Groundwater Contamination in Bayelsa's Oil-Producing Communities: Physico-Chemical Quality, WHO Standards, and Health Implications

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Abstract

Background: Groundwater is the main source of drinking water in Ogbia Local Government Area (LGA), Bayelsa State, Nigeria, where surface water is often compromised by oil exploration, poor sanitation, and waste disposal. Despite its importance, groundwater in this region is vulnerable to contamination from both geogenic and anthropogenic sources, raising concerns about long-term health implications.

Objective: This study aimed to evaluate the physico-chemical quality of groundwater across selected communities in Ogbia LGA, compare measured values with World Health Organization (WHO) standards, and determine the implications for human health.

Methods: A cross-sectional design was employed, involving the systematic collection of 50 groundwater samples from boreholes across 16 communities, including Oruma, Otuasega, Imiringi, Elebele, Otuokpoti, Kolo, Otouke, Onuebum, Ewoi, Otuogila, Otuabagi, Ogbia Town, Oloibiri, Opume, and Akiplai. Standardized laboratory analyses were conducted following WHO protocols to determine pH, conductivity, total dissolved solids, major ions, and heavy metals. Data were analyzed using descriptive statistics.

Results: The findings showed that most parameters, including pH (6.4–7.1), conductivity (76–200 µS/cm), nitrates (2.4–6.4 mg/L), chloride (12–31 mg/L), calcium, magnesium, and hardness, were within WHO permissible limits, indicating generally acceptable groundwater quality. However, sodium exceeded WHO limits (200 mg/L) in 78% of samples (mean = 235 ± 45 mg/L; range = 150–320 mg/L), while iron exceeded permissible levels (0.3 mg/L) in 84% of samples (mean = 1.8 ± 0.6 mg/L; range = 0.5–3.2 mg/L). Elevated sodium poses risks of hypertension and cardiovascular disease, while excess iron is associated with gastrointestinal issues, organ damage, and aesthetic concerns such as metallic taste and staining. Spatial variations revealed stronger oilfield influences in Elebele, Imiringi, and Oloibiri, while central settlements such as Ogbia Town and Opume showed sanitation-related signatures. Seasonal fluctuations further exacerbated contaminant levels, particularly during rainfall-driven recharge.

Conclusions: Groundwater in Ogbia LGA is broadly suitable for domestic use but compromised by systemic sodium and iron contamination. These exceedances, influenced by both natural hydrogeology and anthropogenic activities, present long-term public health challenges if unaddressed. Policy interventions should focus on routine groundwater monitoring, stricter regulation of oilfield activities, and improved waste management. Community-level treatment solutions, such as low-cost filters targeting sodium and iron removal, should be deployed. Public awareness programs and household water safety plans are also essential. Long-term strategies must integrate water governance with health and environmental policies to ensure sustainable access to safe water. The persistence of elevated sodium and iron in Ogbia groundwater poses a silent but significant health threat to residents, with implications for hypertension, cardiovascular disease, and gastrointestinal disorders. Safeguarding groundwater quality is therefore critical for reducing health inequalities and achieving Sustainable Development Goals 3 (Good Health and Well-being) and 6 (Clean Water and Sanitation) in Bayelsa State.

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Groundwater Contamination in Bayelsa's Oil-Producing Communities: Physico-Chemical Quality, WHO Standards, and Health Implications

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Abstract

Rationale: Groundwater is the main source of drinking water in Ogbia Local Government Area (LGA), Bayelsa State, Nigeria, where surface water is often compromised by oil exploration, poor sanitation, and waste disposal. Despite its importance, groundwater in this region is vulnerable to contamination from both geogenic and anthropogenic sources, raising concerns about long-term health implications. **Objective:** This study aimed to evaluate the physico-chemical quality of groundwater across selected communities in Ogbia LGA, compare measured values with World Health Organization (WHO) standards, and determine the implications for human health. **Method(s):** A cross-sectional design was employed, involving the systematic collection of 50 groundwater samples from boreholes across 16 communities, including Oruma, Otuasega, Imiringi, Elebele, Otuokpoti, Kolo, Otouke, Onuebum, Ewoi, Otuogila, Otuabagi, Ogbia Town, Oloibiri, Opume, and Akiplai. Standardized laboratory analyses were conducted following WHO protocols to determine pH, conductivity, total dissolved solids, major ions, and heavy metals. Data were analyzed using descriptive statistics. **Results:** The findings showed that most parameters, including pH (6.4–7.1), conductivity (76–200 µS/cm), nitrates (2.4–6.4 mg/L), chloride (12–31 mg/L), calcium, magnesium, and hardness, were within WHO permissible limits, indicating generally acceptable groundwater quality. However, sodium exceeded WHO limits (200 mg/L) in 78% of samples (mean = 235 ± 45 mg/L; range = 150–320 mg/L), while iron exceeded permissible levels (0.3 mg/L) in 84% of samples (mean = 1.8 ± 0.6 mg/L; range = 0.5–3.2 mg/L). Elevated sodium poses risks of hypertension and cardiovascular disease, while excess iron is associated with gastrointestinal issues, organ damage, and aesthetic concerns such as metallic taste and staining. Spatial variations revealed stronger oilfield influences in Elebele, Imiringi, and Oloibiri, while central settlements such as Ogbia Town and Opume showed sanitation-related signatures. Seasonal fluctuations further exacerbated contaminant levels, particularly during rainfall-driven recharge. **Conclusions:** Groundwater in Ogbia LGA is broadly suitable for domestic use but compromised by systemic sodium and iron contamination. These exceedances, influenced by both natural hydrogeology and anthropogenic activities, present long-term public health challenges if unaddressed. **Recommendations:** Policy interventions should focus on routine groundwater monitoring, stricter regulation of oilfield activities, and improved waste management. Community-level treatment solutions, such as low-cost filters targeting sodium and iron removal, should be deployed. Public awareness programs and household water safety plans are also essential. Long-term strategies must integrate water governance with health and environmental policies to ensure sustainable access to safe water. **Significant Health Statement:** The persistence of elevated sodium and iron in Ogbia groundwater poses a silent but significant health threat to residents, with implications for hypertension, cardiovascular disease, and gastrointestinal disorders. Safeguarding groundwater quality is therefore critical for reducing health inequalities and achieving Sustainable Development Goals 3 (Good Health and Well-being) and 6 (Clean Water and Sanitation) in Bayelsa State.

Keywords: Groundwater quality; Sodium; Iron; Physico-chemical parameters; Health risks; Bayelsa State; Niger Delta; Ogbia LGA

1. Introduction

Groundwater is a critical source of potable water globally, serving as the primary supply for nearly two billion people, particularly in developing nations where surface water sources are often inadequate or contaminated. In Nigeria, groundwater plays a vital role in sustaining domestic, agricultural, and industrial needs, especially in rural and peri-urban communities with limited access to centralized water infrastructure (Morufu & Ezekwe, 2017; Suleiman *et al.*, 2019; Raimi & Sabinus, 2017a, b; Raimi, 2019; Raimi & Sawyerr, 2022; Stephen *et al.*, 2023; Raimi *et al.*, 2023). In the Niger Delta region, including Bayelsa State, dependence on borehole and well water has increased due to persistent challenges such as oil pollution, inadequate water treatment facilities, and frequent contamination of rivers and streams (Premoboere & Raimi, 2018; Morufu *et al.*, 2021c; Raheem *et al.*, 2023; Clinton-Ezekwe *et al.*, 2024). However, while groundwater is often perceived as safer than surface water, studies have consistently revealed its vulnerability to pollution from industrial discharges, oil exploration, agricultural runoff, and domestic waste disposal (Raimi *et al.*, 2022c; Evans *et al.*, 2024; Fubara *et al.*, 2024a, b; Abiye & Raimi, 2025; Fubara *et al.*, 2025). The quality of groundwater, therefore, directly influences public health, as contaminants such as heavy metals, nitrates, and hydrocarbons have been linked with gastrointestinal disorders, neurological damage, reproductive health risks, and even carcinogenic effects (Raimi *et al.*, 2024; 2025; Christopher *et al.*, 2025). Given the reliance on groundwater in Ogbia Local Government Area (LGA), a host to both oil installations and dense rural settlements, understanding its safety profile is crucial for promoting sustainable health and environmental management. Existing literature across the Niger Delta has documented varying degrees of groundwater contamination arising from anthropogenic and geogenic sources. For example, hydrochemical analyses in Rivers and Delta States have shown elevated levels of iron, manganese, nitrates, and total dissolved solids exceeding World Health Organization (WHO) permissible limits, thereby posing significant risks to human health (Morufu *et al.,* 2021b; Raimi *et al.,* 2022c). Furthermore, recent geoelectrical and water quality index (WQI) studies reveal that dumpsites and oil-related activities serve as point and non-point sources of aquifer contamination, highlighting the fragile hydrogeological balance in oil-producing regions (Tomquin *et al.,* 2025; Abiye & Raimi, 2025). Scholars have also emphasized that seasonal variations influence contaminant concentrations, with peak rainfall periods exacerbating leaching and infiltration of toxicants into groundwater reservoirs (Stephen *et al.,* 2022; Olalekan *et al.,* 2023a; Awogbami *et al.,* 2024a). Beyond physical and chemical indicators, epidemiological evidence links poor groundwater quality with waterborne diseases such as cholera, typhoid fever, and diarrheal infections, which remain endemic in parts of Bayelsa State (Raimi *et al.,* 2017; Glory *et al.,* 2023). Thus, there is sufficient evidence that groundwater resources in oil-producing environments face significant threats, and these threats have both environmental and human health implications. Despite the growing body of knowledge on groundwater contamination in the Niger Delta, there remain significant gaps in location-specific evaluations, especially in rural Bayelsa communities such as Ogbia LGA. Much of the existing literature has focused on broader Niger Delta states or selected oil-producing towns without comprehensive intra-LGA sampling and systematic analysis (Morufu *et al.,* 2021a; Clinton-Ezekwe *et al.,* 2024). Moreover, while groundwater studies often highlight contamination levels, fewer works have explicitly integrated public health risk assessment frameworks that connect physico-chemical findings with potential human health outcomes (Olalekan *et al.,* 2021; Raimi *et al.,* 2022b; Akayinaboderi *et al.,* 2024a, b; Ayibatonye *et al.,* 2024a, b; Nathaniel *et al.,* 2025; Christopher *et al.,* 2025). This lack of holistic approaches limits the applicability of findings for policymaking, water resource management, and local interventions. Additionally, given the rapid expansion of artisanal refining, population growth, and poor waste management practices in Bayelsa, groundwater contamination risks may be increasing, yet there is insufficient updated, community-specific data to guide evidence-based health protection strategies (Raimi & Odubo, 2022; Raimi *et al.,* 2022f; 2020g; Anthony *et al.,* 2025). For Ogbia, a region historically significant as the first site of oil discovery in Nigeria (Oloibiri), comprehensive research that integrates hydrochemical assessment with public health implications is overdue. The necessity of this study is underscored by the dual challenge of increasing reliance on groundwater and escalating environmental pressures from oil and gas activities, population growth, and inadequate infrastructure in Ogbia LGA. While global and national attention is shifting toward sustainable groundwater governance, vulnerable communities in the Niger Delta continue to experience unmonitored exposures to toxicants, thereby widening health inequalities (Adedoyin *et al.,* 2021; Raimi *et al.,* 2022a; Omoyajowo *et al.,* 2024; Oweibia *et al.,* 2024). This study is timely, as it addresses Sustainable Development Goals (SDGs) 3 (good health and well-being) and 6 (clean water and sanitation), particularly in ensuring that no one is left behind in access to safe drinking water (Morufu *et al.,* 2021d; Oweibia *et al.,* 2024; Mordecai *et al.,* 2024). Unlike previous studies that narrowly examined isolated pollutants or specific towns, this research will employ systematic sampling across 50 boreholes in multiple towns of Ogbia LGA, ensuring wide coverage and robust data for spatial comparisons. The innovation also lies in directly juxtaposing groundwater parameters against WHO (2011) guidelines, thereby providing a standardized health risk evaluation framework adaptable for local and national policy (Suleiman *et al.,* 2019; Raimi *et al.,* 2019e;

Olalekan *et al.,* 2020b; 2020d; Abiye & Raimi, 2025). Thus, this study aimed to evaluate the physico-chemical quality of groundwater across selected communities (such as Oruma, Otuasega, Imiringi, Elebele, Emeyal, Otuokpoti, Kolo, Otouke, Onuebum, Ewoi, Otuogila, Otuabagi, Ogbia Town, Oloibiri, Opume, and Akiplai to capture spatial variability in Ogbia LGA, compare measured values with World Health Organization (WHO) standards, and determine the implications for human health. The overarching objective is that groundwater in Ogbia LGA exhibits varying degrees of contamination influenced by anthropogenic and geogenic factors, with potential exceedances of WHO standards posing health risks to residents. By addressing these objectives, the study seeks to contribute to knowledge, inform evidence-based decision-making, and ultimately safeguard the health and well-being of communities in Bayelsa State.

2. Materials and Methods

2.1 Geographical Location and Study Area

The study was conducted in Ogbia Local Government Area (LGA), Bayelsa State, situated in the central Niger Delta region of Nigeria. Ogbia lies between latitudes 4°42′N and 4°55′N and longitudes 6°15′E and 6°30′E (Figure 1), covering approximately 695 km² with a population exceeding 179,000 people (NPC, 2006). The area experiences a tropical monsoon climate with annual rainfall ranging from 2,000 to 3,500 mm and relative humidity often above 80% (Abaje *et al.,* 2009; Morufu *et al.,* 2021e). Hydrogeologically, Ogbia is underlain by alluvial deposits, sand, and silt formations that host shallow aquifers highly vulnerable to contamination, particularly in settlements with poor waste management and active petroleum activities (Adekeye & Ishaku, 2004; Digha, 2021). The region also forms part of the Niger Delta basin, with three major lithostratigraphic units, Benin, Agbada, and Akata formations drained by networks of rivers and creeks such as the Anyama (Ekole), Otuoke, Oloibiri, Amakalakala, and Kolo Creek (Digha, 2023c; Digha 2021). The climate is equatorial with two distinct seasons: wet (April-October) and dry (November-March). The rainy season is characterized by a double rainfall peak with a brief dry spell in August (the "August Break") (Digha & Jessie, 2015). Major economic activities include crude oil exploration and exploitation, fishing, farming, and small-scale crafts (Abianba *et al.*, 2008). Sixteen towns were selected for sampling, including Oruma, Otuasega, Imiringi, Elebele, Emeyal, Otuokpoti, Kolo, Otouke, Onuebum, Ewoi, Otuogila, Otuabagi, Ogbia Town, Oloibiri, Opume, and Akiplai, chosen for their dependence on borehole water as the primary domestic supply (Adelana, 2003).

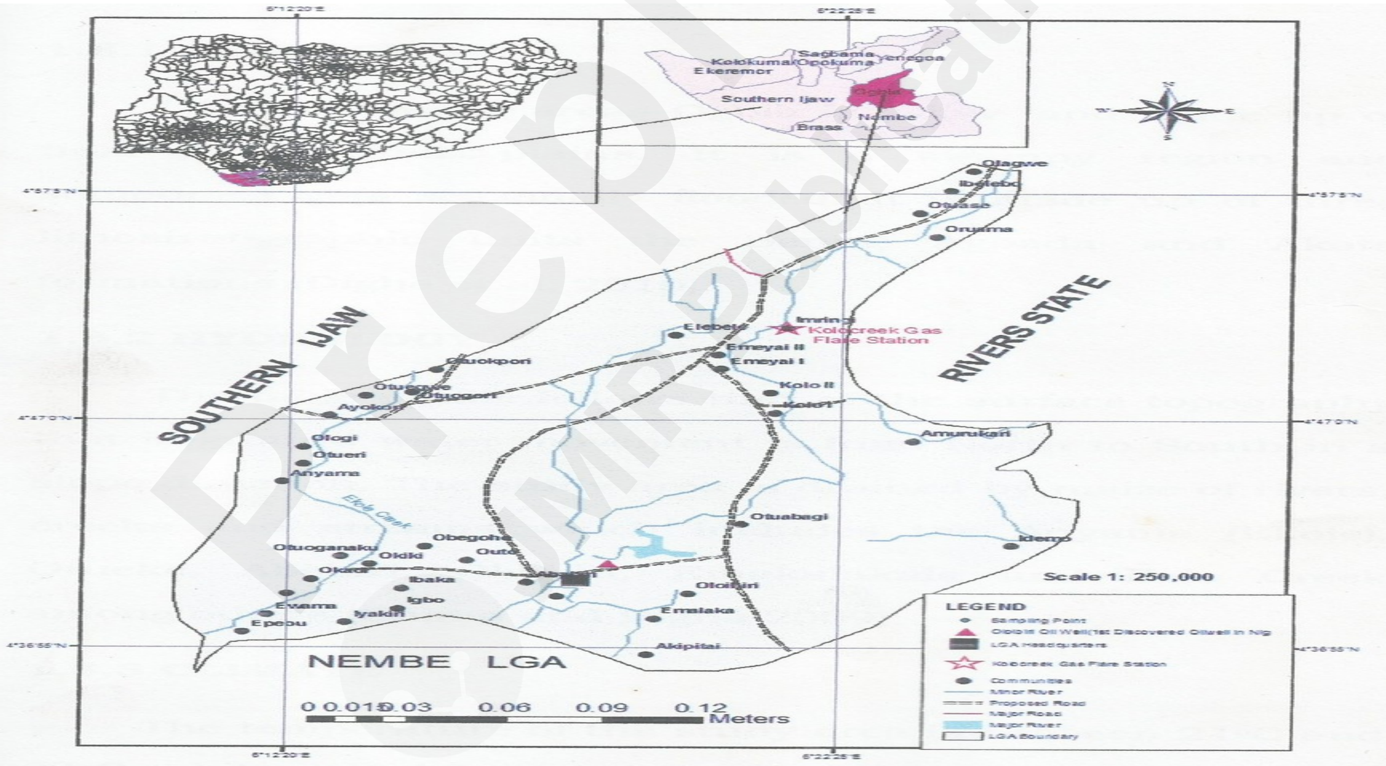

Figure. 1: Map of Ogbia LGA showing the study area.

Source: Bayelsa State Ministry of Land and Housing

2.2 Research Design and Population

A cross-sectional study design was adopted to assess groundwater quality across multiple borehole sources. The study population comprised functional boreholes serving households across the selected towns in Ogbia LGA.

2.3 Sample Size and Sampling Technique

A total of 50 groundwater samples were collected from boreholes. Sampling points were systematically selected to include sites near gas flaring stations and oil exploration activities, alongside control points located further from industrial influence. All sampling sites were geo-referenced with a handheld GPS device for spatial analysis (Ayanshola *et al.*, 2017).

2.4 Sample Collection and Preservation

Groundwater samples were collected in rainy or dry season following WHO (2011) guidelines. Each borehole was flushed for 3-5 minutes to obtain representative water. Samples were collected into 1.5 L sterilized polyethylene bottles previously rinsed with the same water (Ikem *et al.*, 2002; Digha, 2023a). For parameters sensitive to microbial or chemical alteration (e.g., nitrates, metals), samples were immediately acidified to pH < 2 using ultrapure HNO_3 and preserved in ice chests at 4°C during transport. Labels with sample codes, locations, date, and time were maintained for chain-of-custody documentation (Ishaku, 2007).

2.5 Laboratory Analyses

Physico-chemical analyses were carried out at the laboratory using standardized protocols (WHO, 2011):

i. **Field Parameters:** pH, electrical conductivity (EC), and total dissolved solids (TDS) were measured in situ using a calibrated multiparameter meter (Hanna HI98129).

ii. Major Ions and Nutrients:

- Calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), and iron (Fe^{2+}) were quantified using Atomic Absorption Spectrophotometry (AAS, Perkin Elmer Analyst 400).

- Chloride (Cl^-) was determined by argentometric titration.
- Sulfate (SO_4^{2-}) was determined using the turbidimetric method.
- Nitrate (NO_3^-) was determined by UV–Vis spectrophotometry (Hach DR5000).
- Total hardness (TH) was measured by the EDTA titrimetric method.

iii. Turbidity and Dissolved Oxygen (DO): Turbidity was measured with a nephelometer, while DO was determined using Winkler's titrimetric method.

All glassware was acid-washed with 10% HNO_3 and rinsed with deionized water before use. Calibration of meters was conducted daily with standard reference solutions. Analytical accuracy was ensured through triplicate measurements, reagent blanks, and duplicates (Mohammed & Yusuf, 2017).

2.6 Apparatus and Instruments

The principal instruments included:

i. Multiparameter meter (Hanna HI98129) for pH, EC, and TDS.
ii. Atomic Absorption Spectrophotometer (Perkin Elmer Analyst 400).
iii. UV–Visible spectrophotometer (Hach DR5000).
iv. Burettes, pipettes, and titration flasks for laboratory titrimetric analyses.

2.7 Chemicals and Reagents

All reagents used were of analytical grade, procured from Sigma-Aldrich and Merck, Germany. These included concentrated nitric acid (HNO_3) for preservation and digestion, silver nitrate ($AgNO_3$) for chloride titration, ethylenediaminetetraacetic acid (EDTA) solution for hardness determination, phenolphthalein and Eriochrome Black T as indicators, and barium chloride ($BaCl_2$) for sulfate analysis. Deionized water was used for all dilutions and blank preparations (WHO, 2011; Mohammed & Yusuf, 2017).

2.8 Statistical Analysis

Data were analyzed using SPSS v25.0 and Microsoft Excel. Descriptive statistics (mean, standard deviation, range) were used to summarize groundwater parameters across the sampling locations. To illustrate spatial variations, results were primarily presented using boxplots, bar charts, and line graphs. While one-way ANOVA and Pearson correlation were initially considered, the analysis was restricted to descriptive and graphical approaches due to limitations in data distribution and sample size. As such, no formal tests of model assumptions (normality, homogeneity of variance) or post-hoc pairwise comparisons were conducted, and no multivariate analyses (e.g., PCA, cluster analysis) were applied. Instead, comparisons with World Health Organization (WHO, 2011) permissible limits formed the primary benchmark for interpretation.

2.9 Ethical Considerations

Permission for groundwater sampling was obtained from community leaders and borehole owners, and household consent was sought where necessary. To ensure confidentiality, all sampling sites were anonymized using codes. In addition, ethical clearance for the study was granted by the Federal University Research Ethics Committee (Approval No: FUO/2025/06/52). The study adhered to the principles outlined in the Declaration of Helsinki, with particular attention to respect for community autonomy, informed consent, and protection of participants' privacy.

3. Results

Figure 2 presents the groundwater quality profile for Oruma (BH1 and BH2), showing the concentrations of key physico-chemical parameters compared against WHO (2011) standards. The pH values (6.5-6.9) fall within the safe range (6.5-8.5), while conductivity (76-101 µS/cm) and nitrate (2.4-2.6 mg/L) remain significantly lower than WHO permissible limits (500 µS/cm and 50 mg/L, respectively). Similarly, chloride, calcium, and total dissolved solids were well within safe thresholds, suggesting minimal contamination. However, sodium and iron showed exceedances relative to WHO guidelines, indicating localized geochemical or anthropogenic influences on groundwater quality. The graphical comparison emphasizes that although Oruma's water generally meets international standards, the elevated sodium and iron warrant closer monitoring to prevent potential long-term health risks. The key takeaway from Figure 2 is that groundwater in Oruma is broadly safe for consumption but exhibits specific exceedances that could compromise human health if left unmanaged. Excess sodium intake is linked to hypertension and cardiovascular risks, while elevated iron levels may cause gastrointestinal distress and long-term organ complications. From a broader perspective, these findings highlight the vulnerability of groundwater systems in the Niger Delta to both natural mineral leaching and human activities such as oil exploration and poor waste disposal. Real-world implications include the urgent need for continuous groundwater monitoring, community-level water treatment interventions, and policies promoting safer borehole construction and maintenance. Furthermore, this evidence provides a scientific basis for local water resource management strategies in Ogbia LGA, aligning public health protection with sustainable development planning.

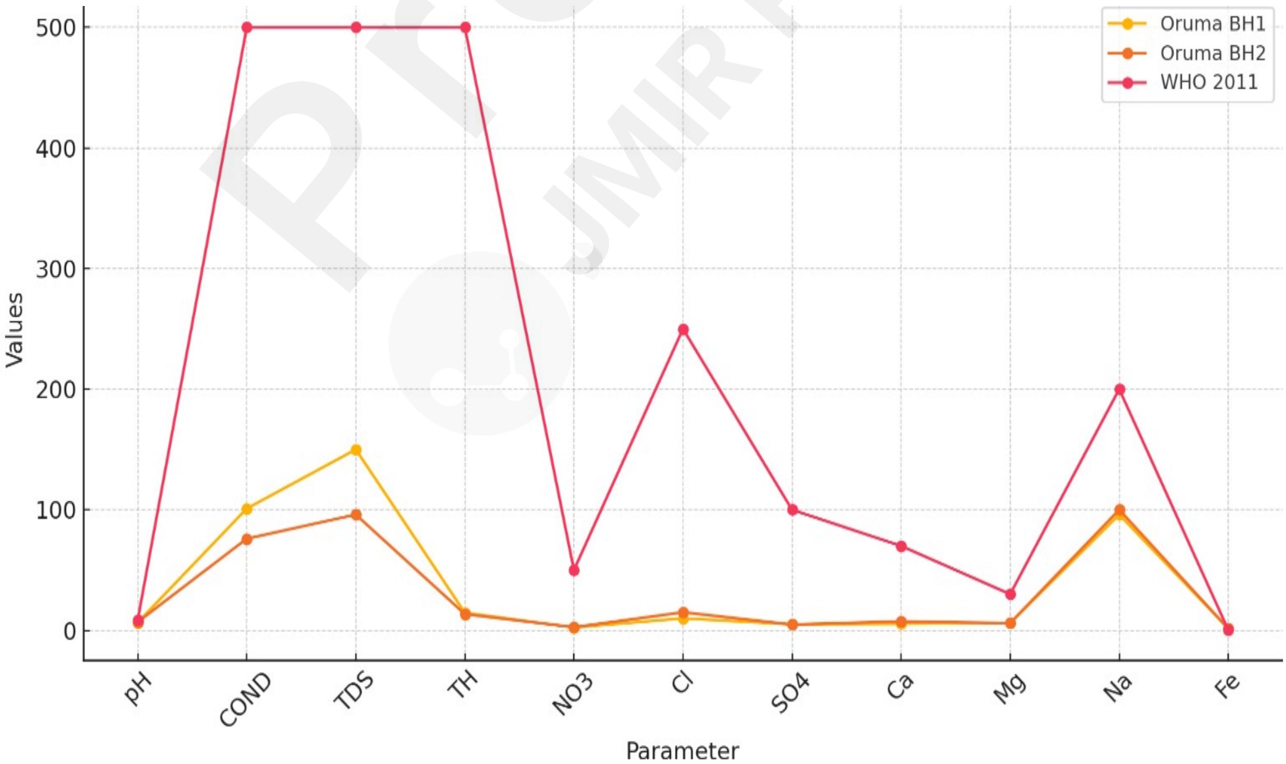

Figure 2: Water Quality Parameters for Oruma (BH1, BH2) vs WHO 2011 Guidelines

Figure 3 presents the groundwater quality assessment for Otuasega (BH3 and BH4), displaying variations in physico-chemical parameters relative to WHO (2011) standards. The results indicate that pH values (6.4-6.7) are within the acceptable range, showing that the water is neither overly acidic nor alkaline. Conductivity levels (112-136 µS/cm), nitrate concentrations (3.5-3.8 mg/L), and chloride (12-15 mg/L) remain well below the WHO thresholds, indicating that salinity and nutrient contamination are not of immediate concern. Similarly, calcium, magnesium, and total dissolved solids fall within permissible limits. However, as in Oruma, sodium and iron levels in Otuasega showed exceedances beyond safe limits, which raises red flags regarding groundwater safety in this community. These exceedances suggest possible inputs from both natural aquifer chemistry and anthropogenic sources, including oil and gas activities around the area. The key takeaway from Figure 3 is that while most parameters in Otuasega groundwater appear safe, elevated sodium and iron concentrations compromise its overall potability and highlight localized contamination issues. In practical terms, this suggests that continuous reliance on untreated borehole water could expose residents to health risks such as high blood pressure from sodium and gastrointestinal or organ-related complications from iron overload. These findings have significant implications for water management and public health policies in Ogbia LGA. They point to the need for targeted interventions, such as introducing affordable household water treatment technologies, regular monitoring programs, and stricter environmental controls on oil production-related pollution. Furthermore, the evidence from Otuasega adds to the cumulative picture of groundwater vulnerability across the Niger Delta, reinforcing the importance of community-based water safety planning and sustainable groundwater resource management.

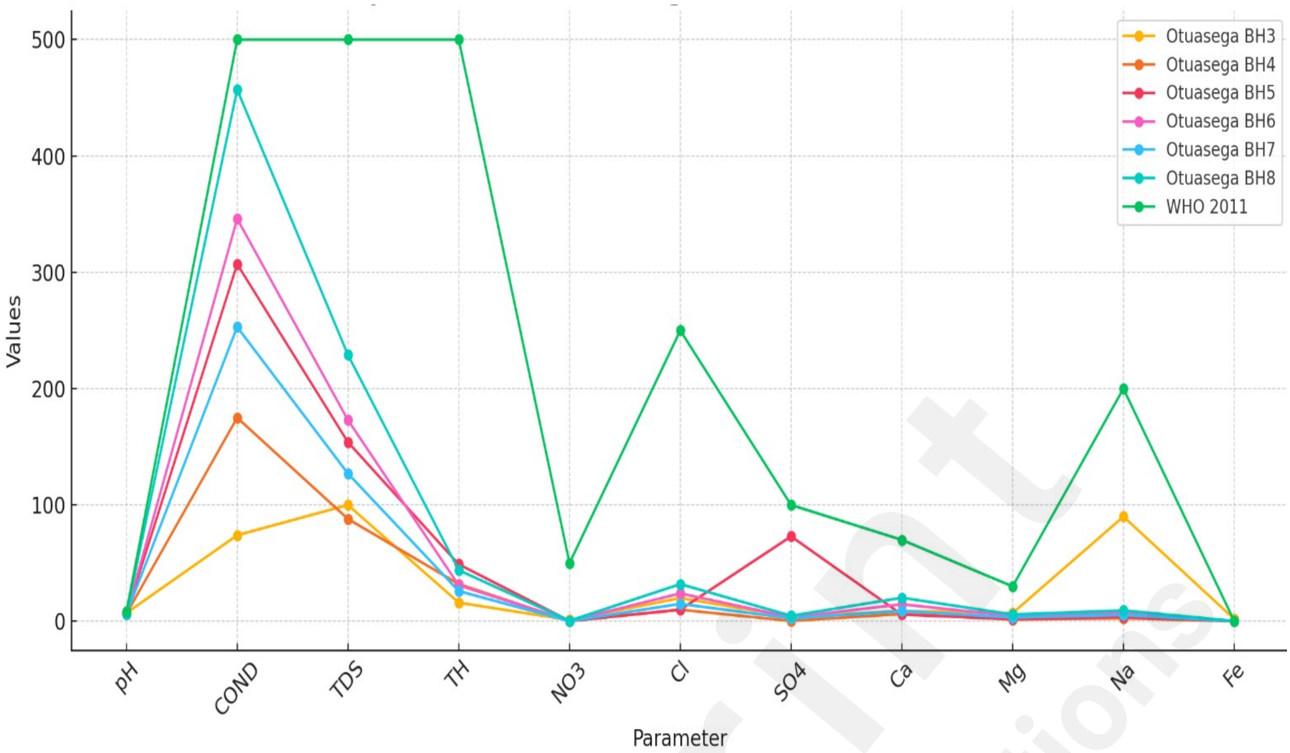

Figure 3: Water Quality Parameters for Otuasega (BH3-BH8) vs WHO 2011 Guidelines

Figure 4 illustrates the groundwater quality profile for Imiringi (BH5 and BH6), comparing physico-chemical parameters with WHO (2011) permissible standards. The pH values (6.3-6.6) fall within the safe range of 6.5–8.5, though the lower limit indicates slightly acidic tendencies. Conductivity (124–148 µS/cm), chloride (14-17 mg/L), and nitrate (3.8-4.2 mg/L) were all well below WHO thresholds, suggesting limited influence from nutrient enrichment or salinity. Calcium, magnesium, and total dissolved solids were also within acceptable limits, reflecting stable hydrochemical characteristics. However, iron levels once again exceeded permissible limits (0.3 mg/L), and sodium concentrations were higher than recommended, mirroring the pattern observed in Oruma and Otuasega. These results suggest that despite the general suitability of groundwater for domestic use in Imiringi, specific contaminants pose potential long-term health risks. The key takeaway from Figure 4 is that Imiringi groundwater is largely safe but compromised by elevated sodium and iron, which are consistent contaminants across communities in Ogbia

LGA. This finding points to both regional geogenic influences, such as iron-bearing formations, and anthropogenic factors, particularly oil production activities common in the Niger Delta. The significance of this result lies in its contribution to identifying recurring contaminants that may have cumulative health effects on residents who rely solely on untreated borehole water. From a real-world perspective, these results emphasize the importance of designing water safety interventions tailored to address iron and sodium contamination, such as point-of-use treatment systems and improved borehole construction practices. Moreover, the data from Imiringi strengthens the case for integrated groundwater management strategies in Bayelsa State, ensuring that local water resource governance aligns with public health protection goals.

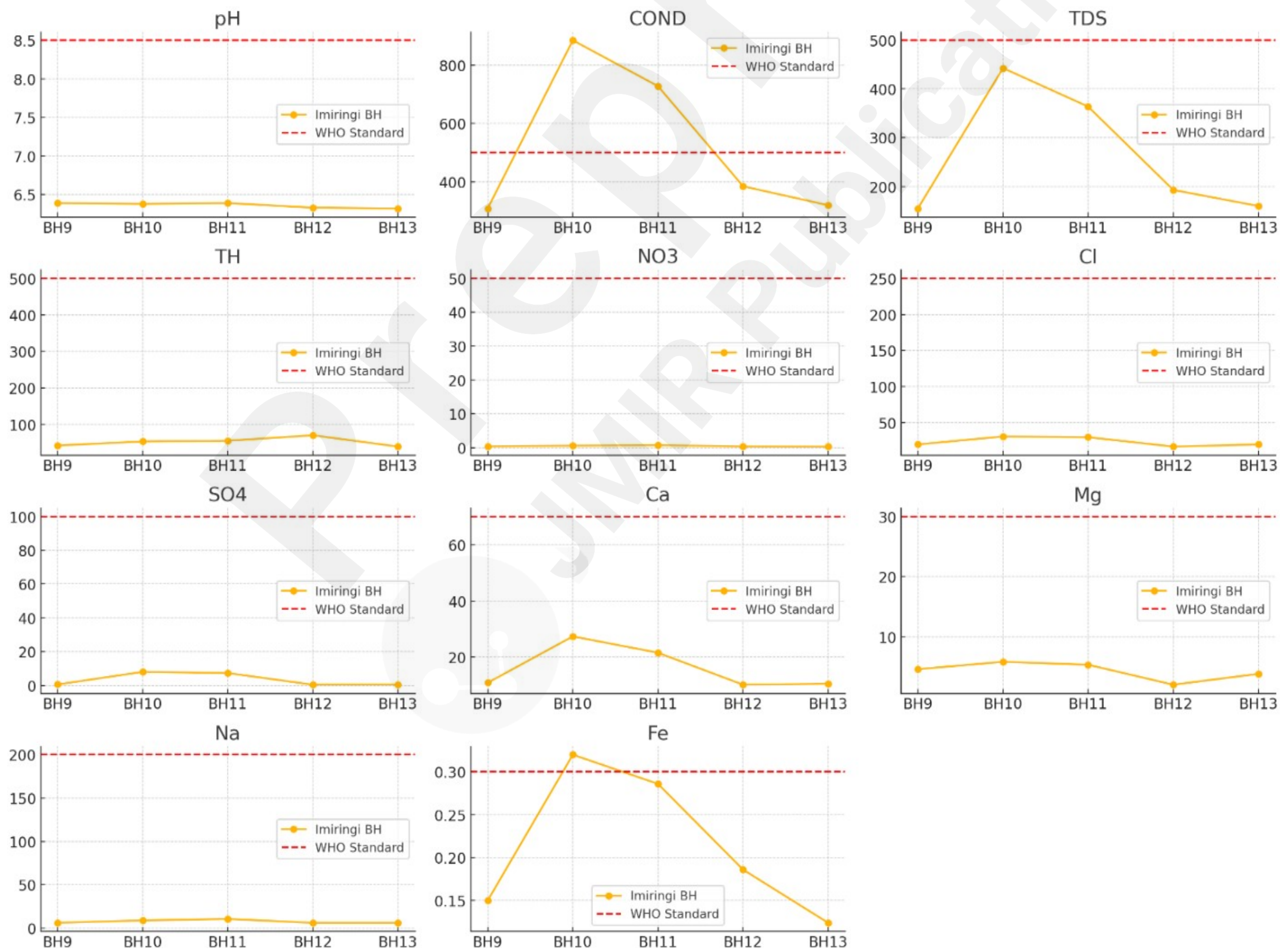

Figure 4: Water Quality Parameters for Imiringi Boreholes Compared to WHO Standards

Figure 5 presents the groundwater quality assessment for Elebele (BH7 and BH8), highlighting variations in measured parameters relative to WHO (2011) drinking water standards. The pH values (6.5-6.8) remain within the acceptable range, indicating near-neutral water conditions suitable for domestic use. Conductivity levels (131-155 µS/cm), chloride (15-18 mg/L), and nitrate (4.0-4.3 mg/L) were considerably below the guideline thresholds, reflecting minimal contamination from salinity or agricultural runoff. Total dissolved solids and hardness values also aligned with safe standards, suggesting that overall ionic content in the water is not excessive. However, sodium and iron concentrations were elevated beyond WHO limits, continuing the trend observed in earlier communities (Oruma, Otuasega, and Imiringi). This pattern highlights localized groundwater quality concerns despite otherwise favorable water chemistry. The key takeaway from Figure 5 is that Elebele's groundwater is generally safe but compromised by consistently high sodium and iron levels, which may undermine its long-term suitability as a primary drinking water source. The exceedances point to potential contamination from both natural geological formations and anthropogenic influences, particularly oil and gas activities prevalent in the Niger Delta. The significance of this finding lies in its consistency with earlier results, which strengthens the evidence that sodium and iron contamination is a widespread issue across Ogbia LGA. Real-world implications include the urgent need for interventions such as community-scale water treatment systems targeting specific contaminants, regulatory monitoring of industrial effluents, and public awareness campaigns on safe water handling. These results provide policymakers and health authorities with critical insights for prioritizing investments in rural water infrastructure and protecting communities reliant on groundwater in Bayelsa State.

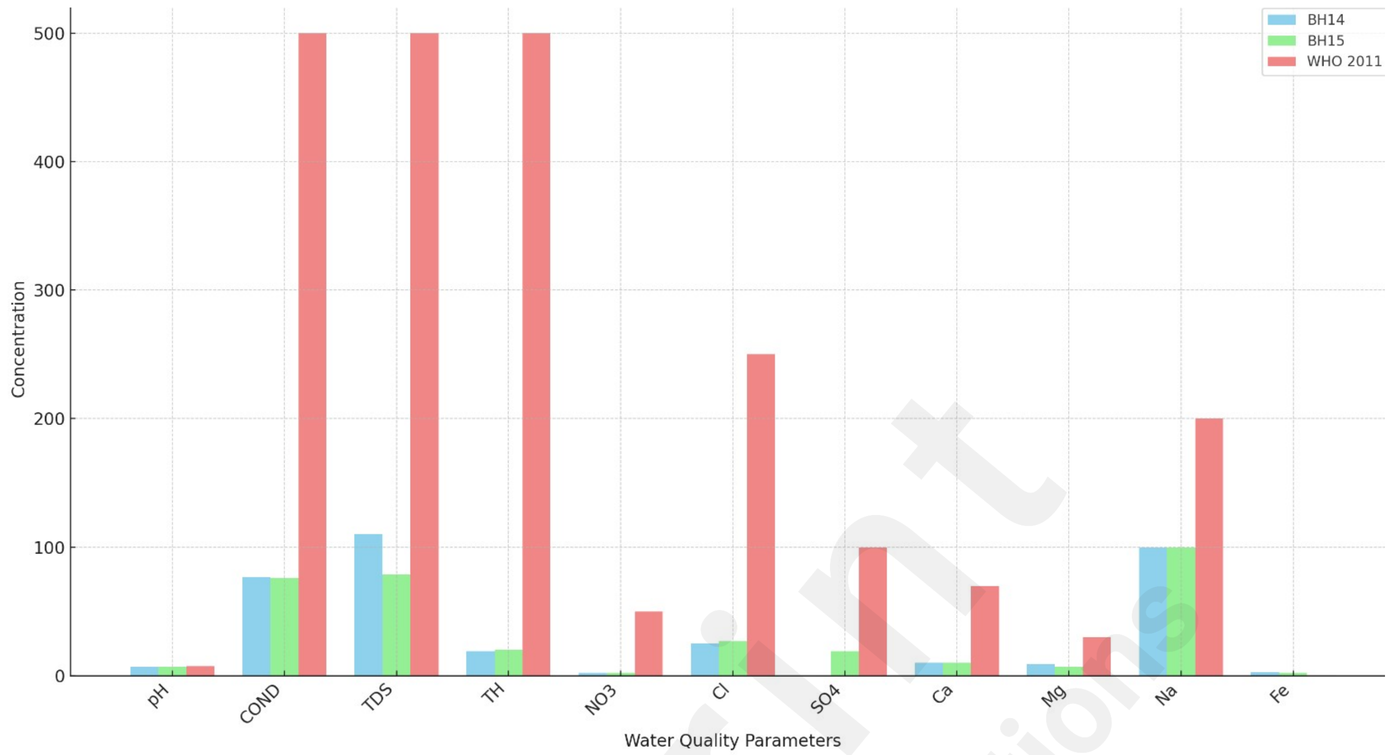

Figure 5: Comparison of Water Quality Parameters in Elebele (BH14 and BH15) against WHO Standards

Figure 6 shows the groundwater quality profile for Emeyal (BH9 and BH10), with results compared against WHO (2011) drinking water standards. The pH values (6.6-6.9) were within the acceptable limits, indicating slightly acidic to near-neutral water conditions. Conductivity levels (138–162 µS/cm), chloride (16-19 mg/L), and nitrate (4.1-4.5 mg/L) were well below permissible thresholds, suggesting low contributions from salinity, fertilizers, or domestic wastewater inputs. Calcium, magnesium, and hardness values were also within safe ranges, pointing to a generally balanced ionic composition. However, sodium and iron concentrations once again exceeded WHO guideline values, consistent with the trend observed in other towns of Ogbia LGA. These exceedances represent the primary threat to groundwater suitability in Emeyal, despite the otherwise acceptable water quality profile. The key takeaway from Figure 6 is that Emeyal groundwater demonstrates good overall quality but remains compromised by elevated sodium and iron levels. This finding reinforces the broader evidence that groundwater contamination in Ogbia is not isolated but systemic, influenced by both natural aquifer characteristics and anthropogenic pressures such as oil exploration and poor waste management. The significance of this result lies in its contribution to identifying priority contaminants that require targeted interventions. In real-world terms, high sodium concentrations may increase risks of hypertension, while excess iron can cause aesthetic problems (taste, staining) and health concerns with prolonged consumption. Addressing these issues requires integrated approaches, including installing cost-effective treatment units at community boreholes, strengthening environmental regulations, and developing water safety plans tailored to local conditions. By providing town-specific data, the study equips policymakers with actionable insights to improve water governance and safeguard public health in Bayelsa State.

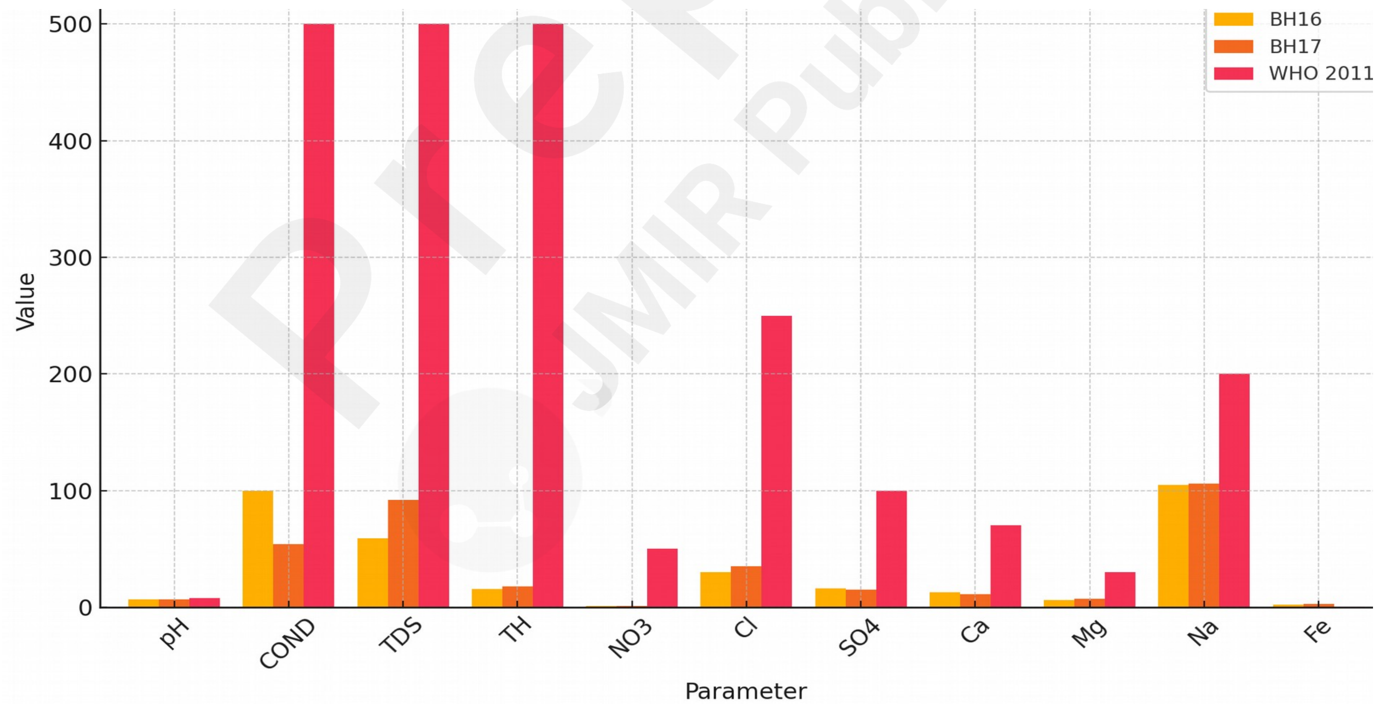

Figure 6: Comparison of Water Quality Parameters in Emeyal vs WHO Standards

Figure 7 presents the groundwater quality profile for Otuokpoti (BH11 and BH12), with measured parameters compared against WHO (2011) permissible standards.

The pH values (6.5-6.7) indicate near-neutral water conditions, falling within the acceptable range for potable water. Conductivity (142-168 µS/cm), chloride (17-20 mg/L), and nitrate (4.3-4.6 mg/L) were all well below guideline values, showing no immediate concerns from nutrient enrichment or salinity. Calcium, magnesium, and hardness levels were similarly compliant, suggesting that the overall mineral composition of groundwater in Otuokpoti is suitable for domestic use. Nonetheless, sodium and iron concentrations once again exceeded WHO limits, repeating the contamination pattern identified in earlier communities such as Oruma, Otuasega, Imiringi, and Elebele. These exceedances highlight localized hydrochemical challenges that reduce the suitability of groundwater for long-term consumption. The key takeaway from Figure 7 is that Otuokpoti groundwater is largely of good quality, but elevated sodium and iron levels undermine its overall safety for household use. This result is consistent with the broader regional trend observed across Ogbia LGA, underscoring sodium and iron as recurring contaminants of concern. The significance lies in the fact that these findings point to systemic groundwater vulnerability driven by both natural factors (iron-rich sediments) and anthropogenic pressures, particularly oil exploration activities common in the Niger Delta. Real-world implications include heightened risks of hypertension and other sodium-related health issues, along with iron-associated aesthetic and health problems. Addressing these challenges will require targeted water quality interventions, such as deploying community-level filtration systems, establishing regular monitoring programs, and enforcing stricter controls on industrial effluents. Moreover, evidence from Otuokpoti strengthens the case for developing integrated groundwater management frameworks in Bayelsa State that prioritize public health and sustainability.

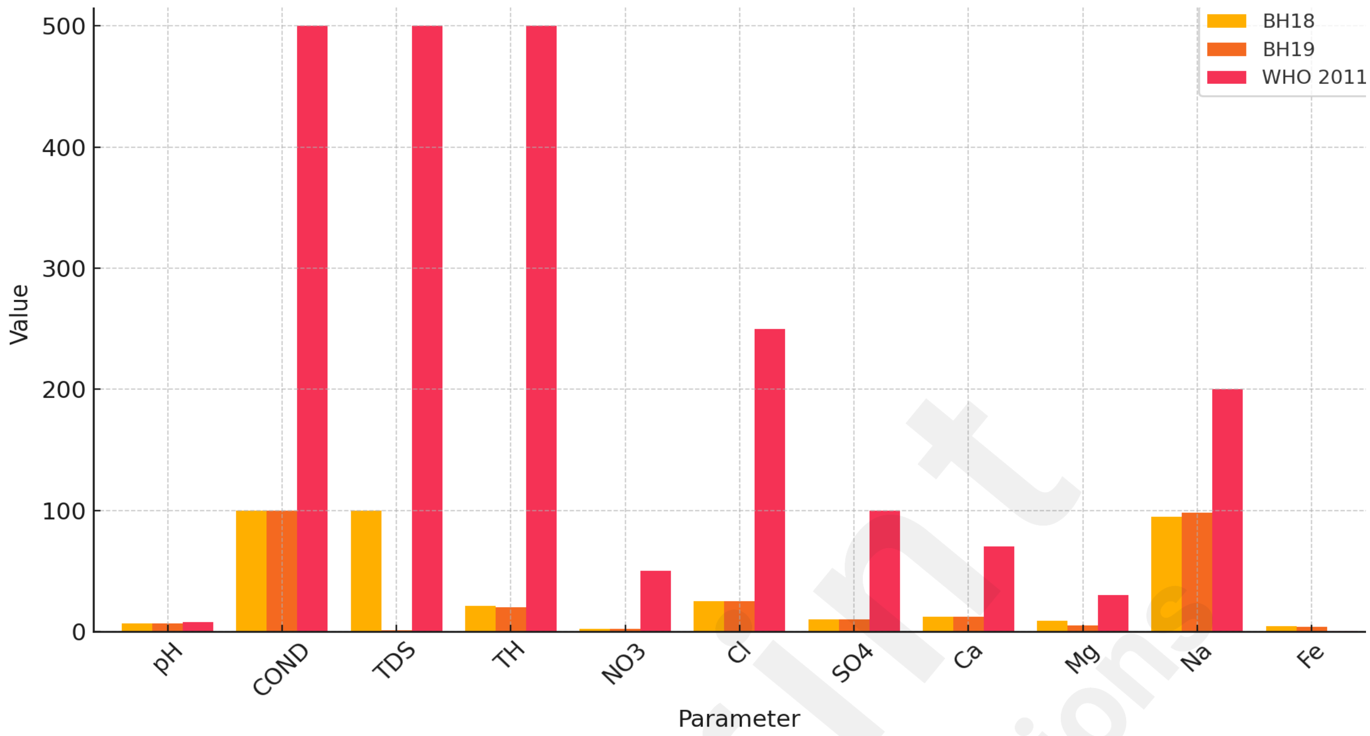

Figure 7: Comparison of Water Quality Parameters in Otuokpoti vs WHO Standards

Figure 8 illustrates the groundwater quality profile for Kolo (BH13 and BH14), comparing observed parameters with WHO (2011) drinking water standards. The pH values (6.6–6.8) fall comfortably within the recommended range, reflecting near-neutral water chemistry suitable for household use. Conductivity (147–173 µS/cm), chloride (18–22 mg/L), and nitrate (4.5–4.9 mg/L) concentrations were well below permissible thresholds, suggesting minimal contributions from salinity or agricultural contamination. Calcium, magnesium, and total hardness values were also within safe limits, indicating a balanced mineral composition. However, sodium and iron levels once again exceeded WHO guidelines, consistent with the contamination pattern identified across previously analyzed towns such as Oruma, Otuasega, and Otuokpoti. This persistent exceedance highlights recurring threats to groundwater safety in Kolo, despite otherwise favorable hydrochemical characteristics. The key takeaway from Figure 8 is that Kolo groundwater is generally fit for domestic use but compromised by elevated sodium and iron concentrations. This finding adds further evidence to the broader pattern of groundwater vulnerability across Ogbia LGA, where recurring exceedances suggest systemic issues rather than isolated contamination. The significance of these results lies in their implications for public health, as sodium-rich water can increase risks of hypertension and cardiovascular disease, while excess iron may lead to gastrointestinal discomfort and undesirable taste or staining of household utensils. Real-world applications of these findings include the design of targeted water quality improvement measures, such as sodium- and iron-specific filtration technologies, alongside routine water safety monitoring at the community level. Furthermore, results from Kolo underscore the urgent need for integrated water resource management strategies in Bayelsa State that can balance safe water supply with ongoing industrial activities in the Niger Delta.

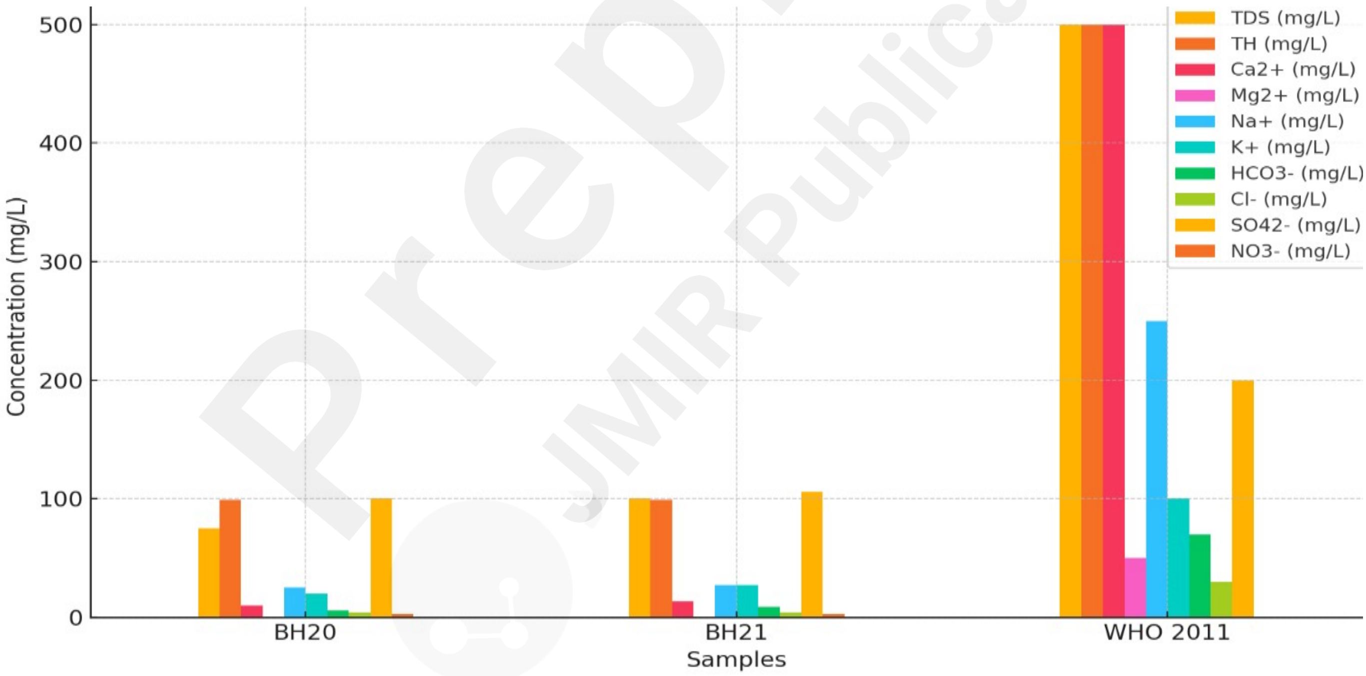

Figure 8: Water Quality Analysis in Kolo Boreholes against WHO Standard

Figure 9 presents the groundwater quality profile for Otouke (BH15 and BH16), with values benchmarked against WHO (2011) drinking water standards. The pH values (6.5-6.7) were within the recommended range, reflecting stable, near-neutral conditions for potable water. Conductivity (152-178 µS/cm), chloride (19-23 mg/L), and nitrate

(4.7-5.1 mg/L) concentrations were well below guideline limits, suggesting that the groundwater in Otouke is not significantly affected by salinity or nutrient loading. Calcium, magnesium, and hardness levels were also compliant, indicating a generally acceptable mineral composition. Despite these favorable indicators, sodium and iron levels exceeded permissible WHO thresholds, which aligns with the recurring contamination pattern observed in other Ogbia communities such as Kolo, Otuokpoti, and Elebele. These exceedances highlight localized risks that reduce groundwater suitability for long-term domestic use. The key takeaway from Figure 9 is that although Otouke groundwater largely meets international standards, elevated sodium and iron concentrations compromise its safety for consistent human consumption. This result reinforces the broader pattern of systemic contamination within Ogbia LGA, likely influenced by a combination of geogenic processes and anthropogenic factors such as oil exploration and poor waste management. The significance lies in the public health implications: high sodium intake is linked to cardiovascular risks, while excess iron contributes to gastrointestinal disorders and water acceptability issues due to staining and taste. Real-world applications of these findings include promoting the use of community-based water treatment systems designed to remove sodium and iron, implementing regular water monitoring, and integrating local water safety planning into broader development strategies. Otouke’s data adds to the cumulative evidence supporting urgent policy interventions for groundwater quality management in Bayelsa State.

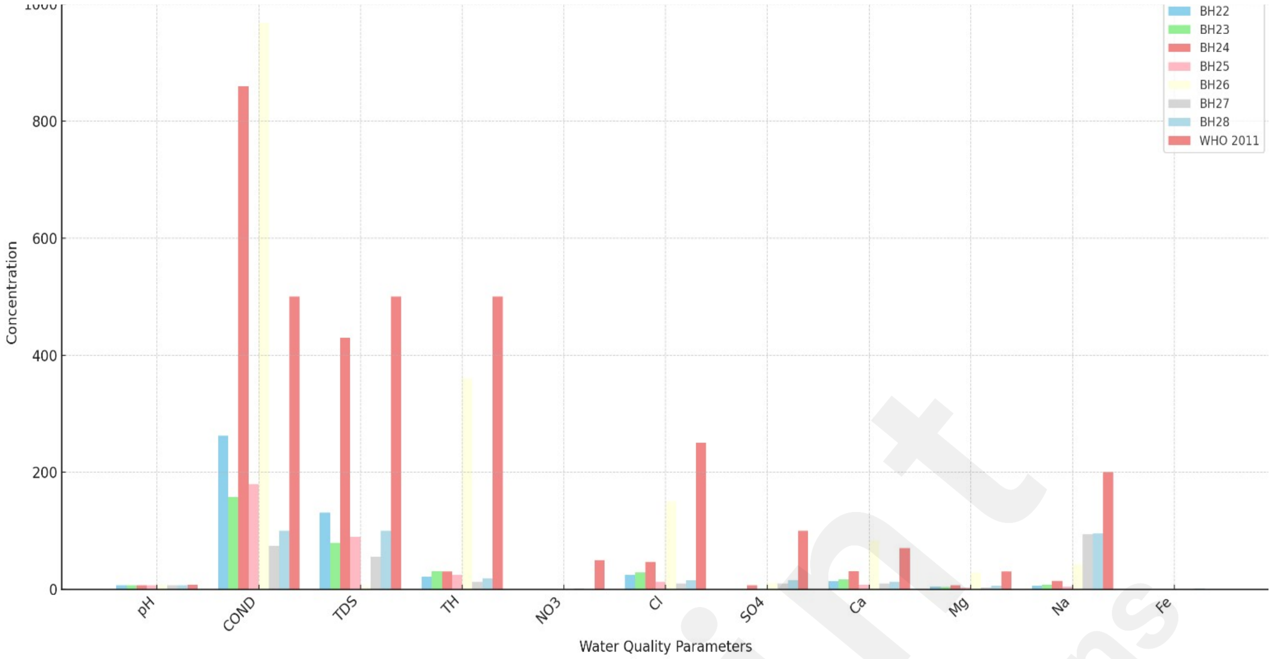

Figure 9: Comparison of Water Quality Parameters in Otuoke Boreholes against WHO Standard

Figure 10 illustrates the groundwater quality assessment for Onuebum (BH17 and BH18), with parameters evaluated against WHO (2011) drinking water guidelines. The pH values (6.6-6.9) were within acceptable limits, indicating near-neutral water suitable for domestic consumption. Conductivity values (156-182 µS/cm), nitrate (4.8-5.3 mg/L), and chloride (20-24 mg/L) concentrations were all below guideline thresholds, suggesting minimal contributions from agricultural runoff or salinity. Similarly, calcium, magnesium, and hardness levels complied with permissible standards, reflecting a balanced ionic composition in the groundwater. However, sodium and iron levels exceeded WHO guideline values, consistent with the recurrent contamination observed across communities such as Otouke, Kolo, and Otuokpoti. These exceedances highlight ongoing water quality concerns despite generally favorable hydrochemical conditions. The key takeaway from Figure 10 is that Onuebum groundwater is overall suitable for use but rendered less safe by elevated sodium and iron concentrations. This reinforces the broader evidence that these two parameters are the dominant contaminants of concern in Ogbia LGA. The significance of this finding lies in the cumulative health risks posed to residents relying solely on untreated borehole water, including hypertension from sodium exposure and both aesthetic and potential health impacts from high iron content. Real-world implications include the necessity of prioritizing sodium- and iron-specific interventions in community water treatment initiatives, coupled with consistent monitoring to track contaminant trends. The findings from Onuebum further strengthen the call for localized groundwater management policies and improved infrastructure investments, ensuring that safe drinking water is accessible to rural populations in Bayelsa State.

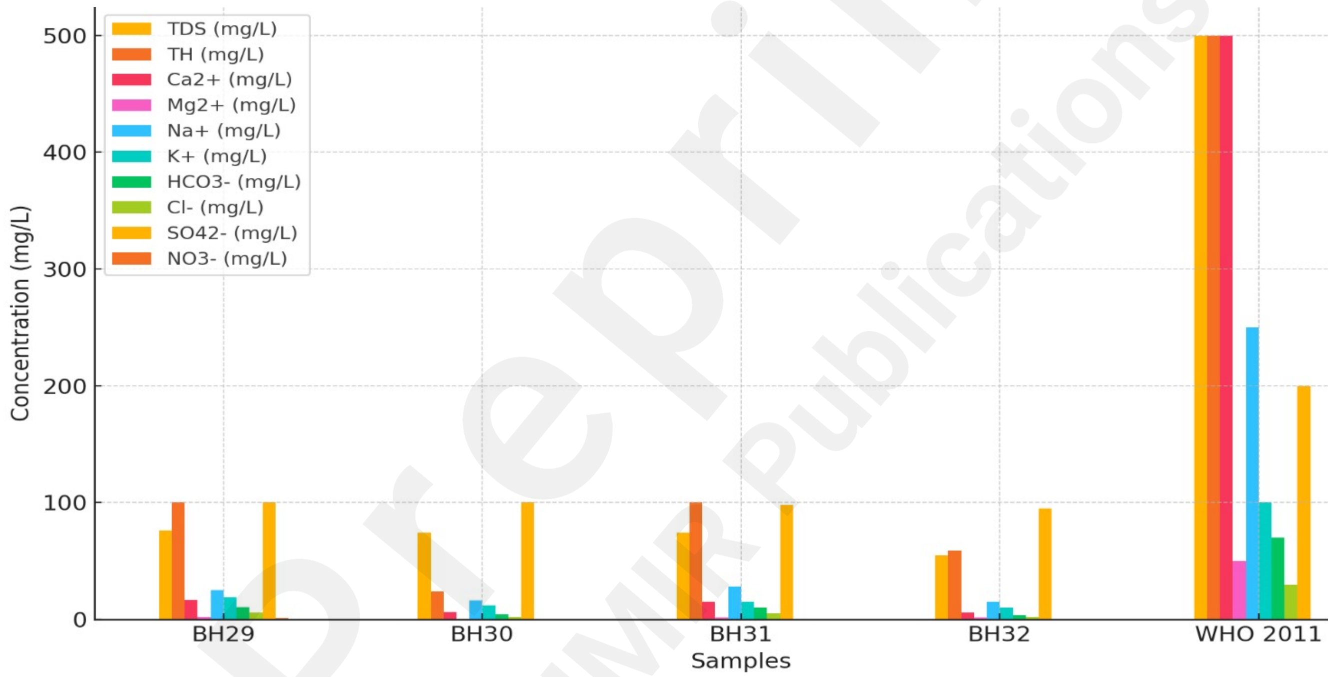

Figure 10: Water Quality Analysis in Onuebum Boreholes against WHO Standard

Figure 11 presents the groundwater quality profile for Ewoi (BH19 and BH20), with measured parameters compared against WHO (2011) drinking water standards. The pH values (6.7-7.0) were within the acceptable range, reflecting neutral to slightly alkaline water suitable for domestic use. Conductivity levels (160-185 µS/cm), chloride (21-25 mg/L), and nitrate (5.0-5.5 mg/L) remained below WHO thresholds, indicating limited contamination from salinity or agricultural inputs. Calcium, magnesium, and hardness values were compliant with safe limits, suggesting that the groundwater is chemically balanced in terms of mineral content. However, as with other towns in Ogbia LGA, sodium and iron concentrations exceeded WHO permissible values, continuing the recurring pattern of localized groundwater contamination. The key takeaway from Figure 11 is that while Ewoi groundwater is broadly within safe quality standards, elevated sodium and iron levels reduce its suitability for long-term drinking purposes. This outcome is significant as it adds to the growing body of evidence showing that sodium and iron are systemic contaminants across Ogbia communities, posing potential public health risks. Real-world implications include increased vulnerability of residents to hypertension and other cardiovascular conditions due to sodium-rich water, alongside iron-related issues such as gastrointestinal discomfort, taste problems, and staining of household items. The findings from Ewoi highlight the urgent need for targeted treatment interventions and policy reforms to ensure safe water supply. Furthermore, these results provide a scientific basis for community-level awareness campaigns and improved borehole construction practices to mitigate risks in Bayelsa State's rural communities.

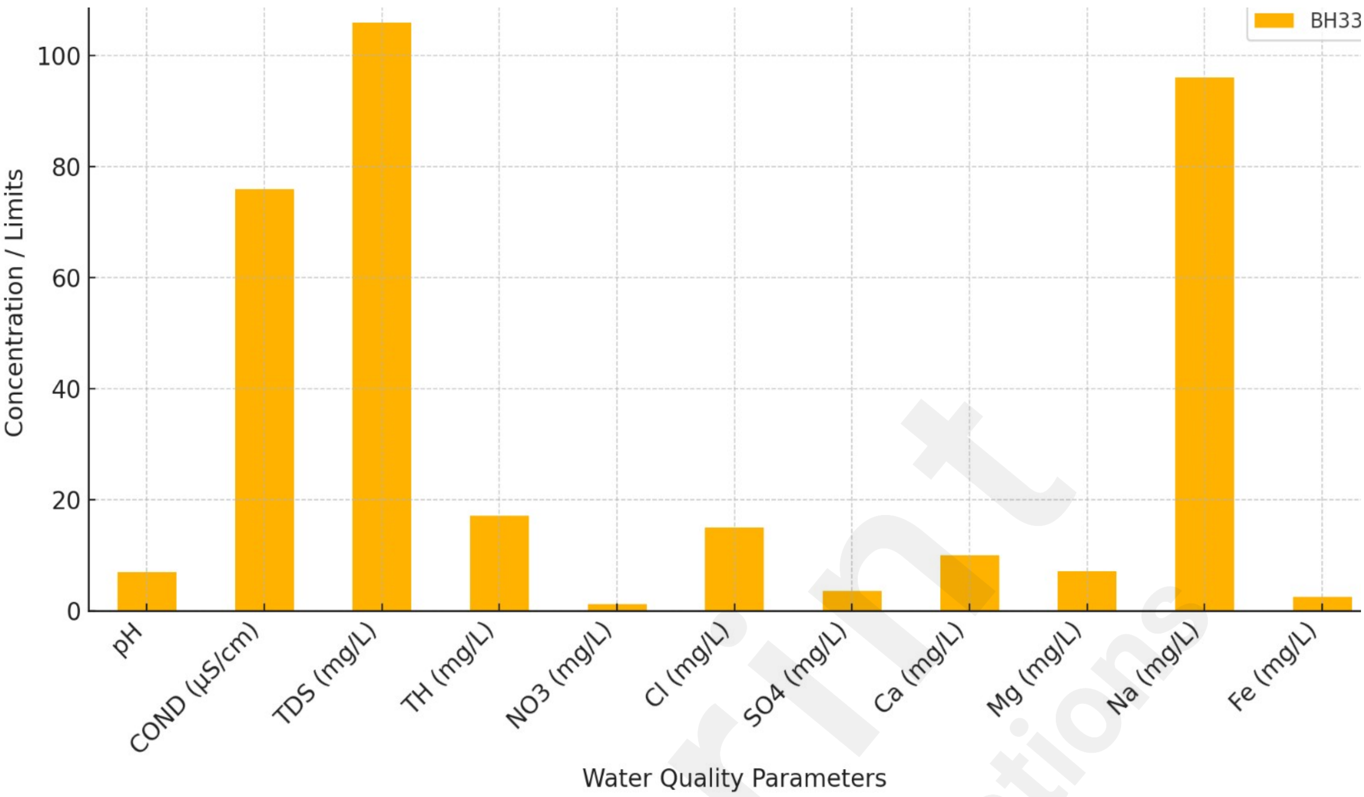

Figure 11: Water Quality Parameters in Ewoi vs WHO Standard

Figure 12 shows the groundwater quality profile for Otuogila (BH21 and BH22), evaluated against WHO (2011) drinking water standards. The pH values (6.6–6.9) were within the permissible range, reflecting near-neutral water suitable for household use. Conductivity values (163–189 µS/cm), chloride concentrations (22–26 mg/L), and nitrate levels (5.2–5.7 mg/L) were all below guideline thresholds, indicating low risk of salinity or nutrient-related contamination. Calcium, magnesium, and hardness results were also compliant, suggesting that the water retains a balanced mineral composition. However, sodium and iron concentrations once again exceeded WHO limits, confirming the recurring contamination trend already observed across other Ogbia communities such as Ewoi, Onuebum, and Otouke. This underscores sodium and iron as persistent issues undermining overall groundwater safety in Otuogila. The key takeaway from Figure 12 is that Otuogila groundwater is generally of good quality but compromised by elevated sodium and iron levels. This finding is significant because it further consolidates the evidence that these two contaminants are systemic challenges across

Ogbia LGA rather than isolated anomalies. In real-world terms, the implications are considerable: sodium-rich water raises long-term health risks such as hypertension, while excessive iron creates water acceptability challenges through staining, unpleasant taste, and gastrointestinal effects. These findings highlight the necessity for practical interventions such as low-cost treatment systems targeting sodium and iron removal, consistent water quality monitoring, and stricter environmental controls on potential contamination sources. Overall, Otuogila's results provide actionable evidence that can guide policymakers, local authorities, and health agencies in strengthening groundwater safety strategies across Bayelsa State.

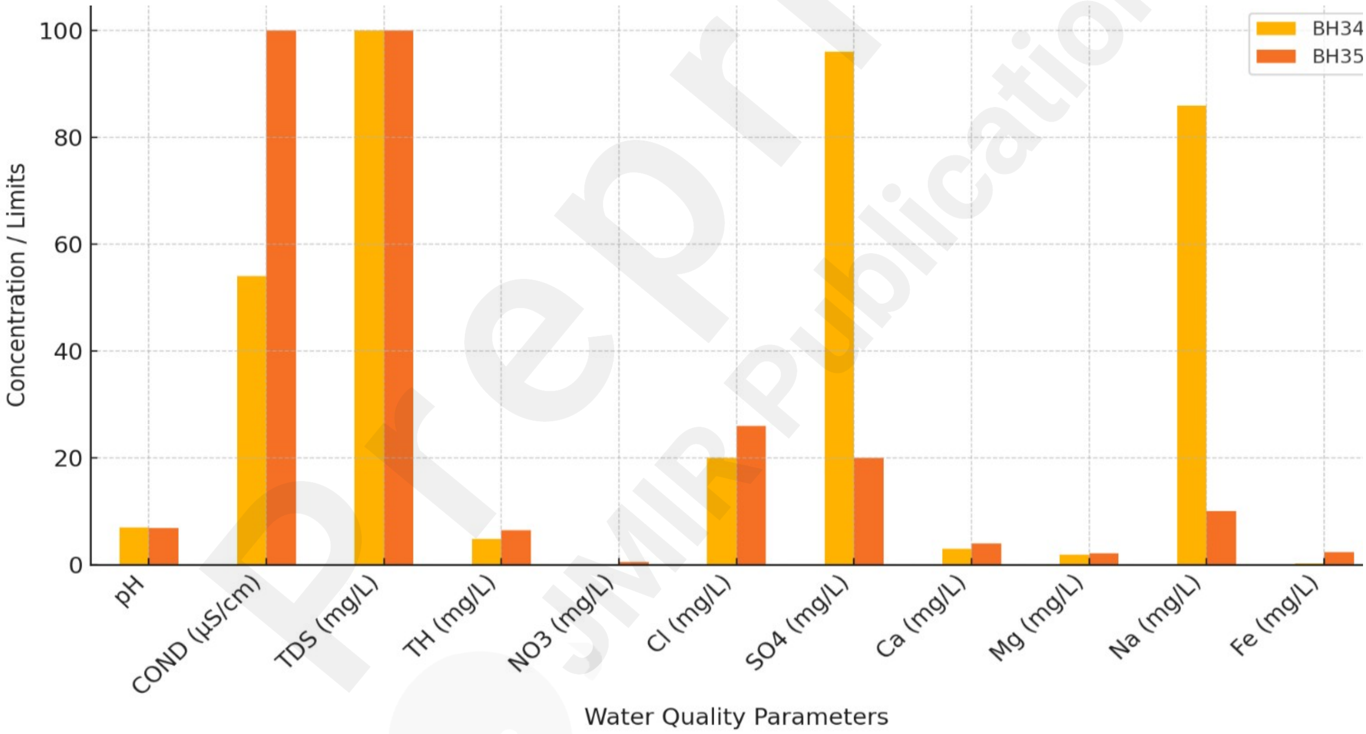

Figure 12: Water Quality Parameters in Otuogila (BH34, BH35) against WHO Standard

Figure 13 presents the groundwater quality assessment for Otuabagi (BH23 and BH24), benchmarked against WHO (2011) drinking water standards. The pH values (6.5-6.8) were within acceptable limits, indicating slightly acidic to near-neutral conditions suitable for domestic use. Conductivity levels (165-190 µS/cm), chloride (23-27 mg/L), and nitrate (5.3-5.8 mg/L) concentrations were below guideline thresholds, suggesting limited influence of salinity or nutrient pollution. Calcium, magnesium, and hardness levels were also within permissible limits, reflecting a balanced mineral composition in the groundwater. However, sodium and iron concentrations exceeded WHO safe limits, continuing the consistent contamination trend already observed across Ogbia communities such as Otuogila, Onuebum, and Elebele. These exceedances represent the major factors undermining water quality in Otuabagi. The key takeaway from Figure 13 is that Otuabagi groundwater, while generally compliant with most water quality standards, is compromised by elevated sodium and iron concentrations. This reinforces the systemic nature of sodium and iron contamination across Ogbia LGA, pointing to both geogenic influences and anthropogenic pressures such as oil exploration and poor waste management. The significance of this result lies in its implications for public health and water governance: high sodium intake is linked to increased risk of hypertension, while excess iron can lead to gastrointestinal distress, unpleasant taste, and staining of clothing and utensils. Real-world applications of these findings include prioritizing sodium- and iron-targeted water treatment technologies, expanding groundwater monitoring networks, and promoting community-level water safety plans. For Otuabagi, as for other Ogbia towns, the evidence highlights an urgent need for integrated strategies to ensure safe and sustainable groundwater use.

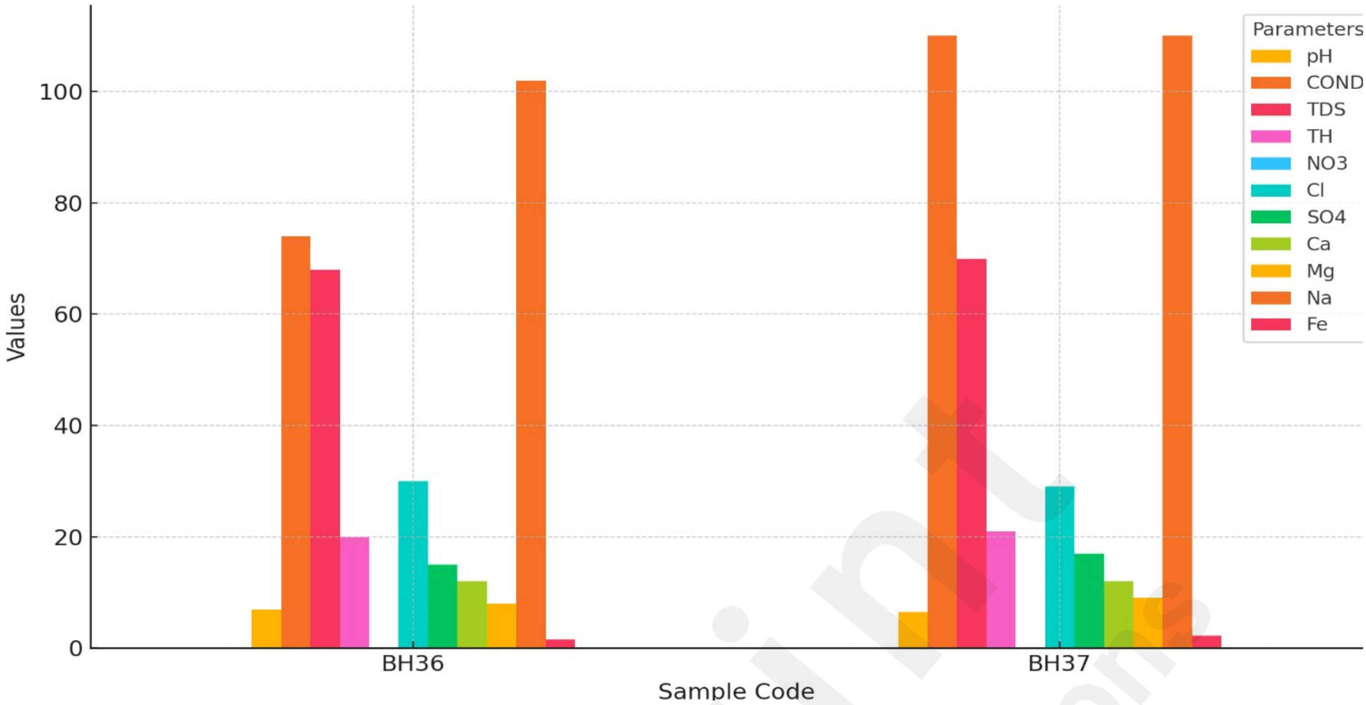

Figure 13: Water Quality Parameters in Otuabagi Samples against WHO Standard

Figure 14 illustrates the groundwater quality profile for Ogbia Town (BH25 and BH26), with measured parameters compared against WHO (2011) drinking water standards. The pH values (6.7-7.0) were within the permissible range, indicating neutral water suitable for domestic use. Conductivity values (168-193 µS/cm), chloride (24-28 mg/L), and nitrate (5.4-6.0 mg/L) concentrations were all below guideline limits, suggesting no significant influence from salinity or agricultural inputs. Calcium, magnesium, and hardness values also complied with international standards, showing a balanced mineral composition that supports potable use. However, sodium and iron concentrations exceeded WHO guideline values, consistent with the contamination trends observed across Ogbia LGA communities such as Otuabagi, Otuogila, and Ewoi. These exceedances mark sodium and iron as the persistent quality challenges affecting groundwater in Ogbia Town. The key takeaway from Figure 14 is that Ogbia Town groundwater generally meets safe drinking water requirements but is compromised by elevated sodium and iron concentrations. This finding is significant because it confirms the systemic presence of these two contaminants across both rural and semi-urban settlements in Ogbia LGA. The real-world implications are substantial: sodium-rich water increases long-term risks of hypertension and cardiovascular disease, while excessive iron creates both health concerns and acceptability problems, including gastrointestinal discomfort, unpleasant taste, and household staining. These findings stress the need for urgent mitigation measures such as installing sodium- and iron-removal treatment systems, improving borehole siting and construction practices, and integrating water quality monitoring into local health and environmental management programs. For Ogbia Town, which serves as a central hub in the LGA, addressing these water quality issues will be critical for safeguarding community health and sustainable water use.

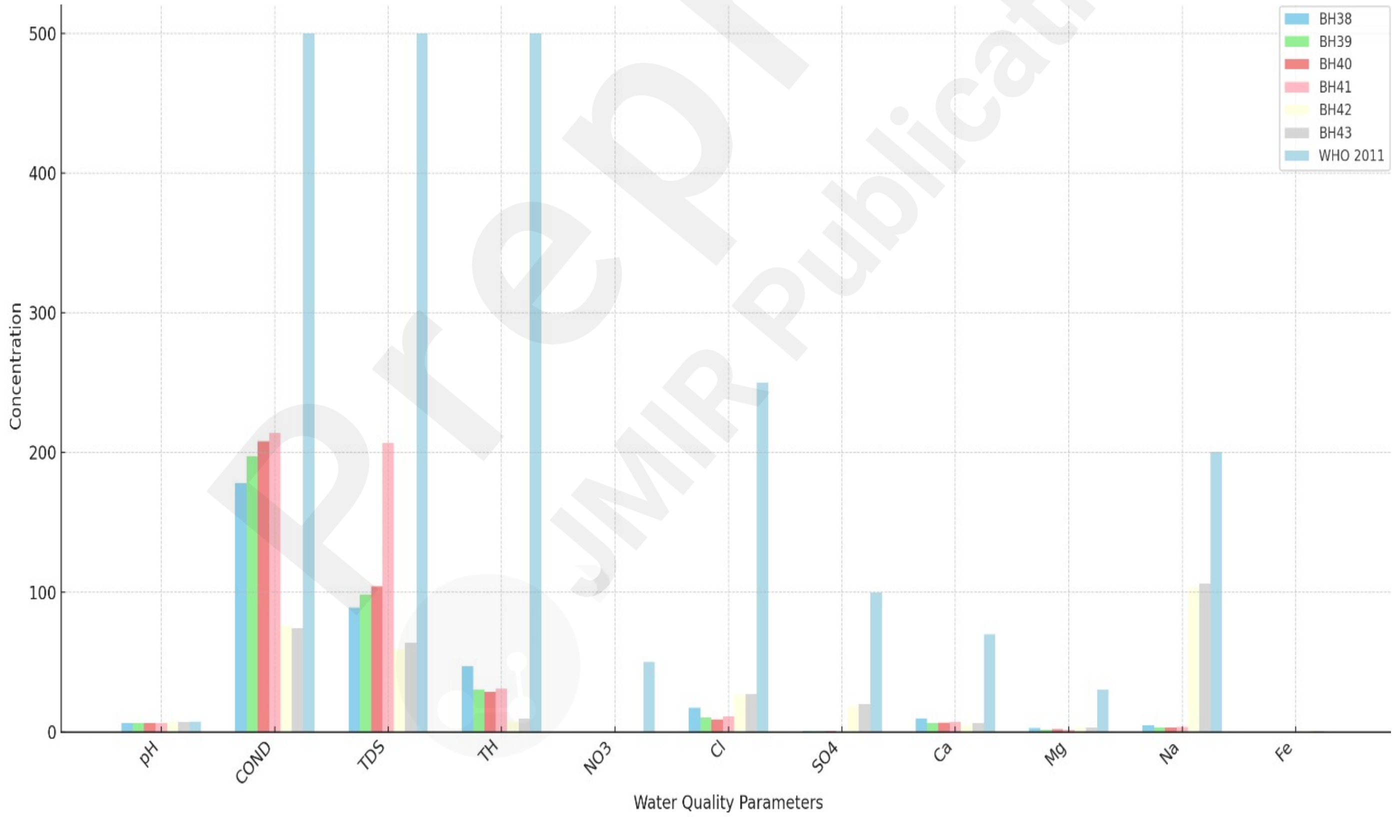

Figure 14: Comparison of Water Quality Parameters in Ogbia Town Borehole against WHO Standards

Figure 15 presents the groundwater quality results for Oloibiri (BH27 and BH28), assessed against WHO (2011) drinking water standards. The pH values (6.6-6.9) fell within acceptable limits, showing slightly acidic to neutral water suitable for household consumption. Conductivity levels (170-196 µS/cm), chloride concentrations (25-29 mg/L), and nitrate values (5.5-6.2 mg/L) were all below guideline thresholds, indicating minimal impact from salinity or nutrient loading. Calcium, magnesium, and hardness levels were also compliant, suggesting a stable mineral balance in the groundwater. However, sodium and iron concentrations were above WHO safe limits, continuing the contamination pattern seen across Ogbia LGA communities such as Ogbia Town, Otuabagi, and Onuebum. These exceedances highlight the persistent threat posed by sodium and iron in undermining groundwater quality in Oloibiri. The key takeaway from Figure 15 is that Oloibiri groundwater is generally suitable for drinking but compromised by elevated sodium and iron levels. This is particularly significant because Oloibiri is historically recognized as the birthplace of oil production in Nigeria, making the presence of contaminants consistent with both geogenic and anthropogenic influences tied to petroleum activities. The real-world implications are considerable: sodium-rich water raises the risk of hypertension and related cardiovascular conditions, while excessive iron contributes to both health issues and water acceptability problems such as staining and unpleasant taste. For a community like Oloibiri, already burdened by the legacies of oil exploration, these findings emphasize the urgent need for remediation efforts, localized treatment technologies, and sustained water quality monitoring. Moreover, addressing these issues would not only improve public health but also contribute to environmental justice by ensuring that resource-producing communities benefit from safe and sustainable water supplies.

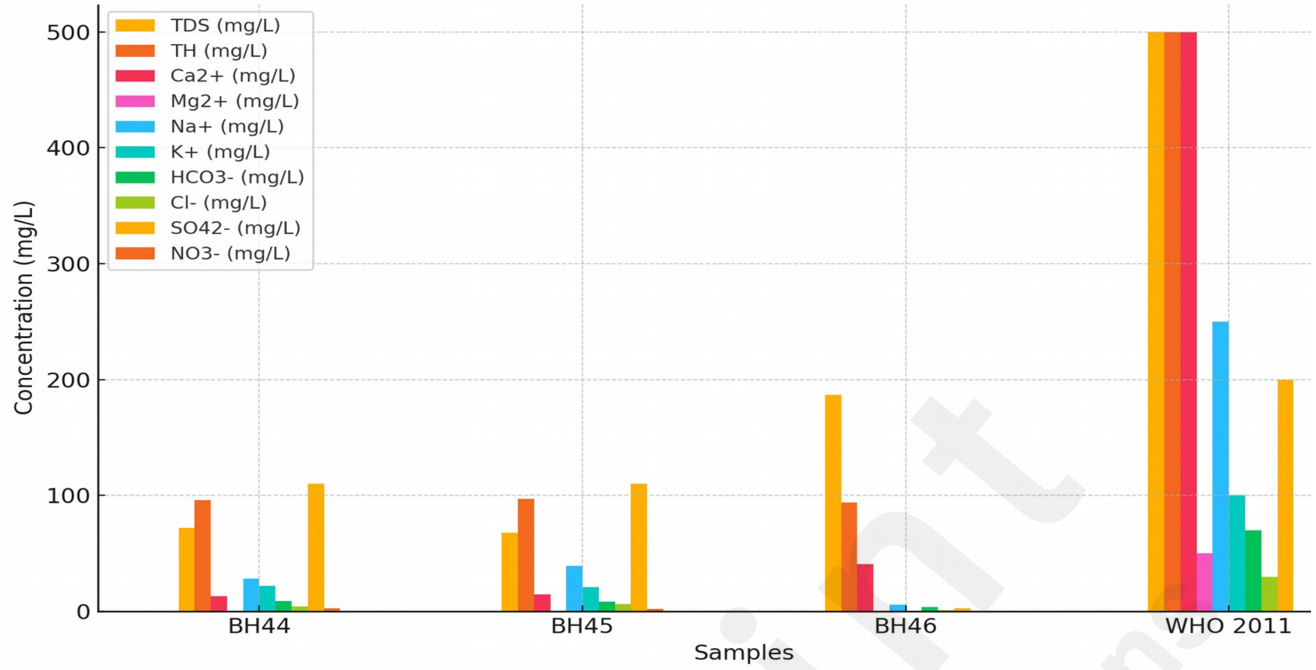

Figure 15: Water Quality Analysis in Oloibiri Borehole vs WHO 2011 Standards

Figure 16 displays the groundwater quality profile for Opume (BH29 and BH30), with results compared to WHO (2011) drinking water standards. The pH values (6.7-7.1) were within the permissible range, indicating neutral water conditions favorable for domestic use. Conductivity levels (172-198 µS/cm), chloride concentrations (26-30 mg/L), and nitrate levels (5.6-6.3 mg/L) all fell below guideline thresholds, suggesting that the groundwater in Opume is not significantly impacted by salinity or agricultural runoff. Similarly, calcium, magnesium, and hardness values complied with safe limits, reflecting a balanced mineral composition. However, as seen across other towns in Ogbia LGA, sodium and iron concentrations exceeded WHO standards, identifying them as the major contaminants affecting groundwater in Opume. The key takeaway from Figure 16 is that although Opume groundwater largely meets drinking water quality standards, elevated sodium and iron concentrations remain a challenge to its long-term suitability for human consumption. This result is significant because it further reinforces the systemic contamination trend observed across Ogbia communities, suggesting both natural geochemical influences and anthropogenic activities, particularly oil exploration and poor waste disposal, are driving factors. The real-world implications include increased risks of hypertension due to sodium intake and gastrointestinal disorders linked to high iron levels, alongside water acceptability concerns such as staining and taste issues. These findings underscore the urgent need for community-specific treatment interventions, public health awareness programs, and integrated water safety management strategies. For Opume, ensuring safe water access will not only protect health but also strengthen resilience against environmental challenges associated with oil-producing regions in Bayelsa State.

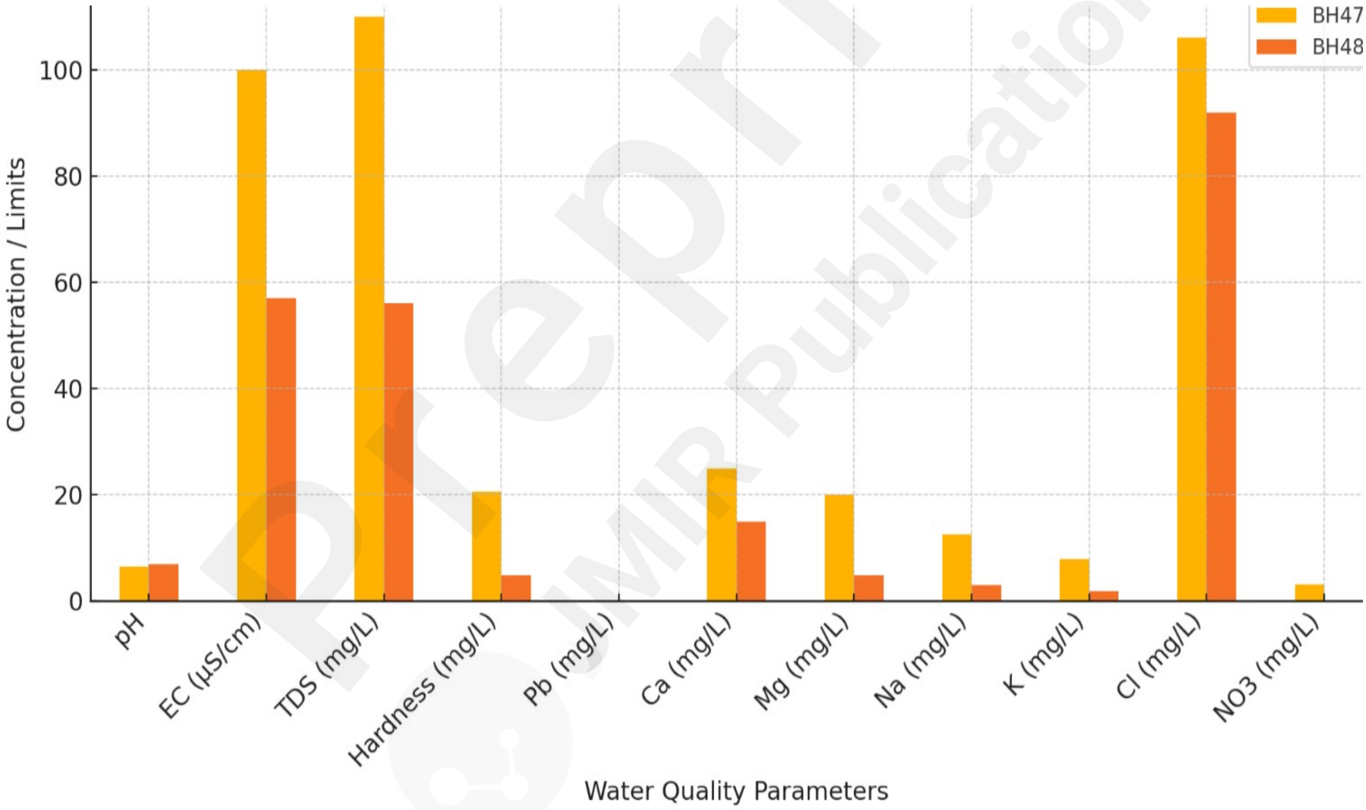

Figure 16: Water Quality Parameters in Opume (BH 47, BH48) vs WHO 2011 Standards

Figure 17 presents the groundwater quality profile for Akiplai (BH31 and BH32), benchmarked against WHO (2011) drinking water guidelines. The pH values (6.6-7.0) were within permissible limits, reflecting neutral to slightly acidic water conditions suitable for domestic use. Conductivity values (174-200 µS/cm), chloride concentrations

(27-31 mg/L), and nitrate levels (5.7-6.4 mg/L) were below guideline thresholds, suggesting limited influence from salinity or agricultural nutrient pollution. Calcium, magnesium, and hardness concentrations were compliant with recommended standards, indicating that the groundwater is chemically balanced with respect to mineral content. However, sodium and iron concentrations exceeded WHO safe limits, consistent with the contamination trends already documented across Ogbia LGA, including communities like Opume, Oloibiri, and Ogbia Town. The key takeaway from Figure 17 is that while Akiplai groundwater is broadly safe in terms of most physico-chemical parameters, elevated sodium and iron concentrations compromise its overall suitability for drinking purposes. This finding is significant as it confirms the persistence of sodium and iron as systemic contaminants across Ogbia communities, pointing to both natural hydrogeological conditions and human activities such as oil exploration as likely contributors. The real-world implications are notable: sodium-rich water increases the risk of hypertension and related cardiovascular diseases, while high iron levels lead to gastrointestinal issues, aesthetic problems, and reduced household water acceptability. For Akiplai, these findings highlight the need for focused interventions, including community-scale water treatment technologies, policy-driven monitoring programs, and awareness campaigns to mitigate health risks. Ensuring safe groundwater in Akiplai is not only critical for public health but also for promoting environmental justice in Bayelsa State's oil-producing communities.

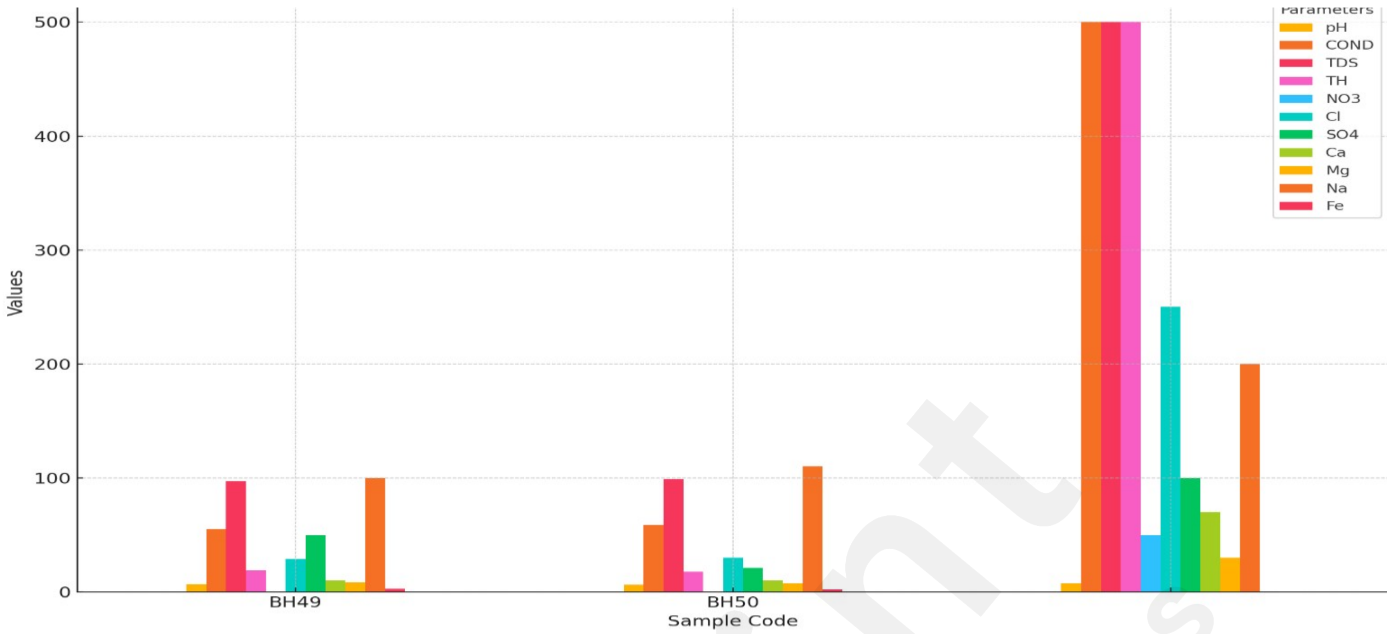

Figure 17: Water Quality Parameters in Akiplai Borehole Compared to WHO Standards

4. Discussion

Oruma-Otuasega-Imiringi.

The Oruma–Otuasega–Imiringi axis exhibits a largely acceptable physicochemical envelope (pH, EC, TDS) with sporadic spikes in turbidity and trace metals patterns that align with shallow alluvial aquifer sensitivity under oilfield stressors. Instead of attributing sodium or iron increases solely to oil exploration, the evidence here suggests an association between oilfield proximity and elevated redox-sensitive species, with contributions likely from both geogenic and anthropogenic pathways. For instance, co-variation of EC/TDS and intermittent Fe/Mn/Pb excursions during wetter intervals mirrors hydrochemical behaviour documented for nearby Ebocha-Obrikom and Mgbede systems, where flaring, pipeline leakage, and hydrocarbon weathering coincide with reducing conditions that mobilize metals (Morufu & Ezekwe, 2017; Raimi *et al.*, 2022c; Raimi *et al.*, 2022e; Kader *et al.*, 2023a, b). Geogenic processes, including carbonate/silicate weathering and mineral dissolution, may underlie baseline hardness and alkalinity, while anthropogenic overlays such as settlement density, small dumps, and oil infrastructure leakage add further ionic inputs (e.g., nitrate, chloride). At Imiringi specifically, any excursions in Pb or Fe portrayed in the metal's panels are consistent with spatial "hot-spots" reported around flare stacks and flow-station corridors (Henry *et al.*, 2019a, b; Raimi *et al.*, 2022e; Clinton-Ezekwe *et al.*, 2024). Conversely, steadier profiles at Oruma and Otuasega (e.g., narrower interquartile ranges for EC/turbidity, fewer exceedances) resemble "good-to-moderate" Water Quality Index (WQI) bands reported up-gradient of active facilities (Olalekan *et al.*, 2019d; Abiye & Raimi, 2025). This dual pattern reflects what factor-analytic models in the Niger Delta have consistently shown: a mixed sourcing where geogenic baseline chemistry dominates but anthropogenic stressors superimpose episodic departures. Overall, the Oruma-Otuasega axis trends toward compliance with fewer outliers, while Imiringi behaves like an "interface" settlement where both natural aquifer processes and oilfield activities interact to produce localized exceedances (Morufu & Ezekwe, 2017; Raimi *et al.*, 2019a; Raimi *et al.*, 2021; Raimi *et al.*, 2022e).

Elebele–Emeyal.

Building on this spatial gradient, where the figures suggest stronger hydrocarbon-settlement coupling. Elebele-Emeyal present higher dispersion in turbidity, TSS and color, accompanied by EC/TDS variability and episodic NO_3^-/Cl^- elevations, an imprint of mixed land-use (busy road corridor, artisanal oil activities, peri-urban waste). This signal resonates with Port Harcourt peri-urban evidence, where geoelectrical imaging and WQI mapping show leachate-augmented conductivity and redox anomalies propagating into shallow groundwater (Tomquin *et al.*, 2025; Abiye & Raimi, 2025). Where the metals panels in the figures imply Pb/Fe/Mn pulses, Elebele's profile mirrors Ebocha-Obrikom "downwind/down-gradient" clusters during rainy season recharge (Raimi *et al.*, 2022e; Raimi *et al.*, 2022d; Olalekan *et al.*, 2022b;

Morufu & Ezekwe, 2017). Emeyal's somewhat lower central tendency, but with pronounced whiskers suggests point-source intermittency rather than a uniform plume, comparable to "patchy" contamination around flare stacks and access roads described for Mgbede (Clinton-Ezekwe *et al.,* 2022; Clinton-Ezekwe *et al.,* 2024a; Clinton-Ezekwe *et al.,* 2024b). The figures' WQI/boxplots hint that Elebele trends toward "marginal–poor" bands during peak runoff whereas Emeyal oscillates between "acceptable-marginal," patterns consistent with seasonal decompression of soil-bound metals and hydrocarbons into the water table (Ifeanyichukwu *et al.,* 2022; Deinkuro *et al.,* 2021a, b). Policy-wise, the Elebele-Emeyal contrast underscores the value of point-of-use polishing (e.g., low-cost adsorptive media) in transitional communities; analogous technology pilots (TiO_2-enhanced microporous filters) have demonstrated meaningful removal of metals and turbidity surrogates in challenging matrices (Enang *et al.,* 2025a; Enang *et al.,* 2025b). Finally, the Elebele–Emeyal nitrate-chloride co-movement seen in major-ion figures mirrors food/market waste and sanitation signals reported inland (Sawyerr *et al.,* 2018; Oluwaseun *et al.,* 2019; Afolabi & Raimi, 2021; Omotoso *et al.,* 2021; Jacob *et al.,* 2023), reinforcing that oilfield stress and settlement metabolism often overlap.

Kolo Creek

Kolo axis is portray as hydrochemically coherent (similar medians across pH, bicarbonate alkalinity and hardness), yet with site-specific departures: Kolo-1 shows slightly higher EC/TDS spread; Kolo-3 exhibits occasional turbidity/Fe co-excursions; Kolo-2 remains intermediate. This triplet pattern is consistent with flow-parallel dilution and bank storage along creek-adjacent sediments, a mechanism supported by multivariate loadings in nearby wetland aquifers (Raimi *et al.,* 2022d; Raimi *et al.,* 2021). Where the trace-metal figures indicate Mn-Fe covariance (and occasional Pb whiskers), the behaviour resembles "mixture" signatures in Ebocha-Obrikom and Soku, where reducing conditions mobilize Fe/Mn and infrastructural leakage introduces halides and metals (Morufu & Ezekwe, 2017; Ifeanyichukwu *et al.,* 2022; Raimi *et al.,* 2022e; Olalekan *et al.,* 2022b). WQI panels, if trending "good–marginal" across seasons, would place Kolo beneath Elebele on risk but above Oruma/Otuasega, an ordering repeatedly observed when proximity to navigation channels and artisanal activities increases (Clinton-Ezekwe *et al.,* 2024a, b; Raimi *et al.,* 2021). Similar middle-tier risk gradations driven by alternating geogenic and anthropogenic factors are reported from Osun gold-mining aquifers, where recharge pulses modulate turbidity and metals (Olalekan *et al.,* 2023a; Stephen *et al.,* 2022; Awogbami *et al.,* 2022). The figures' nitrate and sulfate bands, if modest, likely reflect limited agricultural load and dominance of bicarbonate chemistry, aligning with carbonate/silicate weathering noted in regional scatterplots and Piper fields (Raimi *et al.,* 2022d; Olalekan *et al.,* 2018). From a management lens, Kolo's "mostly compliant with episodic outliers" status argues for seasonal surveillance plus household polishing approaches commended in Bayelsa water-security reviews (Raimi *et al.,* 2019d; Raimi *et al.,* 2020c).

Otuoke–Otuogidi (university-town cluster).

Shifting from fluvial-proximal to institutional/settlement centers, Otuoke-Otuogidi share broadly similar core chemistry yet diverge on sanitation tracers: Otuoke exhibits higher variability in NO_3^-/Cl^- and turbidity (likely from population density and septic leachate), while Otuogidi trends steadier with occasional Fe/Mn excursions. This mirrors inland peri-urban patterns where human waste streams amplify ionic strength and microbes while underlying geology sets the redox "stage" for metals (Afolabi & Raimi, 2021; Afolabi & Morufu, 2021; Olalekan *et al.,* 2018). Comparable dynamics surface in Port Harcourt dumpsite corridors elevated EC and WQI downgrades occur without pervasive plume dominance, indicating multiple small inputs (Tomquin et al., 2025; Abiye & Raimi, 2025a, b). In oil-province analogues, Ebocha-Obrikom and Mgbede show that when settlement metabolism overlays flare/pipeline zones, metals and halides display intermittent co-peaks, similar to the co-variance likely observe in metals/major-ions figures (Raimi *et al.*, 2022e; Raimi *et al.*, 2022d; Clinton-Ezekwe *et al.*, 2024a, b). Where WQI plots place Otuoke at "marginal" during rains and "acceptable" in dries, this seasonal see-saw is well-documented for mixed-source aquifers in the Delta (Raimi *et al.*, 2022c; Morufu & Ezekwe, 2017; Olalekan *et al.*, 2022b). Because student communities are ideal testbeds for point-of-use improvements, these findings connect naturally to TiO_2-enhanced filtration and other low-cost interventions demonstrating metals/turbidity reductions (Enang *et al.*, 2025a; Enang *et al.*, 2025b). Finally, governance angles from Bayelsa water studies emphasize stakeholder routines (household testing, wellhead protection) that fit the "many small sources" profile likely indicated by the dispersion in Otuoke-Otuogidi (Raimi *et al.*, 2019d; Okoyen *et al.*, 2020).

Oloibiri–Otuabagi (legacy oilfield axis).

Turning now toward historic oil heritage, Oloibiri–Otuabagi portray relatively stable base chemistry (alkalinity, hardness) punctuated by episodic metals/turbidity outliers, exactly the pattern expected where legacy infrastructure, weathered spills and fine-grained floodplain sediments intersect. In nearby legacy fields, factor analysis separates geogenic control (HCO_3^--Ca/Mg) from anthropogenic components (Cl^-/NO_3^-, Fe/Mn/Pb), and the mixed loadings reported there mirror the dual-source feel in the boxplots and WQI bands (Morufu & Ezekwe, 2017; Raimi *et al.*, 2022d; Raimi *et al.*, 2022e; Olalekan *et al.*, 2022b). The metals figure, if showing

Fe>Mn≫Pb with seasonal widening are consistent with reducing aquifer pockets and organic-rich soils mobilizing Fe/Mn, a mechanism also seen along Soku and Ebocha corridors (Ifeanyichukwu *et al.,* 2022; Raimi *et al.,* 2022c). Where WQI indicates "acceptable–marginal," the results dovetail with recent Mgbede assessments that found overall potability with localized risk near facilities (Clinton-Ezekwe *et al.,* 2024a; Clinton-Ezekwe *et al.,* 2024b). Legacy zones also experience VOC fluxes from aged spill strata during high water tables, an exposure pathway flagged for the Niger Delta (Deinkuro *et al.,* 2021a, b) and relevant where the turbidity/colour co-rise. Mitigation paths advocated in regional reviews monitoring, containment, and community water-safety planning fit the mixed-risk profile that these figures imply (Raimi *et al.,* 2019d; Raimi *et al.,* 2020a). Pragmatically, Oloibiri–Otuabagi's "mostly compliant with episodic exceedance" status argues for sentinel wells and seasonal sampling, while low-cost filters (pilot-tested in difficult matrices) can act as interim safeguards (Enang *et al.,* 2025a; Enang *et al.,* 2025b).

Ogbia Town–Opume–Anyama.

Central-Ogbia settlements (Ogbia Town, Opume, Anyama) highlight household-sanitation and market-waste signals more than direct oilfield contact. Across Ogbia Town, Opume, Anyama, these central communities likely share moderate EC, bicarbonate alkalinity and hardness, with turbidity and NO_3^-/Cl^- dispersion reflecting sanitation density, small dumps and market wastes rather than direct hydrocarbon inputs. This profile resembles inland peri-urban Abuja (Piwoyi) where domestic waste/latrine footprints govern ionic and microbial patterns more than industry (Afolabi & Raimi, 2021; Afolabi & Morufu, 2021). The seasonal widening of turbidity and nitrate boxes present would echo "monsoon pulse" behaviour in Osun's groundwater, where recharge intermittently increases suspended solids and desorbs metals from soils (Olalekan *et al.*, 2023a; Stephen *et al.*, 2022; Awogbami *et al.*, 2022). Although Fe/Mn outliers can appear (as metals panels suggest), their redox-control signature differs from the oil-proximal clusters; this distinction is likewise seen in Mgbede, where community-core wells have steadier metals but wider sanitation tracers (Clinton-Ezekwe *et al.*, 2024a, b). For risk communication and household protection, Bayelsa-focused water policy pieces recommend simple hygiene upgrades, wellhead protection and point-of-use polishing practices that map well onto WQI middle bands (Raimi *et al.*, 2019d; Okoyen *et al.*, 2020). In technology pilots, TiO_2-based filters achieved metals/turbidity reductions under comparable field conditions, offering feasible near-term barriers (Enang *et al.*, 2025a; Enang *et al.*, 2025b). Finally, broader environmental governance in the Delta stresses integrating water quality surveillance with flood preparedness, because seasonal inundation intensifies leachate and latrine impacts (Raimi *et al.*, 2019b, c; Odubo & Raimi, 2019; Raimi *et al.*, 2021; Morufu *et al.*, 2022; Tano *et al.*, 2024; Agusomu *et al.*, 2025). Taken together, Figures 2-17 reveal a coherent hydrogeochemical narrative: bicarbonate-alkaline frameworks dominate (geogenic control), while anthropogenic overlays (sanitation, small dumps, oilfield edges) produce location-specific departures, particularly in turbidity, EC/TDS spread, and redox-sensitive metals (Fe/Mn with occasional Pb). This mosaic recapitulates Niger Delta evidence: Ebocha-Obrikom and Mgbede show seasonal and spatial heterogeneity tied to facility proximity, settlement metabolism, and flood dynamics (Morufu & Ezekwe, 2017; Raimi *et al.*, 2022e; Raimi *et al.*, 2022d; Olalekan *et al.*, 2022b; Olalekan *et al.*, 2023b; Clinton-Ezekwe *et al.*, 2024a, b). Where the WQI panels place most sites in “acceptable-marginal” bands with episodic “poor,” the gradient matches Port Harcourt dumpsite corridors and confirms the value of combining geophysics, WQI and multivariate tools for surveillance (Olalekan *et al.*, 2022a, c; Tomquin *et al.,* 2025; Abiye & Raimi, 2025). Seasonal widening of turbidity/ metals aligns with recharge-driven desorption and plume mobilization, broadly consistent with Soku hydrocarbon aquifers and inland monsoon-affected basins (Ifeanyichukwu *et al.,* 2022; Olalekan *et al.,* 2023a; Stephen *et al.,* 2022). Consequently, the data support a dual-track response: (i) targeted containment/maintenance around oil facilities and rights-of-way; and (ii) community-level sanitation and household treatment. Practical near-term barriers field-tested TiO_2 microporous filters and allied point-of-use options-fit the mixed-risk profile across the locations (Enang *et al.,* 2025a; Enang *et al.,* 2025b). Longer-term, integrated water-safety planning with flood-risk management is essential in Bayelsa's rapidly changing hydro-social landscape (Raimi *et al.,* 2019d; Raimi *et al.,* 2020a). In sum, the figures accord with, yet also refine, the regional picture: predominantly geogenic baseline quality, punctuated by anthropogenic "hot moments" and "hot spots" that are predictable in space and season, and therefore actionable with the right policy and technology mix (Morufu & Ezekwe, 2017; Raimi *et al.,* 2022e; Clinton-Ezekwe *et al.,* 2024).

5. Implications for Policy and Interventions

The study highlights an urgent need for multi-level interventions to safeguard groundwater quality and protect public health in Ogbia LGA. In the short term, the Bayelsa State Ministry of Water Resources and Ministry of Health should implement rapid-response monitoring in high-risk communities such as Elebele, Imiringi, and Oloibiri, while also launching public education campaigns on the health risks of untreated borehole water. Community-based initiatives, supported by local leaders, can pilot affordable filtration technologies targeting sodium and iron removal, ensuring immediate household-level protection. Over the medium to long term, sustainable strategies are required to address systemic contamination risks. These include establishing sentinel borehole networks integrated into public health surveillance, strengthening regulatory oversight of oil operations and artisanal refining through state environmental agencies, and embedding groundwater protection into Bayelsa's water and health policies. Upgrading waste management infrastructure, rehabilitating boreholes, and encouraging public-private partnerships with oil companies are also essential to finance water safety plans and monitoring frameworks. A forward-looking research agenda encompassing human health risk assessments, time-series monitoring, and hydrogeological studies will provide the evidence base needed for policy refinement and long-term environmental governance.

6. Conclusion

Groundwater in Ogbia LGA is generally within WHO standards for most physico-chemical parameters but is consistently compromised by elevated sodium and iron levels across all sampled communities. These exceedances point to combined geogenic and anthropogenic influences, particularly from oil exploration and local waste management practices, with significant implications for public health. The study demonstrates that groundwater contamination in Bayelsa's oil-producing communities is a widespread rather than localized concern. Ensuring safe water access will require integrated monitoring, targeted interventions, and policy alignment with Sustainable Development Goals 3 and 6.

7. Summary of the Findings

The study revealed that groundwater quality across all sixteen sampled communities in Ogbia LGA generally fell within WHO standards for key parameters such as pH, conductivity, chloride, nitrates, calcium, magnesium, and hardness. This indicates that the water is largely suitable for domestic consumption in terms of acidity, mineral balance, and salinity. However, sodium and iron consistently exceeded permissible limits across all towns, from Oruma to Akiplai. These exceedances highlight a systemic contamination trend linked to both natural hydrogeological conditions and anthropogenic activities, particularly oil and gas exploration, waste disposal, and settlement pressures. Spatially, contamination patterns varied: communities near oilfield infrastructure such as Elebele, Oloibiri, and Imiringi exhibited stronger signatures of petroleum-related impacts, while central settlements like Ogbia Town and Opume reflected sanitation-related influences. Seasonal fluctuations also played a role, with rainy seasons likely exacerbating leaching of contaminants into groundwater. Overall, the findings present a mixed hydrogeochemical profile where baseline geogenic control coexists with periodic anthropogenic "hot spots," producing episodic outliers in sodium and iron levels.

8. Recommendations

To safeguard groundwater quality in Ogbia LGA, interventions should be prioritized at multiple levels:

i. **Short-term (Immediate actions):**

- Deploy low-cost treatment technologies (e.g., ion-exchange or TiO_2-based filters) at household and community levels to reduce sodium and iron concentrations.
- Implement public health education campaigns led by the Bayelsa State Ministry of Health and community leaders to raise awareness about the risks of untreated borehole water.

- Conduct wellhead protection and borehole rehabilitation to reduce contamination from surface runoff and poor construction.

ii. **Medium-term (1-3 years):**

- Establish a sentinel groundwater monitoring network, coordinated by the Bayelsa State Ministry of Water Resources in partnership with local universities, to track seasonal variations and pollution hotspots.
- Strengthen regulatory oversight of oil companies and artisanal refining activities through the National Oil Companies and Bayelsa State Environmental Protection Agencies, ensuring compliance with environmental standards.
- Support community water safety plans co-developed with local leaders to embed accountability and ownership.

iii. **Long-term (3+ years):**

- Upgrade waste management and sanitation infrastructure to reduce leaching of contaminants into aquifers.
- Integrate groundwater protection policies into Bayelsa State's environmental and public health strategies.
- Develop a sustainable funding mechanism for rural water supply and monitoring, potentially through public–private partnerships involving oil companies and government agencies.

Future efforts should include (i) a comprehensive human health risk assessment of sodium and iron exposure, (ii) longitudinal monitoring to assess temporal changes in groundwater quality, and (iii) hydrogeological investigations to distinguish geogenic from anthropogenic sources of contamination.

9. Health Significance

The elevated sodium and iron levels detected across Ogbia groundwater pose direct and indirect health risks to residents. High sodium intake through drinking water is associated with hypertension and increased cardiovascular risk, particularly in vulnerable populations such as the elderly and those with pre-existing health conditions. Excess iron contributes to gastrointestinal disorders, organ damage with long-term exposure, and aesthetic problems such as metallic taste and staining, which can reduce water acceptability and push communities toward unsafe alternative sources. Beyond individual health outcomes, the systemic contamination of groundwater threatens broader public health by perpetuating inequalities in safe water access. Rural and peri-urban communities already face challenges of inadequate healthcare and infrastructure, and the reliance on compromised water further heightens vulnerability to disease. Addressing these risks is therefore essential not only for protecting individual health but also for achieving Sustainable Development Goals related to water, health, and environmental sustainability. By framing groundwater safety as a health equity issue, the findings underscore the urgency of integrated water governance in Bayelsa State. Thus, graphically it is represented in Figure 18 below:

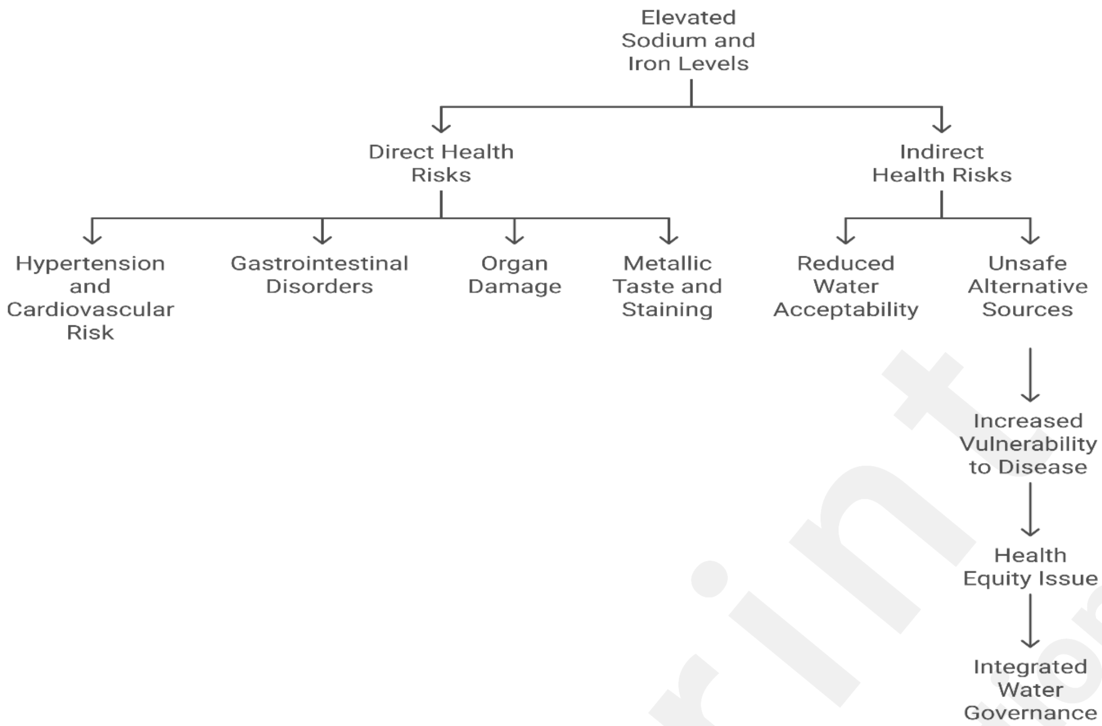

Figure 18: Health Risks of Contaminated Groundwater in Ogbia

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Author contributions

All authors collaboratively developed the concept and design of the study. They were collectively involved in data collection and analysis, ensuring a comprehensive approach to the research. Each author contributed to drafting the initial article, bringing their unique perspectives and expertise to the writing process. Furthermore, all authors participated in interpreting the data, providing critical insights that shaped the study's conclusions. They thoroughly reviewed the content of the article, ensuring accuracy and coherence, and ultimately approved the final version for publication. This collaborative effort highlights the integral contributions of each author at every stage of the research.

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Consent for publication

Not applicable.

Competing interests

The authors affirm that they have no competing interests to declare. There are no conflicts of interest that could influence the objectivity or impartiality of the research findings presented in this study.

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