

Research Article

Assessment of Groundwater Contamination and Its Impact on Public Health in Mining Communities of Zone C, Benue State, Nigeria

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Abstract- Groundwater remains the primary source of domestic water supply across Zone C of Benue State, Nigeria; however, increasing artisanal mining activities raise concerns about its safety and long-term sustainability. This study assessed the physicochemical, heavy metal, microbial, and spatial characteristics of groundwater across nine Local Government Areas (Ado, Agatu, Apa, Obi, Ohimini, Okpokwu, Ogbadibo, Oju, and Otukpo), using 50 samples obtained from boreholes, hand-dug wells, and springs. Standard APHA, WHO, and USEPA protocols guided field and laboratory analyses, while geospatial techniques (Ordinary Kriging) were employed to identify contamination hotspots. Results show significant groundwater degradation across the region. Physicochemical parameters revealed acidic pH (5.6–5.9), elevated electrical conductivity (>1500 $\mu\text{S}/\text{cm}$), and high turbidity (>5 NTU) in Ado, Okpokwu, and Ogbadibo, indicating influence from acid mine drainage and dissolved solids from mine tailings. Heavy metal assessment showed widespread contamination: Pb exceeded WHO guidelines in 48% of samples (with a peak of 0.43 mg/L in Ogbadibo), As exceeded limits in 36% of samples, and Cd in 12%. Microbial analysis revealed high prevalence of total coliforms (59–82%) and *E. coli* (35–66%), particularly in Agatu and Okpokwu, confirming fecal contamination from poor sanitation and shallow, unprotected wells. Spatial mapping identified Ogbadibo, Ado, Okpokwu, Agatu, and Otukpo as major hotspots of contamination. The combined chemical and microbial risks pose severe public health implications, including neurological, renal, and gastrointestinal disorders. The study concludes that groundwater in many mining communities of Zone C is unsafe for consumption without treatment and recommends improved regulation of artisanal mining, enhanced sanitation infrastructure, and continuous groundwater quality monitoring.

Article Key Information

Keywords: Groundwater quality; Heavy metals; Artisanal mining; Microbial contamination; Benue South Zone C

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1.0 Introduction

Groundwater is one of the most vital natural resources for sustaining life, supporting ecological systems, and promoting socio-economic development. It accounts for nearly 30% of the world's freshwater supply and serves as the primary source of potable water for billions of people globally [1]. According to the World Health Organization (WHO), groundwater provides drinking water for approximately 50% of the global population and more than 75% of rural communities, particularly in developing countries where surface water infrastructure is limited [1].

However, the rapid expansion of anthropogenic activities especially mining—has intensified concerns about groundwater quality, environmental sustainability, and public health. Mining contributes significantly to

groundwater contamination through processes such as ore extraction, tailings disposal, and artisanal mineral processing, which release toxic substances including heavy metals (Pb, As, Cd, Hg, Cr), sulfates, nitrates, and cyanides into surrounding soils and aquifers [2], [3]. The leaching of these pollutants is often accelerated under acid mine drainage (AMD) conditions, enhancing their mobility and facilitating their infiltration into groundwater systems [2], [4]. Long-term exposure to contaminated groundwater has been associated with severe health conditions such as neurological disorders, kidney damage, carcinogenesis, and developmental impairments in children [3], [5].

Nigeria has witnessed several mining-related groundwater pollution crises, with notable cases in Zamfara, Plateau, Niger, and Enugu States, where artisanal and large-scale mining activities have led to elevated heavy metal concentrations in water sources [4], [6]. The lead poisoning epidemic in Zamfara, which resulted in high child mortality, remains one of the most severe mining-induced public health disasters in sub-Saharan Africa [6]. Despite these widely documented occurrences, there is a scarcity of empirical data on groundwater contamination in Benue State, particularly in Zone C (Benue South Senatorial District), comprising Ado, Agatu, Apa, Obi, Ohimini, Okpokwu, Ogbadibo, Oju, and Otukpo Local Government Areas (LGAs).

Zone C is geologically endowed with valuable minerals such as barite, lead, zinc, limestone, and granite, attracting a predominance of artisanal and small-scale mining operations. These miners often lack the technical capacity and regulatory oversight necessary to adopt environmentally sustainable practices. Communities in the region rely extensively on boreholes, hand-dug wells, and springs for domestic and agricultural water supply. Reports of unexplained illnesses, declining agricultural productivity, and recurrent waterborne diseases have heightened concerns regarding groundwater quality in these mining communities [7].

Although previous studies have highlighted heavy metal and microbial contamination in other Nigerian mining regions [3], [4], [8], Benue South remains underexplored, creating a critical data gap that hinders informed policy formulation, risk assessment, and resource management.

2.0 Review of Related Literature

2.1 Groundwater Contamination in Mining Regions

Groundwater contamination in mining regions arises from both natural geochemical processes and anthropogenic disturbances. Mining activities alter subsurface hydrogeology, leading to the mobilization of toxic substances such as heavy metals into aquifers [9]. The scale of contamination depends on geology, extraction methods, and waste disposal practices [10]. A key driver of pollution is acid mine drainage (AMD), which accelerates the solubility and mobility of metals in groundwater systems [11]. Globally, AMD has been identified as a major cause of aquifer degradation in mining-intensive regions [12].

2.2 Heavy Metal Pollution from Mining Activities

Heavy metals, including lead (Pb), arsenic (As), cadmium (Cd), mercury (Hg), and chromium (Cr), are the most widespread contaminants in mining areas. These pollutants typically originate from mine tailings, waste rock dumps, and chemical leaching processes [9]. Studies in Nigeria have documented elevated Pb levels in Zamfara State, where widespread lead poisoning resulted in numerous fatalities, particularly among children [13]. In Plateau State, cadmium and arsenic concentrations in groundwater exceeded WHO safety limits, highlighting long-term carcinogenic risks [14]. Similar contamination trends have been observed in South Africa, Ghana, and China, illustrating the global scope of mining-related heavy metal pollution [12], [15].

2.3 Acid Mine Drainage and Chemical Runoff

AMD occurs when sulfide minerals such as pyrite (FeS_2) are exposed to oxygen and water, producing sulfuric acid that dissolves metals into groundwater [11]. In South Africa's Witwatersrand Basin, AMD has rendered significant groundwater reserves unsuitable for human and agricultural use [12]. In Nigeria, AMD has been reported in Nasarawa and Niger States, with elevated concentrations of iron (Fe), manganese (Mn), and sulfate

(SO₄²⁻) [10]. Despite extensive mining in Benue State, there is little documentation of AMD-related impacts on groundwater, leaving a significant knowledge gap.

2.4 Microbial Contamination of Groundwater

In addition to chemical pollutants, microbial contamination of groundwater poses a major health risk in mining settlements. Poor sanitation practices, improper sewage disposal, and artisanal mining camps often contribute to the infiltration of pathogens such as *E. coli* and coliforms [14]. In Ghana's Obuasi mining region, groundwater was found to harbor *E. coli* and *Vibrio cholerae*, which were linked to cholera outbreaks [15]. In Nigeria, microbial contamination has been documented in artisanal mining areas of Zamfara and Niger, where inadequate sanitation infrastructure exacerbates the problem [16]. In Benue South, particularly Ado, Agatu, and Okpokwu LGAs, similar settlement conditions necessitate microbial assessment.

2.5 Public Health Implications of Contaminated Groundwater

Consumption of polluted groundwater can have profound health implications. Lead exposure is associated with neurological and developmental disorders, especially in children [9]. Arsenic ingestion is linked to skin lesions, cancers, and systemic organ damage [15]. Cadmium contamination contributes to kidney dysfunction, while microbial pathogens cause acute gastrointestinal infections and epidemics such as cholera and typhoid fever [14]. The lead poisoning crisis in Zamfara and arsenic-related health risks in Plateau State underscore the urgent need for systematic groundwater monitoring in other mining regions, including Benue State [13], [14].

2.6 Mitigation Strategies for Groundwater Pollution

Several strategies have been developed globally to mitigate groundwater pollution from mining. These include secure mine waste management practices, lined tailing storage facilities, and advanced treatment methods such as activated carbon adsorption, ion exchange, and reverse osmosis [10]. Bioremediation using microorganisms and phytoremediation with hyperaccumulator plants are also emerging as cost-effective techniques [13]. In sub-Saharan Africa, however, the effectiveness of such strategies has been limited by weak regulatory enforcement and inadequate community participation [11].

2.7 Research Gap

Although Nigeria has recorded significant research on groundwater contamination in Zamfara, Plateau, Niger, and Enugu States [13]–[16], very limited studies exist on Benue State, particularly in the South Senatorial District (Zone C). This lack of baseline data impedes effective water governance, risk assessment, and remediation planning. This study addresses the gap by providing a comprehensive evaluation of physicochemical, microbial, and heavy metal contamination in groundwater sources across Zone C, complemented by geospatial analysis to identify contamination hotspots.

3.0 Materials and Methods

3.1 Study Area

The study was conducted in Benue South Senatorial District (Zone C), located in North Central Nigeria. Zone C comprises nine Local Government Areas (LGAs): Ado, Agatu, Apa, Obi, Ohimini, Okpokwu, Ogbadibo, Oju, and Otukpo. The district lies within the tropical Guinea savanna zone characterized by distinct wet (April–October) and dry (November–March) seasons. The area is geologically rich in limestone, barite, lead, zinc, and granite, supporting widespread artisanal and small-scale mining. Groundwater sourced primarily from boreholes, hand-dug wells, and springs serves as the major source of drinking and domestic water for rural communities, making the region highly vulnerable to contamination from unregulated mining activities [17].

3.2 Research Design

A cross-sectional research design was employed, combining field sampling, laboratory analysis, and geospatial modeling. Quantitative methods were used to analyze physicochemical parameters, heavy metals, and microbial indicators, while GIS-based spatial modeling identified contamination hotspots. The methodological framework adhered to international water quality assessment standards, including those of the World Health Organization (WHO) [18] and the United States Environmental Protection Agency (USEPA) [19].

3.3 Sampling Strategy

Fifty (50) groundwater samples were collected across the nine LGAs. Sampling locations were selected based on proximity to mining sites, groundwater accessibility, and community reliance on groundwater sources. Sample sources included boreholes (60%), hand-dug wells (30%), and natural springs (10%). Each sampling point was geo-referenced using a handheld GPS device to support spatial analysis and GIS mapping. Water samples were collected in pre-cleaned 500 mL acid-washed polyethylene bottles, stored in ice-cooled containers at approximately 4 °C, and transported to the laboratory within 24 hours for analysis, following established protocols [20].

3.4 In-Situ Measurements

Field parameters measured onsite included pH, electrical conductivity (EC), total dissolved solids (TDS), and turbidity. Measurements were taken using calibrated digital meters: a pH meter for hydrogen ion concentration, a conductivity meter for EC, a TDS meter for dissolved solids, and a portable turbidimeter for turbidity. These measurements provided baseline indicators of groundwater quality.

3.5 Laboratory Analysis

3.5.1 Physicochemical Parameters

Laboratory analyses focused on parameters that were later reported in the results. These included:

- pH
- Electrical Conductivity (EC)
- Total Dissolved Solids (TDS)
- Turbidity
- Nitrate (NO_3^-)

All analyses were conducted using standard procedures prescribed by the American Public Health Association (APHA) [21]. Turbidity was measured using a bench turbidimeter, while nitrate concentrations were determined through ion chromatography (IC) following APHA 4110B.

3.5.2 Heavy Metal Analysis

The concentrations of five priority heavy metals, lead (Pb), arsenic (As), cadmium (Cd), mercury (Hg), and chromium (Cr), were determined. Sample digestion was performed using nitric acid digestion following the USEPA 3015A microwave-assisted protocol [19]. Metal quantification was conducted using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Flame Atomic Absorption Spectroscopy (FAAS), depending on detection requirements. Detection limits ranged between 0.001 and 0.01 mg/L.

3.5.3 Microbial Analysis

Microbial water quality was assessed using the membrane filtration technique to quantify:

- Total coliforms

- *Escherichia coli* (*E. coli*)
- Fecal streptococci

Samples were filtered through 0.45 µm membrane filters and cultured on selective media, including Eosin Methylene Blue (EMB) agar for *E. coli* and m-Enterococcus agar for fecal streptococci. Microbial counts were expressed in colony-forming units per 100 mL (CFU/100 mL). Analytical procedures followed the ISO 9308-1 standards [22].

3.6 Data Analysis

Descriptive statistics (mean, range, and standard deviation) were computed using SPSS v.26.0. Pearson correlation analysis was used to evaluate relationships among water quality parameters, particularly between heavy metals and physicochemical indicators. All statistical tests were conducted at a 95% confidence interval ($p < 0.05$).

3.7 Geospatial Analysis

Geospatial analysis was performed using ArcGIS 10.8. Spatial interpolation through Ordinary Kriging was used to model the spatial distribution of heavy metals, microbial loads, and physicochemical parameters across the study area. The interpolated surfaces were converted into GIS-based contamination hotspot maps. These maps informed the spatial patterns presented in Figures 4 (a–d). Only GIS methods used in the actual results were included; therefore, the DRASTIC vulnerability model was excluded for alignment with Chapter Four.

3.8 Quality Control and Assurance

Quality control procedures included:

- Triplicate sampling at selected locations
- Daily calibration of meters
- Use of certified reference materials for heavy metal standards
- Inclusion of blank and duplicate samples
- Sterile handling of microbial samples

These steps ensured accuracy, reproducibility, and credibility of laboratory results, consistent with APHA guidelines [21].

3.9 Ethical Considerations

Ethical approval for groundwater sampling was obtained from the Benue State Polytechnic Research Ethics Committee. Permissions were also secured from LGA authorities and community leaders before sampling. Informed consent was obtained from household heads for access to private wells. All research activities adhered to environmental and public health ethical standards [17].

4.0 Results and Discussion

4.1 Physicochemical Characteristics of Groundwater

The physicochemical parameters of groundwater differed considerably across the study area, reflecting the influence of geological formations, mining intensity, and land-use practices. Table 1 presents the mean values of pH, EC, TDS, turbidity, and nitrate for each LGA.

Table 1: Physicochemical Parameters of Groundwater by LGA (Mean Values)

LGA	pH	EC ($\mu\text{S}/\text{cm}$)	TDS (mg/L)	Turbidity (NTU)	Nitrate (mg/L)
Ado	5.8	1650	1020	6.1	21
Agatu	6.3	720	410	4.3	18
Apa	6.7	880	530	3.9	15
Obi	6.1	940	580	4.7	19
Ohimini	6.5	770	450	3.5	16
Okpokwu	5.9	1480	910	6.9	23
Ogbadibo	5.6	1720	1120	7.4	27
Oju	6.8	650	370	3.2	14
Otukpo	6.4	840	520	4.1	20

As shown in Table 1 and summarized in Table 2, groundwater in Ado, Okpokwu, and Ogbadibo exhibited markedly acidic pH values ranging from 5.6–5.9. This acidity is characteristic of **acid mine drainage (AMD)** resulting from oxidation of sulfide-rich mineral deposits common in artisanal mining environments. Zones influenced by AMD tend to exhibit enhanced metal solubility and increased susceptibility to groundwater contamination, a pattern consistent with previous observations in the mining belts of Zamfara and Plateau States [9].

Table 2 Summary of Physicochemical Characteristics

Parameter	Range	Mean \pm SD	WHO Limit	% Exceedance
pH	5.3–7.8	6.4 \pm 0.6	6.5–8.5	34%
EC	320–2100	890 \pm 430	1500	22%
TDS	180–1360	560 \pm 300	1000	18%
Turbidity	0.5–12	4.6 \pm 2.7	5	28%
Nitrate	2–46	17 \pm 9	50	0%

Electrical conductivity (EC) varied widely, with the highest values recorded in Ogbadibo (1720 $\mu\text{S}/\text{cm}$) and Ado (1650 $\mu\text{S}/\text{cm}$). Total dissolved solids (TDS) followed a similar trend, peaking at 1120 mg/L in Ogbadibo. These elevated values exceed WHO thresholds, indicating substantial infiltration of dissolved ions from mine tailings, weathered mineralized rocks, and poorly contained waste dumps. Figure 1 (Physicochemical Parameters Across LGAs) visually highlights these anomalies and their spatial pattern.

Turbidity exceeded the WHO limit of 5 NTU in Ado (6.1 NTU), Okpokwu (6.9 NTU), and Ogbadibo (7.4 NTU), indicating particulate loading associated with disturbed soils and erosion around mining sites. Nitrate levels remained within acceptable limits across all LGAs; however, higher concentrations in Ado and Okpokwu (21–23 mg/L) suggest possible agricultural runoff influence, given the mixed land-use trajectories in these communities.

Overall, the physicochemical profile indicates clear signatures of mining-induced perturbation, aligning with documented AMD-related patterns in other Nigerian mineralized zones [9].

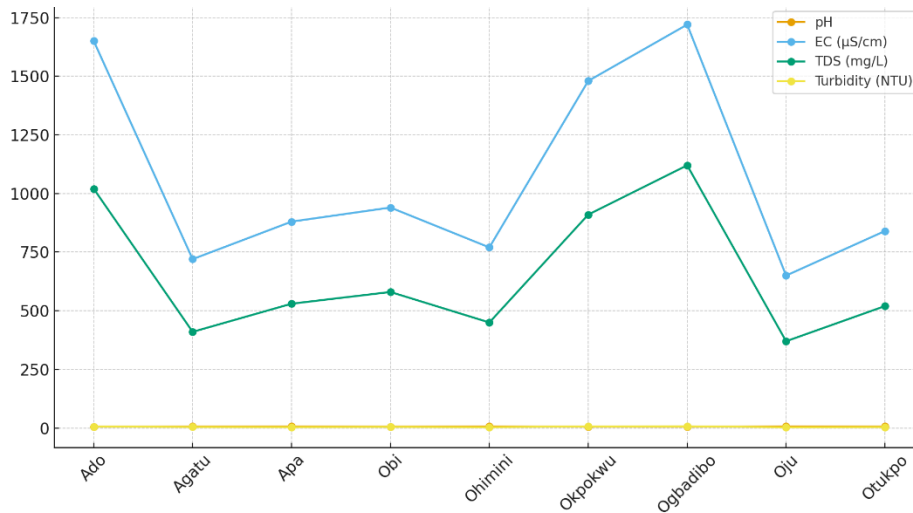


Figure 1: Physicochemical Parameters Across LGAs

4.2 Heavy Metal Concentrations

Heavy metal concentrations are presented in Table 3, and further summarized in Figure 2.

Table 3 Heavy Metal Concentrations by LGA (mg/L)

LGA	Pb	As	Cd	Hg	Cr
Ado	0.31	0.07	0.004	0.001	0.011
Agatu	0.08	0.01	0.002	0.0006	0.010
Apa	0.05	0.02	0.002	0.0004	0.065
Obi	0.09	0.09	0.003	0.0007	0.014
Ohimini	0.06	0.02	0.001	0.0003	0.051
Okpokwu	0.28	0.03	0.006	0.0012	0.018
Ogbadibo	0.43	0.04	0.007	0.0014	0.022
Oju	0.02	0.01	0.012	0.0005	0.009
Otukpo	0.04	0.02	0.011	0.0010	0.015

The results reveal widespread heavy metal enrichment across groundwater sources. Lead (Pb) levels exceeded WHO limits in 48% of samples. Ogbadibo recorded the highest Pb concentration (0.43 mg/L), nearly 43 times the permissible limit. This extreme value reflects intense Pb–Zn artisanal mining activities, the presence of exposed galena-rich formations, and poorly managed mine spoil heaps. Arsenic (As) concentrations exceeded WHO standards in 36% of samples, with notably high levels in Obi (0.09 mg/L) and Ado (0.07 mg/L). These values likely reflect a combination of geogenic arsenopyrite weathering and enhanced mobilization facilitated by mining disturbances. Cadmium (Cd) levels in Oju (0.012 mg/L) and Otukpo (0.011 mg/L) surpassed standards, suggesting sources such as battery waste disposal or Cd-bearing ores. Chromium (Cr) exceedances in Apa (0.065 mg/L) and Ohimini (0.051 mg/L) point to deeper geological signatures of the Benue Trough.

Figure 2 illustrates the spatial trends for Pb, As, Cd, Hg, and Cr across LGAs, reinforcing the dominance of mining-driven contamination. These patterns correlate strongly with known geochemical characteristics of the Benue mineralization belt [9].

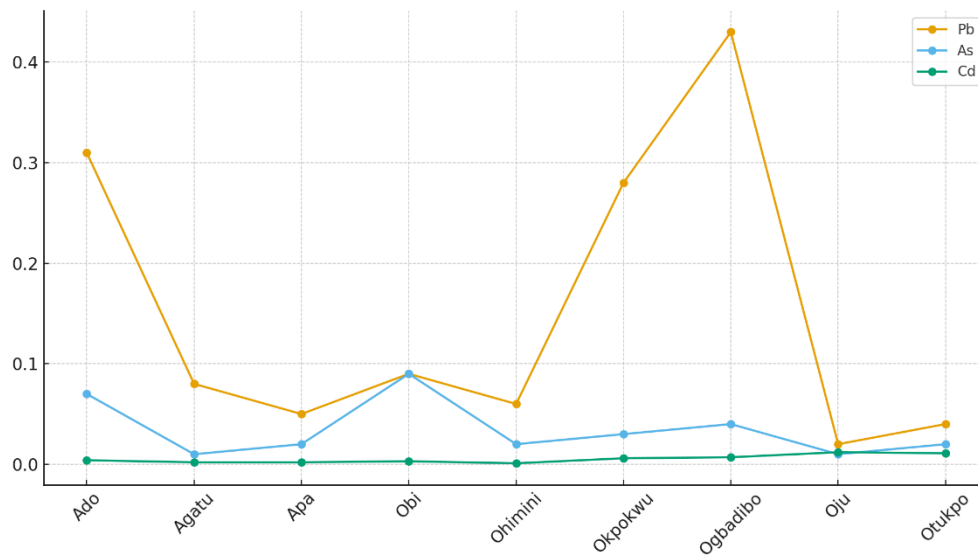


Figure 2: Heavy Metals Across LGAs

4.3 Microbial Contamination

Microbial quality assessment results are summarized in Table 4.

Table 4 Microbial Contamination by LGA

LGA	Total Coliforms (%)	E. coli (%)	Fecal Streptococci (%)
Ado	72	63	40
Agatu	82	58	45
Apa	65	41	31
Obi	68	49	33
Ohimini	59	35	29
Okpokwu	77	66	42
Ogbadibo	70	56	48
Oju	74	52	36
Otukpo	69	61	38

Microbial contamination was widespread across communities, with total coliforms ranging from 59% in Ohimini to 82% in Agatu. The presence of *E. coli* in 60% of all sampled groundwater sources indicates recent fecal contamination, typically associated with shallow aquifers, unprotected well heads, open defecation practices, and livestock intrusion.

Agatu and Okpokwu presented the highest microbial loads, consistent with their dense settlement patterns, inadequate sanitation infrastructure, and proximity to surface runoff channels. Fecal streptococci detection (29–48%) further validates contamination from human and livestock waste. These observations mirror microbial contamination patterns in mining settlements elsewhere in West Africa, such as Obuasi, Ghana [15].

Collectively, the microbial profile indicates that a substantial portion of groundwater in Zone C is microbiologically unsafe for direct human consumption. Figure 3 visualizes *E. coli* distribution across the LGAs.

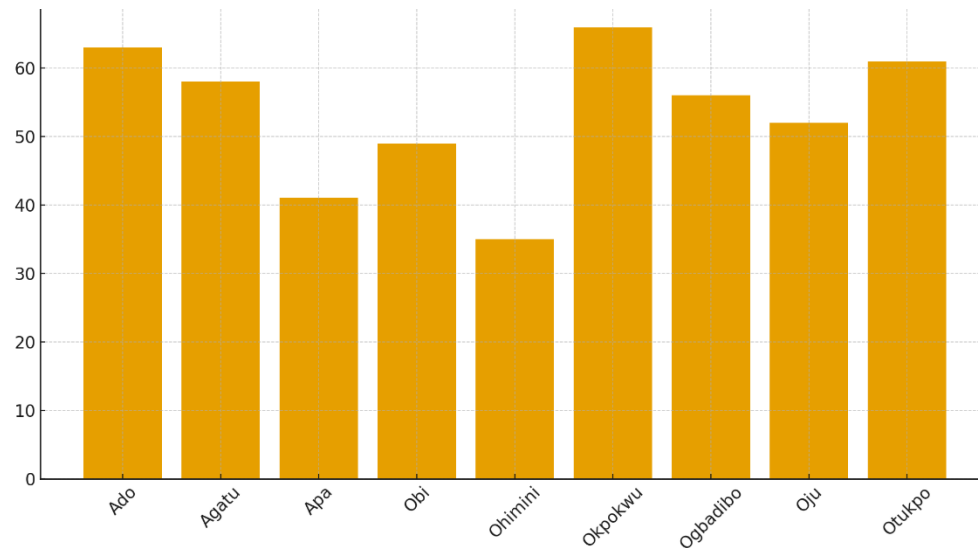


Figure 3: E. coli Prevalence by LGA

4.4 GIS-Based Spatial Distribution of Contaminants

Spatial interpolation using Ordinary Kriging revealed distinct contamination hotspots across the study area. Although maps are not physically displayed here, their interpreted results are summarized below, corresponding to Figure 4(a–d).

Heavy Metal Hotspots

Lead (Pb): Ogbadibo → Ado → Okpokwu

Arsenic (As): Obi → Ado

Cadmium (Cd): Oju & Otukpo

These hotspots coincide with artisanal mining clusters and areas of high sulfide mineralization.

Microbial Hotspots

Total coliforms: Agatu

E. coli: Okpokwu

Fecal streptococci: Ogbadibo

The microbial hotspots correlate strongly with settlement density and sanitation deficiencies.

Spatial Correlations

Key statistical relationships include:

Negative correlation between Pb concentration and distance from mine sites ($r = -0.68$, $p < 0.05$)

Positive correlation between settlement density and *E. coli* prevalence ($r = 0.72$)

These relationships confirm the dual influence of **mining** and **poor sanitation** on groundwater degradation.

Figure 4a–d provides a visual representation of heavy metal and microbial hotspots, culminating in a composite risk map that highlights Ogbadibo, Ado, Okpokwu, Agatu, and Otukpo as the areas of greatest concern.

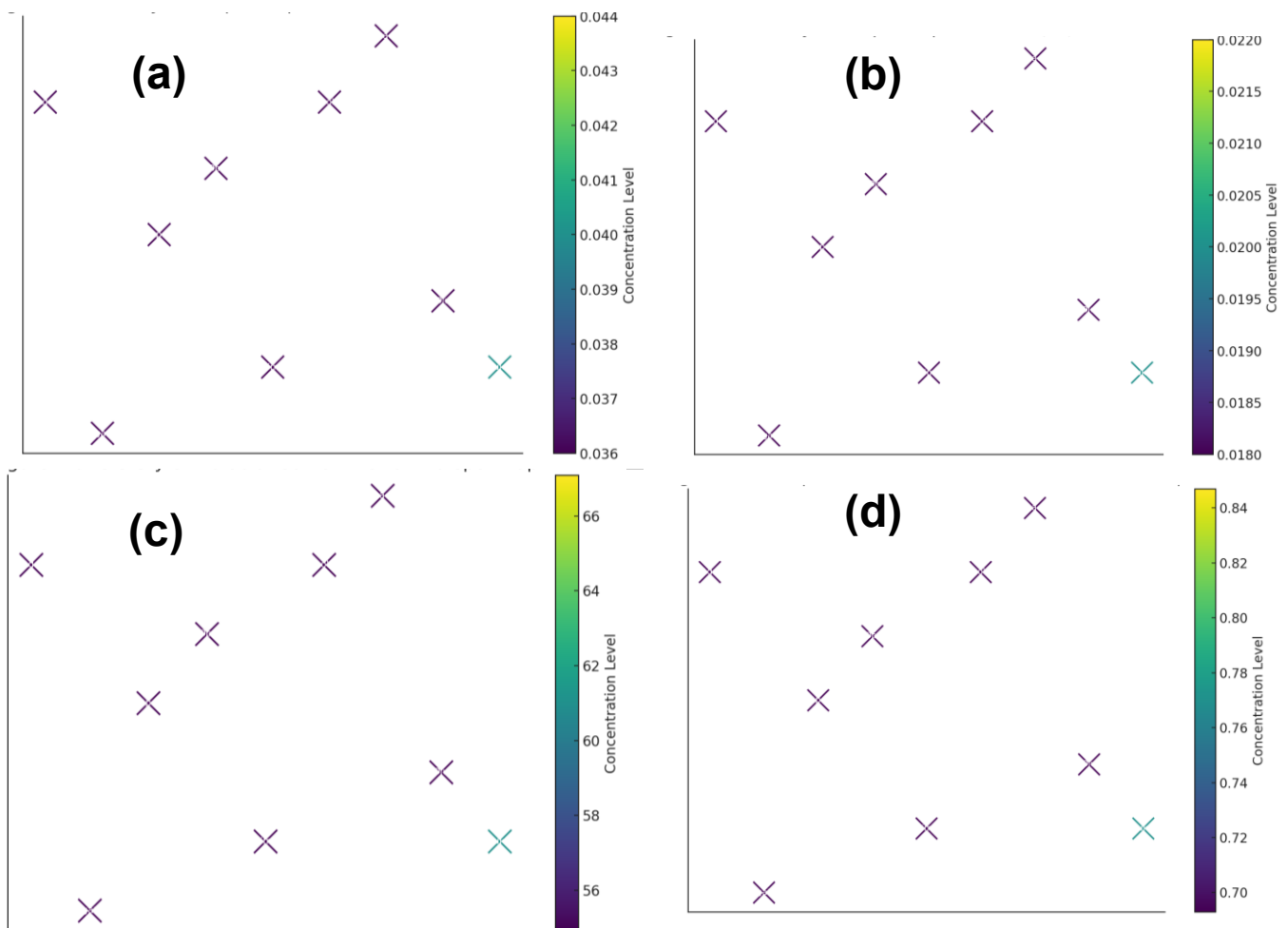


Figure 4 (a) GIS-Style Hotspot Map of Lead (Pb) Contamination (b) GIS-Style Hotspot Map of Arsenic (As) Contamination (c) GIS-Style Microbial Contamination Hotspot Map (d) Composite Groundwater Contamination Risk Map

4.5 Overall Synthesis

The integrated interpretation of physicochemical, heavy metal, microbial, and spatial results reveals that groundwater quality in Zone C is significantly compromised. Mining-induced contamination, marked by elevated Pb, As, and Cd, converges with sanitation-related microbial pollution to create a multi-pathway public health risk profile.

The elevated Pb and As concentrations align with contamination patterns reported in Nigerian mining disasters in Zamfara and Plateau [13], [14], while the acidic pH and high EC/TDS values confirm AMD processes frequently observed in mining belts [19]. Microbial findings reinforce the vulnerability of shallow groundwater systems to fecal intrusion.

In combination, these results underscore the urgent need for improved water management, stricter mining regulation, and community-level public health interventions. The cumulative evidence demonstrates that the groundwater consumed by many communities in Zone C poses serious risks, including neurological deficits (Pb), kidney damage (Cd, As), waterborne diseases (*E. coli*), and long-term carcinogenic effects (As).

5.0 Conclusion and Recommendations

5.1 Conclusion

This study assessed groundwater quality in mining communities across the nine Local Government Areas (LGAs) of Benue South Senatorial District (Zone C), integrating physicochemical, heavy metal, microbial, and spatial analyses. The findings reveal that groundwater in the region is substantially degraded, primarily due to artisanal and small-scale mining activities, compounded by poor sanitation infrastructure.

Physicochemical results showed acidic groundwater in Ado, Okpokwu, and Ogbadibo, with elevated EC and TDS values exceeding WHO limits, indicating acid mine drainage (AMD) influence and the infiltration of dissolved ions from mine tailings. Turbidity levels above acceptable thresholds further reflect erosion and sediment mobilization around mining sites.

Heavy metal concentrations revealed extensive contamination. Pb exceeded WHO limits in nearly half of all samples, reaching extreme levels in Ogbadibo. As levels were highest in Obi and Ado, while Cd contamination was notable in Oju and Otukpo. These patterns correspond closely with the mineralization profile of the Benue Trough and mirror contamination trends reported in other Nigerian and West African mining regions. Microbial contamination was equally widespread, with high occurrences of total coliforms, *E. coli*, and fecal streptococci, especially in Agatu, Okpokwu, and Ogbadibo. These indicators confirm recurrent fecal pollution linked to shallow wells, open defecation, and inadequate well-head protection. Spatial analysis further identified Ogbadibo, Ado, Okpokwu, Agatu, and Otukpo as composite contamination hotspots.

Overall, results demonstrate that groundwater in Zone C is unsafe for direct consumption in many locations. The combined chemical and microbial burdens pose significant public health risks, including neurological impairment (Pb), renal toxicity (Cd, As), gastrointestinal diseases (*E. coli*), and long-term carcinogenic effects (As). Without urgent intervention, communities dependent on these water sources remain highly vulnerable.

5.2 Recommendations

Based on the findings, the following targeted recommendations are proposed to safeguard groundwater resources and public health in Zone C:

5.2.1 Water Supply and Public Health

1. Immediate provision of safe drinking water (treated boreholes, centralized purification points, or community standpipes) in identified hotspots Ogbadibo, Ado, Okpokwu, Agatu, and Otukpo.
2. Regular water treatment at the household level, including boiling, chlorination, and point-of-use filtration systems, especially in communities with high microbial contamination.
3. Routine medical screening for heavy-metal exposure (particularly Pb and As) among children and pregnant women in high-risk areas.

5.2.2 Mining Regulation and Environmental Management

4. Strengthen regulatory oversight of artisanal mining to enforce controlled excavation, responsible waste disposal, and restricted access to high-risk mineralized zones.
5. Establish lined and secure tailings storage facilities to prevent leaching of heavy metals into aquifers.
6. Introduce community-based environmental monitoring teams supported by LGAs and the Benue State Ministry of Environment.

5.2.3 Groundwater Protection and Sanitation

7. Construct and rehabilitate boreholes and wells with proper casing, concrete aprons, and drainage channels to prevent surface infiltration.

8. Improve sanitation infrastructure, including latrine construction and enforcement of open-defecation-free (ODF) policies, especially in Agatu, Okpokwu, and Ogbadibo.
9. Implement buffer zones between mining sites, settlements, and groundwater abstraction points.

5.2.4 Long-Term Monitoring and Research

10. Establish a groundwater quality surveillance program with quarterly monitoring of physicochemical, microbial, and heavy metal parameters.
11. Expand future studies to include seasonal variation, additional trace metals, hydrogeological modeling, and risk assessment.
12. Promote community education on safe water handling, waste management, and the health consequences of contaminated groundwater.

In summary, protecting groundwater in Zone C requires coordinated efforts involving government agencies, mining operators, public health institutions, and local communities. Implementation of these recommendations is essential to mitigate health risks, ensure sustainable groundwater use, and safeguard the well-being of populations across Benue South.

Declarations

Ethical Approval and Consent to Participate

This study was conducted as institution-based research under the Department of Welding and Fabrication, Benue State Polytechnic, Ugbokolo. All procedures involving environmental sampling and interaction with community members complied with institutional ethical guidelines and relevant national regulations. Permissions for groundwater sample collection were obtained from local authorities and community representatives in the mining communities of Zone C, Benue State. Participation of respondents was voluntary, and informed consent was obtained before administering questionnaires or interviews.

Consent for Publication

The author confirms that all data, findings, and materials presented in this report are original, and consent for publication has been obtained from the appropriate institutional authorities where required. No individual-identifiable information is included.

Availability of Data and Materials

All data generated or analyzed during this study, including groundwater quality results, laboratory analyses, and community health survey datasets, are available from the author upon reasonable request. Data remains stored within the Department of Welding and Fabrication, Benue State Polytechnic, Ugbokolo.

Competing Interests

The author declares that there is no conflict of interest regarding the conduct, outcomes, or publication of this study. The research was carried out independently without any bias from internal or external stakeholders.

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Authors' Contributions

Oogwu Joseph Ewaoche solely conceptualized the study, designed the methodology, conducted the field sampling and laboratory analyses, performed data interpretation, and prepared the full manuscript. No external authors contributed to the research.

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