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Microbial Influence on Redox Geochemistry in Enugu Shale Aquifer: Implications for Iron, Manganese, and Arsenic Dynamics

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Abstract

This study investigates the concentrations of redox-sensitive metals—iron (Fe^{3+}), manganese (Mn^{2+}), and arsenic (As)—in groundwater from selected locations within Enugu, Southeastern Nigeria. A total of 25 water and sediment samples were collected from hand-dug wells and streams across five geographical areas: Emene, Ugwuaji, New Artisan, Gariki, and Agbani Road. Samples were collected using sterile bottles, stored under cool conditions, and analyzed in the laboratory using Atomic Absorption Spectrophotometry (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS), following standard EPA analytical methods. All analyses were performed in triplicate, and results were reported as mean concentrations in milligrams per liter (mg/L). The results revealed widespread exceedance of World Health Organization (WHO) permissible limits for drinking water. In the Emene area, Fe^{3+} ranged from 0.280 to 0.350 mg/L, Mn^{2+} from 0.170 to 0.260 mg/L, and As from 0.018 to 0.035 mg/L. At Ugwuaji, Fe^{3+} levels varied between 0.100 and 0.300 mg/L, Mn^{2+} between 0.120 and 0.210 mg/L, and arsenic peaked at 0.050 mg/L, five times above the WHO limit of 0.01 mg/L. New Artisan samples recorded Fe^{3+} between 0.210 and 0.300 mg/L, Mn^{2+} between 0.180 and 0.270 mg/L, and As from 0.011 to 0.022 mg/L. In Gariki, iron concentrations were especially high, ranging from 0.360 to 0.553 mg/L, with manganese between 0.130 and 0.210 mg/L and arsenic reaching up to 0.074 mg/L. The Agbani Road area showed the highest contamination levels, with Fe^{3+} from 0.520 to 0.740 mg/L, Mn^{2+} from 0.600 to 0.780 mg/L, and arsenic values as high as 0.060 mg/L. The consistently elevated levels of these metals particularly arsenic and manganese, indicate the presence of reducing geochemical conditions in the subsurface, likely influenced by microbial activity and the reductive dissolution of metal-bearing minerals. These findings raise significant concerns regarding the safety of groundwater for domestic use in these areas and highlight the need for regular monitoring and remediation strategies to protect public health.

Keywords: Groundwater quality, Iron, Manganese, Arsenic, Redox processes, Microbial activity, AAS, ICP-MS, WHO guidelines.

INTRODUCTION

Redox processes are fundamental to groundwater geochemistry, especially in environments where oxygen is limited or absent. These processes govern the chemical speciation, mobility, and transformation of many dissolved constituents, particularly redox-sensitive elements such as iron (Fe), manganese (Mn), and arsenic (As). The redox potential (Eh) of an aquifer system influences whether these elements remain in relatively immobile oxidized forms or become mobilized in reduced, more soluble states (Appelo and Postma, 2005; Zhu and Anderson, 2002).

In subsurface environments like shale aquifers, redox transformations are often biologically mediated. Microorganisms play a central role by using alternative electron acceptors when oxygen is scarce, thereby driving redox reactions that alter the geochemical landscape. For instance, iron-reducing bacteria such as *Geobacter* and *Shewanella* can reduce insoluble ferric iron (Fe^{3+}) to its more soluble ferrous form (Fe^{2+}), enhancing its mobility in groundwater (Lovley *et al*., 2004; Weber *et al*., 2006). Similarly, manganese-reducing bacteria catalyze the conversion of Mn(IV) oxides to Mn(II), while certain sulfate-reducing and iron-reducing microbes can indirectly mobilize arsenic by reductive dissolution of arsenic-bearing iron oxides (Islam *et al*., 2004; Oremland and Stolz, 2003).

The geochemical behavior of Fe, Mn, and As in shale-dominated aquifers is of particular concern due to the tendency of these systems to support reducing conditions. The Enugu Shale Formation, which underlies much of southeastern Nigeria, is rich in organic matter and finely grained sediments—both of which contribute to low-permeability, anoxic conditions that favor microbially mediated redox transformations (Nwajide, 2013). Under such conditions, Fe and Mn can accumulate in groundwater at levels exceeding WHO standards, posing aesthetic and potential health risks (WHO, 2017). Arsenic, though often present in trace amounts, can become highly toxic when mobilized through microbially driven reductive dissolution of iron oxides (Smedley and Kinniburgh, 2002).

The knowledge of the interaction between microbial activity and redox geochemistry is therefore essential for evaluating groundwater quality and predicting the behavior of toxic metals in shale aquifer systems like those in Enugu. It also provides insight into natural attenuation processes and informs the development of remediation strategies where necessary.

REVIEW OF LITERATURE

The role of redox processes in groundwater systems has been widely studied due to their influence on the mobility of redox-sensitive elements such as iron, manganese, and arsenic. These elements, though naturally occurring, can reach hazardous levels in groundwater under reducing conditions, especially when mediated by microbial activity (Appelo and Postma, 2005; Smedley and Kinniburgh, 2002).

Microorganisms play a key role in driving redox transformations by utilizing elements like Fe (III), Mn (IV), and SO_4^{2-} as terminal electron acceptors in the absence of oxygen. For instance, *Geobacter* and *Shewanella* species are well-known iron and manganese reducers, capable of transforming insoluble metal oxides into soluble forms, thereby increasing their concentration in groundwater (Lovley *et al*., 2004; Weber *et al*., 2006). In addition, arsenic release is frequently linked to microbial reduction of iron oxides that host arsenic, a process that has been observed in various sedimentary aquifers, including those in the Bengal Delta and other tropical regions (Islam *et al*., 2004; Oremland and Stolz, 2003).

In Nigeria, studies on groundwater quality in the Anambra and Enugu basins have highlighted elevated concentrations of Fe, Mn, and occasionally As, particularly in shale-rich zones characterized by low oxygen and high organic matter content (Edet and Okereke, 2001; Eze and Maduka, 2021). These findings suggest a link between the local geology, microbial activity, and the redox status of the aquifers, although microbial contributions to metal mobilization remain understudied in southeastern Nigeria. The knowledge of these microbial-redox interactions is crucial for water quality management, especially in regions dependent on shallow aquifers for domestic use. More localized investigations, such as those targeting the Enugu Shale Formation, are necessary to elucidate the specific microbial processes influencing redox geochemistry and the behavior of toxic elements.

Location of the Study Area

Enugu, the south-east capital of Nigeria, is located between latitudes 6°22′N and 6°39′N and longitudes 7°26′E and 7°40′E. The city measures a total area of about 79 square kilometers (Egboka *et al*., 1989). As the commercial and administrative center of Enugu State, the city is blessed with history that has been irrevocably interwoven with its coal mines, which have served as the driving force behind progress in its development. Enugu is situated in the Anambra Basin, one of Nigeria's principal sedimentary basins. The city's topography has been shaped by the action of various geological processes and human activities over time.

Geologic Settings and Hydrogeology of the Study Area

The study area, Enugu, is situated within the Anambra Basin of southeastern Nigeria—a region with a well-documented geologic history dominated by Cretaceous sedimentary formations. The basin is composed of interbedded sequences of siltstones, sandstones, shales, and coal seams. Among these, the Enugu Shale, Mamu Formation, and Ajali Sandstone are particularly significant due to their hydrogeologic properties, with the Ajali Sandstone recognized as a highly productive aquifer unit (Ezeh, 2012). Groundwater in the region primarily occurs in unconfined to semi-confined aquifers, and its movement is largely influenced by the topography and the permeability of the underlying geological formations. Recharge is mainly from precipitation, although infiltration rates vary locally depending on soil characteristics and vegetation cover. The

Ajali Sandstone, known for its high porosity and permeability, serves as the principal groundwater reservoir in many parts of Enugu.

However, increasing urbanization, agricultural activities, and poor waste management practices have heightened the risk of groundwater contamination. This has created an urgent need for integrated hydrogeological and microbial assessments to ensure the sustainable management of water resources. Recent studies have adopted geophysical and geological mapping techniques to better understand aquifer distribution and groundwater potential. For instance, Ezeh (2012) conducted hydrogeophysical investigations that highlighted the spatial extent and groundwater yield of key formations like the Ajali Sandstone. Similarly, Okechukwu and Ikenna (2024) examined groundwater quality across Enugu Metropolis, emphasizing the need for ongoing monitoring in the face of increasing contamination threats from industrial and urban development.

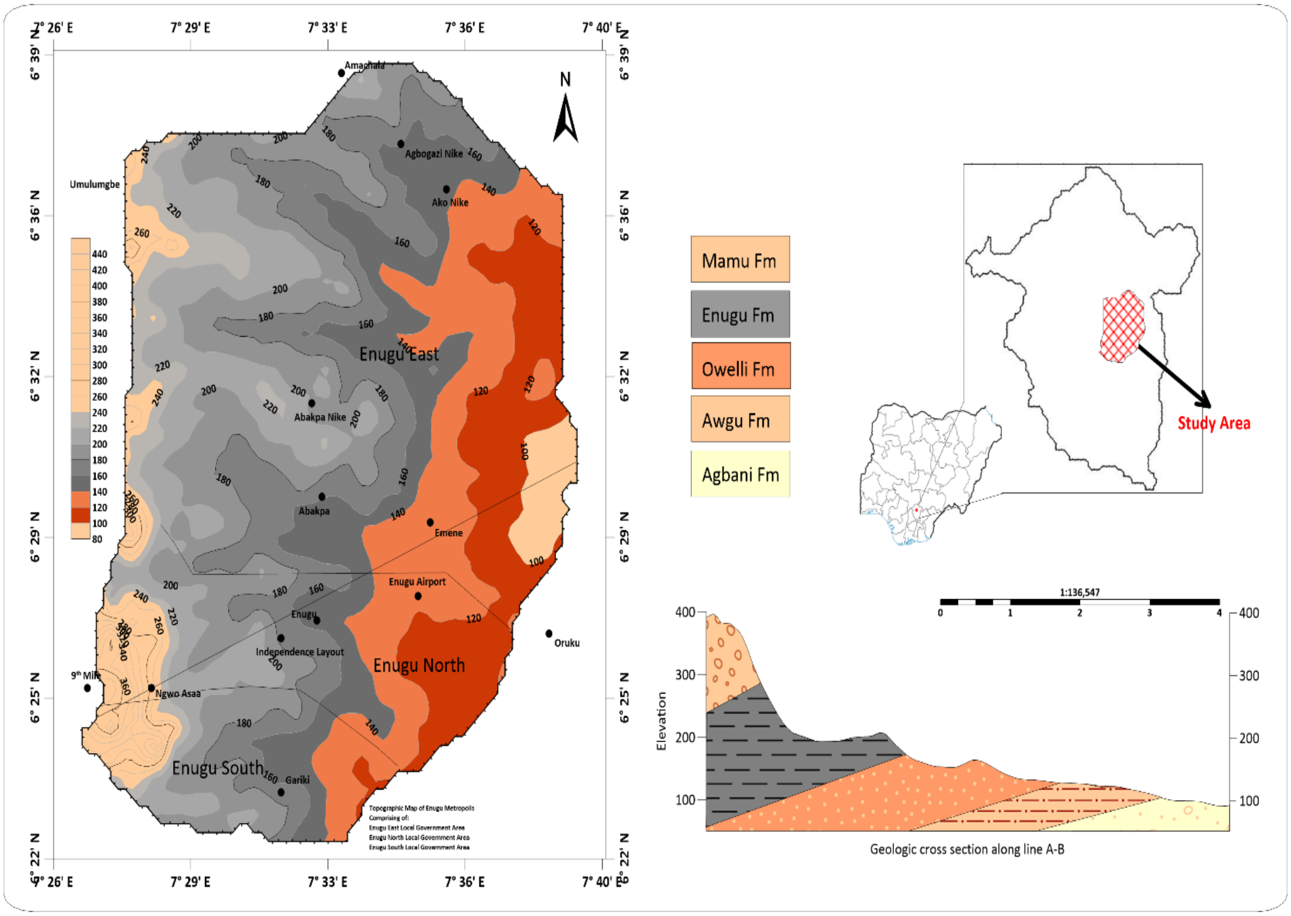

Figure 1: Geologic map of the study area

MATERIALS AND METHODS

Sample Collection

Water and sediment samples of 25 in number from different locations namely; Emene**,** Ugwuaji, New-artisan, Gariki and Agbani Road geographical areas were collected using sterile water bottle. The samples were sent to the laboratory and stored under cool temperature in a refrigerator.

Assay method

The concentrations of iron (Fe^{3+}), manganese (Mn^{2+}), and arsenic (As) in groundwater samples were determined using Atomic Absorption Spectrophotometry (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS)**,** following standard analytical guidelines outlined by the United States Environmental Protection Agency (EPA, 1994; EPA Method 200.7 and 200.8)**.**

Sample Preparation

Water samples were first filtered through 0.45 µm membrane filters to remove suspended particulates. For AAS analysis, filtered samples were acidified to pH <2 using concentrated nitric acid (HNO_3) to preserve metal ions in solution and prevent precipitation. Samples for ICP-MS were similarly acidified and stored in high-density polyethylene (HDPE) bottles at 4 °C until analysis.

Iron and Manganese Analysis (AAS)

Fe^{3+} and Mn^{2+} were quantified using a flame AAS (PerkinElmer AAnalyst 400), with wavelength settings of 248.3 nm and 279.5 nm respectively. Calibration was done using certified standard solutions in the range of 0.1–5.0 mg/L. Blanks and quality control samples were analyzed intermittently to ensure accuracy and instrument stability. Detection limits were approximately 0.01 mg/L for both metals.

Arsenic Speciation (ICP-MS)

Total arsenic concentrations were measured using an Agilent 7700x ICP-MS equipped with a collision/reaction cell to minimize polyatomic interferences. The instrument was calibrated with multi-element standards, and internal standards (e.g., Ge or Rh) were added to correct for matrix effects and instrumental drift. Speciation of As(III) and As(V), where required, was carried out using ion chromatography coupled with ICP-MS, following EPA Method 200.8. The method detection limit for arsenic was 0.001 mg/L. All analyses were performed in triplicate, and results were expressed as mean concentrations (mg/L). Analytical accuracy and precision were verified using standard reference materials and recovery tests, which yielded recovery rates between 95–105%.

RESULT AND DISCUSSION

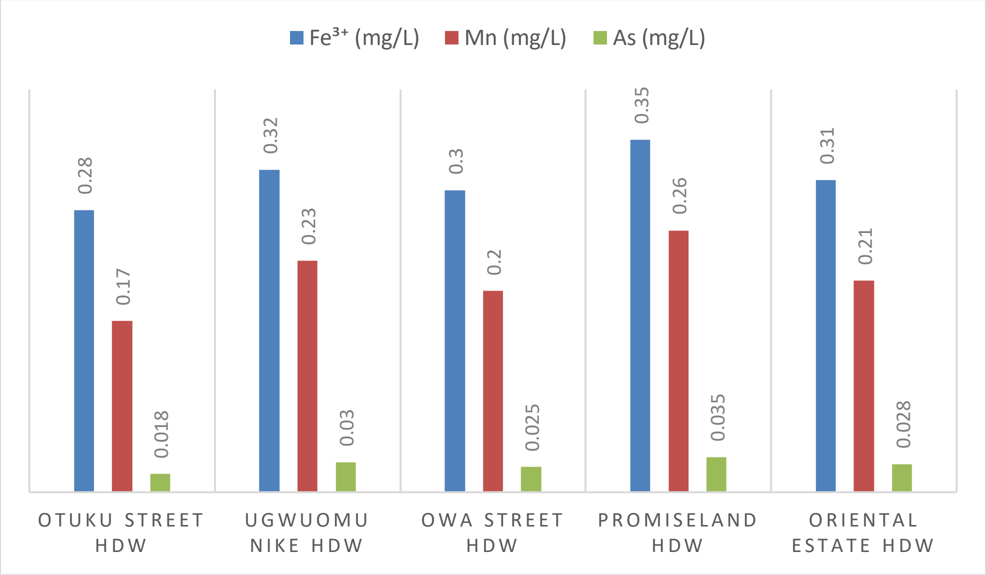

Fig 1: Metal Water Quality Analysis Results for Emene Geographical Area

The groundwater quality results from five hand-dug wells (HDWs) across the Emene area of Enugu reveal notable variations in the concentrations of redox-sensitive metals—iron (Fe^{3+}), manganese (Mn^{2+}), and arsenic (As). Iron concentrations ranged from 0.280 to 0.350 mg/L, with Promiseland HDW exhibiting the highest value. Manganese levels followed a similar trend, varying between 0.170 and 0.260 mg/L, and again peaking at Promiseland. Arsenic concentrations, though relatively low in absolute terms, exceeded the WHO permissible limit of 0.01 mg/L in all locations, with values spanning from 0.018 to 0.035 mg/L. These data suggest a consistent presence of reducing conditions in the subsurface environment of this shale aquifer system, likely driven by biogeochemical processes.

The pattern of elevated Fe^{3+}, Mn^{2+}, and As concentrations, especially in Promiseland HDW, points to localized redox transformations strongly influenced by microbial activity. In anoxic zones common in shale aquifers, microorganisms such as *Geobacter*, *Shewanella*, and sulfate-reducing bacteria (SRB) utilize iron and manganese oxides as electron acceptors during anaerobic respiration. This microbial action reduces insoluble Fe(III) and Mn(IV) to their soluble forms, Fe^{2+} and Mn^{2+}, thereby enhancing their mobility and concentrations in groundwater (Lovley *et al*., 2004; Chapelle, 2001).

Arsenic, often bound to iron oxyhydroxides, is released as a secondary effect when microbial reduction dissolves these iron substrates, a mechanism well-documented in aquifers across Asia and increasingly observed in Nigerian shale environments (Smedley and Kinniburgh, 2002; Islam *et al*., 2004). Recent studies by Ozoko and Ezeugwu (2025) support this mechanism in the Enugu region, identifying active zones of microbial iron and sulfate reduction as primary drivers of elevated Fe, Mn, and As levels in shallow aquifers, particularly in shale-dominated settings like Emene.

The elevated levels of these metals carry important implications. First, their concentrations exceed acceptable limits for drinking water quality, indicating potential health risks such as neurotoxicity (from Mn), gastrointestinal issues (from Fe), and carcinogenicity (from As). Second, their mobilization reflects active subsurface microbial ecosystems that are responding to organic matter availability, oxygen depletion, and geochemical gradients within the Enugu Shale formation. These microbial processes not only alter the redox state of the aquifer but also affect the long-term stability and sustainability of groundwater resources in urbanizing areas like Emene.

Similar findings have been reported in other parts of Enugu State. For instance, Ezeh and Ugwu (2010) described reducing groundwater conditions associated with elevated Fe and Mn levels in the same geological setting. Okechukwu and Ikenna (2024) further emphasized the link between microbial communities and metal contamination, highlighting how urbanization, sewage discharge, and decaying organic matter contribute to the creation of reducing environments favorable to microbial respiration. These studies, consistent with the Emene data and with the findings of Ozoko and Ezeugwu (2025), underscore the critical need for monitoring redox-sensitive metal dynamics and microbial populations in shallow aquifers, especially in regions undergoing rapid development.

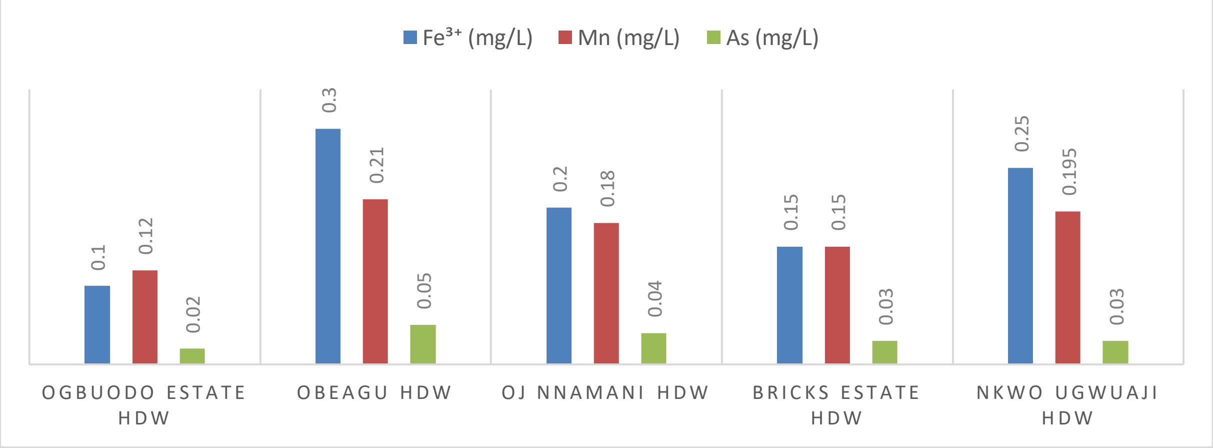

Fig 2: Metal Water Quality Analysis Results for Ugwuaji Geographical Area

The groundwater samples from five hand-dug wells across the Ugwuaji area show varied concentrations of iron (Fe^{3+}), manganese (Mn^{2+}), and arsenic (As). Iron levels ranged from 0.100 mg/L at Ogbuodo Estate HDW to 0.300 mg/L at Obeagu HDW, with most values exceeding or approaching the WHO guideline of 0.3 mg/L for iron. Manganese concentrations ranged from 0.120 to 0.210 mg/L, consistently above the WHO recommended limit of 0.1 mg/L, while arsenic levels were particularly elevated at Obeagu HDW (0.050 mg/L), nearly five times the WHO limit of 0.01 mg/L. This variation highlights spatial heterogeneity in the geochemical environment and suggests differential microbial and redox processes influencing metal mobilization.

The observed trends can be linked to microbial activity driving redox reactions within the aquifer. The higher Fe and Mn concentrations in wells like Obeagu and Nkwo Ugwuaji likely indicate active microbial reduction of Fe(III) and Mn(IV) oxides under anaerobic conditions. Microorganisms such as iron-reducing *Geobacter* and manganese-reducing *Shewanella* species utilize these metals as terminal electron acceptors, facilitating their dissolution and release into groundwater (Lovley *et al*., 2004). Arsenic concentrations, particularly elevated at Obeagu HDW, reflect the mobilization of arsenic bound to iron oxyhydroxides during microbial iron reduction, a phenomenon well-documented in sedimentary aquifers worldwide (Smedley and Kinniburgh, 2002). Similar mechanisms have been identified in the Enugu region, where Ozoko and Ezeugwu (2025) observed elevated levels of Fe, Mn, and As in anaerobic zones of shale aquifers, driven by microbial respiration and the degradation of organic matter.

The lower Fe and Mn at Ogbuodo Estate HDW may suggest more oxic or less biologically active conditions limiting microbial reduction. Such spatial variations in microbial activity and redox state are often controlled by differences in aquifer permeability, organic carbon content, and recharge dynamics.

The implications of these findings are significant for water quality and public health in the Enugu Shale region. Elevated Fe and Mn can cause aesthetic and operational problems in water supply systems, such as discoloration and taste issues, while arsenic exposure poses serious health risks, including skin lesions, cardiovascular issues, and cancer. The microbial mediation of these metals also implies that any changes in organic matter input, aquifer recharge, or land use (e.g., urbanization, agriculture) could alter redox dynamics and promote further metal mobilization. Understanding these microbial–geochemical interactions is therefore critical for sustainable groundwater management and risk mitigation in the area.

Comparatively, these results align with studies conducted elsewhere in Enugu and other shale aquifer systems. Ezeh and Ugwu (2010) reported similar patterns of Fe and Mn mobilization under reducing conditions linked to microbial activity. In addition, Okechukwu and Ikenna (2024) highlighted elevated arsenic levels in urban and peri-urban Enugu groundwater as a consequence of microbial iron reduction and redox fluctuations induced by anthropogenic influences. Globally, research in Bangladesh and India has demonstrated how microbial reduction of iron and manganese oxides drives arsenic contamination in sedimentary aquifers, providing a broader context for interpreting the Enugu data (Islam *et al*., 2004; Ravenscroft *et al*., 2009). These broader patterns reaffirm the findings by Ozoko and Ezeugwu (2025), who emphasized that aquifers in the Enugu region are highly susceptible to biogeochemically driven metal contamination, especially under the stress of rapid urban development.

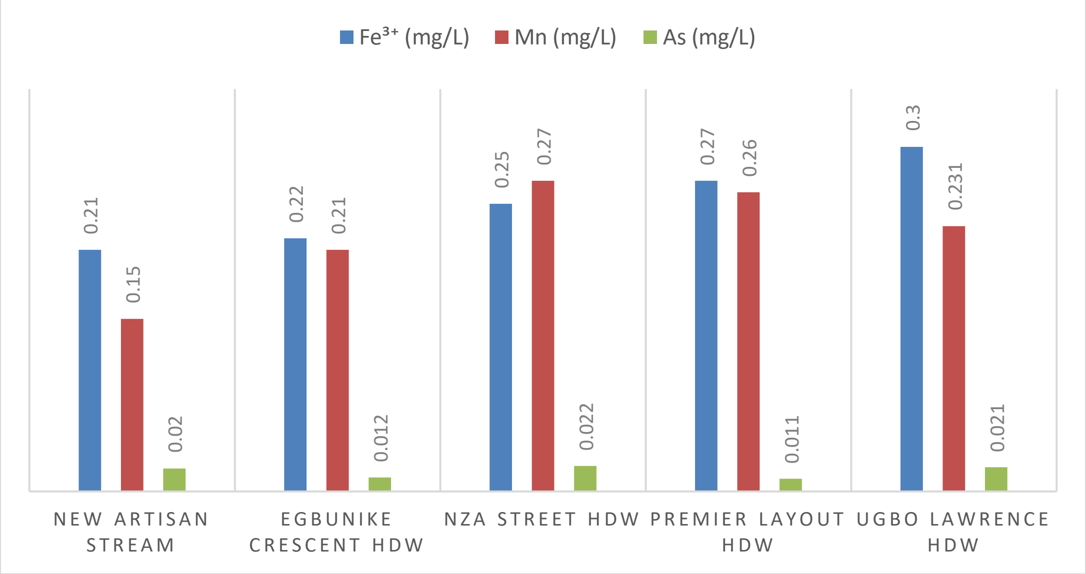

Fig 3: Metal Water Quality Analysis Results for New-Artizan Geographical Area

The water quality results from the New Artisan geographical area reveal moderate but variable concentrations of redox-sensitive metals, particularly iron (Fe^{3+}), manganese (Mn^{2+}), and arsenic (As). Iron concentrations ranged from 0.210 mg/L in the stream sample to 0.300 mg/L in the Ugbo Lawrence hand-dug well (HDW), with several values approaching or meeting the WHO permissible limit of 0.3 mg/L. Manganese levels were consistently elevated across the sites, peaking at 0.270 mg/L in Nza Street HDW and exceeding the WHO recommended limit of 0.1 mg/L. Arsenic concentrations remained relatively low but showed slight variations, ranging from 0.011 mg/L in Premier Layout HDW to 0.022 mg/L in Nza Street HDW, with values exceeding the 0.01 mg/L guideline in all but one location.

The patterns observed across the samples suggest active subsurface redox processes, likely mediated by microbial communities. Higher iron and manganese concentrations in groundwater compared to the stream (New Artisan stream) imply more reducing conditions in the saturated zones of the aquifer. This supports the likelihood of microbial iron- and manganese-reducing activity, particularly by genera such as *Geobacter* and *Shewanella*, which are known to utilize Fe (III) and Mn (IV) as terminal electron acceptors under anaerobic conditions (Lovley *et al*., 2004). These processes not only mobilize Fe and Mn into the aqueous phase but also indirectly contribute to the release of arsenic bound to iron and manganese oxides. The slightly elevated arsenic levels in Nza Street and Ugbo Lawrence HDWs may reflect zones of enhanced microbial reduction and desorption, even though the concentrations are not uniformly high across all locations.

These findings carry important implications for water quality and aquifer health in the New Artisan area. The co-occurrence of Fe, Mn, and As in values near or above guideline limits raises concerns about long-term exposure risks and highlights the potential for seasonal or land-use-driven shifts in redox conditions. Since these redox-sensitive elements are strongly influenced by microbial processes, any changes in organic matter inputs, recharge dynamics, or anthropogenic contamination (e.g., from waste dumps or industrial activity) could significantly alter water chemistry. Monitoring programs should therefore incorporate redox indicators and microbial assessments to better predict and manage contaminant mobility in these aquifers.

When compared with other areas within Enugu's shale terrain, such as Emene and Ugwuaji, the New Artisan region exhibits a similar pattern of iron and manganese mobilization associated with reducing subsurface environments (Ezeh and Ugwu, 2010; Okechukwu and Ikenna, 2024). However, arsenic concentrations in New Artisan are generally lower than in areas like Obeagu or Promiseland, where stronger reducing conditions may prevail. This underscores the localized nature of redox conditions and microbial activity in controlling metal behavior, which aligns with global findings in sedimentary aquifers (Smedley and Kinniburgh, 2002; Ravenscroft *et al*., 2009).

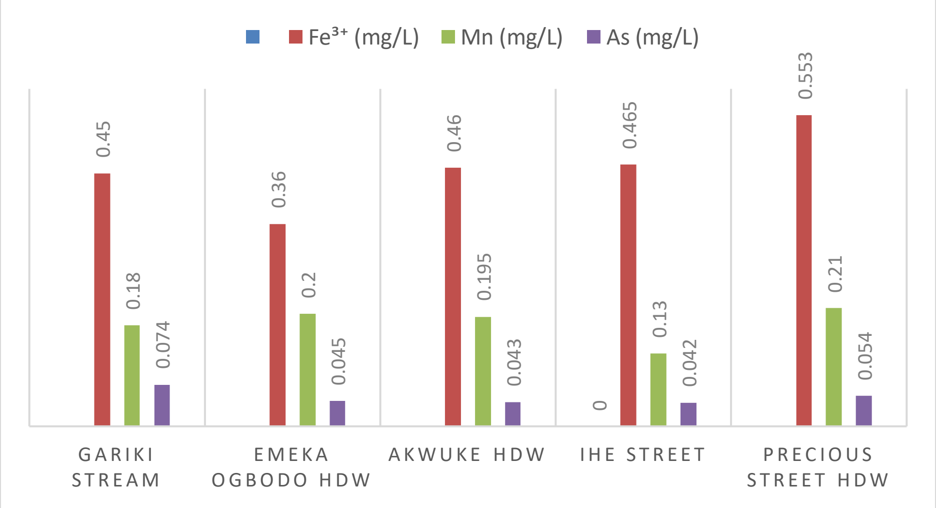

Fig 4: Metal Water Quality Analysis Results for Gariki Geographical Area

The water quality data for the Gariki geographical area show notably elevated levels of redox-sensitive metals across all sampled locations. Iron concentrations are particularly high, ranging from 0.360 mg/L in Emeka Ogbodo HDW to 0.553 mg/L in Precious Street HDW. All values significantly exceed the WHO permissible limit for Fe^{3+} in drinking water (0.3 mg/L), suggesting strong reducing conditions in the subsurface. Manganese levels also remain above the WHO limit of 0.1 mg/L, with concentrations varying slightly between 0.130 mg/L and 0.210 mg/L. Arsenic concentrations are a notable concern, especially in Gariki Stream (0.074 mg/L) and Precious Street HDW (0.054 mg/L), both of which far exceed the recommended 0.01 mg/L guideline, indicating significant mobilization of this toxic metalloid.

The observed trends point toward enhanced microbial reduction of iron and manganese oxides, which are known to immobilize arsenic under oxic conditions. Under reducing conditions, often mediated by anaerobic microbial communities such as *Desulfovibrio*, *Geobacter*, and *Shewanella* species, these oxides are dissolved, releasing sorbed arsenic into groundwater (Smedley and Kinniburgh, 2002; Lovley *et al*., 2004). This microbial mediation is well-documented in the Enugu aquifer system, where Ozoko and Ezeugwu (2025) identified a high abundance of iron- and sulfate-reducing bacteria in Gariki and other parts of Enugu. The particularly high Fe^{3+} and As levels in Precious Street and Gariki Stream suggest that these locations may represent redox hotspots within the aquifer, where the interplay between microbial activity and geochemistry is most intense. This pattern of elevated iron coinciding with high arsenic is consistent with known mechanisms of arsenic mobilization in anoxic groundwater environments.

The implications of these findings are significant. Not only do the high iron and manganese concentrations pose aesthetic and operational challenges for water usage (e.g., staining, taste, biofouling), but the elevated arsenic levels raise serious health concerns. Chronic exposure to arsenic, even at low concentrations, has been linked to skin lesions, cancers, and cardiovascular issues. The fact that these contaminants appear in both stream and well water suggests that both surface-subsurface interactions and broader hydrogeochemical conditions may be facilitating the redox transformation and release of these elements. Ozoko and Ezeugwu (2025) similarly observed that areas with intense anthropogenic input, such as domestic waste and organic-rich sediments, showed elevated microbial activity and redox-driven metal mobilization, particularly for arsenic.

When compared with other locations such as Emene and New Artisan, the Gariki area stands out for its particularly high iron and arsenic levels. This supports earlier suggestions that redox conditions in Enugu aquifers are not uniform but are influenced by local factors such as organic matter availability, lithology, and anthropogenic activities (Ezeh, 2012; Okechukwu and Ikenna, 2024). The Gariki Stream's elevated metal concentrations indicate that shallow surface waters may also serve as sources or conduits for redox-active inputs, further promoting microbially driven geochemical transformations in the underlying shale aquifer (Ozoko and Ezeugwu, 2025).

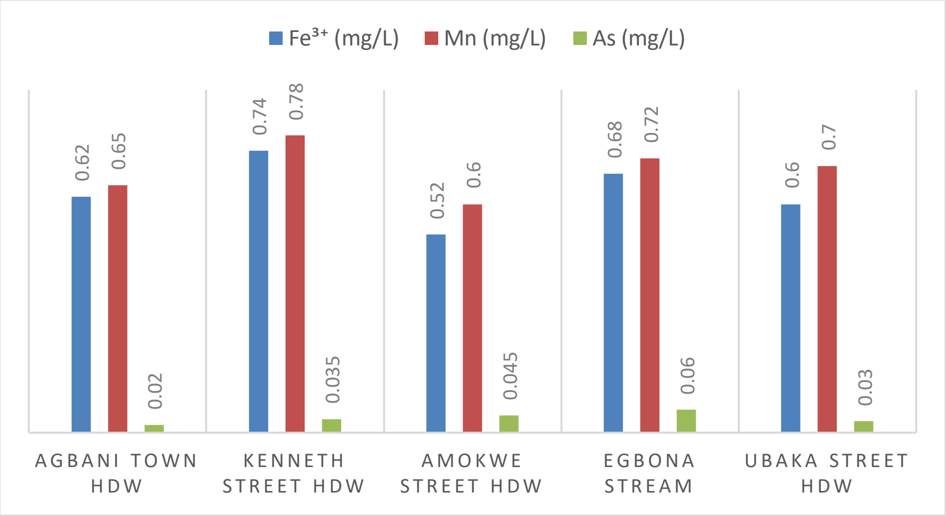

Fig 5: Metal Water Quality Analysis Results for Agbani-Road Geographical Area

The metal water quality analysis for the Agbani Road geographical area reveals consistently elevated concentrations of redox-sensitive metals across all sampled locations. Iron (Fe^{3+}) levels range from 0.52 mg/L in Amokwe Street HDW to 0.74 mg/L in Kenneth Street HDW, all of which substantially exceed the WHO guideline value of 0.3 mg/L for iron in drinking water. Manganese (Mn) concentrations are even more alarming, with values ranging from 0.60 mg/L to 0.78 mg/L, far surpassing the WHO permissible limit of 0.1 mg/L. Arsenic (As) concentrations, though lower in magnitude, show concerning values in Egbona Stream (0.060 mg/L) and Amokwe Street HDW (0.045 mg/L), both exceeding the WHO standard of 0.01 mg/L for safe drinking water.

The trend observed here suggests strong reducing conditions within the Agbani Road aquifer system, likely driven by intense microbial activity. High levels of iron and manganese typically indicate microbial-mediated dissolution of their oxides under low-oxygen or anoxic conditions, processes often facilitated by dissimilatory metal-reducing bacteria such as *Geobacter* and *Shewanella* species (Lovley *et al*., 2004). These redox reactions simultaneously lead to the release of arsenic, which is commonly adsorbed onto iron and manganese oxides under oxic conditions and mobilized into groundwater once these host minerals dissolve (Smedley and Kinniburgh, 2002). Ozoko and Ezeugwu (2025) identified similar microbial patterns in this region, emphasizing the role of sulfate-reducing and iron-reducing bacteria in transforming groundwater geochemistry in shale-dominated terrains like that of Agbani.

The implications of these findings are multifaceted. The high concentrations of Fe^{3+} and Mn pose operational challenges such as pipe clogging, discoloration, and metallic taste, while the presence of arsenic, even in moderate concentrations, raises serious public health concerns. Chronic exposure to arsenic has been linked to carcinogenic, cardiovascular, and neurological risks. The presence of these metals in both stream and well sources, as seen in Egbona Stream and surrounding hand-dug wells, highlights the potential for both surface and subsurface geochemical processes to influence water quality, suggesting active surface–groundwater interactions that enhance redox cycling and contaminant mobility.

When compared to other areas such as Gariki and Emene, the Agbani Road area exhibits even higher manganese concentrations and similarly elevated iron and arsenic levels. This reinforces the idea that local geological conditions, including the presence of organic-rich shales and coal seams characteristic of the Mamu Formation, may be contributing to enhanced microbial respiration and metal mobilization (Ezeh, 2012; Ozoko and Ezeugwu, 2025). Moreover, anthropogenic factors such as waste dumping and septic tank leakage, which are common in peri-urban areas like Agbani, may further supply labile organic carbon that fuels microbial metabolism, thereby intensifying redox transformations.

Conclusion

This study highlights how important it is to understand the natural chemical and microbial processes that affect groundwater quality, especially in areas with shale-rich geology. Metals like iron, manganese, and arsenic can become more mobile in water depending on underground conditions and microbial activity. By using reliable testing methods and carefully collecting samples, this research helps shed light on the potential health risks linked to hand-dug wells in both urban and semi-urban communities. The findings offer valuable information that can support better groundwater management, improve water safety, and guide further research on environmental health in similar regions.

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