geological structures including as faults, fractures, joints, and shear zones. These features can enhance the transport of contaminants by facilitating permeability or serve as barriers that categorize aquifers. However, in ASM-dominated regions of Nigeria, fault-mediated flow systems play an important role in determining the geometric extent and intensity of contamination from mining activities.

4.1 Structural Framework of Nigerian Basement and Sedimentary Terrains

Nigeria's geology is divided into the Precambrian Basement Complex and the Mesozoic to Cenozoic Sedimentary Basins. The Basement Complex, is made uo of granites, gneisses, schists, and migmatites, is systematically fractured, especially in regions like Southwestern Nigeria (Ilesha, Ife, and Ondo) and North-central Nigeria (Minna, Bida). These fractured systems often host weathered regolith groundwaters that are highly susceptible to contaminant infiltration.

According to Obaje, (2009), the Benue Trough and Chad Basin, which are sedimentary, also show structural complexities, normal and listric faults, extensional fractures, and collapsed structures, due to tectonic fadeout and rifting events.

4.2 Faults and Fractures as Contaminant Pathways

Fault zones and fracture channels foster vertical and lateral hydraulic connectivity, thus serving as a preferred flow paths for water and dissolved solutes, including contaminants. However, in ASM regions, where pollutants are released at or near the surface, these structural anomalies, allow contaminants to bypass the natural attenuation provided by soil matrices and reach deeper groundwaters (aquifers).

4.2.1 Fracture-Controlled Flow in the Ilesha Schist Belt

In a case study by Oladeji et al. (2021), he observed that mercury contamination from artisanal gold mining in Ilesha was not restricted to shallow aquifers only, but also appeared in deeper wells (>60 m). Furthermore, structural mapping revealed a high density of NE-SW and NW-SE gravitating fractures, in accordance with regional shearing. These structures, intersecting the quartz-schist and amphibolite units, enabled downward migration of mercury-laden water.

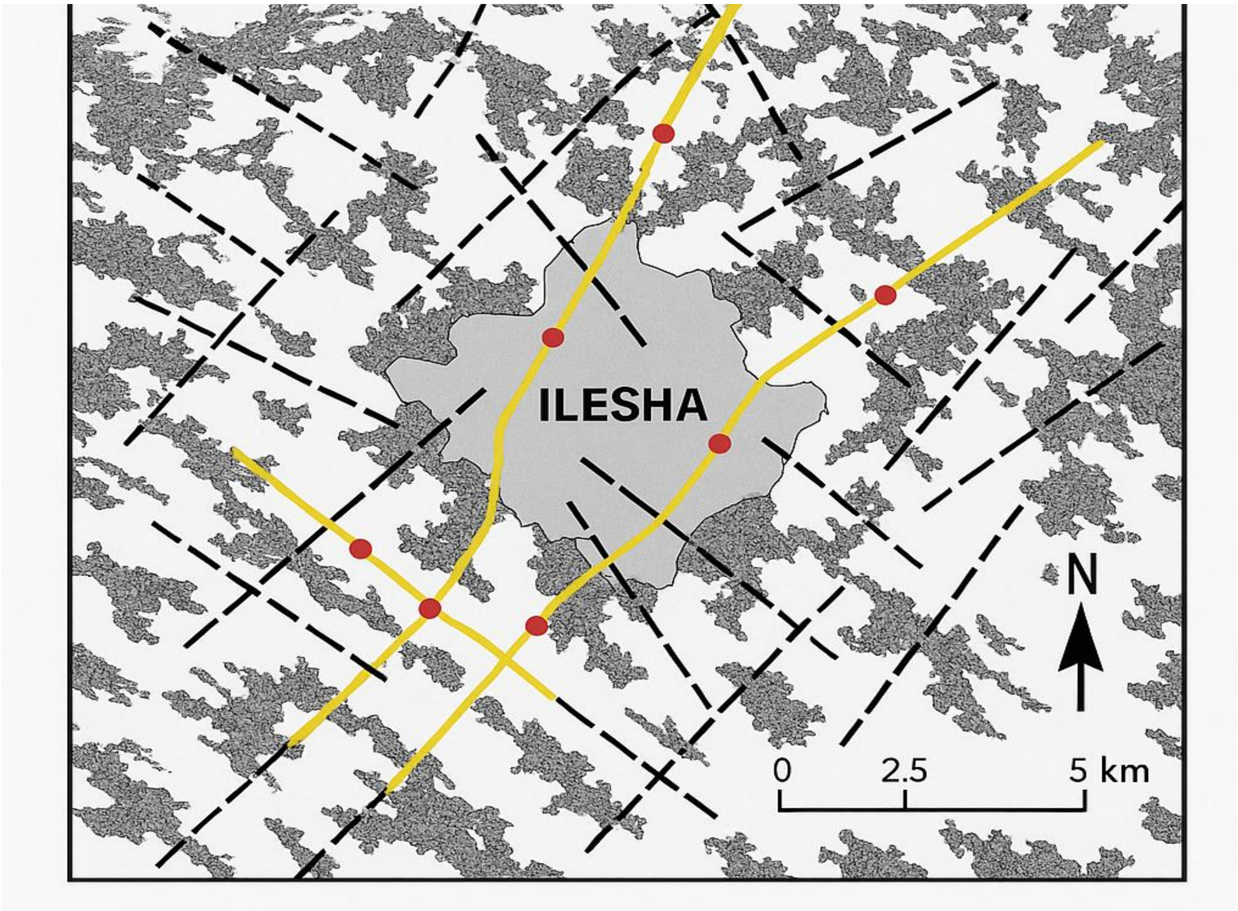

Figure 4.1. Structural Lineaments and Mercury Contamination Pathways in Ilesha
Source: Oladeji et al., 2021

4.3 Fault Zones as Contaminant Barriers

While faults can serve as conduits, they may also act as hydraulic barriers where fault gouge material such as clay-rich fault planes reduces permeability. This dual nature of faults is seen in some parts of Jos Plateau, where fault-bounded compartments hinder the spread of radionuclide and heavy metal contaminants from ASM tailings.

Conversely, water wells found upgradient and outside fault-bounded compartments had lower uranium and thorium concentrations than those within the contaminated zone. This suggests structural compartmentalization and differential vulnerability across fault-blocks (Akanle et al. 2020).

4.4 Interaction Between Tectonic Features and Hydrochemistry

Faults are not only influence by the physical transport of water and solutes, but also by impact water–rock interaction activities. However, fault zones often have increased surface area for geochemical reactions, such as:

i. Sulfide oxidation in fractured lead-zinc deposits of Ebonyi State, thereby enhancing acid mine drainage (Nganje et al., 2014).

ii. Carbonate dissolution in faulted areas of the Sokoto Basin, modifying pH and metal mobility.

iii. Ion exchange processes in fracture-filled weathered schist zones in Minna and Akure (Olayinka et al., 2013).

The combination of structural heterogeneity and hydrogeochemical reactivity intensify the complexity of contaminant transport ASM regions with various lithologies and types of minerals.

4.5 Influence of Shear Zones and Lineaments

In several ASM zones, especially those with minerals such as gold, the spatial distribution of mining activities aligns with regional shear zones and geological lineaments. These features, formed during orogenic and post-orogenic tectonism, does not only localize ore bodies, but also define zones of increased permeability.

For example, The Ifewara-Zungeru Shear Zone. This major NE-SW trending shear zone is associated with gold mineralization and ASM hotspots. According to Adekoya et al. (2018), this shear zone is characterized by fractured mylonites and quartz veins. Contaminants introduced by mining near these zones readily infiltrate through interconnected fracture networks, thus; threatening both shallow and deep groundwaters.

4.6 Summary of Structural Control Mechanisms in ASM Zones

Table 4. Summary of Structural Features Influencing Contaminant Transport in Nigeria

Region	Dominant Structures	Contaminants Involved	Flow Impact	References
Ilesha, Osun	Shear zones, fractures	Hg	Enhanced vertical infiltration	Oladeji et al., 2021
Jos Plateau	Faults, collapsed zones	U, Th, Zn	Compartmentalization, mixing zones	Akanle et al., 2020
Enyigba, Ebonyi	Faulted sulfide veins	Pb, Fe, SO_4^{2-} (AMD)	Facilitates AMD generation	Nganje et al., 2014
Minna-Schist Belt	Foliation-parallel fractures	Nitrate, Pb	Enhanced lateral migration	Olayinka et al., 2013

4. Structural Controls and Fault-Mediated Flow

Fractures and faults enhance vertical and horizontal contaminant migration in hard rock aquifers. For instance:

i. In Zamfara, lead and arsenic contamination in water wells are noted along NE-SW trending faults intersecting schistose rocks.

ii. In the Benue Trough, normal faulting contributes to contaminant pathways through shale-sandstone interfaces.

iii. While geophysical surveys (Vertical Electrical Sounding) across the Middle Belt have revealed the presence of shallow conductive zones near ASM sites (Abubakar et al., 2020).

5. IMPACTS OF ASM ON WATER RESOURCES IN NIGERIA

Case studies provide a valuable means of understanding the local nature of artisanal and small-scale mining (ASM) impacts on water resources in Nigeria. These site-specific analyses illustrate the relationship between geology, hydrogeology, mining practices, and water quality degradation. The sub-sections below examine four notable ASM hotspots across Nigeria. They include Zamfara, Ilesha, Jos Plateau, and Ebonyi State, all of which exemplify the breadth and diversity of ASM-induced environmental stress in the country.

5.1 Zamfara State Gold Mining and Lead Poisoning Crisis

5.1.1 Geological and Hydrogeological Setting

Findings by Bawuro et al., (2018) revealed that Zamfara lies within the Northwestern Basement Complex. It is characterized by granitoids, gneisses, and schists, with localized mineralization of gold-bearing quartz veins, associated with galena (PbS). The fractured crystalline bedrock contain shallow, discontinuous groundwaters (aquifers), with many communities depending on hand-dug wells and shallow boreholes.

5.1.2 Contamination Profile and Health Impact

In 2010, lead poisoning outbreak in Zamfara led to the death of over 400 children, thus; making it one of the world's most severe cases of ASM-related environmental disaster (Human Rights Watch, 2011). This pandemic was traced to illegal ore processing in residential areas, where lead-rich gold ore was pulverized and washed. Accordingly, Bawuro et al., (2018) reported that geochemical analysis revealed groundwater lead concentrations exceeding 1.2 mg/L, far above the WHO permissible limit of 0.01 mg/L.

Figure 5.1. Distribution of Lead in Water Sources in Bagega and Yargalma Communities

High levels of arsenic and cadmium was recorded, and they correlate with oxidized sulfide minerals in mine tailings. However, the lack of natural attenuation mechanisms in the fractured bedrock, coupled with direct contamination channels, enhance widespread pollution.

5.2 Mercury Contamination from Gold Mining at Ilesha, Osun State

5.2.1 Geological Context

The Ilesha schist belt, located at the Southwestern Nigeria Basement Complex, is rich in gold mineralization. This natural resource is associated with quartz veins anchored within amphibolites, quartz-schists, and gneisses (Oladeji et al., 2021). This region is fractured due to regional shearing, with groundwaters made up of weathered regolith and fracture-controlled bedrock systems.

5.2.2 ASM Practices and Water Quality Implications

Artisanal gold miners often use elemental mercury for synthesis, thereby releasing it into soils and surface waters during processing. However, Oladeji et al. (2021) documented mercury concentrations in groundwater of up to 0.012 mg/L, which surpases WHO's limit of (0.001 mg/L) for safe drinking water. Furthermore, shallow hand-dug wells within 500 meters of processing zones, were mostly affected.

5.2.3 Structural Influence

The severe fracturing of the main rocks encouraged vertical movement of mercury into deeper groundwater zones. Local lineament mapping and hydrochemical modelling suggest that contaminated recharge areas align with NE-SW trending shear zones.

5.3 Tin Mining and Radioactive Contamination in Jos Plateau

5.3.1 Geological and Historical Context

The Jos Plateau is part of the Younger Granite Complex. It is made up of biotite granites, rhyolites, and pegmatites. However, tin and columbite mining in this area from time immemorial dates back to ancient times, thus; revealing abandoned pits, tailings dams, and disturbed soils. Furthermore, the region also indicates high levels of uranium and thorium due to naturally radioactive minerals associated with the mother rocks (Akanle et al., 2020).

5.3.2 Hydrogeochemical Findings

Surface and groundwater samples from tailings-contaminated areas reveal:

i. Uranium concentrations of up to 0.02 mg/L (WHO guideline: 0.015 mg/L).

ii. High thorium and radon gas levels.

iii. Presence of heavy metals including zinc (Zn), iron (Fe), and manganese (Mn).

These contaminants were primarily leached from tailings through rainfall infiltration and transported via surface runoff or percolation through faulted volcanic-sedimentary sequences.

5.3.3 Health and Ecological Concerns

Akanle et al. (2020) reported higher radiation levels in wells located near old mine dumps compared to background sites. However, lengthy exposure to radionuclides has been linked to cancer risks, bone toxicity, and kidney damage.

5.4 Lead-Zinc Mining and Acid Mine Drainage (AMD) in Ebonyi State

5.4.1 Geological and Hydrogeological Setting

The Enyigba Mining District lies within the Asu River Group of the Abakaliki Anticlinorium. It is composed of shales, limestones, and sandstone interbeds with huge amount of lead-zinc ore bodies embodied in fractured carbonates (Nganje et al., 2014). Furthermore, the groundwater system is dual-porosity i.e a rock characterized by both primary (original depositional) and secondary (formed later) porosity, with flow occurring in both porous channel and along faults/fractures.

5.4.2 ASM Activities and Environmental Effects

ASM in this area involves open-pit excavation and unregulated ore washing near streams. Sulfide oxidation such as galena, sphalerite leads to AMD, which:

i. Lowers pH to as low as 4.2

ii. Mobilizes Fe^{2+}, Pb^{2+}, and SO_4^{2-}

iii. Degrades aquatic habitats

However, water samples showed lead levels above 0.3 mg/L and sulfate exceeding 150 mg/L, thus; showing high acidification and leaching. Communities located further down the river/stream have reported high levels of skin lesions and gastrointestinal infections, all attributed to water consumption (Nganje et al., 2014).

5.5 Comparative Synthesis of Case Studies

A cross-case amalgamation shows that:

i. In Zamfara and Ilesha, gold mining is majorly associated with mercury and lead contamination.

ii. In Jos Plateau, tin mining results in radionuclide mobilization.

iii. In Ebonyi. lead-zinc mining leads to acid mine drainage and metal leaching.

However, the underground water systems are different in each area. In places like Zamfara and Ilesha, cracked rocks make it easier for pollution to enter the ground. In Ebonyi, loose soil and sand let harmful water move through tiny spaces. Cracks and faults in the ground often lead to both mineral deposits and the spread of pollution.

6. DISCUSSION

Artisanal and small-scale mining (ASM) industry in Nigeria plays a dual role. It helps many rural people earn a living and adds to the country's mineral production, but it also seriously harms water sources, sometimes in ways that cannot be fixed. This explains how ASM affects water in many ways, especially the risks to underground water, how pollution spreads, problems with managing water, and the effects on people's health and communities.

6.1 Hydrogeological Vulnerability and Contaminant Transport

6.1.1 Influence of Geological Settings

Adelana and MacDonald, (2008) reports that the level of pollution caused by small-scale mining in Nigeria depends on the type of local rocks and underground water systems. In areas with cracked, hard rocks like in Zamfara and Ilesha, harmful substances can easily seep into the ground because the rocks have weak spots and faults that allow water to flow through. These shallow water sources, often accessed by hand-dug wells, do not filter out pollution well, so contaminants can quickly reach the groundwater.

In contrast, areas like Ebonyi with softer, layered rocks show more complicated pollution patterns. In these places, acidic water from mining can carry harmful metals far from the source, especially through cracks in the rocks. Also, because underground water systems vary so much across Nigeria, many are not well protected from pollution coming from the surface (Nganje et al., 2014).

6.1.2 Structural and Hydrodynamic Controls

Accordingly, Olayinka et al., (2012) reports that cracks and fault lines in the earth, called lineaments and shear zones, play two roles: they help form mineral deposits and also guide how water and pollution move underground. In places like Ilesha, faults that run from northeast to southwest are where gold is found, but these same faults also let mercury from mining seep deep into underground water. These structures also affect how water enters, flows through, and exits the ground, meaning that each area has its own unique risks that need specific solutions.

6.2 Geochemical Signatures and Contaminant Synergy

6.2.1 Trace Metal Co-contamination

Chemical tests show that small-scale mining doesn't just release one harmful substance it releases a mix of dangerous chemicals. In Zamfara, for example, lead, arsenic, cadmium, and antimony are often found together because the rocks there contain many metals (Bawuro et al., 2018). In Ilesha, mercury used to extract gold reacts with other minerals to form even more harmful and long-lasting chemicals. These mixtures of pollutants are more dangerous to people than each one alone, and they make cleanup harder. In Ebonyi, acid mine drainage lowers the pH of water, which makes it easier for metals like iron, manganese, and lead to dissolve and spread (Nganje et al., 2014).

6.2.2 Biogeochemical Cycling and Retardation

Nature can sometimes reduce pollution through processes like filtering, settling, and breaking down chemicals. However, in Nigeria, the amount of pollution from mining is often too much for nature to handle, especially during the rainy season, when heavy rains wash more pollutants into water sources (Akanle et al., 2020). On top of that, poor waste disposal and washing of ores directly in streams make things worse, turning small rivers into constant sources of pollution.

6.3 Public Health and Socio-Economic Consequences

6.3.1 Waterborne Health Hazards

Pollution of drinking water with harmful substances like lead, mercury, arsenic, and uranium has serious health effects on people. In Zamfara, lead poisoning caused lasting brain damage in children. In Ilesha, long-term exposure to mercury has led to kidney problems and issues with reproduction (HRW, 2011; Oladeji et al., 2021). In Jos, drinking water contaminated with radioactive materials increases the risk of developing cancer over time (Akanle et al., 2020).

6.3.2 Livelihood Conflicts and Water Insecurity

Artisanal and small-scale mining (ASM) often conflicts with farming and access to clean water. Rivers contaminated with acid and metals are no longer safe for irrigation or animals, as seen in parts of Ebonyi and Plateau states. Without proper water treatment systems, rural communities face the challenge of relying on mining for income while dealing with poor environmental health.

6.4 Governance, Regulation, and Data Gaps

6.4.1 Institutional Challenges

The mining sector is poorly regulated because different government ministries handle it, such as Mines, Environment, and Water Resources. This has led to weak enforcement of environmental rules. Many mining activities happen without proper Environmental Impact Assessments (EIAs), groundwater checks, or plans to fix the environment after mining (Oladipo et al., 2020). Also, the Miners' Cooperative licensing system hasn't helped informal miners become responsible because of a lack of support, incentives, and trust in the government.

6.4.2 Research and Monitoring Deficiencies

Many water studies in Nigeria are limited to specific areas, react to problems as they arise, or rely on outside funding. There are very few long-term water quality records. There is also no national list of polluted mining sites, maps showing groundwater risks, or real-time monitoring of water contamination. This makes it hard to plan resources effectively and delays the use of early warning systems for water pollution.

6.5 Toward a Systems-Based Approach

The large and complicated effect of ASM on water in Nigeria requires a systems approach. Instead of treating problems separately, solutions should be combined and take into account:

i. Catchment-scale hydrogeological assessments.

ii. Community-led water monitoring.

iii. Decentralized remediation technologies including biofilters, limestone drains.

iv. Artisanal mining formalization and safer practices training

A basin-wide approach, in line with Nigeria's Integrated Water Resources Management Plan, could improve coordination between water management and mining industries, helping to protect the environment and support rural development (FMWR, 2013).

7. CONCLUSION

The growing presence of artisanal and small-scale mining (ASM) in Nigeria has caused significant effects on both groundwater and surface water. These effects are most severe in areas with vulnerable geology, where poor mining methods, lack of regulation, and weak oversight come together. This conclusion summarizes the main points of the review and outlines key areas for action in policy, research, and community efforts.

7.1 Summary of Major Findings

7.1.1 Hydrogeological Determinants of ASM Impact

The review shows that the extent of water pollution caused by ASM is mainly influenced by the type of geology in an area. Regions with fractured rocks, like Zamfara and Ilesha, don't protect against contaminants moving down into the ground. On the other hand, areas with sedimentary or carbonate rocks, like Ebonyi and Jos, allow contaminants to spread more easily through complex underground water systems (Adelana and MacDonald, 2008; Nganje et al., 2014). Faults, cracks, and other geological features that guide the location of minerals also make it easier for pollutants to travel, creating more risks in mining areas (Olayinka et al., 2012).

7.1.2 Geochemical Risks and Human Health Consequences

Artisanal and small-scale mining (ASM) releases harmful metals like lead, mercury, arsenic, cadmium, and uranium into water sources. These metals enter the water directly from mining activities or through acid mine drainage (AMD). These metals don't break down easily, can build up in living organisms, and often mix together, making them even more toxic (Bawuro et al., 2018; Oladeji et al., 2021). Studies, especially from Zamfara and Ilesha, show that long-term exposure to these pollutants can cause serious health problems, like brain damage, kidney issues, and higher cancer risk (HRW, 2011; Akanle et al., 2020).

7.1.3 Institutional and Monitoring Deficiencies

Even though the risks are increasing, Nigeria does not have a strong system to monitor water quality in mining areas. The rules and regulations are poorly funded, not well-organized, and usually react only after problems happen instead of preventing them. Many mining operations don’t have the necessary environmental permits or plan to clean up after they're done. Also, the overall water management system does not include mining activities as part of a bigger plan to manage water resources (Oladipo et al., 2020).

7.2 Policy and Scientific Implications

7.2.1 Need for Hydrogeological Risk Zonation

One key takeaway is the urgent need to map areas at risk of water contamination from mining. Using data from different fields like geophysics, geology, and chemistry to create a risk model would help with monitoring, zoning, and raising awareness in affected communities (Adelana and MacDonald, 2008). These models should be used in land planning and the licensing process for mining cooperatives.

7.2.2 Institutional Strengthening and Inter-Agency Coordination

Oladipo et al., (2020) reveal that to manage the environmental impact of mining properly, different government ministries—such as Mines, Environment, Health, and Water Resources—need to work together. Setting up state-level task forces with legal and scientific support would help ensure that mining projects follow environmental rules, involve local communities, and enforce regulations better.

7.2.3 Integration of Community and Citizen Science

Because formal institutions have limited resources, community-based water monitoring and citizen science projects could be helpful. Training local people in basic water testing methods, with support from NGOs and universities, can create early warning systems and provide important data for community efforts (Akanle et al., 2020).

7.3 Future Research Directions

The complexity of how ASM affects water in Nigeria opens up many areas for research, including:

i. Long-term studies to track how pollutants change between wet and dry seasons.

ii. Using isotopes and fingerprinting to tell apart ASM contamination from pollution from farming or cities.

iii. Trying out affordable methods to clean water, like using zero-valent iron, constructed wetlands, or biochar filters.

iv. Health studies that monitor people exposed to contamination and link water chemistry with public health.

Additionally, research collaborations across borders, especially in the Sahel and West Africa's gold mining regions, can help understand Nigeria's challenges in a broader context.

7.4 Recommendations

ASM is both crucial for Nigeria's economy and harmful to the environment. This review highlights that understanding the local geology is key to addressing water problems caused by ASM and should be the focus of regulations, research, and community strategies. Protecting water in mining areas requires moving from isolated efforts to a more connected approach that brings together science, public health, and community involvement.

With strong policies, better institutions, and active community participation, Nigeria can move toward sustainable mining practices that protect water resources and public health, while also supporting rural development.

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