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HYDROGEOCHEMICAL CHARACTERISTICS AND QUALITY EVALUATION OF SURFACE AND GROUNDWATER IN AMAI AND ITS ENVIRONS

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ABSTRACT

This study assessed the physicochemical characteristics and quality of surface and groundwater sources in Amai, Ukwuani Local Government Area, Delta State, Nigeria, to determine their suitability for domestic use. Water samples were collected from four strategically selected locations: Novena University borehole, two hand-dug wells (Amai-Nge and Umubu), and the Okwumeshi River. Eighteen physicochemical parameters including pH, electrical conductivity, turbidity, total dissolved solids, major ions (chloride, sulfate, nitrate), and metals (iron, cadmium, selenium, sodium, potassium, calcium, magnesium) were analyzed following standard methods. Water Quality Index (WQI) and Heavy Metal Pollution Index (HPI) were calculated to provide integrated assessments. Results showed that most parameters complied with WHO drinking water guidelines, with low concentrations of sulfate (0.67-2.08 mg/L), nitrate (0.25-3.25 mg/L), ammonia (0.006-0.03 mg/L), and negligible toxic heavy metals, confirming minimal industrial or intensive agricultural contamination. However, three significant concerns were identified: consistently acidic pH across all sites (5.95-6.55), elevated iron concentration in the Amai-Nge well (4.1 mg/L, exceeding WHO guideline four-fold), and high turbidity in the Umubu well (5.95 NTU) and river (5.66 NTU). WQI values ranged from 27.7 to 52.6, classifying the borehole and Amai-Nge well as good quality while the Umubu well and river were rated poor. HPI revealed low contamination in groundwater sources (0.02-14.0) but medium contamination in the river (174.3). The study establishes critical baseline data for water resource management, highlighting the need for site-specific interventions including well rehabilitation, iron removal systems, pH adjustment, and regular monitoring to ensure sustainable access to safe drinking water.

Keywords: water quality index, heavy metal pollution index, physicochemical parameters, groundwater contamination, Niger-Delta, drinking water safety

INTRODUCTION

Water is fundamental to the survival of all living organisms and represents a limited resource requiring sustainable management Alvarez-Bastida et al. (2018). Globally, the achievement of sustainable development goals depends on critical factors including public health, food security, industrial growth, livelihood, and economic development, none of which can be realized without access to quality water Tirkey et al. (2017). The quality and quantity of water resources worldwide remain subjects of ongoing concern Khadr and Elshemy (2017), making knowledge of pollution sources and their impacts essential in environmental water studies Oliomogbe & Emegha (2024); Sallam and Elsayed (2018). Water quality monitoring programs are increasingly necessary due to rising water pollution incidents Nodoushan (2018). However, evaluation of water quality is complicated by the dual contribution of natural and anthropogenic factors to water pollution Zhang (2019). Human activities including the release of domestic wastewater, chemical discharges, pesticides, fertilizers, insecticides, herbicides, radioactive wastewater, petroleum hydrocarbons, dyes, detergents Nasiri, (2018); Nkansah et al. (2019); Emegha et al. (2024), and market waste have resulted in excessive pollutant loading in water sources. Natural factors such as temporal changes in the hydrologic cycle, the origin and constitution of recharged water, and geochemical processes further influence water quality. Water pollution threatens human health, economic development, and social prosperity Jagaba et al. (2019), as exposure to organic pollutants and heavy metal compounds through contaminated water and food can result in chronic and acute toxicities (Nasiri (2018). Consequently, controlling water pollution and monitoring water quality are critical priorities Vasanthavigar et al. (2010).

Groundwater constitutes the major portion of the world's freshwater resources, accounting for 26% of global renewable freshwater Elbeih (2015). Its quality depends on the characteristics of recharged water, atmospheric precipitation, inland surface water, and subsurface geochemical processes Vasanthavigar et al. (2010). Groundwater extracted from deep or shallow hand-dug wells, boreholes, and springs serves as the primary drinking water source for rural communities Bacquart, (2015), representing the most appropriate and accessible water resource for domestic, agricultural, and industrial activities Okeke (2015); Baloyi, (2019); Kanoti (2019). In many developing countries, including Nigeria, surface water systems face significant challenges such as pollution, seasonal flow variability, and inadequate infrastructure. As a result, groundwater has emerged as the principal source of clean and reliable water, particularly for rural and peri-urban populations Adewumi et al. (2023); Akaolisa et al. (2022); Okonkwo, et al. (2025). However, dissolved mineral ions commonly present in groundwater can degrade water quality and limit its usefulness for various purposes, necessitating regular quality assessments to confirm appropriateness for intended use. The availability and affordability of quality groundwater are declining globally Bouderbala (2016), with Nigeria experiencing particularly acute challenges over the past two decades as water supply quantities deplete while demand rapidly increases Hosni (2014). The Nigerian water sector faces enormous challenges requiring integrated mobilization of resources El-Gafy (2018), with rapid population growth and associated human activities identified as root causes of water scarcity Eboh (2017). Improper solid waste management Jagaba, (2019) exacerbates ecological and public health issues Alam (2017) while generating additional socio-environmental effects Sánchez-Arias, (2019). The presence of elevated ion concentrations in groundwater, whether from anthropogenic activities or natural sources, poses threats to human health and can render water unfit for domestic consumption Kanoti (2019), potentially causing waterborne diseases including cholera, typhoid, dracunculiasis, and hepatitis that are common in Nigeria Abubakar, (2016). Therefore, integrated approaches to water quality evaluation are essential to ensure adherence to drinking water standards and protect public health Brhane (2018).

As a developing nation, Nigeria has failed to provide adequate sanitation facilities and potable water from improved sources to its population Oyedele (2019). Citizens rely heavily on unprotected water sources including hand-dug wells, streams, springs, and rivers, while simultaneously using these water bodies and open drainages for waste disposal. This practice creates environments highly vulnerable to flooding and contamination of humans, animals, and the broader ecosystem by pollutants Meride, (2016). The environmental consequences extend to ozone layer depletion, global warming, and sea level rise Jagaba, (2018). Multiple studies have revealed that hand-dug wells in Nigeria require frequent monitoring and protection due to inappropriate siting, shallow depth, inadequate construction standards, and vulnerability to multiple pollution sources Bacquart, (2015); Babu (2013).

Amai, located in Ukwuani Local Government Area of Delta State, exemplifies these challenges. The community relies on poorly constructed hand-dug wells and boreholes, some located near potential pollution sources, without functional surface drainage or waste disposal facilities. Despite these conditions, characterization of groundwater quality for domestic use has not been prioritized, and water from these sources is consumed without quality testing Bouderbala, (2016). Previous research indicates that groundwater near municipal sewage areas can be physically, chemically, and biologically contaminated, posing serious threats to human welfare. However, due to limited community awareness and neglect by authorities, potentially contaminated water from wells in Amai continues to be used for irrigation and domestic purposes without verification of compliance with health standards. This study undertakes physicochemical evaluation of water from selected wells and surface water sources in the research area to determine contamination levels Abusu (2019) and calculate pollution indices that compare individual parameter concentrations against baseline standards Anake et al. (2014). The research aims to assess the vulnerability of groundwater to contamination from wastewater drainage and other pollution sources in the community, establish baseline water quality data, and provide evidence-based recommendations for water resource management and public health protection in Amai and similar rural Nigerian communities.

MATERIALS AND METHODS

Study Area

Amai is a rural community in Ukwuani Local Government Area of Delta State, Nigeria, located within the Niger Delta region between latitudes 5.96°N–6.04°N and longitudes 6.48°E–6.59°E. The area is characterized by two major tarred roads, Obiaruku–Amai and Amai–Ogume connected by several untarred routes. Novena University, the first private university in Delta State, is situated within the community. The inhabitants are predominantly subsistence farmers. The area experiences a tropical climate typical of the Niger Delta, with distinct wet and dry seasons. The study area is characterized by complex sedimentary envi ronments, productive aquifer systems, and high relevance for groundwater development Okonkwo, et al. (2025).

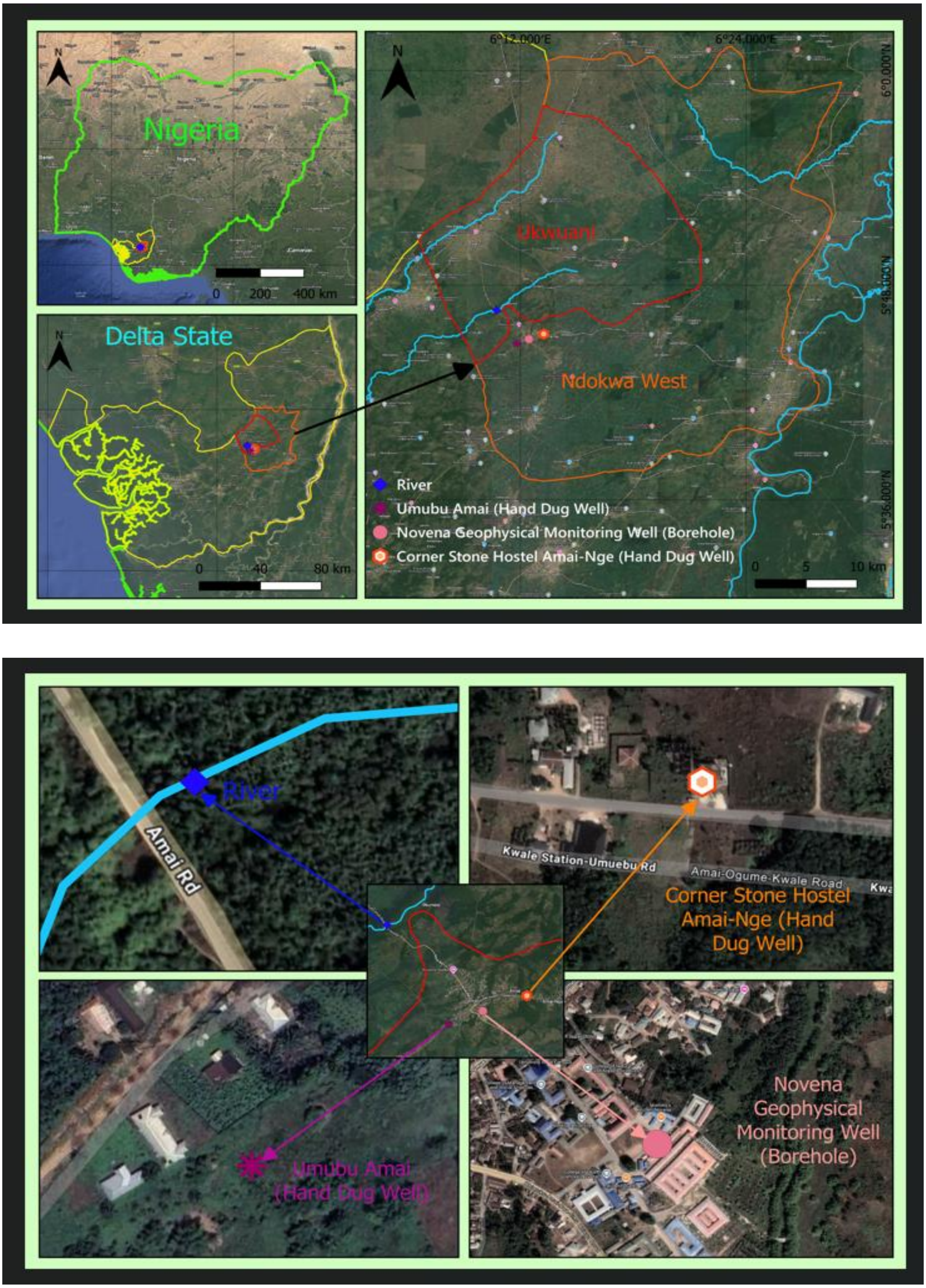

Figure 1: Location Maps of the Study Area and Local sampling Sites and Settlements

Sample Collection

Water samples were collected in June 2025, from four strategically selected locations representing different water sources and varying proximities to the Okwumeshi River. The sampling points included:

1. **Novena University Borehole** (N 05°44'58.9", E 006°12'26.8"; elevation 42 m; depth 23 m),
2. **Amai-Nge Hand-Dug Well** (N 05°45'16.1", E 006°13'14.2"; elevation 22 m; depth 4.6 m),
3. **Umubu Hand-Dug Well** (N 05°44'43.9", E 006°11'49.7"; elevation 29 m; depth 5.47 m), and
4. **Okwumeshi River** (N 05°46'32.1", E 006°10'46.1"; elevation 23 m).

Sampling locations were chosen based on: (i) active use for domestic purposes, (ii) proximity to potential pollution sources, (iii) source type (borehole, hand-dug well, or surface water), and (iv) accessibility. All wells had been in continuous use for at least five years and were structurally intact with no visible cracks or surface infiltration.

For the borehole, water was pumped for 5–10 minutes prior to sampling to flush out stagnant water. Hand-dug well samples were collected using a clean rope-and-bucket method, ensuring no contact between the bucket and well walls. River samples were obtained midstream at approximately 20 cm below the surface using the grab sampling technique.

All samples were collected in pre-cleaned 1-L high-density polyethylene (HDPE) bottles. Bottles were washed with non-phosphate detergent, rinsed with distilled water, soaked in 10% nitric acid for 24 hours, and finally rinsed with deionized water. Before sampling, each bottle was rinsed three times with the water to be collected. Samples for metal analysis were immediately acidified with concentrated nitric acid to pH < 2 to prevent precipitation. Samples were labeled, stored in ice-packed coolers at about 4°C, and transported to the laboratory within 6 hours. Analyses were conducted within 48 hours for most parameters and within 7 days for all parameters.

3.3 Physicochemical Analysis

All analyses followed standard procedures outlined in *Standard Methods for the Examination of Water and Wastewater* (APHA, 2017). Analytical-grade reagents (≥99% purity) and deionized water were used throughout.

- **Temperature and pH:** Measured in situ using a calibrated mercury thermometer (±0.1°C) and a HANA pH meter (Model HI 98129), respectively. The pH meter was standardized with buffer solutions (pH 4.0, 7.0, and 10.0) before each measurement.
- **Electrical Conductivity (EC) and Total Dissolved Solids (TDS):** EC was measured using a HACH Conductivity Meter (Model 446000.00) calibrated with 1413 µS/cm standard. TDS was derived using the relation: TDS (mg/L) = EC (µS/cm) × 0.64.
- **Turbidity:** Determined with a HACH Turbidimeter (Model DR2010) using formazin standards (0.1–800 NTU).
- **Total Hardness, Calcium, and Magnesium:** Determined by EDTA titrimetric methods with Eriochrome Black T (pH 10) and murexide (pH 12) indicators. Magnesium concentration was calculated as the difference between total and calcium hardness.
- **Alkalinity:** Determined by titration with 0.02 N H_2SO_4 using mixed bromocresol green–methyl red indicator to pH 4.5.
- **Chloride:** Determined by argentometric titration using 0.0141

N $AgNO_3$ with potassium chromate indicator (Mohr's method).

- **Sulfate:** Measured spectrophotometrically by the turbidimetric method using $BaCl_2$ at 420 nm.
- **Nitrate and Nitrite:** Nitrate was analyzed via cadmium reduction followed by spectrophotometric detection at 543 nm; nitrite was determined directly by diazotization.
- **Ammonia:** Determined by the Nessler method with spectrophotometric detection at 425 nm.
- **Chemical Oxygen Demand (COD):** Determined by the closed reflux dichromate method with digestion at 150°C for 2 hours, followed by spectrophotometric reading at 620 nm.
- **Metals:** Fe and Mn were analyzed using flame atomic absorption spectrophotometry (AAS, HACH DR 5000™). Na and K were measured by flame photometry, while Cd and Se were determined using graphite furnace AAS. Calibration curves were prepared from certified standards. Detection limits were: Fe (0.005 mg/L), Mn (0.001 mg/L), Na/K (0.01 mg/L), Cd (0.001 mg/L), and Se (0.002 mg/L).

Quality Assurance and Quality Control (QA/QC)

Quality control procedures included reagent blanks, duplicates, and spiked samples to assess accuracy and precision. Calibration was verified using certified reference materials, with precision maintained within ±5% for all parameters. Instruments were calibrated prior to analysis, and calibration checks were performed after every ten samples. All glassware was acid-washed (10% HNO_3) and rinsed with deionized water before use.

Data Analysis

Results were compared with the World Health Organization (WHO, 2008) drinking water standards. Descriptive statistics (mean, standard deviation, minimum, and maximum) were computed using Microsoft Excel 2016. Data were presented in tables and figures for clarity. As this was a preliminary study with single samples per site, inferential statistics were not applied; instead, each site's results were evaluated against WHO guideline values.

3.6 Water Quality Index (WQI)

The Water Quality Index (WQI) was calculated using the weighted arithmetic mean method Horton (1965); Brown et al. (1970) to provide an overall measure of water suitability for drinking.

Step1: Unit Weight: Each parameter was assigned a weight inversely proportional to its WHO standard value. It is calculated using the expression:

$$W_n = K/S_n$$

Where,

S_n = Standard permissibility value of n^{th} water quality parameter.

K = constant of proportionality and it is calculated by using the expression:

$$K = \left[1/\left(\sum 1/S_{n=1,2,\ldots n}\right)\right]$$

Step 2: Quality Rating

The quality rating (q_n) is calculated using the expression:

$$q_n = [(C_i - V_{id})/(S_i - V_{id})]$$

Where

Ci is the measured concentration and *Si* is the WHO standard.

Step 3: Sub-Index

$SIi = Wi \times qi$

Step 4: Overall WQI

$WQI = \sum SIi$

Water quality was classified as follows (Sahu & Sikdar, 2008):

- WQI < 50: Excellent
- 50–100: Good
- 100–200: Poor
- 200–300: Very poor
- 300: Unsuitable for drinking

Parameters used in WQI computation included pH, TDS, turbidity, total hardness, chloride, sulfate, nitrate, iron, calcium, magnesium, sodium, and potassium.

Heavy Metal Pollution Index (HPI)

The Heavy Metal Pollution Index (HPI) was calculated following Prasad and Bose (2001) and Mohan et al. (1996) to quantify the cumulative impact of heavy metals.

Overall HPI

Interpretation of HPI values Prasad & Bose (2001):

HPI < 100: Low contamination (safe), 100–200: Medium contamination (caution advised), 200: High contamination (unsafe)

RESULTS AND DISCUSSION

Table 4.1: Laboratory Analysis Results of Water Quality Parameters in the study area

Parameter	Novena Well (Borehole)	Amai-Nge (Hand Dug Well)	Umubu (Hand Dug Well)	Okwumeshi River	WHO (2008) Guideline
Location (Lat, Long)	N 05°44'58.9", E 006°12'26.8"	N 05°45'16.1", E 006°13'14.2"	N 05°44'43.9", E 006°11'49.7"	N 05°46'32.1", E 006°10'46.1"	–
Elevation (m)	42	22	29	23	–
Well Type	Borehole	Hand Dug Well	Hand Dug Well	River	–
Well Depth (m)	23	4.6	5.47	–	–
Static Water Level (S.W.L) (m)	5.20	3.24	4.57	–	–
Temperature (°C)	26.0	28.0	27.0	26.7	27–28
pH	6.55	6.10	6.00	5.95	6.5–8.5
Electrical Conductivity (µS/cm)	49.53	60.50	110.00	39.20	1000
Total Dissolved Solids (mg/L)	21.00	41.24	71.50	56.50	500

Total Hardness (mg/L)	12.55	21.67	28.94	23.20	–
Turbidity (NTU)	1.05	0.67	5.95	5.66	< 5
Chloride (Cl^-) (mg/L)	7.25	6.55	10.10	14.60	200
Sulphate (SO_4^{2-}) (mg/L)	0.67	2.08	1.18	0.75	200
Nitrate (NO_3^-) (mg/L)	0.30	3.25	1.25	0.25	50
Ammonia (NH_3) (mg/L)	0.008	0.006	0.010	0.030	–
Chemical Oxygen Demand (COD) (mg/L)	1.18	2.86	2.26	4.98	–
Iron (Fe) (mg/L)	0.008	4.10	0.10	0.50	1.0
Cadmium (Cd) (mg/L)	BDL	BDL	BDL	0.005	0.005
Selenium (Se) (mg/L)	BDL	BDL	0.006	0.020	–
Sodium (Na) (mg/L)	0.22	6.45	1.40	0.95	50
Calcium (Ca) (mg/L)	2.45	3.95	4.10	3.10	75
Potassium (K) (mg/L)	2.06	1.86	0.34	0.50	10
Magnesium (Mg) (mg/L)	6.78	8.75	4.56	3.25	50

BDL: Below detectable Limit

Table 4.2: Descriptive Statistical Analysis of Water Quality Parameters

Parameter	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
Temperature (°C)	26.93	0.72	26.00	28.00
Ph	6.15	0.24	5.95	6.55
Electrical Conductivity (µS/cm)	64.81	27.16	39.20	110.00
Total Dissolved Solids (mg/L)	47.56	18.70	21.00	71.50
Total Hardness (mg/L)	21.59	5.88	12.55	28.94
Turbidity (NTU)	3.33	2.48	0.67	5.95
Chloride (mg/L)	9.63	3.17	6.55	14.60
Sulphate (mg/L)	1.17	0.56	0.67	2.08
Nitrate (mg/L)	1.26	1.21	0.25	3.25
Ammonia (mg/L)	0.0135	0.0096	0.006	0.03

Chemical Oxygen Demand (COD) (mg/L)	2.82	1.38	1.18	4.98
Iron (Fe) (mg/L)	1.18	1.70	0.008	4.10
Cadmium (Cd) (mg/L)	0.00125	0.0022	0.00	0.005
Selenium (Se) (mg/L)	0.0065	0.0082	0.00	0.02
Sodium (Na) (mg/L)	2.26	2.46	0.22	6.45
Calcium (Ca) (mg/L)	3.40	0.67	2.45	4.10
Potassium (K) (mg/L)	1.19	0.78	0.34	2.06
Magnesium (Mg) (mg/L)	5.83	2.10	3.25	8.75

Table 4.3: Water Quality Index Summary Result

Site	WQI	Classification
Novena Well (Borehole)	27.70976741	Good
Amai-Nge (Hand Dug Well)	30.85871233	Good
Umubu (Hand Dug Well)	52.64231874	Poor
Okwumeshi River	51.83689425	Poor

Table 4.4: Heavy Metal Pollution Index Summary Result

Site	HPI	Classification
Novena Well (Borehole)	0.020356234	Low Contamination
Amai-Nge (Hand Dug Well)	10.43256997	Low Contamination
Umubu (Hand Dug Well)	13.99491094	Low Contamination
Okwumeshi River	174.3002545	Medium Contamination

The physicochemical analysis of water samples from Amai and its environs, as presented in Table 4.1, revealed considerable spatial variation in water quality characteristics across the four sampling locations. Water temperature ranged from 26°C to 28°C across all sites, falling within the acceptable range for drinking water and indicating no thermal stress that might enhance microbial activity. The Novena borehole recorded the lowest temperature (26°C), while the Amai-Nge hand-dug well showed the highest (28°C). These minor variations reflect differences in well depth and exposure to atmospheric conditions, with deeper boreholes maintaining more stable temperatures due to enhanced insulation from overlying soil layers. Temperature influences various water quality parameters, including chemical reaction rates, gas solubility, and biological processes, though the observed range suggests minimal thermal impact on water chemistry in the study area.

All sampled waters exhibited slightly acidic pH values ranging from 5.95 to 6.55, with the Okwumeshi River recording the most acidic conditions and the Novena borehole approaching the lower WHO threshold of 6.5. As illustrated in Figure 2 and Figure 3, all sampling sites fell below the WHO recommended pH range of 6.5-8.5, indicating a consistent pattern of acidity across different water source types. This uniformity suggests regional geochemical influence rather than localized contamination, likely related to the silicate-rich sedimentary formations characteristic of the Niger-Delta region. Similar acidic pH trends have been documented in groundwater from other parts of Delta State, where values between 5.8 and 6.4 were attributed to limited carbonate buffering capacity in the aquifer systems. While these pH levels are marginally below WHO recommendations, they raise important concerns regarding long-term water quality management. Acidic conditions enhance metal solubility from geological formations and accelerate corrosion of metallic distribution infrastructure, potentially introducing elevated metal concentrations into the water supply over time. The slightly acidic nature of the Okwumeshi River may additionally reflect contributions from dissolved organic acids originating from decomposing vegetation in the watershed.

Electrical conductivity varied from 39.2 µS/cm in the river to 110 µS/cm in the Umubu hand-dug well, with corresponding TDS values ranging from 21 to 71.5 mg/L (Table 4.1). Figure 2 demonstrates that these values are substantially below WHO guidelines (1000 µS/cm for EC and 500 mg/L for TDS), indicating minimal ionic content and limited mineralization. The lower EC and TDS in surface water compared to groundwater sources reflects differential residence times and water-rock interaction processes. Groundwater, particularly from shallow hand-dug wells, undergoes prolonged contact with aquifer materials, facilitating greater mineral dissolution. The elevated EC in the Umubu well, while still within acceptable limits as shown in Figure 3, warrants continued monitoring as it may indicate either natural mineral dissolution or early-stage anthropogenic influence. These findings contrast with water quality studies in industrialized or agriculturally intensive regions of Nigeria, where significantly higher EC and TDS values have been reported due to contamination from industrial effluents and agricultural runoff.

Water hardness ranged from 12.55 to 28.94 mg/L as $CaCO_3$ (Table 4.1), classifying all samples as soft water. This low hardness is consistent with the minimal TDS values and reflects limited presence of calcium and magnesium carbonates in the aquifer. While soft water prevents scaling in pipes and appliances, it provides limited dietary contribution of essential minerals. The calcium and magnesium concentrations measured (2.45-4.10 mg/L and 3.25-8.75 mg/L respectively) were well below WHO guidelines, confirming the soft water characteristics. Figure 3 clearly shows the gap between measured values and WHO standards for these beneficial minerals. These findings align with hydrogeochemical studies in similar geological settings across the Niger-Delta, where low hardness values are typical of rainfall-recharged shallow aquifers with limited carbonate mineral content.

Turbidity measurements revealed notable spatial variation, with the Umubu hand-dug well (5.95 NTU) and Okwumeshi River (5.66 NTU) exceeding or approaching the WHO threshold of 5 NTU, while the Amai-Nge well and Novena borehole showed significantly lower values (0.67 and 1.05 NTU respectively). As shown in Figure 2, this pattern clearly distinguishes shallow hand-dug wells and surface water from the deeper borehole system. The comparative presentation in Figure 3 further emphasizes that only two sites approached or exceeded the WHO turbidity standard. Elevated turbidity in surface water is expected due to natural sediment load and organic matter input from the watershed. However, high turbidity in the Umubu groundwater source is concerning, as it suggests potential surface water infiltration through inadequate well construction or proximity to contamination sources. This observation parallels findings from Edegbene et al. (2025), who reported elevated turbidity in water sources from Benue South, Nigeria, attributing it to poor sanitation practices and inadequate well protection. Turbidity is particularly problematic because suspended particles can harbor pathogenic microorganisms and reduce disinfection efficacy. Given the correlation between turbidity and microbial contamination demonstrated in previous Nigerian studies, the elevated turbidity in the Umubu well may indicate increased health risks that extend beyond the physicochemical parameters measured in this study.

Chloride concentrations ranged from 6.55 to 14.6 mg/L (Table 4.1), substantially below the WHO guideline of 200 mg/L, indicating minimal saline intrusion or industrial contamination. Figure 2 and Figure 3 both demonstrate the substantial margin between observed chloride levels and the WHO standard, with the river showing slightly elevated values compared to groundwater sources. The slightly elevated chloride in the Okwumeshi River (14.6 mg/L) compared to groundwater sources likely reflects cumulative inputs from upstream sources and surface runoff. Sulfate concentrations were similarly low (0.67-2.08 mg/L), well below the 200 mg/L threshold, suggesting minimal influence from industrial activities or agricultural fertilizer use. These findings confirm that the study area remains largely unaffected by intensive agricultural practices or industrial pollution, consistent with its predominantly subsistence farming economy. This contrasts markedly with water quality studies in more urbanized or industrialized regions of Nigeria, where elevated chloride and sulfate concentrations frequently indicate sewage contamination or industrial discharge.

Nitrate concentrations ranged from 0.25 to 3.25 mg/L, considerably below the WHO maximum of 50 mg/L (Table 4.1). The relatively elevated nitrate in the Amai-Nge well (3.25 mg/L), though still safe as depicted in Figure 3, merits attention as it may indicate proximity to nitrogen sources such as latrines or agricultural plots. Ammonia levels were extremely low (0.006-0.03 mg/L), and COD values ranged from 1.18 to 4.98 mg/L, with the river showing the highest value. These consistently low nutrient and organic matter indicators suggest minimal contamination from sewage or agricultural runoff, distinguishing this study area from locations with intensive agriculture or poor sanitation infrastructure. Wonodi et al. (2025) emphasized that agricultural practices and inadequate waste management are major contributors to elevated nitrate and organic pollution in water sources. The low values observed in the present study likely reflect the limited scale of agricultural activities and relatively low population density in Amai compared to more urbanized Nigerian settings. However, the higher COD in the Okwumeshi River warrants consideration, as surface waters typically accumulate organic matter from watershed-scale sources that may not be immediately apparent from point-source assessments.

Metal concentrations, as detailed in Table 4.1 and visually represented in Figure 4, showed dramatic spatial variation, particularly for iron, which ranged from 0.008 to 4.1 mg/L. The Amai-Nge hand-dug well exhibited an iron concentration exceeding the WHO guideline by more than four-fold, while other locations remained within acceptable limits. This anomalous result is clearly illustrated in Figure 4, where the Amai-Nge well shows a pronounced spike compared to other sampling sites. The contrast between the Amai-Nge well and other locations is further emphasized in Figure 3, which compares all measured parameters against

WHO standards. Elevated iron in groundwater typically originates from dissolution of iron-bearing minerals under reducing conditions or from corrosion of metallic well infrastructure. The localized nature of this contamination, absent in the nearby Umubu well and Novena borehole, suggests site-specific factors rather than regional aquifer characteristics. Potential explanations include iron-rich geological strata in localized contact with the Amai-Nge aquifer, corrosion of metallic well lining, or infiltration of iron-rich surface runoff. While iron is an essential micronutrient, excessive concentrations create aesthetic problems including metallic taste, staining, and promotion of iron bacteria growth in distribution systems. These aesthetic impairments reduce water acceptability and may discourage use of otherwise safe water sources. Wonodi et al. (2025) highlighted iron as a priority contaminant in Nigerian water sources due to its prevalence and impact on water quality perception. The findings from the present study underscore the importance of well-specific assessments, as regional water quality surveys may overlook critical localized contamination.

Cadmium was below detection limits in three samples and detected at trace levels (0.005 mg/L) only in the river, while selenium was similarly minimal (BDL to 0.02 mg/L), as shown in Table 4.1 and Figure 4. These negligible heavy metal concentrations confirm that the study area is not impacted by industrial activities, mining operations, or other anthropogenic sources of toxic metal pollution. This finding contrasts with water quality assessments in industrialized regions of Nigeria, where elevated cadmium, lead, and chromium concentrations frequently reflect industrial discharge or mining runoff. Wonodi et al. (2025) emphasized the chronic toxicity risks associated with heavy metals in drinking water, noting their accumulation in human tissues and associated health impacts. The absence of such contamination in Amai represents a positive baseline condition that should be maintained through appropriate land use planning and pollution prevention measures. Sodium and potassium concentrations (0.22-6.45 mg/L and 0.34-2.06 mg/L respectively), as presented in Table 4.1 and Figure 4, were well within WHO guidelines, further confirming minimal contamination from industrial or domestic wastewater sources.

The Water Quality Index values, presented in Table 4.3 and illustrated in Figure 5, ranged from 27.7 to 52.6 across the four sampling locations. The Novena borehole recorded the lowest WQI value (27.7), indicating excellent water quality, while the Umubu well showed the highest (52.6). The Novena borehole and Amai-Nge well were classified as having "Good" water quality (WQI < 50), while the Umubu well and Okwumeshi River fell into the "Poor" category (WQI 50-100). Figure 5 provides a clear visual comparison of WQI values across all sites, making the distinction between good and poor quality water sources immediately apparent. This classification system integrates multiple parameters from Table 4.1 into a single metric, providing a more holistic assessment than individual parameter comparisons. The "Poor" classification for the Umubu well and river primarily reflects the elevated turbidity and slightly higher TDS values at these locations, rather than acute contamination. It is important to note that even "Poor" classification under this WQI system does not necessarily indicate water unsuitable for consumption after appropriate treatment. However, these findings highlight the Umubu well as requiring priority attention for structural improvements or filtration systems to reduce turbidity and associated microbial risks. The WQI approach has been increasingly adopted in Nigerian water quality assessments, as it facilitates communication of complex multiparameter data to non-technical stakeholders and policymakers. Similar WQI classifications have been reported for rural water sources in comparable geological settings across West Africa, where shallow wells and surface waters typically show lower WQI scores than deeper boreholes due to greater exposure to contamination sources.

The Heavy Metal Pollution Index, presented in Table 4.4 and Figure 6, revealed low contamination (HPI < 100) in three locations, with values ranging from 0.02 to 14.0 for the Novena borehole, Amai-Nge well, and Umubu well. The Novena borehole recorded the lowest HPI (0.02), indicating virtually no metal contamination, while the Umubu well showed slightly elevated but still safe levels (14.0). However, the Okwumeshi River exhibited medium contamination (HPI = 174.3), exceeding the critical threshold of 100. Figure 6 dramatically illustrates this contrast, with the river's HPI value an order of magnitude higher than the groundwater sources. This elevated HPI in the river requires careful interpretation. Unlike the localized iron contamination in the Amai-Nge well evident in Figure 4, the river's HPI reflects cumulative inputs across the watershed, including natural geochemical contributions and potential anthropogenic sources upstream of the sampling point. The HPI calculation integrates concentrations of multiple metals from Table 4.1 weighted by their toxicity and WHO standards, making it a sensitive indicator of overall metal pollution. The medium contamination classification for the river does not necessarily indicate acute health risks for short-term exposure, but it does raise concerns about long-term consumption of untreated river water and potential ecological impacts on aquatic organisms. This finding aligns with observations from Nwankwo et al. (2025), who reported bacteriological contamination in surface water sources from Rivers State, Nigeria, emphasizing the multiple pathways through which surface waters become compromised in settings with limited sanitation infrastructure. The present study's HPI results underscore the importance of source water selection, with deeper groundwater sources (borehole and wells) showing substantially lower metal contamination than surface water. This pattern is consistent with hydrogeological principles, as soil and aquifer materials provide natural filtration that reduces metal mobility, whereas surface waters accumulate contaminants from diverse watershed sources with minimal attenuation.

The integration of WQI and HPI, as demonstrated through comparison of Figure 5 and Figure 6, provides complementary perspectives on water quality in the study area. While the WQI identifies the Umubu well as problematic primarily due to turbidity, the HPI reveals no significant metal contamination at this location (HPI = 14.0 versus 174.3 for the river). Conversely, the river shows moderate WQI impairment (51.8) but elevated HPI, indicating that metal contamination is a more significant concern than general water quality parameters in this surface water source. This multi-index approach allows for more targeted intervention strategies: the Umubu well requires physical improvements to reduce turbidity, while the river demands investigation of upstream metal sources and may require more extensive treatment before consumption. Such differentiated assessment is critical in resource-limited settings where water treatment interventions must be prioritized based on risk profiles. The comprehensive parameter dataset in Table 4.1, when synthesized through WQI (Table 4.3) and HPI (Table 4.4) calculations, enables nuanced understanding of water quality challenges that would not be apparent from examination of individual parameters alone.

The consistently low concentrations of sulfate, nitrate, ammonia, and organic matter indicators across all sampling locations, as documented in Table 4.1 and visualized in Figure 2 and Figure 3, confirm that the study area remains largely unaffected by intensive agricultural practices or industrial activities. This finding diverges from water quality patterns observed in more densely populated or industrialized regions of Nigeria, where agricultural runoff and inadequate waste management frequently elevate nutrient concentrations. Edegbene et al. (2025) documented elevated BOD, COD, and microbial contamination in water sources from Benue South, attributing these impairments to poor sanitation practices and proximity of water sources to domestic waste. The present study's results suggest that Amai's predominantly subsistence farming economy and relatively low population density have thus far protected water sources from severe contamination. However, the localized issues identified—particularly the elevated iron in the Amai-Nge well (visible in Figure 4), high turbidity in the Umubu well (Figure 2), and elevated HPI in the river (Figure 6)—demonstrate that water quality cannot be assumed uniform across a region. Site-specific assessments remain essential for identifying localized contamination that regional surveys might overlook.

The consistently acidic pH across all water sources, evident throughout Table 4.1 and clearly shown below WHO thresholds in Figure 2 and Figure 3, represents a cross-cutting concern that warrants regional-level attention. Unlike the localized iron or turbidity issues, the uniform pH pattern suggests a hydrogeochemical characteristic requiring broader intervention strategies. Long-term exposure to slightly acidic water, while not acutely toxic, can accelerate infrastructure corrosion and increase metal solubility from both geological sources and plumbing materials. This secondary contamination pathway may become increasingly important as the community's water infrastructure ages. pH adjustment through simple technologies such as limestone filtration or alkalinity addition could provide cost-effective mitigation at critical supply points.

The absence of significant cadmium, selenium, and toxic heavy metal contamination, as documented in Table 4.1 and Figure 4, represents a positive baseline that should be preserved through proactive land use planning and pollution prevention measures. As Wonodi et al. (2025) emphasized, many water quality impairments in Nigerian settings result from preventable anthropogenic activities, including inadequate industrial effluent treatment, uncontrolled waste disposal, and agricultural intensification without corresponding environmental safeguards. The present study establishes baseline conditions against which future changes can be assessed, providing critical data for monitoring potential impacts of development activities in the region. Given Nigeria's rapid urbanization and agricultural expansion, maintaining the current low contamination status reflected in the HPI values (Table 4.4, Figure 6) will require vigilant enforcement of environmental regulations and community engagement in water source protection.

The microbial quality of these water sources, while not directly assessed in this study, remains a critical knowledge gap. Nwankwo et al. (2025) documented widespread bacteriological contamination in borehole water from Rivers State, with bacterial counts substantially exceeding WHO guidelines and evidence of fecal contamination. The elevated turbidity observed in the Umubu well and Okwumeshi River in the present study (Figure 2, Table 4.1) suggests potential microbial contamination risks, as turbidity is strongly correlated with microbial load. Future research should integrate bacteriological analysis with physicochemical assessment to provide comprehensive water safety evaluation. The detection of pathogenic bacteria including *E. coli*, *Shigella*, and *Salmonella* in other Nigerian water quality studies highlights the public health urgency of such integrated assessments.

The findings from this study have several practical implications for water resource management in Amai and similar rural communities. First, the identification of site-specific contamination through detailed parameter measurement (Table 4.1) and integrated indices (Tables 4.3 and 4.4, Figures 5 and 6) demonstrates that blanket regional assessments are insufficient for ensuring water safety. Well-specific testing and targeted interventions are necessary. Second, the relatively good baseline water quality in terms of nutrients and toxic metals, evident in the comparative analysis presented in Figure 3 and Figure 4, should be preserved through proactive measures including proper siting of new wells away from potential contamination sources, installation of sanitary well seals, and maintenance of adequate separation distances between water sources and latrines or waste disposal areas. Third, the consistently acidic pH documented across all sites (Table 4.1, Figures 2 and 3) suggests a need for pH monitoring and potential adjustment, particularly in distribution systems with metallic pipes. Finally, the elevated HPI in the Okwumeshi River (Table 4.4, Figure 6) indicates that surface water sources require more extensive treatment than groundwater sources, supporting prioritization of borehole development for domestic water supply.

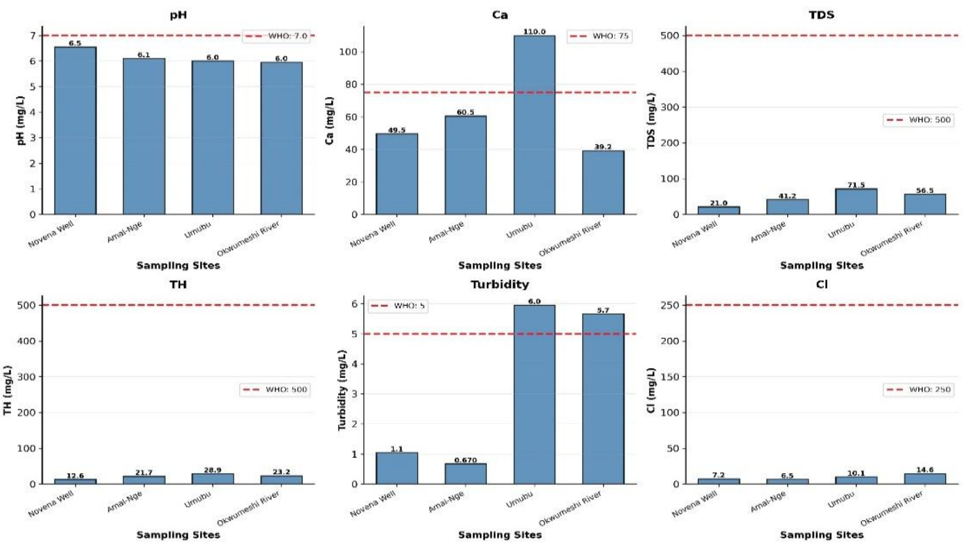

Figure 2: Comparative bar chart of physicochemical characteristics of water samples from the study locations against WHO permissible limits.

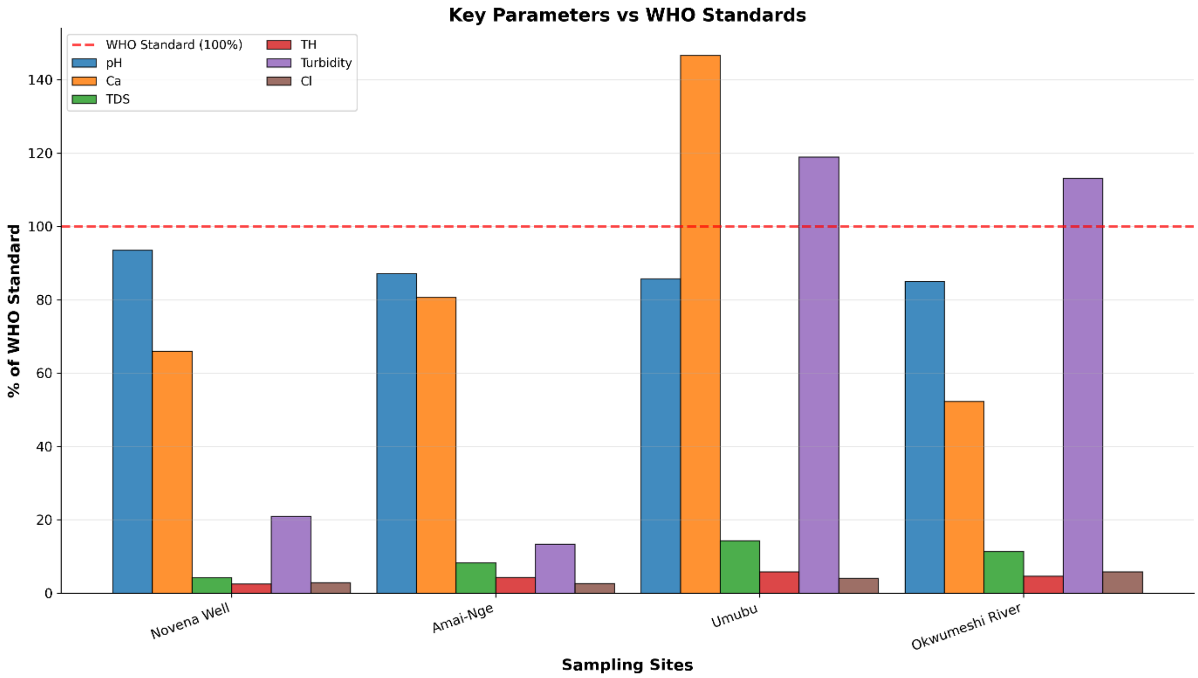

Figure 3: Bar chart showing key physicochemical parameters of the sampled water sources relative to WHO (2008) guideline values.

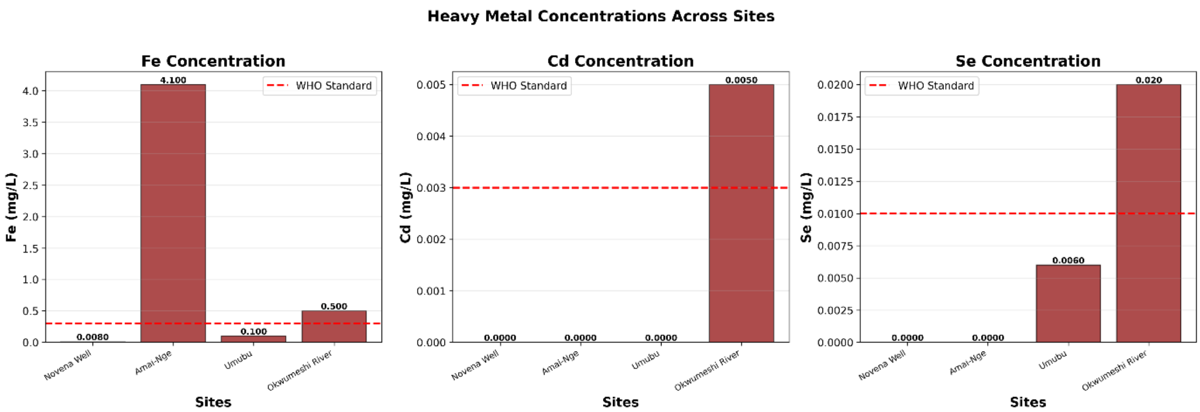

Figure 4: Comparison of heavy metal concentrations across sampling locations relative to WHO (2008) guideline values.

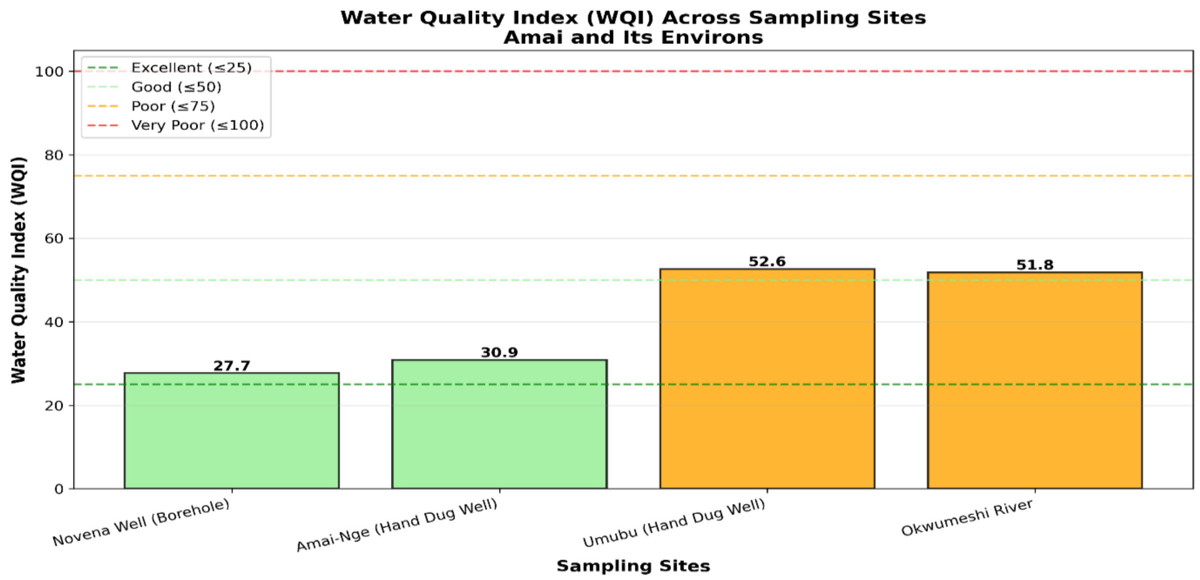

Figure 5: Comparative bar chart of Water Quality Index (WQI) across the sampled locations.

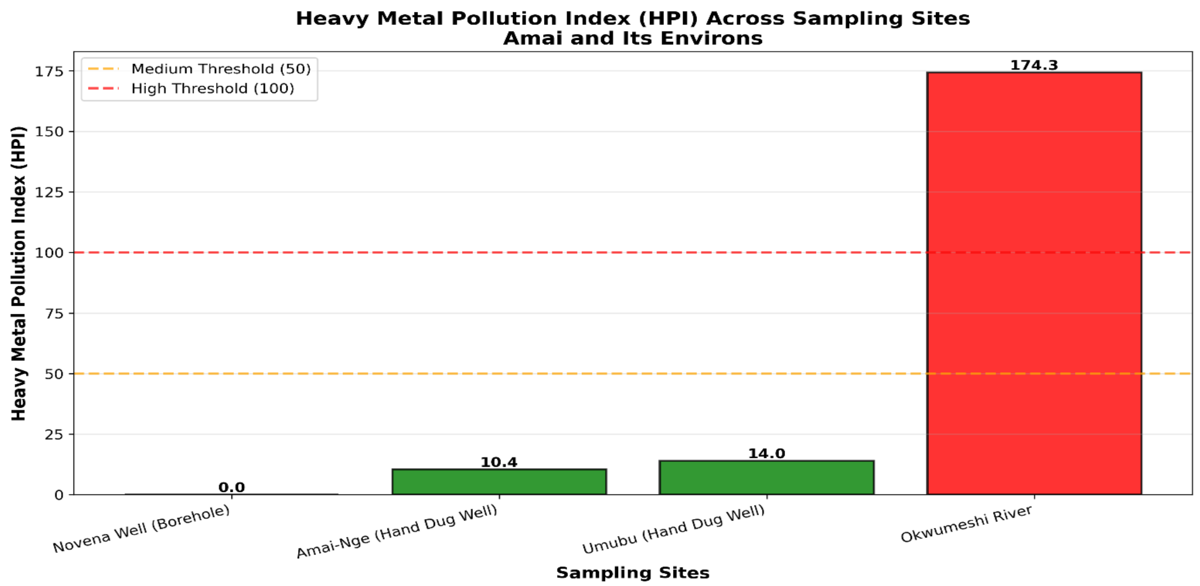

Figure 6: Comparative bar chart of Heavy Metal Pollution Index (HPI) across the sampled locations.

CONCLUSION

This study provides a baseline assessment of water quality in Amai and its environs, revealing generally acceptable physicochemical characteristics across most parameters but identifying specific concerns requiring targeted intervention. The analysis of four water sources, a deep borehole, two hand-dug wells, and surface water from the Okwumeshi River demonstrated that while the area remains largely unaffected by industrial or intensive agricultural contamination, localized issues pose risks to water safety and acceptability. The Water Quality Index classifications identified the Novena borehole and Amai-Nge well as having good water quality, while the Umubu well and Okwumeshi River were classified as poor, primarily due to elevated turbidity. The Heavy Metal Pollution Index revealed low contamination in all groundwater sources but medium contamination in the river, underscoring the differential treatment requirements for surface versus groundwater sources. Three specific concerns warrant immediate attention: the consistently acidic pH across all sites (5.95-6.55), which may accelerate infrastructure corrosion and metal leaching; the excessive iron concentration in the Amai-Nge well (4.1 mg/L), exceeding WHO guidelines four-fold and creating aesthetic impairments; and elevated turbidity in the Umubu well (5.95 NTU), suggesting structural deficiencies or surface water infiltration with associated microbial risks. The absence of toxic heavy metals, coupled with low concentrations of nitrate, sulfate, ammonia, and organic pollutants, confirms that Amai's predominantly subsistence farming economy and low population density have preserved water quality from severe contamination. However, the site-specific nature of identified problems demonstrates that regional assessments alone are insufficient for ensuring water safety. Practical interventions should include: structural rehabilitation of the Umubu well to reduce turbidity, investigation and remediation of iron sources in the Amai-Nge well, pH adjustment at critical supply points to prevent corrosion, and prioritization of deep borehole development over surface water sources for domestic supply. Regular monitoring programs integrating physicochemical and microbiological parameters are essential for tracking temporal changes and detecting emerging contamination before it compromises public health. These baseline data provide a foundation for sustainable water resource management in rural Nigerian communities facing increasing pressure from population growth and development activities.

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