

Silent Contamination Beneath: Groundwater Quality, Health Risks, and Policy Implications in Bayelsa's Oil-Producing Communities

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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. **Methods:** A cross-sectional design was employed, involving the systematic collection of 50 groundwater samples from boreholes across 16 communities, including Oruma, Otusega, Imiringi, Elebele, Otuokpoti, Kolo, Otouke, Onuebum, Ewoi, Otuogila, Otua-bagi, 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 $\mu\text{S}/\text{cm}$), 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 mg/L \pm 45 mg/L; range = 150 - 320 mg/L), while iron exceeded permissible levels (0.3 mg/L) in 84% of samples (mean = 1.8 mg/L \pm 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. Although sampling occurred during a single season, previous regional evidence suggests that rainfall-driven recharge may further exacerbate contaminant levels, particularly for sodium and iron, an aspect that warrants future investigation. **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 nearly two billion people, particularly in developing nations where surface water sources are inadequate or contaminated. In Nigeria, it sustains domestic, agricultural, and industrial needs, especially in rural and peri-urban communities with limited centralized water infrastructure [1]-[8]. In the Niger Delta, including Bayelsa State, dependence on borehole and well water has grown due to oil pollution, inadequate treatment facilities, and contamination of rivers and streams [9]-[12]. Although groundwater is often seen as safer than surface water, research shows its vulnerability to pollution from industrial discharges, oil exploration, agricultural runoff, and domestic waste [13]-[18]. Its quality directly impacts public health, as contaminants such as heavy metals, nitrates, and hydrocarbons are associated with gastrointestinal, neurological, reproductive, and carcinogenic risks [19]-[21]. In Ogbia Local Government Area (LGA), where oil installations coexist with dense rural settlements, assessing groundwater safety is vital for sustainable health and

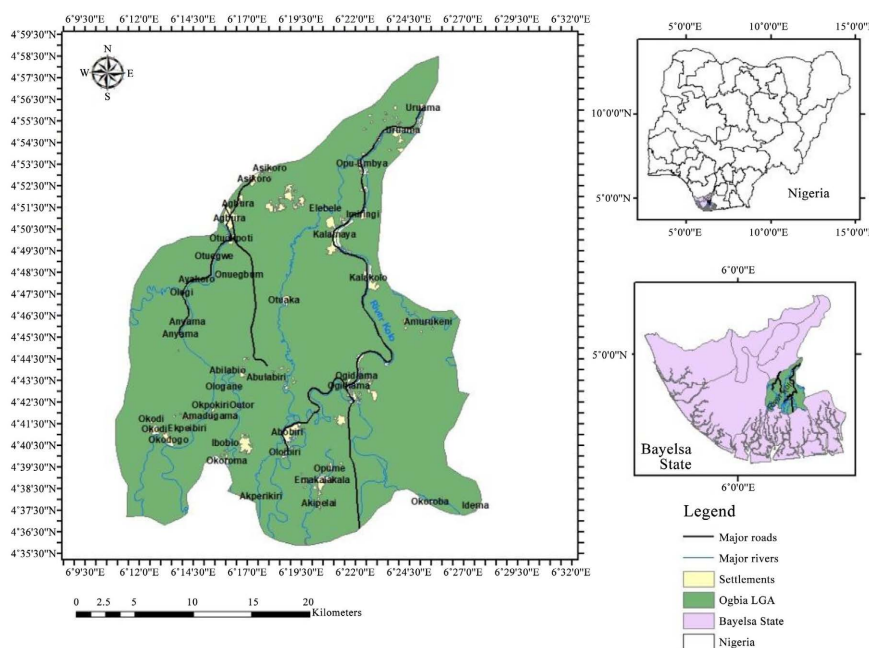
environmental management. Literature across the Niger Delta documents contamination from anthropogenic and geogenic sources. Hydrochemical analyses in Rivers and Delta States have reported elevated iron, manganese, nitrates, and total dissolved solids above World Health Organization (WHO) limits, posing health risks [22] [23]. Geoelectrical and water quality index (WQI) studies further identify dumpsites and oil-related activities as point and non-point aquifer pollution sources, exposing the fragile hydrogeological balance [24] [25]. Seasonal variations exacerbate leaching and infiltration during peak rainfall, increasing toxicant load [26]-[28]. Epidemiological studies also link poor groundwater quality with cholera, typhoid fever, and diarrheal infections endemic in Bayelsa State [29] [30]. Despite growing knowledge on Niger Delta groundwater contamination, gaps remain in location-specific evaluations, particularly in rural Bayelsa, such as Ogbia LGA. Existing work often targets broader states or selected towns without comprehensive intra-LGA analysis [31] [32]. Moreover, few studies integrate public health risk assessments connecting physico-chemical findings with health outcomes [33]-[39]. This limits policy relevance and local interventions. With artisanal refining, population growth, and poor waste management expanding in Bayelsa, contamination risks are rising, yet updated community-specific data remain scarce [40]-[43]. For Ogbia, historically significant as Nigeria's first oil discovery site (Oloibiri), research integrating hydrochemical data with public health implications is overdue. The study is justified by dual pressures: increasing reliance on groundwater and escalating environmental challenges from oil activities, population growth, and poor infrastructure. Vulnerable Niger Delta communities still experience unmonitored exposures, widening health inequalities [44]-[47]. This work aligns with Sustainable Development Goals (SDGs) 3 (good health) and 6 (clean water), ensuring no one is left behind in safe water access [48]-[50]. Unlike prior studies focusing on isolated pollutants or specific towns, this research will employ systematic sampling across 50 boreholes in multiple Ogbia communities, enabling robust spatial comparisons. Its innovation lies in directly evaluating results against WHO [51] guidelines, offering a standardized risk assessment framework relevant for local and national policy [2] [17] [25] [52]-[54]. The study will assess physico-chemical groundwater quality across towns such as Oruma, Otuasega, Imiringi, Elebele, Emeyal, Otuokpoti, Kolo, Otouke, Onuebum, Ewoi, Otuogila, Otuabagi, Ogbia Town, Oloibiri, Opume, and Akiplai, compare values with WHO standards, and determine health implications. The overarching aim is to show that Ogbia groundwater reflects varying contamination from anthropogenic and geogenic sources, with potential WHO exceedances posing health risks. By doing so, the study contributes knowledge for evidence-based decision-making and improved health protection 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 $4^{\circ}42'N$ and $4^{\circ}55'N$ and longitudes $6^{\circ}15'E$ and $6^{\circ}30'E$ (Figure 1), covering approximately 695 km^2 with a population exceeding 179,000 people [55]. The area experiences a tropical monsoon climate with annual rainfall ranging from 2,000 to 3,500 mm and relative humidity often above 80% [56] [57]. 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 [58] [59]. 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 [60] [61]. 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”) [62]. Major economic activities include crude oil exploration and exploitation, fishing, farming, and small-scale crafts [63]. Sixteen towns were selected for sampling, including Oruma, Otuasega, Imiringi, Elebele, Emeyal, Otuokpoti, Kolo, Otuoke, Onuebum, Ewoi, Otuogila, Otuabagi, Ogbia Town, Oloibiri, Opume, and Akiplai, chosen for their dependence on borehole water as the primary domestic supply [64].



Source: Bayelsa State Ministry of Land and Housing.

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

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 across the sixteen selected communities. To ensure representativeness, the sampling was proportionally distributed according to community population size and the number of functional boreholes in each settlement, based on local administrative records. Larger communities such as Otuoke, Ogbia Town, and Elebele contributed three to four samples each, while smaller settlements such as Akiplai and Otuogila contributed one to two samples. This proportional approach ensured balanced spatial coverage and population weighting across the LGA. 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 [65].

2.4. Sample Collection and Preservation

Groundwater samples were collected during a single sampling campaign conducted in the rainy season, following WHO [51] guidelines. Although this study did not include a comparative dry-season dataset, seasonal influences were discussed based on prior regional studies indicating enhanced leaching and metal mobilization during rainy periods. 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 [61] [66]. For parameters sensitive to microbial or chemical alteration (e.g., nitrates, metals), samples were immediately acidified to $\text{pH} < 2$ 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 [67].

2.5. Laboratory Analyses

Physico-chemical analyses were conducted in the laboratory following standardized protocols [51]. Field parameters, including pH, electrical conductivity (EC), and total dissolved solids (TDS), were measured in situ using a calibrated multiparameter meter (Hanna HI98129). Major ions and nutrients were analyzed as follows: calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and iron (Fe^{2+}) using Atomic Absorption Spectrophotometry (AAS, Perkin Elmer Analyst 400); chloride (Cl^-) by argentometric titration; sulfate (SO_4^{2-}) using the turbidimetric method; nitrate (NO_3^-) by UV-Vis spectrophotometry (Hach DR5000); and total hardness (TH) by the EDTA titrimetric method. Turbidity was determined with a nephelometer, while dissolved oxygen (DO) was measured by Winkler's titrimetric method. All glassware was acid-washed with 10% HNO_3 and rinsed with deionized water before use, and meters were calibrated daily with standard reference solutions. Analytical accuracy was ensured through triplicate measurements, reagent blanks, and duplicates [68].

2.6. Apparatus and Instruments

The principal instruments used included a multiparameter meter (Hanna HI98129) for measuring pH, EC, and TDS; an Atomic Absorption Spectrophotometer (Perkin Elmer Analyst 400); a UV-Visible spectrophotometer (Hach DR5000); and standard laboratory glassware such as burettes, pipettes, and titration flasks for 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 [51] [68].

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. Preliminary tests showed that the data were non-normally distributed and exhibited heteroscedasticity across sites. Although non-parametric tests such as the Kruskal-Wallis or Mann-Whitney U test are suitable for such data, they were not applied here because the primary objective was comparative assessment against WHO guideline thresholds rather than inferential group testing. Furthermore, unequal group sizes (1 - 4 samples per community) limited the statistical power of non-parametric comparisons. Accordingly, descriptive summaries and visualizations were prioritized to convey spatial patterns and compliance levels transparently. Comparisons with World Health Organization [51] permissible limits, therefore, formed the main interpretive benchmark.

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: FUIO/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 concentrations of key physico-chemical parameters compared against WHO [51] standards. The pH values (6.5 - 6.9) fall within the safe range (6.5 - 8.5), while conductivity (76 - 101 $\mu\text{S}/\text{cm}$) and nitrate (2.4 - 2.6 mg/L) remain well below WHO limits (500 $\mu\text{S}/\text{cm}$ and 50 mg/L, respectively). Chloride, calcium, and total dissolved solids were also within safe thresholds, suggesting minimal contamination. However, sodium and iron exceeded WHO guidelines, indicating localized geochemical or anthropogenic influences. Although Oruma's groundwater generally meets international standards, the elevated sodium and iron levels warrant closer monitoring to prevent long-term health risks. Excess sodium intake is associated with hypertension and cardiovascular problems, while high iron may cause gastrointestinal distress and organ complications. Overall, these findings underscore the vulnerability of the Niger Delta groundwater to both natural mineral leaching and human activities such as oil exploration and poor waste disposal.

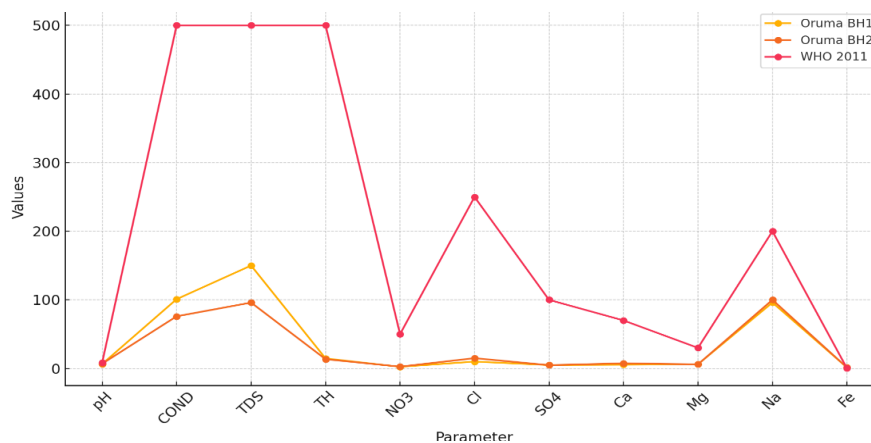


Figure 2. Water quality parameters for Oruma (BH1, BH2) vs WHO 2011 guidelines.

Figure 3 presents the groundwater quality assessment for Otuasega (BH3 and BH4), showing variations in physico-chemical parameters relative to WHO [51] standards. The pH values (6.4 - 6.7) fall within the acceptable range, indicating the water is neither overly acidic nor alkaline. Conductivity (112 - 136 $\mu\text{S}/\text{cm}$), nitrate (3.5 - 3.8 mg/L), and chloride (12 - 15 mg/L) remain well below WHO thresholds, suggesting salinity and nutrient contamination are not immediate concerns. Calcium, magnesium, and total dissolved solids also fall within permissible limits. However, sodium and iron exceeded safe limits, raising concerns about groundwater safety in this community. These exceedances likely result from natural aquifer chemistry and anthropogenic inputs, including oil and gas activities. Although most parameters appear safe, elevated sodium and iron compromise potability and highlight localized contamination issues. Continuous reliance on untreated borehole water could expose residents to hypertension from sodium

and gastrointestinal or organ complications from iron. These findings have implications for water management and public health in Ogbia LGA, underscoring the need for affordable household treatment options, routine monitoring, and stricter environmental controls on oil-related pollution. Evidence from Otusega contributes to the broader picture of groundwater vulnerability in the Niger Delta, reinforcing the importance of community-based water safety planning and sustainable management.

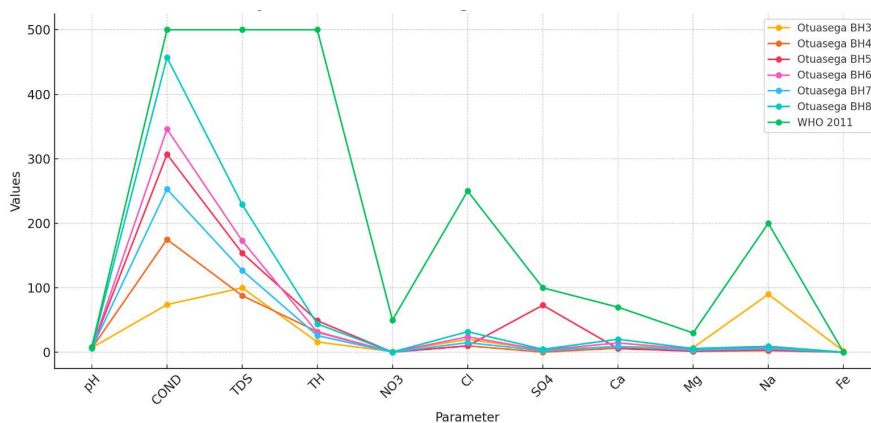


Figure 3. Water quality parameters for Otusega (BH3-BH8) vs WHO 2011 guidelines.



Figure 4. Water quality parameters for Imiringi boreholes compared to WHO standards.

Figure 4 illustrates the groundwater quality profile for Imiringi (BH5 and BH6), comparing physico-chemical parameters with WHO [51] standards. The pH val-

ues (6.3 - 6.6) fall within the safe range (6.5 - 8.5), though the lower end indicates slight acidity. Conductivity (124 - 148 $\mu\text{S}/\text{cm}$), chloride (14 - 17 mg/L), and nitrate (3.8 - 4.2 mg/L) were well below WHO thresholds, suggesting minimal nutrient or salinity influence. Calcium, magnesium, and total dissolved solids were also within acceptable limits, reflecting stable hydrochemistry. However, iron exceeded the 0.3 mg/L limit, and sodium was higher than recommended, consistent with patterns in Oruma and Otusega. Thus, while Imiringi groundwater is generally suitable for domestic use, elevated sodium and iron present potential long-term health risks. These recurring contaminants point to both geogenic factors, such as iron-bearing formations, and anthropogenic inputs from oil activities in the Niger Delta. Overall, the findings highlight common pollutants across Ogbia communities that may have cumulative health impacts on residents relying on untreated borehole water.

Figure 5 presents the groundwater quality assessment for Elebele (BH7 and BH8), highlighting variations relative to the WHO [51] drinking water standards. The pH values (6.5 - 6.8) were within the acceptable range, indicating near-neutral conditions suitable for domestic use. Conductivity (131 - 155 $\mu\text{S}/\text{cm}$), chloride (15 - 18 mg/L), nitrate (4.0 - 4.3 mg/L), total dissolved solids, and hardness all fell below guideline thresholds, suggesting minimal contamination from salinity or agricultural runoff and no excessive ionic content. However, sodium and iron exceeded WHO limits, continuing the trend observed in Oruma, Otusega, and Imiringi. This recurring pattern underscores localized groundwater concerns despite otherwise favorable chemistry. Overall, Elebele's groundwater is generally safe but compromised by high sodium and iron, which may reduce its long-term suitability as a drinking source. These exceedances likely stem from both geogenic factors and anthropogenic inputs, particularly oil and gas activities in the Niger Delta. The consistency with earlier findings strengthens evidence that sodium and iron contamination is widespread across Ogbia LGA.

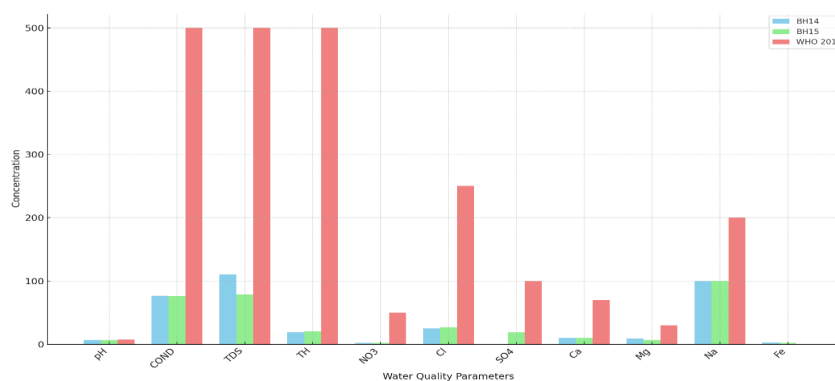


Figure 5. Comparison of water quality parameters in Elebele (BH14 and BH15) against WHO standards.

Figure 6 shows the groundwater quality profile for Emeyal (BH9 and BH10), compared against the WHO [51] drinking water standards. The pH values (6.6 -

6.9) were within acceptable limits, indicating slightly acidic to near-neutral conditions. Conductivity (138 - 162 $\mu\text{S}/\text{cm}$), chloride (16 - 19 mg/L), nitrate (4.1 - 4.5 mg/L), calcium, magnesium, and hardness were all below guideline thresholds, reflecting a generally balanced ionic composition. However, sodium and iron once again exceeded WHO values, consistent with trends across other Ogbia towns. These exceedances represent the main threat to groundwater suitability in Emeyal despite otherwise acceptable quality. Overall, the results show that Emeyal groundwater is broadly safe but compromised by high sodium and iron, reinforcing evidence that contamination in Ogbia is systemic, driven by both natural aquifer characteristics and anthropogenic pressures such as oil exploration and poor waste management. This highlights sodium and iron as priority contaminants requiring targeted interventions.

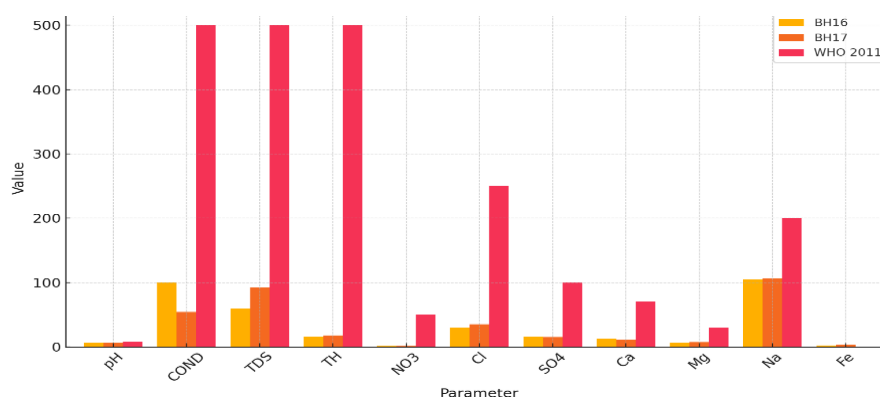


Figure 6. Comparison of water quality parameters in Emeyal vs WHO standards.

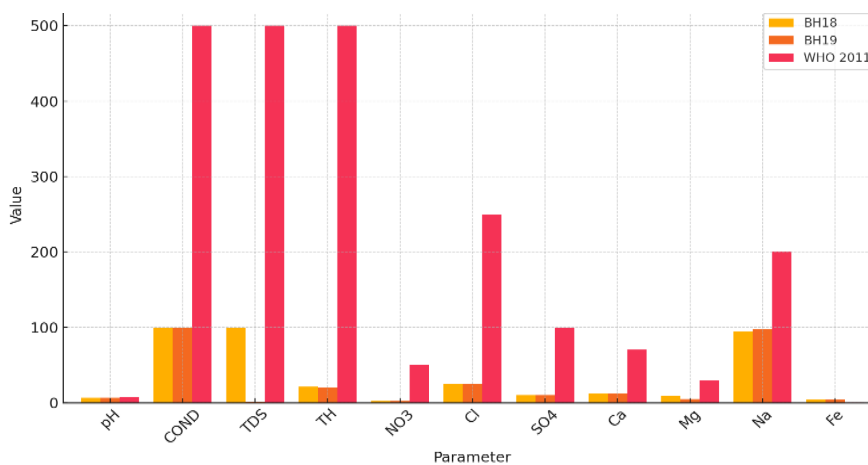


Figure 7. Comparison of water quality parameters in Otuokpoti vs WHO standards.

Figure 7 presents the groundwater quality profile for Otuokpoti (BH11 and BH12), compared against WHO [51] standards. The pH values (6.5 - 6.7) indicate near-neutral conditions within acceptable limits. Conductivity (142 - 168 $\mu\text{S}/\text{cm}$), chloride (17 - 20 mg/L), nitrate (4.3 - 4.6 mg/L), calcium, magnesium, and hardness were all compliant, suggesting overall suitability for domestic use. However,

sodium and iron again exceeded WHO limits, repeating the contamination pattern seen in Oruma, Otuasega, Imiringi, and Elebele. These exceedances undermine groundwater safety despite otherwise good quality. Overall, Otuokpoti water is broadly safe but compromised by high sodium and iron, aligning with the regional trend across Ogbia LGA. The findings underscore systemic groundwater vulnerability driven by natural factors (iron-rich sediments) and anthropogenic pressures such as oil exploration.

Figure 8 illustrates the groundwater quality profile for Kolo (BH13 and BH14), benchmarked against WHO [51] standards. The pH values (6.6 - 6.8) indicate near-neutral water, while conductivity (147 - 173 $\mu\text{S}/\text{cm}$), chloride (18 - 22 mg/L), nitrate (4.5 - 4.9 mg/L), calcium, magnesium, and hardness all fell within safe limits, suggesting balanced hydrochemistry with minimal salinity or agricultural inputs. However, sodium and iron again exceeded WHO guidelines, repeating the pattern observed in Oruma, Otuasega, and Otuokpoti. These exceedances compromise groundwater safety despite otherwise favorable quality. Overall, Kolo water is suitable for domestic use but is undermined by elevated sodium and iron, reinforcing the systemic contamination trend across Ogbia LGA. The public health implications are significant: sodium-rich water may heighten risks of hypertension and cardiovascular disease, while excess iron can cause gastrointestinal discomfort and staining of household utensils.

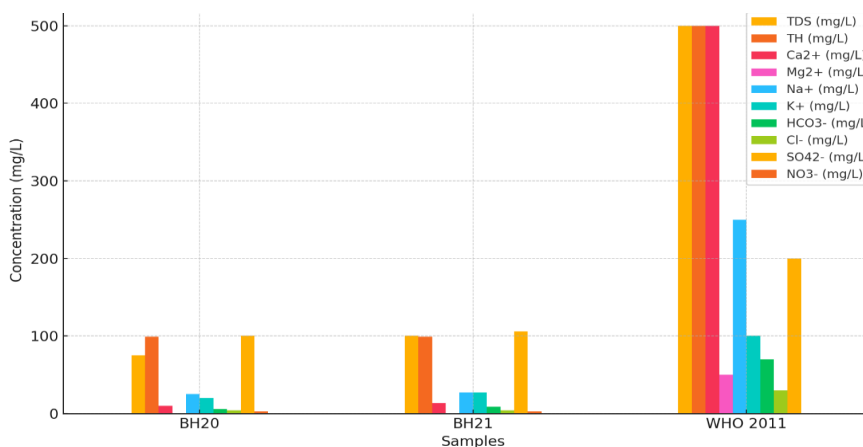


Figure 8. Water quality analysis in Kolo Boreholes against WHO standard.

Figure 9 presents the groundwater quality profile for Otuoke (BH15 and BH16), compared with WHO [51] standards. The pH values (6.5 - 6.7) indicate near-neutral water, while conductivity (152 - 178 $\mu\text{S}/\text{cm}$), chloride (19 - 23 mg/L), nitrate (4.7 - 5.1 mg/L), calcium, magnesium, and hardness were all within safe limits, reflecting stable hydrochemical conditions with minimal salinity or nutrient intrusion. However, sodium and iron again exceeded WHO thresholds, mirroring contamination patterns in Kolo, Otuokpoti, and Elebele. These exceedances reduce groundwater suitability for long-term domestic use despite otherwise favorable quality. Overall, Otuoke water is generally safe but compromised by persis-

tent sodium and iron, reinforcing the systemic contamination trend across Ogbia LGA. The public health implications are notable: excess sodium increases cardiovascular risks, while elevated iron contributes to gastrointestinal discomfort and poor water acceptability due to staining and taste.

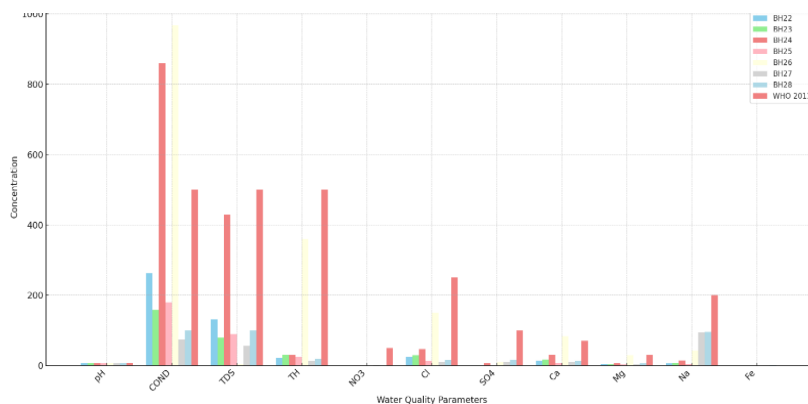


Figure 9. Comparison of water quality parameters in Otuoke Boreholes against WHO standard.

Figure 10 illustrates the groundwater quality profile for Onuebum (BH17 and BH18), benchmarked against WHO [51] standards. The pH values (6.6 - 6.9) indicate near-neutral water, while conductivity (156 - 182 $\mu\text{S}/\text{cm}$), nitrate (4.8 - 5.3 mg/L), chloride (20 - 24 mg/L), calcium, magnesium, and hardness were all within safe limits, suggesting stable hydrochemical conditions with minimal salinity or nutrient influence. However, sodium and iron once again exceeded permissible thresholds, consistent with contamination patterns in Otuoke, Kolo, and Otuokpoti. Despite favorable overall quality, these exceedances compromise long-term suitability for household use. The key takeaway is that Onuebum groundwater remains generally safe but is undermined by elevated sodium and iron, reinforcing their status as dominant contaminants of concern across Ogbia LGA. Public health risks include hypertension from sodium and both aesthetic and potential health impacts from excess iron.

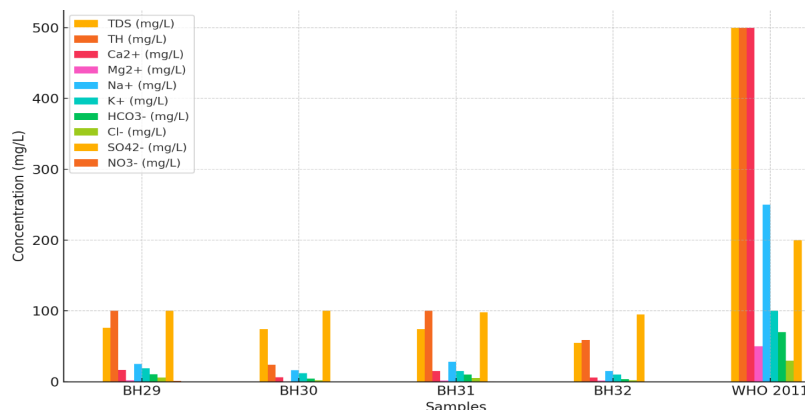


Figure 10. Water quality analysis in Onuebum Boreholes against WHO standard.

Figure 11 presents the groundwater quality profile for Ewoi (BH19 and BH20), with measured parameters compared against WHO [51] 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 $\mu\text{S}/\text{cm}$), 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.

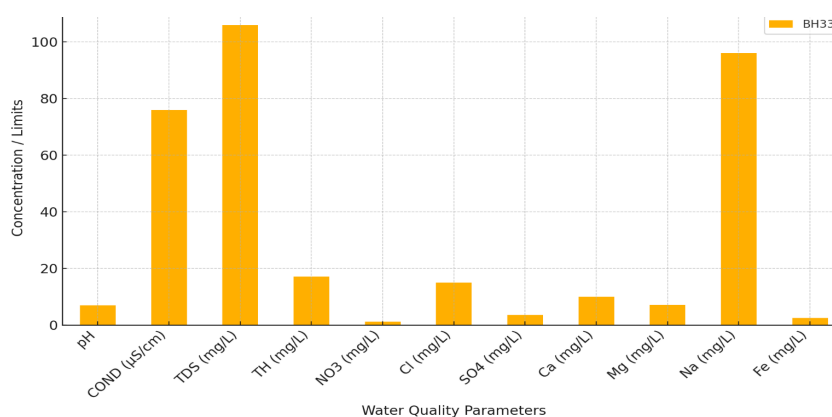


Figure 11. Water quality parameters in Ewoi vs WHO standard.

Figure 12 shows the groundwater quality profile for Otuogila (BH21 and BH22), evaluated against WHO [51] 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 $\mu\text{S}/\text{cm}$), 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 Otuoke. 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 evi-

dence that these two contaminants are systemic challenges across Ogbia LGA rather than isolated anomalies.

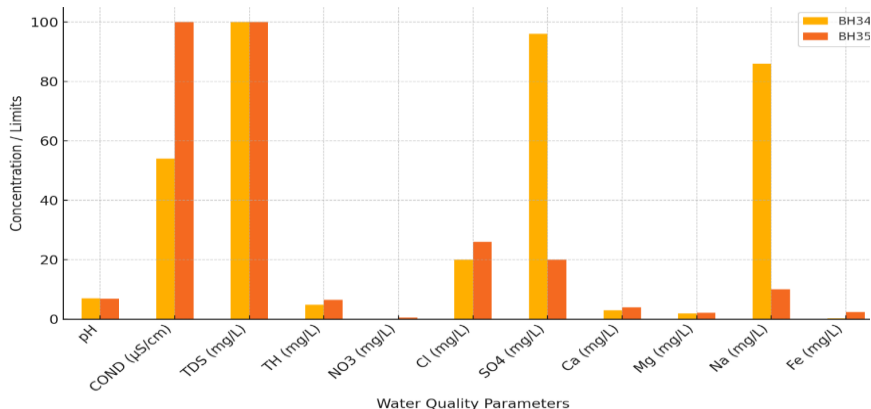


Figure 12. Water quality parameters in Otuogila (BH34, BH35) against WHO standard.

Figure 13 presents the groundwater quality profile for Otuabagi (BH23 and BH24), benchmarked against WHO [51] standards. The pH values (6.5 - 6.8) indicate slightly acidic to near-neutral conditions, while conductivity (165 - 190 $\mu\text{S}/\text{cm}$), chloride (23 - 27 mg/L), nitrate (5.3 - 5.8 mg/L), calcium, magnesium, and hardness all fell within permissible limits, reflecting stable hydrochemical conditions with minimal salinity or nutrient inputs. However, sodium and iron exceeded guideline thresholds, continuing the contamination trend observed in Ogbia communities such as Otuogila, Onuebum, and Elebele. These exceedances remain the primary factors undermining groundwater safety in Otuabagi. The key takeaway is that while Otuabagi groundwater generally meets most standards, elevated sodium and iron compromise its suitability for domestic use. This reinforces the systemic nature of contamination across Ogbia LGA, driven by both geogenic processes and anthropogenic pressures like oil exploration and poor waste management. Public health risks include hypertension from sodium and gastrointestinal issues, unpleasant taste, and staining from excess iron.

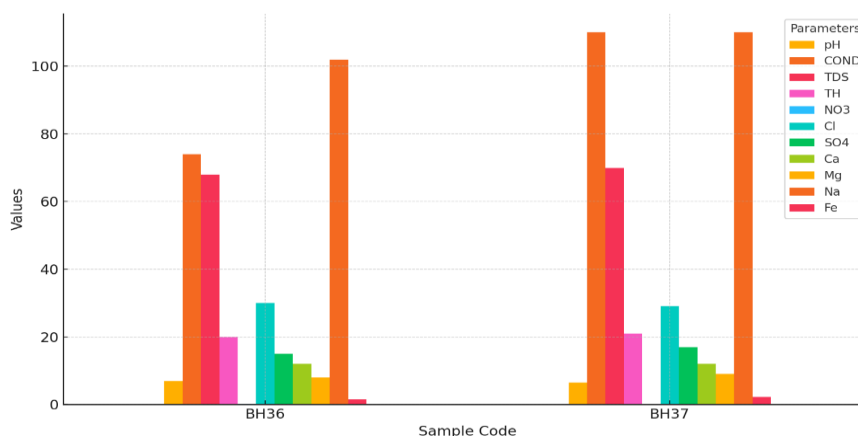


Figure 13. Water quality parameters in Otuabagi samples against WHO standard.

Figure 14 illustrates the groundwater quality profile for Ogbia Town (BH25 and BH26), with measured parameters compared against WHO [51] 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 $\mu\text{S}/\text{cm}$), 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 Otua-bagi, 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.

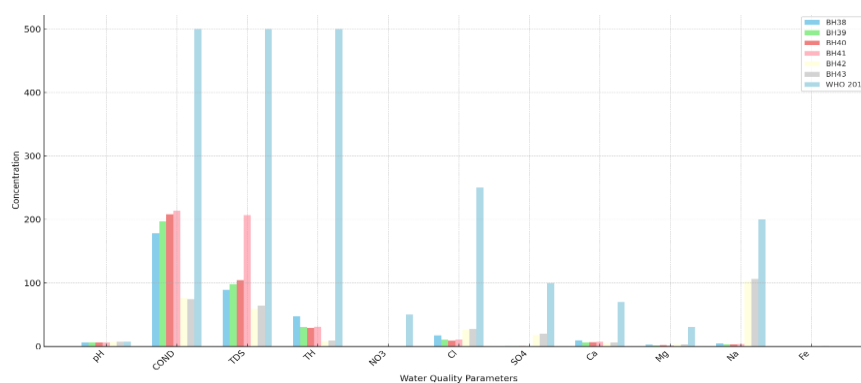


Figure 14. Comparison of water quality parameters in Ogbia Town borehole against WHO standards.

Figure 15 presents the groundwater quality results for Oloibiri (BH27 and BH28), assessed against WHO [51] 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 $\mu\text{S}/\text{cm}$), 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, Otua-bagi, 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.

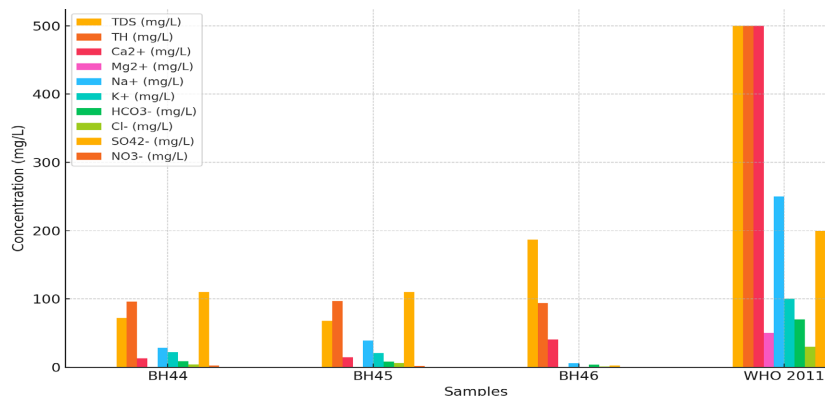


Figure 15. Water quality analysis in Oloibiri borehole vs WHO 2011 standards.

Figure 16 displays the groundwater quality profile for Opume (BH29 and BH30), with results compared to WHO [51] 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 $\mu\text{S}/\text{cm}$), 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.

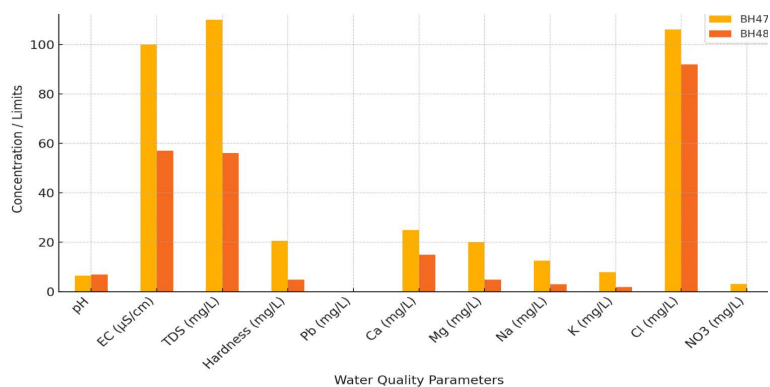


Figure 16. Water quality parameters in Opume (BH 47, BH48) vs WHO 2011 standards.

Figure 17 presents the groundwater quality profile for Akiplai (BH31 and BH32), benchmarked against WHO [51] standards. The pH values (6.6 - 7.0) were within limits, reflecting neutral to slightly acidic water suitable for domestic use. Conductivity (174 - 200 $\mu\text{S}/\text{cm}$), chloride (27 - 31 mg/L), nitrate (5.7 - 6.4 mg/L), calcium, magnesium, and hardness all complied with guideline values, indicating balanced hydrochemical conditions with minimal salinity or nutrient inputs. However, sodium and iron exceeded WHO thresholds, consistent with contamination trends across Ogbia LGA, including Opume, Oloibiri, and Ogbia Town. The key takeaway is that while Akiplai groundwater is largely safe, elevated sodium and iron reduce its suitability for long-term drinking use. This confirms the persistence of these contaminants across the region, linked to both natural hydrogeology and anthropogenic pressures such as oil exploration.

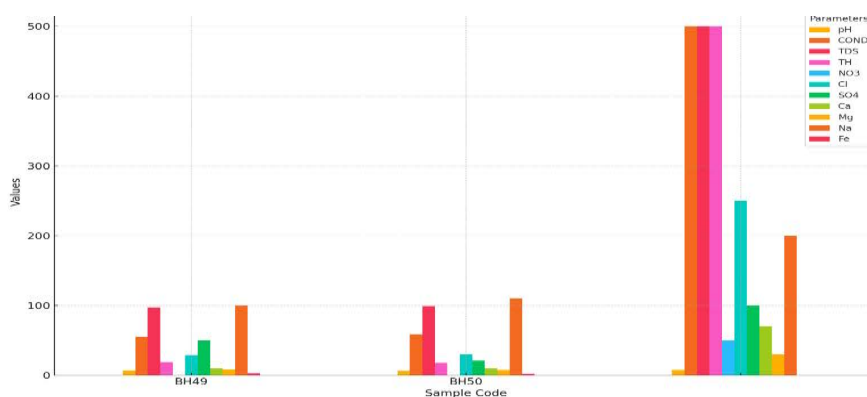


Figure 17. Water quality parameters in Akiplai borehole compared to WHO standards.

4. Discussion

4.1. Oruma-Otuasega-Imiringi

The Oruma-Otuasega-Imiringi axis exhibits generally acceptable physicochemical profiles (pH, EC, TDS), with sporadic spikes in turbidity and trace metals reflecting shallow alluvial aquifer sensitivity to oilfield stressors. Rather than attributing sodium or iron solely to oil exploration, the evidence suggests a link between oilfield proximity and elevated redox-sensitive species, arising from both geogenic and anthropogenic pathways. For example, co-variation of EC/TDS with intermittent Fe/Mn/Pb excursions during wetter periods mirrors hydrochemical behavior in the Ebocha-Obrikom and Mgbede systems, where flaring, pipeline leakage, and hydrocarbon weathering mobilize metals under reducing conditions [1] [13] [69] [70]. Geogenic carbonate and silicate weathering underpin baseline hardness and alkalinity, while anthropogenic overlays such as settlement density, dumpsites, and oil infrastructure leakage contribute further ionic inputs (e.g., nitrate, chloride). At Imiringi, Pb and Fe excursions align with “hot-spots” reported near flare stacks and flow-station corridors [12] [71] [72]. By contrast, steadier profiles at Oruma and Otuasega, narrower interquartile ranges for EC/turbidity and fewer exceedances resemble “good-to-moderate” Water Quality Index (WQI)

bands up-gradient of active facilities [17] [73]. This dual pattern aligns with factor-analytic models in the Niger Delta, which show geogenic baseline chemistry dominated by carbonate/silicate weathering but episodically disrupted by anthropogenic stressors. Overall, Oruma and Otuasega trend toward compliance with fewer outliers, while Imiringi behaves as an “interface” settlement where natural aquifer processes and oilfield activities interact to produce localized exceedances [1] [69] [74] [75].

4.2. Elebele-Emeyal

Building on this spatial gradient, the figures suggest stronger hydrocarbon-settlement coupling in Elebele-Emeyal, where higher dispersion in turbidity, TSS, and color is accompanied by EC/TDS variability and episodic $\text{NO}_3^-/\text{Cl}^-$ elevations, an imprint of mixed land use (busy road corridor, artisanal oil, peri-urban waste). This pattern echoes Port Harcourt peri-urban evidence, where geoelectrical imaging and WQI mapping reveal leachate-driven conductivity and redox anomalies in shallow aquifers [17] [24]. Metal panels imply Pb/Fe/Mn pulses, with Elebele resembling Ebocha-Obrikom “downwind/down-gradient” clusters during rainy recharge [1] [69] [76] [77]. By contrast, Emeyal shows lower central tendencies but pronounced whiskers, indicating point-source intermittency rather than uniform plumes, similar to “patchy” contamination near flare stacks and access roads in Mgbede [12] [32] [78]. WQI boxplots suggest Elebele trends toward “marginal-poor” bands at peak runoff, whereas Emeyal oscillates between “acceptable-marginal,” consistent with seasonal flushing of soil-bound metals and hydrocarbons into groundwater [79]-[81]. Policy-wise, this contrast underscores the value of point-of-use polishing (e.g., low-cost adsorptive media); pilots using TiO_2 -enhanced filters have shown effective removal of metals and turbidity surrogates in complex matrices [82] [83]. Finally, the nitrate-chloride co-movement shown in the figure mirrors food/market waste and sanitation signals documented inland [84]-[88], reinforcing how oilfield stressors and settlement metabolism often overlap.

4.3. Kolo Creek

The Kolo axis emerges as hydrochemically coherent, with broadly consistent medians across pH, bicarbonate alkalinity, and hardness, but site-specific deviations are evident. Kolo-1 registers a slightly wider EC/TDS range, Kolo-3 displays intermittent turbidity-Fe excursions, and Kolo-2 maintains an intermediate profile. This triplet structure aligns with flow-parallel dilution and bank storage dynamics along creek-adjacent sediments, mechanisms corroborated by multivariate loadings in neighboring wetland aquifers [75] [76]. Trace-metal patterns highlight Mn-Fe covariance and occasional Pb outliers, resembling the “mixture” signatures documented in Ebocha-Obrikom and Soku, where reducing conditions mobilize Fe/Mn and infrastructural leakage introduces halides and metals [1] [69] [77] [89]. Seasonal WQI trajectories trending from “good” to “marginal” place Kolo be-

low Elebele in terms of risk, but above Oruma and Otuasega, an ordering recurrently observed where navigation channels and artisanal activity intensify hydrochemical stress [12] [32] [75]. Comparable mid-tier risk gradations, governed by alternating geogenic and anthropogenic drivers, have been reported in Osun gold-mining aquifers, where recharge pulses modulate turbidity and metals [26] [27] [89] [90]. Nitrate and sulfate levels, if modest, suggest limited agricultural contributions and the predominance of bicarbonate chemistry, consistent with carbonate-silicate weathering trends in regional scatterplots and Piper fields [76]-[78]. From a management standpoint, Kolo's profile of "general compliance with episodic outliers" underscores the need for seasonal monitoring complemented by household polishing technologies, a recommendation reiterated in Bayelsa water-security assessments [91]-[93].

4.4. Otuoke-Otuogidi (University-Town Cluster)

Shifting from fluvial-proximal to institutional/settlement centers, Otuoke-Otuogidi share broadly similar core chemistry but diverge on sanitation tracers. Otuoke shows greater $\text{NO}_3^-/\text{Cl}^-$ and turbidity variability, likely from dense population and septic leachate, whereas Otuogidi is steadier with occasional Fe/Mn excursions. This mirrors peri-urban settings where human waste streams elevate ionic strength and microbes, while geology governs redox conditions for metals [86] [93]-[97]. Comparable dynamics appear in Port Harcourt dumpsite corridors, where elevated EC and WQI downgrades arise from multiple small sources rather than pervasive plumes [17] [24] [25]. In oil-province analogs such as Ebocha-Obrikom and Mgbede, settlement metabolism overlapping flare/pipeline zones yields intermittent metal-halide co-peaks, echoing the covariance suggested in metals/major-ion figures [12] [32] [69] [76]. WQI plots typically place Otuoke as "marginal" in rainy seasons and "acceptable" in dry seasons, a see-saw noted for mixed-source aquifers across the Delta [1] [13] [77] [95]-[97]. Given student communities' suitability for point-of-use trials, these findings connect directly to TiO_2 -enhanced filters and other low-cost interventions reducing metals and turbidity [82] [83]. Governance lessons from Bayelsa water studies emphasize stakeholder routines, household testing, and wellhead protection aligned with the "many small sources" profile reflected in Otuoke-Otuogidi dispersion [91] [98] [99].

4.5. Oloibiri-Otuabagi (Legacy Oilfield Axis)

Turning to historic oil heritage, Oloibiri-Otuabagi shows relatively stable base chemistry (alkalinity, hardness) punctuated by episodic metals/turbidity outliers, the expected signature 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 inputs ($\text{Cl}^-/\text{NO}_3^-$, Fe/Mn/Pb), and the mixed loadings reported there mirror the dual-source pattern in boxplots and WQI bands [1] [69] [76] [77]. The metals figure, if showing $\text{Fe} > \text{Mn} > \text{Pb}$ with seasonal widening, aligns with reducing aquifer pockets and or-

ganic-rich soils mobilizing Fe/Mn, also observed along Soku and Ebocha corridors [13] [79]. WQI ratings of “acceptable-marginal” dovetail with Mgbede assessments, finding overall potability but localized risks near facilities [12] [32]. Legacy zones also face VOC fluxes from aged spill strata during high water tables, an exposure pathway flagged for the Niger Delta [80] [81] and consistent with turbidity/color co-rises. Mitigation paths emphasized in regional reviews, monitoring, containment, and community water-safety planning fit the mixed-risk profile implied here [91] [100]. Pragmatically, Oloibiri-Otuabagi’s “mostly compliant with episodic exceedance” status supports sentinel wells and seasonal sampling, while low-cost filters (pilot-tested in challenging matrices) provide interim safeguards [82] [83] [95]-[97]. Thus, to further distinguish geogenic from anthropogenic influences, boreholes located at greater distances from active oilfields such as Ogbia Town, Opume, and Akiplai were treated as relative control points, whereas Elebele, Imiringi, and Oloibiri represented oil-proximal zones. Control sites consistently showed lower mean concentrations of sodium ($175 \text{ mg/L} \pm 30 \text{ mg/L}$) and iron ($1.1 \text{ mg/L} \pm 0.4 \text{ mg/L}$) compared with oil-proximal sites (Na: $245 \text{ mg/L} \pm 50 \text{ mg/L}$; Fe: $1.9 \text{ mg/L} \pm 0.6 \text{ mg/L}$). This pattern reinforces the role of petroleum-related activities in exacerbating redox mobilization and ionic enrichment of groundwater. However, moderate exceedances observed even in control sites suggest an underlying geogenic contribution from iron-bearing sedimentary formations typical of the Benin and Agbada units. These findings substantiate that while natural hydrogeology establishes the baseline chemistry, anthropogenic inputs from oil exploration, gas flaring, and waste mismanagement intensify contamination levels, particularly in Elebele, Imiringi, and Oloibiri. This comparative evidence strengthens the argument that groundwater quality degradation in Ogbia is not purely natural but significantly aggravated by industrial activity.

4.6. Ogbia Town-Opume-Anyama

Central-Ogbia settlements (Ogbia Town, Opume, Anyama) reflect household-sanitation and market-waste signals more than direct oilfield contact. These communities share moderate EC, bicarbonate alkalinity, and hardness, while turbidity and $\text{NO}_3^-/\text{Cl}^-$ dispersion highlight sanitation density, small dumps, and market wastes rather than hydrocarbon inputs. This profile resembles inland peri-urban Abuja (Piwoyi), where latrine and domestic waste dominate ionic and microbial patterns [86] [94]. Seasonal widening of turbidity and nitrate echoes “monsoon pulse” behaviour in Osun groundwater, where recharge mobilizes solids and desorbs metals [26] [27] [89]. Fe/Mn outliers occur, but their redox-control signature differs from oil-proximal clusters; a similar distinction is observed in Mgbede, where community-core wells show steadier metals but wider sanitation tracers [12] [77]. For risk communication, Bayelsa-focused policy reviews recommend hygiene upgrades, wellhead protection, and point-of-use polishing, aligning with WQI middle bands [73] [98]. In pilot studies, TiO_2 -based filters reduced metals/turbidity under comparable conditions, offering feasible near-term barriers

[83] [84]. Broader governance emphasizes integrating water surveillance with flood preparedness, since inundation magnifies latrine and leachate impacts [52] [75] [98]-[104].

Figures 2-17 outline a coherent hydrogeochemical mosaic: bicarbonate-alkaline frameworks dominate (geogenic control), while sanitation, dumps, and oil-field edges drive site-specific departures in turbidity, EC/TDS spread, and redox-sensitive metals (Fe/Mn with occasional Pb). This aligns with Niger Delta evidence: Ebocha-Obrikom and Mgbede exhibit seasonal/spatial heterogeneity linked to facility proximity, settlement metabolism, and flood dynamics [1] [12] [32] [69] [76] [77] [105]. Where WQI panels place most sites in “acceptable-marginal” with episodic “poor,” the gradient matches Port Harcourt dumpsite corridors and underscores the utility of combining geophysics, WQI, and multivariate tools for surveillance [17] [24] [25] [106]-[109]. Seasonal widening of turbidity/metals reflects recharge-driven desorption and plume mobilization, consistent with Soku aquifers and inland monsoon basins [26] [27] [49] [79]. The evidence supports a dual-track response: (i) targeted containment/maintenance near oil facilities; (ii) community sanitation and household treatment. Practical near-term barriers include TiO₂ microporous filters, while longer-term integrated water-safety planning with flood management is essential for Bayelsa’s shifting hydro-social landscape [82] [83] [91] [100]. In sum, the figures refine the regional picture: predominantly geogenic baseline quality punctuated by anthropogenic “hot moments” and “hot spots,” predictable in space and season, and therefore actionable with the right policy technology mix [1] [12] [32] [69]. Thus, while this study provides valuable insight into spatial groundwater quality patterns, it represents a single-season (rainy-season) assessment. Future longitudinal monitoring across both wet and dry seasons is needed to quantify seasonal variability and validate the hypothesized effects of rainfall on sodium and iron mobilization in Ogbia aquifers.

5. Implications for Policy and Interventions

The study underscores the urgent need for multi-level interventions to safeguard groundwater and protect public health in Ogbia LGA. In the short term, the Bayelsa State Ministries of Water Resources and Health should deploy rapid-response monitoring in high-risk communities such as Elebele, Imiringi, and Oloi-biri, alongside public education on the dangers of untreated borehole water. Community-led pilots, supported by local leaders, can introduce affordable filtration technologies targeting sodium and iron removal, ensuring immediate household protection. Over the medium to long term, systemic risks demand sustainable strategies: establishing sentinel borehole networks linked to public health surveillance, strengthening regulatory oversight of oil operations and artisanal refining, and embedding groundwater protection into Bayelsa’s water and health policies. Upgrading waste management, rehabilitating boreholes, and fostering public-private partnerships with oil companies will be critical to financing water safety plans and monitoring frameworks. Finally, a forward-looking research agenda includ-

ing human health risk assessments, time-series monitoring, and hydrogeological studies will generate the evidence base required 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 showed that groundwater across the sixteen sampled Ogbia LGA communities generally met WHO standards for pH, conductivity, chloride, nitrates, calcium, magnesium, and hardness, indicating broad suitability for domestic use in terms of acidity, mineral balance, and salinity. However, sodium and iron consistently exceeded limits in all towns, from Oruma to Akiplai, underscoring systemic contamination tied to both hydrogeological conditions and anthropogenic pressures such as oil exploration, waste disposal, and settlement growth. Spatial variation was evident: oilfield-adjacent communities like Elebele, Oloibiri, and Imiringi bore stronger petroleum-related signatures, while central settlements such as Ogbia Town and Opume reflected sanitation influences. Seasonal fluctuations further shaped water chemistry, with rainy periods intensifying leaching into aquifers. Overall, the findings reveal a mixed hydrogeochemical profile where geogenic baseline controls coexist with anthropogenic "hot spots," producing recurring sodium and iron exceedances.

8. Recommendations

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

1) 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.

2) 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.

3) 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 the Ogbia groundwater pose both direct and indirect health risks to residents. High sodium intake through drinking water is associated with hypertension, cardiovascular diseases, and kidney stress, particularly among vulnerable groups such as the elderly, pregnant women, and individuals with pre-existing health conditions. Excess iron, on the other hand, contributes to gastrointestinal disorders, organ damage under chronic exposure, and aesthetic problems such as metallic taste, staining of utensils, and discoloration of laundry and plumbing fixtures. These issues not only affect health directly but can also reduce public confidence in groundwater as a safe drinking source. It is important to note, however, that the total health impact of sodium and iron exposure depends on cumulative intake from both dietary and water **sources**. For most individuals, food remains the dominant contributor to daily sodium and iron intake, yet groundwater with elevated concentrations can significantly raise total exposure, particularly in rural areas where residents rely exclusively on borehole water for all domestic and drinking purposes. In such settings, even moderate exceedances of guideline values can translate into substantial long-term health risks due to chronic ingestion. Therefore, water quality monitoring should be complemented by public education on balanced nutrition, hydration safety, and the need for simple household treatment systems to limit excess intake from water. Beyond individual health outcomes, the systemic contamination of

groundwater with sodium and iron exacerbates existing public health inequalities. Rural and peri-urban communities in Bayelsa State already struggle with inadequate healthcare, limited sanitation infrastructure, and poor access to treated water. The continued reliance on compromised borehole water compounds these vulnerabilities and increases susceptibility to non-communicable diseases linked to mineral imbalance. Addressing these challenges is thus critical for reducing preventable disease burdens and promoting environmental justice in resource-limited settings. Ultimately, safeguarding groundwater quality in Ogbia LGA is not just an environmental or technical issue but a health equity imperative. Ensuring access to clean, safe, and acceptable drinking water aligns directly with Sustainable Development Goal (SDG) 3 on good health and well-being, and SDG 6 on clean water and sanitation. Integrating groundwater monitoring with community awareness, health surveillance, and responsible industrial regulation is therefore essential for achieving sustainable development in Bayelsa State. Thus, graphically it is represented in **Figure 18**:

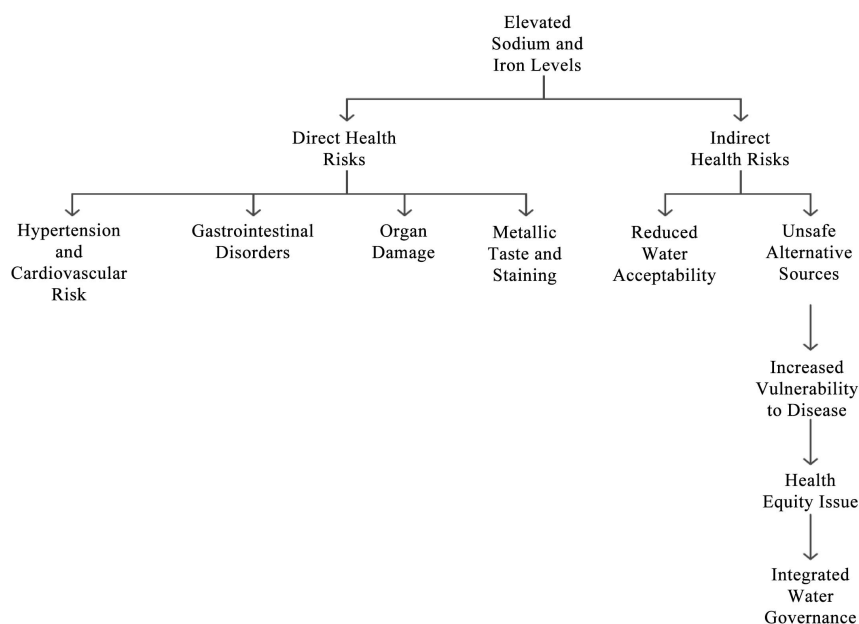


Figure 18. Health risks of contaminated groundwater in Ogbia.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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